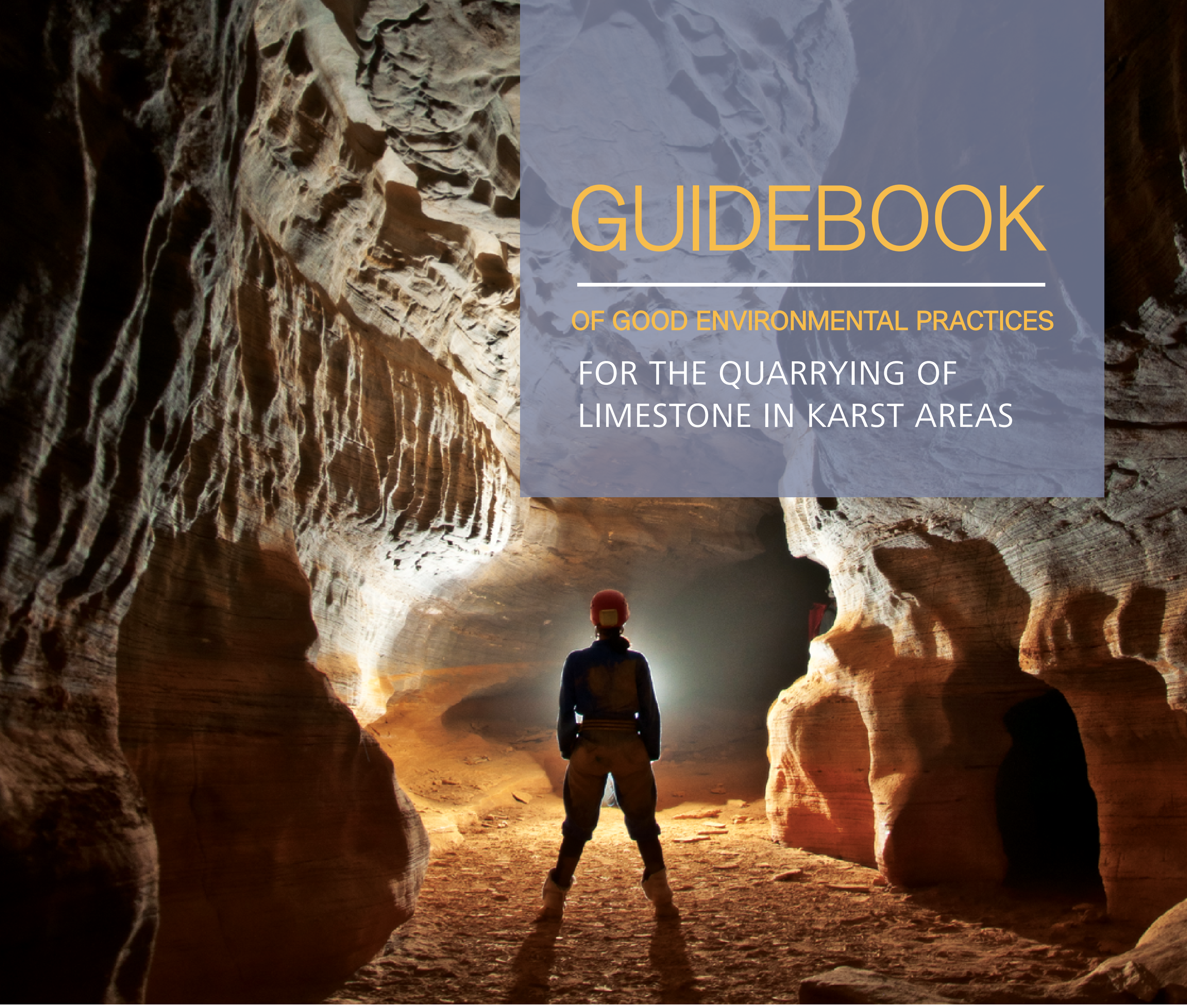

GUIDEBOOK

OF GOOD ENVIRONMENTAL PRACTICES

FOR THE QUARRYING OF LIMESTONE IN KARST AREAS

COOPERAÇÃO TÉCNICA
SBE VC RBMA

sbe Sociedade Brasileira de Espeleologia
www.cavernas.org.br

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(Editors)

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Karst regions, areas with a relief marked by the dissolution of rocks, generally limestone, have as one of their most noticeable aspects, the occurrence of caves, at times housing horizontal and vertical shafts of great beauty and scientific interest. These areas are also important from an economic and social point of view, mainly for the quarrying of this limestone for the production of cement, lime, and other raw materials widely utilized by industry and in civil construction. The reconciliation of the traditional conflict of interests between the speleological heritage and mineral extraction requires finesse in order to propitiate economic exploitation while promoting environmental, historical, and cultural conservation of these important sites.

The Brazilian Speleological Society, since its foundation in 1969, has dedicated itself to the study and conservation of our caves, a concern which has intensified in the past decade, motivated by changes in the legislation which has undermined the protection of the speleological heritage of Brazil while at the same time failing to meet the needs of the productive sector. The Society has made great efforts to improve the legislation, which we believe will only be possible with the approval of a law dedicated to the protection of the speleological heritage, but which will also take into consideration situations where the necessary exploitation of these areas can be contemplated.

Despite the problems faced today, we are lucky to have individuals and entities concerned with the issue, acting not only to respect the legislation, but also concerned with leaving a positive legacy of their work. This was what motivated the agreement for Technical Cooperation between the Brazilian Speleological Society (SBE), Votorantim Cimentos (VC) and the Mata Atlântica Biosphere Reserve (RBMA), an initiative of entities which accept the challenge of understanding their different points of view and are seeking solutions for the responsible management of this heritage, a heritage which also belongs to future generations.

Among the most important initiatives of the partnership is this document, Guidebook of Good Environmental Practices for the Quarrying of Limestone in Karst Areas. This innovative publication, which has involved mining personnel and research workers from various areas, points out trajectories and provides a solid basis for the responsible management of these territories.

The production of this guidebook is an important step, but its success depends on the wide-scale, voluntary adoption of its guidelines by the leading companies in the mining sector, as well as the permanent involvement of research workers, other professionals, and society as a whole in conjunction with the government.

With courage and effort we shall build a better world!

Marcelo Augusto Rasteiro
President of Brazilian Speleological Society (2011 - 2017)

Votorantim Cimentos has been involved in the construction industry for more than eighty years, producing cement, concrete, aggregates, mortar, lime, and other similar products, essential materials in the life of the population. And at the base of our industrial process is the mining of limestone.

However, more than 70% of the caves of Brazil are located in carbonate rocks (according to data from the Brazilian National Register of the Caves of Brazil of the Brazilian Speleological Society) and this is the basic raw material for the manufacture of cement. We must all, therefore, face the challenge of reconciling the conservation of biodiversity and geodiversity and the preservation of landscapes, while respecting cultural issues and tourism in caves and simultaneously meeting the need for development of the society as a whole, an undertaking which requires the utilization of cement in the construction business.

One of the ways of working out this potential conflict was the establishment of a dialogue with the Brazilian Speleological Society (SBE) and the Mata Atlântica Biosphere Reserve (RBMA). This dialogue, historically troubled, has progressed, culminating in 2011 with the signing of a partnership agreement, so that the issues of mining activities and preservation can be discussed together, openly and transparently.

This partnership in itself is already a great victory, since it has succeeded in approximating entities with such distinct and often divergent interests around a common goal of dealing adequately with the challenge of responsible quarrying in areas where caves are found and in the Atlantic Coastal Rain Forest.

Together we have produced this *Guidebook of Good Environmental Practices for the Quarrying of Limestone in Karst Areas*, an innovative publication for the mining sector. It was developed over a period of more than three years, starting with extensive dialogue with the scientific community, the mining sector, and organized civil societies. Its voluntary adoption by companies in the sector should provide a lasting legacy, which can be left for future generations.

We are prepared for the challenges of the present, but are concerned with the construction of the future of the sector; our commitment is to our proposal of perpetuity. We are building our legacy via the work we do, the relationships which we have built up, and our planning for sustainability in the long term. After all, life is made to last.

Walter Dissinger

Director-president of Votorantim Cimentos

The agreement for Technical Cooperation between the Mata Atlântica Biosphere Reserve (RBMA), Votorantim Cimentos (VC) and the Brazilian Speleological Society (SBE) has created an innovative and ambitious partnership. It unites entities with different foci that represent sectors which have traditionally taken different, often conflicting, stands on numerous issues. During the five years of its existence, this partnership has faced the challenge of developing strategic knowledge and useful methodologies which can make a contribution to the society as a whole in the pursuit of sustainable development. In summary, we are attempting to set an example and construct tools for collaboration to enhance the sustainability of mining areas, developing procedures which aggregate value while at the same time decrease the impacts of this extractive activity and promote the conservation of the natural and sociocultural heritage. Conditions must be created to make sustainable quarries feasible, generating commodities and products for this important sector while simultaneously preserving the flora, fauna, and caves, as well as protecting our water supply. We must guarantee the environmental services of social interest in all productive units, and the surrounding environment must be preserved.

This text, *Guidebook of Good Environmental Practices for the Quarrying of Limestone in Karst Areas*, is certainly one of the most ambitious contributions made for promoting sustainability in mining areas. Its indubitable importance is due to the vast knowledge of the renowned specialists participating in its development, engaged in long discussions and exerting great efforts in systematization and summary, and it should certainly be a seminal work in the area. It is hoped that, in addition to providing guidelines for use by mining companies concerned with sustainability, it will contribute to permanent improvement in the legislation and public policies in the country.

Clayton Ferreira Lino

President of Mata Atlântica Biosphere Reserve

INTRODUCTION

Luis Enrique Sánchez

This guidebook was designed to help disseminate good environmental practices in the quarrying of limestone in karst areas. Specialists from a variety of disciplines with professional and academic experience were contacted to prepare a set of recommendations which could help mining companies mitigate the impact of their activities on the natural resources of karst environments and the communities which live there.

The purpose of this guidebook is to (1) provide a summary of information about karst environments, including the processes of formation, their ecological and evolutionary importance, and their role as provider of resources and services for society and (2) contribute to raising the awareness of mining professionals of the importance of karst environments and their vulnerability.

It is hoped that mining companies will adopt the recommendations of this guidebook in their operations and value its contribution to the following:

- Integration of objectives promoting the protection of karst in company policies, procedures, and management control;

- Improvement in the quality of environmental assessments;

- Reduction in risks leading to (1) irreparable environmental damage due to a lack of knowledge or insufficient precautionary measures (ii) operation in non-conformity with regulations, and (iii) damage to the company's reputation;

- Facilitation of the obtention and maintenance of a social license to operate;

- Access of future generations to the resources and services furnished by karst environments.

A realization of the importance of going beyond legal compliance is growing in the mining industry. Generating jobs and paying taxes are only part of what is required for companies to be well received by the communities where they act. Social acceptance, or "social license", has become vital to guarantee the feasibility and permanence of mining in territories endowed with mineral resources. Moreover, business risks grow as social acceptance decreases.

These guidelines provide orientation for the planning and adoption of effective practices for the mitigation of social and environmental impacts in karst areas. They are also intended to help users in understanding the nature and importance of karst environments and the main impacts of quarries on karst and the human populations living there.

Karst regions are characterized by the presence of soluble carbonate rocks, which gives them unique characteristics, such as the presence of caves and underground rivers, unique ecological habitats and frequent paleontological and archaeological sites. The specificities which distinguish karst regions from other kinds of environment should be understood so that economic activities can be developed without ignoring the intrinsic limits to and restrictions on use. Such an approach is necessary if future generations are to have continued access to the resources and social benefits furnished by karst.

Covering some 13% of the exposed land of the globe, or approximately 18 million km^2, karst environments are the source of hydric resources for more than 20% of the world´s population. It is also from karst that most of the minerals utilized in the fabrication of cement are extracted; the annual production of this commodity in the world today is in the order of 4.2 billion tons. Carbonate rocks are also utilized for various other purposes, such as the fabrication of lime, crushed rock for civil construction and powdered rock for the correction of soil acidity in agriculture. It is also used as an input in various other industries, such as those of glass, paper, cosmetics, and pharmaceuticals.

Limestone and other carbonate rocks are among the mineral commodities with the greatest volume of production in the world, being surpassed only by crushed rock and coal, and exceeding that of other important minerals such as iron ore. There are thousands of limestone quarries in the world, from small ones based on manual labor to huge operations supplying large cement factories.

As the demand for carbonate rocks continues to grow (the world production of cement has increased 88% in the ten years between 2005 and 2014 according to data from the *U.S. Geological Survey*), companies, governments, and local communities face growing challenges to reconcile the different interests, needs and perspectives for the use and protection of karst environments.

The importance of karst environments is uncontested. One of the objectives of this guidebook is to show why karst is so valuable and, therefore, why decisions about the use of its resources and the occupation of such areas should be carefully oriented. Quarrying of limestone requires special care and attention because of the vulnerable environment in which it is developed.

Decisions about opening new quarries, as well as about their operation, expansion, and decommissioning *should be grounded on solid knowledge* about the environment, the resources available, and the human communities living there. This principle is especially relevant in karst environments and conveys the main message of this guidebook.

There are numerous cases in which the quarrying of limestone has caused serious and irreversible impacts, such as the loss of caves and the destruction of archeological or paleontological sites. Other noticeable impacts include the loss of outstanding landscapes, the degradation of water quality, the loss of springs which can adversely affect communities downstream, and even the extinction of species.

Prevention and attenuation of these and other adverse impacts is the principle which has oriented the preparation of this guidebook, aimed at professionals in mining companies and governmental agencies, as well as consultants involved in the planning, operation or decommissioning of limestone quarries. The contents should also be of interest to communities, associations, and other civilian entities acting in regions where the quarrying of limestone takes place.

The selection of themes included in this guidebook and the respective issues covered were based on perceived needs and purposes, and reflect the experience and expertise of the individual authors. The specialists who contributed to the elaboration of this guidebook made a great effort to treat each topic clearly and objectively, fully aware of their mission to transmit complex information to uninformed readers.

The use of language accessible to such a heterogeneous public as that targeted by this guidebook does not, however, mean the loss of content, nor its simplification. The effort is reflected in the long period involved in the preparation of this guidebook, which involved intense discussions and debates of the authors.

* * *

Public consultation was also invoked. From December 1 of 2015 to January 18 of 2016, the members of the Brazilian Speleological Society, as well as individuals collaborating with Votorantim Cimentos, environmental and mining consultants, academics and other groups, were given access to the draft of this guidebook and asked for their comments and suggestions using a special form. Fifty-three suggestions were received from nine people; all were considered by the authors, and answers were sent to the respective participants.

* * *

This guidebook presents specific recommendations for karst environments. This means that relevant environmental impacts not specific to such environments, such as degradation of air quality, disturbances caused by light emission, or nuisance resulting from the emission of noise, have not been considered here.

On the other hand, general recommendations for the evaluation of impacts and environmental management, such as the need for involvement of stakeholders, integration of knowledge (including that of the local population), the formation of teams with appropriate ability and competence, and the importance of multi or interdisciplinary work are mentioned in various chapters, although they are not emphasized in the guidebook. Such recommendations can be found in publications of professional and business associations, such as the *International Association for Impact Assessment*, the *Cement Sustainability Imitative, and the International Council on Mining and Metals*.

However, the importance of an ethical stance in the face of the challenges of quarrying in karst environments cannot be overemphasized. For the adoption of the recommendations featured in this guidebook, it is assumed that all agents involved will take an ethical stand. If such an attitude is expected from companies and professionals involved in any kind of mining, this is of paramount importance in karst environments, due to their unique characteristics and fragility, and this will require special efforts to guarantee that future generations will still be able to benefit from resources and services provided.

* * *

The focus of this guidebook is the quarrying of limestone in karst areas. However, it also contains relevant information and recommendations applicable to the mining of other minerals in karst environments, as well as information and recommendations potentially applicable to the planning of mining activities in other terrestrial environments.

* * *

The guidebook is structured in three parts. In the first, the main characteristics of karst environments are summarized in terms of formative processes and their ecological and evolutionary importance, as well as their role in the provision of resources and services for society. It provides information to show why karst is so vulnerable and why human undertakings in such an environment must be so carefully planned, while their implantation and operation should be the object of monitoring and follow-up.

The second part gathers contributions dealing with each of the seven thematic areas: karst systems, caves, biodiversity, underground biology, paleontology, archaeology and community development. The Information summarized in this part of the guidebook provides the basis for the good practices recommended.

The third part presents the actual recommendations for good practices designed to prevent and mitigate adverse environmental and social impacts arising from the quarrying of limestone in karst environments. These are arranged in chronological order according to their relevance in the life of a quarry: feasibility studies, implantation, operation, decommissioning, and post-closure. The recommendations are presented as tables structured in the following manner: 1) statement of the recommendation (what the recommended practice is), 2) justification for that recommendation (why such a practice is important), and 3) examples of how to implement the recommendation.

* * *

The guidebook, in the present version, is not to be considered complete, and perhaps it never will be. The systematic application of these practices, however, in conjunction with the evaluation of the results obtained, should permit the constant updating of the material. This is one of the principles which have oriented the elaboration of this guidebook, as a proposal to be tested by its application in a variety of situations.

Photo: Allan Calux.

PART 1

KARST, A SPECIAL KIND OF ENVIRONMENT

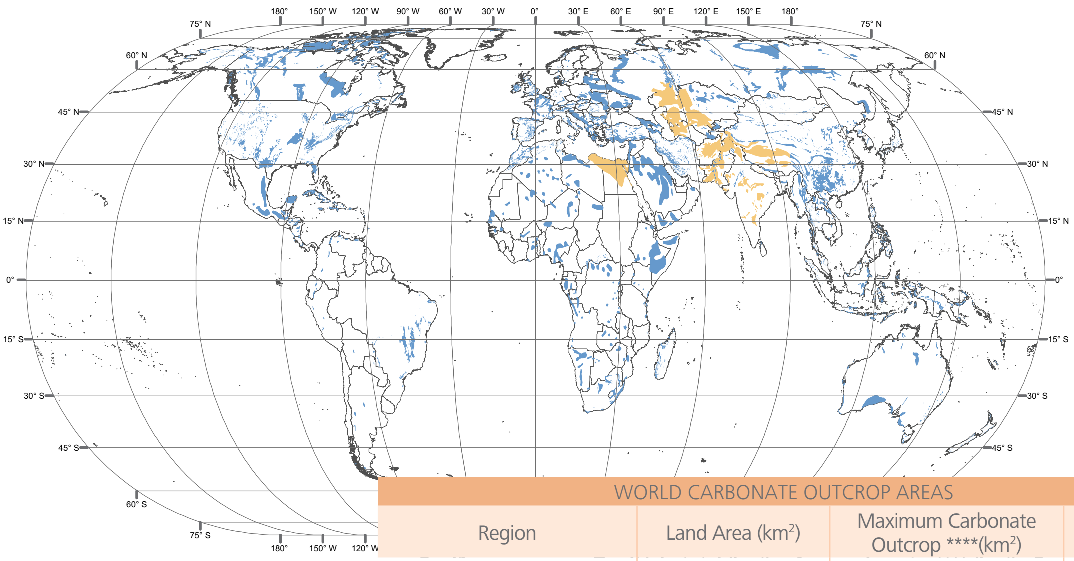
This part of the guidebook provides a summary of the main characteristics of karst areas in terms of the processes of formation and their ecological and evolutionary importance, as well as their role in the provision of resources and services for society. These characteristics show why karst is so vulnerable and why human activities in this environment should be carefully planned.

KARST,
A SPECIAL KIND OF ENVIRONMENT

Mylène Luiza Cunha Berbert-Born, Eleonora Trajano, Allan Silas Calux, Elvis Pereira Barbosa, Luiz Carlos Borges Ribeiro, Francisco Macedo Neto, Luis Enrique Sánchez, Solange Silva Sánchez, Ana Claudia Neri, Heros Augusto Santos Lobo

Planet Earth has an enormous diversity of natural environments, each formed by a set of unique processes and featuring physical and biological attributes that define its landscapes. Mangrove swamps, beaches, deserts, river deltas, lakes, and the abyssal zone of the oceans, as well as karst, are all examples of specific natural environments.

The karst environment is one of the most spectacular in relation to the landscape, the biota, and the dynamics of the processes involved. It is also one of the most fragile, and of greatest environmental and cultural value. Karst environments occupy nearly 15% of the planet's ice-free continental land, expose outcrops of carbonate rocks to geographic and climatic conditions favorable to their dissolution (Ford and Williams 2007; Wiliams and Fong 2010). These environments are found on all continents. For example, they occupy 35% of the territory of Europe, encompassing significant portions of countries such as Italy (15%), Spain (22%), and France (33%) (Zwahlen 2003). In Brazil, vast areas of carbonate rocks are also found, occupying some 200,000km² of the national territory (Figure 1).



WORLD CARBONATE OUTCROP AREAS			
Region	Land Area (km²)	Maximum Carbonate Outcrop ****(km²)	Percentage
World*	133448089	17655024	13,2
Russia	20649781	39936339	19,3
South America	17792882	370809	2,1
Africa	30001574	3041664	10,1
North America**	22229293	4076077	18,3
East and Southeast Asia	15638629	1688219	10,8
Middle East and Central Asia	11129677	2554380	23,0
Europe***	6125842	1337635	21,8
Australasia	9611377	592601	6,2

*Excluding Antarctica, Greenland, and Iceland
**Excluding Greenland
***Excluding Russia and Iceland
****Maximum area of outcrops

Figure 1. World Carbonate Outcrops Areas, v. 3.0. The blue represents relatively pure and continuous carbonate rocks; the orange indicates impure carbonate rocks in discontinuous outcroppings. Williams and Fong (2010). Layout by Mylène Berbert-Born from shapefiles available at *http://www.fos.auckland.ac.nz/our_research/karst/index.html* The University of Auckland, New Zealand).Download 12/04/2014.

Karst includes land of generally irregular relief, with a very diversified but characteristic set of geomorphological features, such as extensive areas of exposed rocks with rough and pointed surfaces, where tower-like rock forms and other exotic formations set up the landscape. Underground rivers and closed depressions generally circular in shape, known as sinkholes or dolines, are other typical karst features (Figures 2 and 3).

Here water easily infiltrates the surface, especially since the soil is generally thin and the underlying rock is highly fissured. For this reason, the majority of the drainage channels found in these areas are not subject to a permanent flow of water, but rather are active only during periods of relatively intense rainfall. The few perennial creeks usually flow for only short distances on the surface before disappearing into swallow holes, many times reappearing again in far-distant locations after traversing long underground passages. It is often possible to enter these passages where the water still circulates or has circulated below the surface. These are the so-called caves, another feature characteristic of karst environments.

Figure 2. Resurgence of an underground river located in the western part of the state of Bahia (Brazil). Underground conduits formed by the dissolution of carbonate rock are typical of karst environments. Photo: Rafael Costa da Silva

Figure 3. Limestone massifin Central Brazil with small to medium-sized surface dissolution features known as karren or lapiez, very common in karst landscapes. Photo: Mylène Berbert-Born.

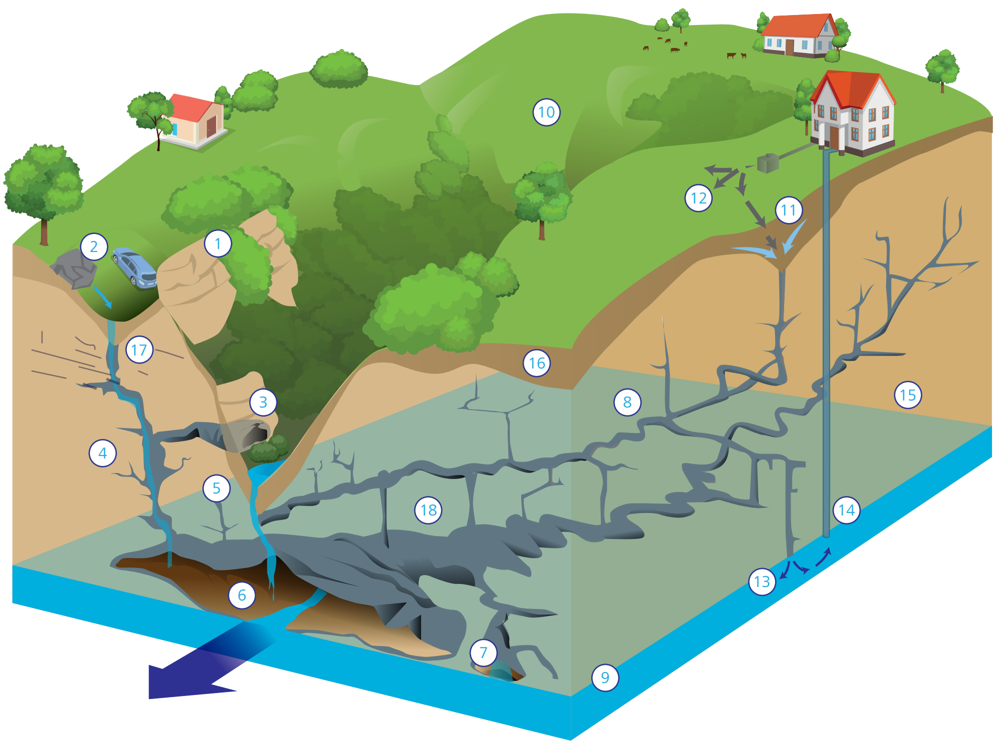
These most noticeable and peculiar aspects of karst –irregular relief/surfaces, outcroppings of ruiniform rocks, sinkholes, underground water circulation and networks of caves (Figure 4)–arise from a basic situation: the existence of carbonate rocks, normally fractured, which can easily be dissolved by water, more so than any other kind of rock.

The most common carbonate rocks are limestone, dolomite and marble, all consisting of more than 50% of calcium carbonate, in the form of calcite [$CaCO_3$]; or of calcium and magnesium, in the form of dolomite [$CaMg(CO_3)_2$]. Varying proportions of other minerals, such as sulphides, sulphates, phosphates, oxides and silicates, may also be present, but even more ubiquous are significant amounts of clay minerals, which are considered "impurities" of the carbonate rock since they greatly reduce the degree of solubility.

The dissolution process depends not only on the chemical and mineral composition of the rock, but also on the chemical conditions of the available water, which must be somewhat acidic. This is characteristic of rainwater, which contains carbonic acid (H_2CO_3), due to the assimilation (solubilization) of the carbon dioxide (CO_2) present in the atmosphere and organic matter from the soil. Other kinds of fluids arising from the rock mass itself, such as deep-formed mineral or thermal solutions, can also be involved in the dissolution of the rock.

The percolation of water through the rock is facilitated by the existence of structural discontinuities, such as sedimentary bedding, mineral veins, laminations, fractures and faults of tectonic origin. These structures are gradually enlarged by dissolution, greatly increasing the capacity of water to flow through the underground environment thus bringing about a progressive increase in permeability. The process evolves by the formation of complex networks of fissures and small channels articulated with larger conduits that act as underground water drains. Some segments of these subterranean networks may be accessible to humans, thus comprising the caves (Figure 5).

The chemical reactions of rock dissolution only cease when the water becomes saturated with dissolved carbonate, i.e., when its dissolution capacity is exhausted. At this point, mechanical erosion becomes more important in the configuration of drainage.



1. Uniform limestone towers 2. Sinkhole with swallow hole 3. Cave entrance in slope 4. Shafts and vertical infiltration 5. Influent Drainage (input from river bed) 6. Main underground conduit 7. Underground overflow conduit 8. Network of secondary conduits 9. Water table 10. Karst hills with ravines 11. Covered sinkhole 12. Source of contaminant infiltration (domestic sewage) 13. Contaminated groundwater 14. Contaminated well 15. Carbonate rock 16. Soil 17. Epikarst 18. Endokarst

Figure 4. Elements of the karst landscape.Adapted by Daniel Borges from MDC State Park *(https://mostateparks.com/content/karst)*, access on 6/17/2016.

Figure 5. Underground conduit in a cave: the morphology and other features present in caves indicate how the water circulates in the underground environment. Water pressure, fractures and rock layers are some of the controlling factors. Photo: Mylène Berbert-Born.

Given the existence of open spaces in the underground environment, these are subject to the influx of materials from the surface, carried in by rivers and runoff, or the creep of masses of soil down the slopes. Slow progressive infiltration through the fissures can introduce material, as well as the drastic collapse of the soil and rock covering the subterranean voids. These dynamic relations between the surface and underground environments give rise to the classic karst landscapes (Figure 6).

Although the karst relief is normally irregular and quite diverse, its forms and drainage system generally have a clear overall organization. They are usually structured from up stream to downstream in areas of absorption and water capture, areas of water circulation (transmission) and areas of discharge. It is worth noting that the volume and chemical composition of the water, as well as the way the water enters the under ground realm, whether diffusely through the soil or punctually in places such as sinkholes or swallow holes, and whether it takes place continuously or in pulses. These are crucial issues for the underground flow regime. Consequently, these are determining factors for the geometric, planimetric and morphologic patterns observed in underground networks.

But it is important to point out that, depending on the stage in the evolution of the landscape and the depth of topographical incision (erosion base level), the karst phenomena can also exist deep underground without any surface evidence. Such non evident karst can occur when rocks subject to dissolution are overlapped or confined by non-soluble rocks (subjacent karst). It also occurs when thick unconsolidated colluvial and alluvial sediments overlie an ancient karst relief (mantled karst, covered karst, buried karst, paleokarst). Or even when fluids promoting the rock dissolution come upward from deep-seated sources, arising from mixed solutions and chemical reactions in the rock itself (hypogenic karst).

One of the characteristic features of karst is caves, which are natural underground voids large enough to permit human access. Caves have extremely varied shapes and dimensions. Their entrances are normally exposed by the subsidence of soil and sediments, the collapse of debris, or the intersection of the cavity by the progressive erosion of a slope (Figure 7). However, a large number of caves remain hidden inside the rock block and cannot be entered.

Figure 6. Typical aspect of karst relief, influenced by man: undulating surface and limestone cliff with cave opening delineating the contour of a depression (sinkhole) which houses a karst pond. Karst lakes often indicate the outcrop of the water table on lowered surfaces, or result from the accumulation of water duetorelatively impermeable clayey soil lying at the bottom of these basins. Given the usual scarcity of surface water in karst areas, and the more fertile soils present in such basins, these sites tend to be used for agriculture, commonly causing the silting up of sinks as well as the contamination of groundwater by pesticides. Lapa Vermelha Cave in Pedro Leopoldo county, state of Minas Gerais (Brazil). Photo: Mylène Berbert-Born.

Figure 7. Entrance of Gruta Angelica (Angelica Cave), state of Goiás (Brazil). Photo: Allan Calux.

Dissolution caves provide registers of the flow of water and the conditions of their formation. The study of marks observable on the roof, walls, and floor of caves often makes it possible to interpret their origin. Galleries represent basically horizontal passages, while shafts and cupolas are predominantly vertical ones. Shafts are generally formed by water flowing vertically along fractures in the vadose or unsaturated area, i.e. above the level of the groundwater contained in a rock massif. Cupolas, on the other hand, may reflect formation in an area of transition in contact with both water and air.

Galleries also vary greatly, and can be found in a variety of forms, such as canyons, tubes, fissures, and slits. Canyons reflect a moment in the evolutionary history of the cave when the underground water in search of the local base level cuts down through the rock in a search for hydrodynamic equilibrium, intercepting all of the obstacles along the course. Tubes, on the other hand, show phreatic or vadose flow under pressure. Fissures are the openings along the discontinuities in the rock, such as faults and fractures and the spaces between bedding planes, all of which can become enlarged and facilitate the circulation of water.

The rooms or chambers in caves generally have relatively large dimensions, i.e., they are more spacious than the nearby conduits. They are commonly formed by the intersection of two or more conduits, with the cause tending to be large collapses. Large chambers can also be the result of erosion and dissolution upstream, caused by overflow resulting from points of narrowing or conduit obstruction.

One especially noticeable characteristic of caves is speleothems, the name given to the formations resulting from the re-precipitation of calcium carbonate dissolved in the aqueous solutions which circulate in the rocky massif. When the slowly flowing water of percolation reaches the air-filled underground void of a cave, the chemical equilibrium of the solution changes, and the dissolved ions re-combine with each other, again forming solid crystals (Figure 8).

Stalagmites (speleothems which grow up from the floor) are of particular scientific interest. Growing very slowly, their very thin layers maintain the chemical signs of the water which dripped down to form them. Thus, they can register atmospheric patterns with a high temporal resolution, including many aspects related to the climate in the past, such as the historical intensity (amount versus time) and persistence of rainfall, temperature variations, type of vegetation, and composition of the soil and the atmosphere in general. Accurate, long-term records of global, regional and local climate changes over the past thousands or tens of thousands of years (Quaternary period) can thus be retrieved from these exclusively karst formations, making caves excellent sources for the study of the Paleoclimate, a topic of great interest in promotinga better understanding of global climate changes.

Not only speleothems, but also the sediments deposited inside caves, provide a register of the recent history of the planet. Underground cavities constitute an important environment for fossilization. They provided refuge for prehistoric animals, butthey also served as traps, and they thus provide a paleontological register of the fossil fauna of the Pleistocene.

The study of fossils found in caves in the karst of Lagoa Santa, in the state of Minas Gerais (Brazil), for example, has generated important scientific information. The naturalist Peter Lund made excavations in more than a hundred caves between 1836 and 1844 and amassed a fabulous collection of Pleistocene fauna. Caves in other parts of Brazil have also brought to light highly relevant paleontological findings which have made it possible to fill in gaps in the evolution of various species, especially terrestrial ones, and have systematically contributed to the advance of the paleontology of the Quaternary. These include the so-called Gruta do Urso Fóssil (Cave of the Fossil Bear) in Ceará, where, in 1979, an almost complete skull of a bear extinct since the Pleistocene was found. The Toca da Boa Vista (Boa Vista Cave), in the state of Bahia, considered to be the largest cave in the southern hemisphere, is another example of a location very rich in fossil remains, such as those of a giant primate extinct for some 15,000 years.

Other relevant discoveries were also made by Lund in the caves of Minas Gerais, where many human bones were found in conjunction with fossils of extinct animals.

Not only do fossils result from the fauna either trapped in caves, or dragged in by the water, but the carbonate rocks in which the cave developed can themselves contain fossils, such as formations of the Eocene epoch (37 - 55 million years ago) in the north of France and of the Ediacaran period (600 million years ago) in the Sete Lagoas geological formation in Brazil. The latter have recently revealed fossils showing the presence of shallow seas on the ancient continent of Gondwana. Moreover, the repeated structures of stromatolites show the exuberance of life forms in the seas during the Proterozoic (2,500 - 600 million years ago). Indeed, the register of the entire evolutionary history of life on the planet is contained in carbonate rocks, from the most ancient and primitive forms to the most recent ones; this is represented by a multitude of fossil groups and is of great significance for the science of Paleontology.

Figure 8. Soda straw stalactites, a frequent type of speleothem in caves.Like many other types of speleothems, stalactites form when the ions dissolved in the percolating solution precipitate (recrystallize) upon entering in equilibrium with the atmosphere in the cave, generally as crystals of calcium carbonate ($CaCO_3$). Photo: Mylène Berbert-Born.

Figure 9. Limestone pavement.Vegetation grows by taking advantage of small amounts of residual soil accumulated in the grooves and dissolution fissures. Photo: Mylène Berbert-Born.

Karst landscapes are found at all latitudes. In the intertropical zones, many karst areas are characterized by a mosaic of different plant formations, composed of both forested and open areas. In general, the forested areas tend to be more prevalent in places where the soil is deeper and water retention is greater, whereas open vegetation is generally found in places with thin layers of soil or on exposed rocks (Figure 9). Factors such as slopes and their orientation, luminosity, and kind of substrate give rise to the formation of various micro habitats, which contribute to the notable biodiversity of karst environments, especially since they host plant and animal species which are often restricted to these environments (Figure 10).

In addition to being a determining factor in the formation of karst, water creates special environments characteristic of these landscapes; these also constitute important habitats for fauna. Due to the hydric dynamics typical of karst environments, the surface water, even in comparatively limited quantities, can form complex systems of lotic (running water) and lentic (still water) environments, including lakes which are connected by natural underground canals. Due to the cycle of rainfall, these environments tend to pass through cycles of high and low water throughout the year, even at times drying up completely. This is important in the dynamics of the biota associated with them, since they host resident and non-resident animal species.

Figure 10: Karst canyon with a river providing constant moisture to the inner habitat, contrasting with the dry upper rims, where more seasonal vegetation is found. Gruta da Igrejinha (Igrejinha Cave), state of Bahia (Brazil). Photo: José Aloísio Cardoso.

Not only is there a great diversity in habitats, but the presence of numerous endemic plant and animal species makes karst areas a high priority for the conservation of biodiversity. However, with few exceptions, most studies of biodiversity in karst areas concentrate on the cave environment itself and the associated fauna, with little attention being given to typical karst surface environments.

The underground environment consists of networks of interconnected spaces of varying sizes underneath the soil; these form large networks of heterogeneous spaces which are filled with water or air. Such continuous networks of spaces can form in solid rock, especially carbonate ones, but also in relatively deep deposits of sediments, such as those found along and under rivers and lakes; this is known as the interstitial medium. Whether or not caves are present, this underground network corresponds to a continuous biological habitat, either a system sheltering aquatic or stygofauna or the rock massif sheltering terrestrial fauna.

In contrast to the surface or epigean medium, the underground (hypogean) medium is characterized by the permanent absence of light and a tendency to environmental stability. In such an hypogean medium, food production is basically restricted to the products of chemical synthesizing bacteria. Only rarely can such bacteria sustain an expressive number of metazoarians. The living beings found there (animals, fungi, protists, and non-chemical-synthesizing bacteria) must thus be basically sustained by the various food resources imported from the epigean surface:

1) remains of plants and animals, dissolved organic material and living animals carried in by the water in rivers and floods, and even that of percolation;

2) feces of animals which enter and leave regularly (trogloxenes; see below), feeding outside the cave, but regularly defecating inside; the guano of bats is especially important. The dead bodies of these animals, as well as those of others which accidentally fall into caves, also constitute sources of food;

3) spores, pollen, and bacteria which may be carried in the air (aeroplankton); and

4) roots, especially when penetrating into shallow caves. However, as a whole, such sources of food available in the underground medium rarely provide as much food as exists in the epigean medium, where the large biomass of photosynthesizing organisms can sustain numerous communities of animals.

Underground organisms are those which have an ecological relationship defined by this environment; the hypogean medium constitutes part or all of the habitat of the species. These organisms are at least capable of spatially orienting themselves in the dark and are usually classified according to their ecologic relationship with that environment, independent of the zoological taxonomy:

1) trogloxenes (organisms regularly found in the underground medium, but which must return periodically to the surface to complete their life cycle);

2) troglophiles (underground populations of species adapted to live both in the epigean and hypogean environment, with individuals able to complete their entire life cycle in either of the two. Those close to the transition are able to move between them);

3) troglobites (species living exclusively in the underground environment, usually characterized by the regression or absence of eyes and dark (melanic) pigmentation of the skin).

Figure 11. Examples of troglophiles: wandering spider (genus Ctenus) eating a cricket (genus Endecous). Photo: Abel Perez Gonzalez.

Figure 12. Brazilian stygobites catfish, with neither melanic pigmentation nor eyes. Photo: Dante Fenolio.

It is important to point out that the trogloxenes, troglobite and troglobites interact with each other in a relationship of interdependence, being equally important from an ecological point of view. All of these groups contribute to biodiversity (including philogenetic and functional diversity), as well as genetic, morphologic, and ecologic diversity. Hence, all should be the focus of attention and concern for the purpose of conservation.

The underground fauna of Brazil is characterized by great diversity, not only the largely terrestrial troglophiles, but also the stygobites. Among these are relict fish and crustaceans (Relict animals are those with no close known living relatives due to the extinction of most of the group.) Stygobite fish are known worldwide due to their diversity, not only in richness of species (some 30 species, mostly catfish) as well as in habitat and degree of specialization in the underground environment. Minuscule relict crustaceans of the order Spelaeogriphacea were distributed in various regions of the ancient supercontinent of Gondwana (Australia, South Africa, and Brazil) and are an icon of the Serra da Bodoquena (Bodoquena Mountain Range) in the Brazilian state of Mato Grosso do Sul, and relict isopods of the Calabozoidea are found in Venezuela and in the states of Mato Grosso and Bahia in Brazil.

The underground terrestrial fauna also show great diversity, especially in spiders (order Aranae), of which there are at least 33 families; these are the main predators in Brazilian caves. Other cave dwelling arachnids include the giant whip scorpions of the order Amblypygi, the miniature Pseudoscorpions, and the omnivorous harvestmen of the order Opiliones (long-legged arachnids often confused with spiders); cave crickets (Class Insecta) and millipedes (Class Diplopoda) are also frequent residents of caves.

Another distinctive characteristic of caves in all of Latin America is the diversity in neotropical bats, with food habits ranging from omnivorous to diets confined strictly to insects, fruit, nectar or pollen, as well as bats feeding on other animals or blood. The only hematophagous vampire bats in the world are found in Brazil. This diversity in diet contributes to the unique diversity in the kinds of guano available as a substrate and source of food for cave invertebrates, and some species are dependent solely on this resource.

Since karst regions intrinsically feature areas of high permeability, they present certain important characteristics in relation to occupation and the use of their resources by human populations. Surface water for consumption may be limited, and the groundwater available is more vulnerable to contamination than is that of other environments, since infiltrating pollutants are quickly carried down to the underground reservoirs without time for filtering and purification.\

Figure 13. Colony of hematophagous bats. Photo: Luis Fábio Silveira.

Moreover, the surface is naturally subject to abrupt subsidence (sinking), either from the sudden collapse of voids existing in the depths or by displacement of large masses of soil into these underground spaces. Even though such changes are part of the natural evolution of karst landscapes, the collapses can be triggered, accelerated, or intensified if the forces controlling the transient state of equilibrium are disturbed. One possible scenario is the reduction of hydrostatic pressure due the lowering of the groundwater level in cases of aquifer overexploitation, as these can cause loss of support for the land cover. Excessive overloading of urban structures and forced changes in runoff conditions are other examples of human interventions that can lead to destabilization of rocks and soil cover, with consequent subsidence (Figure14).

In view of the quite dynamic nature of karst systems, they are normally situated at the threshold of equilibrium. Therefore even small disturbances can give rise to processes of great magnitude and regional expression. For this reason, karst environments are considered very fragile – they are very sensitive to intervention and vulnerable to degradation.

The interactions between humans and karst environments vary across regions and throughout history. Many karst areas of Europe, Asia and the Americas have been inhabited for thousands of years. In these regions, human populations may utilize karst resources such as soil for agriculture and surface and underground water, as well as certain spaces, especially caves, which have taken on special cultural significance. In both Eastern and Western cultures, such spaces have been used as oracles, sanctuaries, and ceremonial sites.

Karst regions are rich in archaeological remains, especially associated with the exokarst, as well as in features such as cliffs and rock shelters. The archaeology of karst is often associated with caves, such as Lascaux and Altamira, famous for their paintings of extinct mammals, as well as others in the Pyrenees and the Cantabrian mountain ranges. However, such sites deep in the aphotic zone of caves are relatively rare.

Rock paintings are relatively common in karst areas (Figure 15); other archaeological remains can also be found, such as the blackened remnants indicative of fires and the remains of prehistoric food, but also lithic and/or ceramic artifacts (Figure 16). These are often preserved by the various layers of sediments formed over thousands of years. Rock shelters at the base of rocky cliffs, which provided protection from wind and rain, are especially propitious for finding archaeological remains.

Caves have also provided other fundamental archaeological finds. The first discovery of Neanderthal man, a hominid extinct for some 29 thousand years, was made in a small cave in a limestone quarry in Germany. Caves on other continents have also revealed archaeological finds of great importance.

Figure 14. A conical subsidence sinkhole (left) and a cylindrical collapse sinkhole (below), both characteristic of karst landscapes. These closed depressions are formed by injection of soil into underground voids and the collapse of cave roofs, respectively. The processes involved can be gradual or instantaneous, as well as natural or induced by human actions, and they represent an effective geologic risk. Such features are especially important in karst because they lead surface drainage and runoff to specific points of the underground system, quickly recharging it.They can also provide direct access of contaminants into the karst aquifer. Photos: Mylène Berbert-Born and Antonio José Dourado.

Figure 15. Cave paintings on a limestone wall in a karst region of Pains, state of Minas Gerais (Brazil). Photo: Luis E. Sánchez.

Figure 16. Ceramic urn found inside the Gruta da Ceramica (Ceramica Cave) in Bodoquena, state of Mato Grosso do Sul (Brazil). Photo: Rafael Rodrigues Camargo.

In addition to the prehistoric uses of karst, modern speleological exploration and the scientific study of caves have been added to the uses of karst since the 19th century, starting in Europe. At present, many karst regions furnish resources not only for local communities, but also for the society in general: scenery, as well as hydric, mineral, biologic, and genetic resources.

Historically, karst regions in many countries did not play an active role in populational and economic dynamics, and even today, land use in karst areas is largely rural. Despite the diversity of such regions, one common trait is their rurality. This characteristic presupposes an especially intense contact of the population with the environment and the locally available natural resources to a much greater extent than in urban centers. Rural populations established in karst regions benefit from the resources, especially the water, as well as the possibilities of specialized use of the land due to peculiarities in its geographic configuration. On the other hand, the use of inadequate techniques of soil management and intensive use of chemicals in agriculture can lead to a significant degradation of environmental quality.

Family or subsistence agriculture prevails in the rural karst areas of Brazil. There are of course regional differences on a national level, and in certain regions, family agriculture is highly integrated into the market, benefitting from the main technical advances and governmental policies designed for the sector. However, rural localities in karst areas may present unique demographic dynamics, whether sparsely or relatively densely populated, with differential indices of human development, which indicate distinct rhythms of advance in the quality of life of the people. Whether located near urban centers or far away, in certain contexts, the rural can be integrated with or linked to the urban, awakening the interest of those who live in the city and who find a sociability in rural areas which reaffirms their identity and local traditions. This can lead to such locations being utilized for a second home or for tourism, with karst being an attraction.

Many rural municipalities have a diversified economic basis capable of generating income as a function of their own dynamics and their insertion in the market, while others are predominantly dependent on public assistance policies. The characteristics of local communities in these regions and their greater or lesser capacity to organize and participate, also help determine the ways in which the available resources are used.

Some municipalities localized in karst regions have a low Human Development Index (HDI below 0.599), such as Campo Formoso in the state of Bahia or São Domingos in the state of Goias, whereas others have an HDI above 0.700, such as Matozinhos and Lagoa Santa in the state of Minas Gerais, both influenced by the dynamics of the metropolitan region of Belo Horizonte.

Even if karst is most frequently associated with rural living, certain urban centers find themselves close to karst regions, a situation intensified by the processes of urbanization and conurbation, such as what is observed in the karst of Lagoa Santa, or in the metropolitan region of Curitiba. In these areas, the karst aquifer is a source of the urban water supply. The fragility of these areas and the intense pressure of urbanization, associated with unordered occupation of the land, are directly related to the occurrence of accidents, such as the ground collapse registered in Cajamar, state of São Paulo, and that in the municipality of Almirante Tamandaré, metropolitan region of Curitiba, state of Paraná.

In addition to the productive functions of rural areas in karst regions, whether this production involves agriculture, cattle raising, forestry, or even mining, the specific natural attributes of these regions provide a diversity of forms of use, attribution of value and interaction with the environment. In spite of the importance represented by the karst for the people who live there, it also attracts visitors and scholars who travel long distances to explore, investigate and conduct technical and scientific studies. In addition to scientific research, the practice of speleology and recreational and sporting activities has become more popular, with cultural or religious tourism still occupying a place of special interest.

Indeed, some karst regions continue to constitute a territory marked by religious symbolism. The identification of caves as sacred spaces or places for religious manifestations is common in the popular culture. Examples in Brazil include the pilgrimages of the Sagrado Coração de Jesus (Sacred Heart of Jesus) in the Lapa da Mangabeira (Mangabeira Cave) in Ituaçú and that in the Santuário de Bom Jesus (Sanctuary of the Bom Jesus Cave) in Bom Jesus da Lapa, both in the state of Bahia (Figure 17), the Vibrações de Cura (Vibrations of Cure) in the Santuário do Roncador (Sanctuary of the Roncador) in the Roncador Cave in Cocalinho, in the state of Mato Grosso (Figure 18) or the Festa da Virgem da Lapa (Festival of the Virgin of the Cave) in the municipality of Vazante in the state of Minas Gerais. These celebrations attract thousands of pilgrims every year; the *cenotes* of the Yucatan Peninsula in Mexico, and the caves used by Buddhists in southeastern Asia are other examples.

Figure 17. Pilgrims in the Santuário de Bom Jesus da Lapa (Sanctuary of the Bom Jesus da Lapa) in the state of Bahia. Photo: Elvis Barbosa

Figure 18. Celebration of the Vibrações de Cura (Vibrations of Cure) in the Santuário do Roncador (Sanctuary of the Roncador Cave) in Cocalinho, state of Mato Grosso, Brazil. Photo: Heros Lobo

Use for tourism, on the other hand, previously restricted to a few caves but which suffered significant interventions for the accommodation of large groups of visitors, has expanded and diversified, including various forms of visitation of little impact. The so-called speleo tourism, associated with ecotourism, and adventure tourism, have developed as activities which contribute to the preservation of the speleological heritage by generating income and increasing the value attributed to the local populations. Around the world, caves are a touristic attraction (Figures 19 and 20). In Brazil, various caves and karst regions already provide consolidated touristic activity; these include the Gruta do Lago Azul (Cave of Lago Azul) in the Bodoquena Mountains of the state of Mato Grosso do Sul, and the caves in the region of the State Touristic Park of the Upper Ribeira (PETAR) in the state of São Paulo, as well as some in the state of Bahia and those of the circuit of caves in the state of Minas Gerais.

The type of interaction between humans and karst regions must be considered on various scales, not only the local scale, but also that of the municipality and region. These interactions need to be studied and understood when identifying and assessing the consequences of a new or existing project.

Figure 19. Cueva de las Maravillas (Cave de las Maravillas) in Aracena in Spain. Photo: Heros Lobo

Figure 20. Gruta do Janelão (Janelão Cave) in the National Park of the Caves of the Peruaçu, state of Minas Gerais (Brazil). Photo: Heros Lobo

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Photo: Mylène Berbert-Born

PART 2

THE STUDY OF KARST, BASIS FOR PLANNING

The main features of karst environments, which are summarized in Part 1, are presented herein in more detail. Based on the uniqueness of karst elements and processes, the fragility of this environment is shown, and the need and importance of adopting best practices in mining activities are subsequently established for this type of environment.

CHAPTER 1:
KARST GEOSYSTEMS

Mylène Luiza Cunha Berbert-Born

1.1. INTRODUCTION: WHY PAY SPECIAL ATTENTION TO KARST?

Karst terrains occupy a significant portion of the planet's surface, at approximately 13% of the emerged land when considering the distribution of carbonate rocks in geographic and climate conditions that are favorable to dissolution (Ford & Williams, 2007; Williams & Fong 2010) (see Figure 1, Part 1). As described in the first part of this Guide, these are very unique areas where the natural dissolution of rocks, such as limestones, dolomites, and marbles, leads to the development of networks of fissures and conduits that can make up complex underground drainage systems.

The water flowing through karst conduits is freer and more concentrated and therefore much faster (turbulent flow) than water that permeates other rocky media that are strictly granular, such as sandstones, or fractured, such as granites and other igneous and metamorphic rocks (laminar flow through the rock pores or in more closed and less interconnected fractures). Figure 1.1.1 illustrates the organization of rock interstices in porous, fractured and karstic environments capable of storing and circulating water under different hydraulic conditions.

The water that seeps through the surface of a karstic terrain flows preferentially along the conduits in underground routes that drain rapidly to sites where there is free discharge once again to the surface (groundwater resurgences), which are karst springs. Along their fast path, the main drains receive water parcels that are diffusely stored in the pores and fractures of the rock.

Water infiltrates more and more easily because the connections between the underground networks and the surface increase as the drainage to the springs becomes more efficient. This drainage organization through underground conduits, which promotes an expressive increase in permeability, is the reason why classic surface drainage networks are poorly structured and even nonexistent in karstic terrains.

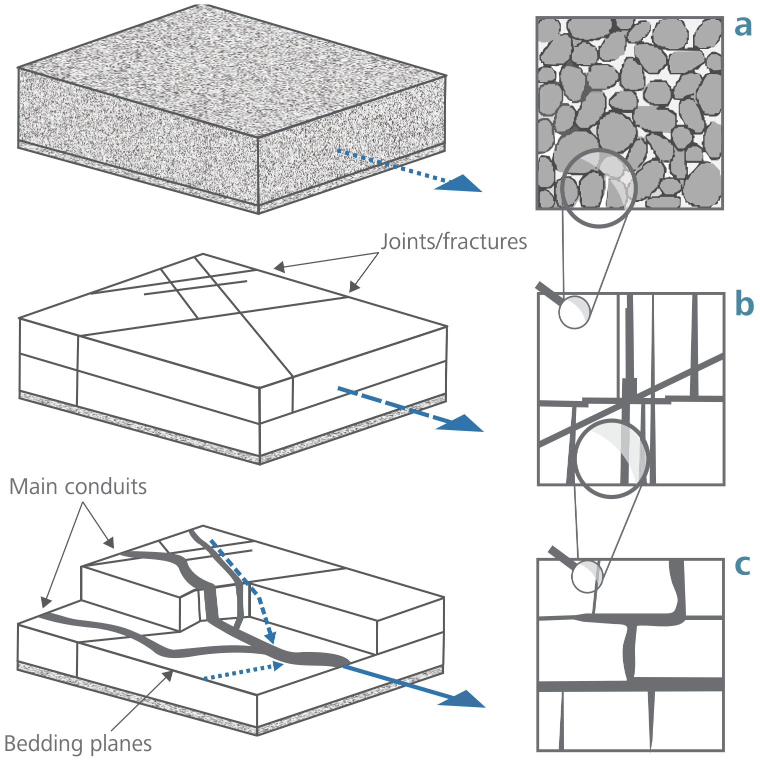


Figure 1.1.1. Different aquifer media and respective flow conditions: (a) intergranular porosity of the rock matrix and laminar flow (dotted arrow); (b) porosity in fractures or fissures with predominantly laminar flow along the fractures (dashed arrow b); (c) porosity of karst or dissolution conduits with turbulent flow (solid arrow), combined with intergranular flow and flow through fractures or small dissolution fissures ("bimodal" character). Modified from Worthington (2003) and the Kentucky Geological Survey (2012).

Easy infiltration and rapid underground flow lead to the transport and loss of large amounts of soil, a process that occurs in a very heterogeneous way. This leads to a morphologically irregular relief that is quite different from non-karst landscapes. The modeling and features of the karst relief are, in short, the surface expression of the particular condition of the underground drainage (White 2002; Goldscheider & Andreo 2007). Exposed or semi-exposed rock with fractures that are progressively widened by dissolution and circular depressions that form closed basins (dolines), which capture surface water and concentrate the surface runoff at certain infiltration spots, are some of the typical resulting features. In turn, these features also promote and increase underground circulation, feeding back the process.

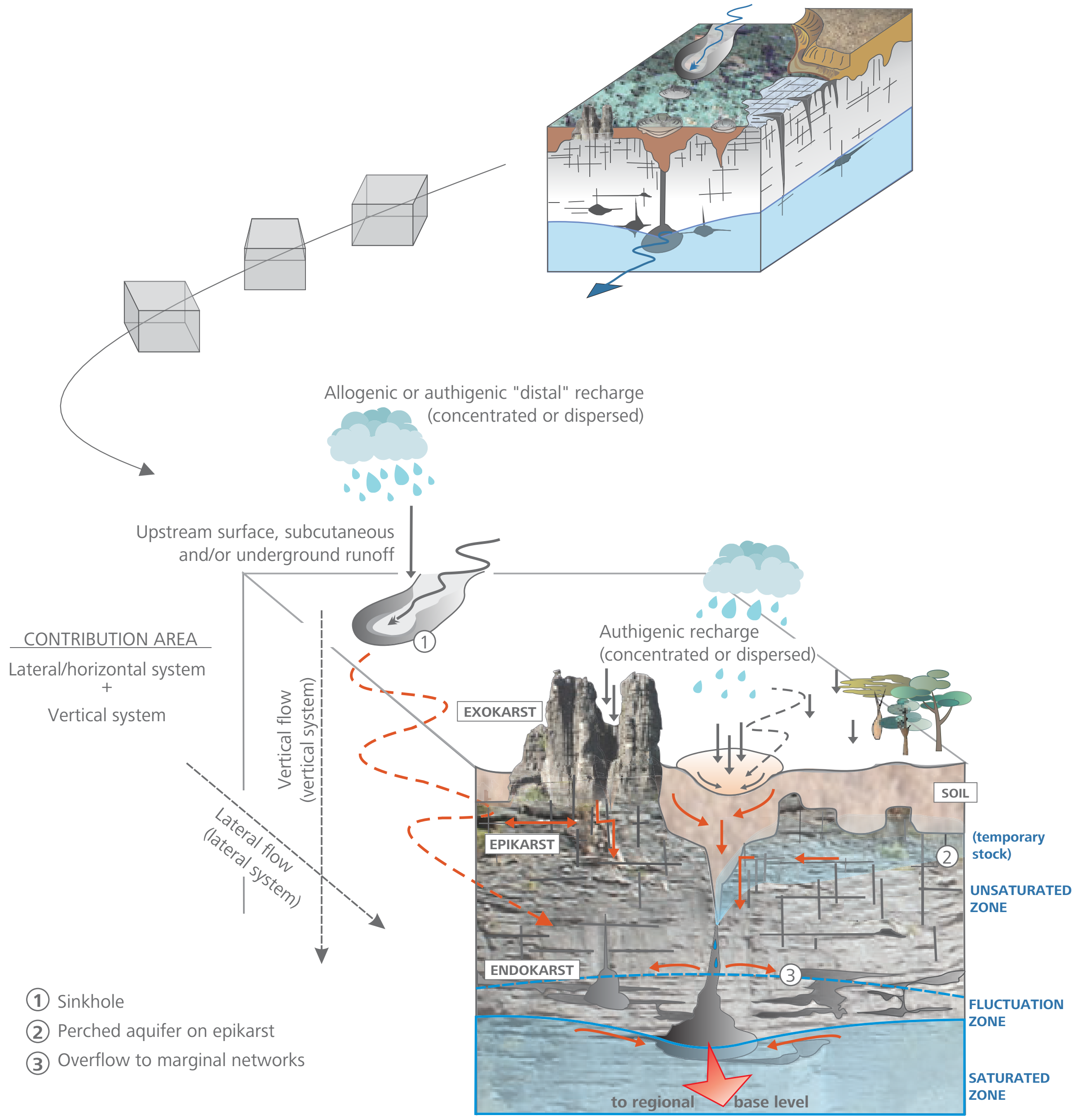


Figure 1.1.2. Main compartments of the karst aquifer system that function in an integrated manner under different water action mechanisms. The way this aquifer is organized and the way it stores and carries water, under a high permeability condition, is both the cause and consequence of the peculiar negative and positive karst relief forms. The following aspects stand out: (a) dispersed recharges and concentrated or convergent, distal and proximal, authigenic and allogenic recharges, represented by black arrows; (b) subsurface and underground vertical and lateral flows, diffuse and concentrated, marked with red arrows; (c) oscillation of groundwater, from baseline (solid line) to maximum level (blue dashed line); (d) soil and the exokarst, epikarst and endokarst; (e) saturated, unsaturated and oscillation (epiphreatic) zones of the water table. Definitions and explanations are provided throughout the text.
Illustration: Mylène Berbert-Born.

This shows that the karst relief, the surface of which is called exokarst, is both the consequence and cause of a unique underground water organization that represents the karst aquifer[1]. The karst aquifer includes the more karstified upper portion of the rock, called epikarst, through deeper portions, which vary in their degree of karstification, comprising the endokarst.

In turn, the endokarst includes both the vadose or unsaturated zone and the phreatic or saturated zone of the aquifer, as shown in Figure 1.1.2. Figures 1.1.3 and 1.1.4 illustrate some characteristic features of the karst relief on the surface and subsurface (see other images in Part 1 of the book).

The close interaction between the surface (atmosphere, relief, and soil) and underground (rock porosity and aquifer), which occurs mainly via water, makes karst a very special geosystem from several aspects that include the following.

- They are natural systems that are very sensitive to climatic conditions, especially rainfall regimes. Intensified by the convergence of surface and underground runoff, rainfall produces rapid and intense effects such as high amplitude fluctuations in groundwater levels, fast flooding and overflowing of underground channels or fast flows between recharge and discharge points, just to mention a few examples of the great physical dynamism of karst environments. It is also worth noting the high erosive energy involved in these processes that causes intense movement of particulate matter.

- Because they are very dynamic, interactive and complex, small disturbances in karst systems can produce unpredictable reactions, with consequences that can manifest themselves at great distances, amplified magnitudes and unexpected response times. The strong associated sensitivity, complexity, and uncertainties reflect the great fragility of karstic systems and their high intrinsic (natural) vulnerability to degradation. The most vulnerable aspects are the water, which is more susceptible to contamination and depletion, the soil, which is very vulnerable to erosion and salinization, the cave (or interstitial) fauna, which are intolerant to changes in their habitats, the natural and cultural heritage often associated with caves, and the caves, which may be irremediably degraded by disturbances to their structure and dynamics.

- Karst areas are generally lacking in surface water resources that are unavailable for consumption, whereas access to underground water sources is not always easy, and their management is delicate. The use of these sources needs to be carefully planned so that they are not exploited beyond the minimum levels that maintain the basic flows, which feed surface rivers and springs during drought periods. Fluctuations and dewatering induced by exploitation can make the surfaces unstable and increase the risk of subsidence, that is, the collapse of rocks and ground that form the cover.

Because they are very dynamic, interactive and complex, small disturbances in karst geosystems can produce unpredictable reactions, with consequences that can manifest at great distances, amplified magnitudes and unexpected response times. The strong associated sensitivity, complexity, and uncertainties reflect the great fragility of karst systems and their high intrinsic (natural) vulnerability to degradation.

It is important to recognize, however, that this particular scenario does not always involve the existence of characteristic karst relief because the inexistence of a "surface karst" does not rule out the possible existence of a "deep karst". In many cases, deeper portions of the rock may have greater permeability due to carbonate dissolution, even if they are overlain by non-karstifiable rocks, or, as discussed in the introductory chapter of this Guide (Part 1), there can be karst relief that is buried or developed under thick unconsolidated sediment cover, with no significant outcropping.

1 An aquifer is any rock formation capable of accumulating and circulating water in the interstices of its mineral grains, cracks (joints, faults, and bedding planes) and other existing spaces, which represent exploitable underground water reservoirs. These reservoirs maintain the baseline (or minimum) flow of the surface rivers. The hydraulic properties of each type of aquifer – granular/porous, fractured/fissural and karstic/conduits – are dictated by the geological nature, considering the lithological, stratigraphic and structural characteristics, as well as by the current geomorphological and climatic characteristics.

Given its size and geographic locations on Earth, much of the karstic terrain is somewhat occupied, and its natural resources are under some degree of pressure, especially the underground reservoirs, due to the inherent scarcity of surface water. For a better understanding, it is estimated that 20 to 25% of the world population fully depends on the groundwater from karst aquifers (Ford & Williams 2007). In the United States alone, 40% of all potable groundwater comes from karst areas, which compose approximately 20% of the country's area (Quinland & Ewers 1986; Weary & Doctor 2014). In some European countries, karst waters may account for 50% of the total drinking water supply and are the only freshwater resource available in specific regions (Andreo et al. 2006).

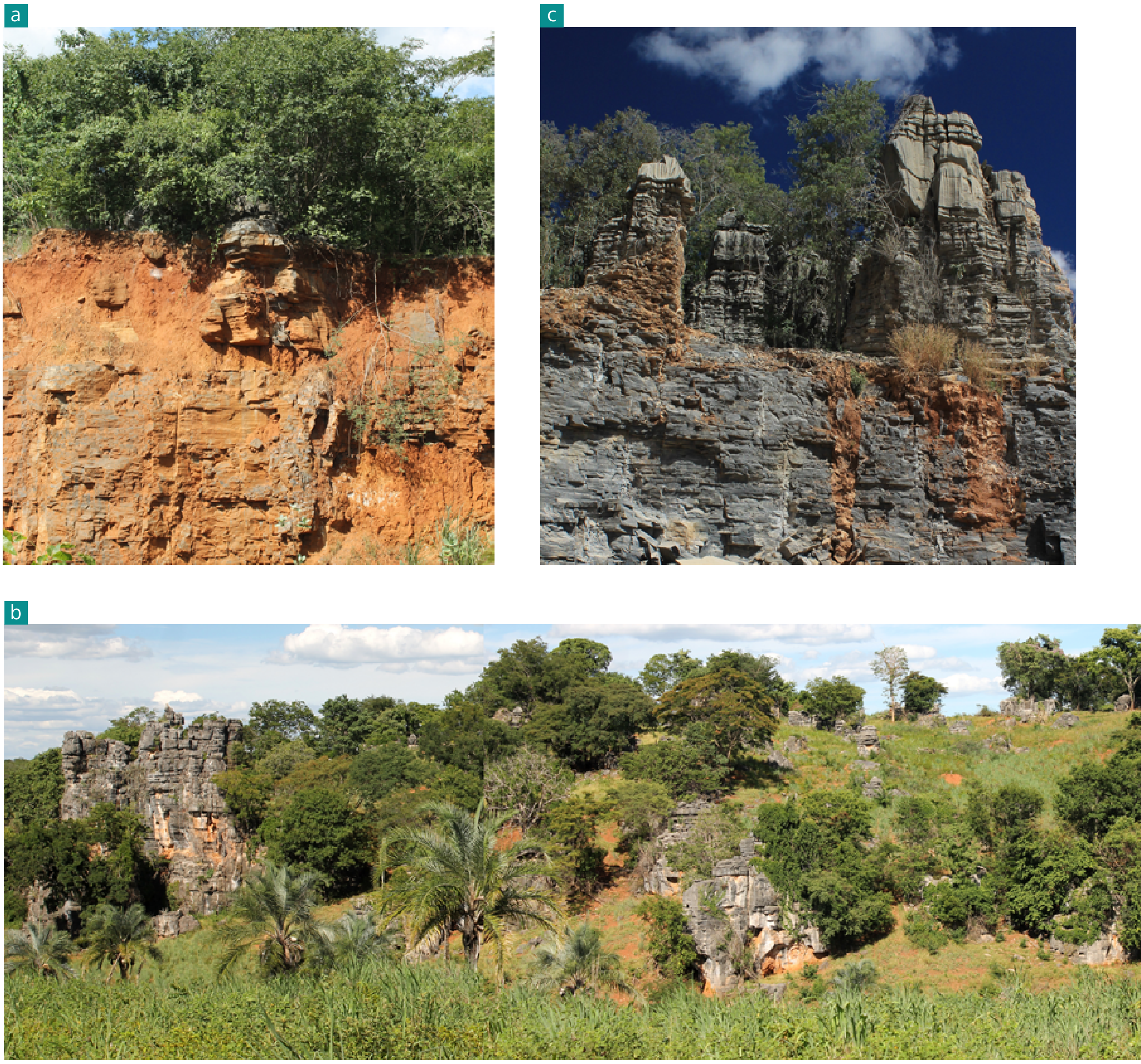


Figure 1.1.3. Exokarst and epikarst aspects: (a) soil layer over limestone rocks with the karstified aspect of the "epikarst" – note the irregularity and dissolution forms in the soil-rock contact and the apparent fractures in the rock; (b) limestone towers outcropping on a slope as a result of soil erosion retreat – note the small rock benches (warts) in the upper part of the slope that distinguish the existence of a "rocky relief" beneath the ground cover; (c) "rock towers" comprising an "exokarst" – note, slightly below, vertical fractures enlarged by dissolution and filled by soil in the more superficial portion of the epikarst. Photos: Mylène Berbert-Born.

a

b

Figure 1.1.4. Exokarst and epikarst aspects: (a) extensive karren limestone pavement representing an exposed exokarst – note the dissolution conduits intersect the mid-height of the limestone cliff, which could be considered an endokarst interface; (b) top of limestone outcrops with pointed shapes (clint/karren) and fissures formed by the dissolution of the rock surface – in the close-up photo, a crevice (rockhole) in which the infiltrated water is temporarily stored and slowly drains through the epikarst. Photos: Mylène Berbert-Born.

Approximately 2.5% of the Brazilian continental area is composed of karstifiable carbonate rocks. This area may seem small, but when one ponders the enormous diversity of rock types (lithologies) in the country, the great significance of these areas becomes clear. Figure 1.1.5 shows the distribution of large geological units (groups and formations) that have carbonate rocks integrating their lithological associations. It is important to note that most of them are located in semi-arid latitudes, where the lack of surface water and consequent dependence on groundwater sources are intensified.

In view of all the above, what warrants special attention for karst environments is that, given the hydrogeological, geomorphological, ecological, economic and cultural values involved, which are discussed throughout this book, disturbances to their natural conditions have environmental impacts and degradation potential that are much higher than in other environment types. The explanation is permeated by complex concepts such as stability, sensitivity, vulnerability and the relevance of "natural environmental systems", which will be addressed throughout this chapter.

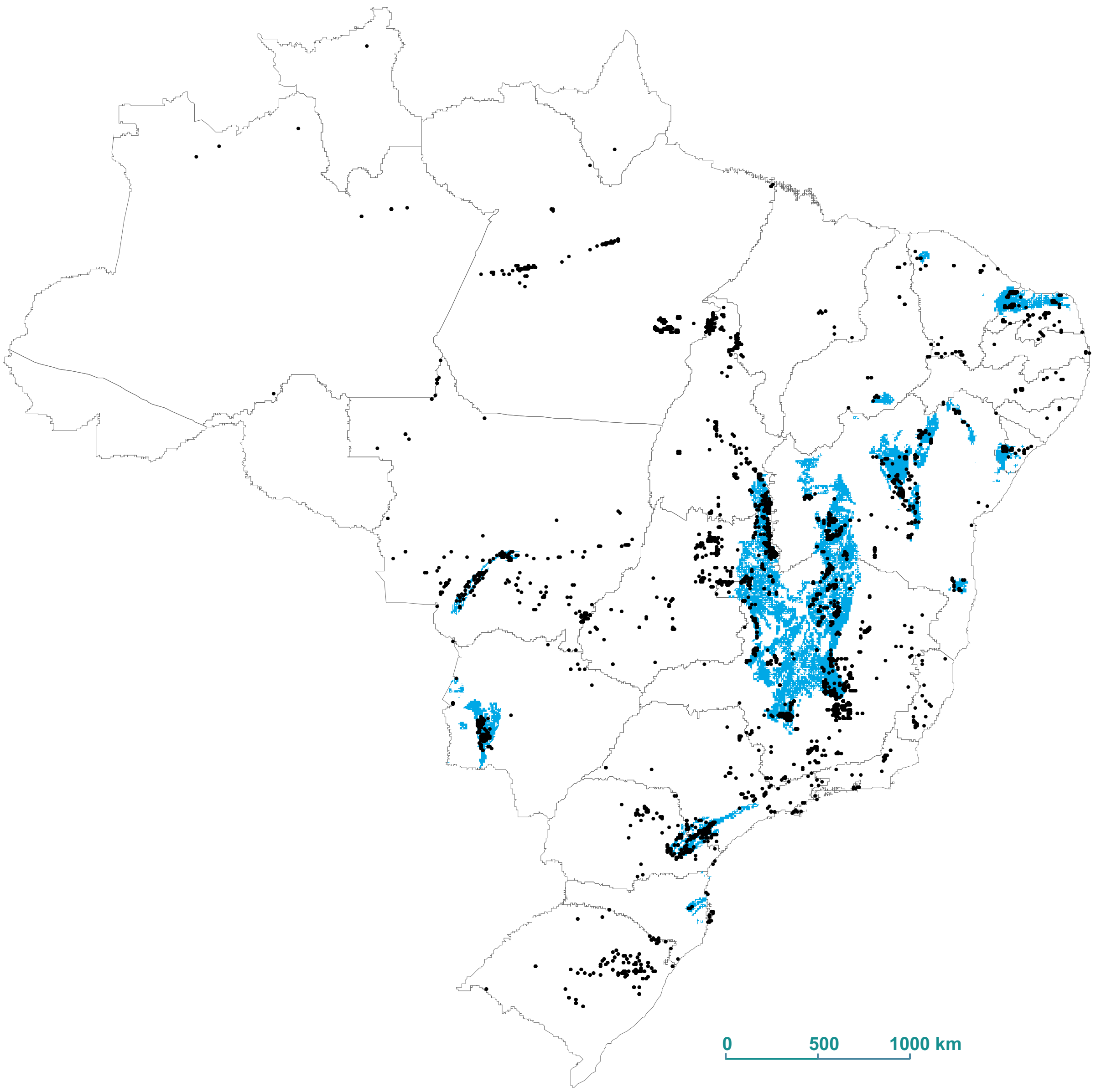


Figure 1.1.5. Map of areas with lithostratigraphic units (groups or formations) where carbonate rocks are present, shown in blue. The black dots indicate the caves registered in the CECAV Natural Cavities Geospatial Database on 12/31/2015, many of which have formed in non-carbonate rocks. Layout of the figure prepared by Mylène Berbert-Born via manipulation of geospatial data from the Brazilian Karst Regions (CECAV 2009) available at *http://www.icmbio.gov.br/cecav/projetos-e-atividades/provincias-espeleologicas.html.* Downloaded on 05/19/2014.

1.2. KARST – LANDSCAPE AND AQUIFER

The many aspects that distinguish the karst environment from other types of natural environments are mainly associated with karstification – or speleogenesis[2] – a specific, expressive and intrinsically heterogeneous natural phenomenon that occurs in terrains with a carbonaceous rocky substrate, whose physical and biological manifestations are highly relevant from environmental, economic, scientific and cultural perspectives. Understanding the basics of karstification is a fundamental requirement for any environmental study of karst. This is what enables recognizing and interpreting the most important active and relic processes in the configuration and functioning of a particular karst terrain under examination to more realistically decipher how it will behave when undergoing disturbances to its natural state.

The karstification herein considered "typical" refers to geochemical dissolution processes involving the chemical system{H_2O-CO_2 (carbonic acid) ←→ $CaCO_3$ (carbonate rock)}, with carbon dioxide (CO_2) as the water acidity factor giving corrosive power over carbonate minerals. It is also called epigenetic karstification because the dissolution agent comes from the surface, that is, meteoric waters absorb CO2 from the atmosphere and from surface biomass and then circulate basically by gravitational action or by hydrostatic pressure. In this process, when the calcium carbonate (rock) is dissolved, a solution composed of calcium ions[3] (Ca^{2+}), bicarbonate (HCO^{-}) and carbonate (CO^{2-}) is produced. The ratio between these components, or chemical equilibrium, is determined by the concentration (partial pressure) of CO_2, the pH and the temperature of the solution, as well as the chemical reaction kinetics and the suitability of the medium to ionic diffusion (Dreybrodt et al. 1996; Liu & Dreybrodt 1997). Further information on this chemical system can be found in Chapter 2 - Caves.

In another karstification mechanism known as hypogenesis, dissolution is caused by thermal solutions or mineralized fluids formed at greater depths in the rock block itself. Although relatively less common, hypogenesis is also a very significant process due to the high corrosive power of the solutions and the geological and hydrogeological conditions normally involved. Regarding the different types of karstification processes, it is important to understand that each has certain dynamics and specific morphogenetic patterns. A deeper discussion of hypogenesis is found in Klimchouk et al. (2000), Klimchouk (2015), and Audra & Palmer (2015). In this chapter, emphasis will be given to epigenesis, and the karstification aspects of non-carbonate rocks will not be addressed.

An essential characteristic of carbonate karstification, be it epigenic or, especially, hypogenic, is that the dissolution rate is very high, that is, the dissolution is more intense compared to non-carbonate chemical systems. Thus, the large-scale and wide spatial distribution of the chemical weathering features, which comprise the classic karst relief, are formed in a relatively short time interval in a synergistic relationship with mechanical erosion.

There are several factors that influence the intensity or speed of karstification so that, depending on the prevailing hydroclimatological pattern and the geological, pedological and topographic context, the dissolution rates greatly vary from site to site. In addition to the type of rock, soil, vegetation and topography, the volume and the temporal distribution of rains as well as the atmospheric temperature, solar radiation and intensity of winds are all aspects that act together.

Some factors may have surprising regional or local relevance to the karstification process such as winds, which interfere with the rates of rainwater evaporation and hence the availability of water for infiltration. The thickness of the soils that cover the soluble rocks is another important aspect. Thicker soils usually store water and distribute it more diffusely to the discontinuities in the rock below. When the region has higher rainfall with well-distributed rains throughout the months, the water stored in the soil tends to regularly migrate into the rocky system, but if the rainfall is poorly distributed, a significant portion of the water may be trapped in the soil over a time period or lost by capillarity during long droughts, thus reducing the water available for karstification. The vegetation and soil, derived from the climatic conditions, are key elements for the distribution, regularization, and renewal of the acid solutions in the system.

The above-mentioned aspects that concern the availability and chemistry of water are associated with other factors that dictate its circulation dynamics through the rock medium, namely, the sedimentary and structural discontinuities of the rock, which provide preferential passages to the solutions; the topographic and hydraulic gradients that impose differences in terrain elevation and water pressure, thereby establishing energy levels and directions of circulation; and finally, time, a determinant factor of the degree of transformations, that is, of the evolutionary stage of the processes.

2 Creation and evolution of organized rock permeability developed as a result of the dissolution widening of previously existing porosity (Klimchouck et al., 2000, p.47).

3 Naturally, the dissolution of calcium and magnesium carbonates also have Mg^{2+} ions in the solution.

This wide range of factors, which are combined in space and ti me, results in a wide variety of karst terrains around the world that are diversified in terms of relief expressiveness and typology, hydrographic organization and hydrological dynamics, connectivity or fragmentation of surface and underground compartments, biological occupation, limitations and potential occupation of the ground.

Further details on epigenic karstification and examples of karst environments in various continents can be found in textbooks such as those by Gillieson (1996), Klimchouk et al. (2000), Palmer (2007) and Ford & Williams (2007).

The classic karstification process – from the underground beginning to water recharge-transmission-discharge systems

For a number of reasons, the dissolution process occurs in a very heterogeneous manner in a given spatial context, starting with the mineral, textural, structural and stratigraphic heterogeneity of the rock itself. The process is heterogeneous also due to the highly variable aggressiveness (acidity) of the water that percolates through the rock and the various mechanisms by which water enters and leaves a rock compartment, in a particular time interval.

The dissolution power of water depends on a very complex combination of physicochemical factors involving the absorption of surface CO_2 (atmosphere and soil), the eventual release of CO_2 back to the atmosphere during flow, and the evolution of the equilibrium chemical reactions with the rock (H_2O-CO_2-$CaCO_3$ system).As previously discussed, these reactions are influenced by temperature, pH, ionic content and by the way the solutions become different and undergo mixing along their paths through the rock interstices.

The solubility of the rock can vary greatly due to the mineralogical composition and even the arrangement of the minerals in addition to the variable presence of cracks that it may have.

Starting from a very small observation scale focusing on the composition and texture of the rock, the global solubility is influenced both by pores that are occasionally left between grains during the rock formation process and the mineral types that can be more or less soluble according to the character of the solution that travels through the medium. The primary porosity of the rock is one "gateway" for the solutions that will act in the process that reverses rock formation, that is, its degradation by dissolution.

In the case of very pure limestone rocks composed almost exclusively of calcium carbonate minerals, intergranular porosity is usually insignificant due to interstitial "cementation" of the grains, which is caused by the recrystallization of pre-existing carbonaceous minerals or the crystallization of percolating carbonate fluids still in the initial stages of lithification (rock solidification). The rock matrix thus acquires a more massive character, and other types of interstices assume a dominant role in the karstification process, in this case, the joints between the bedding and the fractures formed later, when the rocks are exposed to the lithospheric strain. The "fissural porosity" of the rock is very important in the early stages of karstification.

The key issue for karstification is the access of slightly acidic water to soluble minerals. However, in order for the process to evolve, evasion and continuous replacement of already neutralized (carbonate-saturated) solutions over the course of dissolution are also necessary. Sedimentary bedding planes and fracture planes, tectonic laminations and fault complexes are continuous structures that are often extensive and interconnected, where water can infiltrate and circulate more easily when compared to intergranular pores. These rock structures are not randomly distributed; to the contrary, they are organized with some regularity in space. This framework, systematically arranged in the rock, results from very old, large-scale processes that are related to the rock formation itself (depositional processes) or to global or continental scale transformations experienced after its consolidation (tectonic processes).

It is noteworthy that among the rock structures, some assemblies are more prone to dissolution than others. Fractures, tectonic laminations and faults are structures that result from a field of tectonic forces with compression, tension and shear vectors. The structures that result from compression tend to be more closed than those formed from tension. Therefore, the latter are more susceptible to water percolation.

Based on this dissolution conditioning, water flow paths assume some preferential directions. Because of this, the shape, extension, and development of caves and other relief features show moderately predictable regional patterns. The frequent linearity of karstic features such as rectilinear valleys and cliffs aligned to sets of dolines is precisely the result of their association with certain rock structures.

While on one hand the structural conditioning allows some control over phenomena and processes in an area, on the other hand, it causes many uncertainties that give rise, for instance, to sudden route deviations, drainage capture, and a degree of complexity in groundwater elevation levels.

Therefore, understanding the functioning of the karst system requires good knowledge of the regional tectonic context and the existing structural compartments. The typology and spatial organization of the relief features, the patterns of which are recognized through systematic morphometric[4] analyses of the terrain, should be observed from this structural perspective.

The identification of large portions or "blocks" of the rock package that are somewhat homogeneous from structural, compositional and textural perspectives, is another important point because the way these blocks are mutually arranged also influences how dissolution develops.

For example, a portion, level or rock layer with higher clay or siliceous content and lower degree of fracturing may be less permeable to water and act as a local "sealant", retarding, concentrating, or redirecting water percolation. This contact horizon between compositionally distinct portions of the rock can coordinate the onset of the dissolution process at a certain location and be decisive in the evolution of a particular network of underground conduits. Some parts of the rock block may also have concentrations of certain minerals capable of locally increasing the acidity of the solutions or may simply have a higher local density of fractures that are more open and interconnected, favoring percolation and dissolution, in comparison with other portions of the bedrock.

In a given region, it is common to find caves or dissolution conduits concentrated just above a prominent lithological horizon in the local stratigraphy such as a lens or bedding that is more siliceous or clayey and therefore less permeable[5]. When the layers are regionally continuous and horizontal, the caves and other dissolution features may assume, due to these layers, a regular elevation arrangement with locally well-defined morphological patterns. There are several examples of this situation in regions where siliciclastic rocks are interspersed with carbonate rocks, such as in the characteristic horizontal stratigraphy of the Bambuí Group, especially in the states of Goiás, Minas Gerais, and Bahia.

The stratigraphic column of the São Francisco valley in northern Minas Gerais (Iglesias & Uhlein 2009), shown in figure 1.2.1, depicts a typical sequence of lithographic units of the Bambuí Group. It shows the karst aquifer subunits (limestones and dolomites of the Sete Lagoas and Lagoa do Jacaré formations) that may be locally "supported" and dissolutely structured by the existence of the less permeable rocks interspersed in the sequence (siltstones, shales and clayey limestones of the Serra de Santa Helena Formation and the base of the Sete Lagoas Formation), represented in orange. This interbedding appears at different frequencies and thicknesses from site to site and may be more or less expressive according to the considered spatial scale.

An important practical issue of karstification related to the lithological, stratigraphic and structural organization of the rock concerns the continuity, isolation or connectivity of conduit networks or aquifer systems. As a simplified example, two conduit systems that are marked "1" and "2" and for which human access is hypothetically impractical are shown in the diagram in Figure 1.2.2. Direct observation alone of the hydrological behaviors of the two "outlets" of the systems does not corroborate whether they are connected or not. Recognizing the existence and nature of an impermeable unit possibly interspersed with the systems can greatly aid in understanding the structure, functioning, and interaction that may exist between the systems.

Getting back the beginning of the process, before karstification is triggered (breakthrough), the groundwater is only interstitial in a fissured rock environment where cracks are increasingly narrower with increasing depth. The local erosive level is regulated by the lowest water flow level (base flow), marked on the surface by the valley bottoms, plains, and ponds where the water table surfaces. The surface of the water table marks the level below which all rock interstices are filled with water, defining the "saturated zone" of the aquifer.

4 Assessment of forms and their spatial relationships based on their individual and collective measurements.
5 In hydrogeological terminology, they are called "aquitards", which are geological units with low porosity and permeability, and "aquicludes", which are impermeable units.

All interstices of a limestone filled with water are sites where dissolution reactions are carried out, provided that the water is not saturated in carbonate and that there are conditions for ionic diffusion. However, some sections or portions of the rock block have greater dissolution propensities than others due to previously mentioned mineralogical reasons, because they concentrate structural discontinuities, or due to stratigraphic relationships (relationships between lithological units of different solubilities), or even due to hydraulic factors such as water pressure and mixtures of saturated solutions acting together. These portions that are more prone to dissolution end up acting as inception horizons of karstification (Lowe 1992) – sites from which some of the possible chains of dissolution processes are triggered. More detailed explanations regarding the initial karstification stage can be found in Lowe (1999), Lowe & Gunn (1997), Palmer (2003) and Filippone (2009).

The coordination that the stratigraphy and the compositional and structural variations of the rock impose on dissolution, at the local or regional scale, is a very important criterion in the recognition of karst systems. Characterizing the specificities of the stratigraphy and structural geology, considering the detail of the vertical and lateral faciological variations that depict both the depositional environment and the deformational (geotectonic) context of the rock, is a unique requirement of environmental diagnosis studies in karst areas.

One of the dissolution chains may evolve from the preferential widening of structures that are originally more open than others and often at the intersection of distension fractures with bedding planes. It is very common for the dissolution to be more significant at the intersection between rock structures because these are promising meeting and mixing points of solutions from different origins. The solutions may be different as to saturation in dissolved carbonates and, therefore, as to dissolution power, such that there are new ionic equilibrium reactions with the rock at these points.

The expansion from an interstitial water storage condition, where the displacement of solutions is very slow (laminar flow) due to regional differences in hydraulic head, to an actual water "conduit" condition, where the flow becomes faster and directional (turbulent flow), begins when a hydrostatic pressure gradient arises; that is, there is a difference in water pressure between two points such that water starts to flow from higher pressure areas to lower pressure areas. For example, surface erosion (river incision) intercepts the water table at a given place, and the resistance to the flow imposed by the rock is lost. A strong pressure differential is created, and the underground flow capacity is substantially increased.

It is important to realize that the onset and first traces of the spatial and geometric configuration of an endokarst system are critically related to a particular moment when the groundwater retention conditions are halted, and the water is freely discharged at a certain point or site.

In the underground environment, the water displacement due to the hydraulic gradient occurs selectively along routes that have the lowest resistance to percolation. Such routes are enlarged faster precisely because they have a better water flow condition. As the drainage capacity of the water increases in the small channels ("protoconduits"), the flow velocity increases, and the flow becomes turbulent at a certain point – roughly when the conduit reaches approximately 5 mm in diameter (Ford et al., 1988). These slightly more developed channels converge (drain) all the water present in pores, joints and small peripheral conduits that are also being hierarchically enlarged, forming a locally more voluminous flow network.

This progressive hierarchical organization of underground conduits is reflected in the configuration of the exokarst relief, as the infiltration and the runoff of the surface waters (the recharge) are also led to where there is greater underground flow capacity. Accordingly, in the karst surface, there is typically a complex collection of negative (dissolutional) forms such as dolines, but also elements such as rock pavements devoid of soil and other denoting places in condition of good underground water drainage. It can be said that these underground drainage systems, which normally assume a branched pattern, resemble a typical hierarchical surface drainage network but with the erosive base levels located inside the rock massifs (Milanovic 1992) and the headwaters at the multiple points of surface absorption (infiltration).

This is the configuration of a karst drainage system involving water "recharge - transmission (flow/storage) - discharge" flow, with its respective zones and mechanisms of water absorption, circulation, and evasion relative to the underground environment. Each domain gathers geomorphic configurations, materials, and hydraulic conditions of its own, each of which playing a specific role in the behavior of the system as a whole.

Like river basins, these karst drainage systems can serve as an "environmental analysis cell" because they compose a complete chain of matter and energy flow linked to a controlled set of elements, parameters, and variables.

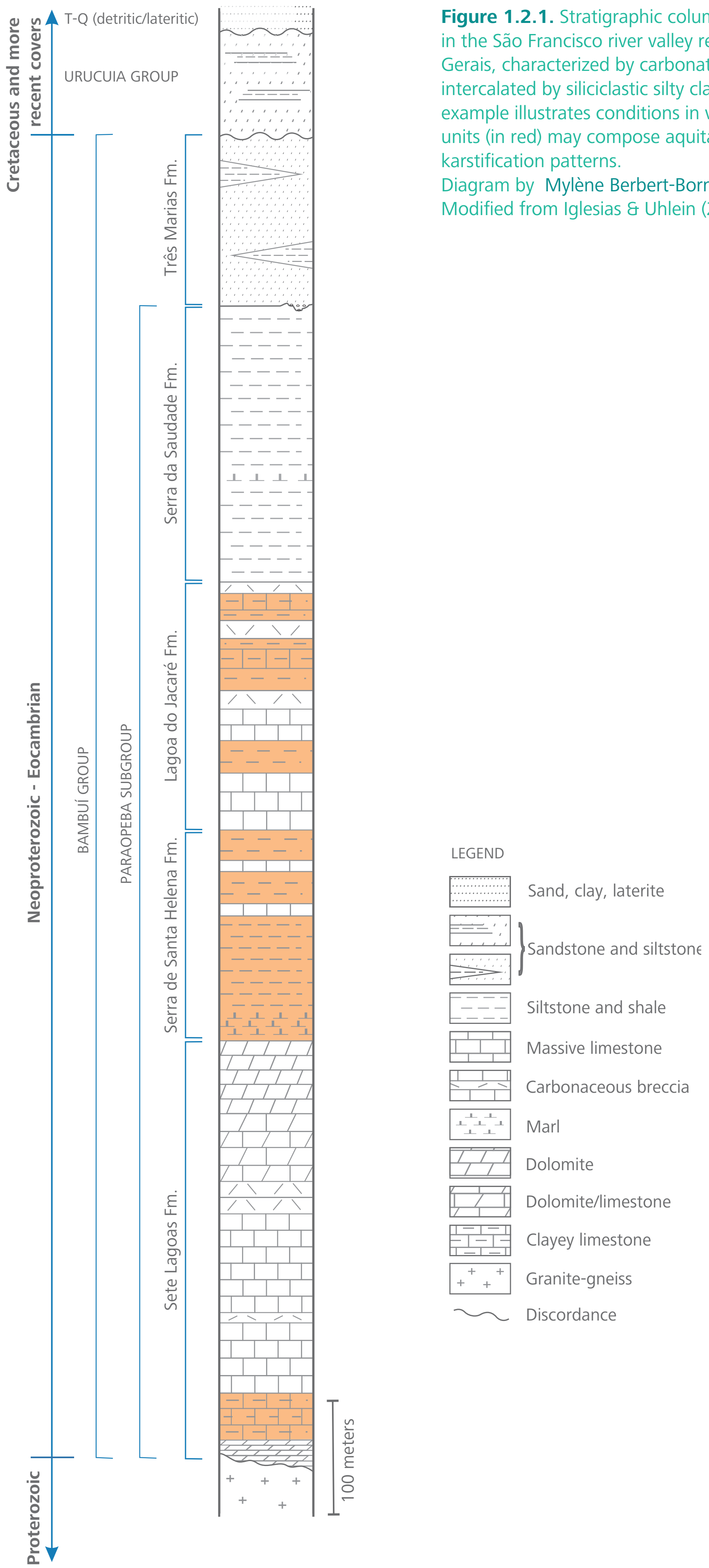


Figure 1.2.1. Stratigraphic column of the Bambuí Group in the São Francisco river valley region, northern Minas Gerais, characterized by carbonate (karst-forming) units intercalated by siliciclastic silty clayey (fissural) units. The example illustrates conditions in which less permeable units (in red) may compose aquitards, influencing local karstification patterns.
Diagram by Mylène Berbert-Born.
Modified from Iglesias & Uhlein (2009).

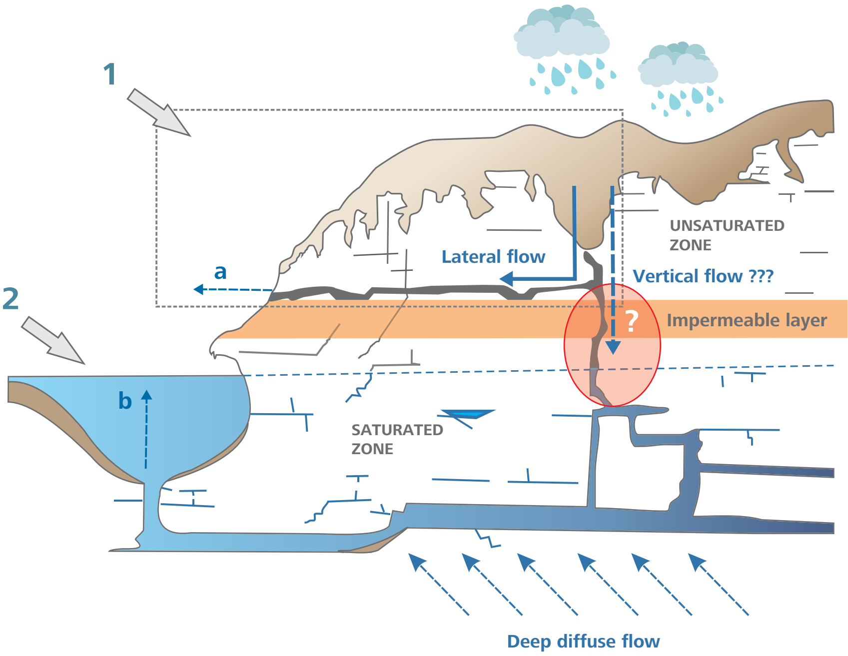


Figure 1.2.2. Less permeable layers (clayey, siliceous, less fractured...) act as "sealants" hindering or retarding vertical infiltration and favoring lateral percolation. This condition can be decisive for the development of conduit systems, both in terms of the shape and the position, extension, and distribution of the network in space. This can be very relevant with regard to the isolation or connectivity between aquifer systems. To understand the structuring and functioning of karst systems, it is very important to know in detail the local stratigraphy and structural geology. Two systems (1, dotted) and (2) with very close discharge sites (a) and (b) can operate completely independently if the connectivity marked in the red circle is unlikely because of a semi-confining unit interspersed with the systems. Diagram by Mylène Berbert-Born. Modified from Lee & Krothe (2001).

