Karstology

Karsts, Caves and Springs

Elements of Fundamental and Applied Karstology

Éric Gilli

Translated from French by
Chloé Fandel

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Preface

As I tagged along with a high school friend, one winter Sunday in 1974, to explore La Ratapignata, a small cave near Nice, France, I would never have imagined that our first foray into the subterranean world would be my first step into the realms of exploration, science, and university study. This textbook offers an explanation of the karst landscape built on more than three decades of firsthand scientific adventures. But many others had a hand in shaping my understanding, and here I thank them: Yves Créac'h for his scientific approach to caving and his appreciation for fine surveys; Claude Chabert for his philosophy of travel; Christian Mangan for his innate understanding of geology in the field; Jacques Mudry for his attentive listening and oft-renewed support; Jean Nicod, who set many people on the path to becoming karstologists and to whom I owe my decision to pursue a career in academia; Claude Rousset for his support during both of my theses; Robert Thérond, indefatigable geologist who welcomed me at EDF (Électricité de France) to write a speleology thesis. They share my passion for karst, and their presence can be felt written in between the lines of this book. I wish to give them credit here.

Time discloses the truth (Seneca)

to my son Paul

Contents

1

Introduction and Definitions

1.1 Karst, Karstic, Karstology

The word karst, of Slovenian origin, indicates a particular type of landscape that occurs in carbonate rocks that have been shaped by water. Typical features in karst areas include closed depressions, caves and sinkholes, rivers that disappear into the ground, and large springs around the periphery of the area. Karst zones are present on approximately 50% of land in France, 20% in USA and make up almost 15% of rock outcrops in the world. These areas are home to 1.5 billion people.

In the French academic world, karstology is not taught as its own subject, and is instead traditionally studied as a sub discipline of geography, although it is relevant to other areas such as geology, hydrogeology, civil engineering, paleontology, archeology, and climate science. As a result, the word karst can have several meanings. It is a model for the geographer, an aquifer for the hydrogeologist, and a simple hole for the geotechnical engineer or the quarry-worker.

The goal of this book is to highlight the wide range of approaches to a subject defined in three different dimensions: the surface, the world below ground, and time. A few examples illustrate the importance of karst. Almost half of France relies on karst hydrogeology for its water supply. The majority of discoveries about prehistoric humans have been made in caves. The largest pools of petroleum lie in cavities in carbonate rocks. Changes in the climate have been recorded for millions of years in cave speleothems. In the field of geotechnical engineering, karstic cavities and groundwater are a source of great worry for development companies. Large-scale civil engineering projects (high-speed railways, dams, tunnels, etc.) often face difficulties related to karstology, and geotechnical engineers' lack of knowledge of the field is often surprising.

From a more recreational point of view, karst areas are known for their extraordinary scenery. In France, the Vercors, the Verdon, the Causses, the Cévennes, the Calanques.… Abroad, Ha Long Bay, the Yunnan Stone Forest, the towers of Guilin, and the Tsingy of Madagascar, among others. The numerous caves that have been made accessible to tourists draw millions of visitors every year.

Many books and movies pull their characters into the mysterious depths of a cave. Lastly, caves, springs, and underground rivers, populated by fairies, dragons, elves, djinns, or other fantastical beings are the center of many myths, legends, and religions.

This book is therefore intended for a wide audience, including both professionals and well-informed amateurs, who wish to understand how karst landscapes and caves come into being. It may also be relevant to engineers responsible for development projects in karst areas.

The scope of the concepts addressed extends far beyond the French border, but the examples used here come primarily from France.

1.2 The Karst Region in Slovenia

The Karst, or Kras, region after which karst is named lies to the north of Trieste. It is a landscape of wooded plateaus, with complex topography and many closed depressions, caves, and sinkholes. The bedrock, when visible, is often sculpted into

Figure 1. Map of the Slovenian Karst (or Kras).

picturesque shapes. Streams are uncommon, and quickly disappear into the ground. Large underground rivers have been found there, such as the Reka in the Skocjan caves, or the Pivka in the Postojna caves. The latter are a popular tourist attraction, drawing several hundred thousand visitors each year to see the grottoes or the Predjama castle, built into the mouth of a vast limestone cave.

Figure 2. Predjama castle in classic Karst (Slovenia). The castle is partially built into the entrance of a cave.

1.3 Definitions

1.3.1 Geomorphology

The strict definition of karst is as follows:

A surface and subsurface landscape created by water dissolving carbonate rocks (limestone and dolomite).