The delineation of recharge-discharge systems can then be the starting point for the diagnosis and assessment of impacts on a particular karst environment. In this delineation, the organization and functioning of the recharge zones should be carefully considered because the dynamics of the surface-underground karst system as a whole are substantially dependent on the way in which the water enters the system, and not only the volume but also the spatial distribution, rates (temporality and absorption speeds), chemical composition, sediment load and associated pollutant loads are all relevant. All of these aspects are related to the infiltration and surface runoff conditions, which can occur either in a concentrated manner, converging to certain points such as dolines, sinkholes, deep crevices in the epikarst, or diffusely, such as when there is dispersion through the soil.

A karst system of water "recharge-flow/storage-discharge" integrates zones with their own geomorphic configurations, materials, and hydraulic conditions, each of which playing a specific role in the system as a whole. Like river basins, these systems can serve as an "environmental analysis cell" because they compose a complete chain of matter and energy flow linked to a controlled set of elements, parameters, and variables. The delineation of these systems can be a starting point for the diagnosis and assessment of impacts on karst environments.

The existence of unconsolidated mantles must always be carefully observed because below them there may be a well-developed epikarst acting in the convergence of infiltration to more karstified portions of the rock. The epikarst can also be considered to be a very delicate subzone within this system, both because of its relevance in the recharge of underground systems and the difficulty of visualizing it when it is covered. Being the most superficial portion of the rock package, which undergoes the greatest degree of karstification, the permeability is higher in this zone compared to underlying bedrock. Because of this difference in permeability, infiltration tends to be restrained, causing water to accumulate in these more superficial portions. As a result, true subsurface reservoirs act as "regulators" of underground recharge throughout dry and wet seasons (Williams 1983, 2008). On the other hand, preferentially karstified structures that are present in the epikarst can also drain the water that is contained sparingly in the cover, directing it to specific points of the system.

Thus, interventions in recharge areas that change the runoff and surface infiltration parameters, such as changes in the topographic profile and the removal of soil cover, may have significant effects on the entire system downstream.

Even the removal of vegetation cover can produce considerable impacts, not only of a physical nature (e.g., erosion) but also of a chemical nature: decreased CO_2 availability and the consequent reduction in dissolution power of the solutions in areas devoid of vegetation; increased CO_2 with the renewal in unsaturated solutions in sites of organic matter accumulation.In the recharge zone, any place where water infiltrates in a concentrated manner should be treated with special attention because it involves rapid access to the underground environment, resulting in a low capacity for purification and natural filtration.

Because the availability of the underground sources in downstream regions can be directly dependent on the volume and quality of the water that is injected at these points, the impacts can reach great social and economic magnitudes. The entire perimeter of these concentrated recharge places should, therefore, be properly managed and as conservatively as possible.

Another fundamental aspect of the classical genesis and configuration of karst conduit systems presented here in the is underground drainage conditions. More than a parameter of water dynamics, flow is among the primordial aspects of the system structure itself. The underground flow is guided by groundwater volumes in discharge areas, that is, the output in springs and karst resurgences. The way the discharge happens influences how water catchment occurs in the headwaters and recharge areas. Consequently, it also influences the chemical conditions of the water, since it varies according to the soil and vegetation cover in the catchment areas, as well as the infiltration dynamics and residence time (time over which the water remains in contact with the rock) in the more superficial portions of the rock block.

Systems that lose their flow capacity because of damming, silting, or flow throttling, for example, may undergo flooding upstream with associated erosion. Alternative flow paths may arise as a result, sometimes accompanied by some surface manifestation. In turn, when the drainage capacity increases in the system, the water level tends to drop, giving rise to erosive processes. The capacity for circulation and renewal of the solutions increases, thus increasing dissolution in the system. In this case, some of the channels may be abandoned, and new flow paths can be established at lower levels.

Therefore, the discharge zones are also areas that are sensitive to interventions. In addition, they are promising places for understanding the structure and functioning of underground systems, especially karst springs.

Karst springs are equivalent to surface discharge points of hydrographic basins, places to where all rainfall converges and is drained off a certain area. More specifically, in karst basins, springs often represent the exit point of all water that flows or is temporarily stored in a given rock compartment or certain network of underground conduits and fissures, which are connected to each other and to the surface (Mangin, 1975; White, 2002; Ford & Williams, 2007). The hydrodynamic conditions (flow rate, oscillation rate, etc.) and the characteristics of the water (chemical, physicochemical, organic, etc.) at this output point can be monitored continuously over a period of time and can be compared to the conditions in which system recharge occurs (rainfall, contributions from external rivers, and artificial supply) for the same time period. The compared results can indicate retentions, dispersions, and derivations inside the system as well as chemical reactions that result from the interactions with the environment. In the hydric balance itself, in which the volumes that enter and leave the karst basin are evaluated over a time interval, the losses from evapotranspiration, runoff to outside the drainage area, and artificial withdrawals (various consumption uses – industry, agriculture, urban supply, etc.) that may occur within the system[6] should be appropriately considered.

A strategy that is widely applied in these studies is the use of an element called a tracer that can be inserted into the system input and securely detected at the output. These elements are more commonly substances differentiated from the study medium but also natural markers that can be controlled at the input and monitored at the output of the system. It is noteworthy that all of these studies can also be performed in wells that are contextually representative of an aquifer or karst drainage system.

The dynamics of the surface-underground karst system as a whole are substantially dependent on the organization and functioning of the recharge zones. Changes in the physical configuration of this zone with alterations in the natural conditions of the water supply – whether in terms of the infiltrated volume, the temporality and rate of the absorption processes, or the chemical composition and pollutant or sediment recharge of the absorbed water – can be reflected throughout the downstream system. The discharge zones are also sensitive to interventions, as they define the flow capacity of drainage systems. In addition, they are important places for understanding the structure and functioning of underground systems, especially the karst springs, whose characteristics represent output signals that aid in understanding the processing within the system.

6 Depending on the soil cover, in terms of composition, extent-distribution and thickness, it is important to estimate the water infiltration/capillary retention ratios in the soil, taking into account the soil moisture conditions prior to the water balance moment.

The hydrodynamic and hydrochemical information obtained in springs as well as in wells and underground river sections can be depicted in graphs representing temporal variation curves of different parameters that include flow rate, temperature, turbidity, pH, electrical conductivity, concentrations of dissolved metals, contaminants and the tracer recovery signal. Using this technique, the curves that record the variation in flow or discharge rates over a given time, called hydrographs, are combined with the respective chemical variation curves (chemographs) and are compared to graphs that describe aspects of recharge or any other induced stimulus.

Figure 1.2.3 shows generic patterns of the "discharge curves" or flow rate curves (volume per unit of time) that can be traced in a karst spring that reflect the behavior of the hydric system in response to some recharge event.

The shape of the curve represents the pulse of the recharge volume through the system, basically depicting its propagation speed and the consequent maximum flows. Each behavior reflects the aquifer organization by combining the water recharge characteristics (concentrated or dispersed), the storage conditions (high or low) and the underground flow characteristics (in conduits or diffuse) dominant in the system (Smart & Hobbs 1986; Bonacci 1993). The signals allow differentiating the systems with fast flow (in red) from those of slow response (in blue). The former may represent situations of more direct water exchange between the surface and underground ("open systems"), greater connectivity of conduit porosity, a greater degree of karstification, shorter routes, and a greater degree of vulnerability of the source and its water system. By contrast, more "conservative" behaviors, having slow responses, generally suggest less karstified and more homogeneous systems, which ensures less vulnerability to its respective source. With this type of analysis that is based on the general configuration and functioning of the aquifer, Hobbs & Gunn (1998) suggested four classes (groups) of systems whose thresholds or "strict" conditions of water recharge, storage, and flow reflect general aquifer sensitivity levels: hypersensitive, very sensitive, moderately sensitive and slightly sensitive. This type of analysis is quite useful for impact predictions and assessments. However, predictions about the behavior of karst aquifers should always be cautious because very complex situations may be involved given the "continuum" of possible combinations of recharge-storage-flow conditions, complicating when hypotheses such as the existence of multiple reservoirs and derivation between systems are plausible.

Whatever the case, interpretation involves very particular concepts concerning the karst aquifer properties, which will be briefly described next. More in-depth concepts on karst hydrogeology, in which the speleogenetic specificities of free (phreatic), semi-confined and confined aquifers[7] are discussed, can be found in Ford & Williams (2007) and Klimchouck (2015).

Important characteristics of the karst aquifer

7 Whereas free aquifers have the top or surface of the saturated zone (water table) only under atmospheric pressure and are "supported" by a less permeable basal unit, confined aquifers are aquifer units (geological formations) bounded by the presence of impermeable (or poorly permeable) units at the bottom as well as at the top (upper bound), so that the water in these aquifers is usually under higher pressure than atmospheric pressure alone. It is because of this pressure, called “artesian pressure”, that some wells drilled in confined aquifers "gush" above the land surface.

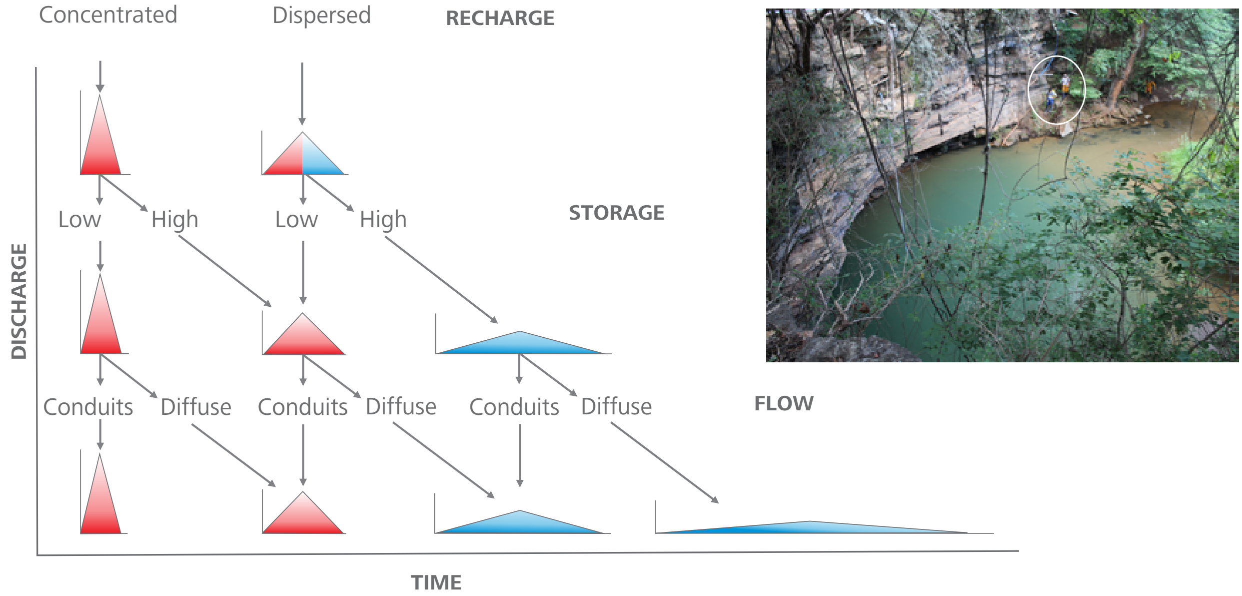


Figure 1.2.3. Simplified patterns of discharge curves (hydrographs) that can be obtained in a karst spring such as that in the image (people as scale) in response to a recharge stimulus in the corresponding aquifer system or drainage system. The traces (responses) are derived from the combination between the type of water recharge, the storage conditions and the characteristics of the underground flow that are dominant in the system, according to Smart & Hobbs (1986, modified). The colors indicate the sensitivity and degree of vulnerability of each system: red = more sensitive and vulnerable; blue = more stable and less vulnerable. Diagram and photo: Mylène Berbert-Born.

A good summary of the physical properties fundamentally related to the karstification process is presented by Goldscheider et al. (2007). They presents six aspects pertinent to the karst aquifer condition that need to be taken into account in a special way in environmental studies. They are hydrogeological aspects that portray the general conceptual model of formation, structuring, and functioning of karst areas. The model constitutes a genetic-evolutionary chain of causes and consequences in feedback (Taylor & Greene, 2008), according to the diagram in Figure 1.2.4, which are listed and explained next.

(1) Heterogeneity of karstification and triple porosity of the rock

The differential dissolution of the rock as guided by the lithostratigraphic organization and the sedimentary and tectonic structures present in a given geological context constitutes a third porosity characterized by more bulky spaces. These larger voids are concentrated in some portions of the rock package, articulating with the primary porosity of the matrix and the structural porosity of fractures also present in the rock. As shown in Figure 1.2.5, this triple porosity has the following character: relatively uniform granular porosity of the rock matrix (little expressive in pure carbonate rocks) and "diffuse" porosity of fissures (more densely disseminated in the rock) + "localized" porosity of dissolution conduits (concentrated in only a few portions of the rock block as a whole and organized hierarchically). Each type of porosity has very distinct individual hydraulic characteristics, and their combination creates a very heterogeneous and peculiar pattern of storage and circulation, as shown below.

(2) Dualistic flow and water storage

The karstic aquifer can be considered very permeable and an excellent reservoir if taken globally, but in a very heterogeneous condition. There is a dualism characterized by high hydraulic conductivity (fast flow) but low storage volumes associated with the macroporosity of karstic conduits, amidst a general condition of lower permeability (slow flow) of fractures. In turn, taken together and in the overall perspective of the aquifer, fractures have the highest volumes of stored water. This means that the hydraulic conditions are very relative to the considered spatial scale, with practical implications for environmental studies.

Figure 1.2.6 highlights different porosity domains and therefore hydraulic conditions that may exist within a regional karst context. The results of studies that focus on a specific domain should be adequately detailed as to its representativeness for the potentially affected environment.

(3) Hydraulic anisotropy

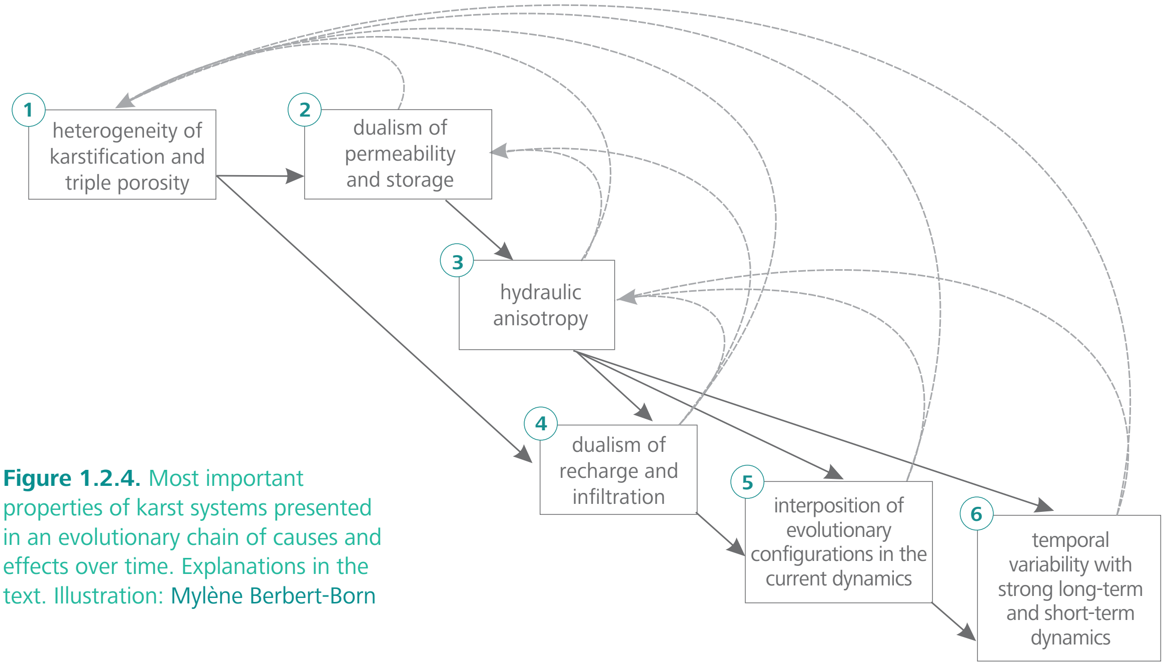


Figure 1.2.4. Most important properties of karst systems presented in an evolutionary chain of causes and effects over time. Explanations in the text. Illustration: Mylène Berbert-Born

It is the condition of heterogeneity or spatial variation of the hydraulic properties in an aquifer environment. In the case of karst aquifers, hydraulic anisotropy results from the coexistence of three different types of porosities, including conduit porosity, which develops in a very irregular manner.

(4) Dualistic recharge and infiltration

As a cause and a consequence of the degree and organization of karstification on the surface and underground, there are dualisms in both the mode and the origin of recharge. For the mode, a portion of the rainfall (i) infiltrates diffusely through the soil and slowly percolates through the unsaturated zone, initially in a dispersed manner through the dense mesh of fissures that marks the top of the epikarst, gradually converging to preferential flow paths as the flow migrates to the endokarst, and (ii) becomes surface runoff that converges directly into the underground environment in a punctual and concentrated manner, quickly reaching the saturated zone.

In the first situation, in addition to diffuse and well-distributed infiltration permeating the soil, the catchment can also be dispersed through multiple sets of surfacing fissures and fractures. The second condition, in turn, can occur both by the directing and concentrating surface (and subcutaneous) runoff to specific points of the terrain, such as to the bottom of dolines or closed depressions, as well as to rivers whose surface beds suddenly convert to underground conduits (e.g., a sinkhole or a river that loses water by infiltration at some point in the riverbed itself). Also, this may occur through straight rainfall catchment through deep shafts that connect the surface directly to the underground conduits. As to the origin of recharge, there is an authigenic parcel that is internal to the considered aquifer system or basin, involving the water precipitated directly on the karst, and in many cases, there may also be an allogenic or external parcel, involving contributions of water coming from outside the aquifer system or basin. The allogenic contributions can come from the surface, from rivers that enter karst domains and deliver non-karstic waters, as well as from underground, such as water that is transferred between different aquifer units. All of these recharge types are illustrated in Figure 1.1.2 that is presented at the beginning of the chapter.

(5) Interposed evolutionary configurations

Carbonate dissolution is a physicochemical process that leads to the relatively rapid decomposition and loss of the rock, as previously discussed. This phenomenon has a chain of consequences that are established equally rapidly and in which geomorphological and hydrodynamic scenarios are modeled and remodeled rapidly and progressively with the variation in the hydraulic conditions, the flow patterns (fissural conditions of laminar flow evolve into the network of conduits with turbulent flow), the increased connectivity and further fragmentation of the systems, and the very rate or speed of evolutionary processes due to crustal dynamics, hydroclimate conditions and water chemistry

Figure 1.2.7 shows the non-cyclic evolution of a karst terrain with the progression of karstification depicting the gradual modeling of a relief with negative water absorption forms and residual positive erosional

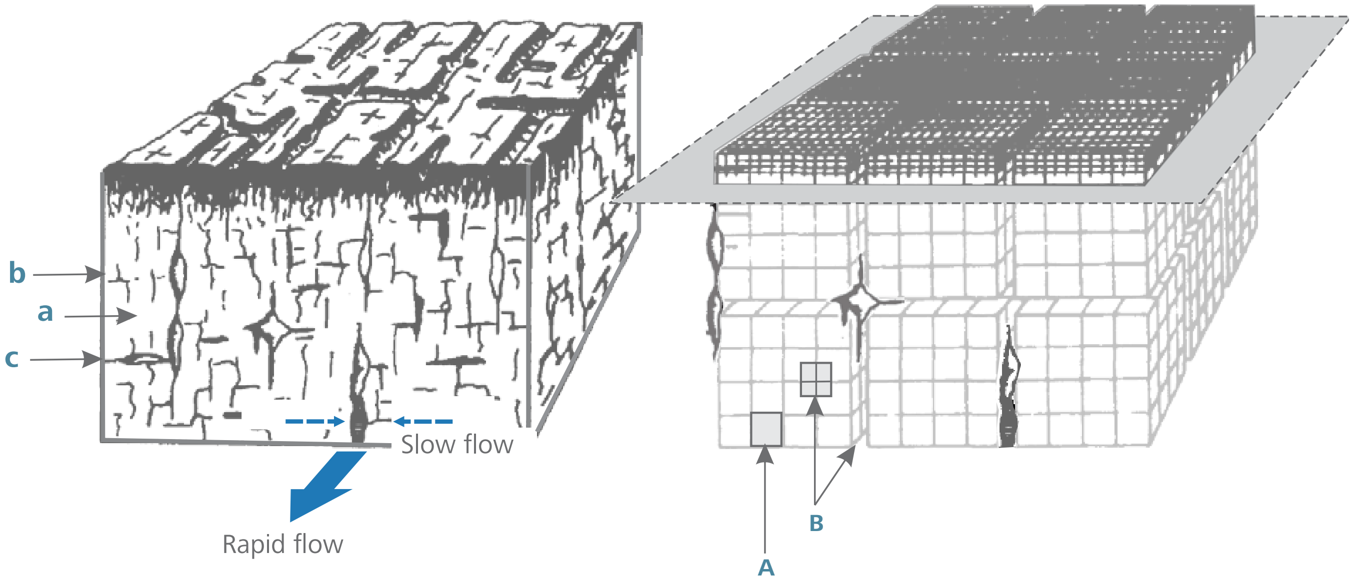


Figure 1.2.5. Karst triple porosity organization model, which is a spatially heterogeneous combination of the following porosities: (a) granular (rock matrix), (b) fissures (or fractures) and (c) dissolution conduits. The block on the left shows the dissolution conduits acting as drains (receptors/conductors) for water that flows slowly through fractures and intergranular spaces. The block on the right depicts a simplified conceptual model for karst aquifers that represents their global permeability condition: networks of high permeability conduits interspersing a rocky medium with low overall permeability. At different scales, the different porosities constitute blocks or "domains" in which a certain condition prevails: (A) very low permeability; (B) combined permeability of drainage fissures and dissolution conduits; and a (C) more superficial portion with a greater degree of karstification (epikarst) that is significantly more permeable than the deeper portions of the rock block. This decrease in permeability causes a delay in vertical infiltration, favoring the formation of more superficial reservoirs. Diagram by Mylène Berbert-Born. Modified from Drogue (1992). Mylène Berbert-Born.

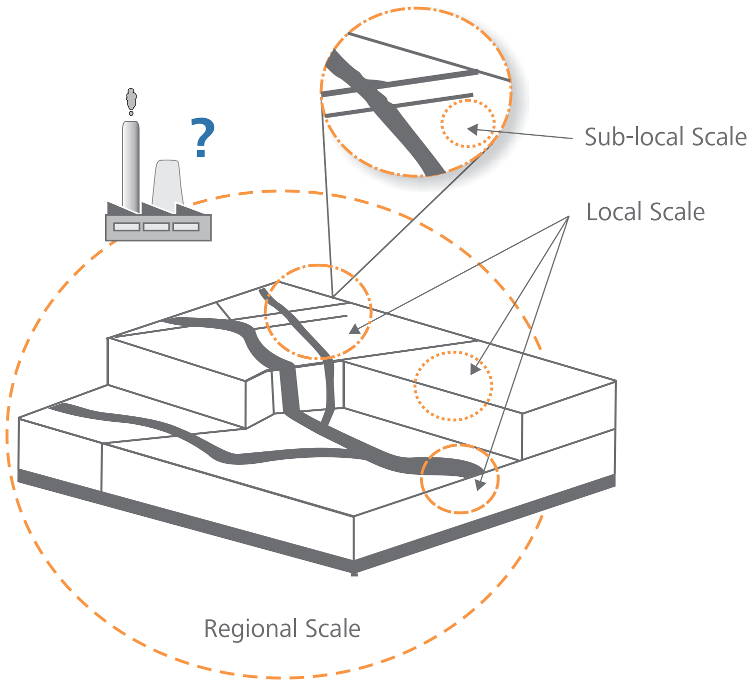


Figure 1.2.6. Heterogeneity of the triple porosity of karst aquifers observed from a scalar perspective, considering possible spatial domains where there are prevailing hydraulic conditions that are not representative of the regional context. It is important that ventures or activities in karst areas be contextualized as to their situation in these possible hydrogeological domains. Diagram by Mylène Berbert-Born. Modified from Worthington (2003) as based on Sauter (1992).

forms following the gradual increase in porosity of conduits and the connectivity of drainage networks. The more advanced stages culminate in the isolation and fossilization of fragments from older drainage systems, usually in association with a significant lowering of the regional base level.

Such scenarios or evolutionary stages are surpassed but often leave some record of their time – some aspect, feature or sign representing a "memory" of the evolution process. This evolution can sometimes be easily reconstituted in view of the obviousness of the preserved evidence; at other times, it is unclear because the evidence has already been greatly obliterated and even destroyed by subsequent phases. The point is that in karst current processes can be influenced to a greater or lesser degree by remnants of past environmental configurations, weakening diagnostics, analyses, and especially projections and predictions that are strictly supported by the most visible "architecture".

In karst, current processes can be influenced to a greater or lesser degree by remnants of past environmental configurations, making diagnostics, analyses, and especially projections and predictions very fragile if they are strictly founded on the most obvious "architecture".

The recognition of the inherited structures or patterns from previous evolutionary phases can strengthen sampling and monitoring programs (hydrochemical, hydrodynamic, sedimentological, biological, etc.) because they make the phenomena to be described and analyzed more understandable and predictable.

Thus, the existence of multiple morphogenetic structures which, when taken together, drive the current functioning of the karst environment constitutes an environmental criterion for in-depth studies that seek to reconstruct the geodynamic history and evolutionary patterns of the environment. This is especially useful for the diagnosis of parameters – not always very explicit – which may play an important role in active processes.

The recognition of these structures or patterns inherited from previous evolutionary phases can strengthen sampling and monitoring programs (hydrochemical, hydrodynamic, sedimentological, biological, etc.) because they make the phenomena to be described and analyzed more understandable and predictable. It may also favor the "extrapolation of patterns" for probabilistic analyses, a prospective tool that is sometimes very useful. All of the above favors a more directed approach for a more accurate prognosis of the impacts that will be produced by some disturbance in the environment.

In short, the relationship between the active processes and their controlling agents often finds explanations in past frameworks that need to be reassembled in the best possible way.

(6) Temporal variability and strong hydraulic dynamics

The temporal variability of hydraulic phenomena (inversions of hydraulic loads, changes in flow regimes and directions, level and hydrochemical variations) with strong long and short-term dynamics (rhythms, cycles, and responses to punctual stimuli) is one of the most striking expressions or consequences of the aspects listed above.

A noteworthy feature is the so-called "bimodality", which refers to the temporally biphasic nature that is often shown by hydraulic phenomena in karst systems due to the dualisms related to the types of infiltration, flow regimes, and organization of water reservoirs. This quality is manifested by phenomena that occur in pulses, often with delays related to specific stimuli such as a torrential rainfall event. This biphasic behavior reflects, at one extreme, the faster and more dynamic phases or parcels related to the hydrological activity of the dissolution conduits, as opposed to, at the other extreme, the slower parcels related to the fractured or massive compartments or even the distal portions connected to the system. The dynamism so unique to karst systems is the most assertive sign of the complexity of the organization and functioning of these systems, which greatly hinder the management of their terrains.

An example of how water dynamism may be reflected in the spatial organization of the aquifer basins is illustrated in Figure 1.2.8, which highlights the connectivity of the networks of fissures and conduits with different drainage systems being activated as a result of seasonal oscillations of the water table. In the diagram, the drainage systems identified as (A) and (B) are independent in the dry seasons, with distinct flow patterns and contribution areas (catchment basins), each dictating the behavior of the respective downstream springs (a) and (b).

The first situation depicts the base hydrological configuration of the regional system. The hydric connection of the two systems, established in flood conditions and according to the hydraulic gradient shown by the

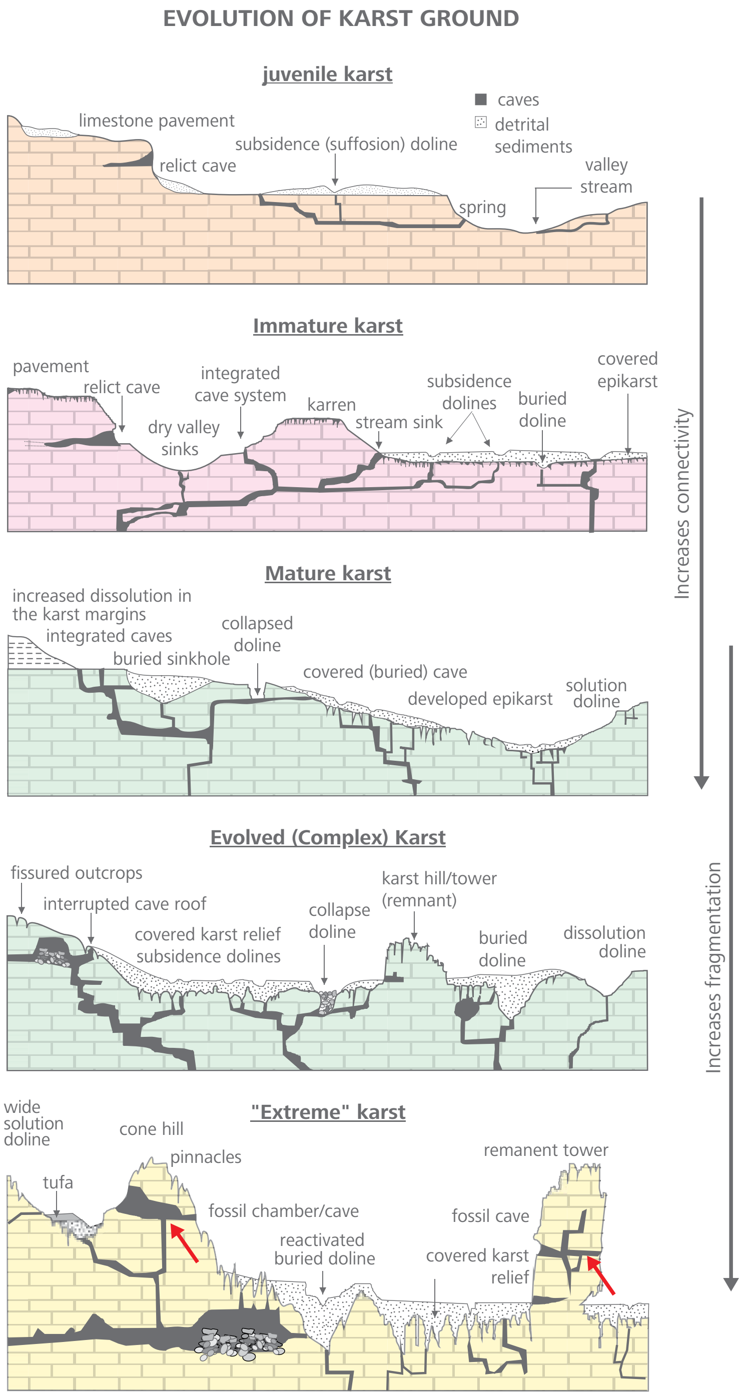
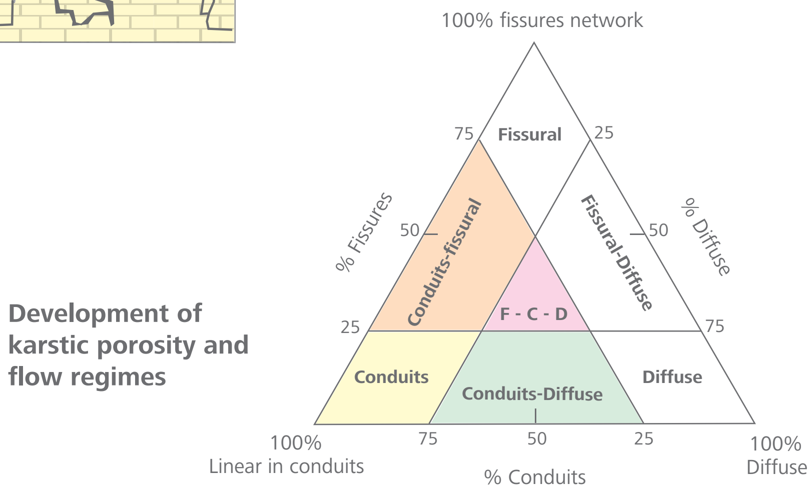


Figure 1.2.7. Evolution of a karst landscape with the progression of karstification. Increases in the conduit porosity and the connectivity of drainage networks lead to gradual modeling of a relief with negative water absorption forms and residual positive erosional forms. The most advanced stage shows the fragmentation and isolation of segments of old drainage systems as marked by the red arrows (bottom panel). Many remaining features have had some type of activity in the recent dynamics such as fragments of inactive conduits receiving the overflow and providing interconnection of aquifer basins during flood periods. Diagram by Mylène Berbert-Born. Modified from Atkinson, 1985 (diagram below) and from Waltham & Fookes, 2005 (left panel).



arrows in the second panel, shows the expansion of the system's contribution basin (B) and, therefore, a new set of factors influencing the behavior of its associated spring. This is an example of how the "catchment area" of a spring can vary in time.

To think systematically is to be able to see the forest AND the trees (Senge 1998). In this analogy, it is to see

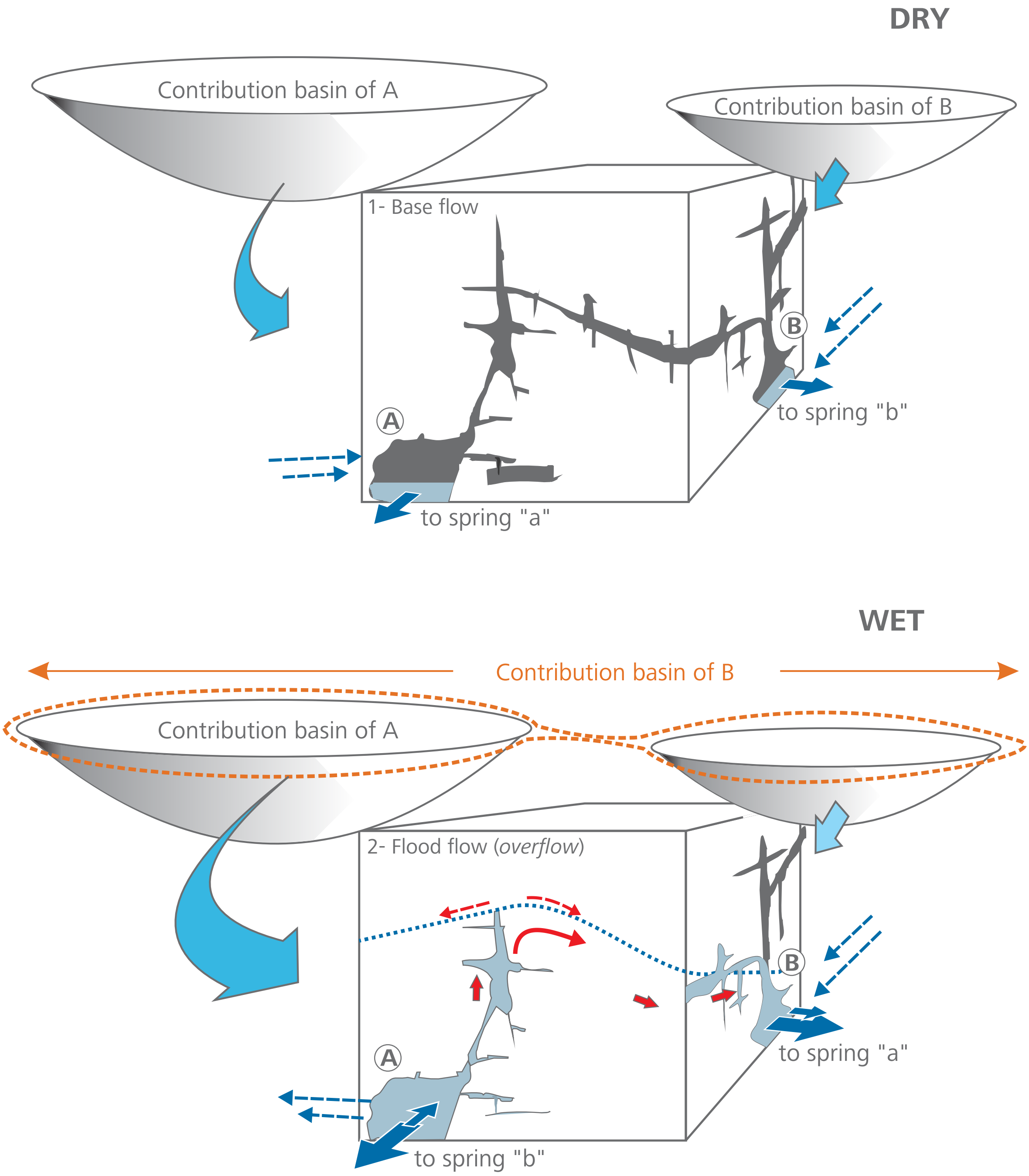


Figure 1.2.8. Seasonal connection between two drainage systems.
In dry seasons, the systems are mutually independent and have distinct contribution basins. In wet seasons, the systems are connected with the overflow of system (A) to system (B) according to the gradient indicated by the red flow arrows. The water basin of this second system is momentarily enlarged and encompasses the catchment area of the first. Additional explanations in the text. Illustration: Mylène Berbert-Born.

1.3. SYSTEMS AND GEOSYSTEMS – APPLIED OVERVIEW

both the karst as a whole and the elements of dissolution.

Forest is a "concept" that emerges from the gathering of trees covering a certain area in a given geographical situation[8]. Forest diversity reveals a wide range of conditions and processes that determine the specific types of trees, their distribution, profiles, and the mechanisms involved in the dynamics of a forest, including climate, soil, fauna and their interactions. Based on the synergies among its specific elements that are regulated by dominant factors, the forest acquires a global identity of its own (dense/open ombrophilous forest, deciduous/semi-decidual seasonal forest, arboreal Caatinga, planted forest...) and specific functions for itself and for the universe that surrounds it, which are the emergent properties of the "whole."

The stability of the forest and its vulnerability to a given "stimulus" depend on its vegetation (trees), substrates, interaction mechanisms, and the sectorial and global organization of all its elements; just as the stability and vulnerability of each tree also depend on the condition of the "forest unit" as a whole. The karst must be understood in the same way, globally: an organized set of certain characteristic elements that exist under specific circumstances, which are related to and interact with each other in a coordinated way through defined mechanisms or processes that produce discernible effects, thus configuring a scenario or mosaic of scenarios with their own characteristics and typical behavior, therefore becoming delimitable as a distinct system. For a truly systemic view of karst, it is necessary that all these points be recognized: components, structure, functioning and controlling factors, as well as its internal (self-regulating) and external functions. This will be discussed in section 1.4 – Karst Geosystem.

One of the crucial questions of any systems analysis is that based on composition (components), organization (structure) and behavior (functioning) criteria the boundaries or limits of the analysis scenario can be defined more accurately for a given analytical scale. The boundaries of the environment in an analysis are one of the most important premises of environmental impact assessment. Basically, the analysis environment is what we seek to recognize as the "whole" in which the conditions of stability, sensitivity, and vulnerability can be observed more clearly.

In this section, we explore these and other concepts that aid in applying the systems analysis criteria to the reality of karst environments, especially for the purposes of environmental impact studies.

Defining a system

When it is possible to recognize amidst a universe (concrete or abstract) a certain set of organized elements exerting interactions that produce perceptible effects in such a way that a scenario with its own characteristic, typical behavior, and determined purpose or function can be described, a system is outlined.

In these terms, the identification of a system assumes a sufficiently clear outline, albeit an imaginary one, that defines its comprehensiveness; that is, a boundary in which the elements and processes that characterize it can be distinguished from the external environment (medium). The boundary is decided according to some purpose or focus of interest, taking into account convenient compositional, structural, functional or finalistic criteria (Christofoletti 1999).

The same environmental context can then contain numerous systems, including those of spatial, temporal, and conceptual natures. For example, in a certain geographic space where karstified carbonate rocks exist, there may be from a functional and compositional perspective, respectively, the perfect overlapping of two hypogene (underground) systems: a hydrological system and an aquatic biological system. Related to these, there may be a partial overlapping or intersection of other types of systems such as sedimentary systems involving erosion and aggradation, faunistic and floristic systems. Figure 1.3.1 illustrates the situation.

For analytical convenience, all of the "thematic" boundaries noted in the example can be integrated to consti-

8 According to the definition by the Food and Agriculture Organization of the United Nations (FAO): "Forest - Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use". (FAO, 2012).

tute the boundary of a single system, whether a karst ecosystem (a given biological occupation of a particular physical environment) or a karst geosystem (a particular physical medium with specific potential for biological use). It is worth noting that, once integrated, each system takes on the identity of interactive subsystems in a larger system. Because of the new "content," especially of the now visible results of subsystem interactions, the greater system acquires new properties, which only appear under the global perspective. Despite the subjectivity in the "boundary" of a system, the delimitation is a fundamental aspect for the practical effects of the systems analysis. A frequent goal of environmental studies is to understand how a particular environment reacts when its structural conditions are disturbed or if the factors controlling its functioning are altered. This type of research is often supported by analytical modeling, usually prescriptive (idealize situations), prospective (explore possibilities) and predictive (project situations) models, involving hypothesis testing and the exploration of scenarios under controlled conditions. These analyses require objective parameters – what/how much/where/when – even though the purpose of the modeling is precisely to test the coherence of the delimitation of the system to the chosen criterion. Considering the existence of boundaries does not mean, however, to isolate or close the system with respect to the environment that surrounds it. Particularly in the case of natural environmental systems, these are "open systems" because there are usually interactions with other systems and exchanges of energy and matter with the "external environment" that guarantee its maintenance and function leading to its evolution over time. This relationship with its external environment is precisely what keeps systems dynamic and adaptable; otherwise, they would be subject to a predictable finite evolution – the stable equilibrium – solely coordinated by their initial state[9].

As per the Energy Conservation Principle (First Law of Thermodynamics), the internal processes of a system that use and "produce" some kind of energy necessarily depend on inputs (energy and matter). The input interactions are identified according to the system boundary. The external factors that control the internal processes constitute the influential environment of the system or simply the system environment. This environment itself also represents a system that in a figurative sense can be called "antecedent" (Christofoletti, 1999). When it is possible to provide geographical boundaries to the influential environment, it takes on the character of an area of influence, a physical space bringing together factors that have a direct or indirect relevant influence on a particular system.

Once energy and matter continually enter the system, as in the case of open systems, the internal flow (throughput) cannot only remain circulating within the system itself, accumulating inside indefinitely. Based on the configuration and interactions of the components, some type of processing occurs – its transformation to new states (the internal "production" of the system), its reuse in the various levels of internal processes, eventually a temporary storage – and somehow what enters the system leaves it in a condition generally quite different from the original one.

The output, which represents a relative loss of the system, is equally allusive to a boundary given to the system. The interactions that occur at the system output represent the influence that the system also has on the external environment, in a subsequent context under a relative temporal perspective. In some cases, it is even spatially subsequent, such as for a chain of "cascade systems". Thus, the output of one system can be the input of another "subsequent" system (Chorley & Kennedy 1971; Christofoletti 1999).

Analogous to the influential area (influence "over" a given system), the geographic environment that receives and is stimulated by what comes out of a given system (its output) is also part of the area of influence of that system. What happens in the (external) environment of the system based on the "output" can then in turn affect the "input" factors, establishing a non-linear chain of causes and effects. Therefore, territorially speaking, the area of influence of a natural environmental system defines the spatial (geographical) scope of the factors, elements, and processes that interact with this system, always having as a reference the boundaries established for it. Due to proximity, convergence, and affinity with the system, the areas of influence should always be observed with great caution, since, in addition to the most notorious aspects of influence, there is a greater probability of other governing and governed factors residing in these areas that are circumstantially less evident.

9 According to the Principles of Thermodynamics: First Law - Conservation of Energy Principle, in which energy (potential and kinetic) can be transformed from one type to another but cannot be created or lost; and the Second Law - Entropy Principle, which addresses the evolution of a system to the state of thermodynamic equilibrium. In isolated systems, starting from an initial energy state, over time there is a gradual loss of free energy capable of producing work, representing the increase in entropy and the degree of irreversibility or disorder of the system (Chorley, 1962).

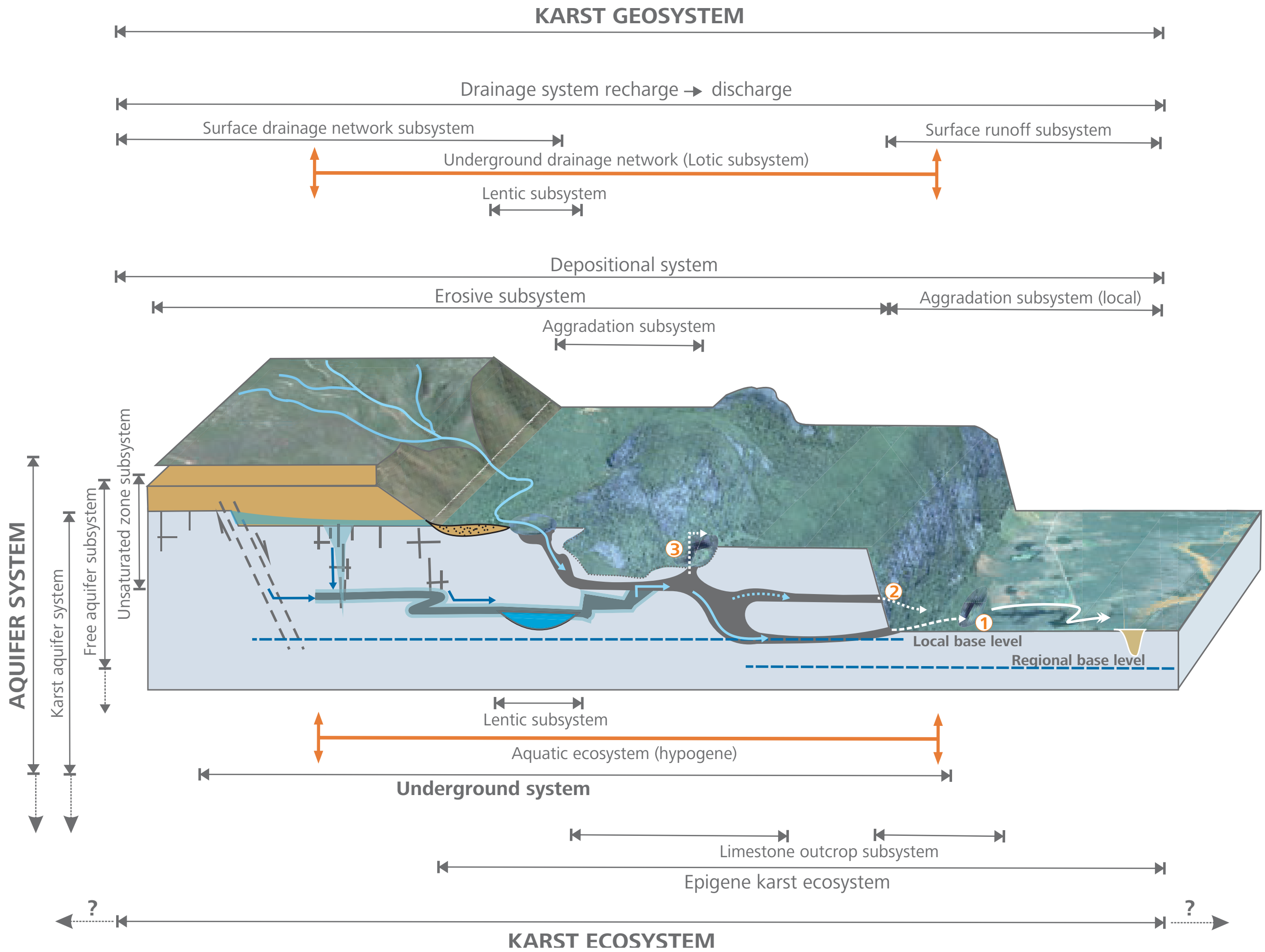


Figure 1.3.1. Some examples of systems and subsystems arranged in a "karst space" (overlapping, with intersections, in chain...). (1) base level discharge (minimum); (2) flood discharge (overflow); (3) estavelle – occasional discharge in high water periods. More detailed explanations are provided in the text. Illustration: Mylène Berbert-Born.

Figure 1.3.2 symbolically summarizes a system and all aspects that involve its definition. The highlighted system (red) is defined as a function of elements that have a mutual relationship and have specific characteristics; in this case, stars of a certain color, size and shape pattern that stand out in the midst of a very dense and heterogeneous "universe". The boundary is arbitrarily interposed by the circular space that circumscribes this specific set, according to panel (a). The factors and elements that exercise influence and strong control over the system (input) are represented by the narrow and wide arrows, respectively, which make up the "influential environment" of the system (panel b). Systems influenced and controlled by everything that "leaves" the system are also depicted by arrows, including yet another external set of elements ("subsequent system") that can be recognized by the "derived" characteristics of the highlighted system (also red stars but of another size and shape). Internally, the interaction networks between the system components are only outlined. Panels (c) and (d) are briefly explained in the figure legend and are related to the concepts discussed ahead.

The subject of inputs and outputs of a system is among the most important in the scope of any systems analysis. It can be understood as a balance of energy and mass: the quantitative difference between what enters and what leaves the system over a certain time interval is what is stored internally in that strict period; whereas the qualitative difference portrays the processing that occurs internally.

In other words, the input-output balance mirrors the system's own momentary internal configuration, the picture of a transient state that is a function of time. If there is no change in the state over time, or there is constant variation, then the system is perfectly adjusted to external influencing factors in a stable condition (equilibrium or dynamic equilibrium) that is maintained as long as the external conditions remain unchanged or variable within the range supported by the system (Howard, 1965; Brunsden & Thornes, 1979; Christofoletti; 1979).

It is worth noting that many systems are studied based exclusively on the input and output relationships – the deductive analysis known as "black box analysis". As discussed in section 1.2, in karst underground hydrological systems, which for the most part are inaccessible to direct observations, this type of analysis is widely used and provides valuable information on the organization and functioning of the system, particularly with respect to flow characteristics and groundwater storage conditions over time (Mangin 1975). Basically, comparative studies are conducted on the conditions of water recharge to the subsurface and underground environments in a given area and time interval and on the characteristics of the discharge of this water back to the surface. In this case, the system represents an aquifer basin (see section 1.2 - The classical dissolution process).

Structure and stability of systems in the space-time perspective

The stability of a system, which is closely related to the system-environment interactions, is an essentially relative condition in terms of time scale and spatial scale. From the perspective of a system as a whole, there can be a relative equilibrium at a given moment due to the action of smaller parts or components of the system that remain in a "state of reaction" to some imbalance stimulus, canceling or attenuating it from the global perspective of the system. This is because each component and certain groups of components also represent (sub)systems with their own gain-interactions-processing-loss dynamics in relation to the greater system, in a hierarchical structure (Von Bertallanffy 1975; Capra 1996) Therefore, the parts of a stable system may exhibit a momentary relative imbalance.

One of the most basic practical aspects of a systemic hierarchical structure is that the results of an analysis conducted in a scalar domain – spatial or temporal – generally do not describe the conditions of another scalar domain. The methods used for the study at one scale may even be unsuitable for another scale.

The issue of hierarchical and temporal scale should always be well defined and considered with great attention in karst environments due to their extreme inherent heterogeneity and high functional dynamics, a subject discussed in more detail in section 1.4 - Karst Geosystem.

One of the most basic practical aspects of a systemic hierarchical structure is that the results of an analysis conducted in a scalar domain – spatial or temporal – generally do not describe the conditions of another scalar domain. The methods used for the study at one scale may even be unsuitable for another scale.

The topic of hierarchical and temporal scale should always be well defined and carefully considered in karst environments due to their extreme heterogeneity.

To illustrate the hierarchical organization of systems, Figure 1.3.3 symbolically shows a dynamic natural system (variable in time) with its general components or subsystems in strong mutual interaction: biotic, physicochemical and anthropogenic components. To provide further detail, the example of a limestone massif is used to represent subsystems outlined by the structural and finalistic criteria. Hypothetically, the water that is stored in the crevices of the massif is pumped for the consumption of animals in a farm. The massif is analyzed from the perspective of a system, in which the perimeter of the rock outcrop is taken as the system boundary. Solar radiation (energy), rainwater (matter) and fuel for the pump (matter or energy) are some examples of input elements to the system. Each of the three components has very particular elements in interaction within its subsystem and with the other subsystems: a certain biocenosis and anthropogenic use of the "rock massif" biotope (geofacies). Each of these elements in turn also behaves as systems at hierarchically smaller scales: organism-organ-cell, lake-water-molecules and pump-motor-valve.

Figure 1.3.4 shows a different and very elementary representation of a generic system, this time focused on the functional criterion. The same reasoning of the hierarchical systems and subsystems organization is valid, now considering the entire flow chain of matter and energy through the system from its input (or inputs) to its output (or outputs). In this flow, it is crucial that the elements or aspects that regulate the processes ("regulators"), or that participate in the temporary storage or retention of some amount of matter or energy ("storages") are identified. More details on system modeling and analysis can be found in Christofoletti (1999).

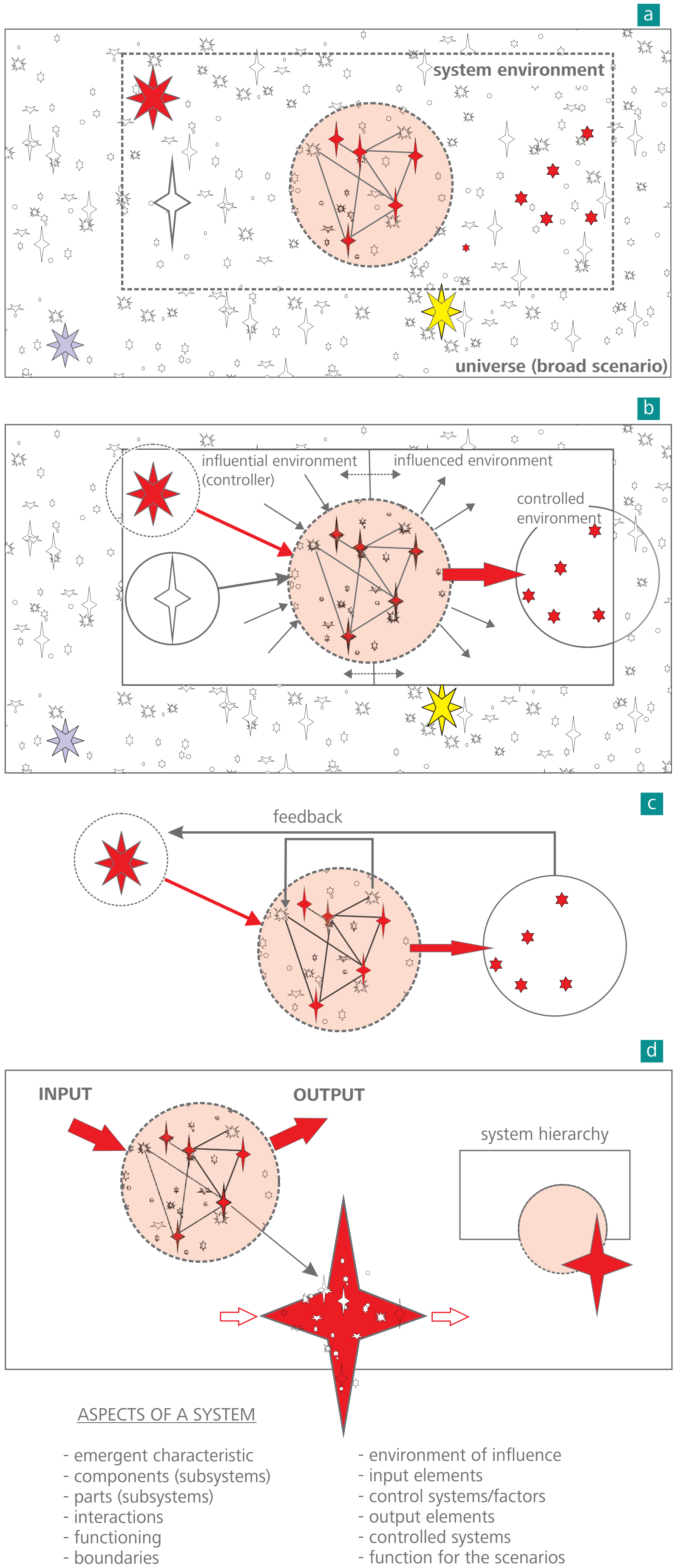


Figure 1.3.2. Diagram of aspects that characterize a system. Panel (a) represents the entire scenario at any given time T. Amidst the diversity of the scenario, it is possible to distinguish a set of interacting elements that have specific characteristics (elongated red stars). Symbolically, from this interaction arises a differentiated "atmosphere" that gives the system its own character (reddish shading). The dotted rectangle defines the immediate surrounding that directly influences the system. Panel (b) shows a more explicit representation of the system interactions with its environment, influenced by some specific "governing factors", and influencing through the exchange of environmental "information" (energy and matter) the external controlled environment. Panel (c) expresses that in one system many processes can occur in cause-and-effect circuits, in which the retroactive effects magnify or attenuate the original causes. Panel (d) demonstrates the "scale effect" inherent to any system, considering that the boundaries are merely conventional – each element or part of the system forms a subsystem with its own internal processes and external interactions. More explanations throughout the text. Illustration: Mylène Berbert-Born.

The concepts of stability and equilibrium of an environment are closely related to the relational and hierarchical structure of its subsystems, given the functional mechanisms and different degrees of sensitivity to disturbances of each one. Further exploring the practicality of these concepts, another example of a hypothetical (karst) system is given: a network of conduits and fissures limited to a particular rock space (defined components and boundaries), which receives water from the surface and transmits it again to the surface after a period of internal circulation and storage (function of storing and transmitting water through the underground environment). This system is the only source for a nearby community, which captures the water at a spring that represents the output point of the entire underground network (social purpose of water supply).

Because of the morphology and distribution of the conduits (structure and arrangement of the system), such an imaginary network forms two branches that constitute distinct hydraulic compartments – a "west branch" with good flow capacity and an "east branch" that is characterized by conduit constrictions that block the flow. Figure 1.3.5 is a diagram of the situation. The entire drainage network is in a balanced drainage and storage condition given the recharges of the system, supporting the seasonal increase in water supply without significant structural instabilities (figure 1.3.5, panels 1 and 2). The figure shows the existence of a smaller relatively isolated conduit located at a high elevation but ancillary to the main gallery. Under the hypothetical climatic and land use conditions considered, this secondary conduit is hydrologically inactive, which gives it very stable atmospheric conditions (temperature, humidity and partial pressure of CO2), relatively differentiated from the rest of the system. The biotopes and biological exploration in this particular medium are also unique and have high entropy (low potential/free energy). At a time when the system is suddenly overwhelmed by a severe and unusual increase in water supply, natural or induced, there is a significant change in the external factors controlling the system; consequently, a strong disturbance occurs in the dynamics of the water flow through the system, as shown in the figure. The upper secondary conduit becomes hydrologically active only in such an extreme episode, functioning as a flow regulating "valve" (figure 1.3.5, panel 3 - "Case A"). That specific part of the system, which under long-term conditions has acquired a stationary condition (water inactivity), undergoes complete imbalance; a biotope restricted to that small compartment may be, for instance, irreversibly destroyed in a single episode in which the secondary conduit functions as an alternative overflow outlet. In turn, by supplementing the system's drainage capacity, large upstream floods that could involve other more sensitive segments are prevented, thus inhibiting a system collapse.

The existence of the "valve-conduit" becomes an effective self-regulating mechanism of the represented drainage system. The activity of this specific component of the system is an example of so-called negative feedback, or "balancing" of the disturbance, that is about cause-effect circuits in which the effects retroact by attenuating or "filtering" the original causes. In this case, the unusual increase in water supply (input disturbance) generates an increase in the hydraulic load and the reversal of gradients in the outskirts of the system, activating side conduits that take on roles in the discharge of the system (consequent disruption of the state of equilibrium of the peripheral portions of the system). This situation prevents upstream flooding (damping of the disturbance), thus ensuring a global level of stability and maintenance of the system as a whole. Observing the system on a time scale greater than the scale of the disturbance episode, thanks to the negative feedback mechanism, it remains globally unimpaired and in balance, and is a practical example of self-organization.

By contrast, considering the lack of such "valves" in the system structure such as in the east branch of the conduit network, or what would happen in the case of obstruction of the apparently small secondary conduit of the west branch (Figure 1.3.5, panel 3 - "Case B"), the exacerbated increase in water supply may momentarily exceed the flow capacity and cause upstream flooding that can reach and erode large surface areas (Figure 1.3.5, panel 4). As a consequence, significant volumes of sediment can be remobilized into the system, causing the obstruction of relevant conduits (Figure 1.3.5, panel 5) and permanently changing the hydrological (and consequently, the biological) dynamics of the entire system.

In this case, there is what is called positive feedback or "reinforcement" of the disturbance, a chain of processes in which an alteration (such as an increase in water supply, obstruction of the flow channel etc.) generates an effect on the system (hydric overload) that reflects on part of the system (flooding reaching the surface), which is responsible for another effect (surface erosion, expansion of the catchment basin, sediment remobilization and aggradation in channels), which expands the initial problem (increased water supply and additional loss of flow capacity), finally de-structuring the system in such a way that its flow condition no longer sustains the return to its original (normal) recharge condition. The flooding tends to worsen and can reach other parts of the system, causing more erosion, more runoff, more water supply and sedimentation, more silting and reduced flow capacity. At some point, the entire drainage system can be abandoned in favor of easier drainage routes, and a new "arrangement" of the drainage arises that could be entirely different from the previous one (Figure 1.3.5, panel 6).

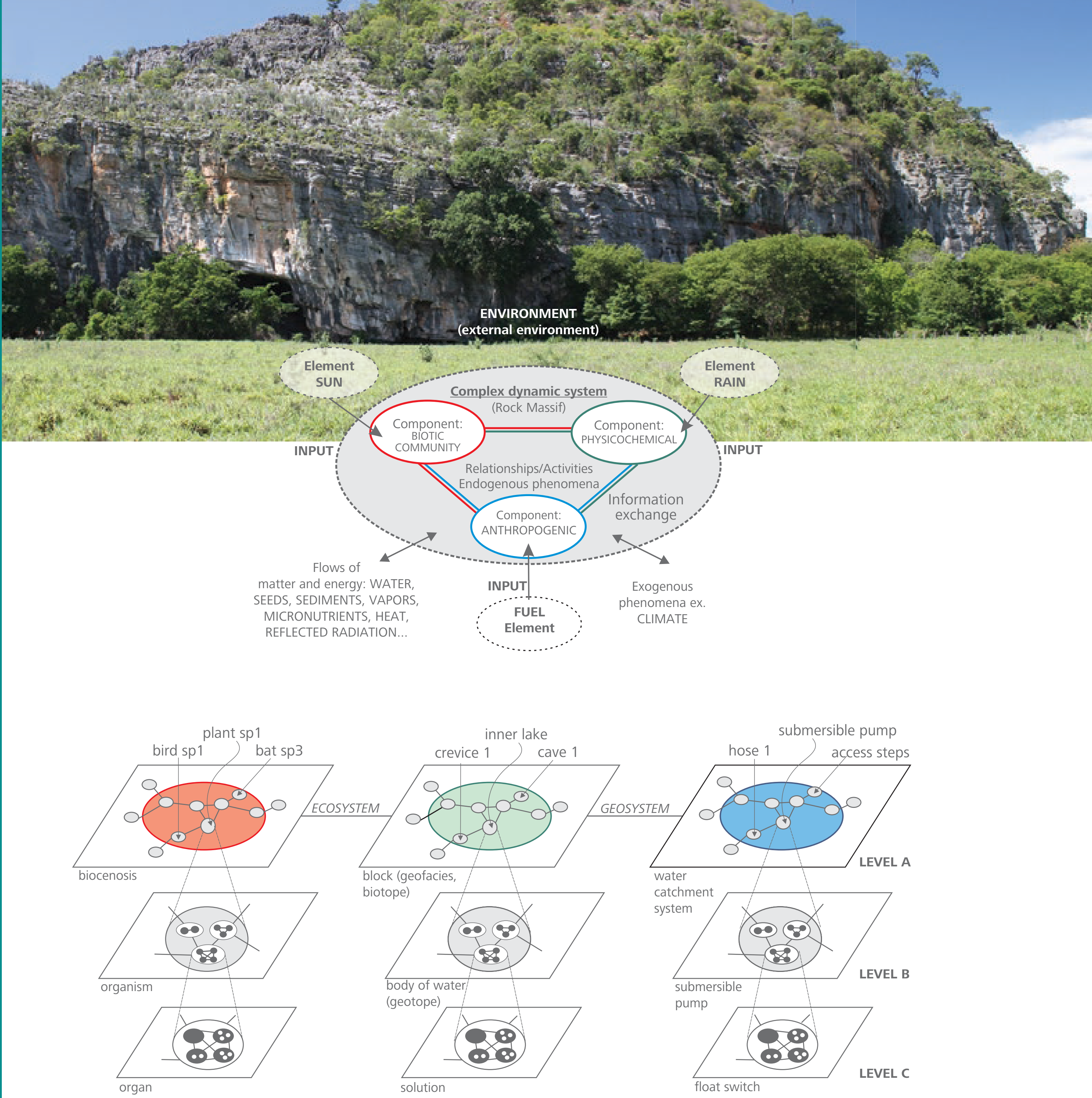


Figure 1.3.3. Representation of a complex dynamic system with its biotic, physicochemical and anthropogenic components, and its respective subsystems in a scalar hierarchy. The highlighted input elements (solar radiation, rainfall, and fuel) are examples of external factors that control the functioning and organization of the system, among other energy and matter input and also output flows. The elements and interactions between the physical and biological environments make up the ecosystem. The geosystem represents the physical natural system which, given its particular characteristics in a given context, allows specific types of biological exploitation, including anthropogenic. Diagram and photo: Mylène Berbert-Born. Top diagram modified from Aumond (2007); bottom panels modified from Frank (1998) apud Aumond (2007).

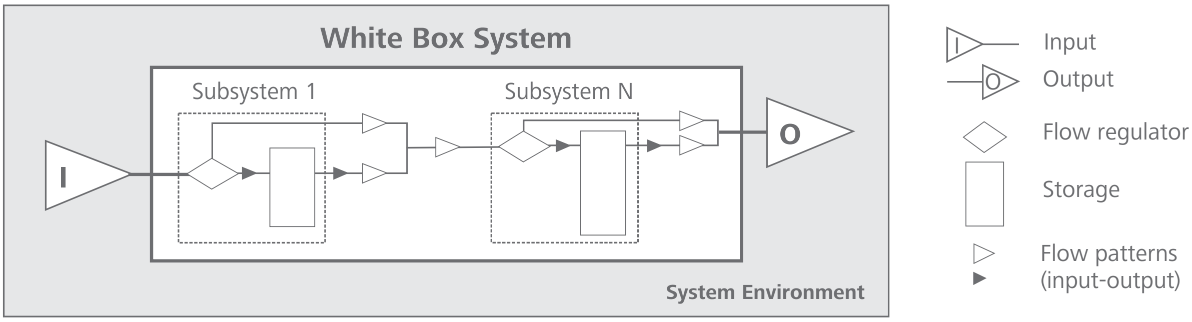


Figure 1.3.4. Elementary representation of a generic system, observing its organization and functioning. In this case, the structure of compartments or subsystems is known, and the way they relate to each other is described based on a chain of matter and energy flows that depends on the role and behavior of each component of the system (regulation, storage etc.). Given the clarity of their nature, these systems are called "white box" systems.
Illustration: Mylène Berbert-Born. Modified from Christofoletti (1999).

In the temporal context considered for this example, it is possible to recognize that the instability process presents a "first" moment that is considered critical: the flow capacity versus the hydric overload and the extent of flooding. From this moment, the system can evolve in different ways, undergoing feedbacks (negative or positive) and from each possible evolutionary response there are new critical points and other possible aftereffects. These critical points can be represented as sequences of "bifurcation points" in the evolutionary path of the system, according to Figure 1.3.6, in which each "branch" to be traversed can only be described probabilistically. In this case, there are combinations between different parameters that define the "system fluctuations": water surplus x conduit configurations x connections to the surface x activation/deactivation of flow valves x types of sediments involved... This unfolding of unpredictable alternatives is what finally leads the system to irreversible transformations.

These are concepts brought in very superficially from the concept of dissipative structures (Prigogine 1977, 1996, 2000), in which new patterns of order are created from non-equilibrium states in a process called order by fluctuations.

An important aspect of how systems behave in the face of a disturbance, which is especially relevant to more complex systems such as well-developed karst systems, is that the components and segments (subsystems) have different degrees of sensitivity to disturbance, reacting very heterogeneously in terms of the intensity and time of response (reaction and relaxation) to the disturbance.

An elementary conclusion is that the more complex the system, the more unpredictable the way it can evolve. In this sense, a key aspect about how systems behave in the face of a disturbance, especially pertinent to more complex systems such as well-developed karst systems, is that the components and segments (subsystems) have different degrees of sensitivity to the disturbance, reacting very heterogeneously in terms of intensity and response time (reaction and relaxation) to the disturbance.

Because complex systems present greater numbers of components and interactions, there is a greater range of possible reactions to changes in external factors. The effects can be attenuated, as indicated by dissipation of energy in some punctual transformation, or can be increased by the synergy between the parts or by the propagation/diffusion of a particular impulse through some chain of interactions (Howard 1965; Brunsden & Thornes 1979; Christofoletti 1999). For the same reason, the effects and adjustments can occur immediately and globally, in stages and sectorially, gradual and slowly, or even manifest with great delay after the disturbance.

The positive feedback explains why a small disturbance such as the silting of a "simple cave conduit" can cause large-scale effects, being a mechanism that tends to obscure the original factors that gave rise to a given effect (such as the erosion of a slope).

Negative feedback, in turn, shows how a major disturbance can be surprisingly attenuated by the environment, which is a particularly useful concept for strategies aiming to mitigate impacts arising from changes imposed on the environment.

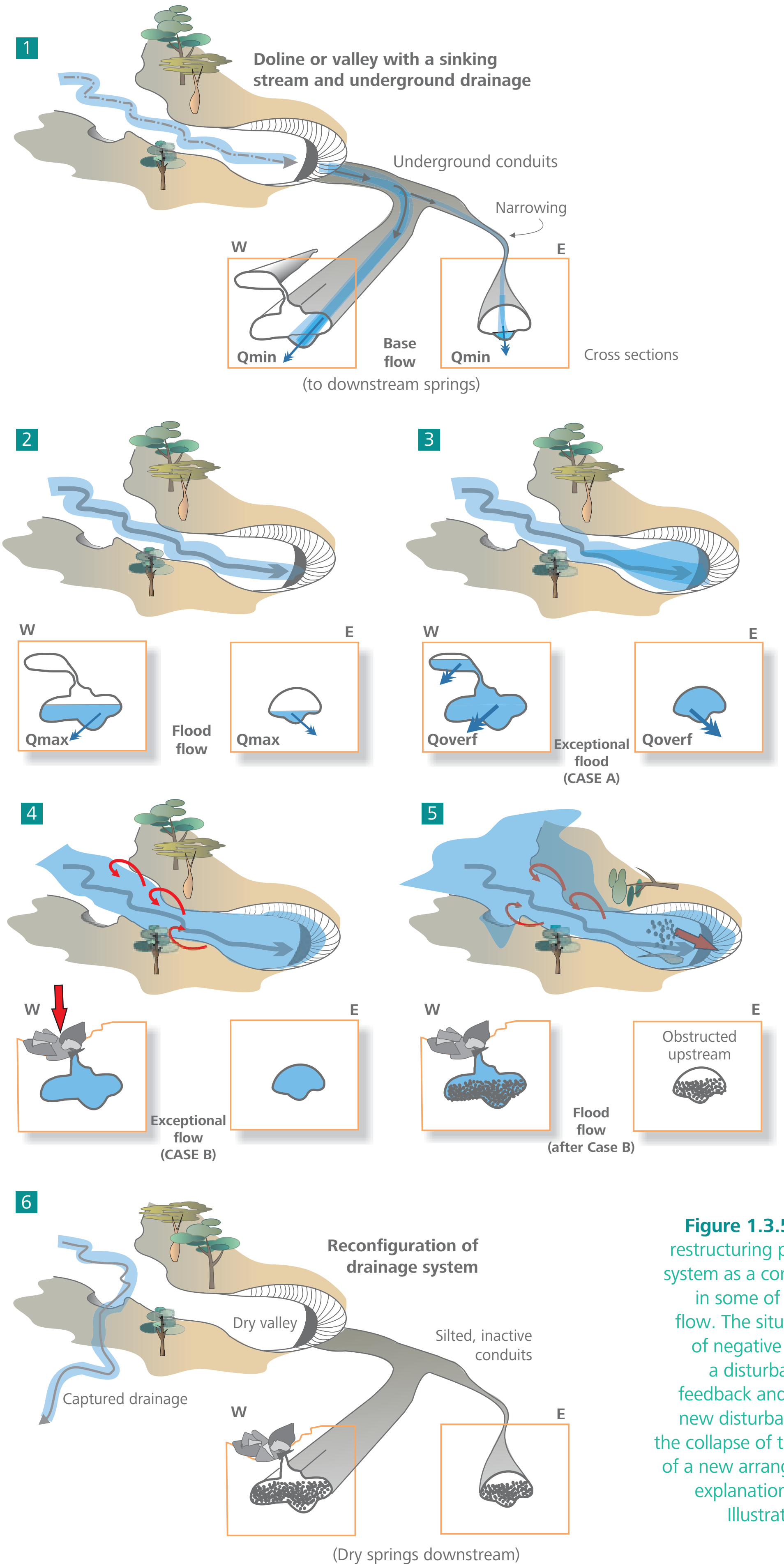


Figure 1.3.5. Schematic example of a restructuring process of a karst drainage system as a consequence of disturbances in some of the factors controlling the flow. The situation illustrates conditions of negative feedback and damping of a disturbance (panel 3) and positive feedback and aggravation/triggering of new disturbances (panels 4 and 5) until the collapse of the original system in favor of a new arrangement (panel 6). Detailed explanations are provided in the text. Illustration: Mylène Berbert-Born.

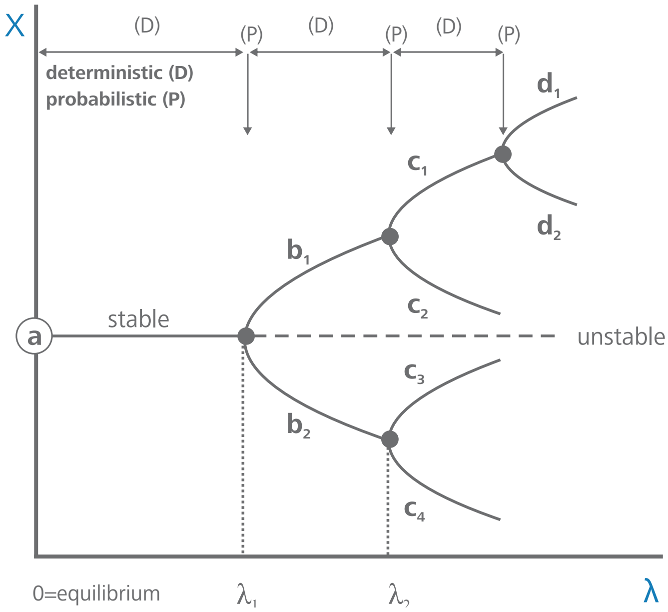


Figure 1.3.6. Representation of the possible evolutionary paths (successive bifurcations) of a non-equilibrium system. Some critical conditions in this path represent bifurcation points from which the system can evolve irreversibly in different ways. X = evolutionary state; λ = distance from the origin "(a) - equilibrium state". Deterministic zones between probabilistic bifurcation points. Further explanations are provided in the text. Diagram by Mylène Berbert-Born. Modified from Prigogine (1996).

Therefore, as much as possible in environmental analysis, it is always desirable to model the theoretical chains of bifurcations of the system, in which the points (situations and elements) of greater potential for instability and uncertainty – the "critical points" – can be prominently suggested, and from them the respective factors that may exert influence in the unfolding of one or another evolutionary branch. It is a more complex and comprehensive modeling of non-linear cause-effect chains.

The positive feedback explains why a small disturbance such as the silting of a "simple cave conduit" can cause large-scale effects, being a mechanism that tends to obscure the original factors that gave rise to a given effect (such as the erosion of a slope). Negative feedback, in turn, shows how a major disturbance can be surprisingly attenuated by the environment, which is a particularly useful concept for strategies aiming to mitigate impacts arising from changes imposed on the environment.

Bases for systems analysis applied to environmental studies

As seen, whatever the application or objective, the characterization of a system begins with the definition of an identity criterion and a first draft of the system boundaries. From this point on, especially when it is intended to assess the reactions of a given system to some disturbance, it is important to identify all levels of the subsystems that can potentially be affected by the disturbance, and to analyze the behavior of each one in the perspective of the hierarchical structure of internal and external "output → input → output", interactions, as previously discussed. This assumes that the individual properties of each subsystem are recognized without losing sight of the mutual relations between the subsystems and between these subsystems and their respective "environments" (their surroundings). Thus, the analysis of linear and circular cause-effect relationships is performed at different scales.

This articulated breakdown of a system into subsystems is an analytical strategy to identify dominant factors and levels of sensitivity and stability at each spatial scale for a given time interval, and consequently verify with a greater degree of control the extent to which the effects of the disturbance manifest themselves, that is, its scope in a broader system. In other words, to investigate what may be the area of influence of the disturbance.

This is a "dynamic focus adjustment" systematic, in which the overall conditions or properties (at any scale) are revealed by the properties, interactions and reactions of/between the parts, which in turn are determined by the overall organization. This idea of "relationship between the parts" suggests that the loss of some part of a larger system or changes in its structure may compromise the interaction of its components, and vice versa, eventually leading to the de-characterization of the system or at least of the "momentary state" in which it is found at a given spatial scale (Von Bertalanffy 2012; Capra 1996; O'Connor 1997; Corning 2002; Morin 2003; Reis Júnior & Perez Filho 2006).

In the initial stage, the internal elements need to be identified and qualified as to their specific attributes (state variables such as size, mass, position in space and time etc.) and their representativeness to the system, which defines the system structure. This step is comparable to a descriptive inventory. From this "general inventory", the most representative or dominant elements can already be perceived, and with attention focused on them, it can be found how the interactions are processed, what they depend on or what controls them, and what they produce, thus configuring the "hierarchical network".

As the processes, inputs, and products are recognized from the hierarchical structure perspective, the level of interdependence or correlation between the components is revealed. For the perception of interactions, it is necessary that the analysis also takes into account the strength (intensity) of mutual relationships, the sign (direct or inverse correlation), sensitivity (degree of induction) and interaction mechanisms (transfers, combinations, synergy, flows, feedback etc.) such that the functions of each element within the system are clear: regulation, reception, storage, retention, production, dissipation, amplification, filtering etc. (Christofoletti 1999). The "external" factors, which represent the inputs and the governing forces to the processes, and the overall structure of the system must be carefully considered in any systems analysis. With this characterization, one has a picture of the system's functioning that expresses the degree of complexity and other aspects such as its stability and sensitivity to internal and external disturbances, particularly in the face of changes in external control factors. However, it is clear that everything – complexity, stability, and sensitivity – is a function of the scale or hierarchical degree involved. The scale is the critical point of analysis.

The "articulated breakdown" of a system into subsystems is an analytical strategy to identify the dominant factors and the levels of sensitivity and stability at each spatial scale, for a given time interval. Thus, to verify with a greater degree of control, the extent to which the effects of the disturbance are manifested, that is, its scope within a broader system. In other words, to investigate what may be the area of influence of the disturbance.

This is a "dynamic focus adjustment" systematic, in which the overall conditions or properties (at any scale) are revealed by the properties, interactions and reactions of/between the parts, which in turn are determined by the overall organization. This idea of "relationship between the parts" suggests that the loss of some part of a larger system or changes in its structure may compromise the interaction of its components, and vice versa, eventually leading to the de-characterization of the system or at least of the "momentary state" in which it is found at a given spatial scale.

This broader and more detailed analysis of a system, as shown, is known as "white box analysis" and is represented in Figure 1.3.4. Differently from what it may seem, it is not an exhaustive procedure of extreme detail but a rationally structured analysis focusing on the aspects that are actually determinant in the structure and especially in the dynamics of the system (state and state changes), encompassing elements and their properties, inputs, forces, interactions, flow lines (linear and circular) and products or results.

According to Senge (1998), simulations with thousands of variables and complex sets of details (called "detail complexity") may be distracting, preventing us from seeing the main patterns and relationships. By contrast, it is the "dynamic complexity" that allows one to see the deeper patterns underlying events and details. "When the same action has dramatically different effects in the short run and the long run, there is dynamic complexity. When an action has one set of consequences locally and a very different set of consequences in another part of the system, there is dynamic complexity. When obvious interventions produce unobvious consequences, there is dynamic complexity" (Senge 1998).

In fact, structured analysis often requires simplifications, abstractions, reductions or extrapolations that find great support in conceptual, graphical, and mathematical models. In the technical and academic literature, there are many examples of models, modeling techniques and representation of environmental systems that are distinguished by their conceptual (principles involved), finalistic (intended objectives) and instrumental (techniques and equipment adopted) natures.

There are descriptive, synthetic, symbolic, simulation, and decision models (Christofoletti 1999), and the most interesting, accurate, and effective models are those that actually synthesize the structure and operation of the system by considering "time" as one of its determining variables.

Models that take into account the state mutations of the system under various temporal prospects, robustly calibrated by temporal rhythms that are relevant to each component – because there are elements sensitive to different cycles: daily, seasonal, annual, diurnal, critical changes etc., with different degrees or indices of mutability – are the ones that provide an actual dynamic perspective of the system. Temporal state changes are another aspect associated with the hierarchical scale of the system. In general, the lower hierarchical levels undergo mutations at shorter time intervals, whereas "larger" and therefore more complex systems usually appear to undergo slower transformations (as a parallel to Sochava 1977).

The proper diagnosis of the system dynamics is what allows recognition of patterns and state trends, when then allows for forecasts of the evolution to future system states, either under natural conditions or considering the repercussions of disturbances. This is an essential test for environmental impact studies.

Geosystems - brief conceptual review

The principles of complexity and hierarchical organization (organized complexity) and the holistic view (emergent totality of the interaction of the parts, with their own functions) are at the heart of the system concept that has been discussed so far. The term "geosystem" emerges when these concepts are applied to the recognition and analysis of geographic space, that is, when they are transposed to the physical geography. Therefore, in geosystems what is fundamentally important is the interactions, the functioning and the temporal dynamics or succession of states, not merely the morphology (Sochava 1977). Basically, a geosystem is a "physical environmental system" (Christofoletti 1999), the expression or physiognomy of which is the landscape (Troppmair & Galina 2006). More broadly, a geosystem is a concrete spatial system with a dynamic territorial character (an open system) shaped by interactive elements of all kinds that act on the land surface and that are arranged in a hierarchical framework, which can be defined based on functional and structural criteria or by some peculiar geographical dynamics, always physical criteria.

> The proper diagnosis of the system dynamics is what allows recognition of the patterns and state trends, allowing for forecasts of the evolution to future system states, either under natural conditions or considering the repercussions of disturbances. This is an essential test for environmental impact studies.

Taken as a whole, geosystems are made up of biological and human elements, which are inherent to the environment. However, they differ from the ecosystem because the focus of the latter is the organisms that interact mutually and with their environment in a given area unit, establishing a scenario that can be considered relatively homogeneous or characteristic from the point of view of biological dynamics and organization. Thus, a geosystem may even coincide with an ecosystem, but in general, it is broader, more complex and often encompasses many ecosystems. The situation is equivalent to a socio-environmental system; the environment is the basis of human behavior and a resource indissociable from its existence, but the focus of this other system lies in the human organization, functioning, and dynamics under the influence of its environment. Figure 1.3.7 schematically expresses these conceptual differences.

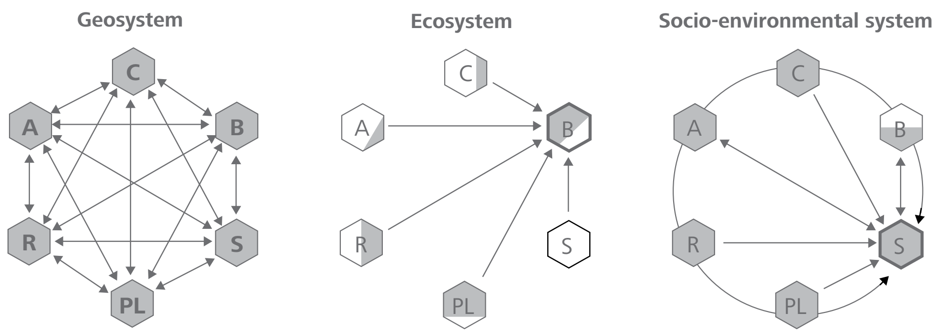


Figure 1.3.7. Conceptual-structural comparison diagram between geosystems, ecosystem and socio-environmental system. (C) Climate, (B) Biosphere, (S) Society, (PL) Pedosphere and Lithosphere, (R) Relief, (W) Water. Diagram: Mylène Berbert-Born. Based on Christofoletti (1999, p.42) and modified from Neves et al. (2014). See text.

It is important to note that since the term "geosystem" was introduced by Sochava (1977), based on Von Bertalanffy's General System Theory (GST) (1951, 2012), as a "concept and method" for the analysis of natural physical systems-[10]there has been a wide range of interpretations and much debate about its applicability (Bertrand 2004; Troppmair 1983; Christofoletti 1999; Monteiro 2000; Rodriguez & Silva 2002; Troppmair & Galina 2006; Reis Júnior & Perez Filho 2006; Bertrand & Bertrand 2007). The main differences lie in two aspects:

(i) Conceptual – whether or not to consider the socio-economic dimension of the given environment for the typification of the geosystemic unit (assuming that the environment is the basis of human behavior and resource indissociable from its existence); and

(ii) Delimitation – the spatial scale or scope of the system's boundary, which is biased in the definition of scalar taxonomic units; its territory delimitation and cartographic representation, which are topics of geographic analysis.

It should be noted that, to some extent, the second aspect is determinant over the first because, for very broad scales, even strong human interventions have very restricted (or null) capacities to disrupt fundamental structures such as a geological units or specific climate conditions (Troppmair & Galina 2006).

Regarding the scalar dimension and delimitation of geosystems, there are two schools of thought: Sotchava (1977) – an expoent of the so-called "Soviet school of thought" – conceives the possibility of geosystems to hierarchically unfold in different scalar orders (as long as they are perceptible in the terrain), being characterized by combinations of hierarchical subunits that form homogeneous and heterogeneous groups (elementary geomers, facies, facies groups, facies classes etc., and heterogeneous associations/geochores of 1st, 2nd, 3rd, etc. order). In turn, Georges Bertrand – supporter of the so-called "French school of thought" – considers a geosystem to be one of the six landscape taxonomic units (Bertrand 2004 presented in correlation with the geomorphological scale of Cailleux & Tricar 1956): upper units – zone, domain and natural region – guided by climatic and structural elements; and lower units – **geosystems**, geofacies and geotope – oriented by biogeographic and anthropic elements.

The classification proposed by Bertrand (op. cit.) is illustrated simply using an example of a karstic area in the north of Spain that consists of three large limestone massifs that form a mountain range known as Picos de Europa. The classification seeks to recognize dynamic combinations between physical, biological and anthropogenic elements (characterizing total landscapes), therefore having a temporal character.

It should be noted that the size of a few square kilometers to a few hundred square kilometers, as suggested by Bertrand for the taxonomic level of the geosystem, should be taken as a relative reference. All levels, especially the lower units (geosystems, geofacies, and geotope), can be classified using the criterion of "evolution systems", which is based on the recognition of one or some dominant factors, which may be biological dynamics, the overall dynamics or stability condition (geosystems in biostasy10 and rhexistasy[11]), or even the anthropogenic use when significant. Therefore, the scope of the units is quite dependent on the degree of their complexity, as emphasized by Amorim (2012). Here, Bertrand's idea is similar to Tricart's (1977) concept of eco-dynamics and differs from the taxonomic classification of Ross (1992), which relies essentially on the physiognomy of relief forms (size and shape allusive to genesis and age).

Summarizing Bertrand's concept (2004, passim) for the geosystem:

> *"It is the result of the combination of geomorphological factors (nature of rocks and surface mantlesslope dynamics...), climate (rainfall, temperature...) and hydrological factors (epidermal water table and springs, water pH, soil drying periods...), which depict a particular "ecological potential". Geosystems are not necessarily homogeneous in features, being formed of different landscapes or "physiognomically smaller units" – the geofacies, in a "mutant mosaic" – that represent the many evolution stages of the geosystems.*

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10 *"In normal conditions (the Physical Geography) should study not the components of nature, but the connections among them; it should not be restricted to the morphology of the landscape and its subdivisions but preferably expand to the study of its dynamics, functional structure, connections, etc." (Sotchava, 1977, page 2)*

11 (1) Geosystems in biostasy: weak or null geomorphogenetic activity, soil-vegetation-climate equilibrium, low erosion and transport, biochemical agents and processes predominate, pedogenesis predominate; individualized into four subtypes according to their higher or lower stability. (2) Geosystems in rhexistasy: geomorphogenesis dominant, erosion-transport-accumulation causing mobility of the slopes with impairment of the ecological potential; individualized into two subtypes according to two intensity levels (Bertrand 2004).

However, it can be assumed that there is a sort of ecological "continuity" within the same geosystem, whereas the transition from one geosystem to another is marked by an ecological discontinuity. Geosystems, like each geofacies, are complementary defined by a certain type of biological exploration in the space, with an evident dynamic relationship between the ecological potential and the biological valorization. The geosystem comes to a climax when there is a balance between ecological potential and biological exploration, an extremely rare situation. The geotope is the smallest homogeneous unit that can be directly perceivable (non-laboratory) on the terrain, for instance, a diaclasis widened by dissolution, a springhead, a valley bottom never reached by the sun, a mountain face...that are biotopes whose ecological conditions are in general very different from those of the geosystems and geofacies within which they are found."

In turn, V. B. Sochava explains geosystems as essentially natural formations that experience social, economic and technogenic impacts, which are examined as influential elements on the structure and dynamics of geosystems:

"Anthropogenic influences concern the many natural components of a geosystem (changes in moisture and soil salinity regime, vegetation changes, air pollution). All these indices determine the variable state of a geosystem in relation to the primitive structure and are reflected in its model. The so-called anthropogenic landscapes are nothing more than variable states of primitive natural geosystems" (Sotchava 1977, page 7).

A large number of studies in Brazil have been applied to landscape classification and geoenvironmental analysis, based on the concept of geosystems. An example can be seen in Vidal et al. (2014), in which "functional units" are mapped overlapping a base of environmental systems, each unit depicting specific functions of components and compartments, types of geoflows and environmental products. There are also important examples dealing with the geosystemic subdivision of state territories, for example São Paulo (Troppmair 1983), Santa Catarina (Veado & Troppmair 2001) and Ceará (Rodriguez & Silva 2002). Among these examples, it is worth mentioning the schematic representation technique used in research on geosystems in the state of São Paulo (Troppmair op.cit). It describes the dominant components and the way they are related in each geosystem, and also addresses the intensities of the dependence relationships that ultimately suggest the functioning mechanisms that are involved. Figure 1.3.8 shows what this author called "system figures", potential variations of which also illustrate the geodiversity.

The emphasis given here to geosystems has a special reason; in addition to being the conceptual basis for identifying and treating karst environments in a truly systems perspective, which is the subject of the next section, impact studies are no less than geosystemic studies, insofar as the anthropogenic actions are included in the analysis as an element that influences and even causes transformations on the spatial and temporal dynamics of the territory.

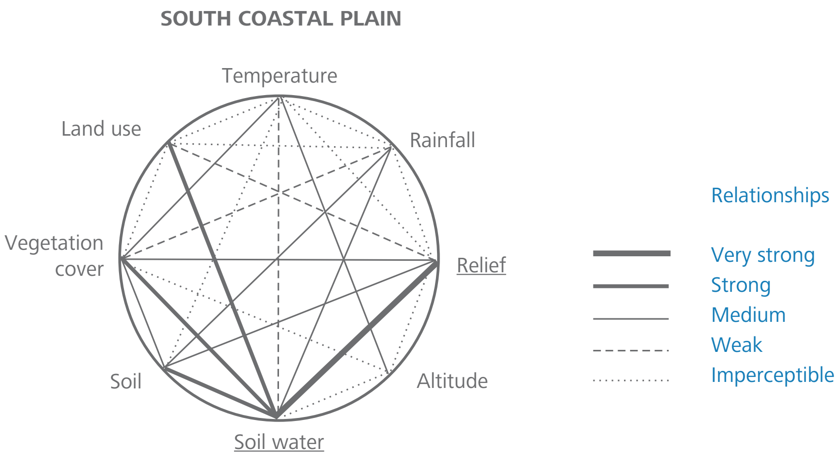


Figure 1.3.8. "System figure" representing one of the geosystems outlined for the state of São Paulo by Troppmair (1983): the "South Coastal Plain". In addition to the different possible combinations for representing the relationships between each "component", the variables that describe one are different than in another geosystem. Diagram: Mylène Berbert-Born

1.4. Karst in the geosystemic perspective – "Karst Geosystem"

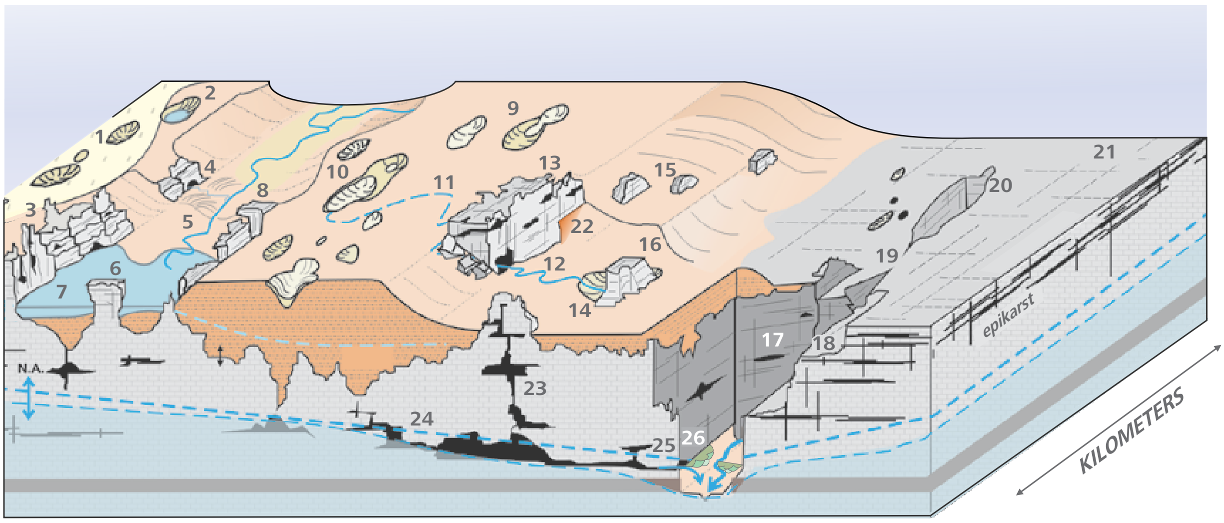
There are many purely descriptive definitions of karst in the literature that indicate "a particular relief with unique and very characteristic forms" – an identity criterion often also used for the term "karst system". The most elementary perception of karst basically involves the aesthetics of its landscapes. The very origin of the term karst, which means "rocky ground" in the derivation of the Slovenian word kras, refers to a landscape that has a certain appearance.

In view of the concepts of the systemic approach hitherto asserted, this is only the perception level of the shapes or components (characteristic elements) of an "environmental unit" called karst. Naturally, the perception is guided by characteristics and magnitudes that are the individual or collective attributes of these specific elements, described according to their own variables, for example:

- "doline (attribute) with depth (attribute) greater than 100 meters (variable)"; and

- "lakes (set of components) in circular (variable) shape (attribute) with homogeneous and constant (variable) temperatures (attribute)".

In the strictly descriptive focus on characteristic components, the karst environmental unit can be circumscribed directly from these elements, and it is relatively easy to delimit it by the morphological criterion. Figure 1.4.1 illustrates typical elements of karst morphology that could be used to delimit the karst block: dolines on plateaus, dolines in alluvial valleys, uvalas, outcropping limestone massifs, towers, warts, canyon valley, blind valley, sinkholes, losing streams, resurgences, karst lagoons, caves, polje, in addition to residual and transported soils.



LEGEND
1. Field of dolines
2. Doline with pond
3. Limestone massif with clint surface (karren), towers and benches
4. Spring or resurgence/outflow cave
5. Polje
6. Hum
7. Karst pond/lake
8. Towers
9. Uvalas
10. Doline with intermittent sinkhole
11. Underground drainage
12. Outflow cave/resurgence
13. Limestone cliff
14. Stream sink/sinkhole
15. Warts
16. Outcrop in doline
17. Karst canyon
18. Plateaus
19. Natural bridge
20. Shaft/skylight-daylight hole/collapse doline
21. Limestone pavement/clint surface
22. Rock shelter
23. Shaft/abysm
24. Cave
25. Intermitent resurgence/outflow cave
26. Calcareous tufa

Figure 1.4.1. Elements and features typical of karst relief. Illustration: Mylène Berbert-Born.
However, many other issues still need to be considered before the karst can be effectively understood as a system.

In one of the sentences that introduce section 1.3 - Systems and Geosystems, several general questions are included, the answers to which raise the karst environment to the actual condition of a geosystem. The following is recalled:

> *"Karst must be understood globally (1) as an organized set of particular elements (2) that exist under specific circumstances (3), relate to each other and interact in a coordinated way through defined processes and mechanisms (4), producing discernible effects (5), thus configuring a scenario or mosaic of scenarios with their own characteristics (6) and typical behavior (7), and therefore are delimitable as a distinct system (8)."*

The questions introduced above are as follows.

(1) What spatial extent and temporal range can be considered for a global systemic understanding of karst?

(2) What elements, especially of a physical nature, are peculiar to karst systems?

(3) What are the fundamental parameters of the existence of a karst system and the main factors that govern its evolution?

(4) How do the elements organize and interact?

(5) How do the elements organize and interact?

(6) What are the "emerging features" of karst systems?

(7) How do these systems tend to evolve and what are their dynamics?

(8) What is the "system figure" that outlines the identity of the karst system?

The answers to these questions are provided in Figure 1.4.2, which involves the vast territory represented there (regional context) to the small details shown (functional subsystems), with water serving as the main organizing agent of the environment.

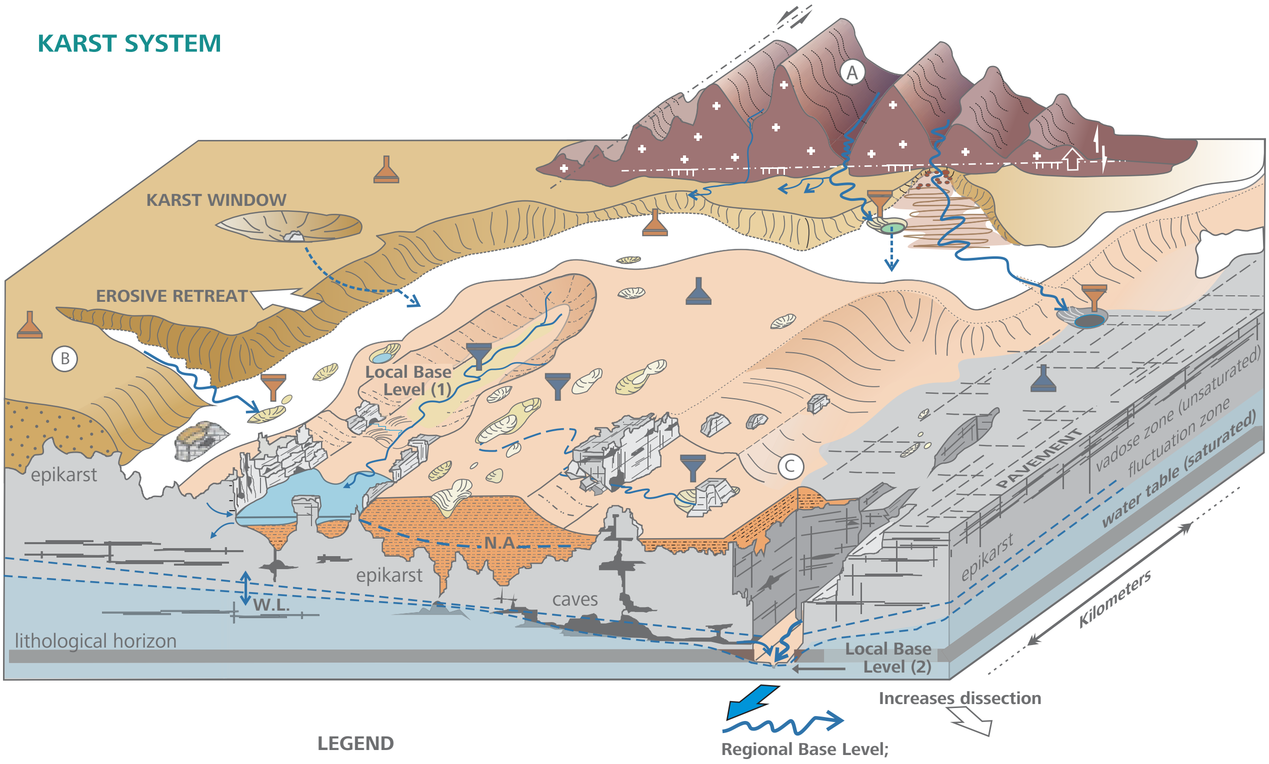
Based on the information presented throughout the previous sections, these answers are somewhat related to the configuration of the karst aquifer which, in a simplified way, depicts hydric flow systems (with associated sedimentary and biological flows) with interdependent recharge - flow/storage - discharge compartments working in a feedback loop.

Considering that water and rock are the main control agents and important limiting factors of karst systems, the model of water flow vectors acting on/in characteristic karst environments can be applied both at the extended scale of the global geosystem and at the scale of a single underground channel section. Between these two scale extremes, this same analysis can be applied to any other subsystem, including those shown in Figure 1.4.2, provided that the systemic criteria for its individualization are met.

In the diagram below, the inputs and outputs of each flow system represent related antecedent and subsequent systems. The cave subsystem, for instance, may have one or more dolines as antecedents and epikarst and/or a particular network of associated fissures; it may also have a spring as one of its subsequent systems. In the chain systems perspective, the cave represents one of the possible inputs of a spring.

The model of water flow vectors acting on/in the compartments characteristic of karst environments can be applied at both the extended scale of the global geosystem and at the scale of a single underground channel section. Between these two scale extremes, this same analysis can be applied to any other subsystem, provided that the systemic criteria for its individualization are met.

KARST SYSTEM



LEGEND

- Alluviums
- Sandy colluvium
- Colluvium/eluvium on limestone bedrock
- Sandstone rocks
- Carbonate rocks (with pelitic interbedding)
- Crystalline rocks

1. Restricted and/or temporary porous perched aquifers
2. Porous or granular aquifer
3. Karst and/or karst-fissural (free/semi-confined) aquifer
4. Fractured aquifer

Recharge:

- Allogenic
- Authigenic
- Diffuse;
- Concentrated

- Surface flow
- Underground flow
- Fault line/plane
- W.L. Water level (water table)

Macro geomorphological compartments

- (A) Mountain Range
- (B) Plateau/low plateau
- (C) Karst/Karst depression

KARST SUBSYSTEMS

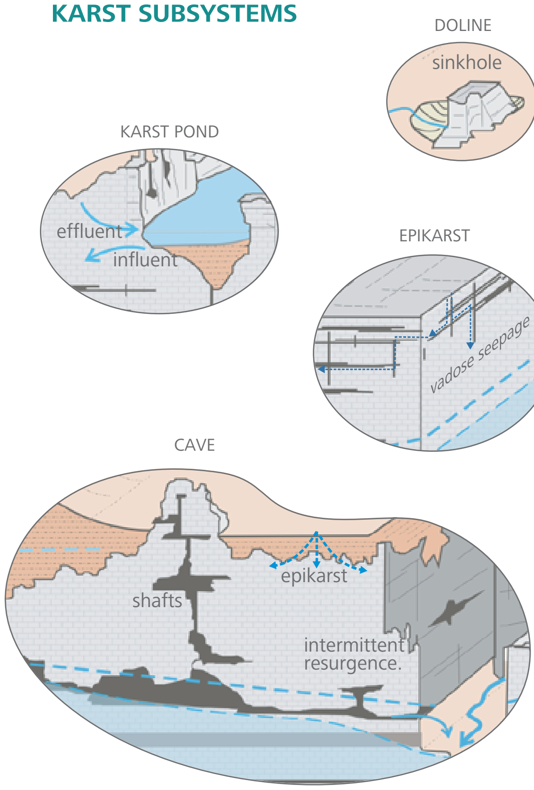


Figure 1.4.2. The entire Karst Geosystem – from allogenic recharge to regional discharge – and some of its subsystems: Karst pond; Cave/Conduit system; Section of epikarst; Doline. Subsystems are not isolated in the context of geosystems; in their analysis, the inputs, circulation (processing and flow) and outflows of matter and energy as well as their relationships with the surrounding systems (antecedent and subsequent) must be verified. Illustration: Mylène Berbert-Born

INPUTS (water, sediments, nutrients...)→

- in the epikarst;
- in the doline;
- in the cave;
- in the spring;
- in a conduit section;
- in a network of fissures;
- in an aquifer unit;

[processing/storage particular to each];

→ OUTPUTS (water, sediments, nutrients...)

Any kind of cave, having as a simple delimiting criterion a space that is accessible (penetrable) to a human, allows practicing systems analysis. In the case of an "open system", all the related inputs and flows surrounding it must be considered, not only of water and air but also of other kinds of organic and inorganic materials, including all types of interactions with the networks of fissures and smaller volume conduits that are connected to it. Under the temporal perspective of system analysis, it is worth noting that even a hydrologically inactive cave can be analyzed qualitatively from the perspective of water inputs-processing-outputs. This is based on relic signs of past water activity such as dissolution patterns imprinted on the rock, the porosity arrangement of conduits and fissures, and residual, remobilized or precipitated sediments. In such cases, the objective certainly cannot be something such as a water balance, but it is perfectly possible to reconstitute the dynamics of the environment and the history of past processes under the action of agents different from the present ones.

Particularly for this cave example, which includes legally protected spaces according to Brazilian laws, this systems perspective offers a better way to recognize the factors that control it and the scope of its most relevant area of influence. It becomes easier to understand the cave when a segment of some larger system is considered, for example, a specific portion of a network of underground voids, a compartment of an aquifer system and the aggradation subsystem of an erosive-depositional system.

From a regional or global perspective, the concept encompasses a large surface water flow system that includes all allochthonous contributions (surface and groundwater flows from non-carbonate domains) and the regional efflux (the mouth of higher Strahler order streams that cross and leave the karst domain as well as transmissions to non-karst aquifers).

In this concept, karst can be described as lateral and vertical successions of subsystems constituting interdependent "geoenvironmental facies" or "geofacies". In functional terms, either laterally or vertically and on any scale or considering any subsystem, water with a specific physicochemical pattern always enters a compartment (or entered at some moment), passes through a certain medium interacting with it, being modified by and modifying it at some level (leaving a record when no longer active), and finally leaves through another compartment in a physicochemical condition that may or may not be different from the original.

Lastly, Figure 1.4.3 summarizes the most important elements and conditions for the karst geosystems discussed so far, highlighting by way of illustration the connectivity and interdependence between two typical karst drainage subsystems: doline-cave. If one of these systems is analyzed individually, the other should be considered from the perspective of an antecedent or subsequent system, featuring the environment of influence on a given scale, or a given extension of the chain of interdependent systems.

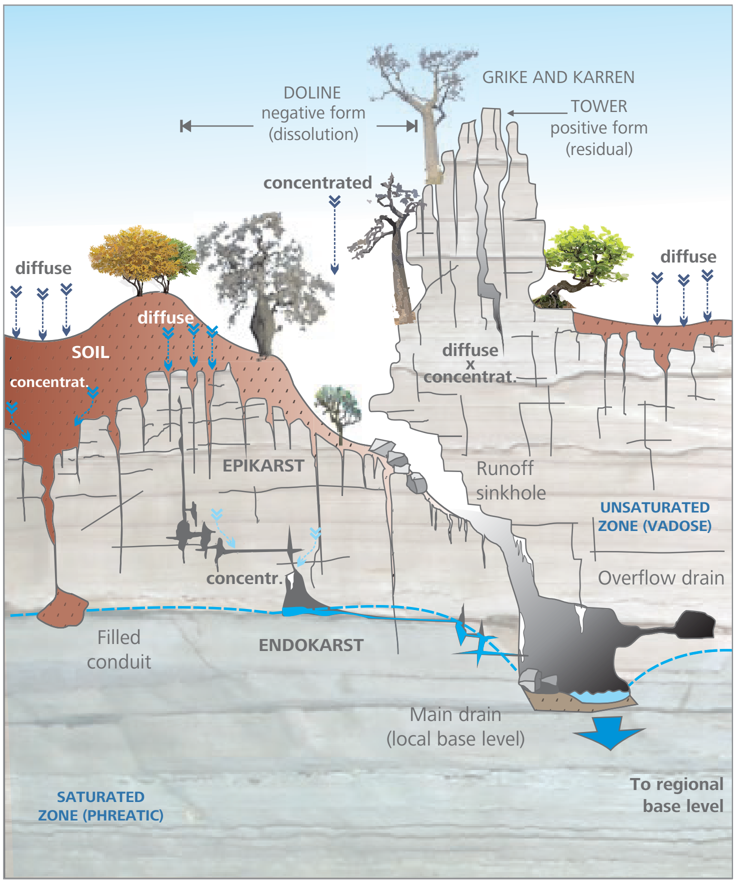
Based on this synthesis, karst geosystems can be schematically represented according to Figure 1.4.4, where the basic water recharge-transmission-discharge conceptual cell, quantifiable through the water balance, is applicable vertically and laterally in any compartment and spatial scale.

Identifying a karst geosystem - practical exercise

In the terrain outlined in Figure 1.4.2, three large physiognomically distinct topographic compartments can be recognized, highlighted as (A) mountainous or highland relief where there is a dense drainage network with strong erosive action, (B) extensive tableland surfaces such as a plateau gradually dissected by well-structured drainages and (C) more depressed areas of very irregular topography with an assorted collection of positive and negative relief forms, where the surface drainage is very poorly organized.

Comprehensive geomorphological compartments, as illustrated in Figure 1.4.2, are fundamentally related to the different existing rock associations. These in turn are formed, transformed and structured under different geo-tectonic contexts[12] and gradually carved and "redistributed" by weathering and transport processes, which are dictated by climatic conditions combined with gravitational forces. There is, therefore, a "genetic equation" for this broader compartmentalization: different rocks formed and structured in a particular geoenvironmental context + transformations and modeling by a particular set of supergenic agents and processes = a landscape with characteristic physiognomy.

Figure 1.4.3. Synthesis of the most important elements and conditions for karst geosystems. Illustration: Mylène Berbert-Born



Born Large-scale geomorphogenesis (regional geomorphology) can thus be considered as a first approximation or preliminary criterion for the delimitation of a larger scale karst geosystem, which represents the entire "C" compartment in the figure, where the characteristic components indicated in Figure 1.4.1 are identified.

All of these features or relief landforms, which allow clearly individualizing a terrain unit, in essence reflect a condition of high permeability of the rock substrate. The increased permeability is the consequence of networks of voids formed underground by the corrosive action of water, which become progressively larger and better connected over time. The progression of dissolution, and therefore of the degree of permeability, is among the factors that give rise to the great diversity of existing karst terrains since each region may be at a different stage of evolution (see Figure 1.2.7).

12 Ambient and tectonic regimes: lithosphere zones subjected to compressions and distensions of different magnitudes, under diverse stress vectors, due to the displacement of the tectonic plates over the Earth's convection mantle.

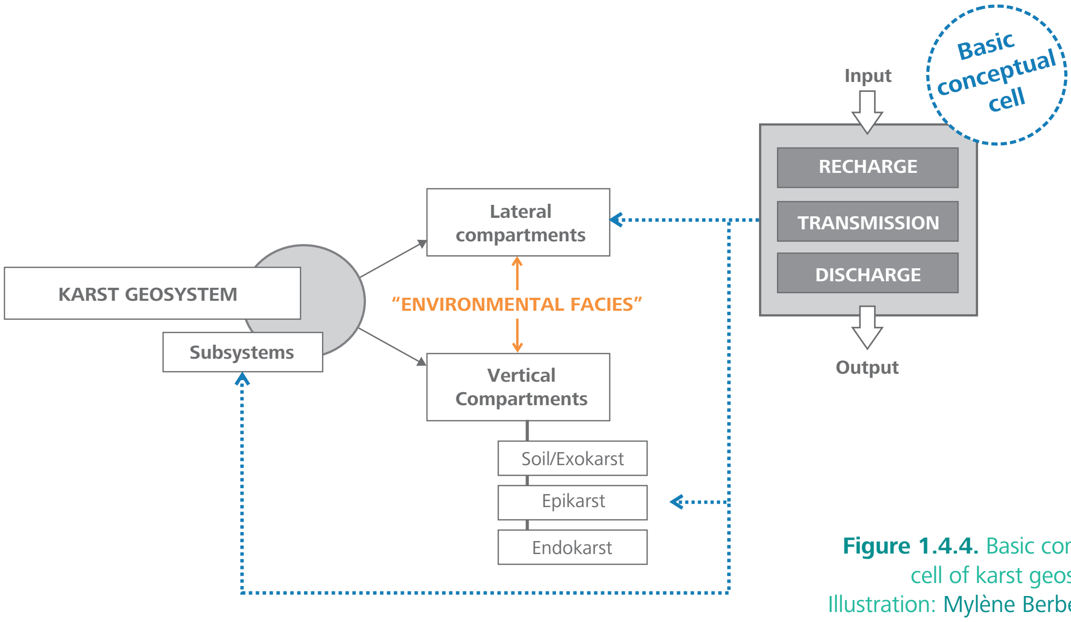


Figure 1.4.4. Basic conceptual cell of karst geosystems. Illustration: Mylène Berbert-Born

Thus far, some questions have already been answered in the systems overview: drafted boundaries (the boundaries between geomorphological compartments in a regional view) delimiting a distinct set of relief and material forms (characteristic features and elements), whose existence is linked to a particular geoenvironmental circumstance: the combination of a particular lithology (limestones and dolomites), climatic condition (presence of humidity) and topographic gradient (generating a hydraulic gradient and an erosive potential). Together, they give rise to the specific process of carbonate dissolution (and other associated erosion and accumulation phenomena), which results in a notable increase in permeability.

However, in geosystems, it is still important to understand the organization and interactions of the components, whose patterns and mechanisms characterize the temporal dynamics, the succession of environment states, and the functioning of the environmental system in general.

Organization and functioning of karst geosystems

It is important to remember that organization and functionality are closely linked aspects in any system. At first glance, the karst landscape may seem chaotic because of its irregularity and heterogeneity, but in fact, the distribution and articulation of the elements are strongly logical on any given scale. For example, regarding relief, some features may be repeatedly combined in space; some types of morphological elements may occupy preferential geographical positions or there may be trends as to the size or expressiveness of each type of feature relative to its geographical location. Consider the following:

- "circular(variable of the attribute "shape") lakes (set of components) dispersed(arrangement) in a creek plain(situation)";

"rock towers (set of a type of component) with pointed (variable) surfaces (attribute) aligned in the middle slopes (arrangement) of the eastern edge of a plateau (situation)";

"dendritic perennial (variable) tributary systems (arranged set of components) upstream (situation) of a sinkhole (component)"; and

"an intermittent (variable of the "dynamics" attribute) cluster of springs (arranged set of components) at the base of a hill (situation)".

With appropriate attention, it is then possible to individualize subcompartments by grouping sets of elements into articulation patterns that nevertheless maintain a predominantly morphological character. Therefore, "a dozen conical dolines with drainage sinkholes, disseminated in an interfluve at elevations above 650 meters" can geomorphologically characterize a "plateau of dolines". Figure 1.4.5 highlights some possible karst morphological compartments.

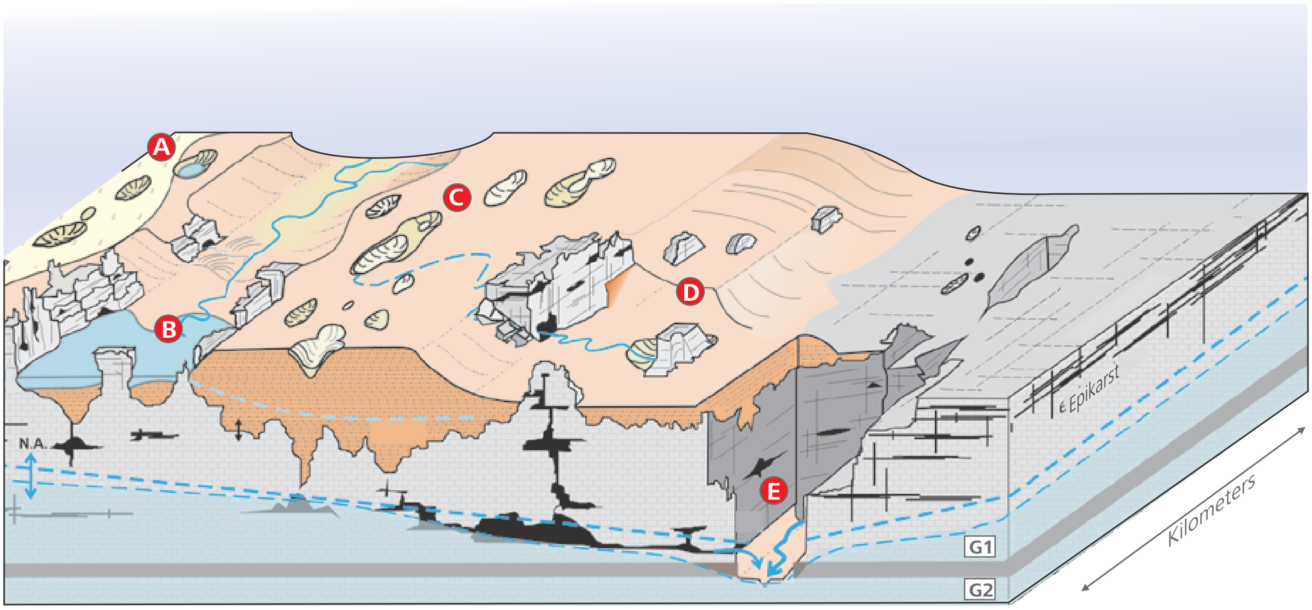
However, it is necessary to go slightly further, leaving the merely descriptive extent of this morphological compartmentalization in search of the reasons or forces that govern the observed organization. To begin with, the very combination or articulation between components or sets of components, and especially between the various compartments suggests some relationship or interaction between them.

To facilitate the understanding of a series of important concepts regarding interactions, a reductionist analysis was performed that was focused on the doline highlighted in Figure 1.4.2. It is treated as a "small" system or subsystem, as detailed in Figure 1.4.6 (a).

This subsystem with specific properties can be considered as a geofacies of the larger geosystem. For analytical convenience, it was delimited by the morphological criterion, so the boundaries are the contour of the doline itself, materialized by the relief break line where there is a sudden increase in the slopes. The doline environment, also called "surroundings" (or area of more relevant influence), corresponds to the entire perimeter where some type of interaction with the doline can occur. On one hand, this could be areas from where water, sediments, fauna etc. are imported, which are inputs for the doline, and on the other hand, it could be areas to where all the outputs (such as water vapor, fauna, and flora) coming from the doline are exported after inner circulation and processing.

The main components of the exemplified doline that may be related are:

- the escarpment occupying part of the doline perimeter (E);
- the slopes and contour of the doline (S) and (C);
- the unconsolidated materials (soil) present in the perimeter, edges, slopes, and bottom of the doline (S);
- the vegetation, which is sectorized according to the soils (V) and (Vs);
- a sinkhole located at the bottom of the doline that extends into an underground channel (Sh);
- all interstitial/cave and non-cave biota (Bi) and (Be); and
- the microclimate (Mc).



Geomorphological units

A. Northern doline field (covered karst)
B. Poljé and slopes dowstream (exhumed karst)
C. Southern dolines field (plateau)
D. "Serra do Calcário" (massifs and rock towers of the south slope)
E. River valley (fluviokarst)

Geological units

G1. Group "G", Sub-unit "G1" (Member 1, facies 1...)
G2. Group "G", Sub-unit "G2" (Member 2, facies 2...)

Figure 1.4.5. Example of a hypothetical karst geosystem based on morphological aspects. Illustration: Mylène Berbert-Born.

In the characterization of the dependency relationships, it must always be possible to describe their manner and intensity, whether the elements are directly or indirectly associated, whether they are mutually dependent or influential, or whether one is consequent to the other. Relationships can initially be verified from two simple questions: "when one element is disturbed, which elements are affected?" and "at what intensities?". For examination of the illustrated doline, the testing of some hypotheses helps to structure the framework of relationships that is proposed in Figure 1.4.6 (B):

Hypothesis A – Eliminating the escarpment (very intense disturbance);

Hypothesis B – Modifying or partially eliminating the escarpment (mild to moderate disturbance);

Hypothesis C – Replacing the doline vegetation with pasture (very intense disturbance); and

Hypothesis D – Completely clogging the sinkhole (very intense disturbance).

Based on the framework of relationships in the figure, the escarpment appears to have some type of direct or indirect influence on the entire arrangement, and the existence of some of the system components depends directly on its existence and configuration, including Vs, Sh, Bi, and Mc. Therefore, the escarpment should be considered an essential or limiting component of the doline subsystem.

The dependency relationships between components only express themselves through the action of some type of interaction mechanism. An important example of interaction mechanism between elements and/or compartments is the "flow or transfer of matter", which can be subdivided into three different processes: disaggregation/removal, movement, and deposition. A sedimentation phenomenon is the effect of incorporating materials in a given space, in this case sediments that have been relocated from other sites. In these other sites, there was obviously a suppression of materials. Grooving is the effect at the other end of this transfer mechanism. These effects are materialized by characteristic morphological features, which on one side are the erosional (denudational) forms and on the other the depositional (aggradational) forms.

Every mechanism in its time needs a force or agent to be processed, undergoing some sort of regulation. The transfer of matter in the example in question can be driven by water (processing agent) responding to gravity (transforming force) and by wind responding to atmospheric dynamics; however, it could also occur in response to a force or a new state of forces that start to act such as the release of some barrier. Water, wind and gravity are always important governing factors of environmental processes, in addition to a wide range of anthropogenic actions.

Regulation, in turn, is performed by both passive parameters (variables) such as the surface geometry (profile, slope, extension...), the nature of the materials in the source area (grain size, cohesion/cementation), plant cover and other aspects of the balance between infiltration and runoff as well as by active parameters such as the volume of water, and the intensity of the impact of the drops on the surface. It is worth noting that some of these regulation parameters define the level of stability of the "transformation substrate", that is, the thresholds of resistance to transformation and resilience, which is the ability to recover from a disturbance. It is the case of the greater or lesser propensity of landsliding under regulation of the forces of friction and cohesion between the soil particles. More cohesive or cemented soils generally withstand sliding phenomena, and soils with better vertical drainage facilitate desaturation and increase waterlogging resilience, thus also preventing mass movements. Both are conditions that increase the degree of stability of the slope.

Lastly, the functioning of the environment is understood insofar as the interaction mechanisms of elements and compartments, their corresponding agents, and the results or products of those interactions are known. Considering a more specific objective such as performing a local water balance to evaluate gains to the underground environment via contribution from the doline, it is possible to resort to an analytical simplification and to analyze the doline system only from the water action perspective in its physical and chemical aspects.

By way of illustration, below are some of the main "inputs" of energy and matter involved in the interaction of the doline with the environment and some possible processed products.

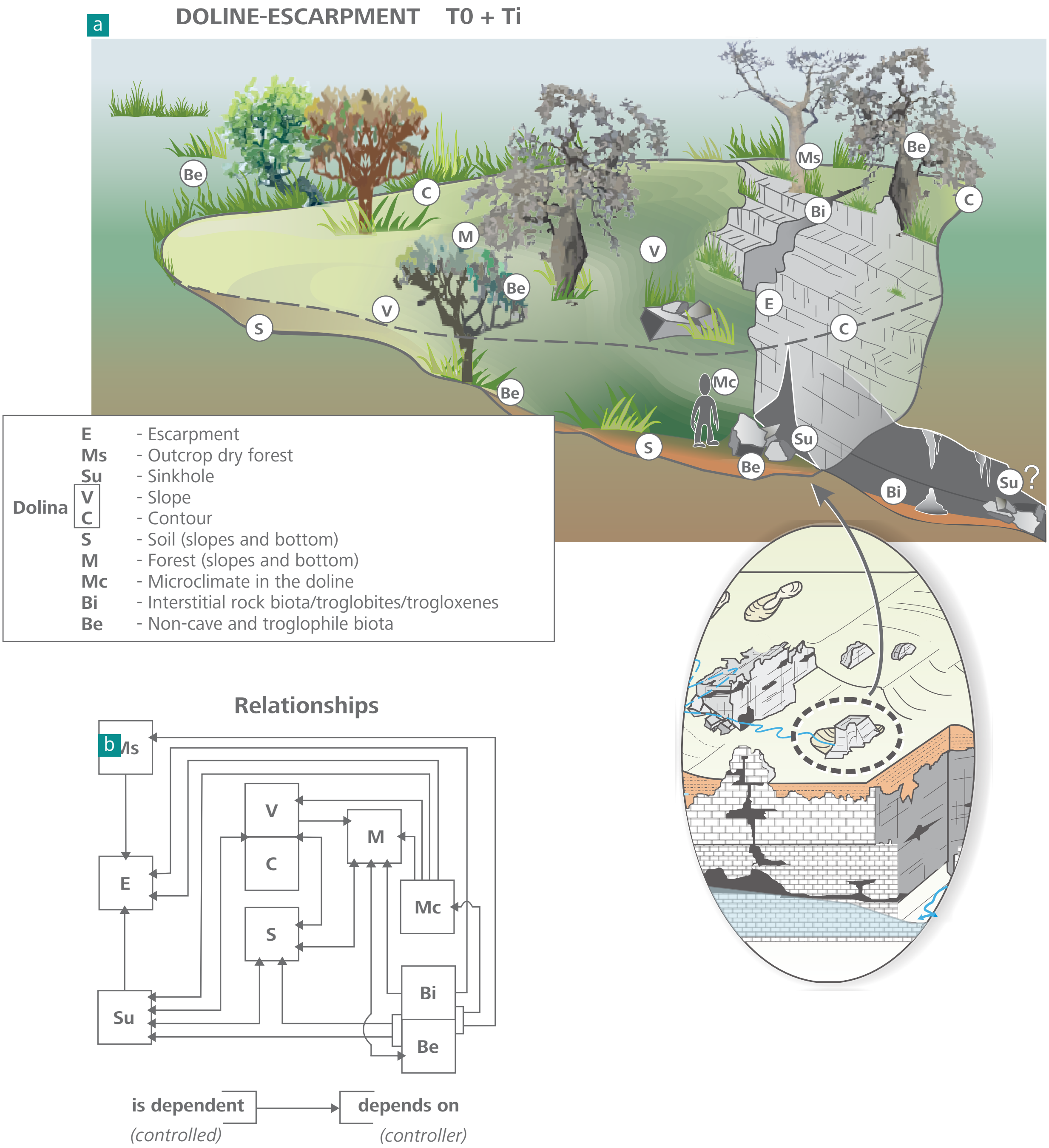


Figure 1.4.6. Aspects taken into consideration in the systems analysis of a doline, considering it as a subsystem or geofacies of a hydrological system in a given karst geosystem. Explanations throughout the text. Illustration: Mylène Berbert-Born

ENERGY

<u>Energy input:</u> solar radiation (electromagnetic waves of different lengths - short/ultraviolet), visible (light), short-medium/infrared (heat); terrestrial radiation and reflected terrestrial radiation (thermal infrared).

<u>Energy output:</u> solar radiation reflected on the surface. Potential energies converted into work in the doline: kinetic (water movements, mass and particle movements...); metabolic, chemical and biochemical processes... (photosynthesis, decomposition, weathering...)

MATTER

<u>Matter input:</u> solutions and solutes - water and dissolved compounds. Rainwater (direct rainfall), surface and subsurface runoff, dissolved chemicals; gases (including air); inorganic and organic particulates carried by water, wind (moving air) and animals; the animals and plants themselves (seeds, pollen etc.).

<u>Matter output:</u> water (by runoff, infiltration, and evapotranspiration); gases (convection, evaporation, respiration, transpiration, and decomposition); inorganic and organic particulates carried by water, wind, and animals; the animals and plants themselves. Transformation matter in the doline (energy ←→ matter).

All of the parts that somehow relate to the doline demarcate a doline "field of interaction". If taken in its entirety, the field of interaction can extend enormously. It can reach, for example, the distant setting of the formation of vapors that after a long journey precipitate on the doline. This is because the chemical (isotopic) composition of the water that enters the doline from the rain may be determined in that distant setting. Regarding the range of relationships maintained with the doline, function is a fundamental aspect of systems analysis because it represents the scope of the relationships considered to be more significant within the great web of interactions. Having identified the functions of a system, the scope of "relevant" relationships can be defined by the point at which a disturbance begins to affect any of its effective functions. According to this criterion, there is no single and permanent delineation of what can be considered the most interactive system, considering that this delineation depends on the type and magnitude of the disturbance and which element it is affecting.

However, based on the contextualization of the doline in an environment in which the relationships with other systems are structured, some combined function (joint or sequenced) or complementary function between systems is also revealed, for instance the hypothetical interaction between different dolines via an underground connection common to all, significantly increasing the complexity of the analysis.

Similar to this brief doline analysis, several other karst subsystems, such as those highlighted in figure 1.4.2, can be outlined and described in the perspective of water/particulates/nutrients/gases/energy input (inputs and agents → circulation/flow and input processing → output of inputs (input/throughput/output).

1.5. FRAGILITY AND VULNERABILITY OF KARST ENVIRONMENTS

The fragility and vulnerability of karst environments are discussed in this section under the terminological and conceptual framework referring to systems and to environmental systems in particular, as discussed in sections 1.3 and 1.4.

A stable environment is a disturbance-resistant environment; in the presence of a disturbance or pressure, it can maintain itself intact, without significant changes that could compromise its structure (components and interactions), functioning (processes and activities), and functions (ecological and social purposes). Environments that can easily recover from a disturbance, quickly regaining their original conditions or being able to adjust without compromising their characteristics, demonstrating resilience, are also considered stable (Brunsden & Thornes, 1979; Christofoletti, 1999). The impacts of disturbances on these more stable (resistant or resilient) environments tend to be small, usually temporary, reversible, and non-comprehensive because the transformation thresholds are not easily reached.

This is different in karst environments; the effects of disturbances can be intense and extensive and usually have a high degree of uncertainty, thus illustrating the great unstable nature of these environments. An example is what happens when the groundwater level lowers beyond the limits of its natural fluctuation. This situation may signal the overexploitation or dumping of regulatory reservoirs that ensures the balance between the supply and discharge of an aquifer, or it can simply indicate a reduction in the recharge to the underground water system. In any case, it is an imbalance that may compromise any type of environment, not only because it jeopardizes the permanent groundwater storage but also because it severely reduces the supply to surface water bodies. The consequence is reduced flow rates (volumes) and a decrease in base flow during drought periods, which damages the ecological functions of stream flows and the availability of surface water sources. In karst areas, where water seasonality is especially significant due to permeability, the situation becomes more serious because the additional deficit in water supply leads to stronger ecological stress during drought periods and, consequently, more critical dependence on wet periods (Figure 1.5.1).

In karst areas, it is common for springs to dry and perennial streams to become intermittent or even dry due to the unavailability of underground supply, which would exacerbate the surface deficit. As an example, in the interfluve between the Corrente and Carinhanha rivers, a karst region in the western Bahia state known as Serra do Ramalho. Here, some springs at the foot of the limestone plateau became inactive during the first decade of the millennium, impairing small rural communities downstream. The period was marked by increased deforestation in highlands with consequent erosive processes, with some implications (Figures 1.5.2 and 1.5.3):

(a) increased runoff, reduced infiltration and increased evapotranspiration in the recharge compartments; and

(b) reduced conduit flow due to the decrease in diffuse infiltration rate and increased sedimentary inflow, with generalized silting of some underground sections.

There is another important issue related to water dynamics beyond this water availability aspect. The lowering of the water level (water table) is also followed by a decrease of hydrostatic pressure, which results in an imbalance of forces that can lead to sudden sinking and large mass movements such as rock and soil collapses or subsidence. These are abrupt, significant and virtually irremediable – therefore severe – transformations on the surface and in the underground environment itself.

In the case of subsidence phenomena, it is very difficult to know the water-rock-soil equilibrium thresholds because, given the vertical and lateral heterogeneity of the karst dissolution, it is virtually infeasible to reassemble the soil-rock contact configuration, the epikarst structure (the most superficial and karstified rock horizon) and the deeper karstification in the entire area potentially influenced by the lowering of the water level. More accurate analyses can be done in relatively small areas by applying high resolution geophysical methods and drilling, which are generally expensive methods. For a regional analysis of the susceptibility to subsidence processes, it is necessary to consider probabilistic estimates based on the regional geology and guided by the arrangement of landforms that are linked to the structural configuration, always devoting special attention to any evidence of cover movement.

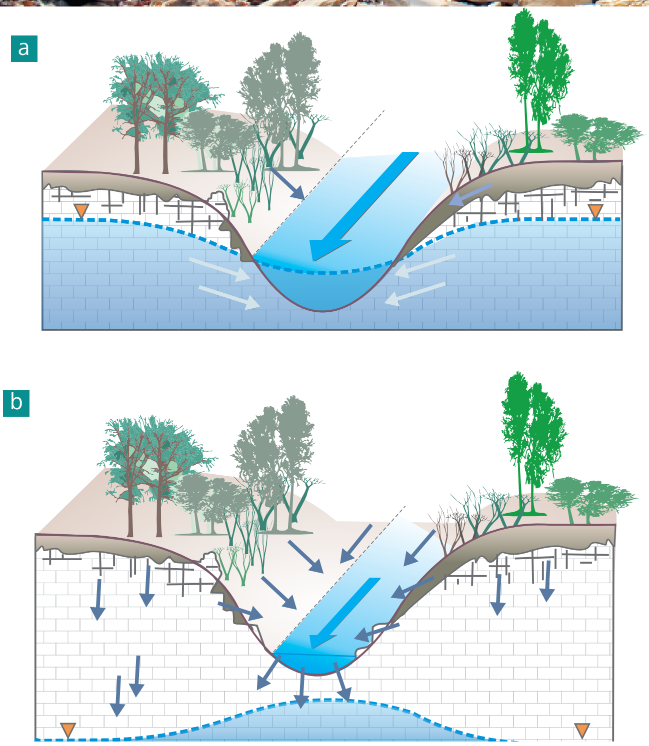


Figure 1.5.1. Ephemeral limestone stream bed. The flow in the channel depends on the water inputs from (1) surface runoff, (2) subsurface seepage through the bedrock fissures in the epikarst (unsaturated/vadose zone) commonly fed by water temporary stored in the soil, and (3) discharge from the saturated/phreatic aquifer zone in case the channel intercepts the water table, adding up contributions that increase downstream. Imbalance in any parcel of the suppliers affects the physical, chemical and temporal dynamics of surface drainage. The top close-up photo shows a small flow discharge through the rock joints; the bottom figure illustrates the seasonal relationship of the underground contribution due to fluctuations of the local water table: effluent (a) and influent (b) behavior. In the background of the main image, a person standing in the channel is a scale. Photos and illustration: Mylène Berbert-Born.

Figure 1.5.2. Erosion due to loss of vegetation cover. The surface runoff intensifies in volume and energy, increasing the detrital load entering the underground water flow systems through sinks and dissolution fissures in the rock. The conduits end up being filled by sediments, organic debris, and contaminant materials that can harm important groundwater sources. (a1) Aerial image of recharge area in karst relief (Google Earth image of May 22, 2013, central coordinate 13o33'06"lat. S and 43o51'03" long. W, inverted image) and (a2) view of a karren limestone outcrop surface, which is receiving a sedimentary load from slope erosion. (b) Linear erosion related to livestock activity (deforestation and animal transit). (c) Surface flow with high detrital load. d) Sediments, branches, and waste carried into a swallow hole and clogging an underground conduit. Photos and illustration: Mylène Berbert-Born.

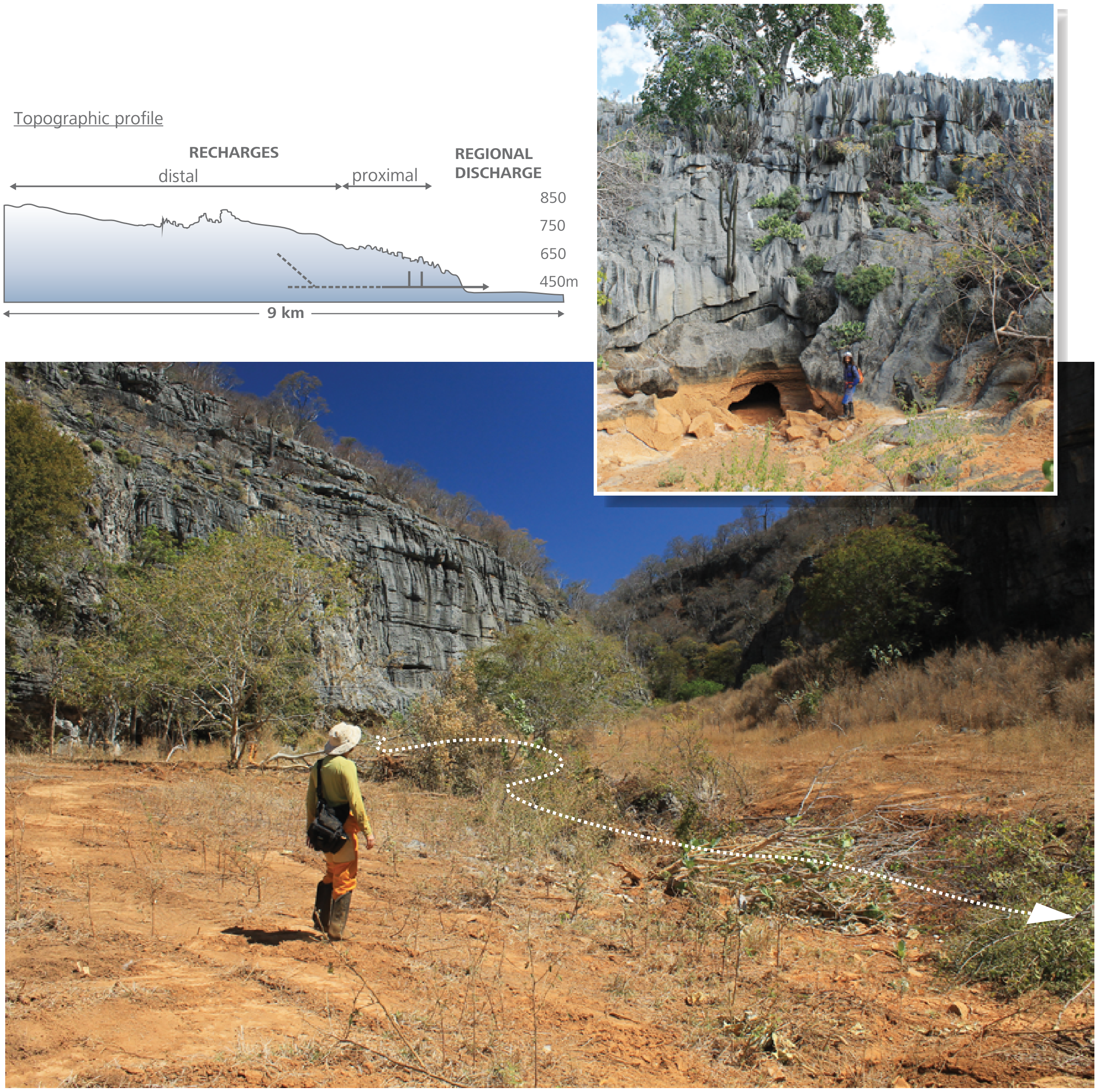


Figure 1.5.3. Karst springs located in zones of hydric discharge. Erosional processes in recharge areas (see Figure 1.5.2) can fulfill conduits in which water flows toward discharge zones, thus drying or changing the behavior of the hydric system's resurgences. In the larger photo, the removal of the riparian forest also causes silting of the drainage channels, and may affect the dynamics of the underground circulation in upstream systems. In the top close-up photo, a seasonal karst spring in Serra do Ramalho, western Bahia, is shown: some of these springs have become inactive over the past 15 years, possibly due to deforestation at the top of the limestone plateaus. Photos: Mylene Berbert-Born.

In addition, contamination of watercourses can also be widely disseminated through karst aquifers if pollutants reach the typical network of interconnected underground conduits. The extent, orientation, and degree of connectivity of the conduit-fissure-pore karst network are in turn uncertain characteristics for which it is difficult to predict the speed, time and extent of contamination. The uncertainties are aggravated because there may be temporary reservoirs of indeterminate water volumes and places interacting with each other only for some periods. Under such conditions, it is consequently problematic to discriminate the repercussions over time on the health of the human populations and faunal communities that use the water, a scenario which is very unfavorable to remediation. Even small disturbances may have broad repercussions on the configuration and functioning of karst environments, especially because the structure of these environments – a structure of strongly interconnected and interdependent components – gives rise to chain effects.

The induced drainage of a small, naturally flooded area can be explored as another example of a chain reaction that can occur from punctual disturbances in a karst area. The drain may suddenly favor the leakage of an aquifer zone that was at a hydraulic load threshold, thus promoting a new design in hydraulic gradients. Based on the lowering of the water table, the increase in the upstream gradients may induce the water volumes stored in superficial compartments (epikarst and soil) to transfer to deeper levels, thus reducing the water availability to the vegetation cover and modifying the mechanical conditions of the soil (retraction of clays, compression of sands, etc.). Moreover, lowering the water table may dry wells and springs upstream of the drain.

> Even small disturbances may have broad repercussions for the configuration and functioning of karst environments, especially because the structure of these environments – a structure of strongly interconnected and interdependent components – gives rise to chain effects.

The surface water reservoirs formed in the rainy season are those that often ensure the slow water supply to deeper zones during the dry season, helping to maintain a minimum level and baseline flows in local drainage. The change in the infiltration dynamics and surface storage induced by the hypothetical draining, which leads to the reduction or exhaustion of these reservoirs, can make local drought deficits more critical, compromising several water functions during this period.

Chain reactions triggered by minor disturbances show that karst is a generally sensitive environment at "transformation thresholds". The stability and sensitivity of karst environments can best be understood from two extreme perspectives, considering at one end the hydrologically active and very dynamic compartments and at the other end the "confined" compartments that no longer have water activity. Of course, there are several intermediate possibilities between these two conditions, in terms of dynamism and "degree" of isolation, including:

- unconfined compartments with permanent and constant water activity ("time-invariant" – short and medium term stationary state) that are located in the unsaturated/vadose zone or in the saturated/phreatic zone;
- hydrologically inactive compartments that are not necessarily confined and that occur in the unsaturated zone in connection with the surface or with dynamic compartments; and
- confined compartments in a renewable saturated zone (confined to semi-confined aquifer condition).

These are some of the "intermediate" situations that show the coexistence of sites in the karst system with very different sensitivity levels. In a very heterogeneous and unique way, and due to its structural nature and the evolutionary dynamics previously discussed, there is a very well-established compartmentalization in karst, both lateral – upstream (recharge) to downstream (water discharge) – and vertical (soil - epikarst - unsaturated rock - saturated rock). These lateral and vertical compartments overlap in space in a complex way, as discussed in section 1.4. As a result, more active and dynamic compartments – notably through the action of water – are often juxtaposed to compartments in an almost complete state of isolation or "confinement", thus making up the strong heterogeneity characteristic of karstic environments.

It is known that water is a transformation agent and a resource for the adaptation and renewal of the environment, especially when there are flow conditions. A footprint can be readily erased in a riverbed but can remain untouched for a long time where there is no water action or some other potentially transformative element. More confined places are more stable and are subject to no or minimal natural fluctuations of the surrounding environment; however, they are potentially less resilient and less resistant to disturbances, and are therefore more sensitive than hydrologically active compartments.

Disruption of a confinement state gives rise to significant changes in the physical environment which can, for example, seriously compromise the survival of species that are very adapted to the small range of original environmental conditions (according to the Underground Biology section). In turn, the more hydrologically dynamic karst compartments are those whose responses to short-term controlling agents (seasonal climatic variations, for example) are expressed in wide process fluctuations. From another point of view, the strong dynamism, which approaches the more global definition of karst, also characterizes a condition of high environmental sensitivity. Precisely because karst environments are usually in extreme natural conditions – large seasonal variations in water level, very variable water flow energy, steeper slope profiles, extremely adapted fauna etc. – the equilibrium thresholds are always close to rupture such that there is already a great natural potential for significant transformations to occur in the event of changes in external control agents.

Nevertheless, it is important to consider that natural transformations are a continuum of environmental self-adjustments, given the conditions emerging from its own natural evolution that compose the so-called "internal controls"; the transformations are not necessarily induced by changes in the external factors controlling the environment such as, for example, a change in the inflow of water to the environment. The difference is that self-adjustment and self-regulation are adaptation mechanisms that seek the conservation (persistence) or "survival" of the environment in new equilibrium states ("dynamic homeostasis", Chorley & Kennedy 1971) – known as "negative feedback" (Christofoletti 1979, 1999), where the effects of disturbances are mitigated or neutralized by the system's own reactions – whereas acute changes in external and internal controls can lead to an equilibrium breakdown and rapid destruction of the environment or to significant losses that require strong adaptations in search of a new equilibrium (see the example in Figure 1.3.5).

The existence of this "damage and loss" perspective of an original condition in the face of a state disturbance that can be considered acute, even with a small magnitude, depicts the high susceptibility and vulnerability character of karst. This is obviously a generalization abstracted from the great diversity of "time and space factors" that control the evolutionary stages of the environment, the rhythm and its predisposition to transformations. In this sense, the most important control factors must be recognized prior to any intended intervention.

In summary, it is clear that the magnitude and extent of the changes (impacts) in an environment do not depend only on the action or factor that drives them (magnitude, range, frequency etc.) but also on how sensitive and complex, that is, prone to change, the environment is at a given moment (Brundsen & Thornes 1979). According to Sánchez (2013, p.125-126), the "environmental impact potential" is indicated by comparing the demand or pressure of the action with the vulnerability of the environment and considering the perspective of the importance of the environment as a "social criterion". The impact potential evidently grows with broader demands on more vulnerable and important environments, as illustrated in Figure 1.5.4.

> The magnitude and extent of the changes (impacts) in an environment do not depend only on the action or factor that drives them (magnitude, range, frequency, etc.) but also on how sensitive and complex, that is, prone to change, the environment is at a given moment.

Karst environments occupy the shaded area of the figure, where the threshold for an impact to be considered significant is lower when compared to other types of environments. This is the best representation to show that the occupation of and activities in karst environments usually involve a high impact potential, even if the imposed demands are relatively small.

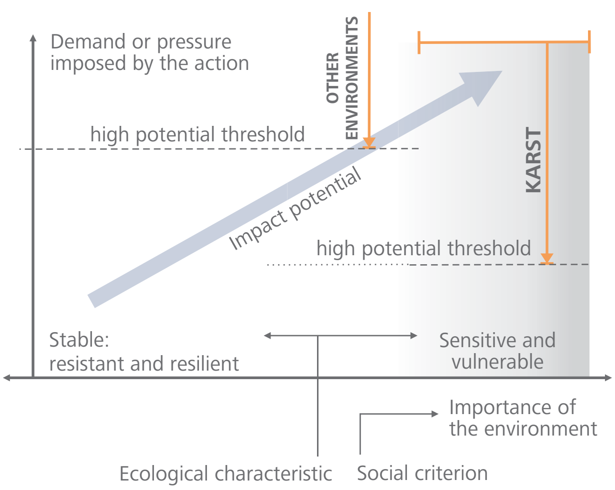


Figure 1.5.4. Impact potential according to the characteristics of the environment and the pressure on it. Illustration: Mylène Berbert-Born. Modified from Sánchez (2013).

1.6. SNAPSHOT OF THE IMPORTANCE OF KARSTIC ENVIRONMENTS

Considering the importance of karst, it is worth noting the existence of several scientific and governmental programs that are focused specifically on the knowledge, control, and protection of these environments, interdisciplinarily articulated and often with broad international cooperation, which demonstrates the strong concern with kart environments. This attests to the importance and vulnerability of karst environments and supports their position on the right side of Figure 1.5.4.

An emblematic example is the joint operation that UNESCO and the International Union of Geological Sciences (IUGS) have been undertaking for 25 years, with international programs aimed at understanding karst. Since 1990, there have been five specific programs (International Geoscience Programme - IGCP):

Project	Title	Duration
IGCP 299	Geology, Climate, Hidrology and Karst Formation	1990-1994
IGCP 379	Karst Processes and the Global Carbon Cycle	1995-1999
IGCP 448	Global Correlation of Karst Hydrogeoloy and Relevant Ecosystems	2000-2004
IGCP 513	Global Study of Karst Aquifers and Water Resources	2005-2010
IGCP/SIDA 598	Enviromental Charge and Sustainability in Kars System	2011-2015

(**Source**: Tales Set in Stone – 40 Years of the International Geoscience Programme (IGCP) – Unesco/IUGS, Derbyshire (2012), *http://unesdoc.unesco.org/images/0021/002152/215219e.pdf*

Given their natural, cultural, and scientific importance and especially the importance and vulnerability of their water resources, concern for the integrity of karst areas is also widely highlighted in the thirty-one Guidelines for Cave and Karst Protection (Watson et al. 1997), which is a guiding document for the management of karst areas developed by the World Commission on Protected Areas of the International Union for Conservation of Nature (WCPA-IUCN).

Another example can be taken from "Action 620 – Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" developed by the European Cooperation in Science and Technology (COST) in support of the management of European karst areas and their water resources. This summarizes a methodology for assessing aquifer vulnerability – "COP + K" method – and the identification of recharge areas more vulnerable to pollution (Zwahlen 2003).

Vulnerability maps of karst aquifers have been developed for a long time, notably in countries that depend heavily on the water resources associated with karst terrains such as the United States and Canada. The United States Geological Survey (USGS) maintains a Karst Interest Group (KIG) of researchers that is especially focused on the extensive and important karst aquifers of the country. In Canada, specifically through the governmental initiative of the British Columbia province, extensive attention has been devoted to the management of forests and water resources in karst areas, with initiatives involving inventories of karst features and associated resources, mapping of karst potentials and classification of areas by vulnerability degree (B.C. Ministry of Forests 2001, 2003; Pike et al. 2010). Also on the international perspective, the World Karst Aquifer Map (WoKAM) intends "to increase awareness of kart groundwater resources in the context of global water issues and to be a basis for other karst-related research question at global scales, as those related to climate change, biodiversity, food production, geochemical cycles and urbanization" (BGR, IAH, KIT and UNESCO 2017).

In Brazil, measures aimed at the management of large karst aquifers are very recent and began in the São Francisco river basin with the project "Hydrogeological assessment of karst and fissure-karst aquifer systems in the São Francisco river basin for the shared management of water resources "(National Water Agency - ANA, unpublished). Approximately 20% of the area of this basin is formed by carbonate rocks that constitute three extensive karst aquifer systems associated with the rocks of the Bambuí and Una Groups and Caatinga Formation.

Although these aquifer systems are storages and transmitters of enormous volumes of water to the São Francisco river, thus regulating its base flow, only recently has the importance of these aquifers received attention, the moment being timely given that the São Francisco Basin Water Resources Plan is being reformulated for a new decade of actions. It is worth recalling that the São Francisco river is strategic for the regional development programs drawn up by the federal government and state governments of six states, which are based on large irrigation projects and the water diversion (transposition) between river basins (i.e., project for the water transposition of the São Francisco River to northeastern regions with high water deficits).

Still focusing the São Francisco Basin, it is also worth noting the long-term coordinated actions of the "National Action Plan for the Conservation of Speleological Heritage in the karst areas of the São Francisco River Basin - PAN São Francisco" (2012-2017, with planned subsequent phases), which include various regional and local issues related to the physical, biotic and socioeconomic factors associated with karst environments such as promotion of karst research, geological and geotechnical risk assessment, valuation studies of the environmental services provided by karst environments, and many others (Cavalcanti et al. 2012).

In conclusion, the environmental uniqueness and intrinsic importance of karst environments should be a permanent reference to subject use and occupation projects in these environments to impact assessments based on broader spatial and temporal diagnoses than those required for other types of terrain, which need to be more detailed, thematically integrated, and technologically specific.

In this sense, the "Manual of Standards and Procedures for Environmental Licensing of the Mineral Extraction Sector" (MMA/IBAMA 2001) is very pertinent in recognizing karst terrains as "environments that are especially sensitive to impacts to water and underground fauna and to speleological and archaeo-paleontological heritage" (p. 45); also in prescribing environmental studies and an environmental control plan to emphasize the most vulnerable aspects of karst in the face of mining activities.

1.7. FOUNDATION OF BEST PRACTICES FOR THE DIAGNOSIS OF KARST

The differential of environmental studies in karst areas is concentrated in what clearly sets them apart from other areas: their environmental, scientific and cultural importance; the structural and functional sensitivity of the environment (ecological fragility); and the high degree of uncertainty regarding the hydrological complexity of these areas. It is often difficult to accurately characterize the functioning of a karst system, and this aspect is critical to studies because it can lead to inconsistencies and gaps in the identification and interpretation of the impacts that arise from actions or activities projected on it, leading to inaccuracies, especially in the delineation of its areas of influence. Recognizing this critical condition is the first major step toward a consistent environmental impact assessment.

In other words, the categorically distinctive aspects of karst – those associated with the karstification phenomenon – are the environmental criteria themselves and the requirements for different diagnostic approaches that support the prognosis, mitigation, monitoring, recovery, rehabilitation, and compensation that are actually appropriate to karst. Some important conditions need to be observed in environmental and impact assessment studies:

a) a sufficiently broad spatial scope (geographic extent) that allows, in accordance with a pre-established conceptual model for the karst system, the identification of continuous underground-surface systems and mosaics of physically and biologically integrated systems, thus ensuring at a minimum that aquifer basins or potentially affected underground water and biological flow systems are covered with their respective catchment areas and other areas of influence;

b) a temporal range that allows the characterization of the standard environmental conditions, such that the rhythms and amplitudes of the existing physical and biological processes (basic conditions and cyclical variations) can be discriminated and, as far as possible, critical (non-standard) phenomena and behaviors can be described;

c) a spatial resolution (more "details") and temporal resolution (higher "frequency") that ensure good representativeness amid the great heterogeneity, diversity, and dynamism of the karst environment, in the face of rapid fluctuations in hydrological conditions and other changes in response to the oscillation of the climate and other stimuli that affect the environment;

d) methodological rigor by adopting tools and procedures appropriate to the specificities of karst; and

e) an effective transdisciplinarity – hierarchy, sequencing and mutual commitment of disciplinary approaches.

Best practices for mining in karst areas are derived from these requirements, with the following main goals:

1. More realistic environmental diagnosis
2. More accurate projection of possible impacts, considering the magnitude, scope (extension), temporality (duration/permanence), potential synergy, and derived effects
3. More accurate delimitation of the area of influence of the project/activity
4. Better strategy for monitoring the effects of installation, operation, and shutdown
5. Effective control and more effective mitigation of the impacts.

Justifications
a) Main reasons for more spatially extensive studies:

1. The organization and functioning of karst systems are often coordinated by regional factors, especially lithostratigraphic relationships of the main geological units and the regional hydrology.

   Annotation.
   The regional hydrology includes the specific drainage conditions of a wide geographical area and is usually marked by an important river of high order or hierarchical degree, which coordinates the discharge and the regional hydraulic gradient. Consideration is given to regional rainfall patterns and the dominant infiltration mechanisms (recharge), runoff, evaporation and water storage.

2. Regional analyses of landscape morphogenesis and morphodynamics are crucial to trace the evolution of the environment and thus to recognize the governing parameters of its organization and behavior, current and past.

3. The conceptual model of the given karst geosystem, that is, of the broader environmental system, needs to be defined so that the functional compartments potentially affected by the disturbances to the environment can be recognized with a reasonable level of accuracy, thus enabling a more accurate delimitation of the area of influence of the project.

4. The macroporosity of conduits typical of the karst bedrock represents spaces connected in the underground environment that are linked to the surface in a punctual or diffuse manner, forming networks that can extend heterogeneously over large areas. Thus, they constitute physically and biologically continuous environmental compartments that are integrated such that the effects of a disturbance to a segment of the system can manifest themselves at great distances.

Annotation.
These networks of fissures and voids usually grow around some larger conduits that work in draining the entire system. The better the drainage or underground flow through these conduits, the larger they tend to be, and the network of spaces associated with them tends to be more developed and extensive. Various types of materials can be transported over long distances through these large flow systems, from surface to remote points that are outlets of the underground system. The movement is driven either by the force of the water, mobilized by the force of gravity or even by the exchanges provided by the fauna that transit through the system.

The flow becomes increasingly easier with the progressive enlargement of the channels, and the base level tends to become lower, promoting morphogenesis. As erosion evolves, the original flow system (network of conduits) is dissected and fragmented, leaving some segments hydrologically inactive. In this context, the caves are nothing more than the largest spaces of the network, the volumes of which can fit a person.

All of the aspects that characterize a cave – its morphology, geometry, position in space and all the elements inside them such as water, gases, terrigenous sediments, speleothems, nutrients and fauna – must be observed and understood under this broader spatial, functional and temporal perspective. In these conditions of connectivity and comprehensiveness, it is still important to consider that the chance of interactions among different elements available in the system and synergistic effects resulting thereby are significantly increased, as well as chain reactions.

5. The macroporosity of conduits and all aspects derived from their formation also give rise to very heterogeneous and contrasting environmental conditions even in small geographic spaces such that very punctual characteristics do not reveal the systemic functioning of the environment.

Annotation.
The hydraulic properties of karst aquifers are fundamentally determined by the combination of three types of porosity that coexist in carbonate rocks - intergranular, fissural (of fractures), and dissolutional (of conduits) porosity. Each provides very different conditions of water storage capacity and flow regimes – diffuse or concentrated, laminar or turbulent. The triple porosity combination varies greatly from region to region and even from location to location in the same region. In addition to the differences in composition, texture and structure of the rock itself, which primarily define the granular and fracture porosities, each region is also at a different stage of karstification, and therefore, the conduit porosity may be more or less developed.

In general, more karstified regions are subject to large heterogeneities and hydraulic contrasts: rock zones of high permeability and low storage capacity represented by the conduit drainage systems "linearly" concentrated among blocks of low to very low permeability and good storage capacity, where sets of less open and more tightly connected fractures lie. In environmental diagnostic studies of karst areas, the first issue is to establish a general triple-porosity model, considering mainly the evaluation of the karstification pattern (degree, spatial arrangement, and control factors) as well as more detailed geological and hydrogeological data.

6. The previous aspects express the high degree of uncertainty involved in the characterization of the environment and, consequently, some degree of uncertainty in the delineation of the project's influence areas. This predicates more conservative studies and control measures.

b) Main reasons for long-term diagnostic studies (several hydrological cycles):

1. Many phenomena that reveal important aspects of karst functioning and organization only manifest themselves during critical climate events, and it is highly desirable to detail them in the chronology of the studies. A relevant example concerns the delineation of watersheds and aquifer boundaries, and therefore catchment areas, which in karst can vary significantly due to connections that only become active after system "overflows" and floods.

Annotation.
It is not a matter of overvaluing exceptional events, but, especially for karst, it is fundamental to know the behavior of the environment over the range of maximum and minimum oscillations of the main environmental parameters, which in the case of water applies mainly to the assessment of water availability. In this sense, good historical contextualization of the climate parameters are essential to quickly evaluate the temporal conjuncture of the studies.

In turn, the base conditions (minimum environmental constants), especially the baseflow, also must be well established. It is important to avoid diagnostics and models that are based only on unconventional or anomalous system conditions that are drawn in a momentary observation, or those that do not show the short, medium and long-term cycles, unrevealing possible fluctuations.

2. In turn, the base conditions (minimum environmental constants), especially the baseflow, also must be well established. It is important to avoid diagnostics and models based only on unconventional or anomalous system conditions that are drawn in a momentary observation, or those that do not demonstrate the short, medium and long-term cycles, which do not reveal possible natural fluctuations.

Annotation.
The conceptual geosystem model must consider standard and non-standard environmental rhythms, thus providing more accurate projections of the effects of disturbances on the environment.

3. Karst environments are very prone to secondary, in chain, cumulative, synergistic and delayed effects after a disturbance – from which their high degree of fragility stems (sensitive and vulnerable); therefore, experiments regarding the behavior of karst environments must be performed in more detail and must also be done over a longer time of application and evaluation.

Annotation.
Emphasizing that in addition to the trials and tests that are part of diagnostic studies, which may present longer-term responses, and the natural disturbances that generate or result in chain/cumulative/synergistic effects, it is also important to take into account other unnatural disturbances deriving from the more global scenarios of land use and occupation, current and projected, to which the environment is subjected in a broader temporal context.

Note: Based on a set of information that offers a good degree of environmental safety for the implementation of some mining project/activity, the environmental diagnosis must be continuously assessed throughout the life of the mine and after its closure, being progressively refined with the systematic production of new data and incorporation of information produced by other sources. Based on the bias of the progressive refinement of the environment diagnosis throughout the operation of the activity, the concept of "long-term studies" greatly extends that one merely focus on the disturbances caused by the project. In this condition, one can look for a specific program of Permanent Environmental Diagnosis Studies, which always focuses on the analysis of synergies of land use as a whole. The tool for the continued diagnosis is the physical Database, and at the same time one of its products are the Data Files (produced information) is the configuration of a historical collection of information under constant expansion and update.

c)) Main reasons for studies with higher spatial and temporal resolution:

1. As widely discussed, the karstification phenomenon confers great heterogeneity to environmental parameters, and there may be significant changes in the conditions and characteristics of the environment over short distances. If the karst landscape symbolically integrated a puzzle, its pieces would be small, and each one would contrast greatly with the neighboring pieces. The karst environment can then be understood as a complex mosaic of horizontal (lateral) and vertical subsystems with their own characteristics, which nevertheless strongly interact. Characterizing the karst environment and understanding its functioning requires greater attention to each piece or segment of the system (spatially detailed studies), without losing sight of what each one represents in the global landscape or system (spatially comprehensive studies).

Annotation.
An example that depicts the "mosaic" of interacting subsystems, each requiring detailed attention, is the lateral and vertical recharge, storage-circulation, and discharge compartments of a drainage system, which include the following aspects: (i) the influence of relief forms on headwaters and recharge areas (forms of absorption and dispersion), (ii) the triple-porosity arrangement in the circulation (flow) and storage zones, (iii) pattern of relief and exudation of the system in discharge areas, (iv) composition, thickness, and arrangement of unconsolidated covers (pattern of infiltration and subsurface drainage/storage) and (v) characteristics of epikarst (degree and organization of subsurface karstification and karstification under covers), which coordinate the dispersion/concentration and acceleration/retardation of infiltration.

2. Karst environments are highly dynamic because of rapid processes (for instance, accelerated morphogenesis), vigorous processes (e.g., floods and subsidence), energy conditions varying widely in time and space (e.g., fluctuations in hydraulic load and hydraulic gradient inversions, with temporal changes in watershed/aquifer boundaries), low frequency and wide amplitude rhythms (e.g., seasonal hydrochemical variations and sedimentary pulses), and high sensitivity to the behavior of the controlling parameters, particularly to climate variations (e.g., rapid hydrochemical and hydrodynamic variations related to specific climate events). To evaluate the behavior of the environment and, based on its dynamics, its structural arrangement, it is necessary to observe how fast changes take place, from the initial stimulus (reaction) to the return to the conditions prior to the stimulus (relaxation). In this analysis, it is also important to observe the recurrence (rhythm) of these short-term variations, combining short- and long-term studies.

Annotation.
Another important aspect is that in view of the characteristic heterogeneity and anisotropy, the conceptual model of the karst geosystem is closer to reality when calibrated by a satisfactory volume of data. In view of these same characteristics, it is worth noting that data taken regularly in space and time are not usually fully applicable to karst. The data planning and acquisition should be carried out in an oriented manner based on the combined analysis of geological, hydrological, hydrogeological, speleological and geomorphological parameters, thus ensuring the coverage of unlikely response situations.

d) Main reasons for methodological rigor and improved disciplines:

1. For the reasons explained above, many of the traditional techniques and methods usually used in diagnostic, impact assessment and environmental control studies are not very effective for the karst environment such as in classical hydrogeology studies, which may contain large inaccuracies in potentiometric surveys, false meanings due to failures in the spatial and temporal configurations of hydraulic tests and hydrochemical surveys, modeling of flow regimes not applicable to the environment, and vulnerability analyses based on inadequate parameters, to cite a few.

Annotation.
It may be said that the main adaptations is related to the spatial and temporal approach strategies, i.e., to the definition of observation networks, data collection and sampling, such as continuous monitoring and good planning for the recovery of response signals to natural or artificially induced events on the environment.

2. In turn, procedures often vilified in environmental studies due to simplifications and cost and time restrictions are those that present significantly enhanced responses in karst and are often indispensable for its diagnosis and control. Some relevant examples are cited in the next annotation.

Annotation.
(i) Use of artificial and natural tracers (typically dyes, biological, stable and radiogenic isotopes) in hydrological and hydrogeological studies involving trials during different hydroclimate conditions. This tool is particularly useful for tracing underground paths, delineating basins, verifying source areas of percolating fluids, as well as for hydrodynamic studies in which the flow and storage regimes of the systems are evaluated.

(ii) Formulation of continuous hydrographs and chemographs, which are graphs that represent the (uninterrupted) temporal behaviors of certain parameters or analytes associated with flow (both natural and from tracer or hydraulic tests), usually taken in springs and karst windows or even in monitoring wells. These curves represent characteristic hydrodynamic signals that elucidate aspects of the spatio-functional configuration of karst porosity.

(iii) Digital spatial analysis techniques involving the spectral processing of orbital images that are pertinent to the carbonate lithologies and to relief organization; surface morphometry at a detailed scale with a focus on karstic features (shape, size, distribution, arrangement etc.), supported by mathematical and statistical tools; analytical automation and supervised classifications; cartographic modeling (map algebra, chronological analyses) and three-dimensional analyses that integrate surface relief and various parameters of the underground environment. All these tools and techniques are considered essential for analytical/reductionist and synthesis/systemic studies on the karst geosystem morphodynamics.

(iv) Consideration of specific environmental parameters for aquifer vulnerability analyses (degree of karstification, geoforms of absorption and dispersion, infiltration and runoff regimes, thicknesses of pedological and lithological horizons, characteristics of unsaturated and saturated aquifer zones etc.), adopting principles that effectively account for the high but localized water permeability and the means for the dispersion, diffusion or concentration of water flow.

(v) Multiple geophysical tests to meet different karst conditions, involving electrical methods (electrical resistivity from drilling and walking profiles), electromagnetic (electrical conductivity and ground penetrating radar - GPR) and gamma spectrometry methods, gravimetric (density) and seismic refraction and reflection methods (cross-hole experiments and multichannel analysis of surface waves - MASW). Regarding geophysics, it is worth noting that all of the aforementioned methods are fluently applied to mineral exploration and geotechnical studies of mine installation and operation, but in karst studies, they are considered to be particularly useful for assessing the relationships between the unconsolidated cover and the rocky substrate, with particular attention to the "epikarst" configuration – a very important compartment in the structural and functional mechanism of karst. Additionally, to assess the thickness and structure of the unsaturated zone (groundwater depths), the thickness of the carbonate cover/bedrock and relationships with noncarbonate lithologies (aquicludes and aquitards), examination of the vertical and lateral relationships between small aquifers, and identification of fissures and underground channels with and without water activity (degree of karstification and arrangement of karst structures), among other aspects.

According to the convenience and specific objectives of the applied geophysical technique, which must be very well defined, all techniques are subject to a very meticulous data acquisition plan (such as the network layout of signal transmitters and receivers) guided by prior detailed analyses of the environment. Given the heterogeneous and anisotropic properties of karst, geophysics applied to this type of environment must be understood as an essentially complementary strategy to direct observations, which cannot be waived or deferred.

3. Some environmental aspects are derived exclusively from the karstification process, and there are not, at least in the same proportion, equivalents in non-karst environments. The triple-porosity is an example of a singular aspect that provides turbulent flow regimes associated with complex underground drainage systems, with linked sedimentary systems (erosion and aggradation) and ecosystems that are equally unique and have a high degree of vulnerability. These drainage systems are in turn influenced by recharge-discharge relationships that are also unique, with the prominence of some relief forms (dolines and karst springs, for example), soil covers and epikarst. Unlike the processes that occur on the surface in non-karstic environments, most of the underground karst processes are not visible, so that it becomes necessary to resort to indirect methods and analysis, valuing input-output system balance studies ("black box" analyses), for which karst springs are extremely valuable. Under these conditions of difficult observations of the environment, any "window" that allows direct observations is particularly valuable and therefore must be taken into account. This is the case for caves, which make it possible to enter parts of these "occluded systems", and of water monitoring wells, which should also be utilized to the maximum.

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4. There are exclusive factors that regulate the configuration and functioning of the karst environment and that are especially sensitive to disturbances to the environment. Nevertheless, they are aspects that are often overlooked in environmental studies of karst environments. One important example is the chemical and physicochemical condition of the waters that percolate through the subsurface, despite its implications are only in long-terms; another example is the characteristics of water discharges and flow regimes. Both are decisive aspects in the carbonate dissolution process and, consequently, in the constitution of karst aquifer systems, once they are related to the aggressiveness and competence of solutions for rock dissolution, and with the conditions for solution renewal and diffusive efficiency (ionic diffusion) that are necessary for the continuity of the karstification process.

Annotation.
Modifications in any parameter influencing the dissolution properties of water (acidity, temperature, volume, permanence, turbulence etc.), such as qualitative or quantitative changes in the pedological and vegetation cover as well as in the infiltration, storage, and water flow regimes, should always receive careful attention.

e) Main reasons for effective transdisciplinarity:

1. Systemic analysis facilitates and strengthens environmental studies in karst geosystems. Systemic analysis is transdisciplinary by concept and principle.

Annotation.

The foundations of systemic analysis are to identify and delimit compositional, organizational and/or homogeneous functional units controlled by a set of notable factors, and it is essential to characterize the following: the components, the way they are organized in space and the way(s) they interact, influence or are influenced by each other; the resulting products and changes, their various functions and purposes (ecological, economic etc.); the most important control parameters (essential to the system's constitution and equilibrium – the inputs and even the outputs of the system when they represent control parameters); and aspects that become control factors of subsequent systems. These analyses favor the order of information collection, in which key questions specific to each case and condition are gradually unraveled by data that congregate in the fields of knowledge needed at that time. It is a rather different approach than the usual study of thematic or disciplinary blocks conducted by individual teams, whose information is only superimposed at times considered to be convenient in the process, usually in the work completion phase, and merely integrating the materials for the presentation of results. From a systemic perspective, a question is always present with the participating teams: "How do my method and my data serve yours?".

2. The repercussions of disturbances caused in karst environments are often disproportionate to the disturbances themselves, as these environments are particularly susceptible to positive feedback processes. That is, a disturbance that triggers a sequence of effects that in the end amplifies or aggravates the impacts, giving rise to strong instabilities in the system and even its functional or structural collapse. This is one of the strong reasons for the adoption of systemic analysis supported by surveys with temporal cadence and by the modeling of scenarios based on the simulation of "critical points" of the environmental system.

Annotation.
It is worth acknowledging that negative feedbacks provided by systems capable of mitigating the effects of the disturbances acting on it are also very plausible in karst environments, and it is important to consider them in favor of the project/activity itself. In both cases – positive and negative feedbacks – investigating the enhancement or attenuation of disturbances in a given system requires examining the structural details of the system and how its attributes work in an integrated manner, relying on refined transdisciplinary studies performed on appropriate timelines.

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CHAPTER 2:
CAVES

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Heros Augusto Santos Lobo

2.1 INTRODUCTION

Caves are natural underground voids large enough for human access. This anthropocentric definition has been widely adopted throughout the world, including by the International Speleological Union, the entity which congregates speleological societies of various countries.

Caves can be formed in several types of rock, but the most common are in carbonate rocks such as calcites and dolomites. However, also occur in siliciclastic rocks such as quartzites and sandstones, and ferriferous rocks such as jaspillite, itabirite, and ferruginous laterite covers in varying degrees of lixiviation/enrichment.

In a karst landscape the process of dissolution is the most important agent in the formation of the relief (Sweeting, 1973; Jennings, 1985; White, 1988; Ford and Williams, 1997). This occurs because the predominant minerals in carbonate rocks, calcium carbonate and, secondarily, magnesium, are highly soluble in water.

The process of the dissolution of the carbonates depends on the chemical equilibrium of the system of carbon dioxide gas – water- calcium carbonate (CO_2- H_2O - $CaCO_3$). Basically, the process for the generation of exokarst forms (superficial features) and endokarst ones (caves) can be represented by the following equations:

$$CO_{2(g)} \rightleftharpoons CO_{2(aq)}$$

$$CO_{2(aq)} + H_2O \rightleftharpoons H_2CO_3$$

$$HCO_3 \rightleftharpoons H^+ + CO_3^-$$

$$HCO_3- \rightleftharpoons H^+ + CO_3^{2-}$$

$$CaCO_3^- + H_2CO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^-$$

Equation 2.1. Basic equations for the chemical system of carbon dioxide – water – calcium carbonate.

2.2. CLASSIFICATION OF CAVES

Caves can be classified in relation to their genesis, size hydrogeological, morphological and atmospheric characteristics.

One **genetic classification** of caves is that they are either primary or secondary (Auler and Pilo, 2011). Primary caves are those which where formed at the same time as the host rock, with the best example being volcanic caves, formed in the interior of lava tubes. Secondary caves are those which development after the formation of the rock, including most of the caves known today. Another way of classifying caves according to their genesis distinguishes various different types, including fluvial, vadose, phreatic, marine, eolic, and talus caves, as well as those of mixed form (Jimenez et al., 1984). Fluvial caves are those formed by the abrasive action of rivers and creeks, and are usually located along the borders of such drainage systems; vadose caves are those formed by vertical infiltration in a subaereal environment; freatic caves are formed entirely under water; marine caves, like fluvial caves, are formed by the abrasive action of water, but in this case the seawater. Eolic caves form by the abrasive action of the wind, while talus caves are unique in that they form from the piling up of large blocks of rock, leaving empty spaces under and around them. A third type of genetic speleological classification distinguishes three types of caves: i) epigenic (formed by the dissolving action of meteoric water filtering downwards, ii) paragenic (formed by the upward dissolution of a cave ceiling in a passage where sediments have been accumulated); and iii) hypogenic (formed by waters rising from the depths (Palmer, 2003; Palmer 2011).

Speleometric classification is a somewhat unusual term which is used to distinguish caves according to parameters of size. In Cuba, for example, the Cuban Speleological Society defines seven classes of cave: *abrigos rochosos* (rock shelters), *grutas* (caves with a single underground room), *cuevas* (caves with more than one room and up to 1 km in development), *cavernas* (caverns from 1 to 10 km in development), *gran cavernas* (large caverns with more than 10 km in development), *sistemas subterrâneos* (underground systems), and *sistemas con canales fluviales y galerias sin comunicación* (non-communicating systems with fluvial channels and galleries) (Jimenez et al., 1984). Each of these classes is defined by the format of the rooms and galleries in association with their size. A parallel in Brazil would be that observed in the mid-1970´s (Lino, 1975), which defined caves as natural underground cavities and distinguished various typologies: *grutas* (which were caves with predominantly horizontal development); *abrigos sob rocha* (rock shelters or cavities of limited depth); *tocas* (corresponding to caves with intermediate dimensions between rock shelters and *grutas*, with a development of less than 20 meters), and *abismos* (which were pits or natural cavities with predominantly vertical development). These definitions were widely spread in the speleometric norms and conventions of the Committee for Registration and Mapping of the Brazilian Speleological Society (SBE, 1991). However, this kind of classification fell into disuse in relation to the original meaning of the concepts, although the terms are still utilized loosely in the specialized scientific literature.

Hydrogeological classification distinguishes caves according to the origin of the water running through them and their regime. There are five classes of regime for caves: permanent, intermittent, seasonal, occasional and inactive. Permanent regime describes caves through which drainage flows the whole year. Intermittent regime refers to caves where the flow of water is interrupted during certain periods, but is reactivated in others. Seasonal regime refers to caves which are only active when it rains. Occasional regime involves caves in which water is only present during specific events, such as floods. Inactive caves are fossil caves which are disconnected from the fluvial system and are no longer involved in drainage. The origin of drainage provides three categories: autochthonous, allochthonous, and mixed. Autochthonous drainage refers to recharge resulting from the accumulation of rainfall in the karst massif itself, whereas allochthonous drainage results from recharge originating in non-karstic areas, frequently contiguous to the massif; mixed drainage is that with both allogenic and authigenic components.

Morphological classification is widely used. It distinguishes caves in regard to the planimetric patterns, i.e., the form observed in representations in maps (Palmer, 1991; 2003) The advantage of the use of this classification is related to the fact that the morphological pattern and organization of conduits, which are the product of the processes acting on the materials available (rock and sediments), reflect the kind of recharge/discharge and hydrodynamic and structural conditioners (Figure 2.1). The morphological classification is that which seems the best to portray the evolutive history of caves, favouring paleoenvironmental interpretations (in combination with other elements).

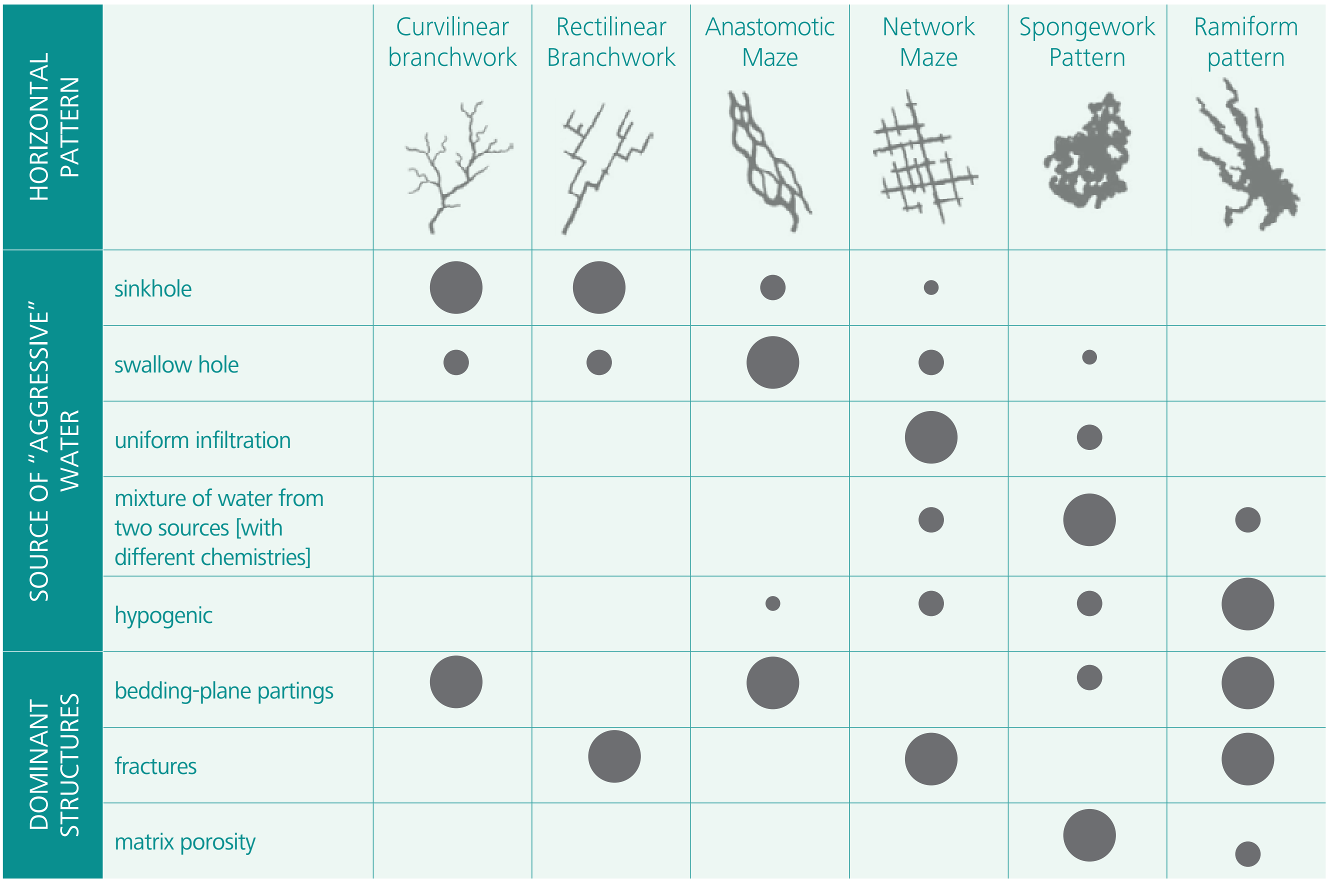


Figure 2.1. Most common planimetric patterns of carbonate caves. The size of the circle represents the relative abundance of each type. Adapted from Palmer (2003, p. 146) by Allan Calux.

Atmospheric classification is used when it is necessary to understand the circulation patterns and air concentration in vadose environments. The complexity of this classification depends on factors such as the number of entrances to the surface which a cave has and their relative altitude. In general, more common classifications are of air pockets (inferior and superior) and ventilation ducts. An inferior pocket of air, also known as a cold trap, is formed when levels of conduits develop below the horizontal axis of the cave (Figure 2.2A). A superior pocket or hot trap is formed when conduits develop above the horizontal axis (Figure 2.2B). In caves with more than one distinct entrance, differences in the density and temperature of the air between the cave atmosphere and the microclimate outside result in a flow of air (Figure 2.2C). The interpretation and classification of atmospheric patterns, in addition to serving climatic studies and those of conservation, also contribute to the realization of paleoenvironmental studies.

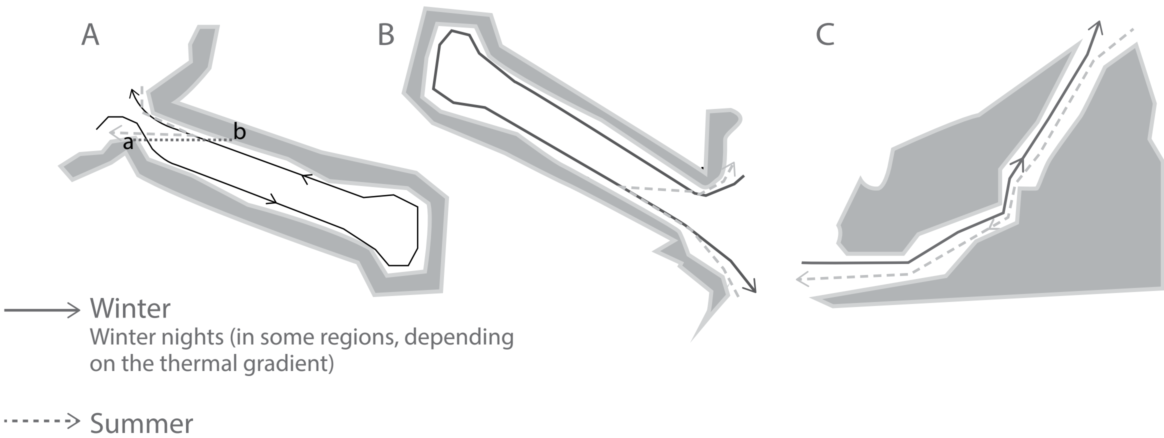


Figure 2.2. Simplification of patterns of air circulation in caves. Adapted from Eraso (1969), Cigna (2004), and Lobo (2011) by Heros Lobo.

2.3. MORPHOLOGICAL, HYDROLOGICAL AND SEDIMENTARY ASPECTS OF CARBONATE CAVES

One of the most important aspects of a cave is the registry which it provides of water flow and the conditions of their formation and the flow of water (Sweeting, 1973). The characteristics which permit these interpretations are inscribed in the ceiling, on the walls, and on the floor of caves. To determine the origin of a cave, it is necessary to examine the general patterns, the nature of the galleries, and the details of each conduit (Palmer, 2007). These records contain precious information about the evolution of the relief, including the behavior of the surface and underground rivers.

Cave **entrances** can be of various configurations, such as springs, swallow holes, openings at the base of sinkholes, and vertical shafts. They are usually exposed by the sinking of the soil and sediments, by the collapse of debris (Figure 2.3), or the interception of the cavity by the natural evolution of the slopes as it recedes along the erosive front (Figure 2.4). However, it is important to emphasize that a large number of caves have no entrance accessible to humans. These cavities are known as closed caves and are inserted in the interior of rocky massifs. Figures 2.5 – 2.9 provide some example illustrations.

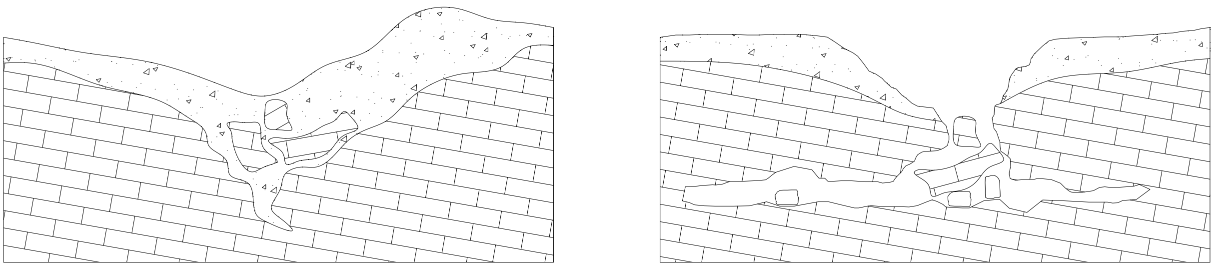


Figure 2.3. Entrance of a cave developing from sinking and collapse to form a sinkhole. Allan Calux.

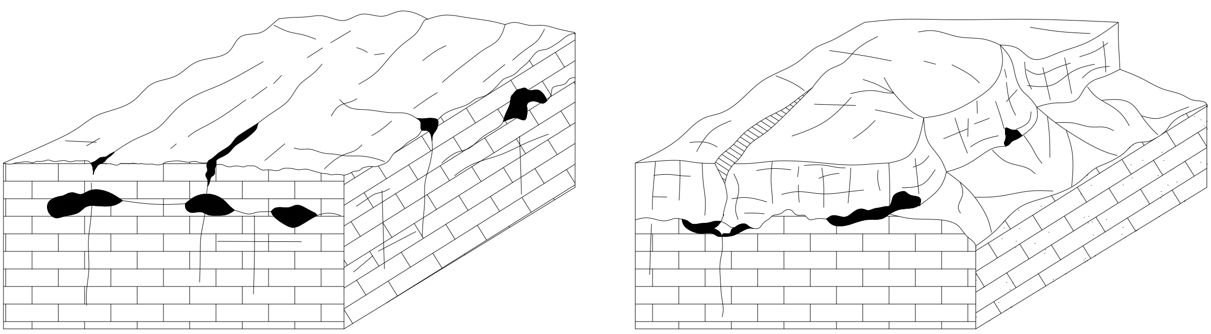


Figure 2.4. Closed cavities intercepted by the evolution of the erosive front. Allan Calux.