A wider definition includes all soluble rock types that water can infiltrate into, dissolve below ground, and create durable cavities in. This requires on the one hand that the rock have a mechanical resistance great enough to prevent the immediate collapse of cavities, and on the other hand that there be a path for the dissolved minerals to exit the system. These concepts are important, as they differentiate karst from other landscapes. Some forms of surface dissolution can in fact be observed in most rock types, particularly in intertropical zones where basalt and granite weather easily. In these cases, however, the effects of water do not extend to great depth, because the products of collapse or alteration quickly fill any cavities as they are created.

Non-carbonate rocks such as gypsum, salts, and certain sandstones are soluble and can therefore form comparable landscapes. The word karst is then sometimes used, but the term parakarst is preferable. Finally, the action of warm water in periglacial regions can open cavities and create thermokarsts. Chapter 9 is dedicated to these types of landscapes.

1.3.2 Hydrogeology

Karst being a result of water's effects at the surface and below ground, it can also be approached from a hydrogeological standpoint. Karst, from this angle, is a limestone unit where the surface hydrographic system is partially or completely sunk below ground, and travels through the limestone, forming aquifers that feed springs. Together, the zone of infiltration, the aquifers, and the springs make up a karst system.

1.3.3 Thermodynamics

Karst can also be approached from a thermodynamic angle, by considering the energy required for its creation. Water sculpts rock at the surface, infiltrates below ground, shapes the bedrock, and then emerges in springs. Karst is therefore a dynamic system, to which thermodynamic laws apply. Fluids transfer mechanical and chemical energy in a resistant environment, where this energy is dissipated. The system is driven by the kinetic energy of water due to its hydraulic gradient, and the chemical energy associated with the dissolution of limestone (Mangin, 1975). At the most basic level, the whole system depends on the sun, which drives the water cycle: caves, a key part of the karst landscape, are therefore indirectly created by the sun!

1.3.4 Civil Engineering

Finally, it is common practice among civil engineers to label as karst any cavities encountered on construction sites or in boreholes. This is a terminological error and is to be avoided. Civil engineering nevertheless holds significant economic value, and part of this book is dedicated to "karst" as defined by geotechnical engineers.

1.4 Components of the Karst Landscape

The shapes that can form in karstic topography are immensely varied, but the characteristic components of Slovenian karst are generally as follows:

- Picturesque water-sculpted rock formations, karren or lapies.
- Closed depressions (dolines, sinkholes, poljes).
- Presence of caves and caverns.
- Streams frequently disappearing below ground.
- Few springs, but often with very high discharge.

The relative frequencies of these components can vary, and some may be absent, depending on the nature and structure of the rock and on the climate. Additional features may appear as well, such as turrets, mogotes, pinnacles, giant chasms, or tsingys, characteristic of intertropical zones (see chap. 6).

A karst zone may be easily identified by looking for these indicator formations on a topographic map.

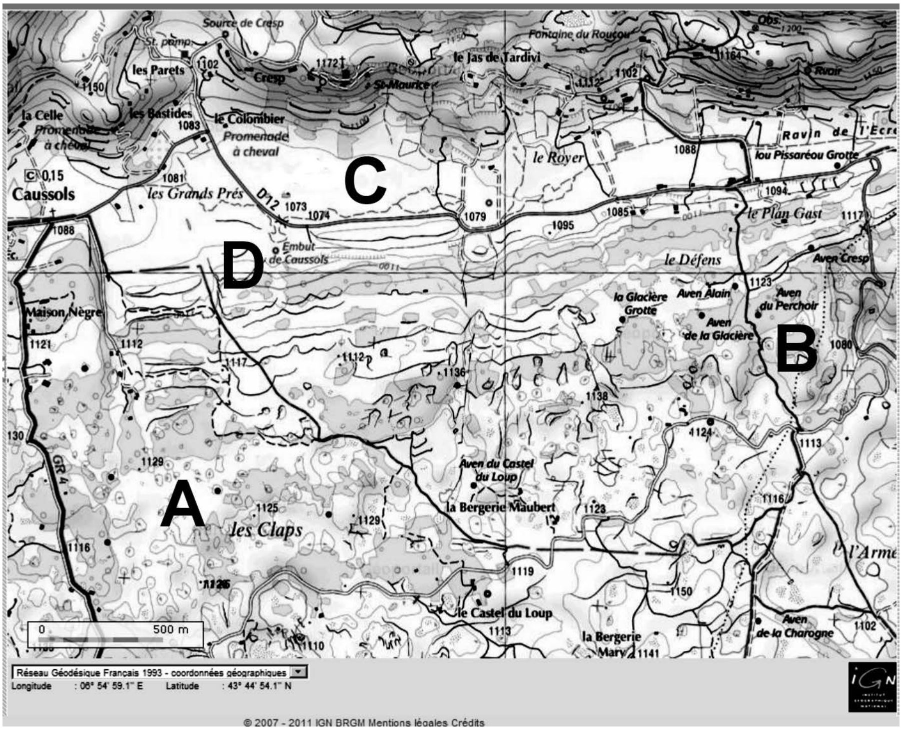

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Figure 3. Caussols karst plateau (Alpes-Maritimes, France). (**A**) doline field; (**B**) caves and caverns; (**C**) polje (closed depression and stream); (**D**) river disappearance below ground.

Karst topography is made up of a surface component, the exokarst (or karst *sensu stricto*) and a subsurface component, the endokarst, which contains caves and caverns. While, like other landscapes, exokarst may be studied from the surface or from space, through either direct observation or remote sensing, the endokarst remains invisible. Part of it is, however, accessible via caves and caverns, the realm of speleology. But endokarst must not be simplistically defined as only caves, for these represent only the karstic cavities accessible to humans. For the remainder, information comes only through indirect methods, such as geophysical sensing, geodesy, and hydrogeological studies. Our gains in knowledge therefore depend on technological advances.

1.5 The Great French Karst Regions

Karstic surfaces (chalk included) cover approximately 170,000 km^2 of the French territory, or around 30%. Counting karst formations that do not outcrop but are present at depth, half of France is affected by karstic phenomena (Renault, 1992). Water resource management is therefore highly dependent on karstology.

Several specific types may be defined:

- chalky karsts (Normandy, Paris Basin, Aquitaine Basin),
- karsts in limestone plateaus (Jura, Vercors, Chartreuse, Causses and Cévennes, Provence limestone, Lot and Dordogne),
- mountainous karsts (Pyrénées, Marguareis, Bauges, Savoie, etc.),
- submarine karsts (Provence and Corsica).

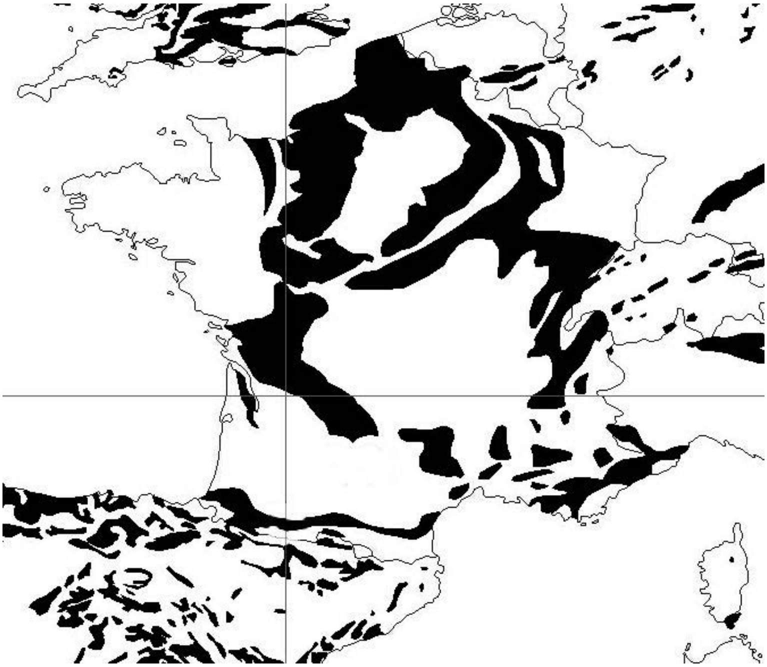


Figure 4. Map of the principal carbonate rock outcrops in France (after Ford and Williams, 2007). Areas affected by karstification are more widespread, given that many carbonate units outcrop either only partially or not at all.

1.6 Worldwide Distribution of Karst

The following map shows the world's great karst regions. They make up approximately 15% of dry land, and are more common in the northern hemisphere, but their distribution in Antarctica is unknown (Bini et al., 2003).