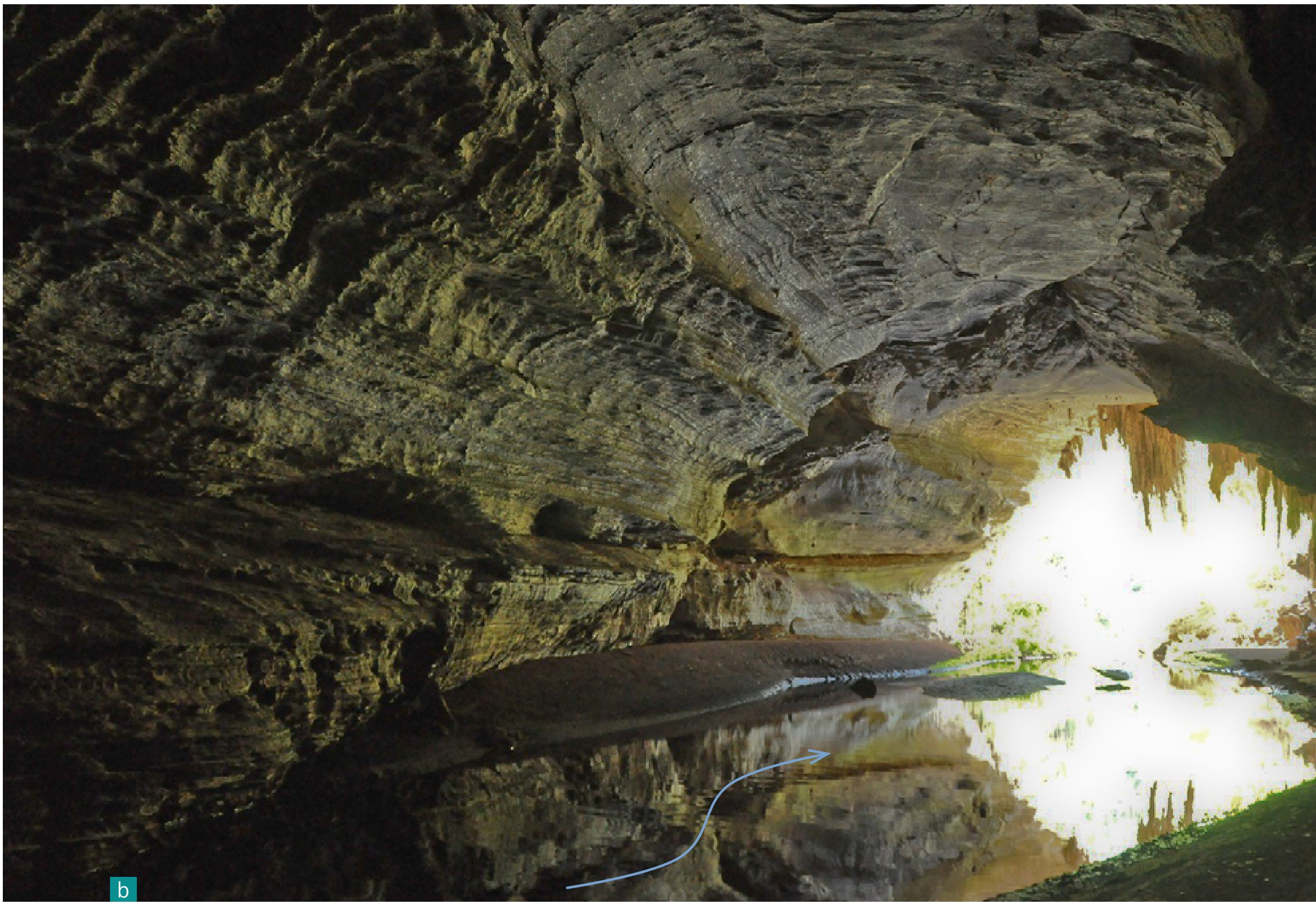


Figure 2.5. Swallow hole of the Gruta Angelica, a cave in the State Park of Terra Ronca, in the state of Goiás; drainage indicated by the blue arrow. B) Resurgence of the *Gruta Cascudos*, one of the caves in the National Park of the Caves of the *Peruaçu* in the state of Minas Gerais (Brazil). Photos: Allan Calux.

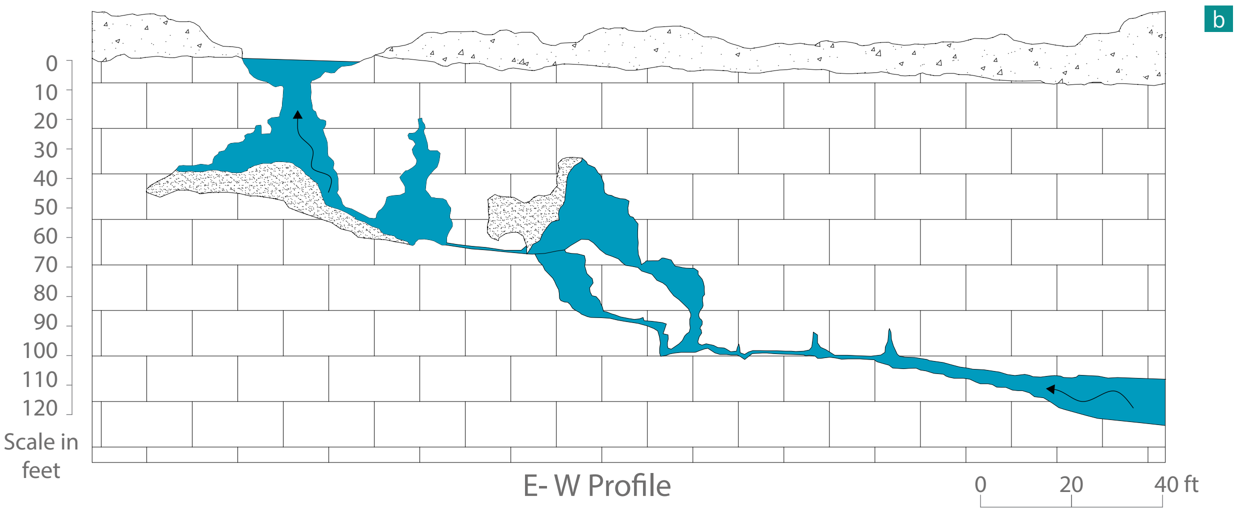


Figure 2.6. a) Resurgence of the Blue Hole Spring, an underwater cave located in Ichetucknee Springs State Park in Florida (USA); b) Schematic profile of the same cavity. Photo and diagram: Allan Calux.

Figure 2.7. Resurgence of the *Gruta Troncos*, one of the caves in the National Park of the Caves of the Peruaçu, in the state of Minas Gerais (Brazil). Photo: Allan Calux.

Figure 2.8. *Gruta do Janelão,* a cave in the National Park of the Caves of the *Peruaçu* in the state of Minas Gerais (Brazil): a) entrance of the sinkhole *Dolina dos Macacos*; b) the same sinkhole seen from below. Photos: Allan Calux.

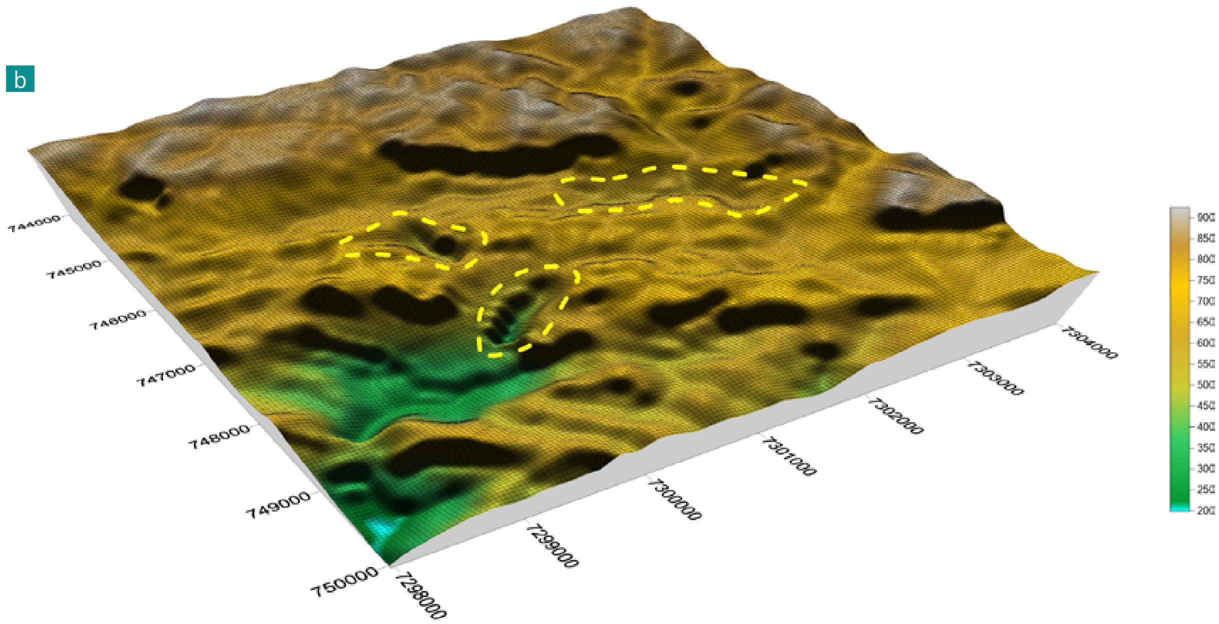


Figure 2.9. a) *Gruta da Temimina III*, a cave in the State Touristic Park of the Upper Ribeira in the Valley of the Ribeira in the state of São Paulo (Brazil). Note the speleologist with the red coveralls in the center of the photo; b) three-dimensional model of the relief, identifying (in yellow) the sinkhole depressions. Note that the drainage which it feeds discharges in springs several kilometers from the region of the swallow holes of the cave. Photo and diagram: Allan Calux.

Most carbonate caves consist of a matrix of conduits with interlinked passages (Palmer, 2007). These passages are denominated dissolution conduits and may have a variety of shapes, sizes, and patterns of development. The galleries correspond to predominantly horizontal passages, while shafts and cupolas are predominantly vertical.

Each of these passages reflects the nature and water flow pattern which formed it, allowing to interpret about the origin of the cave (Palmer, 1991; 2007). The shafts, for example, are generally formed in a vadose environment (above the level of underground water contained in a rocky massif) by water flowing vertically along fractures. In this case, hydrodynamic control, i.e., the injection of water tends to follow pre-existing structures, and the predominantly vertical flow is registered via the grooves or furrows oriented by gravity (Figure 2.10), which often carve through fractures and bands.

Figure 2.10. Shaft in the cave *Abismo do Sumidouro* in Itaoca in the state of São Paulo (Brazil), a vertical feature oriented by gravitational vectors in a vadose environment. Photos: Allan Calux.

Galleries also vary greatly, and can present a variety of formats of transverse incisions in shapes such as canyons, tubes, and fissures, (Figure 2.11). Canyons reflect moments in the evolutionary history of the cave when there was a tendency for hydrodynamic equilibrium: the underground drainage, attempting to reach the local base level (which can be an external discharge point or a layer of impermeable rock) carves downs and sculptures the rock, intercepting all obstacles, in search of the phreatic level. Tubes, on the other hand, show a phreatic or vadose flow under pressure. Fissures correspond to fractures or faults where the water was favored by the ease of circulation generated by these structural discontinuities, enlarging them vertically and horizontally. The rooms (Figure 2.12) correspond to open spaces of relatively large dimensions, i.e., they are more ample than the near-by conduits. They can be formed by the intersection of two or more conduits, by large collapses or breakdowns, or exclusively by dissolution, although this latter process is less common.

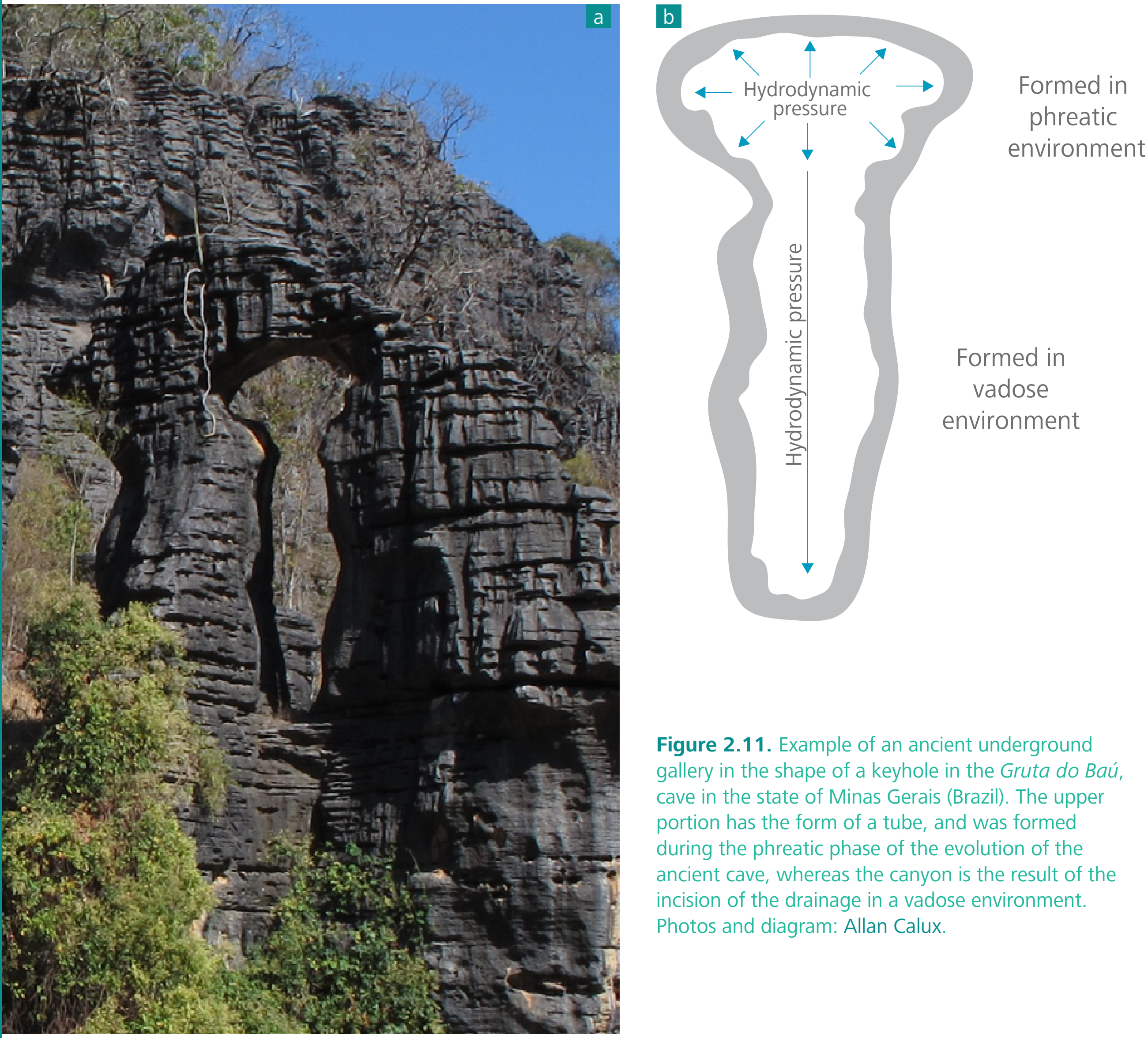


Figure 2.11. Example of an ancient underground gallery in the shape of a keyhole in the *Gruta do Baú*, cave in the state of Minas Gerais (Brazil). The upper portion has the form of a tube, and was formed during the phreatic phase of the evolution of the ancient cave, whereas the canyon is the result of the incision of the drainage in a vadose environment. Photos and diagram: Allan Calux.

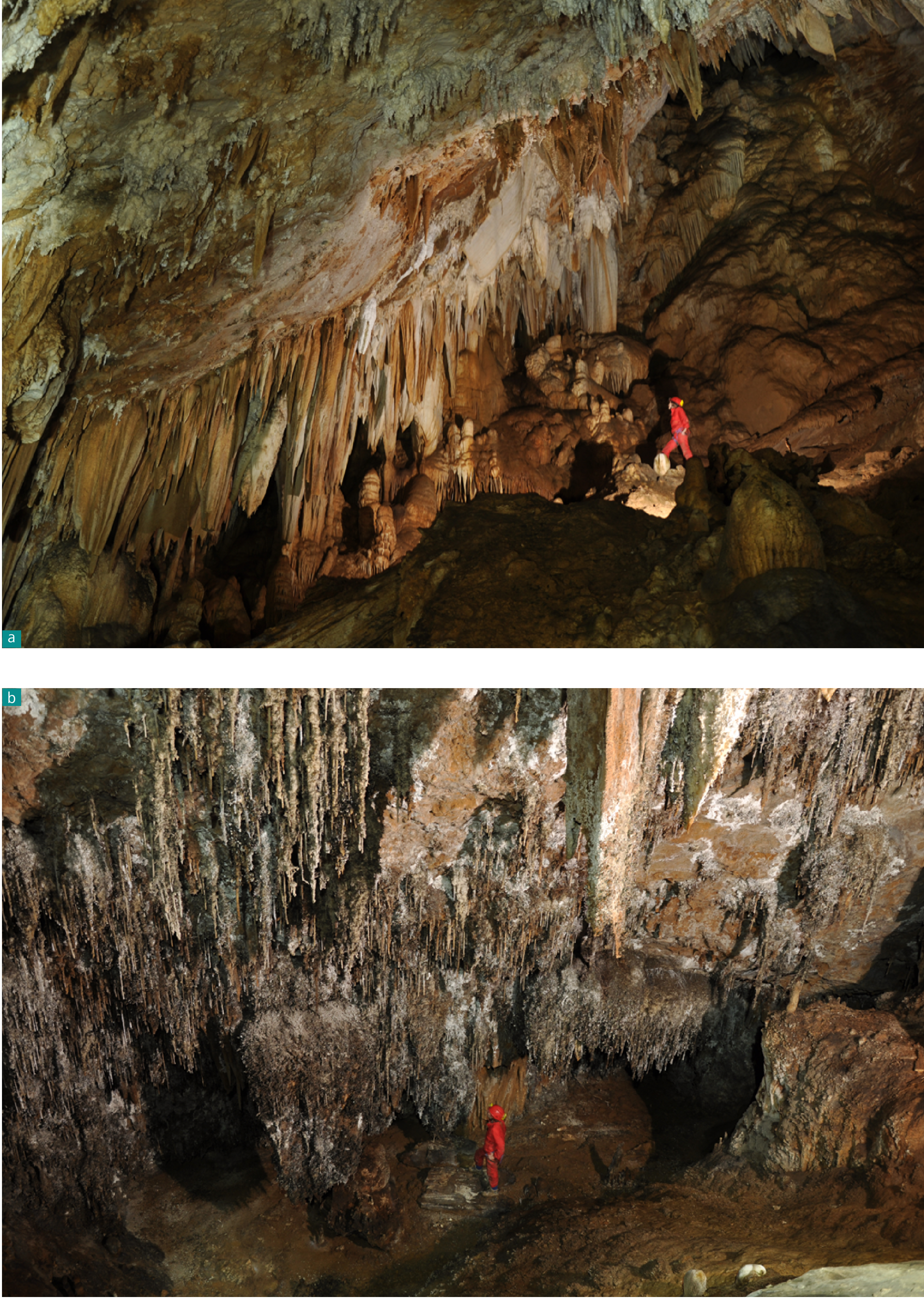


Figure 2.12. Ornamented chambers in the Gruta do Seo Jonas, a cave in the Valley of the Ribeira River in the state of São Paulo (Brazil). Photos: Allan Calux.

Caves are often filled by sedimentary deposits. These deposits can be of two types: clasts or chemical/biochemical.

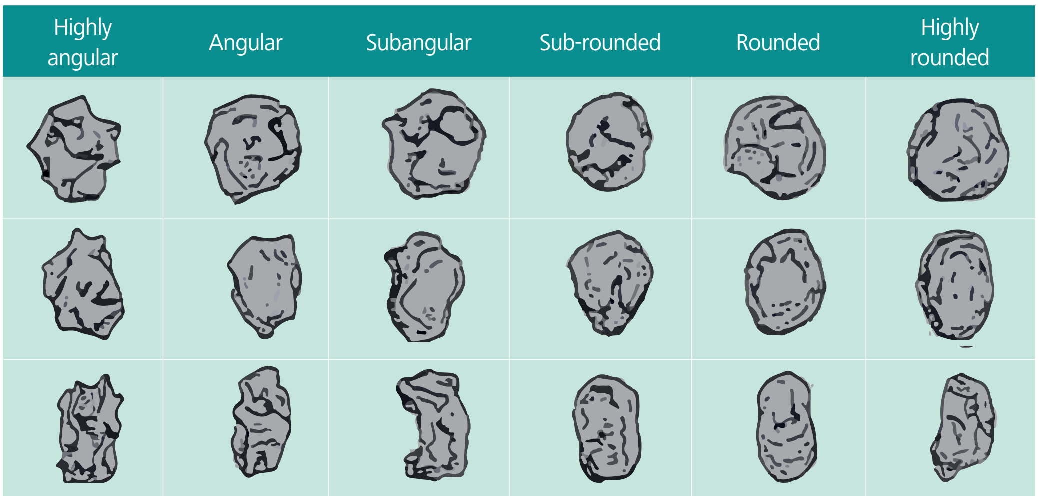
Clasts refer to all debris transported and deposited in the conduits of caves; they are reworked by fluvial or gravitational action, and can be classified according to their origin, granulometry, and rounding. The origin can be authigenic, generated inside the cave or in the rocky massif by the accumulation of non-carbonate minerals from the rock, or allogenic, generated by the erosion of soil and rock and transported to the interior of the cave by creeks and rivers, or by mass movement, such as landslides. Granulometric classification considers the size of the material deposited, which can vary from silt/clay to boulders (Table 2.1). The classification of rounding, as the name suggests, consists of the evaluation of the material deposited in relation to degree of rounding, which can vary from sharply angular to rounded (Figure 2.13). The degree of rounding is related to the transport of these materials, with those originating further away revealing greater rounding.

Table 2.1. Granulometric classification (Phi scale).

φ scale	Size range (metric)	Aggregate name (Wentworth class)	Other names
<–8	>256 mm	Boulder	
–6 to –8	64–256 mm	Cobble	
–5 to –6	32–64 mm	Very coarse gravel	Pebble
–4 to –5	16–32 mm	Coarse gravel	Pebble
–3 to –4	8–16 mm	Medium gravel	Pebble
–2 to –3	4–8 mm	Fine gravel	Pebble
–1 to –2	2–4 mm	Very fine gravel	Granule
0 to –1	1–2 mm	Very coarse sand	
1 to 0	0.5–1 mm	Coarse sand	
2 to 1	0.25–0.5 mm	Medium sand	
3 to 2	125–250 µm	Fine sand	
4 to 3	62.5–125 µm	Very fine sand	
8 to 4	3.9–62.5 µm	Silt	Mud
10 to 8	0.98–3.9 µm	Clay	Mud
20 to 10	0.95–977 nm	Colloid	Mud

Source: W. C. Krumbein & L. L. Sloss, Stratigraphy and Sedimentation, 2nd edition (Freeman, San Francisco, 1963).

Figure 2.13 . Degree of rounding



Although it is not always true, gravelly sediments, i.e. of a size from a pebble to a boulder, tend to be of autochthonous origin, with greater angularity. Those of soil vary from silt/clay to granular in size and tend to be of allochthonous (or mixed) origin. Certain endokarst features such as abatement cones (Figure 2.14), and sedimentary fans are associated with these dynamics of sedimentary accumulation.

Clastic deposits in caves are important for various reasons, but mainly because they make analyses about the geomorphological and paleoenvironmental processes of a region possible (Auler et al., 2005). In the karst of Arcos-Pains-Doresópolis, in the state of Minas Gerais (Brazil), for example, alluvial fans expelled from caves during the Pleistocene serve as tools in morphotectonic investigations (Saadi, 1991).

Figure 2.14. Gruta do Janelão, one of the caves in the National Park of the Caves of the Peruaçu in the state of Minas Gerais (Brazil): cone of clastic sediments, the product of abatement of the overlying substrate. Photo: : Allan Calux.

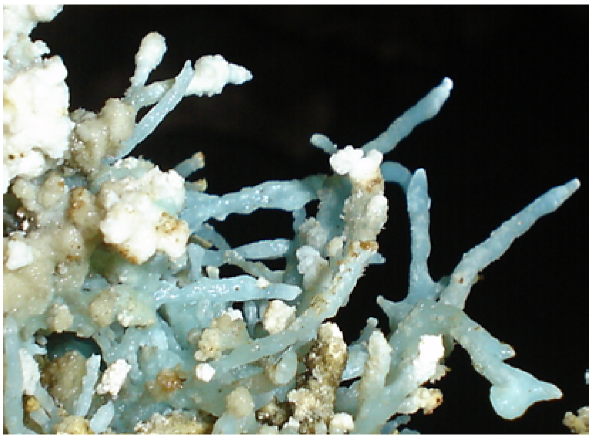
Modifications in the pattern of circulation in underground rivers, registered by sediments imprisoned in caves, protected from the action of the weather, allow paleoenvironmental studies involving dating of terraces and the determination of the rate of denudation.

Chemical sedimentary deposits, denominated speleothems, represent endokarst features of great scenic appeal. Hundreds of shapes of various sizes, colors, textures, structures, and mineralogy generated by the processes of dissolution and precipitation are known. They can be classified in various ways, but the most commonly utilized is that in which the environment of formation is considered. There are three classes: 1) deposits formed by circulating/dripping water, 2) deposits formed in still water; and 3) exudation deposits. However, most speleothems are formed by a combination of more than one class, which makes it difficult to provide a more exact classification.

In carbonate caves, the most common speleothems are stalactites, stalagmites, draperies, columns, and concretions of various types on the floor. These are formed from water rich in calcium carbonate (or other mineral) dripping from or running down surfaces and the precipitation of the mineral (See Equation 2.1). The most common minerals are calcite ($CaCO_3$), aragonite (a polymorph of calcite with the same chemical formula, but distinct crystallization) and gypsite ($CaSO_4.2H_2O$). These formations are predominantly white, with variations in color associated with the presence of other minerals in the solution. The presence of iron results in orangish to reddish speleothems, while manganese results in colors ranging from brown to a bluish-black; copper oxides generate bluish speleothems (Figure 2.15). For more information, consult Hill and Forti, (1997).

Coralloids, microcoralloids, helictites and heligmites are also common speleothems, but these are frequently formed by exudation. The size, color, shine, and habit of crystallization depend on the minerals dissolved. Calcite normally results in rounded and gently curving features (Figure 2.16 b), whereas aragonite results in sharply pointed, needle-like features (Figure 2.17d).

The damming or obstruction of water can lead to the formation of speleothems in non-flowing water. Cave pearls (Figures 2.16-c and 2.16-d), cave rafts (Figure 2.17-c) and clubs are examples of formations of such deposition. The first are the result of the successive coating of an insoluble particle present in a pool filled with water rich in calcium carbonate. Cave rafts are formations which result from precipitation around the edges of a pool. Clubs are formed from successive coating during the oscillation of the level of standing water.



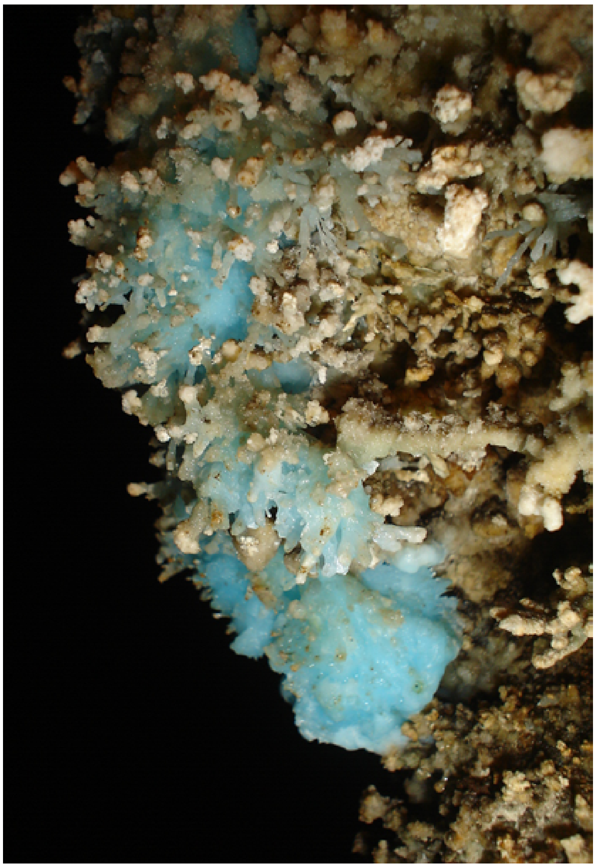


Figure 2.15. The bluish tone of these speleothems is due to natural "contamination" with copper minerals in the Gruta Azuias, a cave in the Valley of the Ribeira in the state of São Paulo (Brazil). Photos: Allan Calux.

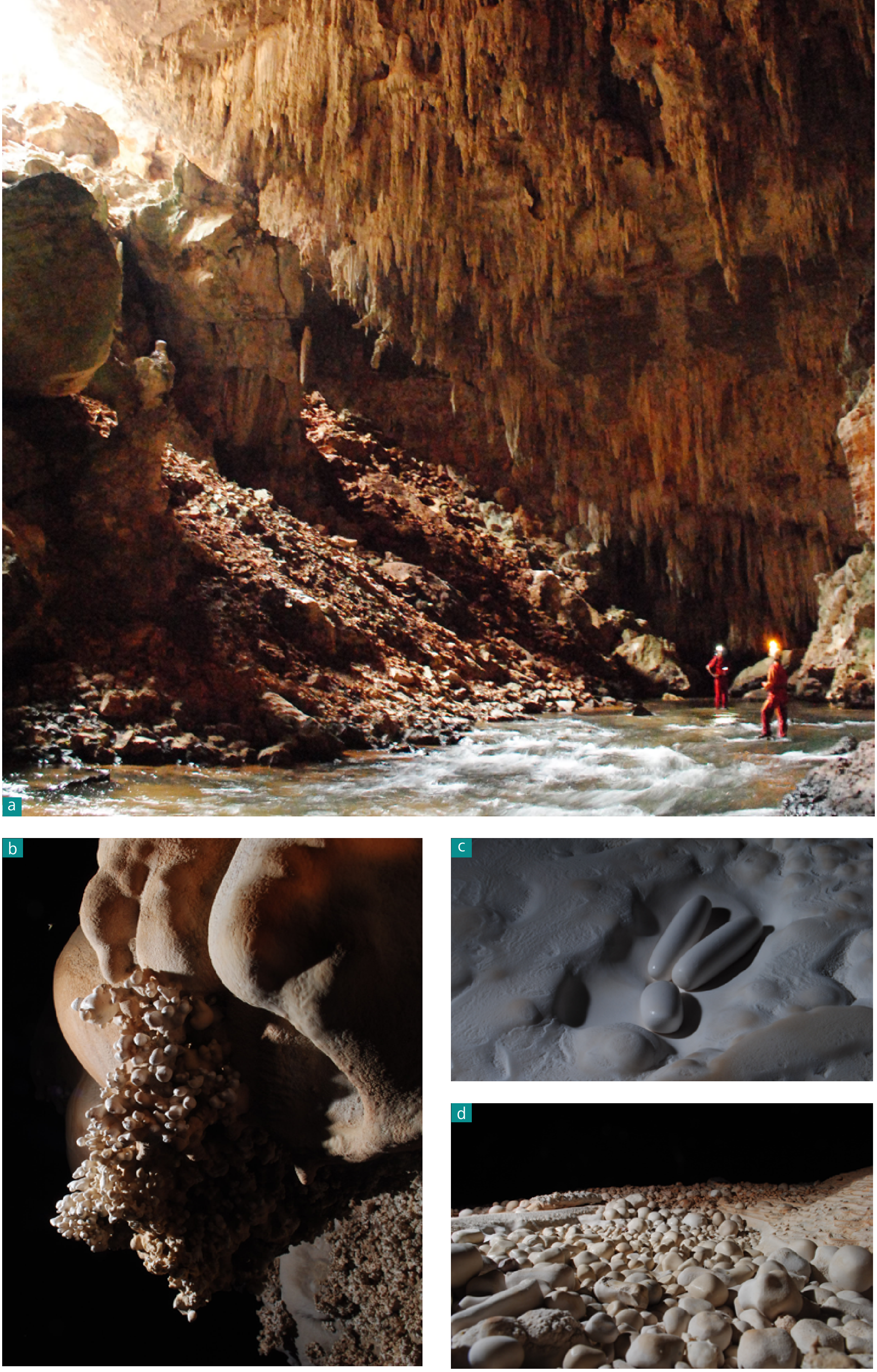
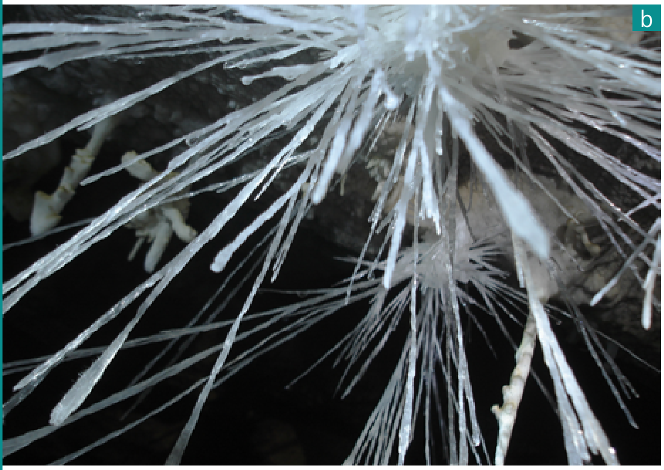


Figure 2.16. *Gruta São Bernardo*, a cave in the State Park of Terra Ronca (PETeR) in the state of Goiás (Brazil): a) Giant stalactites of more than a meter in length in the entrance zone of one of the entrances to the cave; b) botryoidal coralloids, an exudation deposit; c) and d) Cylindrical and spherical cave pearls, speleothems formed in environments of still water confined in cave pools. Photos: Allan Calux.



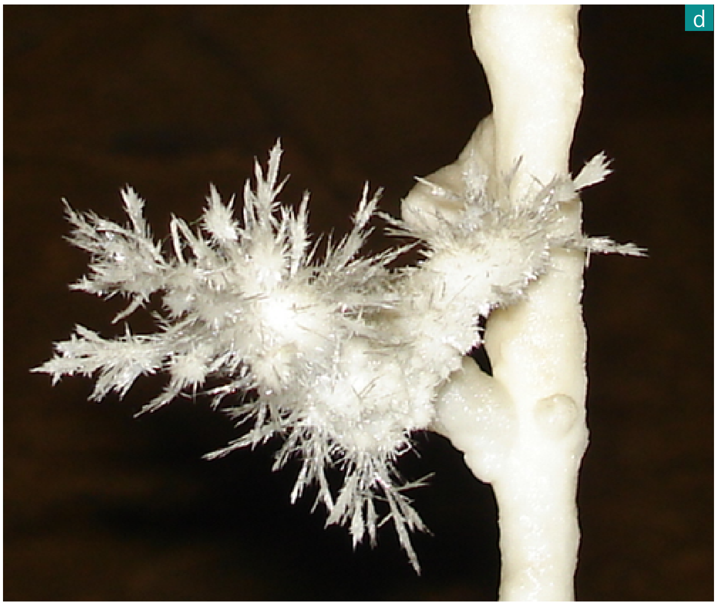


Figure 2.17 Speleothems in the Taquêupa chamber in the cave of Santana in the State Touristic Park of the Upper Ribeira in the state of São Paulo (Brazil): a) and b) aragonite flowers; c) cave rafts and dogtooth spar, speleothems formed in the environment of still waters; d) helictite of aragonite on a stalactite. Photos: Allan Calux.

2.4. SPELEOGENETIC, GEOCHRONOLOGICAL AND PALEOCLIMATIC ASPECTS

A carbonate cave, as pointed previously, is by definition a void in the rock, the product of the chemical and mechanical removal of material. For them to be formed, the underground waters must dissolved the rock rapidly enough for it to be removed by superficial erosion (Palmer, 2003). In other words, the formation of conduits and galleries must take place before the evolution of the landscape intercepts and extinguishes them. Since carbonate rocks are very susceptible to the action of the weather, there is a certain consensus that the evolution of the karst systems we know took place predominately in the geologic period known as the Quaternary, which began some 1.8 million years ago, although some developed in geomorphological contexts inherited from previous periods.

The formation of most caves begins in the depths, below the water table (in the saturated zone). In this initial phase, the proto-cave consists of a cylindrical tube of less than 1 cm in diameter, with enlargement resulting in the conformation of a cave as such. When the underground channel reaches the width of approximately 1 centimeter, the flow of water is converted from laminar flow to turbulent flow. This phreatic phase of evolution is intimately related to the initial organization of the karst aquifer, when the hydrological connections of recharge and discharge of the system are established.

After this phase of horizontal enlargement of underground galleries and conduits, the evolutive dynamics depends on the geomorphological context. In stable reliefs or those associated with processes of uplifting, the lowering of the local base level causes the expansion of the cave to be oriented vertically by gravitational vectors in the vadose or subaereal environment. This model of evolution is denominated epigenesis. There is evidence that some 90% of the caves known in the world had such an origin (Palmer, 2011). In Brazil, caves were formed by epigenetic processes can be found in numerous karst areas, such as the Valley of the Ribeira River, in the southeastern part of the state of São Paulo (Brazil) (Figure 2.18).

On the other hand, if the karst system develops in a lowered area, the conduits of the cavities tend to fill with a progressive accumulation of sediments, resulting in a progressively rising circulation of underground water. This circulation results in the excavation of the roof of the caves, which only ceases if some environmental change interrupts the dynamics of accumulation, such as neotectonic events. This speleogenetic model is denominated paragenesis, and takes place mainly in areas where the carbonate rock is found under a thick mantle of soil (covered karst), such as that in Lagoa Santa in the state of Minas Gerais (Figure 2.19) or zones of depression such as those found in the Pantanal of the state of Mato Grosso.

Some caves were formed at great depths, where the dynamics of the circulation of fluids obeys hydrothermal dynamics, i.e., with routes established independently of the vectors of gravitation. In this model of evolution, denominated hypogenesis, the fluid tends to be ascending and abrupt. The Toca da Boa Vista, the largest Brazilian cave, with over 100 kilometers of development, is one example of a cave formed by this process (Auler and Smart, 2002).

Given the relative stability of the cave environment, it is very propitious for the preservation of paleoenvironmental indicators. Some researchers consider the entrance zone to be the richest in vestiges of the occupation of pre-historic humans and animals, although the zones further back may also preserve clastic and chemical sediments which furnish further evidence of such occupation (Auler et al., 2005). The main elements, the major source of information about past climatic conditions, is found in the clastic sediments, the registers of oscillation of the water table (WT), the speleothems, and the archeological and paleontological remains (Table 2.2).

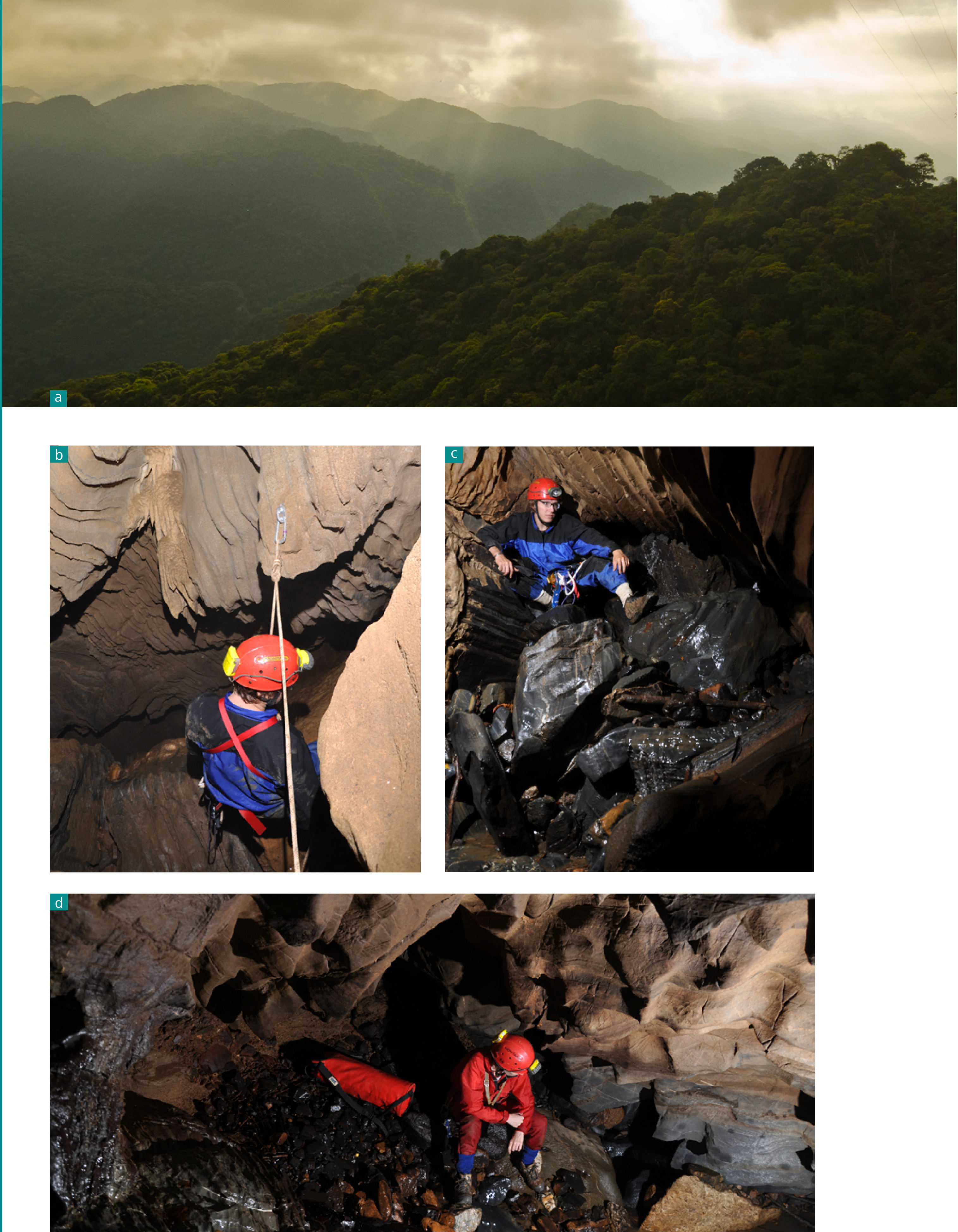


Figure 2.18. Valley of the Ribeira in the state of São Paulo (Brazil). a) Overview of the valley of the Betari River in the State Touristic Park of the Upper Ribeira; b) c) and d): *Abismo do Zero*, a typical epigenetic cave in the Valley of the Ribeira. Allan Calux.

Figure 2.19. Gruta Tuneis, cave in the State Park of the Swallow Hole, an example of a paragenetic cavity in the region of Lagoa Santa, in the state of Minas Gerais (Brazil): a) roof carved by the drainage action in a gallery filled during the past; and b) ceiling pendants (central upper part), features typical of paragenetic caves. Photos: Allan Calux.

Table 2.2. Possible paleoclimatic indicators for studies in endokarst environments.

ELEMENT	INDICATORS	ANALYSIS TECHNIQUE	POTENTIAL USE
Clastic sediments	Fluvial terraces	Radiometric, isotope, and cosmogenic (14C, U/Th/Pb ^{10}Be) dating; paleomagnetism, thermoluminescence	Paleoclimate, sedimentology, fluvial geomorphology
Oscillations in water table	Precipitation of underwater speleothems; Levels of saturated water precipitated on walls; varves (banded layers of silt and sand)	Radiometric and isotope dating (14C, U/Th, ^{10}Be) and paleomagnetism	Paleoclimate, tectonic and neotectonic studies
Speleothem analysis	Pollen trapped in speleothems	Palynology	Paleovegetation
	Frequency and rate of growth of speleothems	Radiometric dating (U/Th/Pb)	Paleoclimate
	Petrology and mineralogy	Petrology and mineralogy – X-ray Diffraction; X-ray fluorescence; petrographic microscopy	Paleoclimate
	Trace elements		Paleoclimate; paleovegetation
	Stable isotopes of oxygen and carbon	Isotope dating (^{18} O), fluid inclusions	Paleoclimate (temperature); paleovegetation
	Luminescence		Paleoclimate
	Position and direction of coralloids	Visual comparison	Paleocirculation in atmosphere
Paleontology	Taphonomy and chronology	Radiometric dating (^{14}C; U/Th/Pb)	Paleoclimate / Paleofauna

Source: Hill & Forti (1997); Auler et al. (2005).

Hundreds of caves studied throughout the world have furnished relevant information in geomorphological, sedimentological, paleofaunistic, and paleoclimatic studies. To cite only a few examples, in China, the monitoring of resurgences has been utilized to understand the carbon balance in the atmosphere. In Brazil, pioneering research conducted in the entire national territory have revealed important information about climatic changes during the past 600 thousand years (Fioravante, 2009), even showing that the climate of the Northeast of Brazil took on its present characteristics only in the past 4,000 years; it was more humid in the past. In Europe, the United States, and Brazil, a network of researchers have taken advantage of techniques of with cosmogenic isotopes (^{10}Be and ^{14}Al) to determine the rates of entrenching of underground fluvial channels (De Waele et al., 2012; Laureano and Karmann, 2013).

2.5. CONSERVATION OF THE SPELEOLOGICAL HERITAGE

Caves are fragile environments, formed over a period of hundreds of thousands of years. They constitute unique and relatively stable environments, although they are vulnerable. The great challenge for the conservation of caves is related to the recognition of their biological, geological, historical, and cultural importance (Sessegolo et al, 2006). Moreover, caves are being more frequently recognized for their ecological, climatic, economic and social importance.

The importance of a cave must also be observed as a function of the specific localization. Some caves are more important locally, while others have acquired global status. The variation in location, in conjunction with other variables inherent in caves, such as lithologies, forms, and processes of formation, are among the elements which characterize their diversity, recently denominated geodiversity.

Geodiversity, as a branch of natural diversity, arises from the profusion of geological environments, phenomena and active processes. The action of these phenomena and processes culminates in the production and transformation of elements such as rocks, minerals, fossils, soils and other surface deposits, as well as environments (Stanley, 2000). However, not all geodiversity can or even should be conserved. The strategy most often adopted is the setting aside of representative parcels for the adoption of strategies of biological conservation (if the focus is on the life that the elements of geodiversity house) or geoconservation (when the focus is on representative elements of geodiversity, denominated geosites by Brilha in 2005.

The criteria for the selection of representative elements are defined both by specific legislation in each country, and transnational agreements. In the case of caves, Lobo and Boggiani (2013) defend the adoption of criteria of representativity and uniqueness for characterization as part of the speleological heritage. In this way, the understanding of the heritage also refers to elements which have a diffuse and collective interest, but without focusing only on the human perception of nature. For this, the Convention for World and Cultural Protection or 1972 of Unesco should be adopted; this convention emphasizes specific attributes which distinguish parcels of natural areas, including caves, for their effect on conservation as part of the Heritage of Humanity. Some of these attributes stand out as examples: superlative phenomena, esthetic importance, examples marking the stages in the history of the earth, and evolutionary ecological and biological processes; and habitats for the in situ conservation of biological diversity. These aspects are dealt with internationally by various strategies of conservation, both in terms of habitats and biomass and, more recently, by initiatives of geoconservation. Geoconservation emerges as a branch of studies and proposals idealized for the conservation of nature. In this context, geoconservation applied to caves or systems of caves is understood as the adoption of strategies and actions for the conservation of representative parcels of the speleological heritage.

Conserving a cave or system of caves means guaranteeing geoecological equilibrium and physical and esthetic integrity, as well as maintaining the functioning of the evolutionary processes (including the circulation of water and air and transport of sediments). Effective conservation starts with an understanding of the inter-relations between the underground environment and that on the surface, especially in relation to the dynamics of transport of food to the interior, called trophic or nutritional transport. The conservation of a cave or system of caves will generally not be effective if the practical limits of protection are focused only on the cave as such. It is necessary to consider the relations between the cave and the surrounding environment, especially aspects of the dynamics of recharge of the system and the area needed to maintain the food supply of the species living in its interior so that the most adequate spatial limits for its maintenance can be better understood.

The reason for adopting such strategies of conservation in a wider perspective is to avoid possible negative anthropic impacts on the cave environment. Among the activities potentially causing impact, in addition to the direct suppression by mining activities, are large agricultural enterprises, lumbering, the raising of cattle, and even the expansion of urban networks. The development of these activities commonly leads to the alteration of the surface landscape and the removal of the existing plant cover. Such alterations can result in a reduction in the transport of food for the organisms living in a cave, an alteration in the local microclimate, and a reduction in the rate of infiltration of meteoric water (rainwater), among other consequences. One example of the problems arising from these modifications is the alteration in the volume of recharge of aquifers so that some underground drainages can simply dry up. Another consequence is an increase in the rate of erosion of the soil and the transport of terrigenous sediments by creeks and rivers, leading to the silting up of underground drainage connected to these surface rivers. Moreover, urban expansion (or even urban occupation in rural areas when developed in a random manner) can result in the contamination of karst aquifers responsible for the supply of water for various groups of humans. More information about these and other problems can be obtained in Chapter 6 of this part of the Guidelines.

2.6 EVALUATING SPELEOLOGICAL POTENTIAL

In general, the evaluation of the speleological potential can be defined as the remote process which attempts to establish the degree of favorability for the occurrence of natural underground cavities in a given spatial sample. It should be conducted during during the economic/financial feasibility study, since it impacts directly on the potential use of mineral resources.

The evaluation constitutes an important phase in the set of environmental studies related to speleology, especially in areas where there is a shortage of information. Knowing where there is greater or lesser potential for the occurrence of caves can provide support for the decision-making process, both in the public sphere to support policies of territorial ordering, and the private, facilitating the taking of decisions and improving the accuracy of feasibility study, risk management, deadlines and costs. In addition to strategic objectives and those of management, the evaluation of the potential also attempts to rationalize efforts in the field and promote safety (from the point of view of occupational risks) and effective prospective surveys.

The evaluation of the potential for the occurrence of caves via remote analyses (photointerpretation, assisted and semi-assisted remote classification, multicriterial analyses, etc.) always make up part of the speleological practice. With the objective of finding the best access routes, speleologists spend hours leaning over maps looking for typical features such as sinkholes, swallow holes, and resurgences. The cartographic bases most often used in these analyses are those based on geology (lithostratigraphy and structure), geomorphology (compartments, slope, hypsometry, hydrography (fluvial and morphological hierarchy), hydrogeology, and topography. Certain steps are common to all of these:

i. Bibliographic and cartography survey: fundamental step for the identification of the characteristics of the general area of study.

ii. Survey of the speleological data bases: it is important to consult the speleological data banks. Brazil has two of these: that managed by the Center for the Study and Conservation of Caves (CECAV) and the other by the Brazilian Speleological Society (SBE).

iii. Hypotheses for work: these are related to the interpretation which is made about the geomorphological evolution in the area in question and the speleogenetic process associated with the development of the model.

iv. Theoretical development of a model: Elaborated on the bass of the hypotheses for work, with an eye to the recognition of the “signature of the landscape”, which identifies the processes generating the karst features, especially caves.

v. Application of the model: according to the theoretical model, which is normally operationalized with the SIG platform (System of Geographical Information) via multicriterial analysis and Boolean logic, among others.

vi. Field control: This is necessary to verify the results and adjust the model.

2.7. SYSTEMATIC PROSPECTION AND DIRECTED FIELD SURVEY

Prospection, a fundamental step in speleological study, corresponds to a set of tasks which attempt to identify and provide an inventory of caves and exokarst features, such as sinkholes, swallow holes, springs, and poljes. This inventory can consist of a sample, directed to some specific objective, or be systematic, a preliminary characterization of the speleological heritage, a "basic inventory" of a target area to serve as the basis for later diagnoses. Directed prospection mostly concentrates on areas of greater potential for the occurrence of caves, whereas systematic prospection should encompass the entire area of study. Table 2.3 presents a synthesis of the main characteristics of the two modalities.

Table 2.3. Synthesis of main characteristics of directed and systematic prospection

DIRECTED PROSPECTION	SYSTEMATIC PROSPECTION
Sample nature	Systematic nature
Specific objectives	General objectives
Localized survey	Ample survey
Focus: area with greater speleological potential	Focus: overall area of study
Scope oriented to specific objectives	Scope oriented to the inventory of the heritage
Information: specific forms, oriented to the objectives of the project; storage electronically.	Information: standardized forms, stored in computerized data banks
Register of exact trajectory optional	Register of exact trajectory required
Examples: preliminary evaluations of speleological heritage, risk analyses, speleological compensation, etc.	Examples: Environmental licensing, zoning, policies for territorial demarcation, etc.

Source: Calux (2011).

The organization of a prospective survey should consider the details of the network to be prospected and the methods for the control of the procedure. This details of the network of prospection are pertinent only for systematic studies, where the register of the exact locations visited in the field is obligatory. This subject will be treated later. As for the methods of control, there are basically three: i) those oriented by a network of points; ii) those defined by lines of control, and, finally, iii) those delimited by polygons/quadrants (Figure 2.20).

In the network of points, an experienced professional must use remote analyses (photointerpretation) to determine the points of interest, which are then entered into the GPS of the field team. Based on this previous planning, the teams attempt to visit the pre-determined points in order.

The method of control lines is quite similar to that of points, but instead of a network, the teams receive lines marked in their GPS, and these should be generally followed. This method gives greater autonomy to the field teams, which may make short incursions outside the limits of these lines.

The method of polygons/quadrants consists of the delimitation of areas on the basis of characteristics of interest. It offers autonomy, making it possible for decisions to be taken in loco on the basis of the characteristics of the landscape in agreement with the objectives of the project.

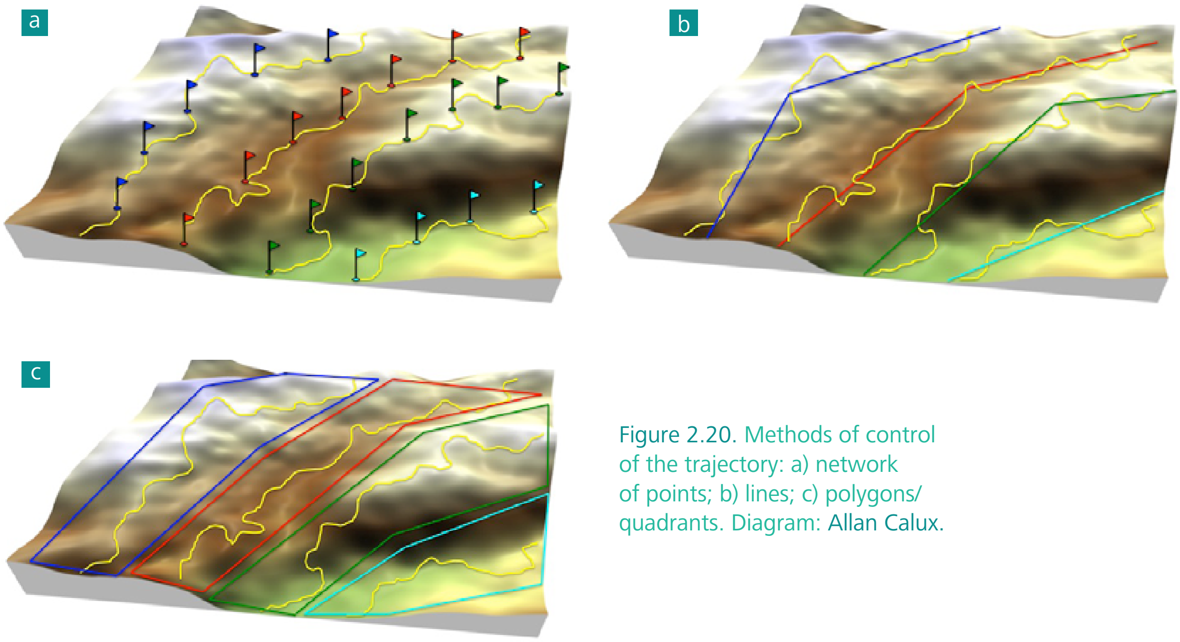
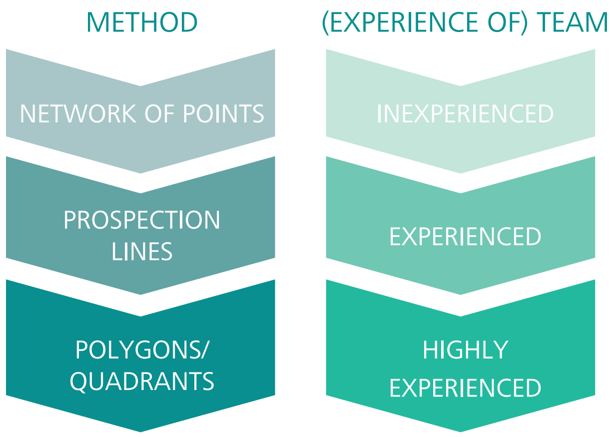


Figure 2.20. Methods of control of the trajectory: a) network of points; b) lines; c) polygons/ quadrants. Diagram: Allan Calux.

The efficacy of each of the methods depends on the experience of the field team. The method of polygons/ quadrants, given the high degree of autonomy in the field, is recommended only for teams with a lot of experience. The method of lines, with limited freedom, should be utilized by relatively experienced teams, while that of points is recommended for teams with less experience (Figure 2.21).

Figure 2.21 – Methods of control of trajectory in relation to experience of teams in the field.



Despite the diverse methods of survey, the following doubt remains: how can one determine if the sampling efforts have been sufficient? As mentioned earlier, in systematic surveys the register of the trajectory realized in the field is mandatory. This register results in a network of that trajectory and can be used to measure the sufficiency of the sample. Although there are no legal parameters of methods for this measurement, various proposals have arisen in speleological studies related to environmental licensing: the matrix of the trajectory and the coefficient of coverage.

The Matrix of the Trajectory consists of a method by which the sufficiency is measured on the basis of a comparison between the density of the trajectory in operational compartments and a matrix of empirical parameters. The density of the trajectory corresponds to the ratio of the sum of the linear distances traversed in the field within an operational unit and the surface area (Equation 2.2), preferentially measured in km/km^2. The operational compartments correspond to spaces defined by the topology of the undertaking, its structures and the speleological potential. The Matrix of the Trajectory, on an empirical basis, attempts to establish what the necessary minimum effort will be for each of the compartments defined (Table 2.4).

Equation 2.2. Density of trajectory

$$Dc = \frac{dt}{As}$$

Where

Dc = [km/km²]: density of trajectory

dt = [km]: total distance traversed in the area of study;

As = [km²]: surface area

Table 2.4. Matrix of the Trajectory

TOPOLOGY	STRUCTURE	SPELEOLOGICAL POTENTIAL (km/km²)			
		Very high	High	Average	Improbable
Linear (e.g. roads, railways, transmission lines)	Linear axis	1	0,5	0,25	-
	Surroundings	5	-	-	-
Small or medium-sized polygon (e.g. mining undertakings)	Mine site	20	10	5	3
	Sterile piles	20	10	5	3
	Dams	20	10	5	3
	Other structures	0,1	0,025	0,005	-
	Surroundings	10	2 to 5	1 to 2	1
Large Polygon (e.g. hydroelectric units)	Reservoir	15	2 to 5	1 to 2	1
	Surroundings	5	1 to 2	0,1	0,01
	Area of direct influence	1	0,25	0,01	-

The coefficient of coverage corresponds to the ratio of the area covered during the prospection and the surface area (Equation 2.3). The area of coverage is calculated on the basis of the definition of the "visible horizon" of the teams in the field, determined mainly by the plant coverage and the conditions of the relief. The greatest challenge of this method lies in the heterogeneity of the visible horizon or line of sight of the teams in the diverse compartments of the landscape and the lack of comparative parameters. Figure 2.22 provides a hypothetical example of how this value can be calculated.

Equation 2.3. Coefficient of coverage

$$Cr = \frac{Av}{As}$$

Where

Cr = [non-dimensional] coefficient of recognition

Av = [km²]: area visualized in the study area

As = [km²]: surface area

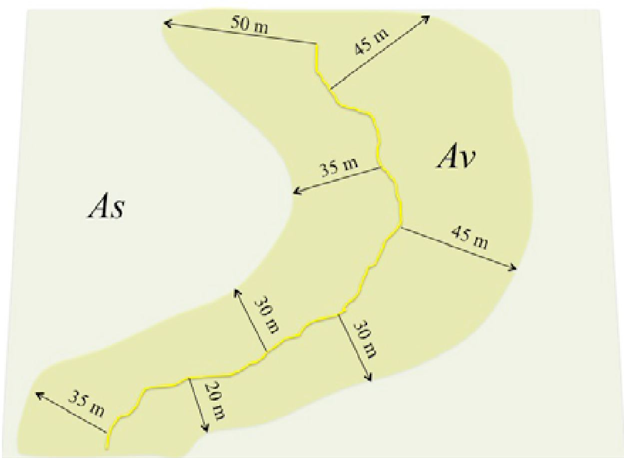


Figure 2.22. Example of calculation of the percentage of coverage in a hypothetical area of prospection: the yellow line corresponds to a hypothetical trajectory and the area in yellow the area encompassed by the line of sight. Diagram: Allan Calux

2.8. SPELEOTOPOGRAPHY, SPELEOMETRY AND GEOSPELEOLOGY

Speleological surveying is a technical activity which attempts to represent the geometric arrangement of underground routes and the internal features of a cave. The methods used involve adaptations of traditional surface topographical surveys. Using a compass, clinometers, and tape measure (Figure 2.23) speleotopographers measure angles and distances and make sketches in the field. Later, with the help of specific software, the field data are reworked and transformed into a map (Figure 2.24 and 2.25).

Figure 2.23. Equipment utilized in speleotopographic surveys: a) calibrated tape of PVC, b) laser rangefinder; c) compass clinometer. Photos: Allan Calux.

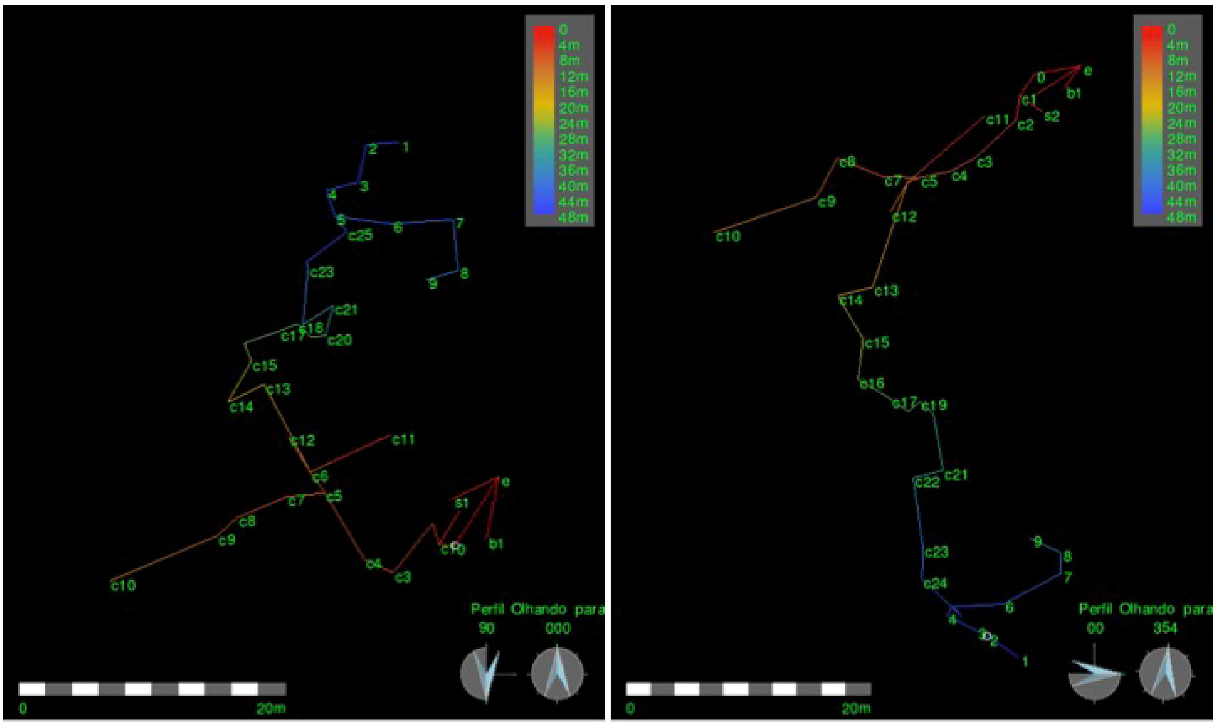


Figure 2.24. Sightings in a speleotopographic survey reworked with Servex software: a) plan view; b) cross-sectional profile. Diagram: Allan Calux.

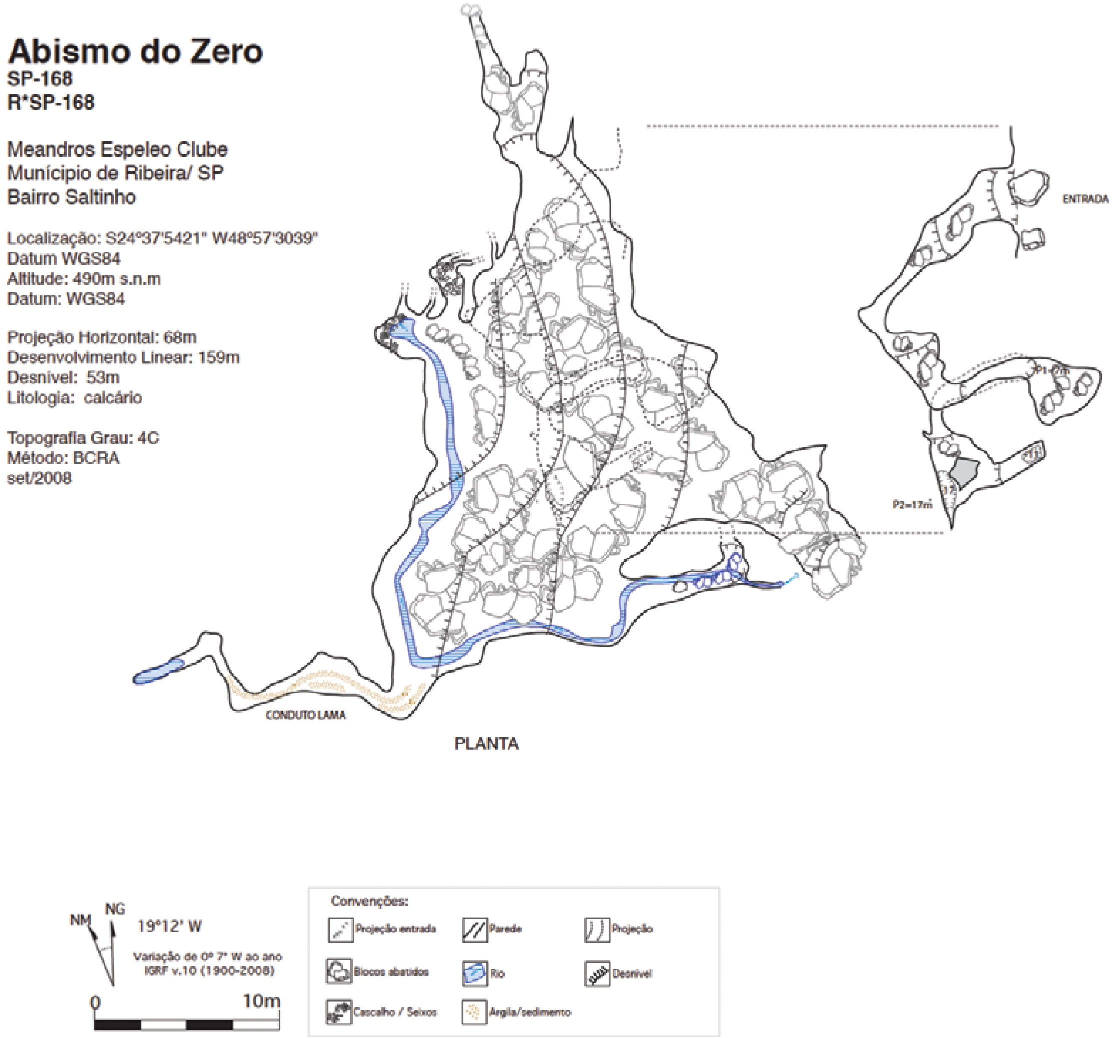


Figure 2.25. Example of a finished cave map. Diagram: Allan Calux.

In a speleological study, the map of the cave constitutes the basis for the realization of all other studies, whether geospeleological, speleoclimatic, biospeleologic, arqueologic, paleontologic, or any other kind. For a speleologic study to be consistent, the speleotopographical map is an mandatory tool.

The precision of a speleotopographic survey can be classified accord to two main methods, the BCRA Survey Grades (2002) or the UIS Mapping Grades (2010). In the BCRA method, probably the most widely used in the world, the precision is classified on the basis of two parameters, one related to loop-closure errors and the other to the detail of the sections (Table 2.5). In the UIS method, the classification is more complex and is made on the basis of the calibration of the tape, the detailing of the map, and the inclusion of a qualifying suffix (Table 2.6).

Table 2.5 BCRA Classification.

Topography Grading	Description
Grade 1	Sketch of low accuracy where no measurements have been made
Grade 2	To be used only if necessary (see note 7). May be used, if necessary, to describe a sketch that is intermediate in accuracy between Grade 1 and 3.
Grade 3	A rough magnetic survey. Horizontal and vertical angles measured to ± 2.5o; distances measured to ± 50 cm; station position error less than 50 cm.
Grade 4	To be used only if necessary (see note 7). To describe a survey that fails to attain all the requirements of grade 5 but is more accurate than a grade 3 survey.
Grade 5	A magnetic survey. Horizontal and vertical angles measured to ± 1o; distances should be observed and recorded to the nearest centimeter and station positions identified to less than 10 cm.
Grade 6	A magnetic survey that is more accurate than grade 5 (see note 5).
Grade X	A survey that is based primarily on the use of a theodolite or total station instead of a compass (see notes 6 and 10)

1. The above table is a summary, and is intended only as an aide memoire; the definitions of the survey grades given above must be read in conjunction with these notes.

2. In all cases it is necessary to follow the spirit of the definition and not just the letter.

3. To attain Grade 3 it is necessary to use a clinometer in passages having appreciable slope.

4. To attain Grade 5 it is essential for instruments to be properly calibrated, and all measurements must be taken from a point within a 10 cm diameter sphere centered on the survey station.

5. A Grade 6 survey requires the compass to be used at the limit of possible accuracy, i.e. accurate to ± 0.5o; clinometer readings must be to the same accuracy. Station position error must be less than ± 2.5 cm., which will require the use of tripods at all stations or other fixed station markers ('roof hooks').

6. A Grade X survey must include on the drawing notes descriptions of the instruments and techniques used, together with an estimate of the probable accuracy of the survey compared with Grade 3, 5 or 6.

7. Grades 2 and 4 are for use only when, at some stage of the survey, physical conditions have prevented the survey from attaining all the requirements for the next higher grade and it is not practical to re-survey.

8. Caving organizations, etc., are encouraged to reproduce Table 1 and 2 in their own publications; permission is not required from BCRA to do so, but the tables must not be reprinted without these notes.

9. Grade X is only potentially more accurate than Grade 6. It should never be forgotten that the theodolite/Total Station is a complex precision instrument that requires considerable training and regular practice if serious errors are not to be made through its use!

10. In drawing up, the survey, co-ordinates must be calculated and not hand-drawn with scale rule and protractor to obtain Grade 5.

Degree of detail	Description
A	All details based on memory.
B	Passage details estimated and recorded in the cave.
C	Measurements of detail made at survey stations only.
D	Measurements of detail made at survey stations and wherever else needed to show significant changes in passage dimensions.

1. The accuracy of the detail should be similar to the accuracy of the line.

2. Normally only one of the following combinations of survey grades should be used: 1A; 3B or 3C; 5C or 5D; 6D; XA, XB, XC or XD.

Source: Day (2002).

Table 2.6 UIS classification.

Survey grade	Description	Precision			
		Length	Compass	Clinometer	Accuracy
-1	No map available.	-	-	-	-
0	Ungraded.	-	-	-	-
1	Sketch from memory, not to scale.	-	-	-	-
2	Map compiled from annotations, sketches and estimates made in the cave. No instruments used.	-	-	-	-
3	Directions measured by compass, distances measured by cord, paced, or body dimensions. Significant slopes estimated.	0,5 m	5°	-	10%
4	Compass and tape survey, using deliberately chosen and fixed stations. Slopes measured by clinometers or horizontal and vertical components of line.	0,1 m	2°	2°	5%
5	Compass and tape survey. Directions and slope by calibrated instruments, distances by fiberglass or metallic tape, or tacheometry.	0,05 m	1°	1°	2%
6	Survey or triangulation using calibrated, tripod-mounted instruments for directions and slope. Distances by calibrated tape, precise tacheometry, or DistoX.	0,02 m	0,25°	0,25°	1%
X	Survey by theodolite or equivalent.	variable			variable

Map detail grades	Description
0	Ungraded.
1	Sketch from memory. Not to scale, but indicates approximate proportions.
2	Details from annotations, sketches and estimates of directions and dimensions made in the cave.
3	Details from drawings made in the cave. The drawing need not be to scale, passage dimensions can be estimated. Significant details should be drawn with sufficient accuracy.
4	Details from drawings made in the cave to scale, based on measurements of significant details with respect to surveyed points, usually at least grade 4. All details of general speleological interest should be shown with sufficient accuracy so as not to be appreciably in error at the mapping scale. Passage dimensions measured.

Qualifying suffixes	Description
A	Nothing done to obtain additional certainty of accuracy
B	Survey loops are closed and adjusted
C	Survey is dependent on instruments and people, with possible anomalies checked and corrected for effects
D	Survey is checked and corrected by electromagnetic methods
E	Survey data has not been transcribed manually, but has been downloaded electronically
F	Entrances have been precisely measured.

Source: UIS (2012).

One product of speleotopographic surveys involves speleometric attributes. In Brazil, the most utilized are: horizontal projection, difference in level (depth), area and volume.

For the calculation of horizontal projection, the principle of discontinuity should be used. This ignores the width of the conduits in the final calculation. In this way, the lengths of the segments of a conduit along the central axis are summed. When two conduits cross, measurement is interrupted so that the width of the side conduit will not be included (Figure 2.26). The difference in level or depth is the result of the altimetric difference between the uppermost floor and the lowermost one (Figure 2.26). When platforms or paleofloors or upper levels are present, their height should be considered in the calculation of the difference in level.

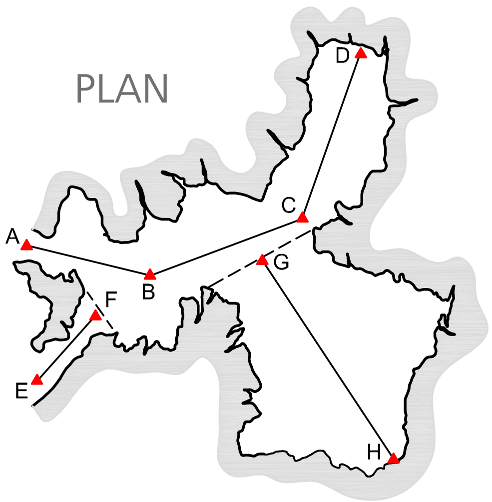


Figure 2.26. Measurement of horizontal projection (method of discontinuity) and depth of a hypothetical cave. Source: Calux (2013).

HORIZONTAL PROJECTION (HP)

$$PH = \overline{AB} + \overline{BC} + \overline{CD} + \overline{EF} + \overline{GH} + \ldots + \overline{NN}$$

Depth (D)

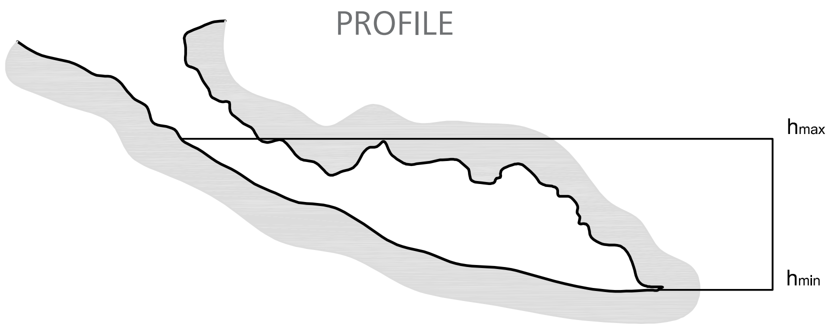
$D = h_{max} - h_{min}$

Where

D = Depth

h_{max} = maximum height of floor

h_{min} = minimum height of floor



The *area* should be calculated using specific programs. The most common is using CAD software and based on the horizontal plan of the cave. When there are columns, their area should be calculated individually and subtracted from the total measure. The total area is the result of the sum of the areas of the plan view of all of the levels of the floor, discounting the areas of the pillars (Figure 2.27). The volume is the product of the total area of the cave and the average height of the galleries and shafts. To obtain the average height, cross-sections must be made at representative points of the cavity where there are morphological changes in the floor, ceiling, or walls. In order to calculate the most realistic value; longitudinal sections are made along the central axis of the conduit, as well as for as many transverse sections as possible. The more sections considered, the greater will be the precision of the calculation of the volume (Figure 2.27). However, the best way of calculating this parameter is the use of a laser rangefinder.

The geospeleological diagnosis involves the description and analysis of the lithostructural, morphological, hydrological, sedimentary and speleogenetic attributes of caves, as well as surface elements (exokarst) which characterize the karst environment of the area of study.

The lithostructural analysis attempts to characterize the rocks in which the caves are inserted, which may be described and analyzed chemically and mineralogically. Structures such as banding, foliation, fractures (tectonic or not), folds and faults should be described and measured. These structures represent important discontinuities which condition the circulation of material and energy in the interior of the system interfering directly in the process of genesis and development of caves. Often these structures control the morphology, as well as condition the processes of collapse of walls and ceiling.

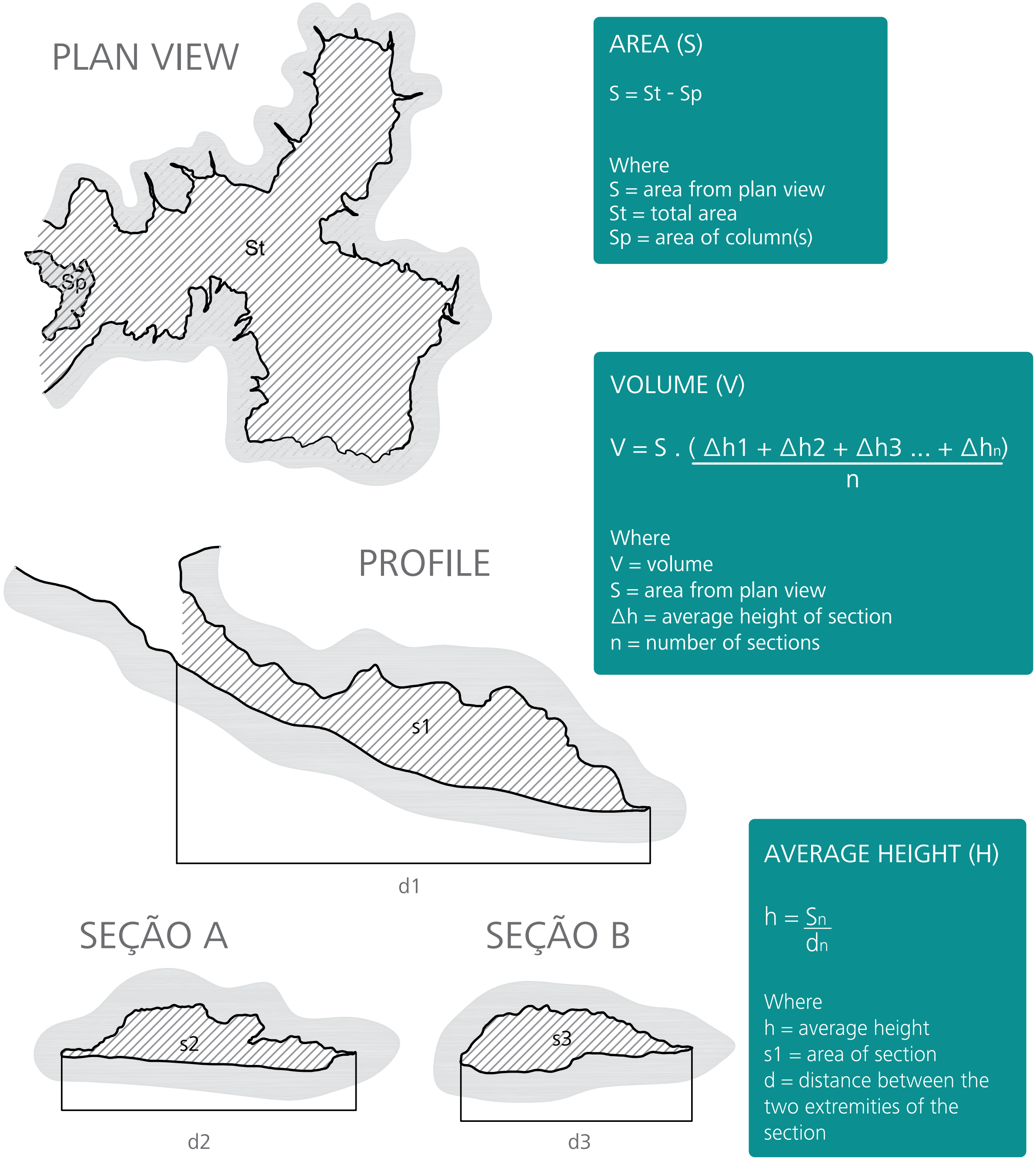


Figure 2.27. Measurement of area and volume of a hypothetical cave. Source: Calux (2013).

In the morphological analysis, the objective is to identify evidence of the processes responsible for the initiation and development of caves. The analysis of features in various scales of observation (micro–meso-macro) makes possible inferences about the environment of formation and development of cavities. One important tool for this analysis is speleotopographical or survey maps, since the analysis of planimetric patterns helps in the interpretation of speleogenetic evolution.

Thy hydrological dynamics must also be evaluated from a systemic perspective. A karst system can be considered to be like a filter which transforms an entering signal (input) into an outgoing one (output), and its functioning must be determined.

Deposits of clastic sediments should be classified according to granulometry, rounding, and color, to provide information about origin and sedimentation. Organic deposits should also be described, when applicable, since they constitute an important source of trophic or food resources. The chemical deposits (speleothems) should also be identified, described and photographed. When possible, it is useful to conduct petrographic and mineralogical studies.

2.9. MONITORING OF IMPACTS TO THE SPELEOLOGICAL HERITAGE

During the steps of implantation and operation of a mine, caves and their respective areas of influence should be monitored. The monitoring system constitutes a fundamental instrument for the analysis of caves and, in the case of environmental licensing, is designed to guarantee that they do not suffer impact during the activities of the undertaking. It is recommended that this monitoring be structured in the form of a "management plan" with well defined methods, goals, indicators and instruments for evaluation.

It is often necessary to increase our knowledge about the speleological heritage inserted in the context of an active undertaking. This may involve new campaigns of exokarst prospection, with greater depth in diagnostic studies (such as those of hydrology, geospeleogy, and biospeleology). These studies' goal to provide a better understanding of and respect for the evolutionary dynamics of the set of speleological forms and guarantee the continuity of the processes and the equilibrium of the underground ecosystem.

Each context will require the monitoring of a set of sub-elements; however, the most frequent are the following:

- Seismic monitoring
- Hydrological and hydrogeological monitoring
- Geostructural monitoring
- Photographic monitoring
- Atmospheric monitoring of the gradient between the regional climate, the microclimate, and the speleological climate.

2.10. INCIDENTAL FINDINGS

Conservative estimatives suggest that only 5% of the underground drainage network is accessible to humans (Palmer 1991). A large part of this network corresponds to inaccessible macrocavities, known as closed caves. In some situations it is possible to identify them via geophysical studies; however, normally the results are inconclusive, especially when the closed cavities are located in the deeper portions of the rocky massif.

It is thus possible that during the operation of a mine, the advance of the front intercepts such underground voids. When this happens, operation should be stopped immediately and the fact should be communicated to the competent environmental authorities. Such a cavity should be evaluated in all of its speleometric, biological, and environmental aspects before other measures – whether suppression or conservation — be taken. However, it is usually the case that such cavities cannot be studied because of the imminent risk to the workforce. It is then necessary to negotiate with the competent environmental agency the best possible solution for reestablishing the operation.

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CHAPTER 3:
BIODIVERSITY IN KARST ZONES

Eleonora Trajano
Ana Claudia Neri

3.1. INTRODUCTION: KARST SINGULARITIES

The objective of conservation is to preserve significant samples of biodiversity, including the processes and patterns that originated such biodiversity. This classical definition can also be extended to geodiversity, which has just recently become a concern to the conservationists. Therefore, currently we can talk about samples representing environmental diversity as a whole. The problem is how to define what is comprised in such samples, as well as to establish their temporal and spatial limits.

In terms of priority for conservation, the areas and systems which comprise elements considered as unique, singular, not found anywhere else, are specially important, and the bigger the differences they present, the more urgent is their need for preservation. This is because such systems greatly contribute to the natural diversity and, if they are destroyed or significantly altered, the consequence will be an important loss for the general diversity of our planet. Other than this, ecosystem services, which can be fundamental for a balanced and integrated operation of the ecosystem and for the environmental health, will be lost without the possibility of being replaced or substituted, frequently generating social and economic damages (Table 1).

The karst, with its epigean and subterranean, geological and biological components, presents many singularities in relation to the non-karst environment. This is because the conditions for the chemical dissolution of the rocks, which is a determinant process for the karst landscape, occur in delimited areas occupying about 13% of the emerged land in our planet.

The karst landscape is characterized by surface features like steep walls, deep valleys, towers and ground pits (for instance, dolines) –exokarst – and by predominantly subterranean drainage through conduits, which are called caves when they are large enough to allow the access of a human being – endokarst. It is formed in areas presenting soluble rock outcrops, mainly carbonates. Other soluble rocks, even though less soluble than the carbonate ones, such as siliciclastic rocks (whose main component is silica) can also undergo karstification. It is noteworthy that, in addition to a reasonable degree of solubility, other conditions are also required to the karstification process, for instance, the presence of breaches in the rock where the water can percolate, like bedding planes (separation of layers of different types of sediments, due to changes in the sedimentation environment) and fractures caused by metamorphism processes deep down in the earth's crust. That means, not all carbonate rocks are karstifiable or can be karstified, therefore the places that are interesting for limestone quarrying are not always karst areas.

3.2. THE KARST LANDSCAPE AND ITS VEGETATION

A predominantly subterranean drainage has a very important effect on the surface environment, providing the conditions for a very characteristic kind of vegetation. Frequently, the karst soil is not very thick or even not present, leaving the rock exposed, mostly in higher grounds where sediment is easily leached. These features can provide the conditions for semi aridity. On the other hand, in ground depressions such as dolines, the climate is more humid and milder because of the shading and the proximity to the water table

Therefore, mainly in intertropical zones, where the differences between shading and direct exposition to sun light are more remarkable, the typical vegetation for the karst zone is a mosaic of formations being open on plateaus and tops of outcrops. In this case, the vegetation comprises sparse arboreal elements and deciduous bushes (that lose their leaves seasonally). It also features xerophytic plants (adapted to dry climate) like cactuses, as well as spots of denser and higher vegetation, that is typical of more humid zones, in depressions and river valleys. In Brazil, this kind of landscape is common in karst areas in regions with a low water availability, such as the Caatinga and Cerrado phytogeographic domains (very dry landscapes) (Figure 1A).In the catchment basin of the São Francisco River, in the States of Minas Gerais and Bahia, this type of vegetation is called Dry Forest (Mata Seca). The Danish scientist E.

Warming incorporated this term in the scientific literature, by the end of the 19th Century. Warning was a member of P. Lund's team that visited Lagoa Santa, Minas Gerais, and followed the local denomination. However, today the term is used to refer to dry tropical forests in general, not necessarily associated with karst itself.

The combination of these various aspects, among which the steepness and orientation of the slopes are very important, generates a remarkable biodiversity with endemic (geographically restricted) species. The spots with denser vegetation may be important refuges for ombrophilous species, which do not tolerate direct exposition to the sun nor to drought. According to Batori et al. (2014), who have studied the vegetation in dolines at different regions in Hungary, such features are important reservoirs of species for many vascular plants. Therefore, they are particularly important for conservation as refuges for biodiversity in view of the global warming phenomenon (Figure 1B).

Such spots of hygrophilous ("humidity friendly") vegetation could have reached the current refuges with the expansion of the humid forests, by the time when paleoclimates were more humid than today. The last interglacial peak occurred around 5.000 years ago and currently, under natural conditions, planet Earth could be in route to a glacial age. The progressive decrease of the general humid conditions associated to the glacial phases of paleoclimate cycles causes the retraction of forests and their substitution by more open vegetation formations. These latter are more tolerant to lowered water availability, but small islands of hygrophilous vegetation are left behind in refuges located in dolines and other karst depressions. Other than being reservoirs of biodiversity, those refuges have a high scientific value, as they are testimonies of ancient climate conditions.

On the other hand, in karst areas located in currently humid regions, like the Atlantic and Amazon Forests, the so-called covered karst is frequently found, which presents a thicker layer of soil and a more homogeneous kind of vegetation, as it can be seen in the region of Upper Ribeira River Valley, Southeastern Brazil (Figure 1C).

Rodrigues & Travassos (2013) remark the importance of the concept of "Dry Forests" for the karst landscape. This term dates back the 19th century, initially quoted by Warming as being the local name for the vegetation occurring on limestone. Currently it would be used for Dry Tropical Forests, closely linked to the "karstsfere", as a part of the "lithosphere that is the scenario for the karst". Nevertheless, it is very important to remark that, in current times, the designation "Dry Forest" refers to forest formations undergoing seasonal climate regimes independently of the lithology. This kind of formation is also called Deciduous Dry Forest, Calcicolous Forest, Dry Forest in Limestone Soil, Limestone Forest, and Seasonal Deciduous Forest in Slopes. In Brazil, dry forests are widely distributed in the Cerrado, also occurring in the Caatinga and Pantanal zones, mainly as spots of vegetation, in the States of Bahia, Minas Gerais, Goias, Mato Grosso, Mato Grosso do Sul and Tocantins (Rodrigues & Travassos, op. cit.).

Losing some leaves during the dry season is an important characteristic of the Dry Forest system. Besides the considerable reduction of the water lost by evapotranspiration, which is a strategy for the survival of the vegetation during the phase of stress, the discarded foliar biomass becomes an available nutrient input to the endokarst.

The importance of deciduous forests is most oftenly underestimated and they get little or no attention, because these forests do not have a lush appearance, suggesting a low richness, mainly in the dry season. This is a false concept. Studies carried out in China show that the idea of a low epigean biomass in open areas is not applicable on the sub-surface. The biomass of the roots is the same both in karst areas covered by forests as in areas covered by herbaceous and shrubby vegetation. Therefore, it is possible to conclude that the restoration of degraded karstic grounds, even the ones featuring open vegetation with low superficial biomass, significantly enhances the regional subterranean stock of carbon.

In Brazil, the few detailed floristic studies in karst areas were carried out in localities at the Upper São Francisco River basin (e.g.in the municipalities of Januária and Pains) in the State of Minas Gerais. This area is historically important because it is where E. Warning, accompanied by the famous paleontologist P. Lund, made his first observations on vegetation associated to limestones. Those studies revealed a high diversity of species.

Until the present days, there are not enough comparative data to conclude if there are floristic or faunistic elements that are exclusive to the Brazilian karst. Representatives of some lithophilous taxa (preferring rocky substrates) are evidently common in Brazilian karst areas, but they are not exclusive to them. That is the case of bromelias, some orchids, cacti, swiftlets (birds of the Order Apodiformes), mocós (medium-sized rodents, typical to the Cerrado and Caatinga areas), to name a few. Many further studies are necessary, both in karst and non-karst areas, to the understanding of the ecology of such a fragile and important landscape.

Figure 1. Different patterns of vegetation in karst areas, varying according to their location in relation to the climate zones of the Earth and their relative location in the ground. a) Xerophytes and caducifolious trees in São Desidério, Bahia (above). In the same region and in the same season of the year, the vegetation remains preserved inside a doline (b) below left); c) Dense vegetation covering a karst area in the valley of the Betari River (below right), inside the Parque Estadual Turístico do Alto Ribeira - PETAR (State Park of the Upper Ribeira River) in São Paulo. Photos: Heros Lobo

3.3. THE IMPORTANCE OF KARST: ECOSYSTEM SERVICES

Ecosystems can provide valuable services, in this regard the karst is very important for providing some of them, such as the following: water supply by means of water springs, reservoirs and especially by aquifers; pollination and biological control, providing shelters for key species, for the reproduction of plants (as it is the case of nectarivorous/pollinivorous bats) and for insect predators (insectivorous bats) (see Box 1); refuge for species threatened with extinction; leisure and culture because of its scientific, aesthetic, artistic and educational value, providing opportunities for nature tourism and adventure sports.

BOX 1. Ecosystem services provided by bats

A study done in Texas in the decade of 2000 showed that the elimination of pests in a 4,000 hectare cotton plantation by Tadarida brasiliensis, a species of insectivore bats, represents an annual saving of about U$ 740,000. In other study, in the State of Nuevo Leon, Mexico, the value of the service of pest control by the same species was estimated to be in the range from U$ 480,000 to U$ 1, 2 million. In Southern Texas, pest control done by bats would decrease the damage to the plantations from 20% to 50% (Kunz et al., 2011). T. brasiliensis is a typically cave dwelling species in North America, forming huge populations in New Mexico that emerge in a synchronized way at dusk putting on a show that attracts tourists from all over the world; being so, the economic value of touristic activities can be added to the pest control service value.

The efficiency of the insect control by bat predation does not decrease in the long term, on the contrary of what happens with the use of pesticides or even genetically modified plants designed to resist agricultural pests. As time passes, insects get adapted to the chemical defenses of the modified plants, which implies the need to develop even more resistant plant species, involving ever-higher costs for research. It is a vicious cycle that results in an ever-greater dependency of the biotechnological companies supply. It would be more practical, logical and cheaper to leave the service of pest controlling to the bats by protecting their refuges.

The glossophagines that belong to the Neotropical family Phyllostomidae, just like many megachiropterans (flying foxes, Pteropidae family) from Southeastern Asian, feed on nectar and pollen, therefore providing pollination for the plants they visit. Many plants are adapted to the pollination by bats, depending on them for their reproduction, in such a way that the extinction of the pollinating species should drive to the simultaneous extinction of these plants. That is the case of the banana tree, from Southeastern Asia, and of the blue agave from Mexico, that supplies the raw material for tequila making. The banana we usually eat was domesticated and has no seeds, reproducing asexually by sprouting; that means that current banana trees are clones, without genetic diversity what makes them highly vulnerable to diseases (huge banana plantations have already been lost for that matter).