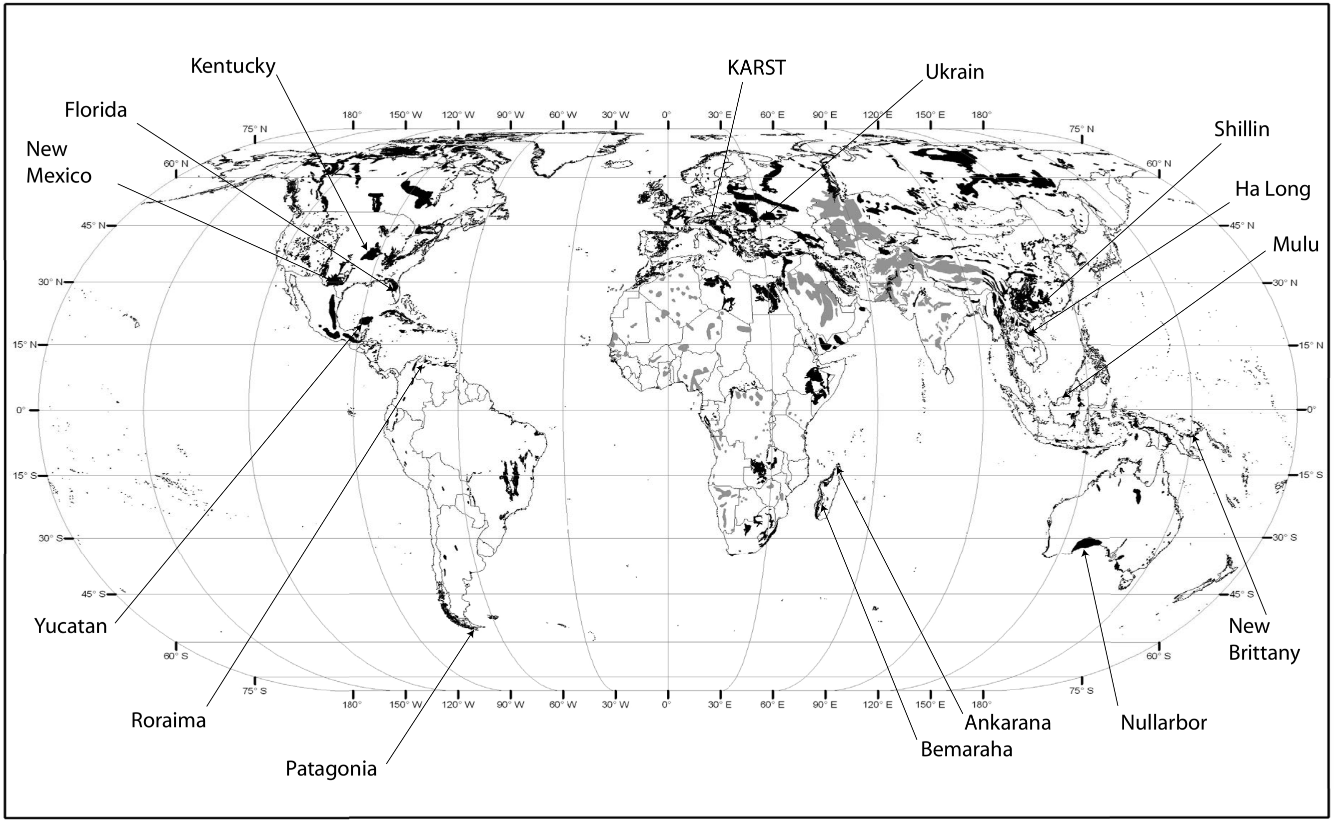


Figure 5. Map of the planet's principal carbonate outcrops (after Ford and Williams, 2007). Pure limestone is in black and other carbonate rocks are in gray. Non-outcropping units are not shown.

The most spectacular topographies occur near the intertropical zones, particularly in southern China, but gigantic underground networks can be found at higher latitudes. Mammoth Cave in Kentucky, for example, is the longest cave in the world with over 640 km of underground passageways.

2

The History of Karstology

2.1 Precursors

Humans have inhabited karst areas since prehistoric times, when springs and caves offered water and shelter. The puzzles of karst have therefore been the subject of investigation for a long time, and it is difficult to pinpoint the birth of karstology. A cuneiform text, carved around 840 B.C. at the entrance of the Tigris Tunnel (Lice, Turkey), describes the Assyrian king Shalmaneser III's visit to a few hundred meters of the underground segment of the Tigris River (Seneca cites this same visit). A bronze plaque, discovered in the king's palace and now housed in the British Museum, describes this excursion and shows percolating water's role in stalagmite construction (Hill and Forti, 1997). This is the first known text describing karstic phenomena.