The few megachiropteran species that pollinate banana trees are threatened of extinction, therefore the wild banana is threatened as well. If there is a wide epidemic and the domesticated bananas are lost, it will not be possible to re-domesticate them and we shall loose an important food source. The blue agave is adapted to sandy soils in altitudes of more than 1.500 m and is pollinated by one species, Leptonycteris nivalis. The fructose-rich agave core is used to produce tequila, a very important product for the Spanish American countries, both from an economical and a cultural point of view. Recently, L. nivalis became threatened with extinction due to both natural and anthropic environmental disturbance, and a huge conservation campaign was designed to protect this important species.

Many species of bats also contribute to the regeneration of forests. Frugivorous bats are much more efficient in promoting the regeneration of degraded areas than the reforestation made by men. Bats release their feces when flying causing a "rain of seeds". As these animals can fly long distances, they have a very important role as seed dispersers. Just like in the case of pollinator bats, some plant species rely on bats for the dispersion of their seeds.

Even hematophagous bats, which sadly have a very bad, but not deserved, reputation (some cases of human rabies have been wrongly attributed to bat transmission) render very important services to humankind. Their saliva contains a very potent anti-coagulant that has been used in the studies of new drugs to fight diseases of the circulatory system that affect millions of people.

Figure 2. Ha Long Bay, one of the most popular destinations in Vietnam, located in the North of the country, near the border with China. Photo: Eleonora Trajano

Karst landscapes have a high aesthetic value and, consequently, high economic value once they sustain activities linked to tourism and leisure. Such activities are a very important asset for regional and national economies. A very well known example is the tourism in the Ha Long Bay, in Vietnam (Figure 2). The outstanding beauty of the karst in the Southern China and Southeastern Asia has been fully enjoyed by the media and appeared in many movies.

In the bottom of depressions or in open areas leading to caves, it is common to find clear bodies of water that can be beautifully blue. The combination of those different elements results in a beautiful scenic landscape for the viewers to enjoy. Just to name a few examples, we can mention walls, towers, valleys, rocky plateaus, deep grooves forming exquisite views covered by a diversified vegetation, with cactus gardens and lush green vegetation in the lower levels (inter-tropical zones), leading to a subterranean scenario with lakes, and "gardens of stones" represented by the speleothems. Consequently, karst zones and particularly caves are used for touristic purposes all over the world, providing important income for the local, regional and national economy. Due to their unique characteristics, karst landscapes provide leisure and cultural ecosystem services of high value for humankind.

3.4. QUARRYING ACTIVITIES AND THEIR IMPACTS

Figure 3 shows the main limestone quarrying activities and the impacts in the areas influenced by them.

Karst systems may be regarded as networks of highly permeable conducts surrounded by a huge volume of impermeable rocks. Through the process of diffuse infiltration or concentrated in the recharging points, water can be stored in the underground in great quantities (Travassos, 2007) what makes karst system a highly important water source for human consumption. Karst systems are highly sensitive and their aquifers can be negatively affected by anthropic pollution discharges. This natural vulnerability to Impacts (Hirata, 2001) is caused by the dynamics of the subterranean drainage. This happens because the waters of a karst system can run long distances in a relatively short time, depending on the structure of the endokarst and, more important of all, the subterranean drainage does not always coincide with the surface drainage.

According to Ford & Williams (2007), aquifers are the sole source of potable water in vast areas of the globe, especially in karst regions. Box 2 shows the example of an urban region highly dependent of karst aquifers. About ¼ of the world population and 50% of the alpine regions are supplied by this kind of water source. According to Forti (2002), it is possible that, by the year 2025, around 80% of the world population will use water from the karst. Although this scenario seems to be overestimated, it is understood that the preservation of karst areas is extremely important for the survival of the communities that are associated to them.

BOX 2. WATER FROM KARST SUPPLYING THE METROPOLITAN AREA OF THE OF CURITIBA – PARANÁ STATE – BRAZIL

"Currently, the main catchment areas that supply water for the Metropolitan Region of Curitiba reached their limit due to the degraded state of their waters. To face such a situation, the Karst Aquifer of Curitiba is the feasible alternative to mitigate the water deficit of the city of Curitiba. The aforementioned aquifer supplies water for the following cities: Almirante Tamandaré, Bocaiúva do Sul, Campo Largo, Campo Magro, Colombo, Itaperuçu e Rio Branco do Sul. The average water flow of the 27 wells drilled in the mentioned region is 40 Ls-1, not including the natural sources whose total discharge are over 300 Ls-1. Pumping water from the wells that were drilled has already had environmental impacts on the region, such as ground collapsing and causing cracks in dozens of buildings and reduction of the discharges in the drainage whose springs come from the karstic aquifer. The rational exploitation of the mentioned aquifer without environmental impacts can be reached by the catchment in natural sources, without compromising the discharges in the drainage net of the region."

Source: Hindi et al, 2013

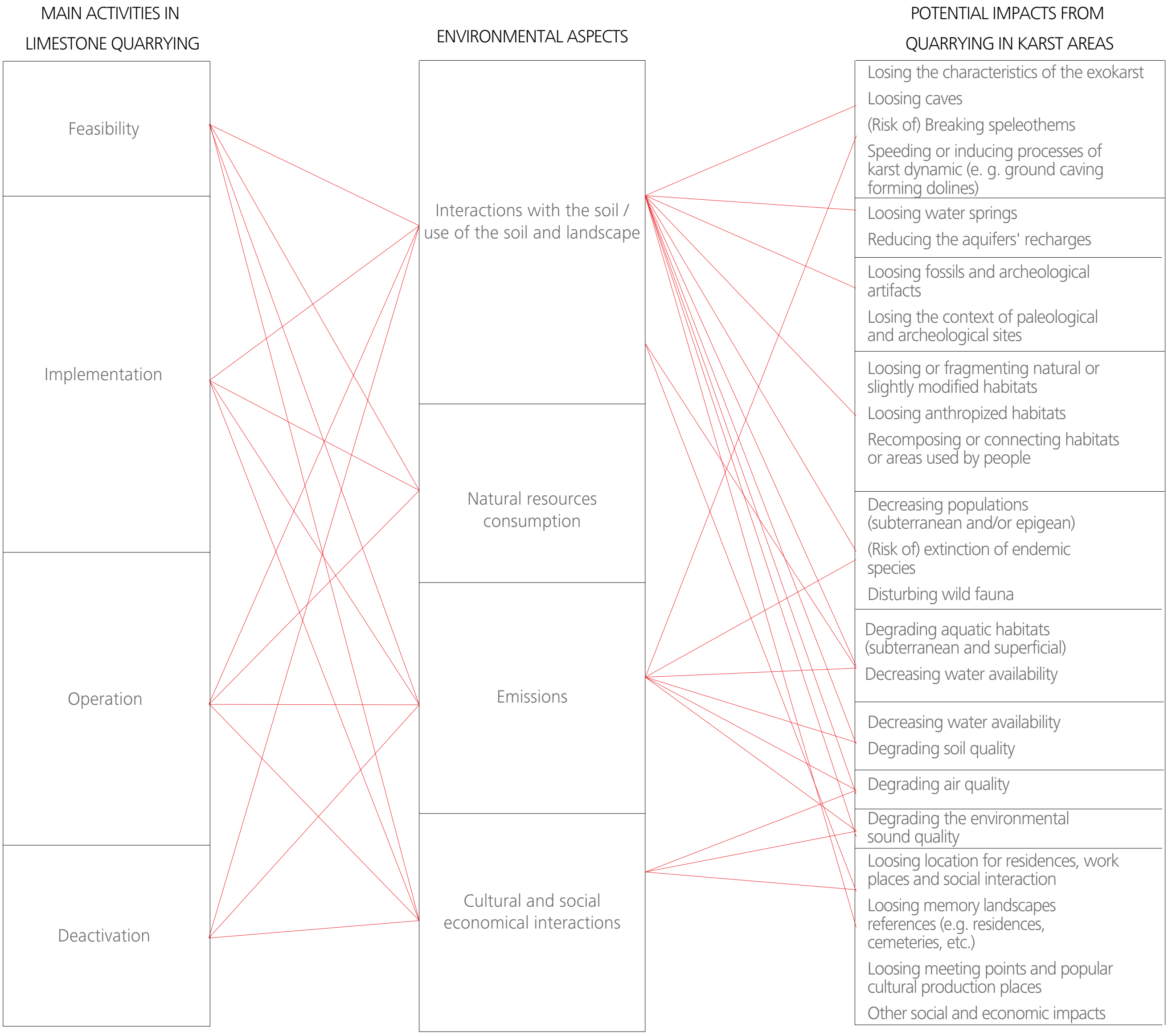

Figure 3. Limestone quarrying main activities and their impacts. Designed by : Ana Neri

Removing the vegetation to implement quarrying pits and other structures required for quarrying operations implies the reduction of nutrients carried in to the subterranean environment, negatively impacting the food chain as the food supply sometimes is drastically decreased both in the epigean (to trogloxenes, mainly bats) as in the hypogean (for troglophiles and troglobites) environments.

The increase of the superficial erosion and the decrease of the capacity of the soil to retain water can result in a lower water flow reaching the caves by percolation. A reduced water influx can lower the air humidity in the underground. This could be fatal to specialized troglobites, which have lost their capacity to tolerate a drier environment. Furthermore, low humidity is not favorable to fungi growth, an important food source for many detrivores, like collembolans, mites and isopods, which are in the basis of the subterranean food pyramid.

Vegetation removal, even not directly on karstified rock formations, can also cause the loss of shelters for bats, once many species use tree hollows as day shelters or night roosts for resting and digestion between foraging bouts.

The intensification of erosion processes in hydrographic basins upstream karst areas must be very well understood, because the sediments carried into the underground conduits tend to muddy the water and change the flow regimen, transforming the aquatic environment, from lotic (fast flowing and well oxygenated waters) to lentic (still or slowly running waters), and can even fulfill the conduits themselves.

The fauna of streams, which is a typical lotic habitat, includes many species specialized to live in such environments, having ecological and physiological requirements totally different from species living in still or slow running waters (lentic habitats, like lakes, lagoons and lowland rivers, and the subterranean water table).

Removing the vegetation coverage oftenly leads to loss and/or changes of habitats. The impacts from those changes can reach alarming proportions, as it can be currently seen in Serra da Bodoquena (State of Mato Grosso do Sul, Central Eastern Brazil). In this area there are several caves, some of them are the sole habitat of troglobitic species. Those caves are undergoing a quick siltation process due to the deforestation in springs that are located outside of the protected area of the Parque Nacional Serra da Bodoquena (Serra da Bodoquena National Park), in spite of the existing laws forbidding deforestation in springs and river margins. Unfortunately, this is not the only example but one of the best-documented cases. Given the hydrodynamics of the karst, the impacts of deforestation and the increasing erosion can be felt long distances away from their source.

The removal of the vegetation cover negatively affects the services rendered by bats, as well as other cultural services, because it threatens the preservation of the biodiversity.

Digging for quarrying purposes can also cause changes in the direction and the flow of subterranean waters, because of the removal of the soil from the surface, the exposition of the rocks and/or alterations on the relief of the terrain. At first, a higher recharge of the aquifer can have positive impacts, like a higher level of the water sources for catchment and consumption of local populations. On the other hand, in a karst system, the elevation of the water table and of the water flow in a conduit can accelerate the erosion of sedimentary deposits accumulated inside caves in past times, therefore it could cause negative impacts, for example, losing the karst features.

In addition, the removal of rocks during the opening of quarrying pits is the gravest of the risks to subterranean ecosystems, as it is for any other environment around the world that means the destruction of the habitats. The decreasing availability of rocky shelter for bats , especially the lithophiles, i.e., the ones that prefer or even depend on these shelters, can make them to abandon a region, even if there is a sufficient source of food, therefore damaging the ecosystem services provided by those animals.

Explosives used in quarries generate movements in the rocky massifs and, consequently, there may be changes in the subterranean water flows. The quantity of available water in one given water conduit in a karst system can also be changed, decreasing the water flow downstream from the quarry as well as damaging the water supply for the local population (Hess & Slaterry, 1999).In extreme cases, it is even possible that subterranean streams inside active caves dry out.

During the operation of a quarry, in case subterranean waters have been found, it is very important that the water table be lowered to propitiate good working conditions in a dry environment, so that floods can be avoided inside the quarry, which could damage the equipment and cause accidents.

On the other hand, pumping subterranean water changes its flow and can negatively affect the environment reducing the flow in superficial water bodies and springs, inducing subsidence and creating dolines.

Figure 4 presents the potential effects of lowering the water table due to water pumping to open a quarrying pit.

Several authors report that, in the Transdanubian Mountains in Hungary, pumping water to lower the aquifer in large limestone areas, to extract coal and bauxite, has been done for more than 80 years. It resulted in lowering the aquifer from 15 to 150 meters deeper, creating a lowering cone that have dried out some springs and damaged some of the famous thermal springs in Budapest (Hess & Slaterry 1999).

Over-pumping water can decrease the volume of habitat available for the aquatic fauna, which can become ever more inaccessible. A typical Brazilian case refers to the Tetragonopterinae fish, Stygichthys typhlops, from southeastern Brazil (Jaíba karst area), State of Minas Gerais (Figure 5). As the sole South American troglobite representative of the Order Characiformes, S. typhlops is highly specialized, featuring a unique set of characteristics associated to the phreatic way-of-life, which appeals to international interest. This important species is being threatened by the rapid process of lowering the water table level, caused by subterranean water pumping to irrigate large banana plantations and other crops. There are serious social impacts as the wells that supply potable water to the rural population dry out, leading them to depend on external water supplies once they cannot afford drilling artesian wells.

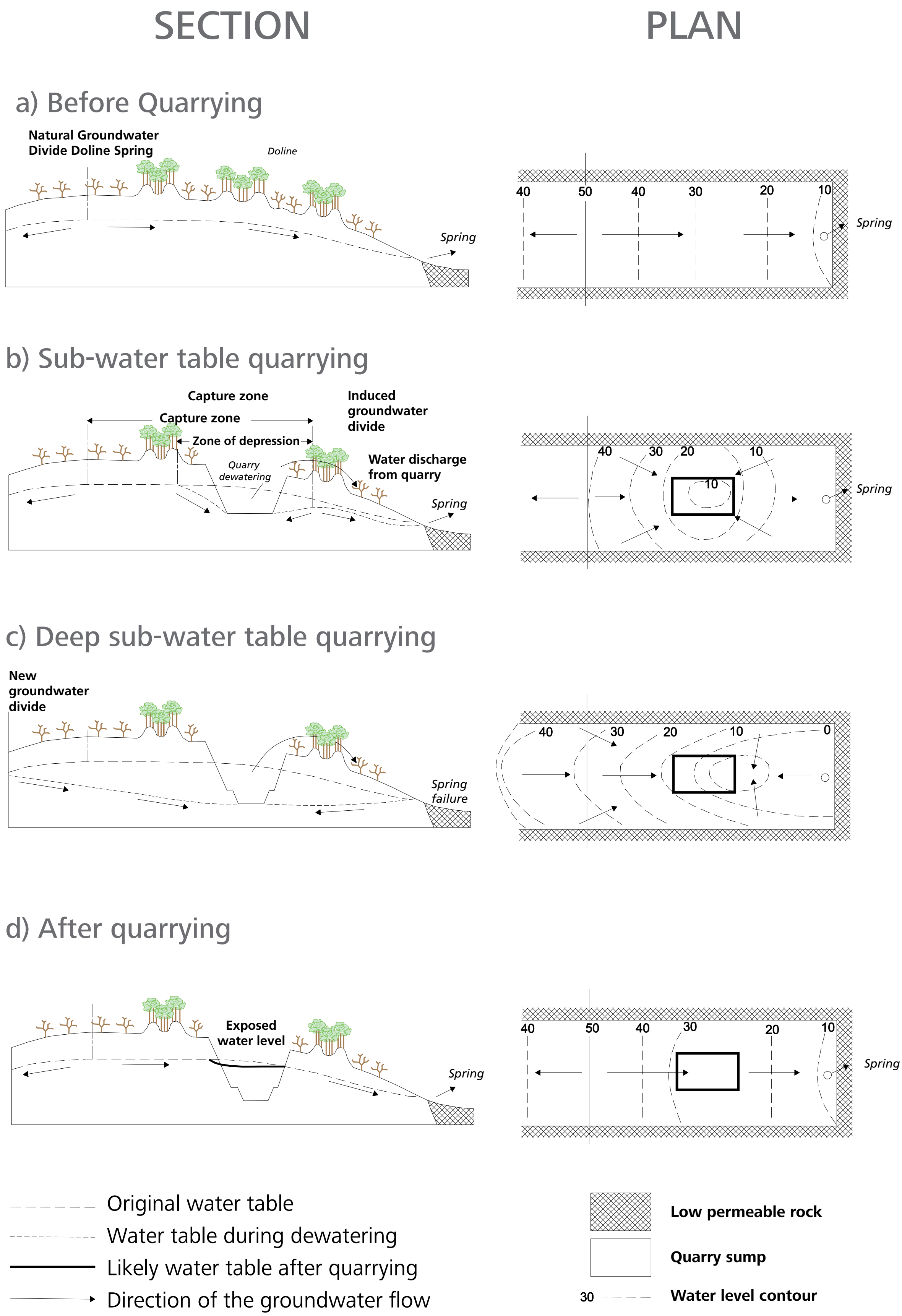

Figure 4. Schematic diagram showing the potential effects of sub-water table quarrying on the water table.
Assembling: Ana Neri. Illustration: Mirna Mangini. Modified from Hess & Slaterry (1999), and from Harrisson (1992)

Figure 5. *Stygichthys typhlops*, from the municipality of Jaíba, State of Minas Gerais, Brazil (5 cm maximum length), highly specialized phreatobic troglobite, threatened by over-pumping water to irrigate crops. Photo:Dante Fenolio.

Besides decreasing the flow of watercourses near quarrying pits, lowering the water table by pumping can, in some instances, cause subsidence and speed the process involved in doline development. Whenever a water table is lowered, a new level of sub-superficial erosion begins and, consequently, the material located on upper layers can move down to the caves intensifying the karst process like subsidence of the roofs. This whole process may result in damages to buildings and operation infrastructure from the soft soil consolidation originated from ancient dolines or by the removal of the soluble material from the soil by the sub-vertical percolation. Densification may occur because of the lowering of the water table, external recharges caused by landfills (dumps, rubble-piles) or the migration of sandy soils to the interior of the cavities.

Figure 6 shows the balanced situation before the water table is lowered (A) and after (B, C, D). The paleo-doline is not seen in the surface but the line of pebbles and rubbles near the rocky top indicates it.

Figure 6B-D shows the situation after the water table is lowered. The development of the doline is seen when the densification of the soil leads to the superficial subsidence. The periphery is characterized by a shearing zone and distention fractures (release). Figures C and D show the compression of the soft soil and its repercussion on the surface, causing the doline to deepen.

Figure 7 shows the same mechanism as Figure 6 with the densification of the soft soils produced by leaching. Densification and, for that matter, the settlement of the surface can happen due to the water table lowering as well as because of the weight of new landfills.

Changes in karstic processes, due to changes in the physio-chemical properties of subterranean waters, may occur because of the accelerated dissolution process related to the increase of the acidity of the water. Such increase may be caused by an ill done acidic drainage from the quarry; or it may occur by the infiltration of waters coming from upstream the quarry that may be contaminated. Acidic drainage of quarries (usually metallic) in aquifers may seriously affect the quality of waters by chemical alteration (mainly pH).

In the literature, there are reports about karst waters affected by acidic drainage that present a low pH, a high concentration of sulfates and low alkalinity (Sasowsky & White 1993 apud Hess & Slaterry 1999). In this kind of environment, the processes of dissolution of limestone rocks can be intensified. The consequences may be the following: a) reduction of the flow of superficial bodies of water (including springs drying out) compromising the water supply for the local population; b) decrease in the volume of the habitat available for the aquatic fauna; and c) disappearance of highly regarded landscapes. It is important to notice that any change in the quality of subterranean waters directly affect the water supply for the population settled around a quarry.

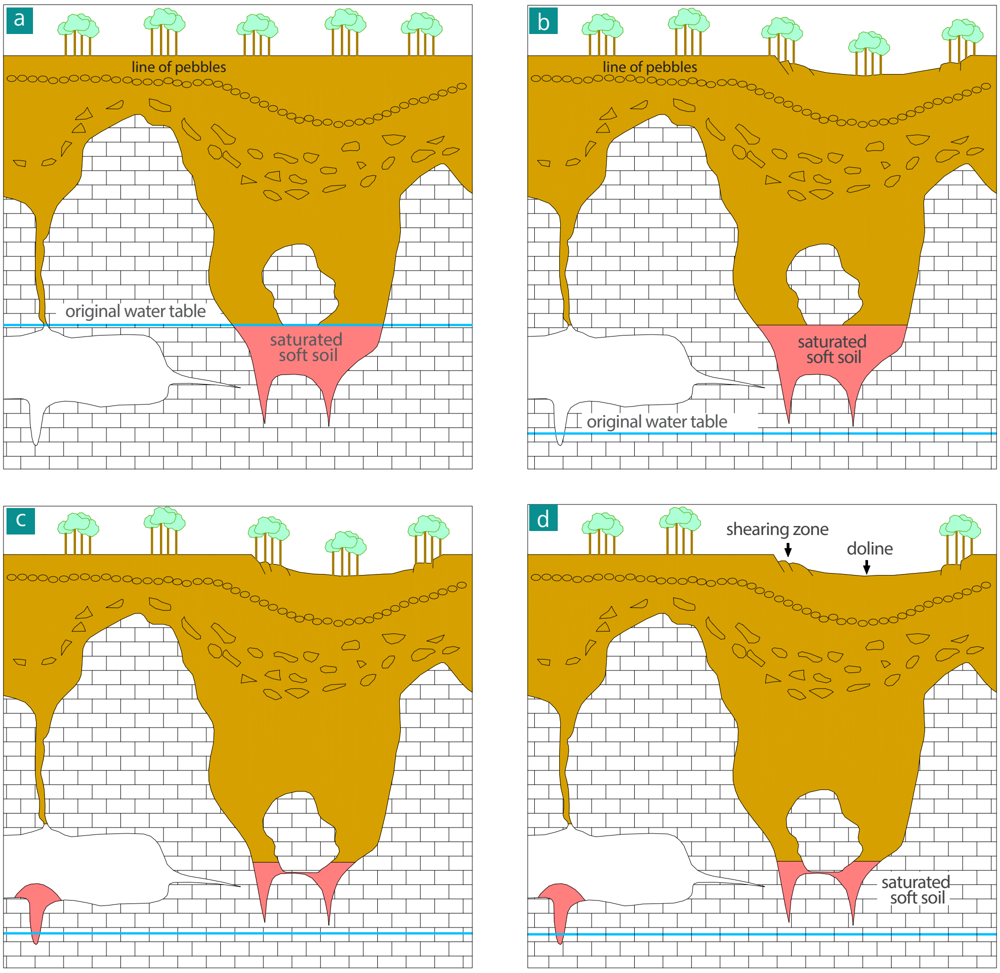

Figure 6. Mechanisms that form roof subsidence dolines due to soft soils originated from ancient dolines. Assembling: Ana Neri. Illustration: Mirna Mangini.

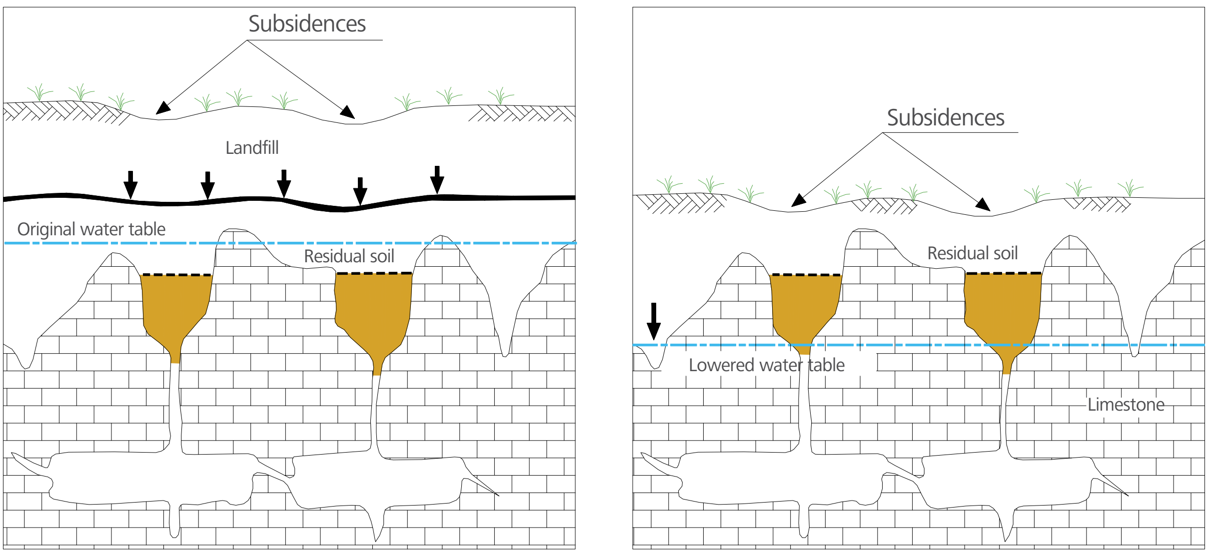

Figure 7. Mechanisms that form roof subsidence dolines due to soft soils caused by leaching. Assembling: Ana Neri. Illustration: Mirna Mangini.

The first seen impacts from quarrying activities are the ones related to the changes in the landscape and in the endokarst and exokarst formations. In addition, the extraction of limestone may also destroy caves and other limestone deposits, many of which are valuable for scientific purposes. To name a few examples of destruction, we can mention Mt. Etna in Queensland; Quarry Cave in Weardale, England, where 400 meters of caves (passages) were destroyed; and Eldon Hill Mine, in Peak District, England, where cave passages and important sediment deposits have been destroyed. In Brazil, there many cases of total or partial destruction of caves because of quarrying activities. It is worth mentioning Trevo Cave (Sete Lagoas), Agonia Cave (Itacarambi), Igrejinha Cave (Ouro Preto) and Eden Cave (Pains), all located in the State of Minas Gerais (Piló, 1999), and the total destruction of Lapa Vermelha de Lagoa Santa, an important archeological and paleontological site, which was studied by Peter Lund in the mid-19th century.

3.5. BIODIVERSITY STUDIES

Whether the aim of a project is the preservation of an area or its recuperation, it is fundamentally important to know its original condition. Even when the objective is to restore an area for a different use, a good practice should be to establish how different it is from the one that has been removed. Such acknowledgement necessarily derives from studies based on strong scientific criteria included in a previously established project.

The first step into the study of regional biodiversity is to identify and describe the phytophysiognomy, which can be done using updated maps, but remote sensing is the best method, crossing as many available databases as possible both analogical and digital ones. The databases must be checked against the project´s field data, so that a precise, detailed and realistic picture is revealed. Next step is to collect the floristic and faunistic taxonomical data.

The criteria for the collection, identification and sampling sufficiency are the ones discussed in details in Chapter 4 (Subterranean Biology), item 4.5 (Study of the Subterranean Biota). In the afore mentioned chapter, it is highlighted that it is necessary to perform tests to check the sampling sufficiency as it is important to have a periodical sampling (3-4 collections regularly distributed in the annual cycle in order to cover all seasons)during at least three annual cycles to understand the seasonal patterns of how the ecosystems works.

Generally, environmental studies emphasize the survey of the vertebrate fauna, mainly mammals and birds, and most of such studies are restrained to that, what makes them very limited. A good study should encompass the largest possible number of taxa, including indicators of the integrity of all habitats. Arachnids are one of those bioindicators (most of the orders include predators, while harvestmen, highly hygrophilous, are indicators of well-preserved forests) and aquatic insects like juvenile forms of ephemeropterans and trichopterans, which indicate pristine waters. The fauna of anuran amphibians is well acknowledged to be sensitive to disturbances and promptly reacts to them with a rapid decline in its diversity.

The methods used for faunistic surveys in karst areas are the same ones used anywhere else, and are under the responsibility of the biologist conducting the study. As outlined by Silveira et al. (2010), it is fundamental to use other complementary methods, especially in long-term studies with samplings in different seasons of the year. Using case studies, the mentioned authors show the dangers of drawing conclusions from insufficient data, based in partial and short-term studies.

All the above advice is also applicable to studies of the vegetation, which must count on specialists on botany to support them. Those methods are basically the same applied to other biomes, and the technics of collection and preservation of the vegetal species (exsiccates) are the usual ones for the taxon.

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CHAPTER 4:
SUBTERRRANEAN BIOLOGY

Eleonora Trajano

4.1. THE SUBTERRANEAN ENVIRONMENT

Subterranean Biology, or Speleobiology, is the field of Biology dedicated to study the ecosystems that are established in the subterranean environment as well as its components, from the molecular to the systemic levels.

Subterranean or hypogean environment (they are synonyms, coming from Greek “hypos” meaning under and “geos” meaning earth) comprises a set of inter-connected underground spaces, of various sizes (since small fissures to large conduits and salons), forming large networks of heterogeneous spaces, that may be filled with water or with air. These networks of continuing spaces may be formed in massive rock, especially the soluble ones, like limestones, but also in relatively deep deposits of sediments, like the ones found in the margins and under rivers or lakes (hyporheic and interstitial media). The spaces between the rocks are extremely variable in size, especially in limestones, where some fissures tend to enlarge more than others because of the water activity. The ones that have been so enlarged, so that a human being can pass through them and enter the subterranean realm, are called caves. Caves are “windows” to that intriguing world. Nevertheless, it is important to understand that they are just a little piece of the subterranean realm, which goes forward through small cracks that can be penetrated by small organisms (meaning, all invertebrates and many vertebrates, including fish). Those organisms may freely transit between the caves that are accessible for human beings (or macro-caves, under the view of the subterranean biology) and smaller spaces (meso and micro-caves). Caves are not isolated units, but they are connected to other subterranean habitats, establishing a unique functional system.

Therefore, the spatial unit “cave” is an element of a habitat that is defined in an arbitrary and anthropocentric way, based on the size of a sole species, i.e. the human species, without having a biological meaning by itself. For each species, depending upon the organism size and mobility,, “cave” i.e., the accessible subterranean habitat would be a different set of spaces, usually much wider than human cave systems since the great majority of species are smaller-sized than the human one. It is important to mention that, from the evolutionary point of view, the human presence inside caves evolutionary is very recent, sporadic and irregular, without the possibility of co-evolution with other components of the subterranean ecosystems. The human presence always causes impacts, which in terms of conservation must be weighed case by case as to the cost and benefits to the system.

In this regard, the biogeographic subterranean unity corresponds to a continuing habitat unit, either being a system for aquatic fauna or a rock massif for the terrestrial fauna. As a matter of fact, many highly specialized subterranean communities are known from non cave areas, both in karst as in non-karst areas; these communities become accessible to humans when boreholes, mines, wells and other artificial entrances are open.

Although humans are not important for the survival of cave ecosystems, caves are relevant in various aspects for mankind. At first, the scientific relevance will be highlighted. By its own definition as subterranean spaces where humans can get into, caves provide access, even a limited one, to the subterranean realm allowing the collection of data about these ecosystems and their composition, structure and operation.

4.2. STRUCTURE AND FUNCTIONING OF THE SUBTERRANEAN ECOSYSTEMS

In contrast with the surface realm, the subterranean environment is characterized by the permanent lack of light (except near the points of contact with the exterior, i.e., the twilight and the entrance zones) and tends to an environmental stability, due to the buffering effect of the surrounding rock.

Inside the subterranean realm, the primary production is restricted to chemoautotrophic microorganisms that use chemical energy from simple molecules of iron, sulfur, nitrogen etc., minerals available in most caves (known as iron bacteria, sulphur bacteria, nitrobacteria etc.). Iron is a very common element in soils and nitrogen comes from excreta of trogloxenes (see below) like bats. Sulfur usually comes from outside the carbonate massif carried in by the running water. Those kinds of bacteria demand special conditions to proliferate and very rarely form large biomasses that could bear, by themselves, a rich and diversified subterranean community, as observed in Cueva de las Sardinas (or Villa Luz), in Mexico, or in Movile Cave, in Romania. In Brazil, there is not a known example.

The vast majority of the subterranean ecosystems depends on the energy and matter derived from photosynthesis, therefore from the external environment, with the nutrients being imported from the surface in various different ways. The running water is one of the most common and important mean of transportation into caves with perennial or temporary water bodies. Flash floods drag logs, parts of living plants, vast quantities of vegetal debris and animals. Percolating water carries both dissolved and particulate organic matter as well as animals from the surface. Gravity also plays an important role, when animals fall from karst windows and openings of dolines and pile up under them. Trogloxenes (see below), both vertebrates and invertebrates, contribute not only with their feces but also with their own bodies, mainly in dry caves. Roots that penetrate into the superficial caves provide support for specialized communities, and even spores and pollen suspended in air currents that penetrate the caves contribute to the nutrient intake.

Figure 4.1 is a simplified diagram of the food web in a hypothetical cave in the karst area of the Upper Ribeira River Valley, in São Paulo, Brazil, comprising all the diversity of typical subterranean habitats of that region, for instance, aquatic environment composed by creeks, sediment banks that receive organic matter from moderate seasonal floods, small colonies of itinerant bats. This example of cave supports a high taxonomic diversity, i.e., a community composed by representatives of the high-level taxa (orders, families) found in the set of caves located in the region. Among the caves in the Upper Ribeira River Valley, the Areias System, is the closer to this condition. It comprises the Areias de Cima, Areias de Baixo and Ressurgência das Areias da Água Quente and is a spot of high diversity of troglobites (so far 24, the highest number in Brazil - Trajano et al, 2016) (for more information see Trajano, 2007 among others).

Even when considered as an ensemble, those food sources available for the animals that live in subterranean habitats are generally scarce when compared to what is available in the epigean habitat. A remarkable exception are the so called “bat caves” where there are big and stable bat colonies, that stay in the cave for long periods of time depositing large quantities of guano (accumulated feces) that are available as a source of energy for other subterranean organisms, basically invertebrates. However, those caves are relatively rare, as observed in Brazil.

Subterranean ecosystems, in general, are highly dependent on nutrients from the surface, which can come from large or small areas, sometimes from a long distance of the caves. Bats that produce guano (a food source and substrate for many cave organisms), may have large and seasonably variable foraging areas, which can go well beyond the karst areas. This is why studies on the landscape ecology are so important. The recharge areas of the aquifers and the system dynamics vary according to each case (see Chapter 1). Therefore, each hypogean ecosystem is under the influence of an area whose extension depends upon a series of factors, such as the connections of their food web with the external variables, including hydrology, climate, population ecology of trogloxenes etc., which may fluctuate annually and infra-annually (cycles with periods shorter than one year).

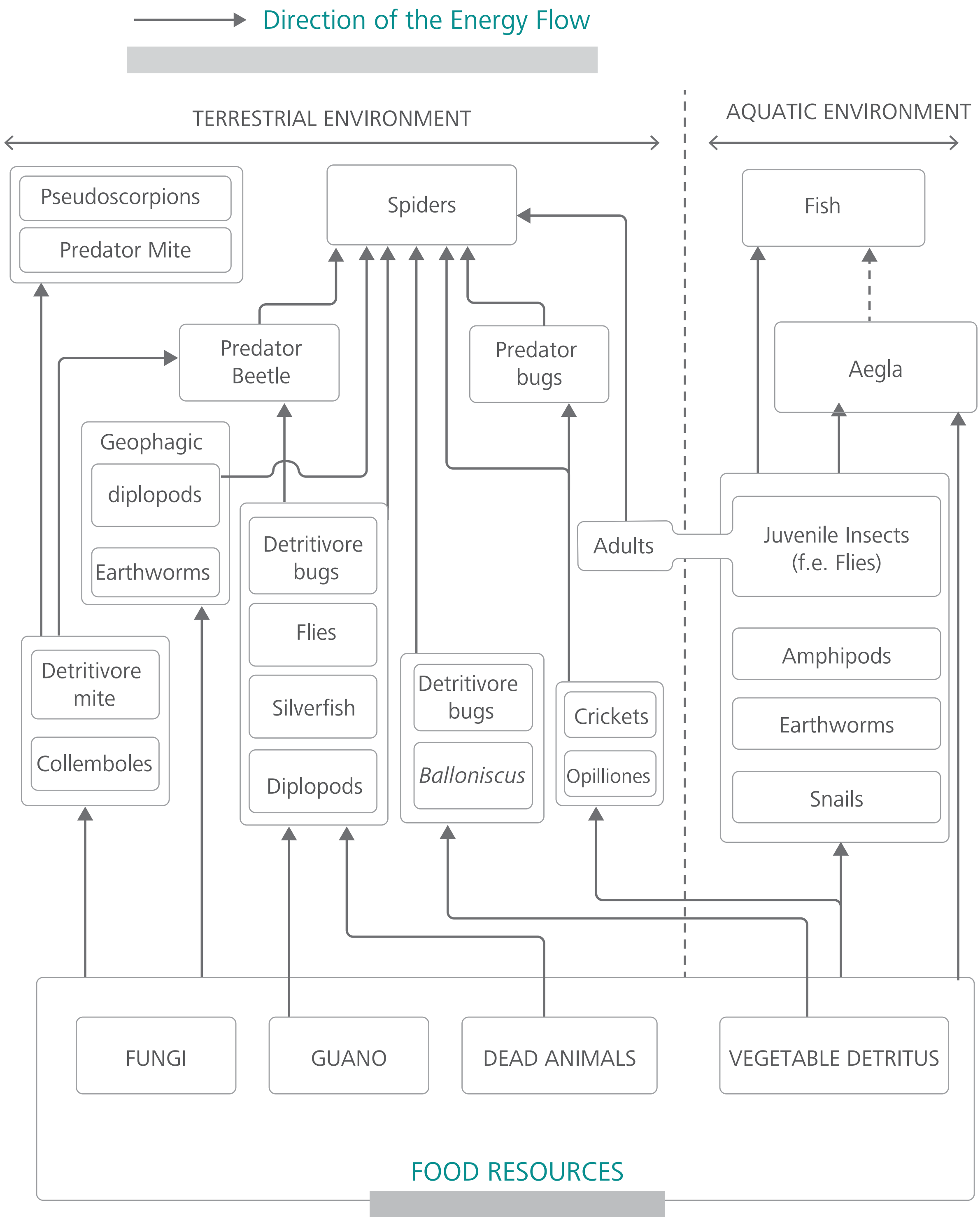


Figure 4.1. Simplified diagram of the food web in a hypothetical cave in the karst area of the Upper Ribeira River Valley, Southeastern São Paulo, Brazil. The arrows indicate the direction of the energy and carbon flows.

The characteristics of subterranean environments provide living conditions that are quite different from the ones found on the surface and impose harsh conditions for the survival of epigean populations. Therefore, not all the populations that live in a given region with a developed hypogean habitats are able to effectively colonize them, i.e., to live and reproduce for many generations, generating well-established populations. Epigean nocturnal animals or the ones living in permanently dark habitats, like crevices, under rocks, amid the foliage, in the ground or in murky waters are more likely to colonize subterranean habitats successfully. They are not exclusively dependent on their vision to locate themselves topographically, to find food as well as mates to reproduce. A generalistic diet, i.e., including a wide variety of food (omnivory, detritivory, or carnivory) is advantageous to colonize subterranean environments., That is the case of catfish, among fish, as well as many arachnids (as spiders and harvestmen) and insects as crickets, among terrestrial arthropods. Some characteristics are selected as a result of a given way of life (for instance, nocturnal activity) but by a coincidence of conditions (in this case, lack of light) are favorable to adopt another way of life (subterranean life), which is not related to the first one. Those characteristics are called pre-adaptations (or exaptations).

4.3. ECOLOGICAL – EVOLUTIONARY CLASSIFICATION OF SUBTERRANEAN ORGANISMS

Subterranean organisms are the ones that maintain a defined ecological relationship with this habitat that encompasses part or the whole habitat of the species. At least, those organisms can orient themselves topographically in the darkness.

Subterranean organisms are usually classified into three categories in an ecological-evolutionary meaning (independently of the taxonomic classification), as they were firstly proposed by Schiner in 1854, with some changes made by Racovitza, in 1907. In the following paragraphs, we present the classification from Schiner-Racovitza modified by Trajano (2012) to fit the source-sink population model (source populations are self-sufficient populations that continue to grow even if they isolated from migrant sources, contrary to sink populations that become extinguished once isolated):

1) Trogloxenes – individuals regularly found in subterranean habitats but they need to move periodically to the surface to complete their life cycle. In general, the limitation that forces trogloxenes to go to the epigean habitat is food, which in a hypogean habitat is not enough to fulfill the needs of the specie. The best-known trogloxenes are bats, that leave the caves every day to feed outside, but several other vertebrates (small mammals, otters, water rats) as well as invertebrates (some species of harvestmen, Pholcidae spiders and Noctuidae moths, in Brazil) are also in this category, which includes organisms that hibernate (bats in temperate zones) or stow in caves (frogs, flies, some harvestmen in dry and hot zones in Brazil), and those that reproduce and/or spend part of their life cycle in the hypogean, especially during the juvenile stage, when they are more vulnerable and benefit from the better conditions for protection inside caves. Some trogloxenes, called obligatory trogloxenes, also must spend part of their life cycle in the subterranean habitat, therefore, they depend on the integrity of both environments for the species survival. This is the case of the harvestman *Acutisoma spelaeum*, from the Upper Ribeira karst area, in São Paulo, Brazil. These animals can be seen in great numbers at the entrance and twilight zones of several caves, where the females protect their eggs attached to the walls (Figure 4.2).

Figure 4.2. Harvestman, *Acutisoma spelaeum*, obligatory trogloxene, a typical inhabitant of the twilight zone and the surroundings of caves in the Upper Ribeira karst area, Southeastern Brazil; female tending its eggs. Photo: courtesy Renata Brandt.

2) Troglophiles – source populations either in the epigean as in the subterranean habitat, with individuals commuting between these two habitats and promoting the genetic flow between the respective populations, thus keeping a connectivity between them. This is the reason why the individuals from the surface and the subterranean populations are taxonomically indistinguishable among themselves, i.e., they are recognized as belonging to the same species. Nevertheless, troglophile populations can be ecologically distinct from the epigean population, with their own populational parameters (population density and structure, growth rate, etc.) in response to the special conditions of the hypogean habitat. Most of the Brazilian cave organisms, both aquatic and terrestrian, are troglophiles, including representatives of several taxonomic groups, like most orders of hexapods (the commonest being springtails and insects such as crickets, coleopterans, dipterans, trichopterans, cockroaches in warmer regions), myriapods (mainly diplopods), crustaceans (oniscoid isopods, amphipods, aeglas), arachnids (mainly spiders from various families, like the wandering ctenids – Figure 4.3 –,harvestmen, pseudoscorpions), oligochaetes (earthworms), planarians, etc.

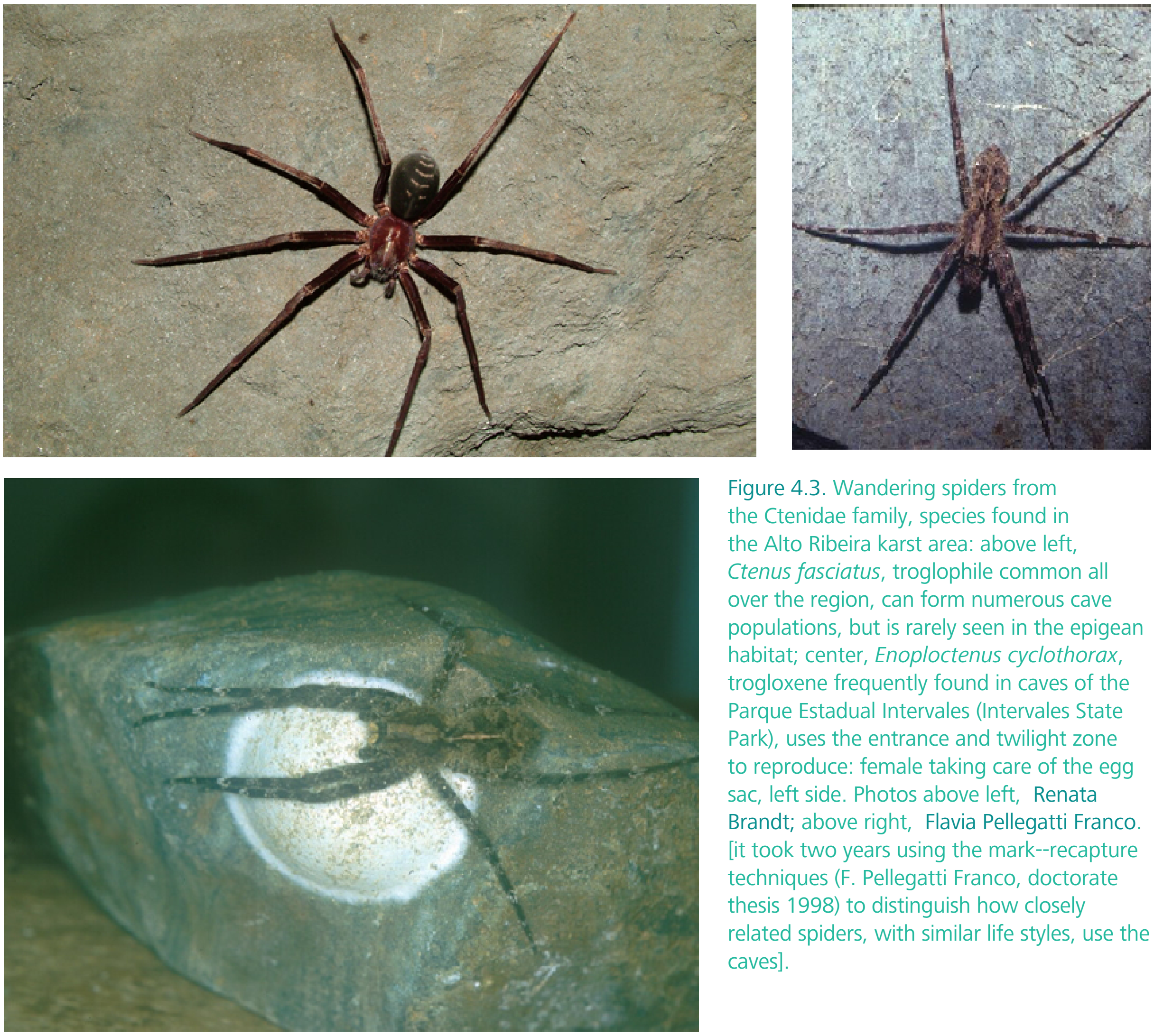


Figure 4.3. Wandering spiders from the Ctenidae family, species found in the Alto Ribeira karst area: above left, *Ctenus fasciatus*, troglophile common all over the region, can form numerous cave populations, but is rarely seen in the epigean habitat; center, *Enoploctenus cyclothorax*, trogloxene frequently found in caves of the Parque Estadual Intervales (Intervales State Park), uses the entrance and twilight zone to reproduce: female taking care of the egg sac, left side. Photos above left, Renata Brandt; above right, Flavia Pellegatti Franco. [it took two years using the mark--recapture techniques (F. Pellegatti Franco, doctorate thesis 1998) to distinguish how closely related spiders, with similar life styles, use the caves].

3) Troglobites – exclusively subterranean source populations, endemic to subterranean systems or continuous karst areas, because the individuals, highly specialized to the hypogean life, do not survive for a long time in the epigean habitat and cannot disperse through the surface. It is generally accepted that the majority of the troglobitic species originate from troglophile populations genetically isolated in the subterranean habitat. These populations evolve under a selective regimen quite different from the one on the surface. Without the influx from the epigean population genes, they gradually diverge and accumulate specializations that will ultimately make it impossible to live out of hypogean habitats.


Figure 4.4. *Litoblatta camargoi*, from the Chapada Diamantina karst area, Bahia State, Brazil, this is the first troglobitic cockroach recorded in Brazil. Those animals do not have the melanic pigmentation, and the light brownish color, which is very typical of troglobitic insects, is provided by the chitin that makes up the exoskeleton. Photo: Alexandre Camargo.

Among the specializations of the troglobites, the more common and recognized ones are the reduction until complete loss of visual structures and the dark cutaneous pigmentation. Such reduction must always be considered in comparison with the condition observed in epigean relatives, i.e., it is a state of a character that resulted from an evolutionary process of regression, after the isolation in the subterranean habitat. As the ancestral population is lost in the past, the method foresees the comparison with the closest living epigean relative. Characteristics of troglobites that are exclusive of these species (autapomorphies) and which may be associated to their particular way of life are called troglomorphisms. Just like in the case of the troglophiles, there are examples of troglobites in almost all high level taxonomic animal groups including planarians, mollusks, all groups of arthropods, fishes, etc. There are troglobites in various kinds of subterranean habitats, both in karst and non-karst areas (that is the case of the catfish from the genus *Phreatobius* found in sedimentary areas in the Amazon Basin).

Figure 4.5. *Phreatobius cisternarum*, phreatic species distributed around the Amazonas River Delta, reached through wells and cisterns. The reddish color is provided by the hemoglobin, visible by transparency, indicating an adaptation to life in waters with a low concentration of oxygen. Photo: Janice Muriel Cunha.

It is important to remark that, in non-subterranean habitats that share biologically fundamental characteristics with hypogean habitats, such as the absence of light (for instance in the soil, the bottom of large rivers and oceans, or even the habitat of endoparasites, there are species displaying some characteristics that, in subterranean habitats, are called troglomorphisms, especially the reduction of eyes and melanic pigmentation.

This is very common in animals that live in the soil, like diplurans (a "silverfish" look alike), some chilopods (predator myriapods) and small spiders, etc. Therefore, it is noteworthy that just the observation of troglomorphisms is not enough to attribute the status of troglobite to a subterranean organism: it is necessary to compare it with its epigean relatives, to verify if it is not one the above-mentioned cases. This procedure requires going beyond identifications based on morphospecies, positioning it in the classification according to the state-of-art of the systematics of the group, and to understand the phylogeny to have a proper comparison.

It does not mean that a representative of a troglomorphic epigean group found in a subterranean habitat is not a troglobite. A troglomorphism, by itself, is not a criterion to define the status of an organism. It requires a conceptually proper criterion, which is not the non-occurrence in the epigean habitat (an absence is impossible to verify from a logic point of view, but can be statistically applied). The same way, and according to this same criterion, not every troglobite, i.e., species with an exclusively subterranean source-population, is troglomorphic. These criteria have important implication on fauna surveys that cannot be restrained to study hypogean populations.

The transition from troglophile to troglobite, as a result from the evolutionary process, is irreversible. What may occur, during the divergence in isolation, is that the process of differentiation does not affect the reproductive characters, and the complete reproductive isolation may not be reached. In this case if a latter secondary contact with epigean populations little modified in relation to their common ancestor happens, these fish may reproduce producing a hybrid population, with intermediate characteristics. There are some examples, like the blind fish, *Astyanax jordani* (Characiformes: Characidae) from Cueva la Chica, Mexico.

If the transition troglophile-troglobite is irreversible, the same is not true for troglophiles and trogloxenes. In general, the limiting factor that determines that trogloxenes must periodically leave caves to complete their life cycle is. However, in caves with an exceptionally high food availability, animals that are usually trogloxenes can establish troglophilic populations. In Brazil, spiders of the genus *Mesabolivar* (Pholcidae), are common trogloxenes observed on the walls in the twilight zone of caves all over the country, in rich sandstone bat caves in the Altamira-Itaituba karst area Pará State, they establish large troglophilic populations. That is, the distinction between troglophiles and trogloxenes is not evolutionary but it is basically ecological. In fact, it can be very difficult to unquestionably classify subterranean populations into one of the aforementioned categories, which are basically distinguished by one subtile characteristic: troglophiles can leave the subterranean habitat, whereas trogloxenes **must** leave. Other than this, as mentioned above, the same species **can** form troglophilic populations under given circumstances, and trogloxenic populations under different circumstances. In the practice, it is necessary to study each case based on solid experience and knowledge on both taxonomy biology and ecology of the populations, to be able to classify subterranean organisms according to the Schiner-Racovitza system (Trajano and Carvalho, 2017).

In a visit to any cave, it is possible to find organisms that are there by an accident, they may have been carried by water, fallen through an upper opening, or may have entered the cave in search of a milder habitat ("accidentals"). As they cannot orient themselves in the complete darkness to find their way out and are not adapted to the subterranean life, they do not survive there for a long time.

From the evolutionary point of view, subterranean organisms (*cavernicoles sensu latu*) may be defined as evolutionary units responding to subterranean selective regimens, which are typical of the hypogean realm. For the cavernicoles, these habitats would provide resources, e.g. food, shelter, substrate, climate, which affect their survival and reproductive rates. Such units have a historical connectivity through the ages, therefore they can be classified as being systematically meaningful biological systems. In contrast, accidentals are evolutionary *culs-de-sac*. From an ecological point of view, accidentals are potential resources for subterranean organisms (food, substrate etc.). Resources *per se* have no historical connectivity (that is what characterizes evolutionary units recognized as taxa). When an organism becomes a resource, it makes no sense to classify it taxonomically, identifying species or higher categories. A biologically meaningful classification of a resource would be done according to its availability, nutrition value etc. That is, the concept of “accidental” has a different nature from that of troglobites, troglophiles and trogloxenes, therefore should not be included in the Schiner-Racovitza system (Trajano et al., 2012).

It is important to highlight that trogloxenes, troglobites and troglophiles interact. They are interdependent and equally important from the ecological point of view, and contribute to the biodiversity, not only the taxonomic (including phylogenetic and functional too) as well as genetic, morphological, ecological ones. Therefore, they should also be the focus of attention and care for conservational purposes, once they represent the results of special processes and ecological patterns. That meaning that even in the absence of troglobites, the subterranean communities should be cared and preserved.

4.4. IMPORTANCE AND SINGULARITIES OF THE SUBTERRANEAN ECOSYSTEMS

Every ecosystem is the result of the interaction of historical and present day ecological factors. Those factors include the geological and geomorphological evolution of the region; the regional climate and its history; opportunities of colonization, dispersion and isolation; hydrology and connectivity; topography (there are no two identical caves); habitat heterogeneity and its proportion; proper food sources available to different species; and the set of species interacting between themselves and their relative abundance, etc. Ecosystems are also subjected to random and unpredictable variables.

Due to the multiplicity of variables that are involved, each cave ecosystem is unique, just like individuals that share the general patterns of their species with their co-specifics, but can be distinguished from everyone else because their particularities. One evident case of singularity is the existence of caves with exclusive troglobitic species. Less evident, but as relevant as, is the case of caves with troglobitic species whose distribution goes beyond its topographic limits. Even in the latter, each individual population may be fundamental for the maintenance of the genetic variability of the species as a whole (which is directly related to its capability to adapt to new situations). The integrity of these specific populations also depends on the minimum effective size required to the maintenance of the species.

Caves where there are no records of troglobites are also unique because they host different ensembles of species that interact in a particular and distinct way. In fact, the differences in the relative abundance of populations, together with the richness of species, can result in functionally distinct ecosystems. This assertion was evident in the speleobiological studies carried out in 2009 for the management plans of 32 caves from three State Parks in the Alto Ribeira karst area, State of São Paulo, Brazil, (Lobo et al, 2013): the composition of the fauna was not coincident in two caves, even when troglobites and other rare species were excluded (E. Trajano, F. Pellegatti Franco, M.E. Bichuette, unpubl. data). In conclusion, in faunistic and functional terms, each cave ecosystem has its own particularities.

As aforementioned, it is generally accepted that the majority of the troglobites are originated from troglophilic populations that were isolated in subterranean habitats, either by the extinction of the epigean populations (e. g. as a consequence of severe climate fluctuations) or by the occurrence of geographical, geological, topographical and/or hydrological barriers. Subterranean populations are generally small, because of the fragmentation of the subterranean habitats geographically restraining dispersion (hence the high degree of endemism), associated to the low availability of nutrients. Small populations evolving in isolation, mostly under a selective regimen quite different from that of the original population, tend to differentiate very quickly (bottleneck-effect). Consequently, these species accumulate many specializations (autapomorphic states of characters), as in the case of many troglobites.

Among the most conspicuous and acknowledged specializations of the troglobites, there is the reduction until, total loss of visual organs and of dark pigmentation of the tegument, generally melanin. All though those changes are not exclusive of subterranean animals and may occur in other aphotic habitats, like deep soil, bottom of big murky rivers etc. As evolution is a continuous process and the time lapse since the beginning of the isolation, as well as the rates of divergence, vary according to the population, it is possible to find troglobites in different evolutionary stages of eye and pigmentation regression: since populations without any trace of photoreceptor structures (including eyes, ocelli and, in vertebrates, the photoreceptor part of the pineal gland) and pigment, to species featuring a little, but significant, reduction of eyes and/or pigmentation. There are some populations showing a high variability in those characters which may display a mosaic of conditions, including individuals with slightly reduced eyes, others totally depigmented without eyes, others with eyes but depigmented and so on. Even they are not as spectacular as the most specialized troglobites, species in intermediate stages are fundamental for comparative studies and have a high scientific value, and therefore they should be the object of conservation procedures.

As an answer to similar selective regimens, at least with respect to the permanent lack of light, organisms far related such as planarians, crustaceans and fishes from different families can converge in terms of troglomorphisms, which are independently originated in each group, carrying similar features. All those species are highly important because they can be seen as a model to evolutionary studies aiming the processes of adaptation and convergence.

For decades, genetic studies have searched for explanations for the regression of characters (decreasing size accompanied by a structural disorganization and loss of function), that is not limited to subterranean organisms; one of the best-known example is the reduction of the wings in several terrestrial birds, like the flightless ratites such as the kiwi and large running birds such as ostriches, rheas, emus etc. Currently there are two main theories. The first one, the Theory of Neutral Mutations, has been in force since de 1950's. This theory states that mutations that affect negatively the structures related to vision, which would be eliminated by natural selection in the epigean habitat, are not eliminated in the subterranean aphotic habitats, where there is no difference between either having or not having eyes.

The same would be true for the dark pigmentation that protects against negative effects of light such as the mutagenic effect of UV rays.

This theory would explain the reduction of any characteristic in any organism, which loses its function in a new environment or by adopting a new way of living, like snakes losing their limbs or the extreme reduction of wings and the loss of the capacity to fly of certain birds from islands, such as the cormorant from Galápagos, and the kiwi and the kakapo (a giant parrot) from New Zealand. On the other hand, based on studies, but with just a few troglobite species, it has been proposed that such a loss would be the result of a tradeoff compensating the development of structures that are positively selected in the subterranean (Pleiotropic Theory - for instance, the loss of the eyes in Mexican *Astyanax* cave fish would allow the increase in number of taste buds). The problem with this theory is that it lacks the necessary generality to explain any kind of regression. The most important thing is to appreciate the importance of troglobites in studies aiming general evolutionary processes, which inclusively affect the comprehension of the human evolution. For example, what does the accentuated decrease of melanin of the skin mean as a characteristic of the Nordic Paleo-Europeans? Is this a kind of neutral character or was it selected? Furthermore, does this characteristic provide any specific advantage to the population, or is it just a part of a mosaic of specializations to a new environment?

Other regressive characters of troglobites could also be framed into the neutralist model, since they could be explained because of the lack of the selection of adaptations to light and photoperiods, associated with the relaxation of the pressure from predation. Here are some examples: the loss of the capacity to stand environmental fluctuations, mainly the intolerance to desiccation of many troglobite arthropods; loss of the photophobia (the majority of the troglobites have photonegatives nocturnal ancestors); loss of the general phobic reactions, in general, like the habit of hiding (that makes them particularly vulnerable to disturbances like the collection of individuals) that is very common in troglobite fishes; and the regression of the mechanism of internal time control (known as the ”internal clock”). Troglobites are excellent models for studies on biological rhythmicity, an issue with serious repercussions in human behavior and physiology, and whose knowledge is very important for the quality of life of people through advances in Medicine, Psychology, etc. In addition, adaptations to the low quantity and unpredictability of nutrients availability, including the high resistance to starvation and metabolic rates lower than the observed for epigean close relatives, make the troglobites excellent models for studies on physiology of metabolism.

At the same time, troglobites may present traits that are clearly adaptive, especially the ones that emerge because of the so-called “sensorial compensation”: in face of the impossibility of using visual orientation, other sensorial systems tend to be more developed, like mechanoreception (touch, perception of vibrations in the environment) and chemoreception (perception of molecules). Therefore, non-visual sensorial structures that have chemical and mechanical receptors, like antennae and legs for arthropods, snout and the lateral line system in fishes, can be enlarged (both in area and/or length). Many specialized troglobitic arthropods have elongated appendices, slender delicate bodies when compared to related epigeans (interpreted as a strategy to save energy). Cases of miniaturization frequently occur, probably as an adaptation to life in small spaces in the subterranean realm. All together or separately, such characteristics bestow the troglobites a singular look.

The relative environmental stability is a characteristic of subterranean habitats and grants them the condition of an ecological and evolutionary refuge. In such a refuge, populations can be kept for long periods, reaching dozen millions of years, while epigean groups can totally disappear leaving behind the troglobites as their only survivors. Those organisms are called “relicts," they are highly regarded by science because they are testimonies (sometimes the only one) of their evolutionary history. In addition, the distribution of troglobites can work as a biological tracker, sometimes more efficient than the chemical ones, to delimitate subterranean systems.

Troglobitic populations present a very special ecology in view of the particular characteristics of the subterranean realm. First of all, as already mentioned, due to the fragmentation of the subterranean habitats, which present a geographic constrain to dispersion and a poor availability of nutrients, troglobite populations are usually small with a low density (all though it must be clear that those two parameters are independent: small populations may have high densities and vice-versa). Furthermore, their life cycle is much slower than their relative epigeans’, tending towards K-selected life history (or precocious life style): the reproduction is not frequent (in general the individuals do not reproduce every year), fecundity (number of descendants generated) is low, the individual growth is very slow and the life expectancy is high, therefore the populational turnover is very slow. For example, while medium-sized epigean catfish, *Pimelodella transitoria*, from the Alto Ribeira karst area, São Paulo, live around 5 to 7 years, the troglobitic close relative *P. kronei* has an estimated medium lifespan of around 15 years, in some cases reaching more than 30 years, which is an exceptional longevity for relatively small animals.

Because they live in isolation in an environment that is more stable than the epigean one, troglobites tend to lose the tolerance to environmental fluctuations, in a process similar to the one that affects the eyes, pigmentation and other structures and functions. This kind of reduction is more evident in terrestrial arthropods, which also have their capacity to resist to desiccation reduced because of the reduction of the thickness of their exoskeletons, especially the water-repellent cuticles. In very humid environments, where there is no risk of desiccation, to save energy by reduction of the exoskeleton becomes a feasible strategy.

However, this specialization becomes a liability when all sudden changes modify the environmental dynamic balance in temporal scales that are incompatible with the biological evolution. This happens, for instance, when artificial entrances are open and the air circulation is modified, altering the speleoclimate.

As a result of these specializations, the population turnover is very slow and the ability to recover from losses, either due to natural impacts or as a consequence of human disturbances, is decreased compared to epigean taxa. If the disturbing situation continues, it may lead to a rapid extinction of the population or the whole species. For this and other reasons, troglobites are intrinsically fragile, fitting the criteria for inclusion in Red Lists of threatened species, at least, in the category of Vulnerable.

The habitat fragmentation, the high degree of endemism of the species, the high evolutionary rates leading to a rapid divergence in comparison to their epigean relatives, together with the recurrent convergent evolution of characters that are subjected to troglomorphism, those are characteristics of the troglobitic fauna with very few parallels in other habitats. The closest examples are the archipelagos, which have been calling the attention on them for centuries because of the singularity of their fauna and the need of special protection. Due to processes as the founder effect and genetic drift following isolation, different subterranean populations derived from one same epigean species end up diverging, not only in relation to the epigean ancestor, but also between themselves, so that the results will always be populations that are distinct, unique and unrepeatable.

However, the troglobites are not the sole source of diversity. Troglophilic populations can also ecologically differ from the epigean populations belonging to the same species, but showing some quite different population parameters such as population density and life cycle strategies. Those populations can be an important source of re-colonizers of the epigean habitat and, therefore, should also be the focus of conservation measures.

As a conclusion, it is important to remark that biological diversity, even in small patches of subterranean environment, can be very high in terms of processes and patterns and should be a priority in national plans to evaluate and protect natural environments.

BOX 1. BATS AND CAVES

When tropical caves are compared to caves in temperate zones, the first usually present a higher total diversity, i.e., troglobites + troglophiles + trogloxenes. This result may be directly related to the high epigean diversity that can be a source of potential colonizers. In caves where bat guano is a very important source of nutrients, the variety of the diet of the tropical species contributes to the taxonomic richness, once different types of guano support different communities. In the Neotropical region (South, Central and North Americas, from Central Mexico southwards, and Caribbean), the variety of guano is even bigger. There are aerial insectivorous bats; there are carnivorous bats that capture insects and other arthropods when they are landed; bats that predate on other vertebrates, including smaller bats; specialized piscivore species; bats that are specialized in eating nectar/pollen; specialized frugivores (e.g. the majority of Stenoderminae phylostomids) and other bat species that are not so specialized but they may complement their diet with insects whenever it is necessary (e.g. *Carollia perspicillata*); omnivorous bats, that is, they consume animal and plant items; and finally the hematophagues (vampires bats, three species),which are exclusive to the Neotropical region.

On the left, an aerial insectivore from the Emballonuridae family, in a cave; photo: Eleonora Trajano; On the right, *Chrotopterus auritus*, a large predator bat that is common in Brazilian caves, where they form small groups from 2 to 6 individuals hanging from the roof; photo : William Sallun Filho.

On the left, an aerial insectivore from the Emballonuridae family, in a cave; photo: Eleonora Trajano; On the right, *Chrotopterus auritus*, a large predator bat that is common in Brazilian caves, where they form small groups from 2 to 6 individuals hanging from the roof; photo: Wilson Uieda.

Three main types of bat guano can frequently be found in Brazilian caves: 1) guano from insectivores: relatively dry guano composed by insect remains and their chitinous exoskeleton (that the great majority of the animals do not digest); 2) guano from frugivores: containing remnants of fruit pulp and seeds, it is humid when recently dropped and has high contents of sugars; 3) guano from hematophagous: it is pasty and has a high content of ammonia when recently dropped, which changes as the guano dries up. In addition, small portions of guano from carnivorous bats may be found. Differences in the structure, chemical composition and microclimate are the reason for the presence of specific species that are adapted to the specific conditions of each kind of guano, together with more generalist species that can be found in any type of guano. The organisms found exclusively in guano deposits (except when dispersing from one guano patch to another, and then as rare occurrences) are called guanobious, and the ones that may live either in guano as in other substrates are called guanophiles; both of them can be either troglobites or troglophiles, i.e., they may be strictly subterranean or they may the subterranean populations of species also living in epigean habitats(Troglophilic guanobites are found exclusively in guano also in the epigean realm).

Acherontides eleonorae, springtails exclusively found in guano (guanobites) from hematophagous bats, they might reach quite high population densities as the guano dries out. Photo: João Allievi

Different bat species use their shelters in various ways, as daytime shelters in which they spend most of their life, as well as night shelters where they can spend a brief period during their night foraging activities, to eat their food (in case of large items like some fruit) or simply to have a break to rest. Some bat species are very demanding as to the kind of shelter they prefer. Some species are very specific only using the broad leaves of certain plants. Other species, like many stenodermines, prefer the foliage at the canopy of trees. Carnivorous phyllostomid prefer rocky shelters, including caves, and some other species, which are ecologically very flexible, use whatever shelter is available. Anyway, when there is no selection for gregarious behavior to keep their temperature (as observed in cave bats in temperate zones), the high demand of energy to fly would favor an opportunistic use of shelters, so that they would guaranty a quick return from the feeding source used every night to the nearest shelter.

A study based on the mark-recapture technique, showed that the individuals of the more abundant species in the Alto Ribeira karst area State of São Paulo, southeastern Brazil, frequently move between the nearest caves, apparently in a random way and not following seasonal patterns, forming "itinerant colonies" in these caves (Trajano, 1996). Evidence show that such itinerant pattern is generally observed in areas presenting a high degree of availability of shelters, i.e., high concentration of caves. In some cases, proved by the direct observation of the bats and/or of the variation in the condition of the deposits of guano, colonies abandon the caves for long periods, sometimes years, and then return without an apparent cause or pattern. It could mean that the residence area (Trajano, 1996) of an individual, i.e., the area used for shelter and foraging during a season or phase of life can comprise a series of shelters closely located. Residence area is different from home range, which is the total area used by a bat during its lifetime, that is, the total sum of the residence areas and migration routes, should it be the case.

Therefore, the unity of a study to investigate the distribution and the ecology of bat population, mainly in well-developed karst areas, should comprise, at least initially, the several cave systems located within a radius of 6 kilometers around the caves (an average estimated foraging area for medium or highly mobile bat species). Infra-annual differences (with over an annual cycle period), without an identified pattern (if there is any pattern, studies carried out, so far, were unable to detect it), require long term studies over many years in order to make it possible to understand the space-time dynamics of the cave ecosystems associated to the presence of bats.

Metallic bands with a code are attached to the forearm of bats allowing to identify each individual and to monitor it along its lifetime, Photo: Hertz Figueiredo.

4.5. THE STUDY OF THE SUBTERRANEAN BIOTA

Contrary to the current practice, which has proven to be disastrous when the goal is to understand the functioning, importance and singularities of the subterranean ecosystems, the elaboration of faunistic lists is just the first step to study the subterranean biota. Lists are just the first, but they are a fundamental step providing the basis for all further studies that depend on their reliability to be consistent.

For this first step to succeed, it is very important to have some general principles in mind. The methods should be established according to the goals of the study. Therefore, if there are previous data about the subject and the area to be studied, the so-called secondary data, the evaluation of the need of new data, the primary data, must undergo a judicious comparative analysis. Such analysis should focus on the sampling design and the techniques to collect and analyze the data, as well as on the availability of the examples to compare with the ones that were used in the previous studies, which generated the secondary data. If there is not a total correspondence with the methods as foreseen in the new study, the secondary data may be used as complementary data, but the latter do not dismiss the need of a specific study on the established goals.

For a study to be conclusive, some conditions must be fulfilled: the sampling must be sufficient, that is, it must be representative of the community being studied; the data must be reliable and be treated the proper way; the research must accomplish with the basic principles of a scientific work, being able to be verified and repeated by any other qualified researcher. The ethical principles of transparency, capacitation of the technical team and the specific competence of the professionals for the subject of the study must be firmly observed.

4.5.1 Collection

Sampling methods applied to subterranean spaces are just the same applied to comparable epigean habitats and substrates, including lotic and lentic bodies of water, soil, rocky substracts, etc. There is plenty of literature about the collection methods that any experienced field biologist must master. In addition, for, non-cave subterranean habitats, such as the epikarst (Figures 4.6.1 and 4.6.2), the MSS - superficial subterranean environment (Figure 4.6.2), the hyporheic habitat (Figures 4.6.5 and 4.6.6) and even small bore holes that become available during mining activities, there are specific collection techniques such as filtering percolation and dripping water, Karaman-Chappuis wells, Bou-Rouche pumps, some kinds of piston pumps, different kinds of traps, and so on [11].

11 For a description of the mentioned methods, see, for example, *http://www.snh.org.uk/pdfs/publications/commissioned_reports/397.pdf*.

The high degree of endemism and slow populational turnover, which results in a low capacity to replace the population loss, together with the fragility of the subterranean habitats impose a special caution as to the collection of specimens. Over-collections in the subterranean realm have worse consequences than the ones on the surface and require special attention. It is necessary to avoid excesses as well as loosing material and/or information, for instance, for badly preserving or losing specimens, losing or mistaking labels, or providing incomplete data. Such events would make the collection useless and unjustified. Obviously, this special attention must be paid to every and each biological collection, but the risks are higher for the subterranean fauna. This is the reason why collections inside caves must be performed by biologists who are competent and experienced in the techniques required by the protocol of the study.

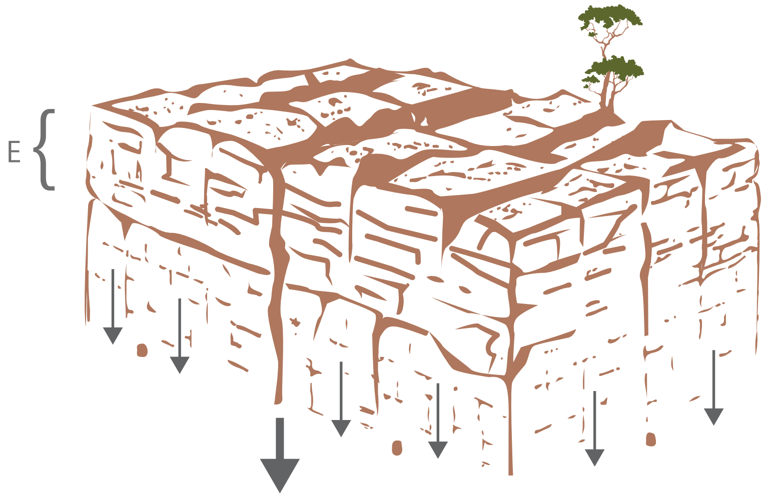


Figure 4.6.1. Diagram showing the Epikarst (E). Illustration: Daniel Borges. Modified from Bakalowicz (2004), from Mangin (1974).

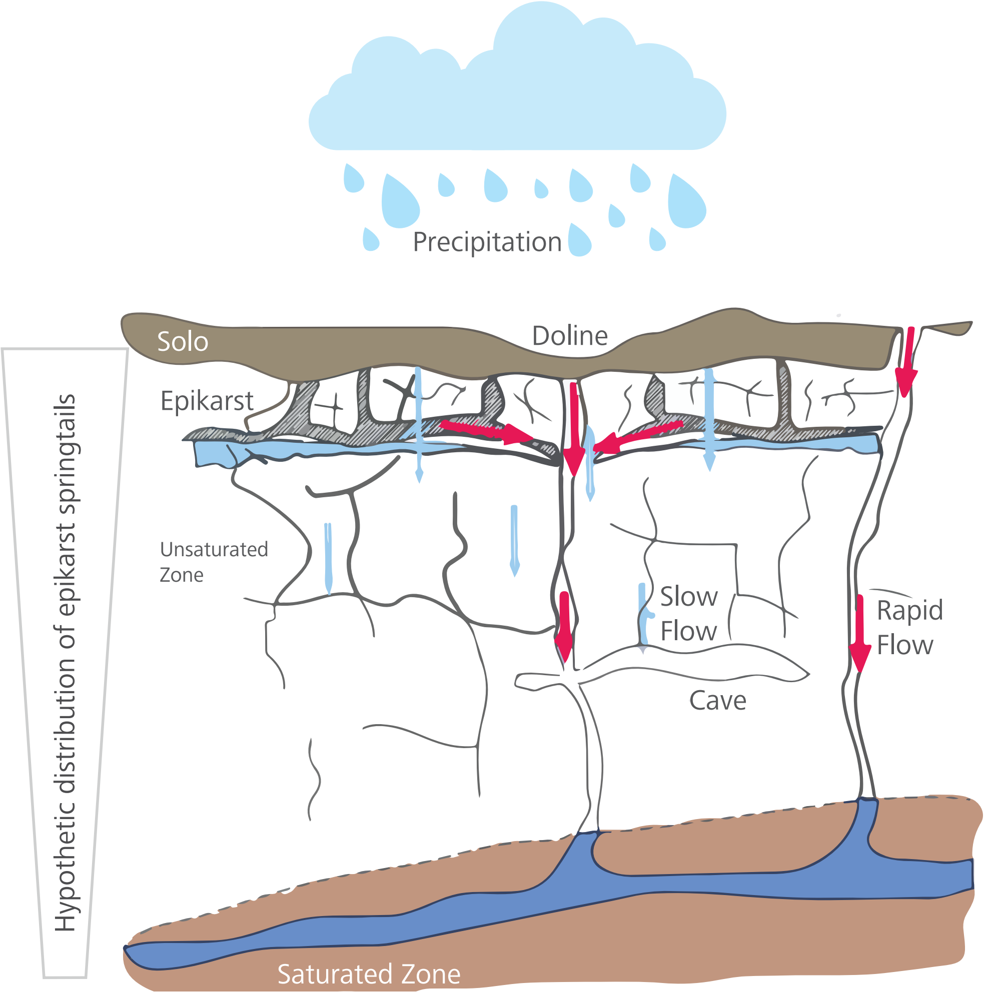


Figure 4.6.2. Diagram of the Subterranean Superficial Environment (MSS) in a scree limestone zone in the base of a limestone cliff connected to a cave system. Illustration: Daniel Borges.

Diagram of the mesovoid shallow substrate MSS (Subterranean Superficial Environment) in a gravel karst zone in the base of a limestone scarp connected to a cave system.

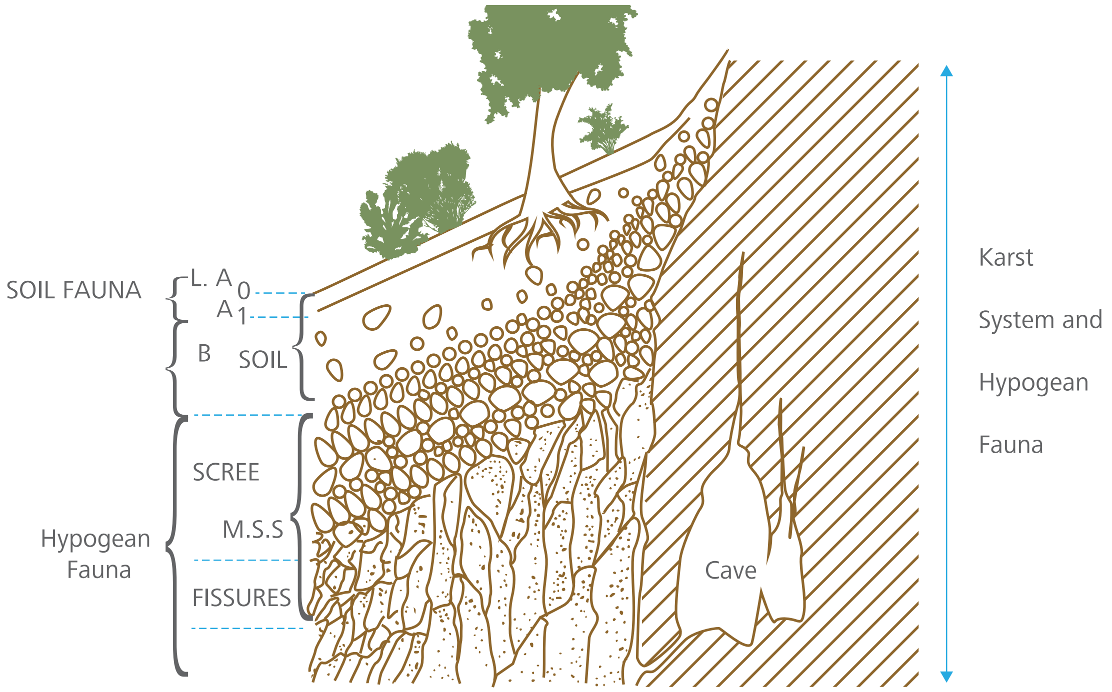


Figure 4.6.3 Diagram of the Subterranean Superficial Environment (MSS) in the Pyrenees and in the Carpathians in Romania. Illustration: Daniel Borges. Modified from Juberthie (2000).

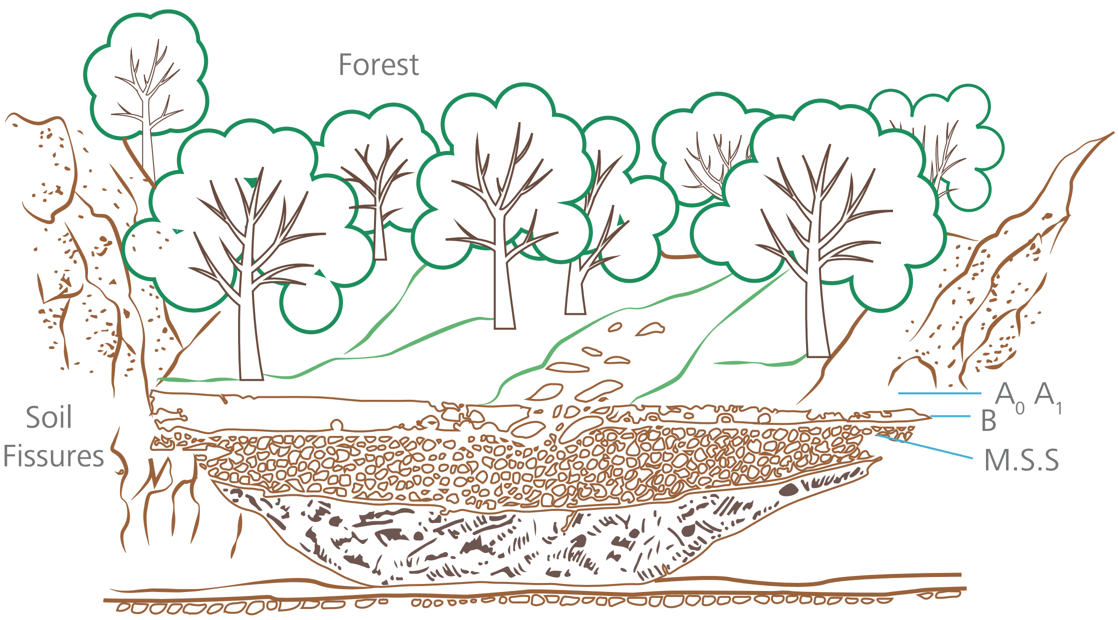


Figure 4.6.4. Diagram of the Subterranean Superficial Environment (MSS) in the Pyrenees and in the Carpathians in Romania. Illustration: Daniel Borges. Modified from Juberthie (2000).

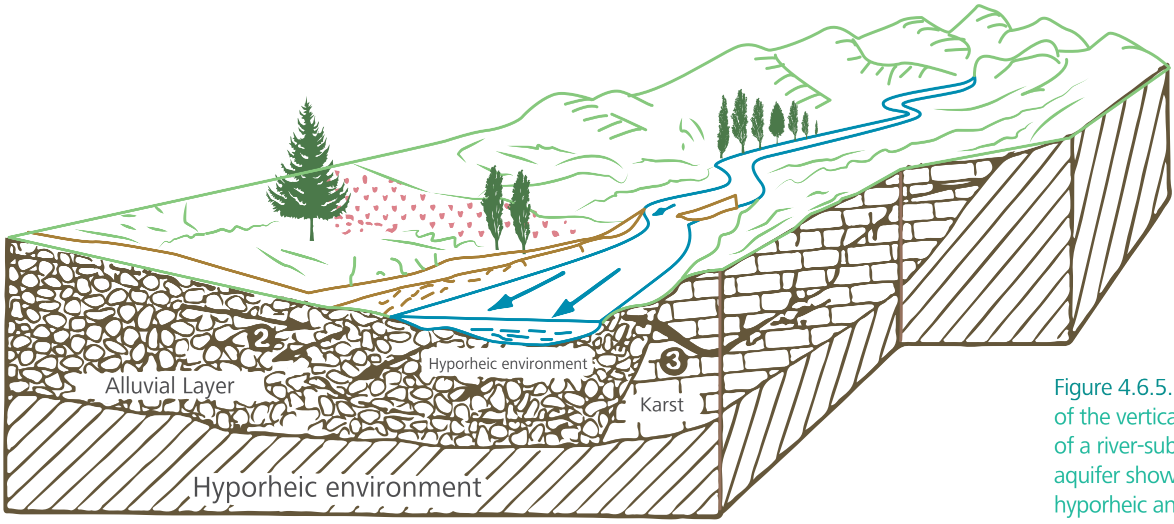


Figure 4.6.5. Diagram of the vertical structure of a river-subterranean aquifer showing the hyporheic and water table zones. Illustration: Daniel Borges.

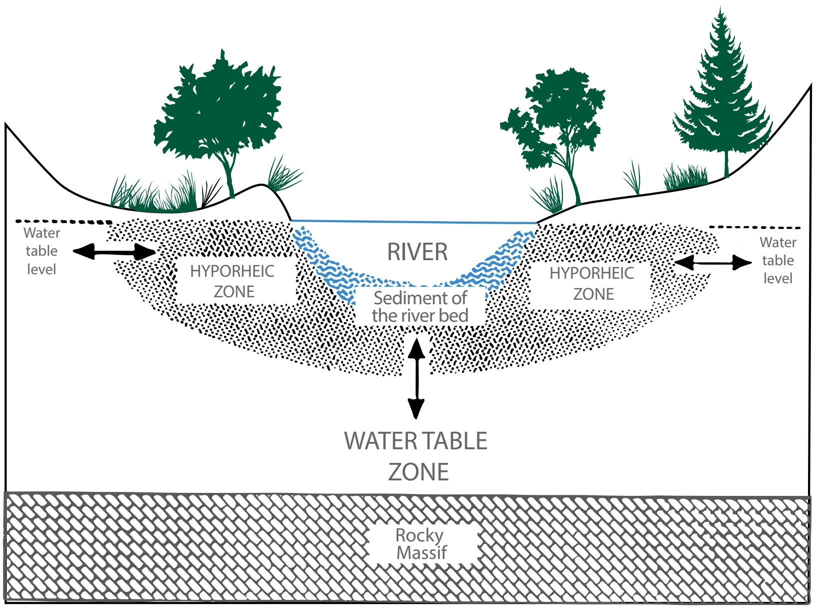


Figure 4.6.6. Diagram showing the vertical structure of a river-subterranean aquifer system showing the hyporheic and water table zones. Illustration: Daniel Borges. Modified from Ward et al. (2000).

The collector must be aware of the variations within each subgroup (sexes, age range, etc.) that are characteristic of each taxon, so that suitable samples are taken. At the same time, the collecting methods should be suitable for fragile habitats and allow a previous selection to establish the quantity of individuals to be taken out of the population. For the visual inspection, (Figure 4.7) either for the total available habitat (in the case of small caves) or for samples of it, the use of squares, transects, etc. has proven to be fully satisfactory. Most of the arthropod species can be distinguished studying the adults, generally males, and it is useless to collect very young individuals. Therefore, the collectors must be able to distinguish adults from juveniles. In threatened habitats, it is acceptable to describe the variation in the species based on few adult individuals, but only if there are no close species (congenerics) living in the same habitat. This is not trivial. Even small samples may be excessive.

It is easy to recognize excesses in absolute numbers of individuals being collected, as it is the case of about 5,880 invertebrates that have been collected from five relatively small caves in Goiás, Minas Gerais and Bahia, in Brazil, in a single visit to each of the caves; of about 4,500 aquatic invertebrates collected in a single event in a small cave (120 m. of a creek) in Minas Gerais ; or even the 3,325 individuals belonging to a single troglobitic species, the gastropod *Potamolithus troglobius,* endemic to the Areias System (Upper Ribeira River Valley, São Paulo, Brazil) and therefore listed as a threatened species.

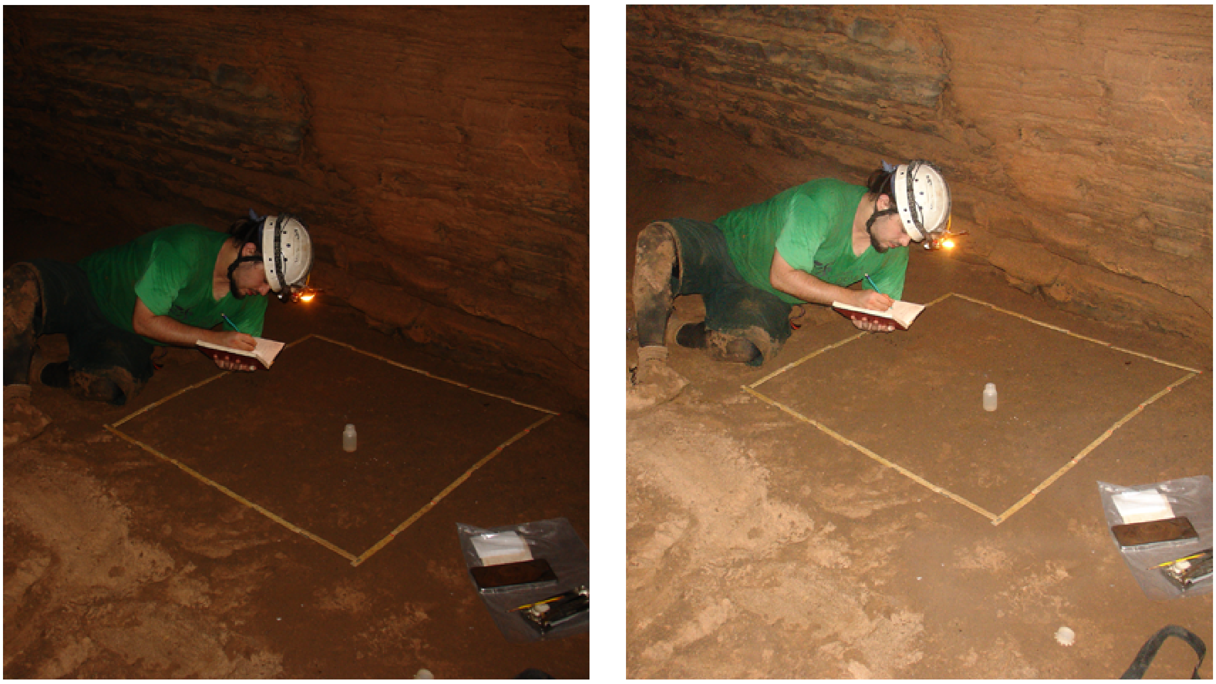
Those bad practices illustrate the importance of adjusting the collection method to each collection event. To copy experimental designs is not scientifically valid without a previous analysis of their application and appropriation. For instance, if samplings fitting the studies of caves presenting a low diversity of species are applied to richer caves, without the proper analysis, the results could be excesses like the ones just mentioned above. This is why this kind of studies require professionals who are experienced in conducting them, and who are able to make the proper adjustments, when needed.

The above mentioned excesses are frequently associated to the use of nonspecific methods, like pit fall traps, which are very damaging if left in place for a long time (it is not rare to find this kind of traps "forgotten" by researchers in caves). The same happens with Surber nets, to collect benthic organisms that are very efficient and therefore must be used very carefully. The ideal duration of the collection also depends on the previous experience of the researcher, because it varies according to the specific goals of the study, the physical conditions of the cave and the taxa aimed by the study.

It is very important to highlight that, as caves are a fragile habitat, collections must be very well justified and the populations must be monitored, because of external interferences (water pollution, insecticides and heavy metals carried by the rain, by the subterranean rivers and by the soil) as well as the impacts from the collection itself. Even small samples may prove to be excessive, in the case of small populations, species endemic to a system or to a reduced karst area, particularly when it is a source-population. Once again, an experienced researcher will establish the size of the sample that could provide a trade off between the study and the minimum necessary number of specimens that can be withdrawn causing an acceptable impact on the population. Collecting even a small number of specimens is not justifiable if the project is scientifically questionable and/or if the specimens are lost or are not available for the scientific community in general (see below).

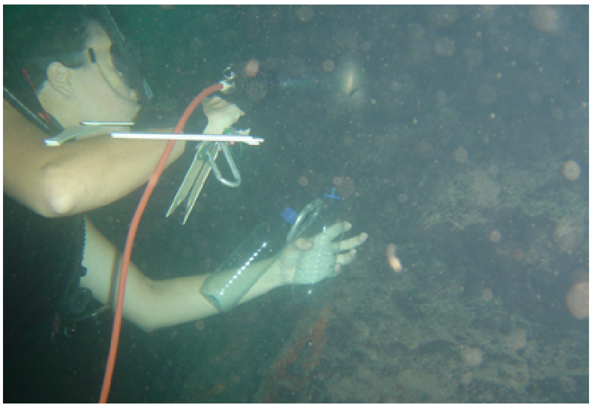
Special care must be taken to cleaning material and equipment once many diseases, especially the ones whose agents are fungi, bacteria and viruses that can be brought from and out to the external environment carried by traps, nets, caving equipment, clothing and shoes worn by the researching teams. The rapid spreading of the WNS (White Nose Syndrome), which is a very serious disease that is decimating cave bat populations in the USA, is the best example of the serious consequences of anthropic actions. Other than causing the outbreak of the disease as the organisms are waken up in the middle of their hibernation, the transit of humans taking contaminated equipment between caves has also contributed for the mentioned disease to spread.

Figure 4.7. Collection methods used to obtain samples from caves by visual inspection of the habitat: a) Hand collection of invertebrates on a wall (above to the left) and guano (to the right). Photos: Abel Perez Gonzalez.



b) Hand collection in squares marked on the soil. Photos: Abel Perez Gonzalez.

c) Collection of fish and aquatic macro-invertebrates with a hand net, inside a rimstone pool (to the left), in marginal pools (below to the left) and in a stream (to the right) Photos: Abel Perez Gonzalez.



d) Underwater collection of small invertebrates in flooded caves, by suction in a plastic bottle (to the left); using a square to visually count crustaceans (to the right). Photos: Marcos Philadelphi.

The solution to reduce the impacts of collections is not just to collect "one couple of each species", like it is mentioned in collection permits issued by Brazilian authorities, once this kind of requirement is not adherent to the understanding of the "raw material" of evolution, that is the intrinsic variability within each species. Depending upon the group, such variability is visible as small or large differences between sexes, ages and between individuals of the same age and sex. Therefore, researchers seek a balance between a certain number of individuals that can be taken out of the population causing the minimum impact, but enough to provide a robust identification, the most conclusive as possible, carried out by a specialist in the taxonomy of the group being analyzed. Therefore, the collector must be permanently in touch with specialists so that he/she acknowledges the specificity of the groups being studied.

In fact, with just a few exceptions, to be evaluated by highly experienced biologists with a wide previous knowledge about biodiversity, collections are indispensable. In most of the cases, an accurate identification of the specimens depend on the examination of the characteristics in details that require it is preserved, frequently dissected and prepared with special techniques to be observed under a microscope. Collections can only be dismissed in areas that have already been investigated, and whose material has been properly studied, is deposited in official collections thus is available for the scientific community (this latter should be a "sine qua non" condition for a collecting license to be granted). Only highly trained biologists, who are able to recognize taxa that have already been recorded, should do the identification on the field, and only for species that can be macroscopically identified.

In many cases, however, the identification even at high taxonomic levels cannot be done on the field. For instance, no expert in Collembola would risk a 100% identification of a sample of those minuscule soil "insects" at the order or superfamily level on the field. Likewise, there are not Brazilian experts who are able to visually distinguish, with 100 % certainty, diplopods from the orders Spirobolida and Spirostreptida, millipedes that include the biggest diplopods of the world. Unfortunately, this kind of bad practice results in ill identification, without the possibility of a late verification, is frequently found in environmental studies caused by lack of time or the hurry to conclude them.

4.5.2 Identification

Trustable taxonomic identifications are essential because it is impossible to protect organisms that are not identified. If it is not possible to recognize and describe the species that constitute the communities living in subterranean habitats, the attempts to understand the environmental changes will be impaired. The identification is the process to attribute a scientific name, generally a specific name, to an evolutionary unit, which is no easy task, because the name contains biological and phylogenetic information. To recognize a taxonomic unity, as well as to delimitate a species, requires a high level of specialized knowledge, once evolutionary processes, like convergence, could shadow phylogenetic relationships leading to wrong identifications. An expert taxonomist specialized in a given group is able to recognize taxonomic units with a lesser chance of making a mistake. It is very important to highlight that an expert is needed, whether or not there already is a name for the species. Only an expert can distinguish species that have not yet been described – frequently mentioned as "'name of the genus sp. nov. or more correctly as "sp. not described"- from the ones that cannot be identified at that moment because, for example, they can be included in groups that do not have a proper taxonomic resolution ("name of the genus" sp.).

It takes around 5 to 10 years to train a taxonomist in the level required to prepare faunistic lists for environmental studies. It might take even more for particularly complicated and poorly known groups. By definition, and mainly in countries presenting a huge biological diversity, just like in Brazil, there are no specialists simultaneously working with several different groups of organisms (Trajano et al., 2012).

No wonder there is a shortage of taxonomists, and this is causing troubles for the purposes of monitoring and managing species, mainly in poorly studied habitats like caves. The majority of the surveys are incomplete or even mistaken as to the taxonomic completeness and accuracy due to the "taxonomic impediment" (lack of trustable identification because of the lack of taxonomists). This taxonomic impediment explains the emergence, mainly in environmental studies, of the so-called RTU's (Recognizable Taxonomic Units), such as morphospecies and morphotypes, referred as "'name of the genus' sp." associated to numbers (sp.1, sp.2, … sp. n) when more than one species is distinguishable in the same genus. Nevertheless, the recognition and the distinction of such morphospecies are only reliable when they are confirmed by an expert because each group has its own taxonomic particularities (Trajano et al., 2012).

When the distinction of species based on morphotypes, is not done by an expert (parataxonomy, sense Majka and Bondrup-Nielsen, 2006, defined as ''groupings of similar individuals, categorized bynon–experts, relying on features of external morphology"), it is only acceptable in the sorting phase, in order to separate the groups to be forwarded to the experts, as well as to guide the study. Even so, as in the case of collections, this should only be used by biologists who are aware of the variations inside groups, and are able to recognize juvenile forms and to distinguish the sexes, so that these organisms are not considered as separated morphospecies, avoiding inflated lists. Examples of such ill practice include immature individuals being considered as belonging to a species different from the adults. Such procedure lacks a logical basis, because it is highly improbable that all juvenile forms belong to species that are different from the adults, being expected the opposite to happen. The correct procedure would be discard them, unless it would be possible to ensure the identification based on an undisputable identification confirmed by an expert.

The use of parataxonomy can result in overestimating the species richness, with an error up to 100%, depending on the group, on the sample, and on who is sorting and identifying the material, so that it is not possible to determine its margin nor to use correction indexes. Parataxonomy does not comply with some criteria of scientific methods, creating typological units without defined criteria for separation, making it impossible any falsification of the hypothesis or the repetition of the experiment. Therefore, the results of parataxonomy must be understood as the first step of studies on subterranean biodiversity, and must be used with restrictions and caution in rough comparisons of the species richness or in non-comparative descriptions of diversity in specific localities. Nevertheless this kind of data has no use in biogeographic and autoecological studies as well as in studies aimed to the selection of areas for conservation purposes. Here including environmental studies to grant the licenses for development of projects in karst areas that can result in the destruction of caves, because in these cases the studies must be absolutely conclusive as to the statistically significant improbability of the inexistence of singularities in such locations (Trajano et al., 2012).

Another common bad practice is the use of regional identification keys, which should not be used, especially for subterranean organisms. As it is a refuge (see section 4.4), it is possible, and even probable, that geographical or even phylogenetic relictual taxa are found in the caves, and those taxa will not be included in those regional identification keys. Moreover, using identification keys is just the first step because there may be new species, or species that have not been included in keys yet. Again, all identifications must be confirmed by an expert, especially in studies on areas that may be subjected to impact.

Finally, it is important to make the specimens from collections available for the scientific community and must be cared by independent curators. Institutions grant the continuity of the curator service even if a specialist leaves them. Generally, official museums offer the best conditions and can grant the access to serious researchers.

4.5.3 Sample Sufficiency

A. Number of replications:

A very important question for every biological study is to determine the minimum number of repetitions required to make a sample representative of the studied phenomena. For example, in an experiment about the biology, the behavior or the physiology of a given species, or aiming a given process, the number of replications or the sample size is the number of individuals that are observed or tested (experimentally manipulated). In a study aiming to describe the biodiversity in an area or habitat, the number of replications is the number of occasions independently of the number of samples on each collecting occasion.

It is fundamental to distinguish replications from pseudo-replications, because many environmental studies about caves are mistakenly using pseudo-replications to calculate the sample sufficiency, what could compromise the conclusions. As aforementioned, replications are independent events, while pseudo-replications refer to samples retrieved from the same subject or hierarchically organized, or even the measures spatially or timely related (Lazic, 2010), therefore related to events which are not statistically independent. For example, in the case of samplings in the same cave, in a same visit.

Usually, the so-called "collector's curve" is used to define the sample sufficiency and to estimate the number of species to be sampled. Its format is related to entry order of the sample units in its construction, generating different curves at each ordination. In addition, the relation between the axis of the abscissas and the ordinates influence the perception of a possible asymptote, the stabilization of a trend to variety. A possible solution is to use the so-called "curves of accumulation of species" (Ugland et al., 2003; Colwell et al., 2004), on which the entry order of the sample units is aleatory that results in smoothing the curve, allowing the calculation of an average and a standard deviation of the number of species in the community for each step of the study. Those curves are closely related to the rarefaction curves, from which we deduce the number of species, supposed to be found should we reduce the numbers of sample units. The elaboration of the rarefaction curves can be seen as a process of interpolation of the species richness of the total set of samples to the richness expected for a sub-set of the samples. As they are eager to estimate the number of species in a given community, many researchers wrongly try to visually find a possible asymptote curve, this procedure does not result in an accurate estimate (Trajano et al., 2012).

The researchers are responsible for finding the most adequate method to their study, among the ones described in the literature, if there is any. The data obtained not always fit the available method of analysis therefore most important than to apply a method is to acknowledge its requirements and limitations, only the compatible ones should be adopted. The use of inadequate methods, which is very frequent, endangers the cohesion of the study and the reliability of the results. This is why data related to the collection (at least the location coordinates, other points of reference, the date of the collection and the name of the collectors) and destination of the biological material, which must be deposited into official collections that are registered with official agencies, must always be available to the scientific community for verification or further re-analysis.

The high proportion of rare species in a given habitat may result in an underestimate of its species richness, because such species have the lowest probability of being sampled (just because they are rare). Those very same rare species have the higher chance of becoming extinct, and their presence is a criterion of singularity. Therefore, surveys should incorporate the strategies of additional searches to ensure that the species that are "difficult to collect" can be sampled. Because the rare species are very important, the researcher has to perform an intensive sampling effort enough to accurately foresee the total number of species in a given area (Trajano et al., 2012).

It is impossible to get a general indication of how much effort is required to foresee the species richness in one site, once the accumulation curves are highly influenced by the characteristics of the site itself. Nevertheless, we know that the species richness cannot be accurately inferred from a small number of sampling units, whatever method is used (Trajano et al., 2012). Here is the mathematic impossibility of two sampling points to define a curve. Data from the literature, as well as the professional experience from the author of the present chapter, indicate that more than 10 points (= sampling occasions), distributed along several annual cycles, are necessary for an accumulation curve to reach its asymptote, which represents the stabilization of the sampling and allow to infer its sufficiency in terms of the number of collections.

If knowing the diversity is important, rapid and immediate studies are not fit to estimate the species richness accurately. It is necessary to adapt the collection protocols to the goals of the research, to the characteristics of the cave and to the taxa that will be sampled. Anyway, the sampling efforts should be intense and the sampling units must be well distributed in time and space, and the researcher must demonstrate that the sampling was sufficient for the purposes of the study.

B. Spatial range:

The heterogeneity of the habitats must be taken into consideration, by the sampling effort, because it influences the establishment of an estimated number of species. If in a given cave there are several different environments, the sampling can be stratified, placing sampling units systematically or randomly, being preferable the later. In this case, the measurement of the heterogeneity and the complexity of the habitats can be related to the sampling efforts required by each stratum, providing a reliable estimate of the number of species (Trajano et al., 2012).

Another important aspect related to the study of the subterranean biota, mainly when one of the goals is to highlight its singularities and fragilities, is the classification of the population according to the Schiner-Racovitza categories (as per the definition of Trajano, 2012 and Trajano & Carvalho 2017). To accomplish with this classification it is also fundamental to study the epigean fauna of the region, focusing on the groups whose members may occur inside the caves. This is the way to correctly apply the criteria that are the basis of the Schiner-Racovitza which are the distributions per habitat (hypogean versus epigean).

It is clear that it is impossible prove the presence or absence of the species, therefore the approach must be statistical, based in the sampling sufficiency, by means of tests performed separately from the ones related to the subterranean communities. The epigean collections must be done out of the area of the influence of the cave on the epigean realm, to avoid that the sampling of the species of the troglobitic sinkhole population in the surface be wrongly classified (they could be wrongly considered as troglophiles). For instance, in the case of resurgences, the collection must be done at hundreds of meters downstream.

It is important to highlight that, in many cases, as expected because of the higher interspecies competition, the population density of species with troglophiles is inferior in the epigean realm. This is what was observed, for instance, for the *Ctenus fasciatus* troglophilic spiders very common in the Alto Ribeira karst area, in São Paulo-Brazil, but they are rare outside the caves (Pellegatti-Franco, 2004). The same occurs with the troglophilic cricket *Strinatia brevipennis*, causing it to be wrongly considered as restricted to caves (Hoenen & Marques, 1998). That means, for the classification of the subterranean organisms in the Schiner-Racovitza categories, the sampling effort in the epigean habitat should be higher than the one in the hypogean. On the other hand, as the epigean is more accessible, in terms of its components, such effort can be more timely concentrated.

C. Temporal range and periodicity of the sampling:

Every biological system is dynamic, that is, there is a temporal dimension that is likewise determinant of its properties and functioning. Therefore, the periodicity is an important aspect of the sampling process. One very important aspect of the natural ecosystems is seasonality, which is the equivalent to a period of circa one year. When the description and the understanding of a given system is the scope of a study, it must encompass the time dimension in its methodology. Seasonality is a widely recognized rhythm. Chronobiology (the study of biological rhythms) shows that to determine the rhythm of a certain period, for instance a seasonal one, it is necessary to study at least for three times this very same period. To understand the seasonality, in any environmental study, the minimum period of study must be three years. Environmental studies for quarrying operations in karst areas must fit this requirement (Trajano & Bichuette, 2010).

To a fully understanding of this dynamism, it is necessary to collect samples in different phases of the annual cycle, regularly spread along the time line. There is no use in concentrating the samplings in a short time, as it is usually done in environmental studies, in an ill methodological attempt to abbreviate the time of study, because an asymptote would only reflect a punctual situation. Taking into consideration that the total number of replicas will be used in tests of sampling sufficiency, like the ones that involve building the accumulation curves of the species, it is possible to accept 4 to 6 collection events by annual cycle, happening every 2 or 3 months. A good sampling design should include collections in the beginning, in the middle and in the end of the dry and rainy seasons, being repeated at least for a three-year period. Figure 4.8 illustrates a case study in which with five or more collections the samples were not sufficient, demonstrating the importance of an adequate time range.

It is important to highlight that three years is the minimum duration of the study. Should there be any inconsistency among the initial three years, it means that at least one of them were not typical, requiring additional annual cycles to detect patterns of structure and functioning of the ecosystems being investigated. This is really important when one of the goals of the study is to classify caves according to their degree of relevance and to evaluate the impacts on them.

There is more: in addition to seasonal fluctuations, i.e., fluctuations with periods of ca. one year, circa-annual fluctuations, i.e. fluctuations with longer periods, more than a year, may also affect subterranean systems, as have been reported for various caves in Brazil (Trajano, 2013). This kind of variation seems to be more frequent in caves where there are permanent or temporary bodies of water, in regions where seasonality is accentuated. However, such fluctuations have been observed in dry caves or conducts with a significant presence of bats, at least in some phases of the year. It is clear that speleobiological studies from medium to long term are required, instead of trying to characterize subterranean ecosystems based on punctual aspects, like guano stains or any other unstable substrates. There is hard evidence of temporal variation in the distribution, location and permanence of guano patches. Such variations are caused by the itinerant movement of the cave bat colonies, mainly in regions with a high availability of rocky shelters (Box 4.1). Likewise, it is common to observe changes in the distribution of riparian substrates (by the water) e even in sediment banks not so closed to rivers, mainly after very rainy years (Trajano & Bichuette, 2010).

Conclusion: it is indispensable to apply methods for testing the sampling sufficiency (see, for instance, Lehmann & Romano, 2006; Pillar, 2006) that statistically demonstrate that the study is conclusive for its own objectives. The experimental design must encompass the following criteria:

1) The collection and identification must be performed by qualified professionals. The material must be identified by specialists in each taxon under study and must be deposited in official collections where there is a curatorship service available;

2) The sample representativeness (number of sampling events) must be tested, at least in relation to the species richness, which currently can be done with the curves of species rarefaction using replications (not pseudo-replications). There is no way how to establish this number previously, because caves are unique and each system demands its own frequency of sampling events;

3) Spatial representativeness: the study must encompass the whole system and every habitat, as well as the epigean realm, for comparison purposes;

4) Temporal representativeness: the study of seasonality must go through, at least three annual cycles, i.e., three year sampling in all seasons, with the sampling events being regularly distributed in each year.

Finally, we must keep in mind that individual quarrying operations have a cumulative effect that must be taken into consideration every time an quarrying operation is granted a license. Should any impact happen, reversible or not, the conditions for the analysis of the other quarrying operations must be changed. The analysis of simultaneous projects, belonging to the same or to different entrepreneurs must be done in an integrated and **complementary way**.

For example, one species or system may not be threatened by each individual quarrying operation but, in the sum, the impacts could be highly relevant. Therefore, the concept of complementarity must always be applicable.

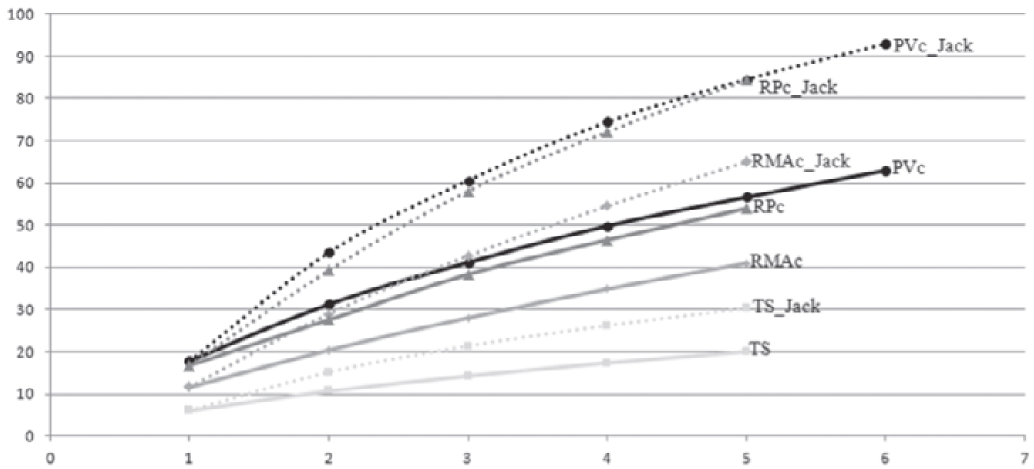


Figure 4.8. Data from Gallão & Bichuette (2015) that show the results of the surveys on the fauna in sandstone caves of Igatu, Bahia- Brazil. Even though there is a tendency towards stabilization, five or more collection events were not sufficient to the rarefaction curves of the number of species recorded in each cave to reach the asymptote.

4.6. AREA INFLUENCING ON CAVES

As any cave or cave system is unique, it is logical to think that the area having any influence on it is also unique. Its extension depends on the characteristics and functioning of that system, and it can vary in a temporal basis, circa and infra-annually. Therefore, no pre-established area imposed by legislation is arbitrary, and just by chance could correspond to the real area influencing a cave. That is, the determination of the areas influencing caves always depend on studies of case-by-case, according to what is explained in section 4.5.

First of all, the studies must be thematic, integrated to the other studies about the environmental impact from the quarrying operation, including the following topics, among others:

- The identification of the water recharge (continuous and/or diffused) and discharge zones of the cave system;
- Mapping the remainder underground systems located in the region, which could interact with the studied cave system;
- Studies on the possible connection with other caves and systems, based on chemical or biological tracers, including molecular, morphological and taxonomic studies (for instance, the presence of the same species).

The extension of the influence area is a direct function of the kind and the dynamics of the contribution of resources from it. As water is an agent of the contribution, the characteristics and delimitations of the karst system (or underground system) are some of the most important aspects, once the interferences from upstream can cause greater impacts on a cave, like for instance water pollution and the silting caused by deforestation. Therefore, the area influencing a cave encompasses the total area of recharge of the system, i.e., all the drainage upstream.

Trogloxenes, such as the case of bats, as well as any accidental ones, are sources of nutrients that in many cases are extremely important. There are some subterranean communities, mainly the ones living in permanently dry caves, which depend almost only on the food carried inside by trogloxenes, as for instance guano dropped by bats. Therefore, the determination of the area of influence has necessarily to include the study of the **ecology and distribution of the chiropteran fauna** (see box 1) and **other trogloxenes** that are recognized as important members of the hypogean fauna.

In the case of caves close to the surface, roots of plants can appear and can be an important contribution of trophic resources (the survey of the cave fauna may indicate if it is the case). Should it be the case, this **root system** has to be accounted for in the study, and be identified so that the vegetal species can be protected in the epigean habitat.

The use of the soil is another very important issue because it interferes not only on the soil itself but also in the food contribution. It must be taken into consideration when the influence area is established. The influence area on a cave, or on a subterranean system, is that area whose deforestation can cause:

- sediments to be carried into the cave, causing silting and other not natural changes in the habitat;
- **decrease in nutrients input** (for instance, vegetal debris, animals and organic matter in general carried by flash floods);
- **changes in the speleoclimate,** etc.

The estimate of such an area depends not only on speleobiological observations but also on the studies on the flora, the landscape and the climate, both local and regionally.

4.7. CONSERVATION

Conservation aims to preserve representative samples from the biodiversity, its processes and patterns. This definition brings a fundamental concept: biodiversity is the result of the processes and evolutionary patterns, therefore they should be the focus of conservation. Not only the so-called alfa diversity, that is, the diversity of species, showed on the lists of species, as it has been done, which is superficial and simple but incompatible with the beauty and complexity of natural phenomena.

Several factors contribute to the high subterranean diversity. Genetic isolation followed by differentiation under a very distinct selective, associated to the fragmentation of the subterranean habitat leading to high endemism rates, cause a high biological diversity expressed by the morphological, physiological, behavioral, bionomic and auto-ecological, as well as ecosystemic diversity. This latter includes the contribution from the alpha diversity (= richness of species in a given location/cave) to the gamma diversity (= regional), as well as the functional and phylogenetic diversities. Phylogenetic diversity is related to the number of the higher groups (Orders, Families, etc.) in which the species are distributed, that is, the greater the proportion of great groups in relation to the species themselves, the greater the phylogenetic diversity. Functional diversity is related to the diversity of ecological functions within each group.

All though the alpha diversity of subterranean communities is usually low, when compared to the epigean communities occupying similar areas, its contribution to the gamma diversity is much bigger due to the presence of troglobitic species, generally with very small distribution areas (= highly endemic). Same way, phylogenetic diversity tends to be higher than the one in the epigean communities, because of the exclusion of closely related species. In the epigean realm, it is common to find genera with many species and families with many genera, but it is very difficult to happen in the subterranean realm that "disperses" few species in the higher groups. Other than this, because of the food shortage in the subterranean realm, animals of the same great group (for instance, Oniscidae isopodes from the same family), with ecological niches overlapped in the epigean realm, they tend to split their niches, what leads to modifications in their morphology, even subtle ones. This explains how the functional diversity may be enhanced in subterranean communities.

In conclusion, all the above-mentioned aspects support the importance of the subterranean ecosystems, must be taken into consideration, and must be analyzed for conservation purposes.

From the point of view of the species or populations, troglobites are particularly vulnerable to anthropic disturbances, which occur in very short time scales that are not compatible with the capacity of those populations to adapt to new environmental conditions. Among the vulnerability factors is the life cycle tending to type K (adaptation to the low and fluctuating availability of food), leading to a slow population replacement in case of declining because of natural causes or not, and the loss of tolerance to environmental fluctuations. Likewise, in many fishes it has been observed the loss of the reactions to avoid damaging stimuli like the presence of predators, including humans (who are not a natural part of their habitat). That means troglobites are intrinsically fragile organisms, potentially threatened, albeit the threat level may vary according to the context. Almost all troglobites fit the criteria used to create lists of threatened species, at least being classified as Vulnerable.

Summarizing, the biologic diversity present in small fragments of subterranean habitats can be very high in terms of the processes and patterns and it should be a priority in national actions for the appreciation and protection of natural environments.

BOX 2. NOT ALL TROGLOBITES ARE CAVERNICOLES: the case of *Stygichthys typhlops,* a highly specialized and threatened fish.

Stygichthys typhlops, locally known as "piaba-branca" (white fish), is a small subterranean fish from the phreatic habitat; currently it is only accessible through wells in the karst area in Northern Minas Gerais State – Brazil. This is a highly specialized fish, one of the most troglomorphic in Brazil, and the only South American troglobite of the Neotropical Order Characiforms; the only other known troglobitic characiform is the blind Mexican fish from the genus *Astyanax. S. typhlops* is so morphologically modified that its taxonomic position in the family is not yet well established. Besides the extreme reduction of the eyes and melanic pigmentation, these fish have a series of morphological and behavioral troglomorphisms associated to the long term isolation in the subterranean realm and to the adaptation to life in the phreatic habitat: they are adapted to breathing in a poorly oxygenated medium (they are pink when in their natural environment), present a reduced lateral line (related to life in narrow spaces), an accentuated regression of the locomotory circadian rhythm, and cannibalism, probably as a mechanism to regulate the population size, among many other specializations, justifying the high degree of interest from the scientific community and, as a consequence, its conservation.

Above *Stygichthys typhlops.* Photo: Dante Fenolio; to the left, drilled well to access the habitat of Stygichthys typhlops showing an ichthyologist collecting specimens with a hand held net. Photo: Maria Elina Bichuette.

Nevertheless, this phreatobic troglobite of international relevance is highly threatened by indiscriminate water pumping for extensive agriculture, which is rapidly lowering the water table in the region (Moreira et al., 2009). This also is damaging the families in the rural and peri-urban zones who have no resources to drill the very expensive artesian wells. It is an example of the negative consequences from an unsustainable use of subterranean waters.

There some news that, some decades ago, there were "piabas brancas" (*Stygichthys typhlops*) in a small cave but it was dumped to expel the hematophagous bats that lived there. *However, as the only access to* the species is through a drilled well, its protection is not granted by the Brazilian legislation that only covers caves. This is a clear example of the inadequacy of the environmental legislation that only considers caves, which, as previously hereto discussed, are components of the subterranean medium whose definition is based in an anthropocentric operational concept, without any biological meaning. In fact, *S. typhlops* remains without legal protection for not been reported inside caves. Species that have been reported in caves but need a much wider area of habitats, other than the caves, to maintain an effective population to grant their survival, are also under threat. Therefore, it is necessary to change the focus of the legislation that aims to protect subterranean systems from the caves to the subterranean habitat as a whole.

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CHAPTER 5:
PALEONTOLOGY

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Luiz Carlos Borges Ribeiro

5.1. GENERAL ASPECTS AND CONCEPTS OF PALEONTOLOGY

Paleontology is also known as the Science of fossils. The name comes from three Greek words put together: *palaios* (ancient), *onto*s (life) and *logos* (study). Paleontology is the science that studies ancient life, that is, the fossils. Coming from the Latin word *fossilis,* meaning extract from the earth, fossils are remains or indirect evidence of living organisms that remained preserved along the ages. They comprise every organism that have ever lived on Earth, from unicellular bacteria to great mammals that went extinct during the last glaciation (also known as the "Ice Age", interface Pleistocene/Holocene, around 11,000 years ago). Bones, teeth, trunks, shells, pollen, tracks, eggs, excrements, plant resins, colonies of bacteria, algae and imprints are just some of the material that can be found preserved. It is a convention to call fossil the remains with a minimum age of 11,000 years or that are extinct. Exemplars aged below this range are known as sub-fossils.

Fossils are already known since prehistoric times, by ancient civilizations. They were believed to be sculptures and toys left here, on Earth, by divine creation. Only after the studies of Charles Darwin (1809 – 1882) and his famous Theory of the Evolution of the Species, fossils became fundamental pieces to understand the several modifications that organisms have endured ever since until today (Figure 1).

Paleontology is as a recent science, and it was consolidated only in the beginning of the 19th century, by the first paleontological scientific societies. Nevertheless the first scientific publication of a Brazilian fossil dates back 1797, by Domingos Vandelli, an Italian naturalist working in Portugal. The first publication in a Brazilian magazine dates back to 1856, by Frederico Burlamaqui, a naturalist who is considered to be the first Brazilian paleontologist and during twenty years he was the Director of the National Museum in Rio de Janeiro State, Brazil (figure 1). The Paleontological Society of London, one of the first societies in this branch of knowledge, operating until today, published its first monography in 1847.

Known as the father of the Brazilian paleontology, the Danish researcher Peter Wilhelm Lund studied the Pleistocene fauna from the limestone caves in the Velhas River Basin, in Minas Gerais State – Brazil, between 1835 and 1846 (Lopes, 2010). He contributed to enhance the knowledge about this region, especially in relation to the karst environments, describing several new species. Most of his findings are deposited at the Natural History Museum of Copenhagen, in his homeland. Nevertheless, in a cooperation agreement between Copenhagen and the State of Minas Gerais, Brazil, a small portion of bones and exemplars of hominids were brought to Brazil, for a temporary exposition in the State Park of Sumidouro, without a foreseen date for returning to Denmark.

Planet Earth is 4,6 billion years old and, as far as we know it, life began around 3,8 billion years ago. The first hominids appeared just 8 million years ago. To understand the biological evolution along this period has not been an easy task, because a fossil record may be fragmented and incomplete. Therefore, the importance of the paleontological studies is to understand this distant past and how populations of different organisms evolved, lasted or were extinguished; also to understand the climate, geographic and chemical changes of our planet, so that one day, perhaps, it may be possible to try to foresee the future.

It is important to keep and preserve the paleontological heritage and, together with the tireless search for new information, spread the idea of this scientific field. Several museums and research centers have played a fundamental role to disseminate and popularize paleontology. A science that marvels people all around the world and lead them to think about the past of the planet and its contribution to the future.

One of the important questions that the science of the fossils asks is how these records of life could be preserved for millions and even billions of years. In the natural life cycle, death is followed by decay, helped by necrophagic organisms (decomposers) and by the oxidizing action of the air, leading to a complete destruction of the soft parts. As the process continuous, the harder parts of an organism are also destroyed.

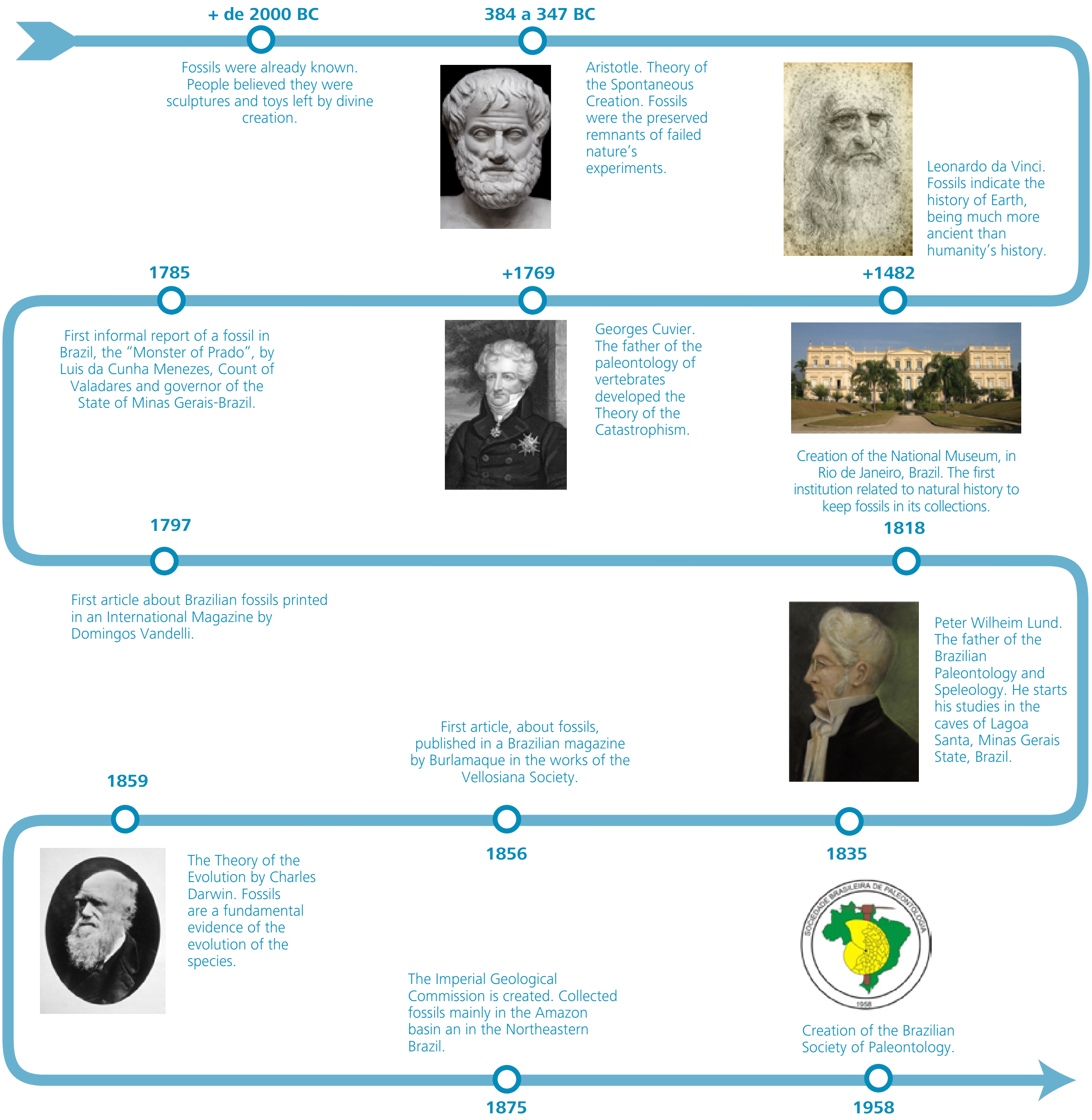

Figure 5.1.1. Time line of the evolution of the paleontological science.
Aristotle, Photo: Mohamed Osama; Leonardo da Vinci, Photo: Jakub Krechowicz; Georges Cuvier, Photo: Georgios Kollidas; Museu Nacional, Photo: Antonio Carlos Sequeira Fernandes; Portrait of Peter W. Lund, pastel on paper by Honório Esteves (1903), Collection of the Mineiro Museum, Photo: Luciano Faria; Charles Darwin, Photo: Samuel Lock & George Whitfield, Collection Everett Historical.

Fossilization is a process that breaks the afore-mentioned life cycle. It is a rare phenomenon and an exception. Sometimes just one individual or a fragment of it, among hundreds of thousands, is preserved until today.

Most of the fossils are associated to sedimentary rocks, that is, the ones formed by the lithification (hardening) of the sediments (sand, clay, gravel, the evaporation of liquids that are rich in dissolved salts) by compression and cementation processes. Metasedimentary rocks, resulting from geological processes (warming and pressure in the depths) working on sedimentary rocks, can also hold important fossil localities, as for instance marbles. Igneous rocks can rarely preserve fossils, except the ones resulting from the deposition of volcanic tuff or ash.

It is necessary that a set of physical, chemical and biological processes work together to a record of life to be fossilized. Among the main factors that allow the fossilization to occur are the following: rapid burial, lack of oxygen and destructive mechanical events after the death, the chemical composition of the liquids present at the burial, the climatic conditions at the burial, and finally, the environment where an organism lived and died (Figure 2).

In this process, the harder parts of an organism, that can be replaced by minerals, as bones, teeth, shells and chitin, are more easily preserved. Fossils having their soft tissue like skin, blood vessels and muscles preserved, are very rare.

Figure 2: Steps of a Fossilization process. Illustration: Daniel Borges. Modified from Reis (2008).

Mummification and amber preservation are amongst the best ways of preservation, in which the individuals are kept almost unchanged. In **Mummification**, the organism undergoes a quick dehydration in a very arid environment (Figure 3 left). Amber preservation occurs when the preservation happens in some substance like a plant resin (amber) (Figure 3 right). In addition, natural asphalt lakes and ice preserve fossils exceptionally.

Figure 3. Mummified skin of *Mylodon* (left) and amber with small inclusions (right). Photo: Thiago da Silva Marinho

Mineralization or **Substitution** is a process of the chemical transformation of the original organism in which the organic matter is replaced by minerals like calcite, silica, to name a few.

Permineralization is similar to Mineralization, but dissolved minerals like calcite and silica fulfill in the interior of the cells and the cavities of the original organism, therefore preserving it. The majority of fossils is the result of this process. Good examples are the pterosaurs from Northeastern Brazil (in the region of the Araripe), the dinosaurs and crocodiles from the Triângulo Mineiro (western part of Minas Gerais State, Brazil), and the fossilized tree trunks from the State of Tocantins-Brazil (*Figure 4*).

Incrustation is a process in which saline solutions, generally carbonate, get in touch with the remains of an organism, precipitate and crystallize in its surface, completely coating it, preserving the hard parts (Figure 5). This is the main process of fossilization in a cave environment.

Recrystallization occurs when the minerals of an organism undergo an alteration in their crystalline structure, changing to a more stable structure, therefore allowing the preservation to occur. During this process, there is a mineralogical transformation, as in the case of calcite – aragonite without a modification of the chemical composition of the organism.

Carbonification, also known as Incarbonization, usually occurs in plants (leaves) or animals with chitinous skeletons, as insects. It happens from the progressive enrichment of the carbon in relation to the remainder elements of the organic matter. They are generally found in the format of thin pellicles, because of the compression they underwent during the deposits of sediments during the fossilization process (Figure 6).

Casting does not preserve the organism itself, but its form. In this process, both the internal and the external parts can be casted. It usually happens with shells (*Figure 7*).

Another different kind of molding is known as imprints, in which thin structures leave their marks in soft sediments, like silt, and they undergo geological processes called diagenesis, in which the sediments became rocks preserving the marks printed on them. Some examples of fossil imprints are leaves, feathers, insect wings and other delicate parts.

As last kind of fossilization, we can mention the indirect records of biological activities as marks and traces. This kind records comprises marks, footprints, tracks, perforations, tubes, eggs, excrements as urine and feces from animals, nests, borrows, among many others (*Figure 8*).

Figure 4. Fragment of a tree trunk *Tieteia singularis*, from the Permian Age (280 Ma), fossilized Permineralization by silica, found in sandstones of the Pedra de Fogo Formation, in the State of Maranhão – Northern Brazil. Photo: Luiz Carlos Borges Ribeiro – Collection GeoPac Consultoria Ambiental.

Figure 5. Skull of *Eira barbara* with the incrustation of calcium carbonate. Photo: Castor Cartelle.

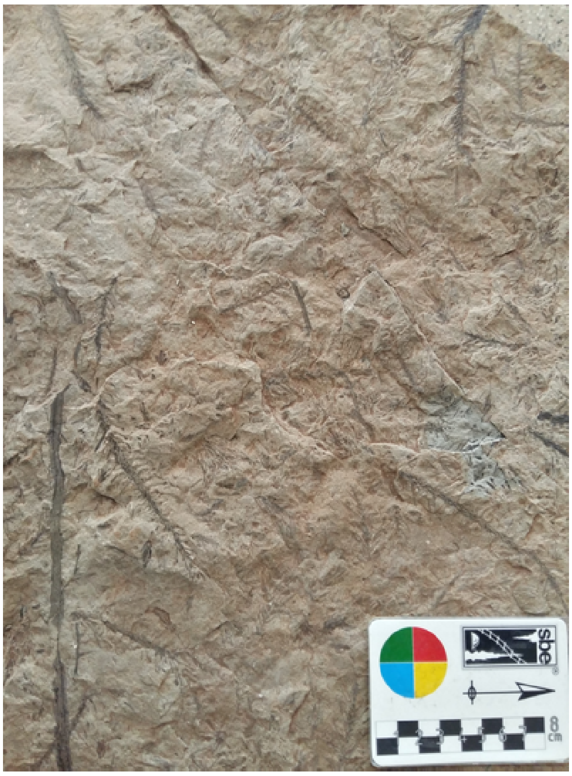

Figure 6. *Krauselcladus* brasiliensis preserved in sandstones of the Terezina Formation (Permian age, Paraná River Basin-Southern Brazil-260 million years). Photo: Luiz Carlos Borges Ribeiro - Collection GeoPac Consultoria Ambiental.

Figure 7. Inprint of *Orbiculoidea* with 2 cm diameter, found in the Ponta Grossa Formation (Devonian Paraná River Basin- Southern Brazil- 380 million years). Photo: Francisco Macedo Neto – Collection GeoPac Consultoria Ambiental.

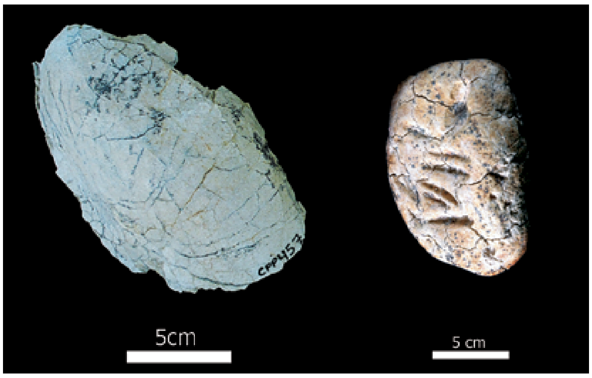

Figure 8. Egg (left) related to Titanosauria e Ichno-marks (*Asthenopodichnium fallax*) produced by bivalves, are present in carbonate rocks (right), from the Marília Formation (Late Cretaceous) found in the Municipality of Uberaba, Minas Gerais State –Brazil (Ribeiro et al., 2012). Photo: Francisco Macedo Neto – Collection Centro de Pesquisas Paleontológicas Llewellyn Ivor Price.

5.2. THE STUDY OF PALEONTOLOGY AND THE IMPORTANCE OF FOSSILS

Fossils are the undisputable evidence of the presence of several forms of life that have lived on Earth in past geological ages. Paleontological studies allowed men to discover his own origins, as well as the origins of many other species that are extinct today.

By studying fossils, it is possible: rebuild environments and landscapes of the past of our planet, acknowledge the age of the rocky strata, and search for fossil fuels like coal and oil, besides many other contributions to the cultural, social and economic development of the societies.

The basis of Paleontology and its principles are inserted both in Biology as in Geology. Biology is indispensable for the study of fossils, because they are the remains or traces of ancient organisms. While Geology allows us to understand the environment and the scenarios of life in the past, because most of the fossils are found in rocks.

5.3. PALEONTOLOGY AND ITS MAIN SUB-AREAS

Just as many other sciences, Paleontology is divided in many areas, among which we may mention: Paleobotanic, Invertebrate Paleontology, Vertebrate Paleontology, Micropaleontology, Paleoicnology, Taphonomy, Paleoclimatology and Paleoecology.

Paleobotanic studies fossil plants, but as a complete exemplar is rarely found, the paleobotanists divide their field in the study of the parts of the plants, as wood (roots and stalks), leaves and fruits. It is fundamental to study plant fossils to reconstruct the ecosystems as they were in the ancient past of Earth. Paleobotanic includes the study of fossil pollens and spores (Palynology), which are very relevant because they are the basis for dating rock layers, for paleoclimate and paleoecologic studies.

Paleontology of Invertebrates, studies fossils of organisms like molluscs, brachiopods, echinoids, and conchostraceans. This kind of research allows us to make stratigraphic correlations between distant sedimentary basins, by suppling information about the ancient sedimentation in ancient environments.

Paleontology of Vertebrates is the area with the highest popular appeal. It concentrates the studies of several animals as fish, amphibians, reptiles and mammals. Among those animals, dinosaurs are outstanding; they are responsible for the widest divulgation and popularization of Paleontology to the public. Dinosaurs are strong allies in the social, cultural and economic development of communities because of tourism.

As it is an essential tool for the prospection of fossil fuel, Micropaleontology is an economically interesting area, and can be used for stratigraphic dating and correlating studies. Micropaleontology studies the microfossils as foraminifera, radiolarian, diatomaceous, pollens and spores.

Paleoicnology studies the vestiges of biological activities preserved on rocks. It is fundamental to understand the feeding habits, the behavior, the mobility and the reproduction of organisms, helping to rebuild them as well as their ecosystems.

Each fossil has its own history and represents an organism that once lived, left vestiges, died and was preserved. Taphonomy is the branch of Paleontology that studies the history of a fossil, from the death of the organism, its burial, the lack of decomposition or partial decomposition, the transportation (or not) of its remains, the process of its fossilization as well as the geological activities it was submitted to.

5.4. PALEONTOLOGY IN KARST AREAS

Karst is a very complex system and has a high paleontological potential. The complexity is due to three kinds of environments that are favorable to the preservation of fossil records: endokarst, exokarst and epikarst (that may be composed by a lithology that can be different from the karst itself).

The endokarst is the most important for paleontological studies, because of its potential to preserve fossils. Cavities grant the fossils protection against the processes working on the surface. When the remains of organisms stay inside cavities, the processes of decomposition are drastically shortened, making the preservation more probable.

Most of the fossils are associated to cavities in carbonate rocks, but they can exceptionally occur in sandstones, granites, gneisses and even in iron formations. The fossilization, in this kind of environment, is due to a chemical process of dissolution of the rock itself or to solutions around the cavities that were carried inside by water flows, which are rich in mineral salts. Inside caves, the organic remains in contact with carbonate, silicon or even oxide solution, become rapidly protected against the decomposition caused by microorganisms, as a result of the process of incrustation. In cavities where there is a bigger water flow, the surrounding mineralized waters accelerate the process of fossilization.

Organisms are much better preserved in carbonate rocks, because these rocks are composed by minerals that are highly soluble in water at the environmental temperature, as for instance, calcite, aragonite and dolomite. Another important issue is the alkalinity, which is a decisive factor for the preservation of fossils of soft tissue as skin, muscles and blood vessels.

Among the recurrent processes of fossilization, that are common in caves, incrustation is responsible for the preservation of the biggest quantity of the species of large mammals that lived in the period between one million and eleven thousand years ago. Incrustation even preserves complete skeletons (Figure 9).

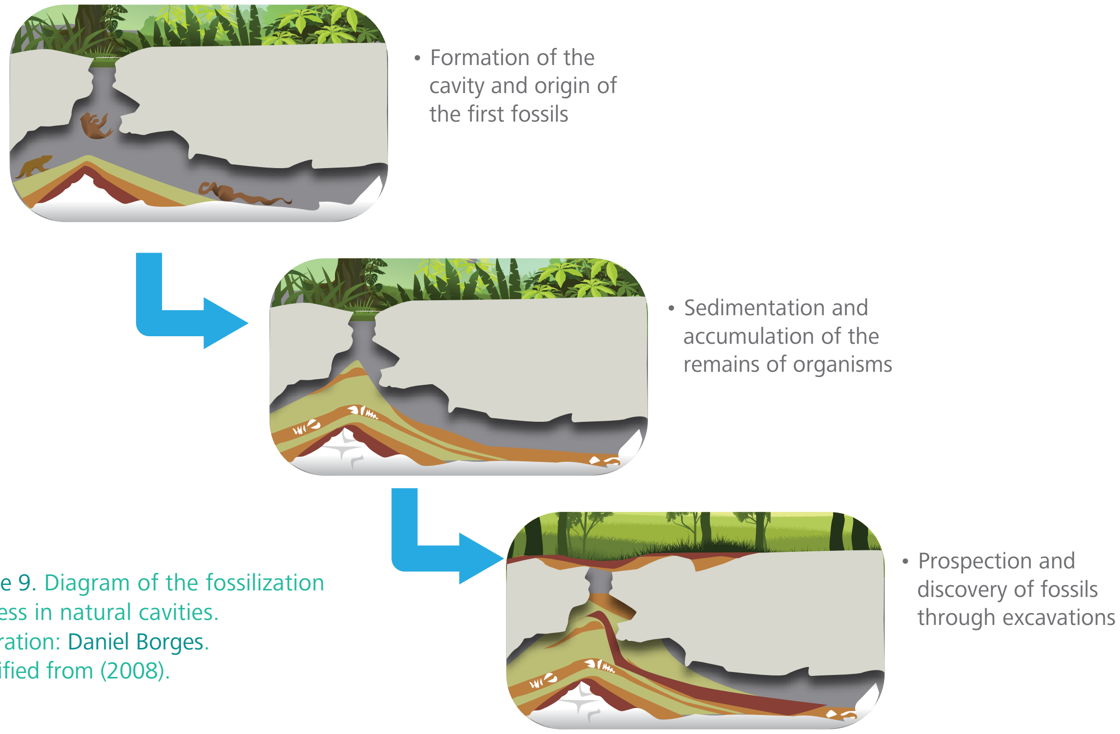

Figure 9. Diagram of the fossilization process in natural cavities. Illustration: Daniel Borges. Modified from (2008).

Figure 10. Diagram showing the interaction of the possible situations that can lead one register of life to be fossilized. Assembling: Francisco Macedo Neto.

Cave environments are highly interesting to a paleontological prospection. As caves can be used as shelters, they may become traps that can catch many animals (Figure 10). Fossils found in the endokarst play a special role in making a paleo-environmental diagnosis and in dating the karst itself.

Caves are key locations to understand the process of the transition of the biodiversity, where past and present time live together by means of fossils, sub-fossils and living elements both from the cavernicolous and the epigean fauna and flora. Caves are complex systems from which the various branches of sciences get contributions to the advance of the knowledge of the pre-history, the history and the current environment.

The second potentially fossiliferous environment is the exokarst. In the exokarst, the paleontological records are inserted into the rock, that is, between the strata that form the very rock. The first forms of life on Earth can usually be found in limestone and marbles.

The majority of the rocks, in which the Brazilian karstic limestone landscapes are developed, belong to the Proterozoic age. Stromatolites are structures formed by sediments inserted between organic remains composed by algae and bacteria, unicellular organisms that were pioneers in our planet and are living here up today. They are the oldest and more common paleontological records found in limestone. In Brazil, the first fossils identified as very old multicellular complex organisms related to the geological age of Ediacaran, circa 600 million years (Figure 11) are located in the rocks of the Bambuí Group, in the State of Bahia, Brazil. All those fossils can be found in the rocky massif that constitutes the walls, ceilings and floors of the cavities, as well as in the exterior of the caves. This kind of fossil provides information about the moment of the history of Earth in which the rocks were formed, about its environment, about the climate and the kind of organisms that inhabited the planet. It is very interesting to note that caves provide a three-dimensional view of the massif from inside, making it much easier to identify the main stratigraphic fossiliferous levels.

The third kind of fossiliferous environment is the epikarst, which is almost unnoticed to most of the paleontologists who investigate karst landscapes. Generally, the epikarst is composed by sedimentary rocks, unconsolidated deposits and even soils that are located right above the massif, which has generated the karst. Epikarst may look little attractive in the realm of Paleontology, nevertheless, it is possible to find a different lithology overlapping the older rocks of the exokarst. Most of the times, this lithology belongs to the Phanerozoic (542 million years to current days) that is the geological time frame in which almost all the paleontological records are located, and that offers a very interesting horizon for future findings. From this perspective, natural cavities are not the only important environment for paleontological studies. Exokarst with its rock massifs and the epikarst, the superficial cover of the karst, also provide a promising environment.

It is possible to observe that quarrying activities, in karst areas, can affect the fossils even if there is no direct interference or suppression of the caves themselves.

Figure 11. Fossils attributed to the Ediacaran biota, with concentric circular structures and the edges ornate with complex organisms of 600 million years of age, found in Bahia. Photo: Carolina Reis – CPRM Archives.

5.5. FOSSIL RECORDS IN THE BRAZILIAN KARST

5.5.1. The contribution from Peter W. Lund for the Paleontology of the Brazilian Karst

In Brazil, the first investigations with a scientific effort, with the scope to discover fossils in caverniculous environments, started in the State of Minas Gerais with the systematic studies carried out by the Danish naturalist Peter Wilhelm Lund. He settled down in the small village of Lagoa Santa, in 1835. His first excavation happened in the cave called Gruta de Maquiné, in Cordisburgo, Minas Gerais. Among the fossil material he found, one finding is very important both historically and scientifically: the identification and description of the smallest species of an extinct ground sloth, called *Notrotherium maquinense*, published in 1839.

Lund's first articles related to the karst, reporting the caves of Maquiné and Cerca Grande (Lagoa Santa), are the first scientific reports of this kind in the Americas. His first publication in the field of paleontology is dated 1838. He mentioned the primate *Protopithecus brasiliensis*, identified in a cave in a farm, Fazenda Escrivânia, in the Municipality of Matozinhos, Minas Gerais-Brazil (oral information from Castor Cartelle). This was the inaugural milestone of the paleontology in the Brazilian karst and was the first occurrence of a primate in the world. The findings included only one femur, one incomplete humerus and some bones of the hand. They were furtherly deposited in the Zoology Museum of Copenhagen. Further studies that were based on more complete findings revealed that, in fact, that primate is *Cartelles coimbrafilhoi* (Figure 12).

Figure 12. Fossil of *Cartelles coimbrafilhoi*. Photo: Castor Cartelle – Collection of the Museu de Ciências Naturais da PUC – Minas Gerais – Brazil.

Until 1846, Lund dedicated himself to the arduous task of exploring the caves of that above- mentioned region, comprising more than 800 locations like grottos, cracks, sinkholes and shelters scattered around the Rio das Velhas river basin. During the 10 years, in which he carried on with his studies, Lund also identified and published papers about the following taxa: Xenarthra: *Pampatherium humboldti* (Figure 13), *Hoplophorus euphractus*, *Catonyx cuvieri*, *Ocnotherium giganteum*, *Propraopus punctatus*, *Propraopus sulcatus* and *Eremotherium laurillardi* (Figure 14); Carnivore: *Protocyon troglodytes*, *Speothos pacivorus*, *Arctotherium brasiliense* (Figure 15) and *Smilodon populator*; Perissodactyla: *Equus* (*Amerhippus*) *neogeus* and *Hippidion principale*; Artiodactyla: *Brasiliochoerus stenocephalus* and Rodentia: *Neochoerus sulcidens*, *Agouti major* and *Coendou magnus*.

Lund lived almost all his life as a scientist. He was an unconditional follower of the French anatomist Georges Cuvier, especially in relation to the Theory of the Catastrophism. According to this theory, life evolved in cycles after natural catastrophic events, in a global scale, as earthquakes, deluges and sudden colds that led to the extinction of all forms of life. After one extinction, new organisms would appear, by means of divine creation, but they would be different from the previous ones. During his investigations, Lund discovered many contradictions in the Theory of the Catastrophism. One of them was the presence of living beings that were identical to the fossils found in the caves. Another finding that led Lund to disbelieve Cuvier's theory was the presence of extinct animals together with human fossils, "The Man from Lagoa Santa". In spite of other factors mentioned by Lund, his discoveries contrary to the Catastrophism may have contributed to his definitive withdrawal of the scientific life.

Below, follows the description of some important areas related to karst environment, which are interesting for the Paleontology in Brazil.

5.5.1.1. The Karst in Lagoa Santa – Minas Gerais State

Thanks to Lund's studies, the karst of Lagoa Santa is important for the paleontology worldwide. It comprises one of the most important carbonate karst landscape developed in Neoproterozoic lithology, from the Sete Lagoas Formation of the Bambuí Group. This characteristic led to its inclusion in a publication by the Comissão Brasileira de Sítios Geológicos e Paleobiológicos –SIGEP (Brazilian Commission of Geological and Paleo biological Sites) as one of the reference sites in Brazil. In this endokarst, the majority of the caves are no more than 500 m long. All though there are some caves, like Gruta da Escada and Lapa Vermelha, which are 1822 m and 1870 m long, respectively. Those caves are spread around a region of about 360 km², North of Belo Horizonte, Minas Gerais State-Brazil. Among those natural cavities, there are some highly paleontologically relevant because they are the location of unique findings, especially from the Pleistocene/Holocene masto-fauna: Gruta do Baú, Lapa do Sumidouro, Cerca Grande, Rei do Mato and Lapa Vermelha. A big part of the knowledge about the cave fauna of the region of Lagoa Santa is the result of the studies and descriptions of Peter Lund.

In this very same geological and geomorphological context of the Lagoa Santa karst, there are many other paleontologically important caves in the State of Minas Gerais: the Lapa do Mosquito in Curvelo, the ensemble Lapa Grande, Southeast of Montes Claros, and closer to the boundary with the State of Bahia, the Montalvânia ensemble is located in the namesake city.

5.5.1.2. Karst and the Caves of the Parque Estadual Turístico do Alto Ribeira (PETAR), SP- State Tourist Park in Upper Ribeira River Valley – São Paulo State- Brazil

The PETAR comprises one of the most important karst provinces in Brazil and is included among one of the seventeen proposals, currently being evaluated, to the implementation of Geopark (CPRM – Serviço Geológico do Brasil). There are more than 350 cavities associated to the Proterozoic carbonate sequence, in the Park and its surroundings. The cave presenting the biggest planimetric development is Caverna Santana, 8,540 m long, and the highest unevenness is in Caverna Água Suja with 297 m.

Fossil, Juvenal e Ponta de Flecha are abysms located in the Betari River Basin and are among the most important paleontological sites of the transition Pleistocene-Holocene. Some of the species found in these abysms are: Toxodon platensis, Eremotherium laurillardi, Megatherium sp., Nothrotherium maquinense, Catonyx cuvieri (ground sloth) and Gliptodon clavipes.

There is a very interesting fact associated to these findings, that is, the contemporaneity of the above-mentioned animals with the pre-colonial man from the Upper Ribeira River Valley. This man was identified by the incisions marks for dismembering and stripping meat that were found on bones and teeth, as per the description of the material found in the abyss called Ponta de Flecha.

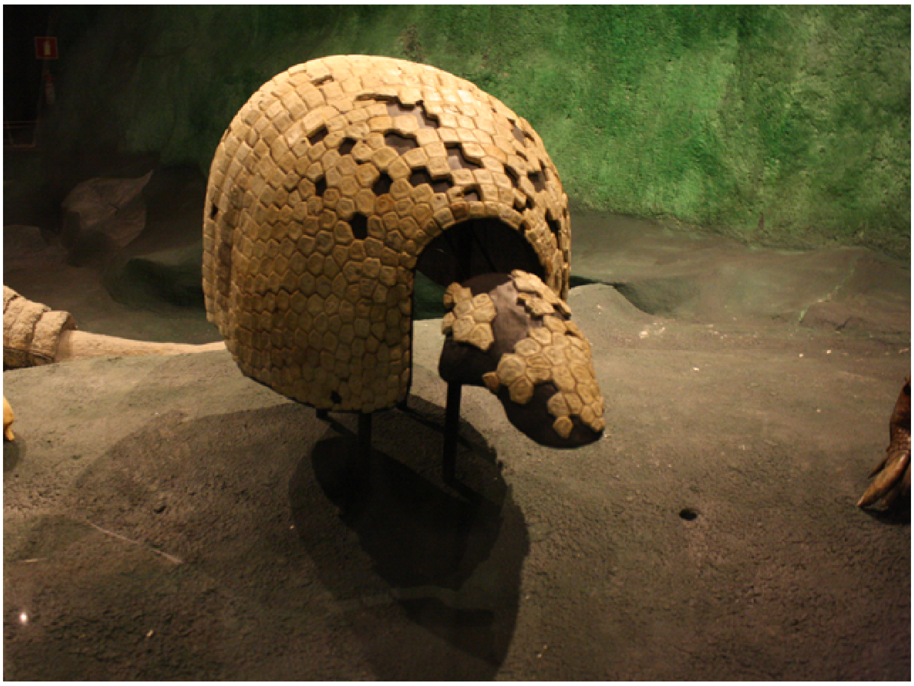

Figure 13. Reconstruction of *Pampatherium* in exhibition in Museu da PUC, Belo Horizonte-Minas Gerais-Brazil. Photo: Castor Cartelle – Collection of Museu de Ciências Naturais da PUC Minas.

Figure 14. Reconstruction of *Eremotherium laurillardi* (up front) and Glyptodon (in the back). Photo: Rodolfo Nogueira.

5.5.1.3. Toca da Boa Vista – Campo Formoso – Bahia State

Toca da Boa Vista is the longest cave in the Southern Hemisphere, with 105 km of development in dolomites of the Salitre Formation of the Una Group. It is included the list of reference sites published by SIGEP.

It is considered the site with the highest amount of geochronological data, thanks to the various ages of the fossils, both from extinct animals as livings ones. The study of the various stratigraphic fossil levels provided a better understanding about the paleo-climate and paleo-environment that prevailed in that region and the transformations occurred during the Quaternary period.

This scientific richness of information about this cave is due to the various skeletons that were found practically complete, as *Cartelles coimbrafilhoi* and *Caipora bambuiorum* (Pleistocene primates), a small fetus of *Nothrotherium maquinense*, the canid *Protocyon troglodytis* and the bear *Arctotherium brasiliense* that granted Toca da Boa Vista a special highlight.

5.5.1.4. Toca da Janela da Barra do Antonião, São Raimundo Nonato, Piauí State

Located in the Municipality of São Raimundo Nonato, Piauí State, in the area of the National Park "Parque Nacional da Serra da Capivara", the cave called Toca da Barra do Antonião is one of the most remarkable in Brazil, due to the number of scientific studies about it and to the diversity of fossil species found there. The geological context is characterized by a combination of siliciclastic rocks especially dolomitic, belonging to the Barra Bonita Formation of the Casa Nova Group, of the Neoproterozoic age.

The importance of the paleo-biological diversity of the Toca da Barra do Antonião is based in the several animal groups that have been identified, as for instance: birds, marsupials mammals, ground sloths (*Catonyx cuvieri, Eremotherium laurillardi* and Megaloniquídeo indeterminate), armadillos (*Pampatherium humboldti*) and glyptodonts (*Hoplophorus euphractus, Panochthus greslebini, Glyptodon clavipes*), bats, rodents, canids (*Protocyon troglodytes*), felids (*Smilodon populator*), litopterns (*Xenorhynotherium bahiense*), notoungulates (*Toxodon* sp.), proboscids (*Haplomastodon waringi*), equids (*Hippidion principale* and *Equus neogaeus*); pigs, camelids (*Palaeolama niedae*) and cervids. Lithic tools and human bones, including a female skeleton dated 9,700 years, were found in association with the paleo-biota from the Pleistocene.

5.5.1.5. Lapa dos Brejões, Bahia State

Located in the Northern section of the Chapada Diamantina, in the Municipality of Morro do Chapéu, Bahia State-Brazil, this cave is outstanding in speleology studies because of its wide galleries, the dimension of its speleothems, the volume of its dolines and its exceptional portal standing 106 m. high that grants it a high tourist appeal. It is included in the SIGEP list of sites and its environmental importance resulted in the creation of a protected area called "Area de Proteção Ambiental Gruta de Brejões/Vereda Romão Gramacho. Its geological context is located in the Salitre Formation (Neoproterozoic) in the Una Group, represented by laminated gray carbonate siltstones interlayed with microbial mats (biogenic rocks).

The fossiliferous assemble contains 1,500 exemplars collected by the team from the Museu de Ciências Naturais da Pontifícia Universidade Católica de Minas Gerais, coordinated by professor Castor Cartelle. The following species were identified among the findings: *Paleolama* sp. (lama), *Nothrotherium maquinense* (sloth), *Eremotherium laurillardi* (giant sloth), *Glossotherium giganteum* (sloth), *Pampatherium humboldti* (giant armadillo), *Myrmecophaga tridactyla* (giant anteater), *Coendou sp*. (hedgehog) and *Lutra sp*. (otter). Many other animals were also found such as birds, rodents, cervids, mastodons, wild hogs, horses, tapirs and bats.

5.5.1.6. Gruta do Urso Fóssil, Ubajara, Ceará State

In relation to Paleontology, Gruta do Urso Fóssil is the most important, among the 14 caves located inside the National Park called Parque Nacional de Ubajara, in the State of Ceará-Brazil. It is a cavity with little development, located in the Proterozoic Limestone of the Ubajara Group. Its paleontological heritage includes invertebrates (Mollusca) and vertebrates (Squamata e Mammalia) among which the bear *Arctotherium brasiliense* (Figure 15) and the taxon Tapirus are the most important. The bear was the first fossil to be found in the cave, in 1978, and the cave was named as Cave of the Fossil Bear after this relevant finding. Other species were also found there: Squamata: Colubridae and Viperidae, *Crotalus*; Mammalia: Marsupialia, *Didelphis*, *Monodelphis*; Xenarthra, Dasypodinae, D*asypus, Euphractus*, Cabassous; Rodentia, Caviidae, *Kerodon*, Echimyidae, *Thrichomys*, Erethizontidae, *Coendou*; Artiodactyla, Tayassuidae, *Tayassu* e Cervidae, *Mazama*; Perissodactyla, Tapiridae, *Tapirus*.

Figure 15. The moment when *Arctotherium brasiliense* was found by the physician Roberto Falzoni and the geologist Coriolano Dias Neto. Photo: Roberto Falzoni.

5.5.1.7. Lajedo Soledade, Apodi, in the State of Rio Grande do Norte (SIGEP)

The Lajedo Soledade locality presents a different karst feature that is not what is usually observed in environments located in soluble rocks. This context establishes the precedent for the identification of this kind of structures in new locations. In this geological context, there are ravines developed in horizontal rocky pavements, where the dissolution of the limestone of the Jandaíra Formation (Marine Upper Cretaceous of the Potiguar Basin) was afterwards replenished with clastic sediments associated to debri flows from the Plesitocene/Holocene age. Those conditions create an exceptional environment for the conservation of the diversified fauna at this moment in the geological time. This is another location registered in the SIGEP as nationally important. Even though based on fragments, studies led to the identification of various groups, among which are: Megatheriidae (*Eremotherium laurillardi*), Glyptodontidae (*Panochthus greslebini*, *Glyptodon sp*.), Dasypodidae (*Tolypeutes tricinctus, Holmesina paulacoutoi*), Canidae (*Cerdocyon thous, Protocyon troglodytes*), Felidae (*Smilodon populator, Leopardus cf., L. tigrinus*), Ursidae (*Arctotherium sp*.), Equidae (*Hippidion sp., Equus* (*Amerhippus*) cf.E. (A.) neogaeus), Camelidae (*Palaeolama major*), Macraucheniidae (*Xenorhinotherium bahiense*), Toxodontidae indet., Cervidae, Gomphotheriidae. In the cave, some crocodilian osteoderms and vertebrae of an undetermined ophidian were also found. Another import fact that has to be highlighted is the record of a rich marine fauna associated to the limestones of the Jandaíra Formation. Remains of gastropods, echinoderms and some teeth of fish, as well as the ichnogenera Thalassinoides represent the marine fauna found at this locality.

5.5.1.8. Gruta do Lago Azul, Bonito, Mato Grosso do Sul State

Located in the Municipality of Bonito, State of Mato Grosso do Sul, the cave Lago Azul is one of the geosites that will be included in the future geological park Geoparque Bodoquena – Pantanal (CPRM). Declared as a National Heritage by the IPHN (Institute of the National Heritage) because of its exceptional landscape value, it is one of the main tourist destination in the State of Mato Grosso do Sul. The cave is located in the dolomite of the Bocaina Formation (Corumbá Group - Neoproterozoic), featuring two paleontological scenarios. One of them is very ancient, related to the rocky massif, in which there are fossils of Cloudina and Corumbella. The other scenario presents quaternary records inside the cavity, which have not yet been thoroughly studied, represented by three genera: *Eremotherium*, *Smilodon* and *Glyptodon*. Divers located those fossils and the identification was made from photos, without removing any material from the lake where they are deposited.

5.5.1.9. Caves in the State of Tocantins

Northern Brazil is currently seen as one the potential grounds for new findings in subterranean cavities, bringing new and valuable information on the paleo-fauna and, as a consequence, a better understanding of the terrestrial ecosystems of that region during the Quaternary.

Recent studies, in several caves in the State of Tocantins, have brought to light new paleontological discoveries. In this context, the Municipality of Aurora do Tocantins is in a special position due to the findings associated to the cavities Gruta dos Moura, Buraco do Junior and one more cave that has not yet been registered.

The following taxon have already been identified: one Llaminae indet., *Mazama cf. americana, Ozotocerus bezoarticus, Tapirus terrestres, Xenorhinotherium bahiense, Tayassu pecari, Tayassu tajacu, Catagonus stenocephalus, Dasypus novemcinctus, Euphractus sexcinctus, Glyptodon or Glyptotherium, cf. Pachyarmatherium brasiliense, Pampatherium cf. typum, Propraopus sulcatus, cf. Propraopus grandis, Gracilinanus agilis, Marmosa murina, Monodelphis cf. brevicaudata, Philander opossum, Sairadelphys tocantinenses, Arctotherium brasiliense, Panthera onca, Procyon cancrivorus, Puma concolor, Lyncodon* and one unidentified canid.

5.6. FOSSILS IN CAVITIES IN FOREIGN COUNTRIES

Just like in Brazil, karst environments with paleontological occurrences are present in almost all the continents. Fossils are highly valuable, because they provide a better understanding of the diversity and the evolution of living beings, and allow the reconstruction of the ecosystems in the last millions of years. In this section, some important examples from the Americas and from Europe are provided, mainly because they represent the mastofauna from the Pleistocene that has lived together with both recent and ancient hominids.

Pikimachay and Três Ventanas are cavities where there are paleontological records in Peru. The cave Cueva Pikimachay, located in the district of Pacaycasa, province of Huamanga, is an important karst locality that has been studied since 1960. From this cavity, some Pleistocene fossils of horses and giant sloths, aged 20,000 years, have been rescued. Associated to the fossils there were lithic tools and human remains of the called "Man of Pacaycasa".

In 1961, in the cave Cueva Três Ventanas, located 65 km Southeast of Lima, in the province of Huarochirí, claws, paw bones and coprolites (fossilized excrements) were found associated to *Megatherium*. Studies estimated that the animal could be well over 35,000 years old because it was impossible to date using the C14/C12 isotopic method. In Peru, there are other cavities presenting paleontological records, like in Cajamarca, Ancash e Arequipa, with special highlight to giant sloths.

In Cuba, there are more than 200 cavities where fossils were located. The fossils were dated from the Tertiary to the Pleistocene and the following groups were found: carnivores, chiropteran, primates, rodents, cervids, sloths and soricomorpha (shrews). The cave Gran Caverna de Santo Tomás located in the mountain Quemado, in Viñales, Pinar del Rio, is the biggest and most important cave in Cuba, with 46,2 km of development, where important fossil records from the Pleistocene are located, as sloths, rodents, chiropteran and shrews.

Located in the city of Burgos, Northern Spain, the paleontological site called Atapuerca was declared a World Heritage, by UNESCO in 2000. This locality is very important because in 1994 the oldest fossils of hominids, in Europe, were found there and were dated more than 300,000 years old. The main cavity is Cueva Gran Dolina, where a new human species was found described and named *Homo antecessor*, which means "The Pioneer". This species could have been the ancestor of the Neanderthal Man. The second more important cavity is the Abysm of the Bones, from where the remains of 32 individuals, men and women of various ages, were collected and described as Homo *heidelbergensis*, an intermediary species between the Antecessor and the Neanderthal, circa 300,000 years old.

5.7. PALEONTOLOGY AND QUARRYING IN KARST AREAS

Paleontology is closed associated to quarrying processes because of its direct relationship with the lithology of karst landscapes. The possibility of intervening into the paleontological heritage is a constant possibility, whether during the process of the decoupage to remove the sterile, to remove the mineral, or in the natural cavities that may be sectioned during the advances of the operation.

In Brazil, among the locations that are associated to limestone quarrying, where there are internationally relevant paleontological sites, we may highlight the sites of Peirópolis and Ponte Alta in the Municipality of Uberaba, in the State of Minas Gerais, and the Chapada do Araripe in the State of Ceará. In the case of Uberaba, the diversified fauna of vertebrates from the Continental Upper Cretaceous occurs in siliciclastic sediments overlapping layers of limestone from the Marília Formation (Bauru Basin). In Ponte Alta, the sediments are used in for the production of cement, and in Peirópolis to correct the soils for agricultural purposes. In the Chapada do Araripe, mainly in the Municipality of Crato, big quantities of fossils, in excellent degree of conservation, occur in association with the laminate limestones from the Santana Formation (Araripe Basin). The limestone is removed by hand to be used as coating stones.

During the stages of the mineral exploitation in karst regions, there are various occasions, ways and locations in which it is possible to find fossils. The first step that could interfere with fossiliferous deposits may happen during the survey for minerals, in which the procedures aiming to delimitate, to measure and to check the quality of the deposit, mainly by probing, could find fossils both in the exokarst and the epikarst.

A second important occasion for paleontological discoveries is during the implementation of the quarry and the construction of the processing plant. Earthmoving, excavations for the foundations and opening the access to the place can cut through fossiliferous deposits.

Even though considered "sterile" under an economical point of view, the layer of material over the mineral cannot always be discarded because it may contain valuable material for a paleontological research. Sometimes there are huge sediment deposits that cover the mineral and may present a high paleontological potential. In view of the auspicious geological context represented by the lithology, ages and environment favorable to the preservation of a paleobiological record, the sediments can be richer and much more important than the mineral itself and its natural cavities (Figure 16).

In the exploitation of a mineral, depending upon its characteristics and age, especially when there are Phanerozoic sedimentary sequences, it is highly probable that fossiliferous deposits might be sectioned. Limestones and marbles, even very ancient ones, can contain important fossils as the stromatolites, and even more advanced forms of life as the ones recently found in the Bambuí Group of Santa Maria, in Bahia State -Brazil. This group is known as the Ediacaran biota, with a worldwide distribution, it was the biological time milestone that allowed the description of a new geological period, the Ediacaran, covering the interval between 630 and 543 million years ago.

Much more relevant is the possibility that excavations sectionalize natural cavities during the advances of the quarrying operation. Caves have proved to be extremely important for the development of paleontological studies due to its well-preserved and diversified fossil contents (Figure 17). This kind of karst environments with plenty of paleontological records can be found in almost all regions in Brazil.

Figure 16. Fossils of the dinosaur *Uberabatitan ribeiroi*, the biggest ever recorded in Brazil, came from the calciferous sandstone located above the limestone of the Marília Formation, in Uberaba, Minas Gerais State - Brazil. Photo:Luiz Carlos Borges Ribeiro – Collection GeoPac Consultoria Ambiental.

Figure 17. Reconstruction of fossils from the Pleistocene found in the regions of Lagoa Santa, Minas Gerais State - Brazil. Photo: Castor Cartelle – Collection Museu de Ciências Naturais da PUC Minas.

5.8. THE PALEONTOLOGICALLY CORRECT EXPLORATION

The mineral exploitation in Brazil, independently of the substance or good to be quarried, can be sub-divided in a set of processes and operations included in five steps: Study of Feasibility, Implementation, Operation, Deactivation and Post Closure Period. One of the most important activity is the one related to environmental issues, that is, implementation of programs aiming the biotic, social-economic and physical realms. Especially in the last 10 years, the analysis of the paleontological potential in a quarrying enterprising has been incorporated in the terms of reference for environmental studies (licensing). It has proved to be an effective tool for the preservation of the Paleontological Heritage in Brazil. For karst areas, this kind of study can become very complex, because of all the care required by the fragility of the system. The decision-making and action taking must be very judicious. Among the five steps comprised in the process of the mineral exploitation, the paleontological investigations may happen during the Feasibility Studies, Implementation and Operation. In these three stages, it is necessary to take special and indispensable care to minimize the impacts, as well as to implement mitigating measures when there is any possibility of interference in the fossiliferous sediments. The stage of Deactivation of the quarry does not pose any risk or is interesting to the paleontological heritage, therefore it will not be discussed hereto.

Studies of Feasibility

This first stage includes the geological survey to verify the existence, the extension and the characteristics of the mineral deposits, they can be carried out by geological mapping, probing, trenches, cubic measurements and several kinds of prospections, as geophysics. It also widely comprises the studies of technical-economic and environmental feasibility. In this stage, the area to be studied will be established by surveying the area that will be directly impacted, comprising all karst systems as defined by the hydrogeological studies. As mentioned before, fossil can occur in different quarrying scenarios and, and this is the reason why, the area must encompass not only the karst system but also the area directly influencing the project.

The main studies to diagnose the paleontological potential of the enterprise must be established in this first stage, because they determine if it is necessary to implement a paleontological program for the quarrying project.

Once the technical and economic feasibility of the quarry is approved, and the initial survey about the hydrogeology and about the karst system is ready, the studies should begin by means of a survey of the inventory of secondary data that are recorded in the official basis of the paleontological registers, as well as the data available in the scientific literature related to the area to be exploited by the enterprise. In Brazil, the data registered in the BASE PALEO of CPRM are regularly used. All though, sometimes there are just a few paleontological data, which are not sufficient to reach a good diagnosis of the actual potential of the area of interest. Complementing the survey, it is important to search for the paleontological and speleological data in the municipality, as well as for data about the lithology and litho-stratigraphic units, in the areas directly or indirectly affected by the quarrying activities, that are published in scientific articles, journals, graduation papers, dissertations and thesis.

Surveying the primary data is the most important step in the stage of the Feasibility Studies, it is indispensable to understand the geology, the landscape and other issues of the physical realm of the area. The survey can be done by walking and observing the interesting points such as outcrops, the presence of potentially paleontological rocks in the epikarst, the lithological contacts, using data from probes and many other tools, which could bring detailed knowledge about the overall paleontological context of the area of interest. As to the karst, the data collection will support the evaluation of the relevance of the cavities, analyzing their potential to contain fossils, and evaluating prospect paleontological sites that could be sectioned, should any alteration in the dynamics of the karst system occur. Therefore, cavities presenting sediments and characteristics that could allow the preservation of fossils must be prospected.

As the last step of this stage, a report with the diagnosis of the paleontological potential must be prepared and it will support the preparation of the study on the environmental impact EIA (Estudo de Impacto Ambiental), or any other document necessary to request the licensing of the project.

If the studies indicate the possibility of paleontological records in the locality, it is fundamental to prepare an executive project detailing the paleontological program to be implemented in the further stages of the quarrying operation. This project comprises all the actions necessary to avoid the destruction of the paleontological heritage. This document is indispensable to request the official License of the Installation of the project. After the license is granted, the construction and the implementation of the quarry may begin.

All the studies must be performed by experts in Paleontology, especially with a wide experience working in programs of paleontological investigation, monitoring and rescue in enterprises that could cause a strong environmental impact, such as quarrying, gas pipelines, energy transmission lines, hydroelectric power plants, small hydroelectric centers, wind farms, roads, railways as well as any other big sized construction work.

Implementation

This is the stage related to building and preparing the quarry and the infrastructure necessary to establish the construction site. That is, in relation to the paleontological studies, the attention must be directed to the movement of rocks and surface material that could split fossil deposits.

During the Implementation, but more importantly in the next stage, the Production, it is necessary to implement a series of measures and preventive actions whose goal is previously identify the problems that may emerge, as well as, the procedures that may grant a total protection of the paleontological sites. Should preliminary studies reveal a real paleontological potential in the area the quarry may affect, one or more than one of the following steps should be totally or partially implemented.

Program for Paleontological Training, Monitoring and Rescue

1st Step: Heritage Education –Courses and Lectures

1. Courses for Technical Capacitation in Paleontology:

As a first action in the Paleontological Program, short courses for the capacitation in Paleontology, directed especially to the employees working the implementation of the quarrying production plant and all its related physical structures, from the opening of the access, scraping the soil, until the conclusion of the construction site. The participants of these courses are the members of the teams involved in the excavations for the foundations and other activities that could move potentially fossiliferous material and that could interfere in the natural cavities. The courses should be theoretical and practical and would allow the teams to previously identify the possibility of a fossil, even in the absence of the team of paleontologists. If necessary the courses should happen once every quarter year, so that all employees could attend, including the newcomers.

2. Educational Lectures on the Heritage Education for Paleontology:

Lectures about heritage education in archeology, environmental education or social communication must be held in schools near the quarry, as well as for the population around the enterprise, with the scope of providing information about paleontology and the need to preserve the cultural-paleontological heritage of the region.

2nd Step: Paleontological Collection Expeditions "in loco"

This is the most important stage of the paleontological program: the expeditions to collect paleontological material "in loco". The collection has to happen as soon as fossiliferous vestiges are identified during the excavations.

The collection must be performed under the monitoring and coordination of a paleontologist or technician that was properly trained. It is necessary to follow up the excavations until they are finished or reach the lithology proved to be fossil free.

The follow up provides the possibility of searching the material that was stripped out, material from the excavations of the foundations, from borrowing areas or earth movements that split a lithology where there is a paleontological potential, during the implementation of the operating plant and in the surrounding areas. This is the way the screening must be performed, searching for any paleontological vestige to be collected. Should any fossil be found, the following procedures must be implemented:

- Take note of the coordinates;
- Take note of deepness from the surface;
- Take note of the stratigraphic level;

- Take photos from the locations;
- Take photos of the paleontological records;
- Take photos of the details of the lithology;
- Description of the lithology of the quarry or the location;
- Remove the fossil specimen;
- Pack the material that has been removed.

The identification of cavities, during this step, will require a paleontological survey and a classification of their paleontological potential, as well as additional studies to classify their importance and to propose what should be done to protect or to rescue them.

3rd Step: Transportation, Curatorship and Custody of the fossiliferous material

If fossils are rescued, they must be packed and transported to a depository in a referenced institution that has been selected during the feasibility studies. The mining company is responsible for the procedure that should be done as soon as the Implementation Stage is completed.

Operation Stage

This is the stage comprising the extraction and processing the mineral. Undoubtedly, it is the most important stage of a mineral exploitation specified in a paleontological program, because of the exceptionally huge quantity of rocky material that is moved. During this process, the sterile (epikarst) is stripped, and the dismantling to withdraw the mineral continues. At this point, the attention paid to the process must be even greater, because the possibility of interfering into the fossiliferous deposits is very high. All the personnel involved in the extraction of the mineral must be prepared for an occasional finding and must call in the technical team to rescue it. In the levels that are proved to be fossiliferous, both in the sterile or in the mineral, the dismantling and removal of the material must be systematically monitored so that any fossil records can be rescued. Special attention must be paid to the cuts of natural cavities, because the latter are exclusive environments that may be parts of a bigger system and any local problem can affect areas located far from the quarrying site. Bellow are described the mandatory activities for the stage of the production:

1st Step: Heritage Education – Courses and Lectures

3. Courses for Technical Capacitation in Paleontology

Just like in the Implementation Stage, depending on the results of the Studies of the Feasibility of the Area, it will be necessary to establish a routine of quarterly courses to capacitate the employees that will work in the excavations in the limestone massif.

As a way to reduce costs, a team of employees can be trained to do the paleontological monitoring. This team must report to a coordinator paleontologist that can be responsible for several quarries at the same time.

4. Educational Lectures on the Heritage Education for Paleontology

The educational lectures must be held after the implementation stage and must integrate the educational programs on heritage, archeology or environmental education. They may be held in schools located in the regions near the quarry as well directed to the population around the enterprises. The main goal is to provide information about paleontology and the need to preserve the cultural-paleontological heritage that can be found in the region.

2nd Step: Collecting Paleontological material "in loco"

As it is a continuous process, that means, it lasts as long as the extraction of mineral happens, monitoring and rescues may be performed by a technician that was trained attending the courses on Paleontology, therefore, avoiding additional costs to have an expert available on site, around the clock. Anyway it is highly recommended to keep at least one paleontologist for a group of quarries to support and control the paleontological investigation.

The basic methodology to follow up the quarrying operation is screening parts of the excavated material, trying as much as possible to avoid delays in the overall operation. Every portion of rocks to be investigated must have their location and elevation properly recorded. If the material is fossil free, it can be released for the continuation of the process of quarrying and grinding. Should fossils be identified, they will be photographed and sent to a laboratory, maintained by the entrepreneur, where they will be packed and undergo the first studies for their classification. When dismantling rocks, especially by detonation or other method that leads to the fragmentation, it is wise to make a rapid screening of the rocky material, with the scope of collecting fossil records.

In case the quarrying site reaches a natural cavity, the quarrying must be stopped for the necessary prospections and studies, including the paleontological ones. The presence of fossils in this situation implies the need of rescuing the material by systematic excavations. The rescue of those fossils may indicate new forms of fossil records bringing important data about the forms of the life and the local ecosystem, during the end of the Quaternary Period. During the endokarst prospection, in case any interference be identified that may affect other hydrogeological systems, and that may put paleontological sites at risk, the sites must be identified and the fossils must be rescued.

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CHAPTER 6:
ARCHEOLOGY

Elvis Pereira Barbosa

6.1. ARCHEOLOGY, WHAT IS IT?

The best answer to understand the meaning of archeology is approximately the following: archeology is the science that studies the material culture of the peoples of the past, the way it was produced, the way it was discarded and the interaction of those material vestiges with the several human groups in which they were produced. This is a complete answer, but it is complex to the majority of people to understand it, mainly people that does not know the science called Archeology.

Paul Bahn, a renowned English archeologist, in one of his works when he was trying to broadcast the importance of archeology in a funny way for the population in general, affirmed that the archeologist is an expert garbage man, because what is interesting to him, in an archeological site, is to find the garbage bin. In the garbage, he can find all the evidences of how the ancient peoples act and interact between themselves producing objects for their daily use.

It is obvious that many archeologists do not feel like an "expert garbage man", but when they are in the field doing excavations, one of their first actions is to try to find the location where the human group, that inhabited the place, discarded their objects. After all, the way they discarded their objects brings a lot of information on how these people lived.

Going back to Archeology, what interests the archeologist is exactly try to understand the way ancient people lived, by understanding the way they produced their material culture, or, in other words, from the production of material vestiges. In this context, the term "material" is understood as any object produced by ancient population, as for instance, lithic material (chipped stone, polished stones), clay, material made of bones, shells, wood and mainly paintings on the walls of caves and shelters that were used as dwellings by human groups in the past.

The Brazilian-Portuguese naturalist Simão Pires Sardinha, who was the son of the famous Brazilian colonial personage Chica da Silva and Manuel Sardinha, performed the first archeological studies in Brazil in the 18th century. Simão was graduated from the University of Coimbra and was called back to Brazil by Don Luís da Cunha Menezes, then governor of the State of Minas Gerais, to study a "skeleton" that was found in Prados, near the city of São João del Rey, when a gold mine was dug. Sardinha collected the small quantity of material that was not damaged during the excavation and prepared a report called Memory, at that time. He reported the description of some unknown bones discovered in May 1785 in the province of Minas Gerais – Brazil. Sardinha analyzed the fossils fragments and the stratigraphy of the region. The fragments and the report were sent to Lisbon and in the "Memory" he concluded that "the strange and monstrous bones must have belonged to some animal that, due to the revolutions of times, must have been a lost species"[14].

During the following century, several foreign naturalists, as the botanists Carl Philipp von Martius and Auguste de Saint-Hilaire, among many others, had Brazil as their object of studies. Those visitors are one of the reasons that motivated the Danish scientist Peter Lund to visit Brazil.

Archeology is a science that has its own methods and theories, but needs the support from many other sciences as History, Anthropology, Geography, Biology, Chemistry, Physics and sometimes Medicine. It is one the sciences that "dialogue" with others searching for a better methodology in the field works but also to build a better theoretical structure. Therefore , more than "expert garbage man", sometimes mistaken as "dinosaur hunters", archeologists and Archeology try to understand the past by means of the evidences found in the present, trying to do a logical analysis of what were the situations experienced by the various human beings that had built those evidences.

14 - ARQUIVO HISTÓRICO ULTRAMARINO. CU 011, Cx. 123, D. 9762, 26 de agosto de 1785.

6.2. ARCHEOLOGY IS HISTORY OR IS HISTORY ARCHEOLOGY TOO?

When Herodotus wrote the History of the war between Greeks and Persians, he had never realized that from that moment on he was creating a legacy for future generations that would be understood as being a science. After all the term "History" that he created was just an abstraction, because it is possible to record the facts that happened in one place according to the convenience of the observer. Therefore, besides being abstract, once it is not an experimental science, History is a creation of the human mind.

When any study in History is initiated, there is a question that is constantly asked: What is History? When formulating one concept of History, many historians face History as being documental records produced by Man along the ages. Therefore, the majority of those records is understood as being written documents, what would lead to the sources of information that are not written being considered not historical, that is, belonging to Pre-History. If we follow this way of thinking, not all the information that is not written would be the object of studies of historians, but they would be the objects of study of archeologists (Trigger, 1973).

If the meaning of History may be seen as an invention of the humans in the Classic Greece age, the concept of Pre-History (formulated in the 19th century by Paul Tournal and Daniel Wilson) is another human invention but much more abstract than the science created by Herodotus. The milestones that divide History and Pre-History can be different according to different authors. The big issue faced by the researchers is the following: up to when does Pre-History (or Archeology) span and what is the difference between it and History?

The question can be related to the 18th century and the Nordic antiquarians that established the system of the three ages[15]:

- Stone Age: the period in when weapons and utensils were made of stone, wood, bone and other similar material;
- Bronze Age: the period when the weapons and cutting utensils were made of copper or bronze and the iron had not yet rule;
- Iron Age: the period when iron was used as a substitute of bronze to make axes and weapons.

Latter on the model of the ages of the Pre-History had been modified as follows:

- Stone Age (primitive);
- Bronze Age (ancient);
- Iron Age;
- Christian Age (this would be the milestone marking the birth of History).

One of the faults presented by this model is that it cannot be applicable to the ancient population in the Americas. The American Man has never dominated the production of metals, mainly iron, and the mass colonization of the American Continents began in the end of the 15th century, when the European colonizers, especially Spanish and Portuguese ones, stopped the social process that was taking place in the American territory.

Vere Gordon Childe (1977, p. 09) *considered that (…) archeological data are the historical documents by their own right and are not just agreements to written texts (…). In the first chapter of the book "Introduction to Archeology", Childe explains that Archeology is a form of History, is not just an auxiliary discipline (…) Just like any other historian, an archeologist studies, and try to rebuild the process by which the world where we live was created (…),* (Childe, 1977 p. 10).

The previously mentioned difference between the pre-historian who studies the bones of a Neanderthal – seen a naturalist- and the one who studies the objects made by a Neanderthal – seen as a historian- would be a fictitious reference, without a theoretic basis in view of the recent advances in the research of both sciences: Archeology and History. Current views try to classify Pre-History as the most remote stage of the studies on History, therefore inside the range of options of the historian to study, but having its own method of investigation. The archeologist studies the material vestiges that he finds in the field, but he/she does not have written documents like the ones that can be read and interpreted by the contemporary historians.

15 - Peter Frederik Suhm, in his work History of Denmark, Norway and Holstein referred to this idea, when the division of the utensils and weapons was established based on three materials: stone, copper and iron. Afterwards, Skuli Thorlacius in his work "Concerning Thor and his Hammer, and the earliest Weapons that are related to it, and also the so-called Battle-Hammers Sacrificing Knives and Thunder-Wedges, which are found in Burial Mounds (1802)" also works with the idea of three ages: stone, copper and iron (DANIEL, 1992, p. 90-91). Lauritz Schebye Vedel Simonsen presents the first reference against this system in his work Udsigt over Nationalhistoriens aeldste og maerkeligste Perioder de 1813-1816. The consolidation of this model is made by Christian Jurgensen Thomsen with the publication, in 1836, of the Guide of the National Museum of Copenhagen called Ledetraad til Nordisk Oldkyndighed and translated to English, in 1848, A Guide to Northern Antiquites. Thomsen was the curator of the National Museum.

When archeologists analyzed several predominantly karst areas, they were able to establish a chain of terms and events that were firstly identified in Europe. Mainly in the caves of Lascaux e Chauvet in France, in the caves of Altamira in Spain, in some locations in Italy, and in the valley of the river Neander in Germany (from where comes the name Homo neanderthalensis for the fossils found in that region). Afterwards, those concepts were extended to other regions of the world, once the differences were taken the consideration.

6.3. THE ORIGEN OF ARCHEOLOGY IN BRAZIL

The studies in Archeology, in Brazil, started with the prospections of caves in the surroundings of Lagoa Santa in the State of Minas Gerais, in the first half of the 19th century performed by Danish scientist Peter Lund. During that century, Brazil was the focus of studies of several naturalists, as the botanists Carl Philipp von Martius and Auguste de Saint-Hilaire, among many others. In a certain way, the scientific thinking of that age motivated Lund to visit Brazil.

Lund's work started with the focus on the caves of Minas Gerais, and besides the discovery of many fossils, the archeological material that he identified is the object of studies of both Brazilian and foreign scientists, until today. One important characteristics of Lund's studies, in Brazil, is that they are all concentrated in a karst area.

Lund surveyed more than 800 caves in the region between Lagoa Santa and Cordisburgo recording all the material he found out, including remains of human skeletons that were fossilized beside animals from the Pleistocene. As there were no reports of fossilized human skeletons in other parts of the world, his peers did not accept the idea of the contemporaneity of the "Man from Lagoa Santa" with the extinct fauna. According to Barreto (1999-2000, p. 37), the issue of the "*Man from Lagoa Santa*" and the subsequent researches in the region were present in the history of Brazilian archeology for the rest of the 19th century and the whole 20th century as well.

After the period dominated by the voyages of the naturalists, there is a real decline in studies of Archeology in Brazil, but the studies resumed with the coming of the French Missions and some North American researchers. The French Missions had the objective of developing archeological studies in the States of Paraná, São Paulo e Minas Gerais. The legacy of the North American researchers was the base for the creation of the *Programa Nacional de Pesquisas Arqueológicas* - PRONAPA, the national program of archeological research. This program was responsible for the development of projects all over the country, in decades of 1960 and 1970.

After the closure of the PRONAPA in the middle of 1970 decade, there was an expansion of the archeological research in Brazil, as the studies in the South of the State of Piauí. Under the leadership of Professor Niède Guidon, with the support of the French Government through the Centre National de la Recherche Scientifique (CNRS), in 1978, an important interdisciplinary mission was carried out in the Serra da Capivara and Serra das Confusões. This first mission was the basis for the identification and the register of a great number of archeological sites in the region of São Raimundo Nonato, in the State of Piauí-Brazil. One of those sites is Boqueirão da Pedra Furada, which is considered one of the oldest archeological sites in the Americas. The main characteristic of this region is the limestone soil.

Currently in Brazil, besides the scientific research conducted by Institutes of Research and Teaching, the Archeology by Contract is growing as a promising way for the development of this Science. The pressure from the archeologists for the compliance of the law has resulted in the increasing number of requests of permits (Permissões Arquelógicas) to the Instituto do Patrimônio Histórico e Artístico Nacional -IPHAN (National Institute of the Artistic and Historical Heritage), in the last three decades, widening the archeological horizons in Brazil. As a previous archeological research is mandatory for the environmental characterization of small, medium and large sized works of engineering, today the activities of archeologists are more respected and are indispensable for the environmental license to be granted. Currently many private companies are able to work exclusively with archeological research, what was unimaginable in decades of 1960 and 1970.

Thanks to the Archeology of Contract, the Brazilian archeological field is significantly growing, and many graduation courses in Graduation in Archeology were created in public Universities.

6.4. TYPES OF ARCHEOLOGICAL SITES

Archeological studies encompass many different materials and locations. Each kind of material found in an archeological site requires a different technique. As to the kind of material, archeological sites may be classified as follows: shell mounds, lithic sites, clay sites, rupestrian sites and historical sites, this last one is valid only for the Americas. As the Americas were the last continent to be occupied by Men, when the European Colonization started, in the end of the 15th century, there was an interruption of the process of the social, political and technological development of the native societies of the Americas, this why the concept of historical site is only applicable to the American Continent.

Shell mounds are archeological sites characterized by layers of shells, clams, fish scales and spines, fire remains, skeletons of animals and human burials that were deposited by pre-historical populations that had these materials as their prime resource (Figure 1). They are usually located near the sea, rivers and forests that offered plenty of resources to the population dwelling these areas.

Lithic sites are typical of hunter and gatherer populations and are plentiful inside the countries, especially were the rubble soil is predominant, as on top of hills, riverbeds and rainwater flow hill sites. Those sites comprise small areas, usually near the sources of raw material as stones and boulders. There are plenty of lithic fragments (Figures 2 and 3) and almost no clay material, in this kind of site.

Martin (1997) highlights the relationship between the production of lithic artifacts and the topographic location of regions that are far from perennial water springs. Lithic sites located far from permanent sources of water and food do not provide the conditions for camping sites, therefore they are only chipping workshops (Martin 1997).

Figure 6.4.1. Shell Mound Ilha do Paty, Baía de Todos os Santos – State of Bahia-Brazil. Photo: Elvis Barbosa.

Figure 02. Stone Axes found in Fazenda Cascata, Teixeira de Freitas- State of Bahia-Brazil. Photo: Elvis Barbosa.

Figure 03. Chipping nucleus found in Ituaçu, State of Bahia-Brazil. Photo: Elvis Barbosa.

Examples of the above-mentioned characteristics are the chipping sites found on top of the hills around the Middle Valley of the São Francisco River. All though not many lithic artifact vestiges have been identified – in spite of the big quantity of rocky material available - it is important to take into consideration the distance between the original São Francisco river bed and its condition as a supplier of raw material, as well as food and building material to create camping sites. As a consequence, the lack of the conditions present in sites near a river, such as water and fair food supply that guaranty the survival of population of hunters/gatherers, may have influenced the establishment of chipping sites on top of hills, where the minimal conditions for the permanence of humans for long periods were aggravated by the shortage of water and food.

Clay sites are typical for populations of horticulturists/farmers and can be found both in the coast as inland. The sites expand to big areas and are near sources of water and food. Besides producing clay material, those populations also were horticulturists/farmers, but that is not the rule. The production of clay utensils included small and medium sized bowls as well as big vessels to store food. The big vessels are usually called funerary urns (Figure 4), because they were also used in funerary rituals.

Other than funerary urns, many other bowls can be found in clay sites, inclusively in shelter located inside caves (Figure 5).

Due to their big dimensions, clay sites indicate a wide territorial dominance from their occupants, mainly because of the zones needed to grow tubers as manioc (Manihot esculenta), pumpkins, beans and corn (Zea mays). Other remarkable characteristic of clay sites is that contrary to original hunters/gatherers, groups that produced clay continued to hunt and collect food to complement their diet. Growing crops demanded a long stay in the site. In other words, horticulturists/farmers were sedentary, changing their dwellings after generations or after the total exhaustion of the natural resources around camping.

Another kind of archeological site found in Brazil is the historical site. Sometimes they are mistaken for ruins of old houses or old miners, fishermen or farmers villas. Historical Archeology firstly got bolder in the Americas where the zones of European colonization provide structures and material vestiges left by ancient dwellers that represent a portrait of the life of the population that took part in the recent colonization of the countries.

In some regions, as the Chapada Diamantina in the State of Bahia-Brazil, ancient miner's historical cities or several abandoned villas in the interior of Brazil make up an archeological portrait of the colonial system implemented by the Portuguese, from the end of the 16th century. Those historical sites also show the way of life of entire populations that settled far from the big colonial centers (Figure 6).

Figure 04. Aratu Funerary urn from Almadina, State of Bahia – Brazil. Photo: Elvis Barbosa.

Figure 05. UClay bowl found inside the cave Gruta da Cerâmica, Bodoquena, State of Mato Grosso do Sul. Photo: Heros Lobo.

Figure 06 – Miners' houses in Cidade de Pedra, Xique-Xique de Igatu, Mucugê, State of Bahia- Brazil. Photo: Elvis Barbosa.

6.5. RUPESTRIAN ART

Rupestrian art is a special case in archeological analysis, mainly because it is difficult to understand. Rupestrian sites may be associated to hunters/gatherers as well as to horticulturists/farmers. Usually they are panels painted over rocky walls, in the entrance of caves and rocky walls in hunting sites. Rupestrian painting is emblematic all though many researchers do not consider it as an art form but as a graphism. Leaving controversies behind, the term rupestrian art is accepted worldwide and is the representation of the day-to-day life of the populations that occupied a given environment.

To understand the meaning of rupestrian art, it is necessary to understand what art represents in the so-called simple societies. Madu Gaspar mentions the division that social scientists made to classify the societies in two kinds: simple and complex. In the simple societies, everybody take part in the processes of production, distribution and consumption of goods, and the social division of the jobs is based in age and sex (2003, p.10). In the complex societies there is a strong social hierarchy that ensures privileges and duties for its different segments (2003, p.10).

In complex societies, there is no association between the producer and the consumer of the so-called artistic goods. This dissociation does not occur in simple societies because there is no "art market" and the dominance and control of what is artistic is connected to the day-to-day life of the community, strengthening the traditions backed by the supernatural realm, the rites and the myths.

Rupestrian art is born inside the simple societies in the paintings on the ceiling and on entrances of caves. Inside the caves, the first individuals from the genus Homo found shelter against the scorching heat of the prairies, against natural predators and the rain. Caves were shelters, dwellings, places to venerate the dead and divinities. This space is a natural locus important for building the human being as a subject that can interfere in the space and transform it according his long term or immediate need, to quench his thirst of knowledge and just to have some rest or keep warm during winter nights.

Depending upon the region of the Earth and mainly in karst areas, caves are seen a common geological phenomenon. Inside caves or in their surroundings, ancient populations made their first recordings in the form rupestrian art. Under the archeological point of view, there is no difference between, for instance, the sculptures in the cave of the Thousand Buddha's in China (Figure 7), the paintings in the caves Lascaux or Chauvet in France, the paintings in the Chapada Diamantina in the State of Bahia in Brazil, or in the Vale do Peruaçu in the State of Minas Gerais in Brazil (Figure 8). The message that the ancient groups wanted to transmit is still there waiting for a logical understanding because, after all, they are means of communication.

Under the concept of simple societies, the Brazilian rupestrian art presents many representations that show the day-to-day of the populations, their rituals, sometimes complemented by body parts paintings, and above all the rupestrian art is a part of a communication system whose printed expression was preserved , as stated by Madu Gaspar (2003, p. 12). In the paintings, there is not only a message, but also a complex system of ideas that a group could decode (Figure 9).

The rupestrian records are important for the current societies to understand the History of Humanity. No matter if the symbol is too simple, just a red line or if it is a detailed representation of an extinct animal. The most important point is the content of the message and the role it played for the group that created it.

Figure 07. Sculptures in the rock of the Cave of the Thousand Buddha's, in the karst of Guillin, China.
Photo: Luis Eduardo Panisset Travassos.

Figure 08 – Paintings in a wall next to the Cave Lapa dos Desenhos, Parque Nacional das Cavernas do Peruaçu, Brazil.
Photo: Heros Lobo.

Figure 09 – Rupestrian painting, Serra da Babilônia, Morro do Chapéu, Bahia, Brazil.
Photo: Elvis Barbosa.

6.6. ARCHEOLOGY IN KARST AREA

In general, the artifacts that integrate the material culture of a group are scattered on the soil and in the sub-soil of an archeological site. Nevertheless, when they are related to a karst area, it is understood that the archeological site may undergo some changes, mainly because of the kind of material that is found. In many karst areas, there is not much soil and clay material available. In most of the sites featuring such characteristics, the vestiges of hunters/gatherers prevail, that is, populations that lived exclusively from hunting and collecting food. Because of their way of getting their resources from nature, those groups could not comprise a great quantity of individuals. Hunting and gathering food every day is a tiresome task and requires the control of a vast territory.

Another characteristic that can be seen in karst areas is the prevalence of places with rupestrian painting or signs. In karst areas, the pre-historic man left his most intriguing testimony, very difficult to understand and that represented his view of the nature surrounding him, his actions and his day-to-day life. Usually, archeological sites with rupestrian paintings feature unique characteristics because of the prevalence of the printed record, and only rarely they have evidences of lithic and/or clay material.

Besides the records on the rocks, it is important to investigate evidences other than paintings. In older shelters, some other material vestiges as remains of fires and food, lithic and/or clay artifacts may lay under the various layers of sediments deposited in thousands of years. An archeological site located in a karst area may be a cave or just a simple rocky shelter. Usually the areas occupied in a cave are restricted to the twilight zone, but we cannot exclude the deepest parts, as in the already mentioned caves of Lascaux and Chauvet in France, Altamira in Spain and Gruta das Mãos, in the Municipality of Rurópolis, State of Pará in Brazil.

It is possible to say that a part of the Pre-History of humanity happened inside or around a cave. More than just being a collective space where men could live their traditions or express their imagination, a cave was the environment that offered the best protection to a human being. A cave was the best natural shelter against rain, sun, cold and heat, as well as it was one of the first human dwellings and meeting place. This connection between men and caves remains until today, in spite of the fear of darkness and closed spaces. In this context, the interaction of men and caves creates a mix of fascination and respect. In the History of humanity, in almost in all the peoples, we can find a reference of this relationship, mainly during the period of Pre-History, where the first human occupation of caves took place. At that age men was still the prey and not the dominant predator in nature.

In karst zones, rupestrian paintings are the predominant archeological evidences, among many others. Most of the panels found in karst zones represent the day-to-day life of populations, their hunting parties, the animals and vegetation living in the zone, some of which no longer exist (figures 10 and 11). A clear example of this situation is in Serra da Capivara, State of Piauí, Brazil, where around 20 thousand years ago (20,000 bp) fauna and flora indicated the presence of a dense tropical forest and animals belonging to the Pleistocene megafauna.

Figure 10. Zoomorphic figures painted in the ceiling of a shelter in Sítio Pequeno, Itaguaçu, State of Bahia, Brazil. Photo: Elvis Barbosa.

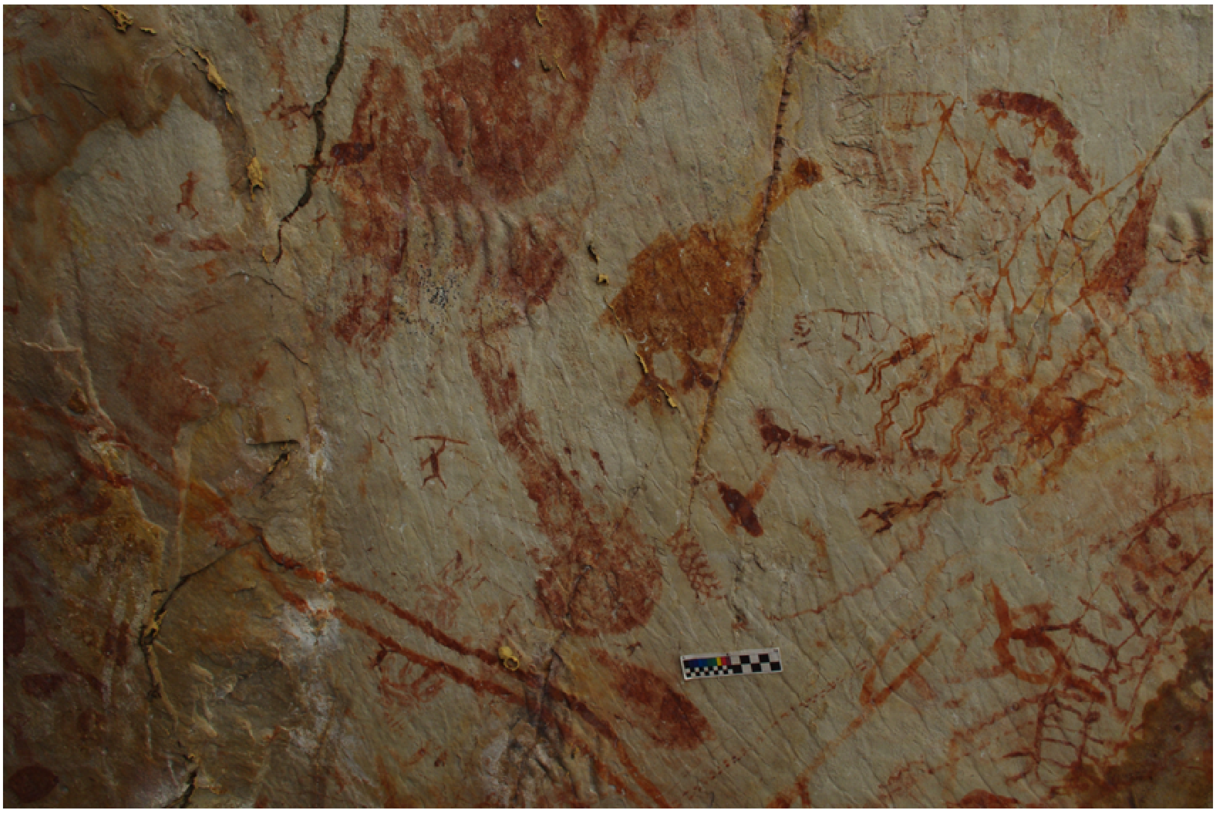

Figure 11. Zoomorphic figures painted in a shelter in Serra da Babilônia, Morro do Chapéu, State of Bahia, Brazil. Photo: Elvis Barbosa.

6.7. STAGES OF A RESEARCH IN ARCHEOLOGY

Very differently from what is showed in some movies with a popular appeal, the Archeological research has its proper methodology and is very demanding in the treatment of the materials and the areas to be studied. Usually, the stages of a research are divided as follows: not interventional prospection; interventional prospection; rescue and monitoring; informing where the archeological sites are located to the local communities as well the academic communities and researchers of correlated areas.

The not interventional prospection is a preliminary stage comprising the search for preliminary data on the region and for previous surveys concerning the area that will be impacted by the research. The search includes, for instance, the identification of archeological sites that had already been registered in data banks of Research Institutes, historical information about the region, geographic and statistic data as well. After this previous search, comes the fieldwork, which requires a series of walks around the grounds that are the scope of the research. In this determined area, a group of archeologists searches for the evidences of a material culture in a thorough scanning procedure. Usually in this stage, there is no intervention on the soil, sub-soil and no material is withdrawn. The methodology is followed with the collection of oral information from the neighboring communities, aiming to gather as many preliminary data as possible about the local archeological material. This stage is useful because it is a preliminary data gathering that may bring evidences that can guide future studies.

The interventional prospection is considered the most important stage of an archeological research. In this stage, the archeological site is delimited, marked and identified according to its importance and its relationship with any other sites located the region encompassed in the research area. Several methodologies can be used in this stage, one of them is the full-coverage survey (Fish & Kowalewski, 1990). This procedure is used in sampling areas where it is not possible to see the surface of the ground because of the vegetation or any other obstruction. There are several methods to identify archeological material, for instance, to align testing wells and excavate in artificial stratigraphic levels that can vary from 5 to 10 cm, according to the understanding of the archeologist in charge, withdrawing and skimming sediments until sterile soil is reached. Besides the testing wells, it is possible to open probing trenches 1 meter wide excavated in artificial stratigraphic levels. With this methodology, it is possible to delimitate the size and range of the archeological site.

Rescue is the longest stage and is the most important stage in the study of an archeological site. One of the methodologies oftenly applied is the decoupage of large areas. It allows the archeologists to thoroughly understand the site and the several stages of the occupation by ancient populations because the area is divided in squares of 1 meter of side. The excavation can be done in artificial stratigraphic levels of 10 cm or following the natural deposition of sediments on the site. By the end of the rescue, it is possible to create a complete map showing the different steps of occupation of the area, according to the material that was discovered and the structures located on the ground.

The scope of the methodologies applied to the processes of excavation and rescue is to provide the best possible understanding of the occupation of a specific area, comparing it to other archeological areas that may be interesting to the studies. The methodology applied by archeological studies, in the rescue stage, has the scope of providing the best possible understanding of the process of the ancient human occupation in a specific location, comparing it to different areas that are interesting from the archeological point of view. Therefore it is easier to establish the importance, both in quantity and quality, of the findings that would characterize the said human settlements, as well as to classify them as a long stay camping sites or temporary activities sites (Schiffer, 1972; Clarke, 1977; Redman, 1987; Hodder & Orton 1990; Renfrew & Bahn, 1996).

At this stage of an archeological research, it is highly recommended to do the monitoring, mainly in projects ruled by Archeology by Contract. During the rescue operation it is not always possible to withdraw all the material that is deposited in the site, therefore monitoring is the last chance to find new evidences of the material culture that have not been found during the excavation.

The last stage of an archeological study is to disclose the information to the communities around the site as well as to the scientific community. This is the way to ensure the preservation of the areas and to raise the awareness of the population about the importance of archeological vestiges.

Archeological sites are part of the Material Heritage of Humanity, internationally recognized by UNESCO on the Letter of Lausanne, the letter dedicated to the protection and management of archeological heritage, ICOMOS/ICAHM (World Heritage Committee/International Scientific Committee on Archaeological Heritage Management). In Brazil, the protection to archeological sites is granted by the Federal Constitution and by some more specific laws.

Archeological studies, which are required to characterize an archeological site, are steadily increasing in Brazil, mainly because private companies are gradually taking social responsibility and abiding the laws currently in force. Therefore, good practices in archeology, as the identification of archeological sites, the rescue of the material, spreading the information to communities and schools around the sites, are seen as a great opportunity for the private companies to add social value to their portfolio through the preservation of the historic and cultural heritage of the country.

The participation of the social groups that are directly or indirectly involved in archeological studies, as for instance, archeologists, entrepreneurs, members of the civil society, schools and communities living in the areas directly affected by the archeological studies, has contributed to enhance the knowledge of the Brazilian archeological heritage.

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CHAPTER 7:

SUSTAINABLE COMMUNITY DEVELOPMENT AND QUARRYING IN KARST AREAS

Solange Silva-Sánchez

People living in karst regions make multiple and varied use of the land. Their use of the karst resources goes from that of the soil for agriculture and urbanization to that of the surface and underground water for drinking or irrigation, as well as the exploitation of the mineral resources. Moreover, in places where caves are found, these features can take on a mystic or sacred significance and be transformed into sanctuaries. In addition to these more traditional uses, tourism and sporting activities often develop, as well as research of a scientific nature.

Given these varied uses, socio-environmental conflicts often arise in response to conflicting claims on the natural resources. The same geological features responsible for the scenic beauty of a karst landscape, which may have led to their preservation in the past, are also responsible for mineral richness of unquestionable economic value. Moreover, even karst regions which have not historically represented any great economic or populational dynamism, are already suffering the pressure of urban expansion, giving rise to new conflicts in use. Even the development of tourism can compete with environmental conservation.

There is a certain conflict inherent in the multiple uses of the natural and cultural resources of karst regions. These conflicts arise from the different forms of use and actions for conservation of environmental resources; they often involve multiple agents, including the government, local communities, businesses, social organizations, and the scientific community. If, on the one hand, conflicts can result from different values and interests, sometimes antagonistic, in both the short and long term, such conflicts can also pave the way for new ways of living together, provided agreements based on actions and strategies designed to facilitate the sustainable development of such different activities are sought.

Although many socio-environmental conflicts arise in association with the multiple uses of the resources in karst regions, it is perhaps quarrying which is the most controversial. Points of view vary widely, with quarrying seen as an activity generating negative socio-environmental impacts by some, while for others it is an activity capable of propelling the local and regional economy and making it more dynamic.

The issues of a social and economic nature associated with quarrying in karst regions are not fundamentally different from those usually arising from mining in general. However, there are certain peculiarities which must be carefully considered in the planning and development of projects, as well as in the implementation of socio-environmental plans and programs for action which are designed for community development. One of these is the use made by human communities of the resources of the karst environment. This should always be considered when the potential impacts of a new project are assessed and the strategies for the establishment of ties with the local community are defined. The conflict involving the use of natural and cultural resources of karst must be recognized, identified, and managed, with the local community, public authorities, organized social groups, and economic agents all included independently, in a transparent dialogue.

7.1 SOCIAL IMPACTS OF QUARRYING IN KARST REGIONS

The social and economic impacts generated by quarrying activities depend on various factors, including the size of the enterprise and the amount of investment, the dynamics of the local and regional economies, and the social context of insertion, as well as the social capital and capacity of communities to govern themselves. Moreover, the impacts will vary according to the stage in the life of the quarry, from the feasibility studies to post-closure. The specialized literature and experience have shown that some impacts on the economy are normally to be expected. These include creation of jobs of different levels of qualification; the local economy can become more dynamic and the prices of goods and services on the local market tend to rise; there is an increase in government revenue from taxes, as well as in the demand for public services of health, education, sanitation, transportation, and security; there may be an inflow of people in search of job or business opportunities, in addition to changes in the previously existing social relationships.

Quarrying can thus contribute to the establishment of a cycle of economic growth in municipalities in which these activities are located. This cycle depends not only on the characteristics of the quarrying activity, but also on market conditions. In situations in which a quarry is responsible for a significant portion of the local economy, this activity can stimulate diversification of the local and regional productive base, but it can also lead to economic specialization and contribute to a reduction in the activity of other economic sectors. However, the most important aspect involves the capacity to take advantage of the opportunities which are opened in relation to the generation of income and jobs and the capacity to turn this growth permanent via policies of sustainable development. The possibility of a quarry to become a sustainable activity, an effective instrument for development, is in opposition to the image of an activity which generates irreversible negative social and environmental impacts (Costa et al., 2011).

In karst regions, one can find mineral enterprises with quite diversified characteristics, from small only partially mechanized quarries with a limited number of workers to large enterprises associated with cement or lime plants employing hundreds of workers and requiring qualified manpower.

It is often the case that quarrying in karst regions takes place mainly in rural areas where the economy is based on family or subsistence agriculture. There are obviously regional differences, whether in relation to economic aspects or demographic dynamics. In some municipalities, the economy is strongly dependent on policies of public assistance while in others, the revenue depends largely on the quarrying activity. The latter results from a predominance of contributions to the gross municipal internal produce resulting from investments in the extraction of minerals. Other municipalities are capable of generating financial resources as a function of the economic dynamics and insertion in the market and the importance of other sectors of the economy.

In certain cases, when a large mining project is developed in rural karst regions, a decrease in local agriculture may results, since most of the products necessary for the supply of the company end up being purchased outside the community. On the other hand, corporate policies that call for establishing links with the community may result in programs which can strengthen and integrate the agricultural production into the supply chain of the quarry.

One should not forget that socioeconomic development driven by the development of a new quarry may cause indirect impacts on the karst itself. The population growth induced by the investments can result in changes, such as the expansion of urban areas, the increase in the volume of waste requiring appropriate disposal, and the expansion of areas dedicated to raising livestock, as well as increased tourism due to the improved access to the region. Certain karst regions already face strong pressure for the expansion of quarrying-related industries and population growth, with the related possibility of compromising the quality of the hydric, plant and scenic resources, a motive which has often been instrumental in the creation of protected areas (Berbert-Born, 2002).

The social and economic impacts are different as a function of the characteristics of each project, but they also vary with the stage in the life of the quarry, whether feasibility studies, development, operation, decommissioning, or post-closure (Sánchez et al., 2013). Specific impacts with different degrees of importance are associated with each step. Thus, in the planning phase of a mine, the most common impacts refer to possible tensions involving expectations related to the construction and operation of the enterprise, real estate speculation, and the rupture of community relations as a result of land acquisition, as well as involuntary resettlement.

The development of a new quarry involves the hiring of workers, and a great influx of individuals seeking work may occur (especially when the investment is large, and when associated industrial units, such as cement factories, are planned). The influx of people leads to increased demands for infrastructure and public services, and general nuisance (due the generation of dust, noise, vibration), as well as an increase in the circulation of unfamiliar persons in the community; the elevation of prices and the cost of life. Outbreaks of new diseases may occur, as well as incidents involving public safety. Moreover, involuntary resettlement involves the reestablishment of the network of public services once evacuation and the demolition of buildings have taken place. The implantation of a quarry can also generate a loss of lands potentially used for agriculture, as well as interfering with indigenous or traditional populations. The increased traffic of trucks can also represent a significant impact for outlying communities, even though they are removed from the area of the quarry as such. Other frequent impacts include changes in or destruction of sites of cultural interest. Positive economic impacts include an increase in income and tax revenue, which can be significant if services, such as civil construction, cleaning and others are contracted locally.

During the operational phase of the quarry, positive impacts such as an increase in economic activity and the generation of royalties will be felt, although sociocultural relationships will be altered, and the population growth can lead to conflicts related to the use of hydric resources, as well as an increase in interference with the cultural heritage.

On the other hand, during the decommissioning phase, the socioeconomic impacts will be largely influenced by the level of dependence of the community or municipality on the activities of the quarry. This dependence also has implications in the territorial scope of impacts (local or regional) and for more affected groups, so the most affected, such as local suppliers and businesses, should be identified. Certain impacts can be anticipated, including the loss of tax revenue, especially at the municipal level, the loss of jobs and income, and a decrease in local economic activity, as well as a frequent reduction in the quality and extent of public services.

The assessment of the social and economic impacts associated with quarrying is no simple task. The importance or vulnerability of a specific environmental or cultural resource can be decisive in evaluating the significance of an impact. Vulnerability should be carefully considered when dealing with karst regions, since their unique characteristics are what make the landscape exceptional (Sánchez, 2003).

The social and economic impacts of mining in general, and of quarrying in karst areas in particular, must be carefully identified and evaluated so that actions aimed at maximizing the contribution of a quarry to the community can be undertaken, especially where the extraction of non-renewable resources represents a significant economic activity. The main objective should always be the promotion of local and regional development on a sustainable basis.

Meeting such goals requires the adoption of a set of Initiatives by the mining companies, ranging from the accurate identification of opportunities to the building up of transparent and lasting relationships with the community. On the other hand, the public authorities must act as a facilitator, mobilizing the governance to articulate the resources and efforts of the civil society with those of economic agents. Herein resides the power of mining, as it can give impetus to a cycle of economic growth by encouraging the development of relevant local enterprises, giving rise to a process of productive diversification and resulting in the effective development of the host community.

7.2. COMMUNITY DEVELOPMENT AND QUARRYING

For many years a large number of mining or quarrying companies have considered the provision of jobs and the payment of taxes to be their contribution to local and regional development. Nowadays, such a relationship is more complex and companies – especially the large ones – are expected to contribute more in terms of social responsibility, committing themselves to the development of host communities and seeking to make a positive and lasting contribution in the long run.

Community development requires a process of strengthening of the self-confidence and capability of the habitants of that community, thus creating conditions for them to play an autonomous and responsible role in influencing and making decisions which affect their lives, becoming true protagonists in the process. Actions which lead to truly sustainable community development will contribute to the consolidation of a community in a lasting way.

The relationship between sustainable community development and quarrying is an issue which has provoked intense debate in the academic area, in government institutions, and within organized groups of the civil society. The debate involves various points of view. On the one side, local and regional governments promote policies for economic development and the mining companies emphasize the capacity of mining to promote such development. On the other, organized groups of the civil society, environmentalists and those involved in social movements are more concerned with the negative impacts generated by mining. Local communities tend to take a stand according to the relationship established with a company, whether employees, suppliers, or only those living in the vicinity of the mine (Silva-Sanchez and Sánchez, 2011).

It is not unusual for a mining company intending to install itself in a community lacking infrastructure and basic social equipment to supply these services, often taking on a task which is actually the responsibility of the public administration. The construction of schools, health clinics, and roads are among the investments frequently assumed by large projects. If, on the one hand, this kind of initiative is well accepted by the community in which the quarry is to operate because it solves certain problems of an often urgent nature, on the other, it does not promote any effective strengthening of the community and its capacity and ability to develop independently, especially after the closure of the quarry. Experience has shown that certain attitudes tend to jeopardize the sustainability of quarrying activities, such as, company planning without the participation of the local community, provision of access to only certain members of the community, or creation of programs which cannot be managed adequately by the persons benefitting from them (ICMM, 2012).

The possibility of a quarry contributing to the initiation of a cycle of economic growth in municipalities and locations in which it functions is related to the capacity (or not) of that community to take advantage of the opportunities offered in relation to the management of income and jobs and the capacity for perpetuating the economic growth via policies of sustainable development to the benefit of future generations. The installation of a quarry can play a central role in community development when it promotes the conversion of a local asset (the non-renewable natural resource) into another asset of a different nature, i.e., human and social capital (ICMM, 2012). For this process to be successful, however, the mining company must formulate long-term strategic objectives which consider, among other aspects, actual and future plans for local and regional development.

Programs, plans and actions implemented by a mining company aimed at sustainable community development must be present in all stages of the life cycle of a mine, although the strategies and the effort which should be used for any given stage vary in accord with the type, localization, and size of the mining activity. However, certain basic principles should orient the actions of the company: i) establishment of a link between the long-term strategic objectives of the company and the local and regional plans for development; ii) guarantee of consultation with and participation of the community; iii) engagement of all stakeholders, public authorities, civil society organizations, and the company; and iv) improving the capacities of the community, organized civil society organizations and the local government (ICMM, 2012).

The great challenge is thus to create conditions for a thriving environment propitious for the prospering of other activities parallel to those of mining. During this process, the involvement and responsibilities of the company should be shared with the local government and the organized civil society acting in the community and region (ICMM, 2012). Moreover, the confidence of the community in the company must be developed by implementing effective and permanent channels for communication.

Each of the social agents involved has a distinct, yet complementary, role to play, and all should work together for the success of initiatives which are aimed at sustainable community development. The company must play an active role in implementing socio-environmental plans and programs which encourage the development of the capacities and abilities of the community. Local governments should take a stand as strategic leaders, coordinating actions, articulating resources and policies in the various spheres of the government, and providing the necessary basic services. The organized civil society, whether an NGO acting on a regional or national level or a community organization operating on a strictly local level, should help in the identification and establishment of the hierarchy of needs and demands in the mobilization of local actives, collaborating with the organization of the population or even with the identification and resolution of eventual conflicts.

7.3 STUDIES AND SURVEYS

The possibilities for promoting local development permeate all levels of the cycle of a quarrying project, and they start long before the actual operation is implemented. At each stage, certain specific challenges and opportunities are faced, starting with the feasibility studies, which can be considered the starting point of the life of a mine, until decommissioning, actual closure and post-closure monitoring (Sánchez et al., 2013).

The adequate assessment of impacts and the design of action plans capable of promoting local development and enhancing human and social capital should be present from the outset. Initially, the company should adopt a variety of initiatives aimed at mitigating the concerns of each stakeholder. Examples relevant to local communities include sharing knowledge and abilities in the areas of commerce, administration, finance, logistics, supply via the promotion of capacitation and qualification of local agents, such as small businessmen and employers. Another initiative would be the development of programs for the alphabetization of adults or of the capacitation of young adults, initiatives which can generate value for the community.

Such programs and projects must be permanent and, in general should not merely provide immediate assistance, but should always attempt to empower the communities and strengthen governance (Enriquez et al., 2011).

Given the importance of the specificities of the context in which it is to operate, quarrying in karst regions has the chance of maximizing use for tourism, facilitating plans and programs adequate for the characteristics and demands identified and promoting for example, speleotourism and its multiple possibilities. The socioenvironmental programs formulated by the company and the social responsibilities assumed should be designed to preserve the speleological heritage and encourage the development of an economic activity based on tourism which will be capable of generating income and contributing to the strengthening and diversification of the local economy (Lobo et al, 2010).

Quarrying can be stimulated to support the creation of local social networks congregating various public agents and social actors in the initial stages of the project, including agents or councils for local or regional development. Such councils or development agencies should respect the principles of public participation and transparency, aiming at sharing experiences and information. Such an approach should strengthen social ties and the confidence of the society in the possibility of development. It should also help discover potentials for local and regional development in addition to the quarry itself. Attaining these objectives will depend on a continuous and long-term commitment of the company with programs and projects designed for this purpose, as well as the characteristics of the communities, i.e., the greater or lesser organizational and participative capacity, the social capital available, and the capacity to mobilize it.

More and more frequently, regional development funds or community foundations aimed at the management of financial resources, social contributions, and other benefits generated by mining are created in order to foster the sustainable development of the affected communities. Such foundations are constituted on the basis of contributions and investments which have nothing to do with the legal obligations of the companies to mitigate or compensate for negative social impacts. They are institutions which are designed to implement social plans and programs in the long run in an attempt to foster local development.

In agreement with the legislation of each country, royalties from mining can also be distributed to municipalities. For example, in Brazil, the federal legislation has instituted a financial contribution (Financial compensation for Mineral exploitation or CFEM) calculated on the basis of the net income obtained by a mining company from the sales of a mineral product, with the intention of creating a tie between mining and local development.

States and mining municipalities can then invest these resources in improvements of the local infrastructure, health and educational services, or other areas which promote the development of the local economy, once the post-closure scenario of the mine is implemented. However, it is important that the municipalities benefitted develop a specific plan or even a law which links the flow of these financial resources to a strategy of productive diversification or a local development fund.

The basis for sustainable community development is the adequate knowledge of the local reality, of its weaknesses and potentials. This includes the identification of economical possibilities of the community and of the region for the generation of jobs and income, the identification of interest groups and local leadership, and the knowledge of social and cultural aspect of the community. In locations highly dependent on mining, more pragmatic actions based on the mobilization of a hierarchy of previously identified economic potentials is of great value. In locations with a more developed economic base, it is possible for municipalities and regions to attract national and international resources (financial, technological, and institutional), as well as public and private investment via a variety of modalities. The greater the dependence, the greater will be the role of the mining company in the development of partnerships and the promotion of actions designed to diversify the local economy. The involvement of the local government, of associations of organized civil society and the community is an important condition for the success of development programs.

Knowledge consistent with the reality in which a company operates, based on a systematic survey and careful analysis of relevant data, in the light of the history of conflicts which may exist or have existed in the past, as well as the demands and aspirations of the population, can orient a company in the selection of those aspects which should be worked on and evaluate the possibilities, the advantages and the disadvantages of associating with organizations which act locally or regionally, thus avoiding the duplication of actions or strengthening those which seem promising.

Knowing the local reality and the identity of the relevant social groups can help the company understand the pre-existing demands and conflicts and promote actions and projects which can be successfully implemented in a community, thus optimizing the resources invested. Historical demands of traditional populations or conflicts due to the overlapping of natural protected areas and those of great mineral potential already under discussion in the community should be carefully considered. Moreover, successful experiences of local governments in articulation and the formation of inter-municipal groups also deserve support by the mining company.

In general, socioeconomic studies and baselines should be prepared during the initial phases of projects, as part of the environmental impact assessment. The initial baseline may rely on secondary data, such as those of the demographic census, as well as of government departments or research institutions, although these should then be supplemented by primary data obtained in field surveys. The baseline should include a consideration of the following: 1) demographic dynamics, ii) economic organization and dynamics; characteristics and conditions of the local and regional productive structure, iii) basic infrastructure and services available, iv) public finances, v) social organization and sociopolitical context, vi) vulnerable social groups, vii) local use of natural resources, and viii) popular culture, including the identification of places relevant for its production and consumption. Precise information about the local and regional job market, its present dynamics, and future tendencies are also valuable.

Although such surveys and analyses of secondary data are necessary, they are insufficient in themselves. They must be supplemented by field surveys, interviews, and questionnaires specially tailored for the specific purpose, with objectives oriented to identify and understand the way in which the key actors perceive and rank problems and the qualities of the location, including their identification of priorities, expectations and receptivity in relation to an enterprise, in addition to their understanding of previous or current socioenvironmental conflicts, if any, in the area of the project and its surroundings. The way in which these key actors relate with the territory and make use of its resources should also be investigated.

During this investigation, it is fundamental to identify the individuals or groups which, directly or indirectly, can be affected (both positively and negatively) by quarrying or any associated activity, as well as those who have special interests or can influence the project. This mapping of these stakeholders (those individuals or groups who may be affected, either directly or indirectly, by the mining activity, or that have an interest or influence on the results) is a critical part of these initial studies. Even though they contain detailed and exhaustive information, they should be periodically updated.

For a mining company, such valuable information will be fundamental for developing a system of socioeconomic indicators to be continuously monitored. These indicators will provide information about local development and changes taking place, and facilitate decision-making, as well as revealing actual tendencies, identifying ahead of time the occurrence of undesirable situations, such as the establishment of new conflicts in relation to the use of natural resources, and identifying possible shortcomings in the coverage of the social plans and programs implemented by the company, or results which fail to respond to what was originally defined by the objectives established.

The indicators of development will be a point of reference for the evaluation of the possible improvement in the quality of life of the municipality and its communities, based on pre-determined parameters. These can include indices of literacy, access to preventive health services, level of individual and family economic well-being, monthly income per household, and frequency of utilization of public space for leisure and culture, as well as satisfaction of the community with the company.

The specialized literature of the field recommends that indictors should be constructed on the basis of a participative approach, i.e. one which involves the community and local leaders, regional public actors, and the organized civil society. These individuals should participate in broad public consultations and workshops to guarantee extensive social mobilization. The participatory construction of indicators of development gives rise to an efficient tool for the measurement of changes over time in the municipality and the region, providing support for public policies and private investment, as well as data for planning.

7.4. PARTICIPATIVE APPROACH: CONSULTATION AND PUBLIC INVOLVEMENT

In various countries, there are legal obligations requiring public consultations in order to obtain authorization and governmental licenses. One frequently criticized deficiency in the formal process of consultation, however, is that they take place quite late in the elaboration of a project, after many decisions have already been taken; this leaves only a secondary role for public consultations such as negotiating compensation. Moreover, many companies consider such legal obligations to be mere formalities, rather than an opportunity to initiate a process of significant and permanent communication with the community and other stakeholders.

Consultation and the engagement of stakeholders are part of an overall and continuing interaction between the mining company and the potentially affected stakeholders; such an approach should be initiated during the feasibility studies and maintained throughout all the life of a mine, (IFC, 2007; Instituto Votorantim, 2012; 2013). Considering that each phase gives rise to distinct questions and opportunities, different strategies of engagement and participation should be adopted, consistently keeping in mind the nature, localization and size of the mining activity.

Experience has shown that communities adjacent to the facilities of a cement industry respond positively to a participative process of consultation. Moreover, communities which have established a channel for dialogue with the company and are able to achieve a certain empowerment present lower indices of pollution and benefit from a better quality of life; this also results in greater profitability for the company, which should take the initiative to establish a positive and continuous dialogue with the host community (Battelle and ERM, s/d).

Potential stakeholders in addition to the local community include representatives of local and regional public authorities, civil society organizations, political and religious leaders, representatives of professional bodies, vulnerable social groups, suppliers, clients, company employees and outsourced workers, and tourist agencies (both receptive and emissive). Moreover, for quarrying in karst environments, the participation of groups with a special interest in such environments should be included, such as speleologists and researchers. Companies are advised to maintain permanent channels of communication with these groups.

In general, the engagement of stakeholders involves a series of actions, including the following: i) identification and analysis of the stakeholders; ii) dissemination of information about the project, iii) consultation with the stakeholders; iv) negotiation and establishment of partnerships; v) management of conflicts; vi) involvement in monitoring; and vii) reporting. The literature provides a great diversity of tools and methodologies which can be used to promote the engagement and participation of stakeholders. The choice of method and tools should consider not only the context in which the quarry is inserted, but also the phase in the life cycle of the mine. There is no single approach for all situations; instead, the whole process should constitute part of a carefully designed and continually reviewed plan (Instituto Votorantim, 2012).

During the stage of feasibility studies for a mining project, it is important that the company establish a plan and strategies for the identification and mapping of individuals or social groups which have a certain interest in the project or can influence its results; certain key questions can be used to orient the mapping of the stakeholders (Table 1). Such an approach can even help in the process of decision making, such as deciding points of access or the route of trucks which will be transporting the mineral, or the most adequate forms of communication for the target public (degree of organization, level of literacy, etc.). There is tendency to give priority to individuals or groups established in the area of the project, or in its immediate surroundings.

However, care should be taken not to narrow the surveys too much nor to underestimate certain groups which can be affected by indirect impacts, or overlook interested groups outside the immediate area. The engagement of stakeholders can result in effectively sustainable decisions because these will be widely accepted and understood by the public, and this public will thus acquire confidence in the agents who make the decisions (Battelle and ERM, s/d).

QUADRO 1 – Stakeholder mapping

Identification of stakeholders: questions which should contribute to the identification of the stakeholders

- What are the legal requirements for the process of public participation?
- What individuals or groups will be negatively affected by the potential environmental and social impacts in the area of influence of the project?
- Who are the most vulnerable individuals or groups among those potentially affected?
- In which phases of the development of a mine will specific individuals or groups be most affected (development (acquisition of land), construction (greater flux of people), operation (increase in demands for infrastructure), decommissioning (decrease in tax revenue; layoffs)?
- What individuals or groups approve of the project?
- What individuals or groups are opposed to the project and what are the main issues raised?
- Who are the representatives of the local public authorities?
- Who are the leaders of those who form opinions on the local or regional level?

Source: adapted from International Finance Corporation (IFC), 2007. Stakeholder Engagement: A Good Practice Handbook for Companies Doing Business in Emergent Markets. IFC, Washington .

In karst areas with potential for tourism or with consolidated tourist activity, the mapping of the stakeholders should also consider an itinerant public, a non-uniform group represented by tourists. These are individuals or groups who only occasionally circulate in and take advantage of the area of influence, but who may be affected by certain mining activities. This public includes not only the tourists, but also operators and tourist guides, government authorities involved with tourism acting in the location, individuals visiting relatives, speleologists, sportsmen, and researchers, as well as specialists who study karst for the most varied of reasons.

The size of the project and, above all, the importance of the environmental impacts generated are issues to be considered in the formulation of company strategies. Highly complex projects require a more sophisticated approach which can effectively reach the increased number of groups and individuals with a certain interest in the project. In all cases, the definition of responsibilities is internal to the company, however, and the engagement of the upper management is essential for the success of the task.

The identification of the stakeholders should be detailed and periodically updated, since the concerns, interests and groups affected can change throughout time and the different stages of the life cycle of the quarry. Whenever there is any important change in the project, in the social plans and programs under the responsibility of the company or in the social, economic and local political conditions, it is recommended that the mapping of stakeholders be reviewed (Instituto Votorantim, 2012).

In the literature and specialized manuals there are a variety of techniques and tools which can be used to proceed with the identification of the stakeholders (IFC, 2007). These surveys should adopt a systematic approach and be oriented by a well-defined strategy, with clear and measurable objectives.

The dissemination of information about the project should consider the diversity of the stakeholders identified and mapped. The language utilized should be clear, objective, and accessible to the public to which it is directed. In general, the information should be comprehensible to all the stakeholders, including those individuals and groups who do not have technical knowledge about the project. Transparency in the communication of information is a condition for avoiding loss of credibility of a project and of its representatives.

Evidently, the information and messages transmitted by the company will be interpreted and perceived in different ways, depending on the target, due to the individual characteristics of the receptor, such as experience, cultural values, expectations, diversity of interests in relation to the project, degree of education, ethnic background and gender, and structure of local leadership. A company should be careful to develop its plan for communication and public relations considering these aspects and should orient a team of qualified professionals in their choice of techniques to be utilized and the information to be presented. Communication at certain times, such as when operations are starting, when there are significant alterations in the project, and when the mine is being decommissioned, is especially important.

Access to relevant, up-to-date, and accurate information about the project and its impacts is crucial for the consultation with the stakeholders to be effective. Informed participation must be established if a qualified dialogue between community and company is to be constituted.

The ideal is that the process of consultation be initiated during the initial stages of a mining project, a practice which should be strictly linked to the plan of communication formulated by the company. Consultation of the stakeholders makes it possible to intensify their understanding of the project and contribute to the establishment of a cooperative and collaborative context, which will be indispensable to the success of the programs for the sustainable development of a community. Moreover, consultations during the initial stage of development of the project can provide information about any components of the project which may prove to be problematic from the point of view of certain stakeholders and which should be reviewed or which alternatives should be pursued. For example, a planned access route may lead to conflict due to the fact that it intersects a village or passes beside a school, or because it puts at risk a spring located upstream from the place where drinking water is withdrawn by the community.

In this interactive process, the manifestation of different points of view, concerns, and expectations of the community and other groups and individuals interested in the project should be guaranteed. It is necessary to guarantee that these points of view be heard and that the concerns and expectations be duly considered. When pertinent, measures to alleviate them should be incorporated into the project. When these cannot be incorporated, it is good practice to register the reasons and provide explanations those who have participated in the process.

Consultation must be conducted in an organized manner, with actions planned and structured for various target groups. The consultation can involve individual or group interviews, workshops, focal groups, sectorial meetings, public hearings, polls and surveys. Various methodologies for participation can be adopted, as long as they are adequate for the target population, which requires the involvement of qualified professionals to plan, implement and evaluate the process. Moreover, there is a vast literature about this, which suggests of different tools, methodologies, and techniques which can be applied in the most diverse of contexts (IFC, 2007); CDA,2005). Good practice recommends at least five basic steps for the development of a process of consultation with the stakeholders that will lead to interaction and make it possible to obtain effective results (IFC, 2007).

1 – Plan ahead of time, considering who should be consulted, what questions are relevant and what the objectives of the consultation are.

2 – Utilize the best practices possible; consultation is always specific to a given context and the specific kinds of stakeholders and, for this reason, can involve different approaches. However, some principles must be guaranteed, i.e., the process must be directed to the individuals/groups affected; it should start as soon as possible, should be significant, interactive and inclusive, and free of manipulation. The documentation of the entire process is also recommended.

3 – Communicate the results: the company should show the stakeholders how possible modifications will be incorporated into its plans and let them know this is the result of concerns expressed during the consultation process.

4 – Document the process of consultation, registering when and where the meetings occur, who participated, what topics were discussed and what the results obtained were.

5 – Inform the results of the process of consultation and indicate what the next steps will be.

The team responsible for conducting a public consultation should share the same information so that the message to be transmitted is clear and coherent (Instituto Votorantim, 2012). The management of the company should always accompany the process and consider the results when making decisions.

The establishment of channels of communication with the community and interaction with leaders, public authorities, and organizations of the civil society can result in the creation of a community council to collaborate in the mapping of the local reality so that more precise goals can be set and programs defined which are designed to strengthen the social capital and improve the socioeconomic indices (Instituto Votorantim, 2012 b).

Even though the engagement of the stakeholders and the regular supply of relevant information about the project contribute to the establishment of a dialogue between the community and the mining company, the company should also adopt a formal channel for receiving and registering complaints. Such an action can facilitate the resolution of conflicts which may arise throughout the useful life of a mine.

The form to be adopted can vary from the creation of a direct channel of communication, such as a freely accessed telephone line, an ombudsman´s office, a website maintained by the company, or a physical office staffed with a dedicated employee who can establish a dialogue with the community. What is really important in this case is that the mechanism for receiving and registering complaints be accessible, commensurate with the complexity of the project, transparent, and effective in relation to the answers given by the company. The registration of complaints is essential and should be forwarded to the sector responsible for the adoption of corrective actions, when necessary, and these should be communicated back to those who are interested.

Monitoring measures designed to mitigate project-related impacts or their compensation should also be participative. By adopting such a practice, the company provides incentives for the community to share responsibilities, and encourages the empowerment of the community in that it has a certain influence and capacity for determining actions and making decisions about questions which directly affect it (IFC, 2007; Sánchez et al., 2013). However, the community does not always have the ability nor the capacity to do this. In such cases, the company can implement programs for training to develop certain technical abilities within the community, such as the accompaniment of analyses of the water quality or the evaluation of certain socioeconomic indicators. Another approach would be for the company to hire external monitors, such as an NGO or local academic specialists to conduct the monitoring with the community, but still in a participative and informative manner.

The entire process of participation and consultation, as well as the environmental and social performance of the company and the results of monitoring and socioenvironmental programs must be documented and communicated to the interested parties. There are international standards to be considered when elaborating such reports (IFC, 2007); however, certain aspects are especially important: furnish relevant information, respond to the expectations of the interested parties, contextualize information and guarantee the comprehensiveness of that information so that the stakeholders can draw their own conclusions (IFC, 2007).

The relations with the resident population and those interested in karst areas is of great importance for mining companies when they are developing new projects and when they operate quarries in these regions. In addition to the care to be taken in the assessment of impacts and the socioenvironmental management of any mining enterprise, in karst it is especially important to pay attention to the local communities and their direct and indirect use of the natural and cultural resources.

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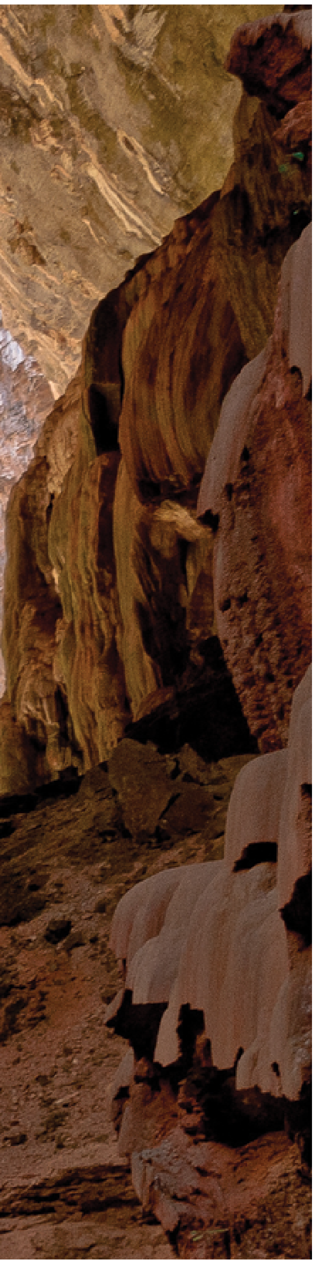
Photo: Allan Calux



PART 3

GOOD PRACTICES FOR QUARRYING IN KARST AREAS

In this section, there will be the recommendations for good practices for quarrying in karst areas in order to prevent adverse environmental and social impacts resulting from quarrying limestone in karst environment. The recommendation are organized according to the main stages of the life of a quarry: feasibility studies, implementation, operation, deactivation and post-closure.

SECTION 1:
IMPACTS FROM QUARRYING LIMESTONE ON KARST ENVIRONMENT

Luis Enrique Sánchez and Ana Claudia Neri

Box 1 pictures a Matrix for the Identification of Impacts that summarizes the main relationships of cause and effect among the main activities along the life span of a quarry and their impacts on karst environments.

The Matrix can help to identify the impacts from new projects as well as projects to expand the activities of already operating quarries. For a proper evaluation of impacts, the activities described on the matrix can be detailed, by adding new activities related to the project or sub-dividing the ones that are grouped, that is, that encompass other activities as, for instance, building activities.

In this box, the expression "environmental aspect" is used according to the definition provided by norm ISO 14001: 2015: "element of the activities, products or services of an organization that interacts or may interact with the environment". On its turn, environmental impact, according to the same source, is "any modification of the environment, bad or good, that results, on the whole or on parts, of the activities, products or services of an organization".

The matrix presents the potential impacts, that means, the ones that may occur when quarrying is done in karst areas. To identify the impacts from a given project, it is necessary to acknowledge: (1) the project in full details (for instance, some impacts are only foreseen when certain activities are performed, as pumping subterranean water, which is not necessary in every quarry); and (2) the environment that was affected (for instance, it is only possible to confirm that fossils could be lost if a proper study was done).

The present guide provides orientation for planning and applying efficient practices to mitigate the social-environmental impacts in karst areas, and to understand the very nature and the importance of karst environments, as well as to learn the main impacts of quarrying on karst and on the human population. Impacts from quarrying that are not specific for karst environments, all though being mentioned on the matrix (for instance, "alteration in the sonorous environment") will not be dealt with hereto.

Previous studies and surveys about the karst systems, in a proper and thorough way, is a condition to achieve a satisfactory planning and to apply the practices hereto described.

When a company elaborates a project and operates an enterprise, it has the control over the environmental aspects of its current or planned activities, for instance, the area that is already occupied and the area to be occupied. A company can mitigate its impacts when it takes action over the environmental aspects.

In the present Guide, mitigation of impacts is understood according to the internationally consolidated idea of "mitigation hierarchy" (Figure 1), according to which when planning, implementing, operating and deactivating an enterprise, a company must search for the solutions to avoid , reduce, correct or compensate adverse impacts, in this very order. To this scale, one must add to take the opportunity to improve the environmental and social conditions in the area under the influence of the quarry, for example, applying measures for an ecological restauration aiming to connect remaining fragments of the native vegetation. Another measure of the same category could be the re-composition of the ciliary vegetation.

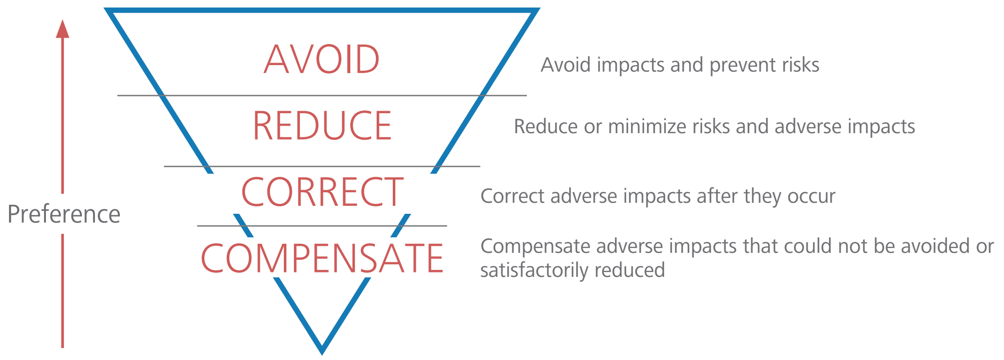


Figure 1. Hierarchy of the mitigation of impacts

Therefore, mitigation encompass:

(1) Avoid impacts, as for instance, by modifying the quarrying design to protect a cave, an archeological site, a water spring, a feature of the exokarst or any other relevant element of the environment, or modifying a pile of sterile to protect a doline that is important to recharging the karst water table.

(2) Reduce impacts, as for instance, by changing the trajectory of a long distance conveyor belt to detour a fragment of native vegetation and reduce the need to remove this native vegetation.

(3) Correct adverse impacts after they had happened, as it is the case to re-stablish native vegetation on an area that has already been quarried, or repairing damages caused by the operation of the site like oil leakages.

Decisions adherent to the notion of hierarchy of the mitigation, taken for each stage of the life of the quarry, contribute to make a quarrying enterprise compatible with the need to protect environmental and cultural resources and with the rights that the communities are entitled to.

(4) Compensate the impacts that could not be avoided and whose mitigation is insufficient or even possible, compensation is the strategy applicable when there is the suppression of a relevant element of the karst, as caves, vegetation or human communities dwellings.

The several surveys recommended in the present Guide aim to contribute to supporting the decisions of the enterprises and governmental agencies, in relation to the protection of the karst and of the communities living in it, by providing relevant information and knowledge about karst.

Box 1 shows the potential impacts of a quarry taken individually. When several companies operate in a same region the impacts accumulate, in time and space, and the management measures taken by one company may not be sufficient to ensure satisfactorily protection to the karst and to the population living in it.

Cumulative impacts are implicit in the present Guide. Some of the good practices hereto as recommended can also be applied to prevent cumulative impacts. Therefore, the adequate evaluation and management of cumulative impacts require coordinated actions from various agents, including the several companies operating in the same region. The present Guide does not include such recommendations, which can be found in specific sources about the evaluation of cumulative impacts.

Decisions adherent to the notion of hierarchy of the mitigation, taken for each stage of the life of the quarry, contribute to make a quarrying enterprise compatible with the need to protect environmental and cultural resources and with the rights that the communities are entitled to.

Main activities in limestone quarrying*

Environmental Aspects	Topography and mapping services	Probing	Real estate survey and acquisition	Hiring services and workforce	Implementing the worksite	Cutting the vegetation	Opening in site roads	Landfilling and preparation for the foundations	Building the industrial plants and support facilities (mills, workshop, etc.)	Building supporting facilities (transmission lines, sub-stations, etc.)	Purchase and delivery of the equipment	Removing the superficial soil	Decoupage	Perforation and dismantling the rock	Loading and transporting the mineral and the sterile	Milling and granulometric classification	Stockpiling the mineral and milled rocks	Maintenance: mechanical, electrical, building	Maintenance: mechanical, electrical, building	Supporting the production activities (administration, etc.)	Reception and storage of the production input	Catching surface water	Pumping subterranean water	Recuperating degraded areas (beginning in the operation stage)	Dismantling industrial structures, demolition of useless buildings and structures	Dismissing manpower	Inspections, monitoring, patrolling and other activities
	Feasibility			Implementation								Operation												Deactivation			
Interaction with the soil/use of the soil and landscape																											
Alteration of the landscape							■	■					■	■				■									
Intensification of the eroding process and the superficial dynamics					■	■	■	■	■	■		■	■	■			■	■									
Exposure of the soil					■	■	■	■	■	■		■	■					■									
Risk of spilling hydrocarbons																			■		■						
Circulation of vehicles in the site	■				■				■	■					■					■	■			■			■
Interruption or reduction of the superficial water flows						■								■								■					
Lowering the water table level																							■				
Occupation of areas covered by native vegetation						■																					
Occupation of areas of direct anthropic use (agriculture, infra-structure, etc.)			■		■	■																		■			
Interference in areas of cultural interest (e.g. Archeological sites)					■		■	■						■				■									
Re-stablishing ecological processes																											
Consumption of natural resources																											
Appropriation of non-renewable natural resources															■												
Consumption of hydrocarbon and other non-renewable resources						■			■				■	■	■	■			■								
Consumption of water			■			■					■												■				
Consumption of other natural renewable resources						■											■										
Consumption of electrical energy						■													■	■	■	■	■				

	Potential Impacts from Quarrying in Karst Areas *																													
	Loosing karst features and visual impacts	Loosing caves	(risk of), breaking speleothems	Speeding or inducing the processes of karst dynamics (e.g. Dolines)	Loosing water springs	Loosing fossils	Loosing archeological artifacts	Taking the archeological sites out of their context	Reducing the water recharge into karst water tables	Loosing or fragmenting natural or slightly altered habitats	Loosing anthropized habitats	Re-composition or connection of habitats or anthropic areas	Reducing the hypogean populations	Reducing the population of rare species	(Risk of) extinction of endemic species	Loosing the wild fauna	Disturbing the wild fauna	Degrading aquatic habitats	Reducing the availability of water	Contaminating the soil	Degrading the soil	Degrading the quality of the air	Degrading the quality of the superficial water (e.g. Eutrophication)	Degrading the sonorous environment	Loosing places to reside, to work and to socialize	Loosing physical references to memories (residences, cemeteries, etc.)	Loosing meeting points and cultural production places	Loosing or limiting access to areas providing ecosystemic resources and services	Environmental disturbance and discomfort	Reducing the inventory of resources	Other socio-economic impacts
	■	■			■	■	■	■					■	■	■	■								■	■	■					
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Main activities in limestone quarrying*	Feasibility			Implementation								Operation												Deactivation			
Environmental Aspects	Topography and mapping services	Probing	Real estate survey and acquisition	Hiring services and workforce	Implementing the worksite	Cutting the vegetation	Opening in site roads	Landfilling and preparation for the foundations	Building the industrial plants and support facilities (mills, workshop, etc.)	Building supporting facilities (transmission lines, sub-stations, etc.)	Purchase and delivery of the equipment	Removing the superficial soil	Decoupage	Perforation and dismantling the rock	Loading and transporting the mineral and the sterile	Milling and granulometric classification	Stockpiling the mineral and milled rocks	Maintenance: mechanical, electrical, building	Maintenance: mechanical, electrical, building	Supporting the production activities (administration, etc.)	Reception and storage of the production input	Catching surface water	Pumping subterranean water	Recuperating degraded areas (beginning in the operation stage)	Dismantling industrial structures, demolition of useless buildings and structures	Dismissing manpower	Inspections, monitoring, patrolling and other activities
Emissions																											
Emissions of particulate material					X			X	X	X	X	X	X	X	X	X	X										
Emissions of combustion gases					X			X	X	X		X	X	X	X	X	X										
Drainage of rainwater (and solid particles)					X	X	X	X	X	X		X	X														
Drainage of water effluents			X															X	X	X							
Emission of sounds			X		X	X	X	X	X	X				X	X			X	X						X		
Vibration on the ground														X													
Emission of light																		X									
Generation of steriles													X	X													
Generation of residues					X				X	X									X	X					X		
Social-economic and cultural interaction																											
External traffic of trucks and other vehicles		X	X		X	X					X											X				X	
Generation of jobs / reduction of workplaces				X																						X	
Generation of business opportunities / reduction of activities				X							X																
Attraction of people				X																							
Involuntary displacement pf people				X	X																						
Increasing demand of goods and services				X	X						X														X		
Increasing demand of public services				X																							
Generation of taxes and contributions				X	X						X														X		

* Related only to activities that can cause significant environmental impacts.
The activities can be detailed and sub-divided to better describe each project.

Source of the matrix: Sánchez, L.E.; Hacking, T. An approach to linking environmental impact assessment and environmental management systems. Impact Assessment and Project Appraisal 20(1):25-38, 2002. DOI 10.3152/147154602781766843

Box 1. Matrix containing the environmental aspects and impacts from quarrying limestone in karst areas.

	Potential Impacts from Quarrying in Karst Areas *																														
	Loosing karst features and visual impacts	Loosing caves	(risk of), breaking speleothems	Speeding or inducing the processes of karst dynamics (e.g. Dolines)	Loosing water springs	Loosing fossils	Loosing archeological artifacts	Taking the archeological sites out of their context	Reducing the water recharge into karst water tables	Loosing or fragmenting natural or slightly altered habitats	Loosing anthropized habitats	Re-composition or connection of habitats or anthropic areas	Reducing the hypogean populations	Reducing the population of rare species	(Risk of) extinction of endemic species	Loosing the wild fauna	Disturbing the wild fauna	Degrading aquatic habitats	Reducing the availability of water	Contaminating the soil	Degrading the soil	Degrading the quality of the air	Degrading the quality of the superficial water (e.g. Eutrophication)	Degrading the sonorous environment	Loosing places to reside, to work and to socialize	Loosing physical references to memories (residences, cemeteries, etc.)	Loosing meeting points and cultural production places	Loosing or limiting access to areas providing ecosystemic resources and services	Environmental disturbance and discomfort	Reducing the inventory of resources	Other socio-economic impacts
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Colored cells: aspecto/impacto ambiental potencial
Gray cells: inexistent or insignificant environmental aspect/ impact

SECTION 2:
STAGES OF THE LIFETIME OF A QUARRY

Luis Enrique Sánchez and Ana Claudia Neri

The impacts on the karst landscape may be different according to the different stages of the lifetime of a quarry, as showed on Table 1. This is why the practices are presented according to the stages as described on Figure 2. Although the terminology employed by the quarrying industry to describe the different stages of the lifetime of a quarry are not standardized, for the purpose of considering the impacts on the karstic environment, it is convenient to employ the sequence of five main stages, as follows:

- Studies of feasibility
- implementation
- operation
- decommissioning
- post closure

For the purpose of geological and economical studies, the stage of the studies of feasibility is usually divided into steps, but such an approach is not necessary for scope of the present Guide.

The duration of each stage is highly variable. The operation of a limestone quarry may last for decades. On the other hand, the decision to open a new quarry may require successive updates and reviews of the economic analysis, which can take years but could also be rapidly settled to seize opportunities in the market. During the operation stage, some quarries may have their activities temporarily halted.

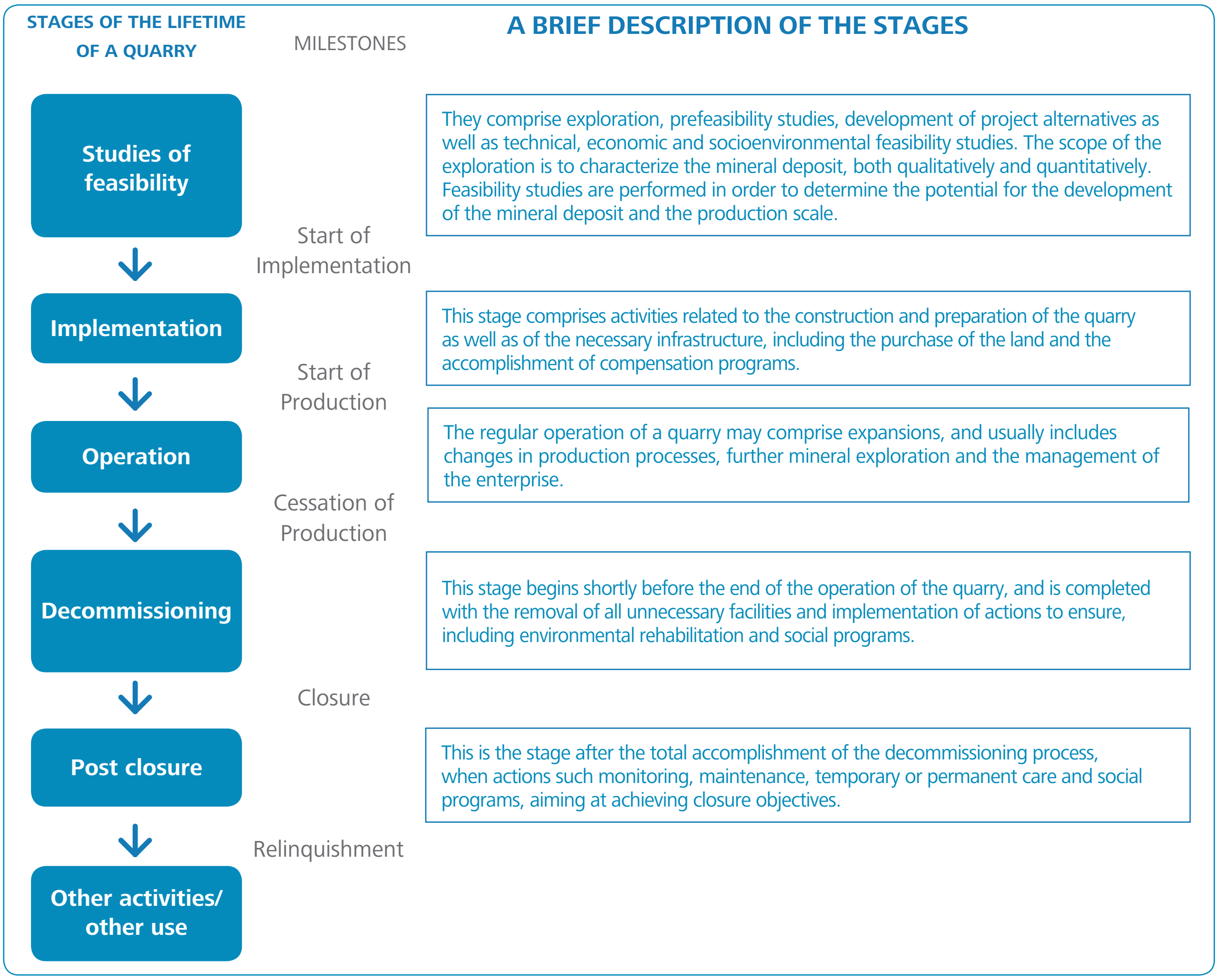

Figure 2. Stages of a quarry lifetime. Source: Sánchez et al. (2013).

SECTION 3:
RECOMMENDATIONS FOR GOOD PRACTICES

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This chapter presents good environmental practices recommended for limestone quarrying in karst areas. Practices are presented for each phase in the life of a quarry, with each divided into four sections encompassing the seven themes featured in the guidebook: karst systems and physical speleology, biodiversity and subterranean fauna, paleontology and archeology, and sustainable community development. The fundamentals for each practice are summarized in a set of tables and based on the details featured in the chapters of the second part of this guidebook.

The thematic contributions in Part 2 served as the basis for the recommendations of good practices. It is necessary to emphasize, however, that a satisfactory understanding of the dynamics of karst areas is required for the planning of projects, with this knowledge integrated with that of the local situation and shared with other specialists. Hence, in addition to the four themes, a separate set of practices for the phase of feasibility studies is also presented under the title of "Integrated Analysis".

For all thematic areas, except "Sustainable Community Development", the majority of the practices are recommended for feasibility studies. This reflects the importance of well-based studies of sufficient detail prior to the opening of a quarry. However, in many operating quarries, some of the surveys recommended were either never undertaken or conducted in only partial accordance with recommended practices or following different methods. For these quarries, many practices recommended for the phase of feasibility studies should be implemented during the on-going stage of operation.

It should be observed that some thematic studies recommended here, such as hydrogeological studies, may have been conducted by a quarrying company for operational purposes, such as determining the need to pump water from the pit floor. In such cases, these studies should be reconsidered to determine whether they are up to date and if they are in agreement with the environmental protection and respect for community rights promoted by the recommendations of this guidebook.

The prevention and minimization of impacts and risks to karst and its resources should be grounded on a solid basis of scientific knowledge.

The practices recommended here are presented in the form of tables summarizing activities recommended for each one of the seven thematic areas covered by this guidebook for each phase in the life of a quarry. The tables are structured around three key questions:

1. What to do? This column presents a synthetic expression of the practice proposed.

2. Why do this? This column identifies the main reasons for the adoption of the proposed practice.

3. Examples of how to do it. This column presents suggestions of techniques, tools, and approaches to implement the proposed practices.

The thematic chapters of the second part of this guidebook provide the basis for the reasons why and the examples presented.

As with every guide to good practices, the content is offered in the form of general recommendations. Application to actual situations requires professional evaluation, usually by a multidisciplinary team, and adaptation to the concrete conditions of each quarry or area of study.

It is important to understand the function of the surveys recommended in this part of the guidebook. The data and information collected should serve to inform project decision-making. For example, waste rock dumps should be located where they will not interrupt the flow of water in the karst, and the final delimitation of the pit should avoid the suppression of important caves. Such decisions require the availability of adequate information soon enough for it to be taken advantage of.

For this to be possible, time is at the essence and the activities must be well planned to the various surveys, especially those of the biotic medium, to be carried out. It may be necessary to reserve fairly long periods for a satisfactory diagnostic to be reached, therefore it is imperative that studies are planned early enough.

Karst studies serve not only to meet the legal obligations, but also to provide relevant information for the planning of the quarry and the management of its operation, thus reducing the risks for the company.

In this context, the managers of a quarry have various responsibilities related to guaranteeing the quality and integrity of environmental studies conducted to provide the information on which they can base the companies' decisions.

It is necessary to consider that the adoption of the practices recommended in this guidebook has two important implications in terms of projecting, planning and management.

- The results of karst studies play a determining role in making decisions about the project; they affect fundamental parameters such as estimates of minable reserves, the perimeter of the final pit, and the location of waste rock dumps and crushing installations, as well as ancillary installations;
- In complex settings, undertaking the studies recommended by this guidebook can require significantly longer time than those usually associated with environmental studies; moreover, they can imply expressive costs, which should be estimated ahead of time and with the greatest possible accuracy.

A number of recommended practices are presented for each phase in the life of a quarry. There are 47 practices for the stage of feasibility studies, 29 for implementation, 27 for operation, 8 for decommissioning, and 3 for post-closure, a total of 114 practices.

Phase	Theme	Nº	Good Practices
Feasibility studies	Karst Geosystems (KG)	F.KG1	Perform a site reconnaissance
		F.KG2	Consult data and information about mineral exploration
		F.KG3	Organize a geo-referenced data bank
		F.KG4	Conduct a hydrogeology study
		F.KG5	Evaluate speleological potential
		F.KG6	Prepare a conceptual model of karst
		F.KG7	Choose "areas of thematic study" from a systemic perspective
		F.KG8	Conduct speleological prospection oriented to the register of exokarst and endokarst features, utilizing methods of survey control and sufficiency of sampling
		F.KG9	Conduct cave surveys with sufficient detail and degree of precision
		F.KG10	Revise and update the conceptual model of karst

Phase	Theme	Nº	Good Practices
Feasibility studies (F)	Paleontology and Archeology (PA)	F.PA1	Define study areas
		F.PA2	Compile secondary data
		F.PA3	Input data in a Geographic Information System
		F.PA4	Analyze data
		F.PA5	Identify gaps in data or the need for more detailed information
		F.PA6	Conduct field activities for collecting primary data and checking secondary data
		F.PA7	Integrate primary and secondary data
		F.PA8	Prepare a map of paleontological and archeological potential
		F.PA9	Prepare the paleontological and archeological diagnosis
		F.PA10	Prepare a program to monitor and rescue paleontological findings
		F.PA11	Prepare a program for archeological prospection
	Biodiversidade (BI)	F.BI1	Prepare a study plan and set its goals
		F.BI2	Make a detailed survey of the landscape, including fauna and flora
		F.BI3	Prepare a rehabilitation plan
		F.BI4	Adopt systemic approaches fit for both aquatic and terrestrial fauna
		F.BI5	Include areas influencing the subterranean systems
		F.BI6	Apply methods that fit the objectives of the study
		F.BI7	Be careful with the scientific material collected from the site
		F.BI8	Ensure that the data collected can be checked at any moment, allowing the study to be reproduced
		F.BI9	Identify any possible sources of risk deriving from quarrying activities
		F.BI10	Verify if the samples are sufficient or near sufficient to characterize the communities under study
		F.BI11	Foresee the need to extend the study beyond three annual cycles
		F.BI12	Use every access to the subterranean medium to collect samples
		F.BI13	Study the speleo-climate in the caves located in the area of the quarrying operation
		F.BI14	Study the connectivity between systems and contiguous areas
		F.BI15	*Include the areas that influence the subterranean systems*
		F.BI16	Ensure the full qualification of the researchers enrolled in the environmental studies, taking into consideration the specific objectives of the study
		F.BI17	Disclose the results from the studies and surveys
		F.BI18	Indicate the priority areas for conservation

Phase	Theme	Nº	Good Practices
Feasibility studies (F)	Communities (CS)	F.CS1	Establish a socioeconomic baseline focused on relevant issues
		F.CS2	Map the stakeholders
		F.CS3	Disclose relevant project information
		F.CS4	Consult with stakeholders
		F.CS5	Analyze impacts and propose mitigation measures
	Integrated Analysis (IA)	F.IA1	Evaluate the importance of karst components which may be affected by the project
		F.IA2	Define, if applicable, restrictions of quarrying activities and support for the protection of relevant karst components
		F.IA3	Establish perimeters for protection for the karst components to be preserved
		F.IA4	Define other specific measures for protection
		F.IA5	Define measures for enhancement of positive impacts
		F.IA6	Establish a monitoring plan
		F.IA7	Consider information about karst in risk analyses

Phase	Theme	Nº	Good Practices
Implementation (I)	Karst Geosystems (KG)	I.KG1	Continue the diagnosis of hydraulic behavior
		I.KG2	Undertake hydraulic, hydrogeological and hydrochemical monitoring
		I.KG3	Monitor the process of subsidence and the formation of sinkholes
		I.KG4	Geo-reference the natural underground cavities and other components to be preserved that are located in the vicinity of the operational areas using a geodesic GPS
		I.KG5	Physically delimit the perimeters of the areas to be protected
		I.KG6	Adapt quarry planning to be compatible with the conservation of the relevant karst components
		I.KG7	Update the conceptual model of karst
		I.KG8	Conduct petrographic, morphologic, chemical and mineralogical studies of the rocks and speleothems If preservation of caves is necessary
		I.KG9	Construct retaining structures for sediments and install systems for drainage of rain waters prior to the initiation of the opening and paving of roads
		I.KG10	Implement systems for the collection and treatment of sewage
		I.KG11	Monitor the effect of vibrations on caves
		I.KG12	Monitor the atmospheric parameters of caves and their immediate surroundings
		I.KG13	Monitor depositional systems
		I.KG14	Suspend any activity representing risk of damage to potentially important fortuitous discoveries (natural cavities, fossils, archeological material, underground courses of water) until all necessary precautions for complete evaluation have been taken

Phase	Theme	Nº	Good Practices
Implementation (I)	Paleontology and Archeology (PA)	I.PA1	Establish the impact of intervention on the soil and subsoil, as a function of the archeological and paleontological diagnosis.
		I.PA2	Heritage Education – Courses and Lectures
		I.PA3	Integrate it with the program of environmental education
		I.PA4	Intervene to make collections "in loco"
		I.PA5	Transportation and curatorship of the paleontological and archeological material
	Biodiversity and Subterranean Biology (BI)	I.BI1	Conserve and maintain evidence of the affected environment, maintaining ecological corridors to connect adjacent habitats
		I.BI2	Implement a rehabilitation plan for the quarry
		I.BI3	Continue the management of the rehabilitation process
		I.BI4	Monitor the re-vegetated area and fauna
		I.BI5	Maintain the areas being rehabilitated
		I.BI6	Monitor the speleo-climate as well as the epigean and subterranean communities
	Communities (CS)	I.CS1	Distribute information about project implementation
		I.CS2	Implement a grievance mechanism for registering complaints and managing conflicts
		I.CS3	Implement relevant management programs and evaluate the results
		I.CS4	Invite entities to constitute a committee to accompany the implantation

Phase	Theme	Nº	Good Practices
Operation (O)	Karst Geosystems (KG)	O.KG1	Establish a plan for management of caves located on company land after consultation with the community and the authorities
	Paleontology and Archeology (PA)	O.PA1	Implement and Monitor the Paleontological and Archeological Rescue Program
		O.PA2	Create/ Implement courses for capacitation in Paleontology and Archeology
		O.PA3	Offer lectures about Heritage Education
		O.PA4	Train technicians to follow upon quarrying activities and monitor the scrapping of the sterile ground
		O.PA5	Monitor the separation, screening, and rescue of fossils
		O.PA6	Rescue fortuitous findings
		O.PA7	Conduct a systematic paleontological review

Phase	Theme	Nº	Good Practices
Operation (O)	Paleontology and Archeology (PA)	O.PA8	Implement laboratories for paleontological and archeological work
		O.PA9	Prepare and identify paleontological and/or archeological findings
		O.PA10	Pack and register fossils and archeological findings
		O.PA11	Transport and file the findings in an official institution
		O.PA12	Prospection of the cavities located in the massif
		O.PA13	Develop a program for the rescue of cavities having paleontological/archeological records
		O.PA14	Documentation
		O.PA15	Implement a Natural History Museum
	Biodiversity and Subterranean Biology	O.BI1	Continue Implementation of the quarry rehabilitation plan
		O.BI2	Continue management of the RDA
		O.BI3	Update the PRDA and closure plan periodically
		O.BI4	Focus attention on the evidence of cavities and subterranean fauna which may be interesting for potential conservation
		O.BI5	Evaluate any new speleological findings with an ad hoc environmental study
	Comunidades (CS)	O.CS1	Update the socioeconomic baseline
		O.CS2	Develop a system of social and economic indicators
		O.CS3	Update stakeholder mapping
		O.CS4	Implement management programs and evaluate the results
		O.CS5	Invite stakeholder organizations to participate in a committee to accompany the operation
		O.CS6	Facilitate and promote access to caves and other components of the karst system

Phase	Nº	Good Practices
Decommissioning (D)	D1	Identify and evaluate the social and environmental impacts of closure
	D2	Update the closure plan, promoting adjustments if necessary
	D3	Update stakeholder mapping
	D4	Communicate information about the process of closure
	D5	Implement the decommissioning programs described in the closure plan
	D6	Monitor the parameters of interest
	D7	Accompany the indicators of development and quality of life
	D8	Develop programs which foster diversification of the local productive base
Post-Closure (PC)	PC1	Monitor regeneration of the flora and fauna if the intended land use involves environmental conservation
	PC2	Involve the stakeholders in post-closure monitoring
	PC3	Maintain permanent or active care of the area, when necessary

3.1 RECOMMENDATIONS FOR THE PHASE OF FEASIBILITY STUDIES

The best opportunities to prevent adverse impacts on karst are to be found during the development of a new quarry project. As part of the technical and economic feasibility studies, geological mapping, drilling, sampling, and marketing studies, as well as economic feasibility analyses would be conducted, and alternatives for quarry development, including final pit, the localization of the waste rock piles and related installations, access roads, etc. should be analyzed.

Feasibility studies should include the environmental studies aimed at providing subsidies for the analysis of alternatives, and the need for mitigation and compensation, as well as granting licenses and governmental authorizations. In some cases, environmental and social evaluations may also be necessary to obtain financing.

The protection of karst areas and its resources requires the constitution of a solid base of knowledge about the area of the future quarry and its surroundings. For this scope, a series of studies and surveys is usually necessary. What should be studied, where, how, and for how long are key questions to be answered during the phase of planning and feasibility studies, both for a whole new project and a project for the expansion of an existing quarry

The role of the manager of a company is to guarantee that the studies meet the needs of the company, thus making it possible to avoid or at least minimize conflicts with the community and reduce the business risks which can arise from failing to adopt good practices.

The studies and surveys described in this guidebook should be conducted in advance, being careful to respect the minimal duration of certain studies such as those of the subterranean fauna, and to allow an adequate period for obtaining information and conducting public consultations.

A large number of recommendations contained in this guidebook are directed to this phase. In many operating quarries, however, the recommended studies may not have been conducted, or were made without following the recommendations. In this case, it is necessary to evaluate the need for further studies or the supplementation of existing studies, with the consequent establishment of a plan of action.

The plan of action for an active quarry should establish a list of necessary studies and a schedule for their realization, including the time necessary for their completion.

For active quarries, the studies of karst already conducted should be critically evaluated and, if necessary, an action plan should be prepared to update the knowledge about the karst systems and their resources.

The logical progression of the main tasks recommended for the phase of feasibility studies is shown in Figure 4. The following tables provide details about these recommendations. It should be observed that this guidebook essentially features recommendations specific for karst areas, as pointed out in the introduction. Therefore, certain other important recommendations, such as the engagement of the stakeholders, are not highlighted in this part of the guidebook.

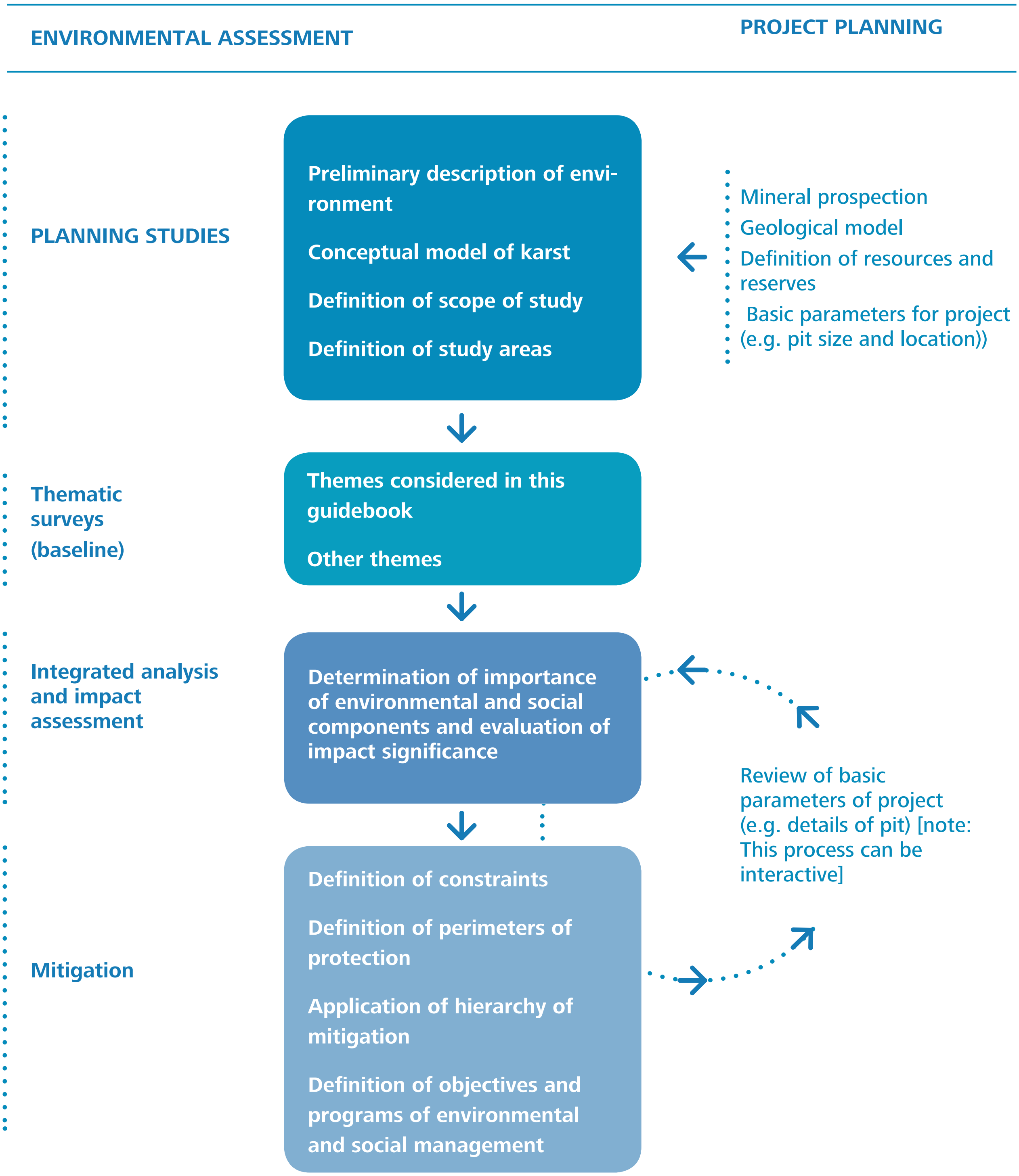


Figure 4. Main stages and chain of activities for environmental assessment and planning of new projects.

Karst geosystems

Feasibility studies - Karst Geosystems (F.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
F.KG1. Perform a site reconnaissance	1. An overall view of the main geological, geomorphological and hydrological characteristics of the region of the enterprise is important. 2. Familiarity with the already available information base can be helpful/useful. 3. Reconnaissance is necessary for the definition of a first draft [of the project?]	• Field visitation • Analysis of maps showing planialtimetrics, geology, geomorphology, hydrogeology, and hydrographics • Consultation of registered data bases (such as tubular wells and registers of natural underground cavities • Processing and analysis of aerial and satellite images to identify surface features and model the relief using morphometric analysis, as well as consultation of all materials usually manipulated for a preliminary geological interpretation of mineral prospection
F.KG2.Consult data and information about mineral exploration	1. The efforts and impacts inherent in mineral prospection(resulting from the opening of trenches, drilling, etc.) can be better exploited and preliminary studies involved in the phase of geological research (image analysis, remote sensing, data integration) can be used to collect information about the nature of the karst (geological factors linked to karstification) and elements of special interest. 2. Environmental complexities and fragilities related to karstification can be identified, as well as elements of special socio-environmental interest; restrictive factors can then be based on this information and eventual impediments to the enterprise identified. 3. The main geological factors that influence the processes of karstification can be detected. 4. Studies can be oriented and planned in accord with the following: √The preliminary idea of the extension and organization of the karst and the main conditioning factors of karstification which constitute a preliminary conceptual model (morphodynamics) (See practice F.KG6.) √Preliminary indicators of special features such as landscape and those of sociocultural and economic interest, geological and stratigraphic structures conditioning karstification, and the presence of speleological, archeological and paleontological sites, and aspects of biodiversity √Preliminary delimitation of areas for thematic studies, with hypothetical outlines which will be fundamental for the implantation of the enterprise, given the conceptual model of karst adopted	• Organization of a preliminary register of points of environmental, socio-cultural and economic interest (especially those related to karst) in the Geographic Information System (GIS) utilized for mineral research • Organization of a description of outcroppings, geological sections and cuts, to emphasize aspects of karst dissolution on specific geological structures • Analysis and organization of the aspects of dissolution in relation to stratigraphy revealed by drilling (horizons of karstification; sealing units) and interpolation between them; extrapolation to underground karstification (3D modeling) • Observation and organization of the evidence of dissolution in petrographic analyses • Elaboration of geological profiles highlighting the organization of the karst relief • Inclusion of geochemical aspects of karstification to increase the focus of exploratory geochemistry • Interpretation of soil profiles focusing on the configuration of the exokarst and epikarst and the interpretation of their interrelationships with the soil cover.

Feasibility studies - Karst Geosystems (F.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
F.KG3. Organize a geo-referenced data bank	1. Spatial data, as well as graphic and alphanumeric information generated by various sources can be collected, stored and integrated precisely and consistently; the primary data produced by the environmental studies can be shared more easily using a standardized cartographic system. 2. A structured data bank will facilitate the incorporation, compilation, updating, recuperation, supplementation, manipulation and integration of large volumes of spatial data, making possible coherent analyses which are varied, complete and precise and which will make the taking of decisions more reliable 3. Spatial contextualization of a technical memory makes working with data more efficient.	• Organization of a platform or unified system of digital information and geo-referenced data bases (GIS format) to be fed by a shared method and adoption of standardized procedures for the insertion and analysis of data, including all of the temporal data obtained throughout the existence of the quarry Note: The structuring should be accompanied by a management plan for the system which guarantees permanent and systematic updating and consistent analyses. • Integration of the geo-referenced data base of the project under investigation with other published bases, and if possible, private ones, in order to facilitate cumulative studies of impacts
F.KG4. Conduct a hydrogeology study	1. To deal with the fact that the karst landscape is both consequence and cause of the organization and dynamics of its aquifers, the following are necessary: √ Better understanding of the organization of the relief, its evolutionary stage, and its functional aspects √ Establishment of a systemic diagnosis of karst which will serve as a basis for the evaluation of possible impacts resulting from disturbances provoked in the medium (i.e. the environment), based on the conditions of hydraulic continuity and connectivity (i.e. behavior when disturbed) √ Visualization of the degree of vulnerability of the existing aquifer(s), as well as their availability, given the hydraulic peculiarities of karst aquifers. 2. Since the hydraulic characteristics of karst aquifers are unique, special methods and strategies can be used for the interpretation of hydrological and hydrogeological data, as well as the characterization of the structure, development (evolutionary stage) and dynamics of karst aquifers.	• Depending on the environmental context and the specific characteristics of the enterprise, formulation of a local and or regional "Hydrogeodynamic Model" which characterizes the following hydrological and hydrogeological aspects satisfactorily: a) relation of triple porosity (granular x fissural x conduit matrix) in the potentially affected aquifer lithotypes/units, conforming to the degree of karstification and its spatial organization (distribution, density, patterns of arrangement and morphology as well as controlling factors); b) relations between the units/compartments with different aquifer properties (functional interaction); c) surface and underground drainage systems; d) dynamics of the aquifers in the short and long term (level, discharge, direction of flow, routes and flow regimes, as well as hydrochemistry); e) seasonal variation in the aquifer basin(s) potentially involved and the characterization of the areas of seasonal contribution to the recharge and discharge (diffuse x concentrated), conditions of flow and storage (regime of flow x residence time x volume); f) intrinsic natural vulnerability of the aquifer. • Performance of tracing studies and other hydrogeological tests (tests of pumping; continuous monitoring of wells, springs and underground drainage; potentiometric studies; and direction of flow, both regional and local).
F.KG5. Evaluate speleological potential	1. Knowledge of the propensity for the occurrence of natural underground cavities via exokarst facilitates prospection when dealing with areas with no previous speleological studies or if these are insufficient. 2. The accuracy of feasibility studies can be improved, thus reducing risks, time periods, and costs. 3. Strategies for prospection using an appropriate approach can reduce the efforts in the field, yet guarantee efficient surveys. 4. A prospective approach which is often of a sampling and/or "hierarchic" nature, represents an "analytic design" of the condition of karstification itself. The "map of speleological potential" which is refined by detailed studies, when facing the projection of environmental impacts, is reverted into a "map of risk to the speleological heritage (map of speleological vulnerability.	• Consultation of data bases about speleological heritage • Elaboration of maps of speleological potential, utilizing the following: a) techniques of remote sensing and photointerpretation; b) techniques of multi criterial analysis and geostatistical tools; c) selected targets for prospection and elaboration of approaches (routes/networks of distances), giving priority to local and geographic sector targets. • Once maps are elaborated, conduction of control in the field

Feasibility studies - Karst Geosystems (F.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
F.KG6. Prepare a conceptual model of karst	1. The adequacy of environmental studies depends on the use of an appropriate preliminary conceptual model of karst. 2. A preliminary Identification of surface and underground systems and mosaics of potentially continuous or integrated systems should be obtained from the physical, climatic, and biological points of view so that the flow of water, sediments, nutrients, and fauna can be adequately inferred. 3. The level of natural complexity and vulnerability of the environment can be estimated. 4. The enterprise can be situated in the functional and systemic context of karst, making it possible to identify the key issues to be addressed and clarified by the environmental studies (both characteristics of the environment and those of the enterprise contextualized in that environment). 5. Information can be synthesized to present hypotheses which can explain the constitution and processes which take place in the area. 6. The gaps in information/knowledge which need to be filled with information from new investigations can be identified. 7. The areas of study can be delimited on the basis of criteria which make systemic sense. 8. The scope of studies can be planned, especially during the experimental design, so that the key questions/issues identified are faced.	Elaboration of an initial concept of morphological and functional organization of the karst, considering the following: a) the most evident morphodynamic compartments; b) the main factors potentially controlling the karstification (lithostratigraphy, geostructures, climate and hydrography). • Definition of hypotheses related to spelogenetic mechanisms, including controlling factors (lithostratigraphy, lithostructures, hydrodynamics, etc.) on the basis of the preliminary conceptual model of karst. • Systematization of strategies of control in the field for the evaluation of the results, in the face of the preliminary conceptual model, facilitating its later improvement.
F.KG7. Choose "areas of thematic study" from a systemic perspective	1. Data collected on the basis of criteria lead to greater coherence and precision in the indication of potential areas of influence of the enterprise. 2. The planning of studies can be optimized by improving the precision and objectivity of the environmental diagnosis and the evaluation of impacts. 3. Unnecessary or insufficient investment (in relation to time, energy, and resources) for the environmental diagnosis can be prevented.	• Delineation of areas of study on the basis of continuous and interconnected systems and mosaics of systems which are influential from physical and biological points of view; direction of studies to a given system or set of systems of potential interest on the basis of the situation of the quarrying enterprise in the context of the karst model and operational characteristics • Identification of points of recharge and discharge of water to and from aquifer basins or systems of hydric flow, as well as of the entire process of hydric activity between them (cause and consequence of the organization) and the use of these as units for analysis; consideration of hydric compartments delimited by non-carbonate units serving as barriers or elements which seal the flow, or are isolated by erosion when hydric activity is limited or non-existent • Consideration of units of analysis representing systems of "integrated flow" of water, sediments, nutrients and fauna between surface and underground media ***Note: 1:*** *The system or mosaic of physical and biologically continuous systems outlined by the preliminary model can be considered an area of potential influence of the enterprise for the effect of studies of diagnosis and the evaluation of impacts. The true area of influence can only be recognized once the environmental studies have been completed.* ***Note: 2:*** *It is important to consider the existence of physical (and biological) continuity outside lithologic limits, such as that which arises from allochthonous hydric transport from non karst areas in non-carbonate lithologies.* ***Note: 3:*** *Although different areas of study can be indicated for the different thematic approaches, with different experimental designs, these areas should relate to common objectives, especially the solution of key questions about functional and environmental dynamics and the environmental services potentially affected by the enterprise.*

Feasibility studies - Karst Geosystems (F.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
F.KG8. Conduct speleological prospection oriented to the register of exokarst and endokarst features, utilizing methods of survey control and sufficiency of sampling	1. Caves and important exokarst features should be identified an inventory made to be able to determine the functioning of the karst system in terms of flow of material and energy. 2. Adequate knowledge about the speleological heritage present in the context of the enterprise being licensed is essential.	• Giving greater attention in the field to areas of greater potential when organizing prospective surveys and considering details of the network and the methods for control of distances during prospection. • Selection of a method of control on the basis of the experience of the field teams: a) orientation by network of points; b) definition by lines; c) delimitation by polygons/quadrants. • Determination of sufficiency of sampling efforts in the field on the basis of a specific method, either the percentage of coverage or a matrix of distances.
F.KG9.Conduct cave surveys with sufficient detail and degree of precision	1. Precision and sufficient details offer support for conducting studies of morphology and morphometrics, hydrology, hydrogeology, sedimentology, paleontology, archeology and speleology. 2. Adequate cave surveys help in the understanding of the geometric arrangement of underground routes and the morphology of the endokarst. 3. Well-conducted surveys offer a basis for the interpretation of the genesis and evolutionary dynamics and functioning of the karst system in which the cave(s) are inserted. 4. Well-conducted cave surveys contribute to the definition of the best microhabitats for the collection of underground fauna.	• Elaboration of speleotopographic maps faithful to the macro and mesofeatures, indicating the occurrences of speleothems, speleogens, courses and bodies of water, and surface fossil deposits on the final product, as well as any evidence of archeological remains. • Utilization of methods for the classification of the precision of topography, such as those proposed by the British Cave Research Association or the International Union of Speleology.
F.KG10. Revise and update the conceptual model of karst	**1.** An up-to-date model of the karst helps summarize the results of activities and define hypotheses to explain the features and the processes which take place in the area. **2.** An up-to-date model of the karst helps identify the gaps in information which might be filled with new investigations	• Updating of the platform or unified system of digital information and geo-referenced data bases (GIS format). • Updating of national data bases, both public and those of associations.

Paleontology and Archeology

Feasibility studies - Paleontology and Archeology (F.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
F.PA1.Define study areas	1. The area of the study is the starting point for the identification of data to be surveyed. This is a previously established geographic boundary for which the following information will be gathered: lithology, stratigraphy, paleontological, archeological and speleological records	• The area must, at least, encompass the same area for which the mineral research area has been requested to the local official agency (in Brazil, the license is requested to the DNPM, the National Department of Mineral Production). The area will be plotted in a geologic and topographic basis, georeferenced in the largest scale as possible in order to provide information and allow the report of all kinds of data that are necessary to paleontological and archeological studies.
F.PA2. Compile secondary data	1. Secondary data are extremely important to compose a systemic view of the regional fossil occurrences, which are previously recorded in official basis of paleontological and archeological registers. Those data are the indicative that will determine the future requirements for studies and, when the data are sufficient, they will determine the structure of a conclusive diagnostic.	• From the information taken from the geological, topographic and political-administrative (as boundaries between municipalities and states) basis on the area to be studied, the survey on the literature will be done. The survey will cover the bibliography on lithic-stratigraphic unities, sedimentary basins, paleontological records, available in data basis (as PALEO – CPRM- Brazilian Agencies), in monographies, dissertations, and thesis (available in libraries in universities and research centers), as well as in articles published in journals, digital and printed media. • As to archeological data, the survey can be done in the data basis of the local regulatory agency, thesis, dissertations, public archives, universities, etc. In Brazil, the survey must include the Sistema de Gerenciamento do Patrimônio Arqueológico – SGPA/IPHAN (the agency that regulates the activities related to the archeological national heritage.
F.PA3. Input data in a Geographic Information System	1. This procedure provides an overview of the data and the area covered, therefore allowing a better understanding of the pattern of distribution	• Georeference all data obtained through the survey on the literature and plot them on the GIS program, file the data according to the theme (maps of the locations with fossils, geological basis, rocky outcrops, paleontological and archeological sites, natural subterranean cavities, etc.), allowing the information, about the units located in the area of the study, to be checked against the paleontological and archeological regional records that are already registered.
F.PA4. Data analysis	1. Define the fossiliferous and/or archeological possibilities of the area, taking into consideration the available data.	• Do a general approach of the paleontological, archeological and speleological potential in the study area, verifying the existence of fossiliferous layers as well as archeological pre-historic or historic sites. It is necessary to take into consideration the age and general conditions of the environment for deposition in these sedimentary sequences, the lithic characteristics and the age to identify possible forms of life and vestiges of material culture that could be found.
F.PA5. Identify data gaps or the need for more detailed information	1. Once all records are available, it is possible to verify the need for additional information or if just the secondary data are sufficient to prepare the paleontological diagnosis	• During the analysis of the Information already collected and processed, it is possible to verify the need of collecting primary data, mainly if there is a potential of paleontological findings in the unities inside the study area, but with no record in the literature. If there are natural cavities, they must also be surveyed for fossils because those are the kind of environment featuring favorable conditions to fossilization.
F.PA6. F Perform field activities for collecting primary data and checking secondary data	Primary data provide new and important information, which is needed for a correct interpretation of the paleontological and/or archeological potential of the area of the study	• The collection of primary data must be preceded by the fieldwork planning, which includes making the access map, a geological map mentioning the key issues to understand the geology and the areas interesting to Paleontology and Archeologya. • Secondary data, already collected, must be verified, in search of a more realistic view of the geological contexts by means of the description of the rocks, the identification of the contacts between the different geological layers, and a preliminary paleontological prospection. Geomorphological and pedological data are important to understand the actual paleontological potential of the study area and must be incorporated to the plan • Secondary data related to Archeology , already collected, must be verified as well as the references of previous studies in the area and the historical data to create the regional archeological picture

Feasibility studies - Paleontology and Archeology (F.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
F.PA7. Integrate primary and secondary data	A procedure that allows a global view of the data and the areas where they occur leads to a better understanding of the distribution pattern	• Gather all the information that was collected – primary and secondary data – to have an overall view of the information, preferably georeferenced in layers, supporting the next stage of paleontological and archeological mapping.
F.PA8. Prepare maps of paleontological and archeological potential	Information about the results from the initial studies of Paleontology and Archeology, plotted on a chart provides a representation making it easy to identify and understand the critical areas for Paleontology and Archeology, and a simple reading makes it possible to see if there are areas of interest and what the level of relevance of the paleontological and/or archeological findings are.	• By means of a thorough study of the area of interest, defined over a geological scale bigger or equal to 1:25,000, together with the data from probing, the lithology with fossiliferous potential will be determined, with a certain degree of precision. The map must also show the natural cavities. The representation in colors will propitiate, in a quick reading, the identification the different levels of paleontological and/or archeological potential: red – high potential; orange – medium potential; yellow – low potential; green – meaningless potential
F.PA9. Prepare the paleontological and archeological diagnosis	This provides the conclusive paleontological and/or archeological text, reporting all the data and analyses. It contains the information needed to drive the Paleontological Program of Monitoring and Rescue, as well as the Archeological Program of Prospection and Rescue, during the construction stages, mainly the production of the quarry.	• A report must be prepared comprising the geology of area of study and the regional geology, the summary of the secondary data, the survey of the primary data, a Paleontological and/or Archeological approach of the area of study, a summary of the conclusions and recommendations to implement a Paleontological and Archeological Program
F.PA10. Prepare the program for monitoring the paleontological rescue	This program provides an essential set of orientations for the implementation of the Paleontology and Archeology programs.	• Prepare a term of reference for the implementation of a Paleontology and Archeology preventive program that must comprise: justifications, objective, scopes, target public, methodology of operation, actions, indicators of results, partnerships with other programs and legal basis
F.PA11. Prepare the program for archeological prospection		• Prepare a term of reference for the implementation of an Archeology program that must comprise: justifications, methodology of operation, target public, heritage education, indicators of results, partnerships with other programs and legal basis.

Biodiversity and Subterranean Fauna

Feasibility studies - Biodiversity (F.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
F.BI1. Prepare a study plan and set its goals	1. Ensure scientific accuracy, granting reliability to the study	• Establish a methodological planning fitting the specific objectives of the study and only use secondary data when they were obtained according to methods that are equivalent to those used in the current study
F.BI2. Prepare a detailed survey of the landscape, including vegetation and fauna	1. Knowing the ecosystems – fauna and flora – before the interference of the quarrying operations is important to planning the environmental recuperation of the area 2. Identify rare species that may be damaged and advise the procedures to preserve them, such as the selective removal of the propagules and epiphytes. 3. Establish one reference for the recuperation procedures. 4. Surveying the fauna provides knowledge about its structure and composition, and allows the suggestion of management procedures	• Do a floristic survey of the area where the quarry will be located and in its surroundings where there are fragments of the native vegetation, mainly when the area to be affected by the quarry is clear of vegetation • Make a faunistic survey around the quarry, aiming to learn the composition and the structure of the ecosystem. In the case of specific groups, as mammals and birds, specific spots or too restrict areas are not sufficient.

Feasibility studies - Biodiversity (F.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
E.BI3. Prepare a quarry rehabilitation plan	1. Quarrying is a temporary use of the soil. When the activities are finished, the affected areas must be qualified for a further sustainable use 2. Several areas can be recuperated while the quarry is operating	• Prepare the quarry rehabilitation plan and the closure plan when the Project of a new quarry is initiated • The quarry rehabilitation plan and the Closure Plan must comprise alternatives for the future use of the area and indicate the preferred alternative • Actions to rehabilitate the area must be implemented during quarrying as far as practical (and not postponed to a later stage) • The quarry rehabilitation plan must comprise a monitoring program and a set of indicators to properly evaluate its outcome • The quarry rehabilitation plan must describe the rehabilitation actions to be adopted during the operational and decommissioning phases, it must be periodically updated according to a critical review arising from their evaluation
E.BI4. Adopt a systemic approach, fit for both aquatic and terrestrial fauna	1. This is the closest approach to the actual distribution area of most of the troglobite species	• In the beginning, the study unity is the subterranean system, as a whole, also taking into consideration its vadose area, which, for the terrestrial fauna, should be expanded to the complete continuous outcrop, which corresponds to the maximum potential area of distribution of the terrestrial troglobites. If this is not feasible for operational reasons, the spatial range encompassed of the biological survey should be as large as possible. **Note**: the more extensive the study is, the lower the number of rare subterranean organisms.
F.BI5. Take into consideration the cumulative impacts of different enterprises in a same karst area	1. Reduce the risks to the biodiversity 2. Avoid cumulative impacts that when isolated could not be significant	• Identify prospect enterprises to cause important impacts on the subterranean environment and integrate them into the analysis of the impacts on the case under study.
F.BI6. Apply methods fitting the scope of the study	1. Grant scientific accuracy and provide trustworthiness to the study.	• The minimal conditions for biological studies are: 1) apply multiple and complementary methods for biological surveys, according to the state of the art in science; 2) seasonal samplings for 3 yearly cycles, with at least four annual collections, regularly distributed during the feasible seasonal time of the study; 3) if the objectives include the classification of organisms according to Schiner-Racovitza, a comparable epigean study should be included (same season, same techniques of collection and data analysis). Should the curves of accumulation/rarefaction of the hypogean versus epigean be quite different, the collection in the sub-sampled environment must be increased.
F.BI7. Be careful with the scientific material collected from the site	Avoid excessive collection and loss of material, which makes unjustifiable to withdraw exemplars from their environment, avoid keeping the scientific material out of reach, making it impossible for other researchers to check the data, which is one of the main scientific criteria, that is repetition	• For all the biological material: • Collect enough samples to be identified, ensuring the adequate preservation of the specimens and their related information; • Validate the identification by experts in the taxonomy of the respective groups; • Deposit all the material in official public institutions with curatorship for the collections that are open to lease the material to the scientific community (having the resources to deliver the material in timely basis) and equipped with a public information system about the collections
F.BI8. Ensure that collected data can be checked at any moment, allowing the study to be reproduced	Grant access to the scientific material that was collected, allowing the verification and trustworthiness of the identifications, as well grant the cross checking among samples collected by different collectors, every sample classified by a system of symbols.	• To avoid the proliferation of parallel systems of ad hoc classification, do not refer to taxon not identified by numbers, letters or any other sequential system of symbols, but associate them to geographically stable references (preferably the name of the locality). • Support the decisions that could involve irreversible impacts on subterranean habitats (cavernicolous or not) only with identifications that are validated by experts in the respective taxonomic groups, with expertise and credibility in the scientific community. • Avoid parataxonomy, i.e., separate species based on morphological types, by someone who is not an expert on the group. • Always inform who identified the material, including name, academic titles and institution.

Feasibility studies - Biodiversity (F.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
F.BI9. Identify any possible source of risk deriving from quarrying activities	Establish the initial status, not altered, to guide the monitoring.	• Thoroughly describe the environment including, in the experimental design, the methods to estimate: • the transport of sediments into the cavity, causing silting or other kinds of unnatural alterations in the habitat; • the decrease in the incoming of nutrients (p. ex. vegetal debris, animals, organic matter, generally brought in by water flows).
F.BI10. Verify if the samples are sufficient or near the sufficiency to characterize the communities under study	Ensure the scientific accuracy, reliability, and repetition for the study.	• Apply methods of sampling sufficiency scientifically validated; do not use pseudo-repetition to calculate sampling sufficiency
F.BI11. Foresee the need to extend the study beyond three annual cycles	There may be some remarkable variations between consecutive years, or very atypical years, so that it is not possible to establish a seasonal pattern. These are the fundamental aspects to characterize an ecosystem and, therefore, they need to be investigated to grant a solid study and reliable conclusions (critical issues when it is possible to have permanent impacts)	• Proceed with the study, according to the methodology previously established and used, until seasonal patterns are detected and lead to an accurate description of the structure and operation of the systems that could be affected, as a basis for a real evaluation of their importance, and to establish the proper mitigating measures.
F.BI12. Use every access to the subterranean environment to collect samples	Expand the possibility to prospect the subterranean fauna, including habitats out of caves	• Optimize the collections, taking the advantage of the artificial accesses to the subterranean realm, including the probing drill holes.
F.BI13. Study the speleo-climate in the caves located in the area of quarrying operations	Establish the initial status, as a control to monitoring during the quarrying operations.	• Follow up and analyze the speleo-climate, along with the biological study. Do sequential and periodical collections with an interval that fits the study, so that it is possible to identify the variation of the diurnal cycle of the speleo-climate and the annual cycles. The minimal required variables are the temperature (air in all cases and water when appropriate) and the relative air humidity; and, when appropriate, use accessory variables, use the intensity and direction of the air currents and the concentration of Carbon Dioxide and Radon.
F.BI14. Study the connectivity between systems and continuous areas	Determine the space limits of the subterranean population and communities, to estimate the size of the minimal effective population (that must be totally preserved) and the area actually occupied by the communities.	• Use chemical and/or biological trackers (presence of the same species – taxonomic, morphologic and molecular studies)
F.BI15. Include the areas influencing on subterranean systems	To accurately evaluate the impacts, providing a solid basis to establish efficient mitigating measures.	• Include methods to determine the areas of influence over the subterranean systems that are directly or indirectly affected by the quarrying operation, during all the stages of the study; from planning to monitoring, focusing on the issues related to wider areas, as upstream drainages, including the recharging areas, and home range of cavernicolous bats. **Note:** we refer to the influence of the epigean processes over the subterranean environments. Do not mistake for the area under the influence of the quarrying operation, which is absolutely different from the one we have just mentioned.

Feasibility studies - Biodiversity (F.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
F.BI16. Ensure the full qualification of the researchers enrolled in the environmental studies, taking into consideration the specific objectives of the study	Given the irreversible nature of the impacts from quarrying, it is fundamental to guarantee that the environmental studies are reliable, as well as to cause minimum damage during the studies, which is highly relevant to subterranean systems because their intrinsic fragility	• Grant the proficiency of the team, carefully verifying their previous activities, only hiring members fully qualified in the specific field, with expertise in speleobiology, as declared on their resume
F.BI17. Disclose the results from the studies and surveys	1. Allow a peer review 2. Facilitate the access to the information that is useful for the studies of cumulative impacts	• Publication in scientific journals • File the reports, studies and data banks in institutions opened to the public
F.BI18. Indicate the priority areas for conservation	1. Subsidize an integrated analysis 2. Avoid irreversible impacts to the biodiversity	• Appoint the areas that due to its importance must present restrictions to the development of the project

Sustainable Community Development

Feasibility studies – Communities (F.CS)		
What to do?	**Why do this?**	**Examples of how to do it**
F.CS1. Establish a socioeconomic baseline focused on relevant issues	Issues which should subsidize the evaluation of social impacts and the proposal of plans for socioenvironmental management can be identified, with an emphasis on the following: • an understanding of the socioeconomic dynamics of the context where the quarry is inserted • the establishment of a solid basis on data to support the analyses and plans of action • an understanding of the use of natural resources by the community and the provision of ecosystem services • the identification of eventual existing conflicts and anticipation of potential future conflicts involving the use of natural resources and their relation with the enterprise • identification of elements of the cultural heritage, both material and immaterial (Those of the archeological heritage are the subject of a specific section)	• Conduction of a survey and analysis of secondary data (available from official sources and the literature), including, among other aspects, demographic and economic dynamics, productive structure, use and income, infrastructure of basic services, education and health, [treatment of] sewage, use and occupation of the soil, public finances, social vulnerability, and the index of human development • Identification of the communities which may be affected by the future enterprise, such as individuals living in the area of the enterprise and its surroundings, both downstream and along access routes, as well as communities situated in areas of future environmental compensation • Conduction of surveys to obtain primary data (collected in the field) with the objective of characterizing the communities which may be affected, identifying the socioeconomic profile of the inhabitants, the conditions of access to services, and the basic infrastructure available, as well as the forms of social participation and organization, cultural traditions, the use of natural resources and dependence on services provided by the ecosystems which may be affected • Conduction of interviews in the communities, with the objective of identifying the level of information and the expectations of the inhabitants in relation to the implantation of the project; identification of the perspective of the inhabitants in relation to the place where they live and their hopes and fears in relation to its future.
F.CS2. Map Stakeholders	Such mapping will facilitate communication and the engagement of the stakeholders: • initiation of the process of engagement of the community and other stakeholders in the project • meeting of individuals and groups which, either directly or indirectly, may be affected by the project, either positively or negatively • identification of possible groups or individuals who may exercise a certain influence on decisions related to the project	• Identification of the social actors or groups which may be directly or indirectly affected by the project and those which may influence decisions about the project, such as local communities, landowners, associations of inhabitants, local, regional, or national NGOs, traditional populations, the local government and other governmental organs of different spheres, syndicates, municipal or regional councils, politicians, universities, and religious entities • Delimitation of the possible areas of both direct and indirect influence of the project and consideration of local and regional social impacts, the main components of the productive chain, and the routes for removal of the production, identification of stakeholders on the basis of this information • Identification of more vulnerable individuals and groups among the stakeholders

Feasibility studies – Communities (F.CS)		
What to do?	**Why do this?**	**Examples of how to do it**
F.CS3. Disclose relevant project information	The promotion of the communication of transparent, accessible, and up-to-date information is fundamental for the construction of an efficient and lasting channel of dialogue between the company and the host community	• Identification of the most adequate ways to establish an effective channel of communication, in agreement with the target public, with the choice of method and the tools to be adopted considering the context in which the project is inserted and the characteristics of the public, such as educational level, modes of social organization, and cultural aspects • Divulgation of information about the project that is up-to-date, objective, relevant, and easily understood • Divulgation of information about project by various means, such as informative bulletins, the press, web pages, public meetings, focal groups, discussion forums, and councils which have been organized
F.CS4. Consultation with stakeholders	Consultation with stakeholders enhances the understanding and comprehension of the impacts of the project and establishes constructive and lasting relationships between the company and the community throughout the useful life of the quarry Note: This consultation is one which must be coordinated by the company itself, although when possible the participation of local partners should be included; it should not be confused with official public consultations promoted by government entities during the procedures for the approval or licensing of projects, as it cannot be replaced by the latter.	• Elaboration of a preliminary plan of communication, considering the social actors who will be consulted and the issues to be addressed • Conduction of the process of consultation in an organized and interactive way, guaranteeing the manifestation of the different points of view • Hiring of a team to facilitate the organization of the consultation • Adoption of one or more modalities appropriate for conducting the consultation, such as discussion groups, public meetings, and workshops • Documentation of the consultation and informing the participants of the results
F.CS5. Analysis of impacts and proposal of mitigation measures	The knowledge of potential impacts can inform investment decisions and influence decisions of the project team in relation to alternatives for the project, facilitating the following: • avoidance, as much as possible, of adverse impacts on the community • definition of programs of mitigation and social compensation for the adverse impacts which cannot be avoided • definition of programs for enhancing positive social impacts and economic benefits • avoidance and minimization of conflicts with the affected communities	• Utilization of the information obtained and the analyses conducted in earlier activities in a systematic way (1 to 4) • Analysis of alternatives for location of components of the enterprise, such as the waste rock dumps and external routes of transport • Involvement of representatives of the stakeholders in the definition of criteria for the identification of significant impacts • Definition of social programs in cooperation with the stakeholders

Análise integrada

Feasibility studies- Integrated Analysis (F.IA)		
What to do?	**Why do this?**	**Examples of how to do it**
F.IA1. Evaluate the importance of karst components which may be affected by the project	1. This evaluation can be used to help define the social and ecological importance of the karst components which may be affected by the project, especially those which should be protected 2. Knowledge about karst components supports the evaluation of the importance of environmental and social impacts and risks 3. Information about important karst components can provide a basis for the definition of programs of environmental and social management	• Inclusion of caves, exokarst features, paleontological and archeological sites, habitats, fragments of native vegetation, and sites of cultural interest • Adoption of criteria of importance for karst components established by legislation, if existent; otherwise, observe international recommendations, when applicable (such as critical habitats and geosites) • Identification of priority ecosystem services and their beneficiaries
F.IA2. Define, if applicable, constraints on quarrying activities for the protection of relevant karst components	1. The adoption of adequate constraints can help avoid significant impacts, especially irreversible ones 2. Unavoidable impacts can be reduced or minimized by initially restricting certain quarrying activities 3. Knowledge about the specific components to be protected can provide a basis for decisions about the choice of alternatives for the project 4. The analysis of the technical-economic feasibility of the project (mineral reserves, final pit, mean transportation distance etc.) can be facilitated by the availability of adequate information	• Limitation of the depth of the pit to avoid interception of underground water • Establishment of minimum distance of pit slopes in relation to areas for the protection of caves and other important sites to be preserved • Avoidance of the use of sinkholes for the disposal of waste rock or other wastes

F.IA3. Establish perimeters for protection of karst components to be preserved	1. Having established perimeters for the protection of karst components provides orientation for the definition of the layout of a future quarry
	2. Knowledge about the perimeters required for protection of karst components will help evaluate if the acquisition of external areas will be necessary or if negotiations with other companies, government officials or the community will be required to reach the required level of protection
		• Establishment of individual perimeters for protection for each relevant component, with the possible determination of a larger area encompassing all components which should be protected when these areas overlap,
		•Delimitation of the perimeter of protection for karst components based on criteria relative to the category of the component in question, with additional support from further studies when necessary Examples:
		  • For geosites, the utilization of main attributes as criteria, possibly focusing on lithologies and their stratigraphic units, paleontological, archeological, pedological, hydrographic and hydrogeologic potentials
		  • For natural cavities, the utilization of the recharge zones of the corresponding karst system (if active) is one possible criterion, as are the microclimatic gradient in the vicinity of the entrance and the area for foraging of the obligatory trogloxenes and troglophiles
		• Maintenance of respect for legally established delimitations, such as, in Brazil, the permanent nature of the protection of legal reserves

F.IA4. Define other specific measures for protection	1. Measures for management must be adopted in the stages of implementation, operation and decommissioning 2. Offset measures and those for compensation for impacts on biodiversity and ecosystem services, as well as social impacts, must be determined	• Prioritize the contiguity of protected areas, maintaining or restoring a connection between fragments • Adoption of participative and inclusive procedures when preparing management plans for protected areas when there are communities in the vicinity • Provision of support for the creation, implantation and management of natural protected areas in the vicinity of affected areas • Stimulation for the creation of cultural spaces for the exposition of natural aspects, such as thematic museums associated with fossils and archeological findings, and the development of educational projects related to the heritage, making possible the perception of the need for protection of the natural heritage in the community to undergo impacts

Feasibility studies- Integrated Analysis (F.IA)		
What to do?	**Why do this?**	**Examples of how to do it**
F.IA5. Define measures for enhancement of positive impacts	1. Potential positive impacts of the project in the socioeconomic area should be identified, as well as the main risks or obstacles to full realization 2. The guarantee of a permanent dialogue with stakeholders is necessary so that subsidies for the permanent evaluation of beneficial impacts can be obtained 3. A permanent dialogue with those who will benefit should improve chances for the reinforcement of positive results. 4. Information and knowledge generated by the studies should be disseminated in benefit of different stakeholders	• Development of capacity-building programs for workers and the formation of local leadership and the strengthening of social organizations and local public authorities • Include in budgeting for specific social programs • Guarantee of access to the results of karst studies • Widespread dissemination of the results of karst studies (via events, scientific publications, lectures in schools, monitored visits, etc.)
F.IA6. Establish a monitoring plan	1. Monitoring should be based on the integration of information of a varied nature, e.g. water quality, hydrochemistry, discharge, sediments, and vibrations, as well as those of a paleontological and archeologic nature. 2. The engagement and participation of stakeholders is important for the monitoring and implementation of mitigation measures, thus encouraging the empowerment of the community	• Selecting adequate monitoring points • Establishment of appropriate periodicity for monitoring campaigns (e.g. monitoring vibration at each blast) • Creation of monitoring commissions with representatives of the stakeholders
F.IA7. Consider information about karst in risk analyses	For those companies that adopt risk analysis as part of the decision-making process, the unique nature of karst environments should be considered to make possible the identification of potentially important risks which might otherwise be concealed	• Consideration of the vulnerability of karst compartments • Development of risk reduction measures

3.2 RECOMMENDATIONS FOR THE IMPLEMENTATION PHASE

The implementation of new projects, or the expansion of existing enterprises, is guided by the studies and surveys conducted in the previous phase, and includes the implementation of various pertinent management programs, and the evaluation of results.

However, during implementation, changes may occur in the project or unanticipated situations may arise. Among these unpredictable situations is the discovery of a karst feature not mapped during the previous phase of feasibility studies (such as a swallow hole or a cave) or of a fossil register. Some changes in a project are to be expected when passing from the basic project to the execution, and these must be evaluated for possible repercussions for the karst resources and the community.

Karst Geosystems

Implementation - Karst Geosystems (I.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
I.KG1. Continue the diagnosis of hydraulic behavior	1. A long-term record of hydraulic behavior helps guarantee the adoption of adequate procedures. 2. Information about the hydrodynamics of the karst systems present in the area of the enterprise makes it possible to take immediate mitigation measures if disturbances in the behavior in the compartment of the system are identified.	• Continuous monitoring of hydrologic parameters such as discharge, conductivity, and turbidity

Implementation - Karst Geosystems (I.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
I.KG2. Undertake hydraulic, hydrogeological and hydrochemical monitoring	1. The effects of possible changes arising from the alteration of the dynamics of infiltration (modifications in volume, orientation and quality/hydrochemistry) and the dynamics of the transport of solids (with the possible interference in or silting up of underground conduits) once roads are paved should be evaluated. 2. Monitoring can anticipate the effects of the lowering of an aquifer and the possible reduction in the discharge of springs and water courses, as well as identify the possible intensification of processes involved in the formation of sinkholes (loss of exokarst and endokarst features).	• Verification of the base level at control points established in three different "scales" for that intervention, starting at the initiation of the intervention and extending for at least one hydrological cycle (for a normal year, climate-wise) after hydrodynamic intervention and water quality have been stabilized. Points of monitoring can include springs, underground drainage inside caves, percolation and underground runoff (dripping and flow inside caves) and wells. Comparison of these variations with local levels prior to installation (comparison of hydrograms) • Examination of hydrochemical parameters, including those of isotopes, which can assist in the recognition of origin and residence time of fluids
I.KG3. Monitor the process of subsidence and the formation of sinkholes	1. The actual effects of the lowering of an aquifer can only be determined by monitoring, since the resulting cone can result in the intensification of processes involved in the formation of sinkholes	• Utilization of morphometric control parameters operationalized by the use of precision technologies of topographic surveying (e.g. use of a laser scanner).
I.KG4. Geo-reference the natural underground cavities and other components to be preserved that are located in the vicinity of the operational areas using a geodesic GPS	1. The use of adequate procedures can guarantee knowledge of the true location of caves and other components to be preserved 2.Only with a knowledge of the true location of elements can the effective preservation of the perimeters laid out for the protection of caves and hydric recharge features (sinkholes, uvalas, and swallow holes, among others) be guaranteed.	• Elaboration of a data base containing information about the coordinates of the features and basic data, such as name, lithology, horizontal projection, etc.) • Confection of maps locating features and their horizontal projection, area of preservation, and area of influence • Insertion of the location of cavities in national data bases
I.KG5. Physically delimit the perimeters of the areas to be protected	1. The establishment of physical delimitation facilitates control, inspection and audits	• Utilization of instruments for marking (e.g. signs, chains, and other physical indications)
I.KG6. Adapt quarry planning to be compatible with the conservation of the relevant karst components	1. Avoidance of irreversible negative impacts in underground natural cavities is preferable to mitigation attempts afterwards. 2. The adoption of adequate planning can help avoid the disturbance of the functioning of the karst system, and the causing of impacts on areas of recharge 3. Adequate planning can help avoid the suppression of exokarst features	• Conduction of geostructural surveys in order to elaborate the zoning of a cave in terms of fragility • Updating of the plan of the pit to include the conditions of geotechnical fragility of the natural underground cavities located in the vicinity of the enterprise
I.KG7. Update the conceptual model of karst	1. Updating of the conceptual model of karst will improve the understanding of the karst system. 2. An update of the conceptual model of karst encourages the review, if necessary, of the	• Interpretation of data obtained from the various monitoring programs • Maintenance of the geo-referenced information in the data bank up-to-date
I.KG8. Conduct petrographic, morphologic, chemical and mineralogical studies of the rocks and speleothems if preservation of caves is necessary	1. An adequate description of the host rock of a cave makes interpretation of its lithostratigraphic control possible 2. Studies of the host rocks of caves may lead to the identification of minerals which are rarely found underground 3. Studies of caves can lead to the identification of eventual speleothems of unusual mineral composition 4. The understanding of the mineralogy of carbonate speleothems can be enhanced by extensive information. 5. Initial studies can lead to future studies and help avoid the need for damage in other cavities	• Selection of representative samples for collection, after obtaining the necessary authorization of responsible organs • In caverns to be suppressed, collection of as large a sample as possible of the speleothems and their deposit in a research institution following adequate protocols for their cataloging and storage • Utilization of techniques for analysis such as the preparation of thin, polished slices, x-ray diffraction and fluorescence • Elaboration of projects for drainage and retention of sediments considering both surface drainage and that under the ground, as well as karst features

Implementation - Karst Geosystems (I.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
I.KG9. Construct retaining structures for sediments and install systems for drainage of rain waters prior to the initiation of the paving and opening of roads	1. Retaining structures can help protect water courses. 2. Adequate drainage systems can help prevent the transport of sediments to sinkholes and caves.	• Implantation of sewage treatment systems taking into consideration permeability and underground drainage
I.KG10. Implement systems for the collection and treatment of sewage	1. Pollution of surface and underground water must be prevented. 2. The health of the population downstream must be protected.	• Implement drainage systems taking into consideration the subterranean drainage and permeability
I.KG11. Monitor the effect of vibrations on caves	1. Vibrations during the implantation of a quarry can compromise the physical integrity of caves	• Installation of geophones and/or other seismographic instruments • Installation of crack and convergence meters for automatic sampling in caves • Use of photographic monitoring to show the initial conditions of physical integrity of caves and control the evolution of these conditions throughout the implantation
I.KG12. Monitor the atmospheric parameters of caves and their immediate surroundings	1. Monitoring can be used to verify if the activities of quarrying developed in the vicinity of caves are not interfering with their environment	• Monitoring of the temperature of the air (and water, when present) and the level of relative humidity of the air, as well as the concentration of CO2 and radon at minimum hourly intervals • Monitoring with high precision instruments, given the limited variability of the variables monitored, with the instruments coupled to automatic samplers, or linked to a system of data transmission (physical cables or Bluetooth) for transmitting to a station outside the cave, making it possible to send information to a control center responsible for storing, treating and analysis of the data • Utilization of techniques of temporal series analysis to trace the natural patterns of variability and identify possible interference, including annotation of anthropic events which may affect the data
I.KG13. Monitor depositional systems	1. It is important to preserve depositional dynamics of the endokarst. 2. Eventual disturbances may result from the silting up of underground fluvial channels or even the vadose sectors of caves, and these must be identified and, if necessary, mitigated.	• Monitoring of sediments • Mentoring of mass movement, etc.
I.KG14. Suspend any activity representing risk of damage to potentially important fortuitous discoveries (natural cavities, fossils, archeological material, underground courses of water), until all necessary precautions for complete evaluation have been taken	1. The temporary suspension of potentially damaging activities can prevent the loss of or damage to relevant fortuitous discoveries until the relevance of these finds can be evaluated and the most adequate measures taken. 2. The risk of damages to the environmental and cultural heritage and infractions of the present legislation can be avoided when risky activities are promptly controlled.	• Systemization of the communication of new finds during routine work or in the field • Rapid ad hoc activation of assessors when supplementary studies are to be conducted • Training of employees and collaborators to identify karst features, fossils and possible archeological remains **Note** : Good practices should be adopted in relation to the general procedures of speleology, speleobiology, archeology, paleontology and hydrogeology.

Paleontology and Archeology

Implementation - Paleontology and Archeology (I.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
I.PA1. Establish the impact from the intervention in the soil and subsoil depending on the archeological and paleontological diagnostic	1. To establish the areas that require more attention during the implementation stage	• Having the engineering projects available, cross check them with the maps to verify if there is any paleontological and archeological potential where the construction will take place, mainly the foundations, that could interfere in the underground where the cultural material could be located; verify which measures proposed in the study of the potential could be implemented to ensure total protection for the geodiversity and the geological heritage.
I.PA2. Heritage Education – Courses and Lectures	1. To provide the employees the identification of any fossil and/or archeological localities that may be affected during the implementation works 2. It is an efficient way to provide additional protection to the paleontological and/or archeological heritage. In the absence of an expert in paleontology and/or archeology, who may not be available during the implementation of the whole quarrying operation, the excavation team will be able to identify the presence of a fossil or a cultural material and communicate it to the paleontologist or archeologist in charge, so that he/she can proceed with the required actions	• Establish a dialogue among the people in charge of the environmental education, paleontology and archeology programs, so that they can be sure about the requirements of each program, and find a way to unite them in lectures in the schools and for the communities. This kind of initiative helps to rescue the identity of the local residents by assembling a theme collection with the fossils and cultural material of ancient peoples. This is a way to add value to the local culture, to educate the population about the importance of the paleontological and archeological studies. Therefore, to show the need to conserve the Geological Heritage focusing on the fossils and archeological findings that are both locally and nationally valuable.
I.PA3. Integration with program of environmental education	1. It has an informative purpose, opening the horizons to understanding the importance of the paleontological and archeological studies, their benefits to science, even to the residents of the region, because fossil and cultural vestiges found in the field could make up a museum exposition, that depending upon its importance, could encourage local tourism, generating jobs and income to the local communities, therefore creating a new way to a regional sustainable development	• Establish a dialogue among the people in charge of the environmental education, paleontology and archeology programs, so that they can be sure about the requirements of each program, and find a way to unite them in lectures in the schools and for the communities. This kind of initiative helps to rescue the identity of the local residents by assembling a theme collection with the fossils and cultural material of ancient peoples. This is a way to add value to the local culture, to educate the population about the importance of the paleontological and archeological studies. Therefore, to show the need to conserve the Geological Heritage focusing on the fossils and archeological findings that are both locally and nationally valuable
I.PA4. Interventions for collection "in loco"	1. It is the only way to ensure protection for the fossils and archeological material, so that they are not destroyed or misrouted during the excavation operations	• As a first action, the excavations in localities where paleontological and archeological material are found must be halted and the place must be isolated, until the person in charge of the technical program of paleontology and/or archeology is advised and determine what must be done. As the next step, the fossil remains should be excavated following the required criteria and methodologies, granting the physical integrity of the findings to be transported to the paleontological laboratory for the next procedures **Note:** the implementation of the project may continue out of the area that was restrained for the paleontological rescue
I.PA5. Transportation and curatorship of the fossiliferous and archeological material	1. Protect the Paleontological/ Archeological Heritage to keep the fossil specimens and archeological material intact, packing them properly, which will also ensure that all the characteristics required by scientific studies and to be shown in museums and public expositions are kept	• Deposit the material in an institution previously chosen by the agencies responsible for it, usually nationally acknowledged research centers and museums • File and register the findings that will make part of a scientific inventory for further studies

Biodiversity

Implementation – Biodiversity (I.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
I.BI1. Conserve and maintain evidence of the affected environment, keeping ecological corridors to connect adjacent habitats	1. To allow the flow of populations and the recolonization.	• From the environmental studies, establish the areas that encompass significant samples (justify) of the regional fauna and flora, both epigean and hypogean, keeping ecological corridors to preserve the species found in the area the quarrying operation is located
I.BI2. Implement the quarry rehabilitation plan	1. The early implementation of applicable actions of the rehabilitation plan leads to: (a) reduce environmental liability; (b) demonstrate to stakeholders the accomplishment of environmental protection and restoration commitments; (c) build knowledge and experience in rehabilitation. Rehabilitation programs can be classified into four groups: soil management practices, topographical and geotechnical practices, water related practices and ecological practices.	• Soil management practices refer to the management and protection of the soil, and to the use of topsoil as soon as possible after its removal • Topographical and geotechnical practices are related to ensuring slope and structural stability, such as a implementing a drainage system for the rainwater in the embankments • Water practices are related to the protection of the water resources, such as re-foresting the area around water streams • Ecological practices are related to the management of the fauna and the vegetation, for instance, restoring the vegetation in recuperated areas accordingly to what was determined in the planning
I.BI3. Manage the rehabilitation process	1. Controlling and managing the rehabilitation processes that are important to ensure that the operational practices reach their goals as established in the plans	• The point of view of the community must be acknowledged • Provide technical guidance for the tasks to be done • Provide technical capacitation for the working team • Develop and implement operational procedures. • Provide resources (human, physical and financial) • Follow up (monitoring, record and documentation)
I.BI4. Monitor the re-vegetated area and the fauna	1. Follow up the restoration of the vegetation 2. Following up the fauna in the recovered areas and in its surroundings provides important information to evaluate the quality of the habitats created by the quarrying operation	• Establish a program to monitor faunistic groups, indicating the methods of the survey, the localities and the sampling frequency • Establish programs to monitor the vegetation, using proper indicators, at least for a sufficiently long period (many years)
I.BI5. Maintenance of areas under rehabilitation	1. Maintenance routines are important to ensure that the recuperation and prevention practices work properly and effectively	• The recuperated areas must be weeded and cleaned of invading species to control pests and diseases • Establish an emergency plan for situations like illegal deforestation, invasion by cattle, fires, etc.
I.BI6. Monitoring the speleo-climate and the epigean and subterranean communities	1. To evaluate the actual impacts and the efficiency of the mitigating measures	• Provide comparisons applying the same methodology of the study – sampling can be reduced to twice an annual cycle, in an adequate interval, once in the rainy season and the other in the dry season

Development of Sustainable Communities

Implementation – Communities (I.CS)		
What to do?	**Why do this?**	**Examples of how to do it**
I.CS1. Distribute information about project implementation	1. Accessible transparent, up-to-date information about the project and its impacts can subsidize participative processes, public consultations, mediation, and negotiation of eventual conflicts 2. Information about possible changes in the project or delays or changes in scheduling during the phase of implantation, as well as about possible accidents which may affect the community should be readily available. 3. Information can be useful for Individuals and groups who may be interested in finding out about job opportunities, furnishing services, or supplying the company, whether during the phase of implantation, or that of operation.	• Emission of bulletins with information about the progress during implantation • Utilization of appropriate means of divulgation of information, taking into consideration the diversity in stakeholders, the level of technical detail involved, the degree of education of the people, the ethnic and gender composition of the community, the structures of local leadership, and the number of associations • Conduction of sectorial meetings with the affected communities, including meetings with small groups which may manifest specific interests and concerns, meetings with community leaders, and the press, as well as the use of electronic media or other means of local communication • Formulation of a system of social and economic indicators which are capable of predicting and revealing tendencies, as well identifying potential undesirable economic and social situations prior to their occurrence
I.CS2. Implant a grievance mechanism for registering complaints and managing conflicts	1. The identification of grievances can help identify possible conflicts of interest between the project and the activities developed by the community, such as, for example, in relation to the use of water or sites of historic or touristic interest 2. A well-designed grievance mechanism can lead to the discovery of ways to manage conflicts	• Establishment of a channel for receiving complaints and a consistent system of register, widely known and easily accessible to the interested parties • Adoption of a direct channel of communication, such as a 0800 telephone number, special auditors, a web site maintained by the company, periodical meetings with specific groups of the community, and the implantation of a company office in an easily accessible location
I.CS3. Implement relevant management programs and evaluate the results	1. The programs and plans of action implemented should be in agreement with the proposals made during the phase of feasibility studies, and avoid or at least minimize adverse impacts and maximize benefits. (Such programs are often external requirements resulting from environmental licensing, financing, etc.)	• Definition of indicators of progress and of the results of social programs with the stakeholders • Maintenance of a systematic register of the advance of the management programs and the corresponding indicators of performance
I.CS4. Invite entities to constitute a committee to accompany the implantation	1. The inclusion of outside entities in the accompaniment of implementation can help guarantee a transparent process and facilitate the construction of a permanent channel of dialogue with the company 2. A committee accompanying implantation can be responsible for informing the community about schedules and the actions to be adopted during the implantation, clarifying eventual doubts which might evolve into situations of conflict.	• Identification of groups and/or individuals who may be involved in the process of accompanying the implantation of the enterprise • Establishment of a calendar of monitored visits to the area of the enterprise • Realization of meetings to inform the community about the actions adopted by the company to encourage environmental protection • Prior elaboration of a plan to conduct the process of accompaniment • Maintenance of a register of the actions developed

3.3 RECOMMENDATIONS FOR THE PHASE OF OPERATION

The practices recommended for the phase of operation of a quarry are largely identical to those recommended for the phase of implantation. In the tables presented in this section, the practices already described in the previous section are not repeated, but only practices pertinent specifically for this phase.

The practices to be adopted in this phase arise largely from the conclusions of the studies and surveys made previously, i.e., they are actions of mitigation designed for a specific quarry, or even for a specific structure in a quarry, such as the location of the waste rock dumps and facilities for the disposal of tailings.

The practices recommended in this section are general in nature, and may or not be valid for a specific quarry as a function of the presence or absence of karst components or the characteristics of the community targeted by the practice. Moreover, in the absence of paleontological or archeological remains, many of the recommendations presented here are not applicable.

On the other hand, various practices mentioned in this section are applicable to most operating mines, especially those related to biodiversity and sustainable community development, such as the practices related to the recuperation of degraded areas and the updating of the mapping of stakeholders.

The practices presented here, focused on karst environments, should be added to other environmental practices adopted during the operation of mines, and may be grouped in related programs or organized in a system of management. Modalities of environmental management are outside the scope of this guidebook, although it should be remembered that the adoption of the recommendations of good practices listed here will generate a large volume of data and information which should be organized in accessible databases.

Well structured data bases can serve not only for the management of the enterprise itself, but also contribute to the management of a territory on a municipal or regional scale and the evaluation of cumulative impacts, scientific research, and other purposes. The management of information and knowledge is a very valuable tool for the effective application of the recommendations of this guidebook.

Karst Geosystems

Operation - Karst Geosystems (O.KG)		
What to do?	**Why do this?**	**Examples of how to do it**
Many of the practices of the phase of implantation also apply to the phase of operation, such as I.KG1, I.KG2, I.KG3, I.PA1, I.BI4, I.BI5, I.BI6, and I.CS1.		
O.KG1. Establish, via consultation with the community and the authorities, a plan for the management of caves located on the property of the company	1. The speleological heritage is very important, and it can be preserved via actions of education and divulgation. 2. The continuity of academic research should be facilitated, as well as that of potential interest for the advance of knowledge about karst. 3. Economic benefits for the community can accrue if there is a regular flow of visitors.	• Determination of possible forms of use in agreement with the requirements of the specific study

Paleontology and Archeology

Operation - Paleontology and Archeology (O.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
O.PA1. **Implementation of the Programs of paleontological and Archeological Monitoring and Rescue**	For the Archeological Operation, this action is indispensable previously to the quarry starts its operation, mainly during the movement of the soils, because this is the best way to protect the archeological heritage against the advances of the quarrying These measures are also indispensable during the operation of the quarry because they are the best way to protect the paleontological heritage that could be split as the quarry operations advance into the rocky material	• Implement some procedures, as mentioned below, that will be done by a paleontology/archeology company or team with a wide expertize in environmental programs who are able to decide at first and furtherly implement courses for the capacitation in paleontology and archeology, qualifying the employees for the systematic monitoring that will last until the quarry is no longer operating
O.PA2. **Capacitation Courses in Paleontology and Archeology**	It is necessary to keep the technical qualification in Paleontology and Archeology of all employees as long as the process of mineral exploration lasts	• Theoretical and practice courses should be offered to employees working in the excavation teams, therefore helping the research previously recognizing paleontological and/or archeological material. The courses should be held once a year aiming to keep the qualified employees updated, and provide the qualification for newcomers
O.PA3. **Lectures about Heritage Education**	They have an informative purpose and help the local population to understand the ancient past, the forms of life and the ancient peoples that inhabited the region; it is a way to value the scientific and social importance of the vestiges of fossils and cultural material in the regional development context through tourism. They provide a steady cultural insertion and help to qualify and motivate new local guides to work in expositions	• Theoretical and practice courses should be offered to employees working in the excavation teams, therefore helping the research previously recognizing paleontological and/or archeological material. The courses should be held once a year aiming to keep the qualified employees updated, and provide the qualification for newcomers

Operation - Paleontology and Archeology (O.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
O.PA4. Training technicians to follow up the quarrying activities and the scraping of the sterile ground (monitoring)	With specific training it is possible to avoid hiring teams of paleontologists/ archeologists to monitor the quarrying works.	• Those are specific and intense training courses that may last from 6 to 12 months. They must begin with theoretical lessons followed by the improvement of field techniques, mainly the recognition of fossils and archeological vestiges (as clay objects, lithic material, malacological material, historical material, rupestrian art) during the quarrying operations
	The sterile ground, which is always disregarded by the quarrying operation, may contain important paleontological records. If the fossiliferous potential is confirmed, by previous studies, it is important to keep paying attention to the scrapping and following up the process systematically. Because of the great quantity of rocks that are removed, there is a higher possibility of finding paleontological material	• The excavations of the sterile rocks must be closely followed, and it may be necessary to separate a portion for further screening. Should paleontological records be found, the extraction must be halted where the material was found, without damaging the adjacent areas that may continue to be explored. The area of the findings must be isolated until the rescue of the fossils is completed. Every paleontological finding must be photographed and georeferenced, and put into the geological context with a description of the rocks, stratigraphic levels, sedimentary structures and, if possible, with taphonomical studies
O.PA5. Separation, screening and rescue of the fossils (monitoring)	Due to the great volume of rocks daily removed during quarrying operation, screening the portions of this material is the most practical way to protect the heritage that could be damaged by the quarrying, it is a kind of systematic monitoring the rocky material	• At every dismantling of the massif, a small portion of the material must be screened by the paleontology technicians, so that they can identify any possible paleontological material. When any material is found, it must be taken to the laboratory to be prepared and packed
O.PA6. Rescue of fortuity or findings	This is the only way to guaranty the findings are protected and are not destroyed during the quarrying	• First of all, quarrying must be halted and the place must be isolated until a technician in charge of the paleontological and/ or archeological program is notified and will determine what has to be done. Next, the fossil or the archeological evidence must be excavated following the criteria required by the methodology, to ensure its total integrity to be transported to the paleontological/archeological laboratory for further procedures
O.PA7. Systematic paleontological review	To ensure and keep the systematization of the Paleontological Program	• By periodic visits and meetings with the paleontological teams, it is possible to add the analysis of the indicators of the quality of the studies and to suggest improvements for the whole process
O.PA8. Implementation of laboratories for the paleontological and archeological works	It is an important place for the proper development of the program, because it provides the environment and equipment to prepare the fossil and to clean and register the archeological evidence	• It is an office with instruments for the study and pre-preparation of fossils and/or to take care of the archeological evidences. It must have running water, binocular magnifying lenses, equipment to prepare fossils (chisels, brushes, pneumatic pens, sand bags) crates for packing, material to glue and restore the specimen or archeological evidences
O.PA9. Basic preparation and identification of the paleontological and/or archeological findings	Comprises the second phase of the paleontological research, just after the field collection. Without properly preparing the fossil there is no way to identify, classify and study it	• Comprises the total or partial removal of the rock that involves the fossil. It can be done by means of pneumatic tools, small pointers and hammers, or even chemically by solving the rock with acids that may dissolve the sediment without damaging the fossil. At the end of the preparation it is possible to identify the parts of the organism that is comprised in the sample , so that the studies on the identification of the material can begin and can lead to its taxonomic classification
	Important stage for Archeology because the vestiges that are collected in the field are analyzed, cleaned and classified according to the kind of material (lithic, clay, malacological, etc.) and are separated according to their characteristics	• Comprises the cleaning, classification, cataloging and restoration of the pieces in order to maintain the integrity of the material, which is indispensable for further detailed studies

Operation - Paleontology and Archeology (O.PA)		
What to do?	**Why do this?**	**Examples of how to do it**
O.PA10. **Packing and cataloging the fossil and archeological findings**	This is a fundamental procedure for the conservation and organization of the paleontological/archeological reports in scientific collections	• Comprises the storage of the fossils after being registered in a catalog (in a printed book or in digital registry) stating all information available for the sample such as: date of collection, person responsible for the collection, geological unity. Each fossil is granted a number of the collection that will identify it among the material of the technical inventory • Comprises the storage of the cultural vestiges after being registered in a catalog (in a printed book or in digital registry) stating all information available for the sample such as: date of collection, person responsible for the collection, level of deposition, UTM coordinates, kind of material. Every piece is granted a number of the collection that will identify it among the material of the technical inventory
O.PA11. **Transportation and register in a referenced storage facility**	Aims to safeguard the Paleontological Heritage to keep the integrity of the material through a proper packing that ensures the original characteristics of the samples which are necessary for the scientific Studies as well as for exhibitions in Museums and public shows	• Comprises the transportation of the exemplars with the authorization of the agency responsible for this issue (in Brazil it is the DNPM). The material must be stored in an institution previously selected by the agency, usually research centers and museums nationally recognized. After that, the fossils will be registered and will make part of the inventory available for further scientific studies
O.PA12. **Prospection of cavities located in the massif**	It is important for attesting or not the presence of paleontological and/or archeological material inside cavities therefore avoiding the destruction of this heritage	• The investigation must be done walking inside the cavity followed by the analysis of the sediments to identify any vestige of fossils. The findings may be associated to different conditions in subaerial or subaquatic areas • Rock painting panels must be identified both in the external and/or internal walls of the cavities. The panels must be photographed and classified according to its tradition. The area presenting big panels must isolated so that a detailed study can be performed in the archeological site
O.PA13. **Program to save cavities with paleontological / archeological records**	Once the paleontological and/or archeological potential of the cavity is confirmed, this is the only way to grant protection to the speleological paleontological and/or archeological heritage	• Every fossil identified during the prospection of the cavity must be rescued and new excavations must also be done to search and rescue paleontological records that must be covered by the sediments fulfilling the cavity .This prospection may be done together with the archeological program, once they share the methods of collection of the material preserved in the sediments of cavities
O.PA14. **Documentation**	Has the function of registering the works and informing the regulatory agencies about the actions performed by the paleontological/ archeological programs during the stages of a quarry	• A report must be prepared consolidating all the Information generated by the paleontological and/or archeological program, since the feasibility Studies to the end of the Operating stage
O.PA15. **Implementation of a Natural History Museum**	To try to guarantee the popularization of the archeological and paleontological knowledge that was rescued	• Implement a museum like place, with the material that is not interesting for scientific studies, so that the knowledge generated by the Archeological and Paleontological programs is shared

Biodiversity

Operation – Biodiversity (O.BI)		
What to do?	**Why do this?**	**Examples of how to do it**
O.BI1. Continued implementation of the quarry rehabilitation plan	Continued implementation of applicable actions of the rehabilitation plan leads to: (a) reduce environmental liability; (b) demonstrate to stakeholders the accomplishment of environmental protection and restoration commitments; (c) build knowledge and experience in rehabilitation. Rehabilitation programs can be classified into four groups: soil management practices, topographical and geotechnical practices, water related practices and ecological practices	• Soil management practices refer to the management and protection of the soil, and to the use of topsoil as soon as possible after its removal • Topographical and geotechnical practices are related to ensuring slope and structural stability, such as a implementing a drainage system for the rainwater in the embankments • Water practices are related to the protection of the water resources, such as re-foresting the area around water streams • Ecological practices are related to the management of the fauna and the vegetation, for instance, restoring the vegetation in recuperated areas accordingly to what was determined in the planning
O.BI2. Continued management of the rehabilitation process	The actions of controlling and managing the RDA are important to guaranty the operational RDA practices continue to reach the results as planned	• The point of view of the community must be acknowledged • Provide technical guidance for the tasks to be done • Provide technical capacitation for the working team • Develop and implement operational procedures • Provide resources (human, physical and financial) • Follow up (monitoring, record and documentation
O.BI3. Periodic updating of the PRDA and of the closure plan CP	Changes in technology, in the Market, in the legislation, in the Project, as well as in the stakeholders' expectation may occur during the quarry lifetime. Therefore reviews and updates in the PRDA and CP must reflect the changes occurring during the quarry lifetime	• Update the evaluation of the social and environmental impacts; • Keep an updated map of the stakeholders; • The period of the reviews of the PRDA/CP must be established by each Quarrying Company. A three to five year period is commonly used. There are some questions that can guide the need to update the PRDA/CP, such as: "was there any change in the quarry plan?" (ex. change in contents) "were new structures added to the quarry?"
O.BI4. Keep being aware for evidences of cavities and subterranean fauna that can be a potential for conservation purposes	Accomplish with the goals for the conservation of the subterranean fauna	• Implement a periodical training program and provide information for the employees and contributors, according to their jobs, showing them the importance of the cave and the subterranean fauna, allowing them to identify probable cavities (fortuitous findings) and take the appropriated action and report them to the team of experts
O.BI5. Should a new speleological finding occur, it must be evaluated by an environmental study Ad Hoc	Because the new findings may be important for the conservation of the subterranean systems	• Stop the operation and call a biologist (preferably the ones that did the environmental studies) for a new study. 1st Stage: provide a rapid evaluation as RAP (Rapid Assessment Procedures), mainly focusing on the environment (kinds of habitats and their distribution, substracts, food sources, etc.) and on the taxon observed during the whole year in other caves located in the area; 2nd Stage: If the new cave is in accordance with patterns observed in other subterranean systems studied in the same area (if they were identified) resume the quarrying operations; If the cave presents singularities not yet observed in the region (or if previously no pattern has been identified in relation to the environment and fauna), proceed with a study following the same criteria and methods of the initial studies

Sustainable Community Development

Operation – Communities (O.CS)		
What to do?	**Why do this?**	**Examples of how to do it**
O.CS1. Update the socioeconomic baseline	1. The socioeconomic characteristics of the communities influenced by the quarry will be changing, due in part to the mining activity itself, but also to external driving forces 2. Up-to-date socioeconomic information can ensure the identification and evaluation of impact significance and, as a consequence, the programs of mitigation or compensation.	• Conduction of Interviews and the application of tailor-made questionnaires • Updating of data about demographics, economic organization and dynamics, infrastructure and basic services, public finances, social organization and sociopolitical context
O.CS2. Develop a system of social and economic indicators	1. Social and economic indicators provide a tool to facilitate the understanding of the local reality 2. The use of such indicators can facilitate the systematic monitoring of changes taking place locally and of the social and economic trends in the area of influence of the project 3. These indicators can be used to verify if and how the company is contributing to the development of the community	Definition of a set of indicators via public consultation which should be monitored. Practices that facilitate engagement include: • Preparation of short booklets for providing information in an accessible language • Holding of meetings of civil society organizations, municipal councils, etc. • Engagement of the local authorities and sharing of information • Printed materials and websites
O.CS3. Update stakeholder mapping	1. Stakeholders and their interests change over the long period of operation of a quarry, with specific groups or individuals becoming interested or losing interest in the activities of the quarry itself or the impacts arising from it as time passes. 2. As the quarry operations evolve and change, they can give rise to new concerns, expectations or demands	• Update the mapping of stakeholders whenever there is a significant project modification or an important change in social conditions, or in the social programs and projects implemented by the company • Consideration of the different interests and positions of stakeholders, decision-makers and beneficiaries of socioenvironmental programs developed by the company, such as workers, local suppliers, and landowners • Elaboration of a matrix of stakeholders, including the identification of organizations, leaders, addresses, and contact information
O.CS4. Implement management programs and evaluate the results	1. Adverse impacts can be avoided and benefits maximized by the implementation of programs and plans of action as set out in the planning stage during the feasibility studies 2. External requirements resulting from environmental licensing, financing or legal agreements must be accounted for.	• Establish, indicators of progress and of outcomes for the social programs via consultation with stakeholders • Maintenance of a systematic register of the progress of management programs and corresponding performance indicators
O.CS5. Invite stakeholder organizations to participate in a committee to accompany the operation	1. The participation of stockholders can guarantee a transparent process and facilitate the construction of a permanent channel of dialogue with the company. 2. The inclusion of stockholders in activities accompanying the operation can facilitate the dissemination of information about the schedule of implementation and the actions adopted, and the provision of timely information upon request prevents misunderstandings evolving into conflict.	• Prepare a plan for accompaniment of the operation • Establish a calendar of monitored visits • Stage meetings to inform participants about actions adopted by the company to promote environmental protection • Maintain a register of actions developed
O.CS6. Facilitate and promote access to caves and other components of the karst system	1. Access to caves facilitates access to Information about the value, characteristics, and importance of karst environments.	Encouragement or support of: • Tourism • Academic research • Caving

3.4. RECOMMENDATIONS FOR THE PHASE OF DECOMMISSIONING

In the phases of decommissioning and post-closure, management actions should be based on information and knowledge accumulated during the previous phases. Only a few additional recommendations of a general nature are possible, as actual actions should be grounded on such information and the knowledge base. Most recommendations for this phase are not specific to karst.

Decommissioning (D)		
What to do?	**Why do this?**	**Examples of how to do it**
D1. Identify and evaluate the social and environmental impacts of closure	1. Decisions about the closure of the quarry should be based on adequate information. Attempts should be made to minimize the adverse impacts of closure 2. Critical environmental issues should be monitored after the closure of the quarry 3. The degree of dependence of the municipality or community in relation to the quarrying activity should be evaluated.	• Evaluation of the effect of the loss of tax revenue (municipal whenever applicable), as well of the loss of jobs and income, a decrease in local economic activity, the reduction in the quality and extent of public services, and the possible decrease in quality of life of the local population • Prediction of the future situation of springs and underground waters if pumping has taken place during the operation
D2. Update the closure plan, promoting adjustments if necessary	1. An up-dated closure plan can orient the actions and measures aiming at (i) guaranteeing the protection of environmental quality at closure and the rehabilitation of degraded areas, (ii) making future land use compatible with local and regional demands, and (iii) leaving a beneficial and lasting legacy for the community.	• Review of the objectives of closure plan to ensure they are aligned with the objectives of local and regional development policies and uses, as well as the expectations of the community, with these in turn being identified via structured processes of consultation
D3. Update stakeholder mapping	1. The groups or individuals potentially affected by closure can differ from those mapped during the feasibility and operational phases; changes may include landowners of neighboring properties, local government authorities, development agencies, and local and regional suppliers 2. Concerns and interests of stakeholders relative to closure are usually different from those during previous phases and may include loss of jobs, decrease in economic activities	• Evaluation of e how and to what extent groups or individuals will be affected, identifying those who are the most vulnerable to the closure of the quarry, what the extent of the impacts associated with closure (local, regional) is, and what groups or individuals may contribute to improve the definition of closure objectives (local government, development agencies, landowners and tenants, neighboring communities, etc.), and consider the effects on those who have benefitted from the social programs of the company, the organized representatives of the workers (councils, syndicates, professional associations) and the direct and indirect suppliers of the company
D4. Communicate information about the process of closure	1. Access to relevant information makes the participation of the stakeholders possible at the appropriate time in planning of closure. 2. Participation, mediation and negotiation of conflicts can be based on information. 3. The participation of residents can be strengthened as they look for solutions to conflicts during the phase of closure	• Preparation of a specific, closure-oriented communication plan of communication with transparent, objective, and up-to-date information made available in an accessible language, considering the differences and diversity of the interests of the various groups and individuals who may be affected by the closure • in the selection of the format and vehicles for dissemination of information, consider the diversity of stakeholders, their level of education, ethnic and gender composition, as well as the structure of local leadership and community associations • Consideration of direct employees (workers, and technical and managerial staff), as well as those who are outsourced or part of the supply chain • Use of a variety of different media and communication tools, such as meetings with affected communities, small groups meetings, and the press, and electronic media
D5. Implement decommissioning programs described in the closure plan	1. It is important to attain closure objectives discussed with stakeholders and approved by the responsible authorities	• Disassembly of electrical installations and equipment • Disassembly or razing of buildings • Removal of residues and rubble to their final destination • Investigation and remediation of contaminated areas • Preparation of report "as built", to describe in detail the work realized and the results obtained
D6. Monitor the parameters of interest	1. It is important to collect evidence of the satisfactory execution of the decommissioning programs closure plans.	• Geotechnical monitoring of waste rock dumps, pit slopes and other structures • Monitoring of the level of underground water • Monitoring of the discharge of springs • Monitoring of the quality of underground waters

Decommissioning (D)		
What to do?	**Why do this?**	**Examples of how to do it**
D7. Accompany the indicators of development and quality of life	1. The possible contributions of the presence of the quarry to local development should be evaluated. 2. Systematic monitoring facilitates the evaluation of changes which may occur during the phases of decommissioning and post-closure 3. Socioeconomic impacts due to the closure of a quarry may require mitigation	• Selection of relevant variables which can show the local social and economic situation and the capacity (or not) of the community to develop in a sustainable way in the absence of the quarry • Selection of indicators, either quantitative or qualitative, which make it possible to develop comparative analyses and identify tendencies • Adoption of explicit criteria for the selection of indicators, such as representativeness, relevance, simplicity and ease of interpretation • Inclusion of stakeholders to make possible the development of indicators better suited to local concerns
D8. Develop programs which foster diversification of the local productive base	1. Economic activities unrelated to quarrying should be promoted or opportunities created to diversify the local economy 2. A long-term model for sustainable local development must be formulated	• Adoption of initiatives to share company knowledge and abilities such as those of commerce, administration, finance, and logistics via capacitation, construction, and qualification of local agents and small businesses • Development of programs of literacy for adults or the capacitation of young adults

3.5 RECOMMENDATIONS FO THE PHASE OF POST-CLOSURE

For the phase of post-closure, the recommendations relative to karst will depend on the arrangements for relinquishment of the area to others, which, in turn, will depend largely on the applicable legal requirements.

The recommendations relative to the post-closure management of the area should result from information collected and knowledge gained during the previous phases. Three generally applicable recommendations are presented in this section.

Post-Closure (PC)		
What to do?	**Why do this?**	**Examples of how to do it**
PC1. Monitor re-establishment of flora and fauna if the intended land use involves environmental conservation	1. Monitoring is necessary to guarantee and to demonstrate the achievement of objectives.	• Definition of appropriate indicators for each situation.
PC2. Involve the stakeholders in post-closure monitoring	1. Stakeholder involvement makes possible the sharing of responsibilities, favoring the process of empowerment of the community and enabling it to influence the post-closure scenario, so it will be able to act and make decisions about themes which directly affect it.	• Involvement of stakeholders in the definition of aspects to be monitored, as well as how data and information will be obtained, stored and made available • Assess the capacity of the community, its leadership and the local institutions to participate actively in the accompaniment of the situation of the area after the closing of the quarry • Establishment of a commission for monitoring, including the participation of other interested groups, such as the local government, representatives of professional bodies, and institutions of higher education, with the responsibility for producing reports and communications containing relevant information about the aspects monitored • Regular review and reevaluation of the objectives, goals and results if prolonged periods of post-closure accompaniment are needed
PC3. Maintain permanent or active care of the area, when necessary	1. A period of several years may be required to guarantee that the company execute the necessary actions to achieve closure objectives.	• Inclusion of contractual or legal warranty for The "permanent care" scenario to guarantee permanent supervision by the new responsible entity after relinquishment

SECTION 4:
EXAMPLES

To illustrate the application of good practices by a quarrying company, three cases were selected as examples. These show how good practices can become effective actions within a company. The selection was made by the Technical Coordination responsible for the elaboration of the present guidebook, in conjunction with the authors in charge of the systematization of good practices. The selected cases are the following:

- Evaluation of environmental rehabilitation for the Saivá Quarry in Rio Branco do Sul, Paraná (Brazil);
- Promotion of awareness of the importance of karst via the development and divulgation of "Green Rules";
- The "Environmental Assets" program.

4.1 EVALUATION OF PRACTICES OF ENVIRONMENTAL REHABILITATION

The Saivá Quarry furnishes limestone for the fabrication of cement in Rio Branco do Sul in the state of Paraná (Brazil). The waste rock is disposed of in piles located in the proximity of the pit. When the piles were being constructed, a system for the drainage of rainwater was installed, and creeping vegetation was planted to avoid triggering erosion. The long term objective was environmental protection and the reestablishment of native vegetation.

Land rehabilitation is an activity with results which can be demonstrated only after a long period of time. For this reason, it is important to evaluate periodically not only partial results, but also the practices being utilized, so that possible problems can be identified and corrected as soon as possible.

An index of applicable recommendations for the evaluation of the activities in this quarry was elaborated on the basis of a set of good practices obtained from national and international sources. The recommended practices included not only well-known measures such as surveying the speleological potential of areas favorable for the occurrence of caves, but also preventive practices designed to deal with situations potentially requiring additional measures of rehabilitation, such as soil contamination due to hydrocarbon spills.

The procedure for evaluating rehabilitation practices (Neri and Sanchez, 2010) listed 150 good practices, classified into aspects of planning, operation, and management. The operational practices were subdivided into those of a topographical and geotechnical nature, water resources protection, soil protection, and ecological practices.

Technical inspections, the analysis of documents (such as rehabilitation plans), and interviews were used to collect evidence about the actual application of relevant practices, as well as to seek evidence of deviations, if any. A weighting system (based on the importance of each practice for achieving the rehabilitation objectives) was devised to inform managers about areas of relative strengths and weaknesses in rehabilitation activities.

This evaluation of current practices makes it possible to improve the control of management, establish targets and improve the practices themselves, reducing the exposure of the company to risks from practices inconsistent with the state of the art of environmental management.

Practices for the management of soil and the vegetation were emphasized in this evaluation. The problem of insufficient supply of organic soil was solved by using weathered soil and clay. Initially revegetation consisted of the planting of quick-growing grasses and legumes adapted to the climate of the regions, as these rapidly contribute to the nutrient enrichment of the soil, making it more adequate for the growth of seedlings of native trees. A compost based on plant residue was prepared in a greenhouse and mixed with vermiculite to fill the sacks for the planting of the seedlings; thus the compost was able to help overcome the deficiency of organic material in the soil.

4.2 PROMOTION OF AWARENESS OF THE IMPORTANCE OF KARST VIA THE DEVELOPMENT AND DISSEMINATION OF "GREEN RULES"

Many companies have developed management tools which can contribute to the minimization of the impacts of their activities on karst. One way of doing this is fostering an awareness of the importance of karst environments and their fragility, as such an awareness can help prevent and reduce certain impacts. The engagement of employees, suppliers, and service providers is crucial for the success of programs and measures designed to protect the karst, its resources and the communities which inhabit it.

One such tool was an initiative of Votorantim Cimentos entitled "Green Rules", which constitutes part of its Global Environmental Policy, initiated in 2015. This policy is based on nine principles, and was elaborated to direct efforts in sustainable development. Based on these nine principles, a set of 10 "Green Rules" was developed to facilitate the comprehension and application of the policy by all employees, and compliance with it in all activities undertaken by the company is guaranteed.

The Environmental Policy and the "Green Rules" (Figure 3) encompass all aspects of the environment linked to the production of cement. Various rules involve the protection of karst, as can be seen below.

Figure 3. Green Rules. Source: Votorantim Cimentos (2015)

A pamphlet for the dissemination of information was distributed to all of the collaborators and those offering services. It provides examples of how these principles can be put into practice (Figure 4).

7 Respect caves, cultural , geological, historical, paleontological, and archeological sites

The caves and historical, paleontological, archeological and cultural sites belong to humanity and should be preserved.

LOOK AT SOME EXAMPLES OF HOW TO PUT THIS RULE INTO PRACTICE

- If you find evidence of a cave or a cultural, geological, historical, paleontological or archeological site, inform the person responsible for the environmental area of your unit
- Look for information about the characteristics of these locations to facilitate their identification

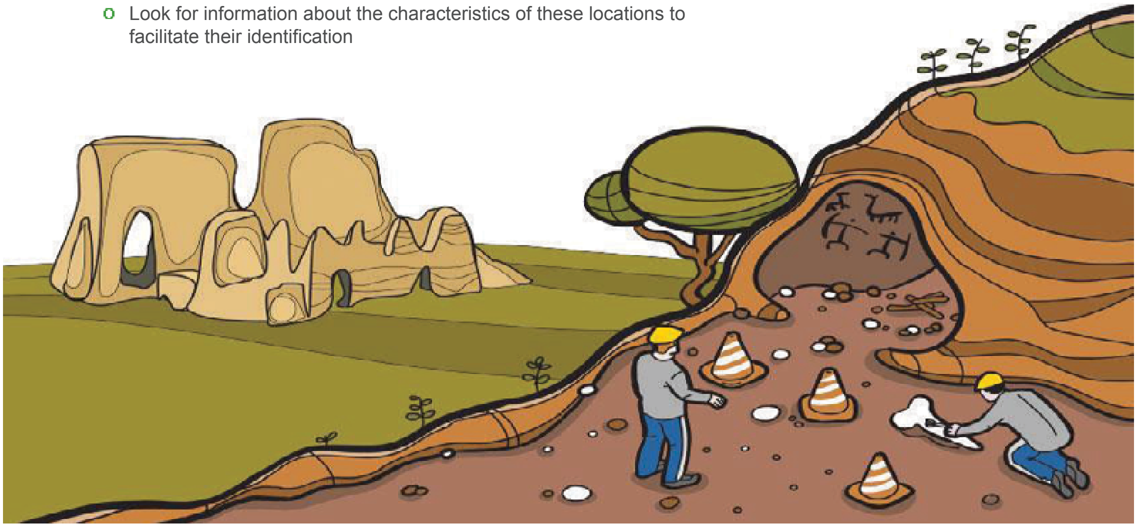


Figure 4. Presentation of Green Rule 7. Source: Votorantim Cimentos (2015)

The global environmental policy and the Green Rules have also been disseminated by means of training programs to capacitate quarry and plant managers to inform their staff about the principles and emphasize their importance. At present, the company has some 500 multipliers.

Many of the mining companies which develop activities in karst areas are very large and operate numerous quarries. However, communicating the policies of the company in relation to karst (and its socioenvironmental responsibility in general) is within reach of companies of any size, including small ones.

4.3 “ENVIRONMENTAL ASSETS” PROGRAM

The Program of Environmental Assets is a product of the Agreement for Technical Cooperation between Votorantim Cimentos (VC), the Institute Friends of the Mata Atlântica Biosphere Reserve (RBMA) and the Brazilian Speleological Society (SBE). It was designed to develop a model for a Territorial Plan for Sustainable Management for the quarrying of limestone for cement production in the area of the Mata Atlântica, and was adopted for conducting case studies for the units of Votorantim Cimentos Ribeirão Grande (state of São Paulo) and Laranjeiras (state of Sergipe), Sobradinho (Federal District) and Oural (Triacastela, Galicia, Spain). At the end of the project, various actions for sustainable use were proposed as Socioenvironmental Assets so that they would be valued and the conservation of biodiversity favored.

The elaboration of the program included three phases:

The preliminary phase of planning and determination of scope was designed to organize the environmental planning and establish the premises of the work, including the definition of the team, the area of study and the surroundings, the socioenvironmental assets to be considered, and the activities to be realized, also defining the physical and financial schedule and consolidating a plan of work.

The phase of diagnosis was designed to elaborate a socioenvironmental baseline, based on an analysis of the information available, a preliminary elaboration of a geographical data bank, recognition, and a field survey.

The phase of analysis and proposals was designed to elaborate the proposal of "Sustainable Territorial Management"(PSTM), which includes a synthesis of the main environmental passives identified and the characterization of the socioenvironmental and institutional actives, the conduction of a strategic situational analysis, the elaboration of a preliminary proposal for creating zones for the property, and the formulation of recommendations for each zone of the property and each institutional axis.

The environmental actives considered were the following: carbon capture and storage; hydric resources; habitats; richness of species; species of special interest; and artistic, cultural, historic, archeological, and spiritual heritage. The potential institutional actives included planning and integrated management of the socioenvironmental heritage, environmental monitoring, protection and supervision of the property, socioenvironmental projects, scientific research, recreation, tourism, and environmental education.

Figure 5. Partial view of lake in the Retiro area of the Laranjeiras Unit in Sergipe. Photo: Patricia Rossi

Recommendations were elaborated for each property and for each zone within each property, as well as for each institutional axis (conformity with legal and agrarian regulations, integrated planning and management of socioenvironmental heritage, environmental monitoring, protection and supervision of property resources, socioenvironmental projects, scientific research, recreation, tourism, and environmental education)

The pilot project of the Laranjeiras quarry and cement plant identified a non-utilized area with resources of potential interest for the implementation of a tourist attraction (a short trail of easy access). The implantation of the Trail of the Retreat provided added value for these attributes, as well as making possible the interaction of the company with the communities of the neighboring towns. This new attraction is used for both recreation and environmental education. In 2015, Votorantim Cimentos, in partnership with the with the Mata Atlântica Biosphere Reserve, developed a technical-executive project and a proposal for the management of the trail, planned for implantation in 2017. The photo (Figure 5) shows a view of one of the points of this trail.

The pilot project of the Ribeirão Grande quarry included the area of Paivas (Figure 6), in the southeast of the state of São Paulo. This is still predominantly a forest area, and should probably suffer little intervention. Despite the reserves of limestone rock, the location is neighbor to two state parks and contains an important concentration of environmental assets, including various relevant caves such as Arcão, Água Luminosa, and the Gruta dos Paivas, the latter considered to be the fifth largest in the state, all with consolidated tourist visitation routes of the Intervales State Park, and established for more than twenty years.

Even though permits for quarrying have been issued by the National Department for Mineral Production (DNPM), Votorantim Cimentos has refrained from quarrying the limestone in the area and, in partnership with the Secretary of the Environment of the state of São Paulo, is negotiating the inclusion of Paivas in the State Park of Intervales and its donation to the state.

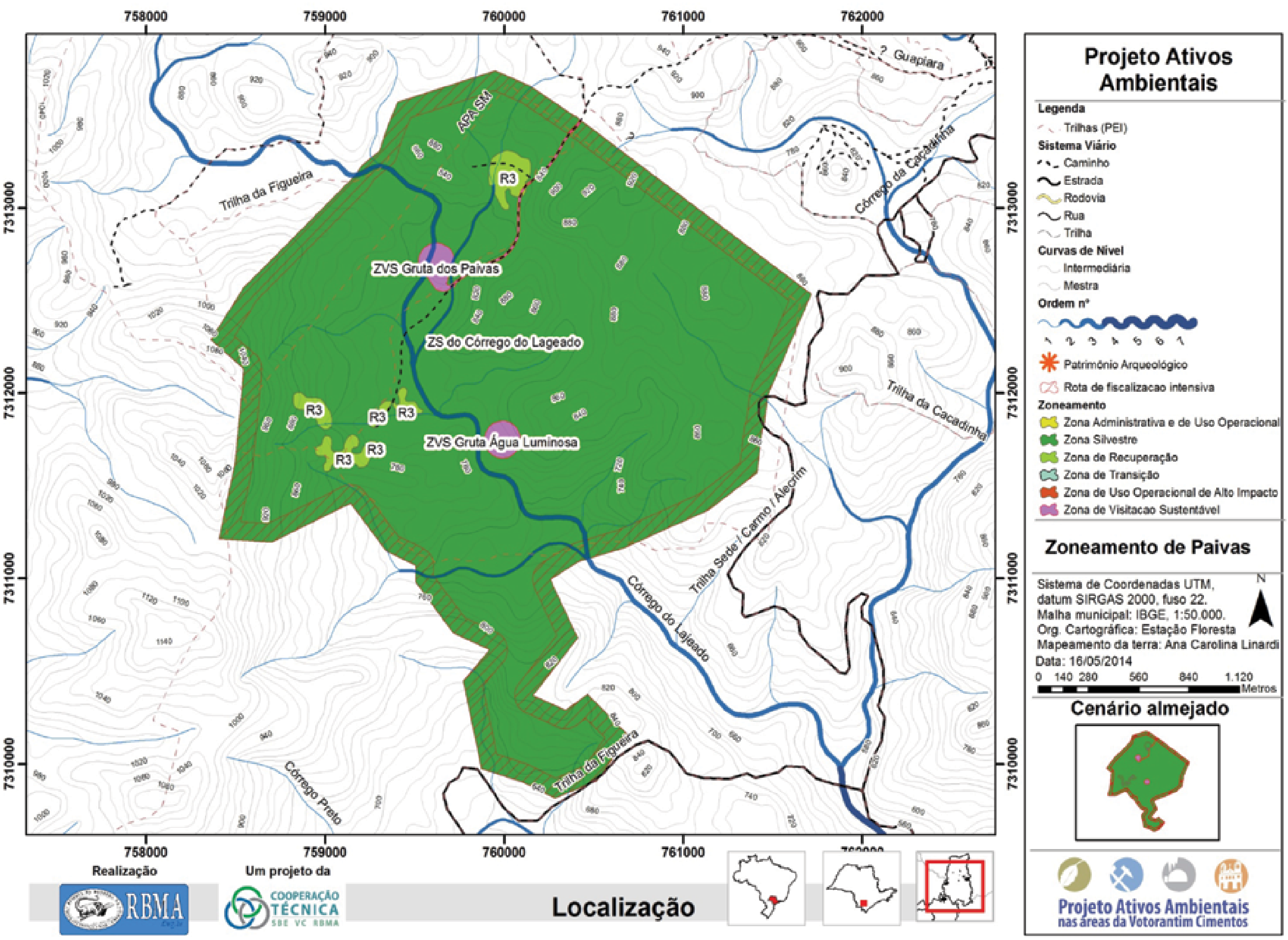
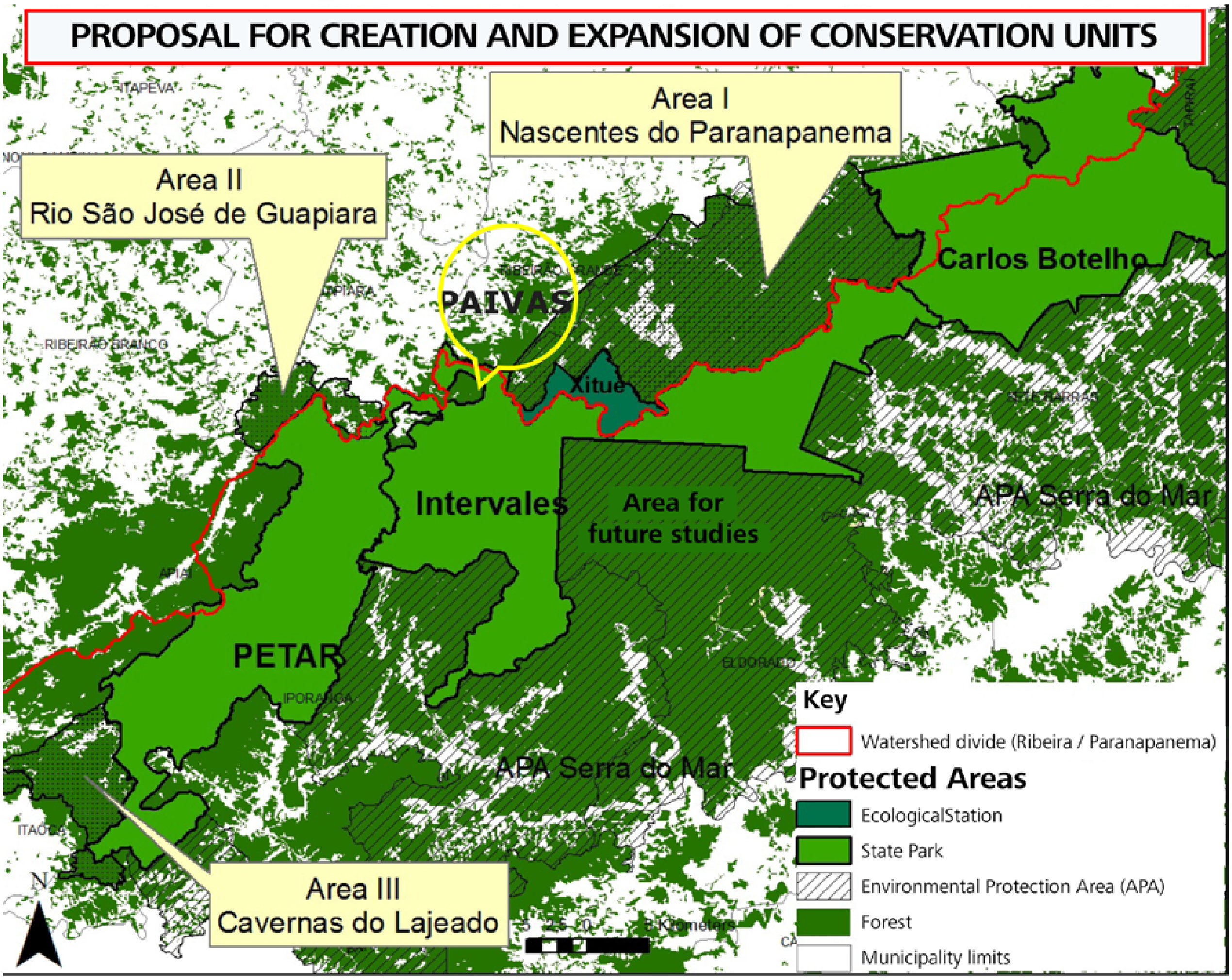


Figure 6. Map of environmental zones of the region of Paivas. Source: RBMA. Projeto Ativos Ambientais (2015)



Proposal for the creation and enlargement of protected areas. Source: RBMA. Projeto Ativos Ambientais (2015).

The figure below synthesizes the steps in the elaboration of the Plan for Sustainable Territorial Management (PSTM):

PLAN FOR SUSTAINABLE TERRITORIAL MANAGEMENT

PRELIMINARY PHASE
Organization of environmental planning
→ **PLAN OF WORK**

↓

PHASE OF DIAGNOSIS
Elaboration of socioenvironmental diagnosis
→ **SOCIOENVIRONMENTAL DIAGNOSIS**

↓

PHASE OF ANALYSIS AND PROPOSALS
Analysis, integration of data, and proposals
→ **PROPOSAL FOR SUSTAINABLE TERRITORIAL MANAGEMENT**

Based on the socioenvironmental diagnosis, this management plan is designed to conciliate environmental conservation with the sustainable utilization of the socioenvironmental heritage via the following:

- Characterization of socioenvironmental and institutional actives
- Creation of zones for the properties
- Strategic analysis of the situation of the property
- Recommendations for each property, zone, and institutional axis

↓

Process of development of the PSTM

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Photo: Allan Calux

GLOSSARY

Term or expression	Explanation from the authors on the expressions used in their respective chapter
Aggradation	Process of accumulation (deposit) of sediments on a specific surface or depositional site.
Aluvium	Unconsolidated deposit of detrital material transported by water, generally associated with a fluvial system; these accumulations accrue in or alongside river beds and on flood plains (aluvial plains); they consist of gravel, sand, silt, and clay.
Apomorphy	The most recent condition in a series of transformations, derived from the modification of an earlier condition (series of transformation: the sequence of modifications that a specific structure has undergone, becoming successively more derived).
Autapomorphy	Apomorphic characteristic for a single branch in a cladogram (phylogenetic tree).
Base level (water table):	Theoretical plane surface denoting the depth below which neither drainage of water nor erosion occurs.
Biological regression	A series of transformation in which the derived status correspond to less developed, disorganized or lost structures or functions.
Biotope	Bios (life); Topos (place). Location characterized by a specific set of abiotic factors, inhabited by group of organisms perfectly adapted to the specific conditions existing in that exact place.
Chipping workshops	A kind of archeological site where ancient peoples manufactured their stone tools, generally hitting a hard rock against a softer rock. In the so called "chipping workshops", it is possible to find remaining fragments from the production of stone tools.
Clogging	Filling of spaces in the rock, such as karst conduits, pores, and discontinuities, either with transported detrital material or by the precipitation of substances in solution.
Colluvium	Poorly graded sedimentary deposits consisting of fragments of rock and other debris transported or dislocated from the slopes of hills by the combined action of gravity and water; this material is often different from that of the underlying rocks. "Transported soil".
Community	Group or set of social groups which occupy a geographically delimited area, the members of which maintain reciprocal relations and share values and the same cultural and historical heritage, especially primary social contacts.
Conflict management	Management which is concerned directly with administration and behavior in situations in which divergences or incompatibility of interests between individuals or within a community occur in relation to a project or enterprise. The management of conflicts can involve various techniques, practices and processes, including consultation, mediation, and negotiation, in an attempt to reach agreement.
Corrosion	Decomposition of rocks (erosion) by the chemical action of water.
Crust dynamics	Action of a set of forces, movements and transformations on the crust of the earth (upper layer of the Earth; lithosphere), operating on both local and global scales.
Diagenesis	Also known as "lithification" (lithos = rock), this includes the set of physical and chemical processes which act in the consolidation of sediments over time until they are transformed into sedimentary rock as such. Exceptionally, some of these processes may take place after the formation of the rock as a function of its new exposure to surface conditions.
Dolomite	Sedimentary rock composed predominantly of the mineral dolomite, a calcium and magnesium carbonate with the chemical formula of $CaMg(CO_3)_2$.
Empowerment	The definition of empowerment approximates the concept of autonomy, since it refers to the capacity of individuals or groups to decide about questions which are relevant to them. Empowerment is the process by which individuals, organizations, and communities acquire the capacity to negotiate, influence, act, and make decisions about themes which affect their lives. In a broader sense, empowerment is the strengthening of the freedom of choice and action, with the transfer of responsibility for the making of decisions.
Facies	Distinctive features (of a compositional, textural, structural, or biological nature) of a rock reflecting the environmental conditions under which that rock developed, whether the depositional environment of a sedimentary rock or the diagenetic/deformational/metamorphic conditions involved in its formation.
Fissure	Any discontinuity in a rock, represented by bedrock planes, veins (discontinuites filled by recrystallized minerals), fractures or cracks (when there is no relative dislocation along the fissure plane), faults (when there is relative dislocation, showing differential movements of parts of the block of rock), and dissolution joints.
Fossil deposits	Natural deposits where fossils are found and are scattered in certain spots on the surface or subsurface of our planet.
Geological risk	Possibility of the occurrence of geological phenomena or events such as drainage, erosion, silting up, flooding, collapse, and subsidence, either induced or of a natural nature, which can cause some type of economic or social damage.

Term or expression	Explanation from the authors on the expressions used in their respective chapter
Homo *neanderthalensis*	Although there is controversy about this being a true subspecies of the current man or if it does not belong to the human lineage, studies about the Neanderthal Man (reference to the place where the first fossils were found, the Neander River Valley, in Germany) state that this is a species that lived around 300 and 29 thousand years ago. The authors that consider the current Man as its descendant, call it Homo sapiens neanderthalensis, whereas paleoanthropologists that do not consider it as pertaining to the human lineage, but consider it as a separate species, and classify it as Homo neanderthalensis.
Horticulturists/ farmers	Group of peoples that managed the techniques of planting herbs, tubers and other kinds of plants. Although they had the skills to grow crops, this does not exclude the continuity of hunting and collecting food practices. Usually, such peoples already had the skills to produce clay utensils (but this is not a general rule). This kind of population was considerably bigger due to the production of food.
Host community	Group of persons who live or work in a given locality (a neighborhood, a village, a city) in which an enterprise operates or will be implanted or disactivated. The community can include individuals who have come temporarily from other locations.
Hunters/ gatherers	Group of peoples comprising exclusively individuals that lived on hunting and /or collecting food. The main characteristics of such groups were: small number of individuals, once they needed to hunt and collect food everyday, the smaller the number of members the higger the chances of surviving; they didn't master agricultural techniques; they didn't produce clay objects.
Hydraulic activity	Behaviour of fluids at rest (hydrostatics) and in movement, reflecting the properties and forces involved in drainage (hydrokinetics and hydrodynamics).
Hypogean	Underground (synonymous).
Hyporeic zone	Region of an aquifer beneath and alongside a stream bed where there is mixing of surface and underground waters (16 - Gibert J, Danielopol DL, Stanford JA (1994) Groundwater ecology. San Diego: Academic Press)[16].
Ichno-marks	These are traces, marks or vestiges, that means, the indirect presence of the interaction between the organisms and substrate. The term Ichno refers to the preservation in rocks, specially sedimentary ones.
Ionic diffusion	Movement of ions or molecules in a solution influenced by differences in their concentration in the solution; movement occurs along a gradient from areas of greater concentration to those of lesser concentration in the search for an equilibrium.
Isotope (isotopic composition)	Atoms of the same chemical element with different atomic masses, although they have same number of protons in the nucleus (Z).
Marble	Rock constituted predominantly of recrystallized calcite and/or dolomite created by the effect of metamorphism (conditions of pressure and temperature different from those under which it was originally formed).
Monophyletic Group	A group (taxon) formed by an ancestor and all its descendants (p.ex. Tetrapoda, including amphibian, reptiles, birds and mammals). If any descendant is excluded, we have a paraphyletic group, such as Reptilia when Birds and Mammalia are excluded, because the latter are originated from different reptilian lineages.
Morphogenesis	Processes of elaboration or modeling of the forms and structure of the relief.
Morphotype	A type based on its morphology.
Omnivory	Feeding behaviour comprising food from animal and vegetal origin, in approximately an even proportion (p.ex. human's feeding behavior).
Orbital image	Data from remote sensorial systems on board artifical satellites orbiting the Earth. The sensors detect the radiation emitted / reflected by the surface and atmosphere of the earth in different wave lengths, which are processed and converted into standarized signals.
Parataxonomy	Classification based on groups of similar organisms which is done by non specialists in taxonomy only using external characterisitics (17 Majka, CG; Bondrup-Nielsen, S. 2006. Parataxonomy: a test case usnig Beetles. Animal Biodiversity and Conservation, 29(2): 149-156)[17].
Plateaus (relief)	Relief in the form of flat-topped hills of limited extent.
Pleistocene fauna	Refers to a group of animals that lived on earth during the Pleistocene period, around 2,58 million and 11,700 years ago.
Pleistocene Mastofauna	In general, big sized Mammals that lived in the Quaternary period between 2,58 million and 11.700 years ago (Pleistocene).
Pleistocene paleobiota	Comprises the ensemble of living beings that inhabited Earth during the Pleistocene period, between 2,58 million and 11,700 years ago.

16 Gibert J, Danielopol DL, Stanford JA (1994) Groundwater ecology. San Diego: Academic Press.
17 Majka, CG; Bondrup-Nielsen, S. 2006. Parataxonomy: a test case usnig Beetles. *Animal Biodiversity and Conservation*, 29(2): 149-156.

Term or expression	Explanation from the authors on the expressions used in their respective chapter
Polje	Wide, flat-floored karst depression forming a closed basin normally bounded by steep valley walls, with the base covered by alluvial deposits; swallow holes and/or karst springs may be present, and the hydrological behavior is complex, with flooding, droughts, and seasonal , annual, or pluriannual activity/inactivity being a function of the organization of the adjacent karst systems.
Rarefaction curve	Relation between the number of species sampled according to the sampling effort (sampling area or number of sampled individuals), that allows the comparison of the number of species among different sampling efforts.
Ruiniform	Resembling ruins. A kind of relief where the landscape resembles abandoned ruins. Generally, it is formed by the erosive action of winds or water (corrosion, in the case of karst).
Salinization	Accumulation or increase in the concentration of salts in the water or soil to a harmful level; this can occur naturally as a consequence of a high rate of evaporation (little rainfall) or be induced by modifications in the drainage conditions and the consequent accumulation of salt compounds.
Sample sufficiency	Sampling effort (area, and number of individuals) minimally needed to establish the "characteristic composition" of a community.
Silting	Accumulation of sediments in a channel or body of water (river bed, underground conduit, or lake) causing its obstruction (clogging) or complete silting up.
Sink Population	Population depending on the influx of migrants from different sources, being extinguished should such influx end (Fong DW, 2004. Op cit)[19].
Social capital	Expression of the capacity of a community to establish relationships of interpersonal confidence and networks of cooperation which aggregate real or potential resources for the production of collective goods.
Source population	Self-sustainable population, that means, whose reproductive rate is enough to balance the local death rate. Should there be any excess, the population can be the source of migration to different locations (18 Fong DW, 2004. Intermittent pools at headwaters of subterranean drainage basins as sampling sites for epikarst fauna. In: Jones WK, Culver DC, Herman JS, editors. Epikarst. Karst Waters Inst Spec. Publ. 9: 114-188. Proceedings of the symposium; 2003 October 1 -4; Shepherdstown, USA)[18].
Stakeholders	The interested parties are all those individuals or groups which, directly or indirectly, may be affected by a project or activity, either positively or negatively. This includes those who have some interest in or influence on the results, such as local communities, representatives of the local and regional governments, representatives of classes, vulnerable social groups, and others.
Stakeholder engagement	Broad and inclusive process which develops between a company and the individuals or groups potentially affected, either positively or negatively, by the enterprise, including the implementation of a set of participative activities, methods and approaches which last throughout the lifetime of a project.
Stratigraphy	Relative spatial and temporal arrangement of rock strata (successive lithologies), reflecting the distribution and organization of layers (strata), and their composition, texture, and primary and secondary structures, as well as fossil content and chronology; it also contemplates the environments of formation and transformation involved.
Stromatolite	laminated, mounded structure built up over a long period of time by successive layers or mats of cyanobacteria that trapped sedimentary material.
Subsurface	The zone located just below the surface.
Taxon	Autonomous unity under a name (p. ex., Pimelodella kronei, Siluriformes, Teleostei), in which the individuals or group of individuals are assigned to.
Water source	Any body of water on the surface or underground used as a source of catchment for human, industrial, animal supply or irrigation purposes.
Zoomorphical	Drawings found on rocky walls featuring animal images

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