In Antiquity, karst areas being common around the Mediterranean, Greek and Roman philosophers and engineers took an interest in the unusual phenomena they found there. Their conceptions of the water cycle drew primarily on karst models: vast abysses, disappearing rivers and seas, deep caverns in the heart of the mountains. Plato's writings on the origin of springs (4th century B.C.) indicate that a relationship had been discovered between springs and disappearing rivers (katavothrons), as well as dolines. Strabo (1st century B.C.) mentions a link between the Reka's disappearance (Slovenia) and Timavo Spring (Italy). Seneca (4 B.C. to 65 A.D.) suggests in "Natural Questions–Volume III" that rock might turn into water in the subterranean caverns that feed surface streams. His model can be taken to suggest that dissolution is responsible for cave formation.

In Roman times, spring catchments such as the Fontaine d'Eure one, feeding Nîmes via the Pont du Gard aqueduct, or the Zaghouan Springs (Tunisia) one with a 100 km-long aqueduct, as well as development around poljes (see chap. 13.1), demonstrate an already well-established analysis of karst systems and of their usefulness as drinking water sources.

In a 10th century Arabian encyclopedia, the "Epistles of the Brethren of Purity" (Rasa'il Ikhwan al-Safa'), a compilation of works by Ismaili scholars, caves and their subterranean bodies of water are described.

The study of karst landscapes in China began in the 17th century (Hu, 1991). During this time period, the geographer Xu Xiake travelled southern China for over thirty years with a naturalist's keen eye. He visited and described a multitude of caverns and constructed theories on cave formation, but he also took an interest in exokarst and created a classification system for the landforms created by surface erosion. His geographic text "Xu Xiake's Voyage" was published in 1642. This enormous work, spanning 10 volumes, can be considered the first treatise on karstology.

In Europe, caves are described in 1665 in Kircher's "De Mundus Subterraneus". In France, Bernard Palissy, although better known for having rediscovered the secrets of enamel, also took an interest in groundwater, and in 1580 he published "On Waters and Fountains," in which he showed that springs were fed by water that filtered through cracks and openings in the earth. His observations linked the plumes of water vapor, exhaled by certain caves in the Pyrénées, to infiltrating water. An enigmatic book titled "Underground World" is said to have been written by Gaffarel in 1654, but only the summary has been found and whether or not the book actually existed remains unknown. From the 18th to the 19th century, many western writers took an interest in caves and in limestone landscapes, but only within the context of their general studies and without an overarching vision. Naturalists most often undertook these investigations, and daringly explored several caves and sinkholes. The Austrian Empire encompassed several karst zones, and the House of Habsburg tasked mathematician Johanes Antonius Nagel (1748) with the study of poljes and their ponors in order to put them to agricultural use. Between 1778 and 1789, Hackuet published a series of books in which he laid the foundations of karstology. He is considered the forerunner of European karstology.

In the 19th century, the natural phenomena of the Karst region in Slovenia were rigorously studied. In 1841 an engineer, Lindner, looking for the underground path of the Timavo in order to supply water to Trieste, found an opening, 329 m below the surface, in the Trebiç chasm, overlooking the subterranean river. But at the time, no pumps existed capable of lifting water to such a height, so he was unable to complete his project. Adolph Schmidl studied the Piuka's subterranean paths, and published in 1854 "Die Grotten und Höhlen von Adelsberg, Lueg, Planina und Laas." It is the first European text devoted entirely to caves and underground rivers.

In 1873, E. Tietze first uses the word karst to describe the landforms near Trieste. The first general descriptions of classic karst are the work of the Serbian geographer Jovan Cvijic (1865–1927) who, by publishing "Die Karstphänomenen" (1893), spread the scientific usage of the word "karst" which is now universally recognized. He explained how dissolution is responsible for shaping the topography and creating dolines, and established a nomenclature for different landforms. Although several other authors made additional contributions, Cvijic, given the magnitude of his work (60 volumes and publications) is considered the father of European karstology.

2.2 Contributions from Speleology

In France, as early as 1856, Abbot Paramelle, based on extensive research in the department of Lot, linked surface topography to underground water flow, and laid the foundations of applied karst hydrogeology. At the end of the 19th century, E. A. Martel, a self-taught geographer with a passion for karst landscapes, published numerous texts on the caves and karsts of France. His 1888 exploration of Bramabiau Cave, following the underground path of Bonheur River, is considered the birth of speleology, with the use of specially adapted, transportable, and reusable caving equipment. He visited all of Europe, crisscrossed the Americas and Asia Minor describing their karst areas, and published a sizeable body of work with twenty-one major texts: "Les Cavernes", "Les Abîmes", "La France ignorée", "Les Cévennes", and "Causses majeurs" to name only the most well-known. He set many people on career paths following his, and many French geographers, geologists, and speleologists continued in his footsteps, publishing a plethora of further studies.

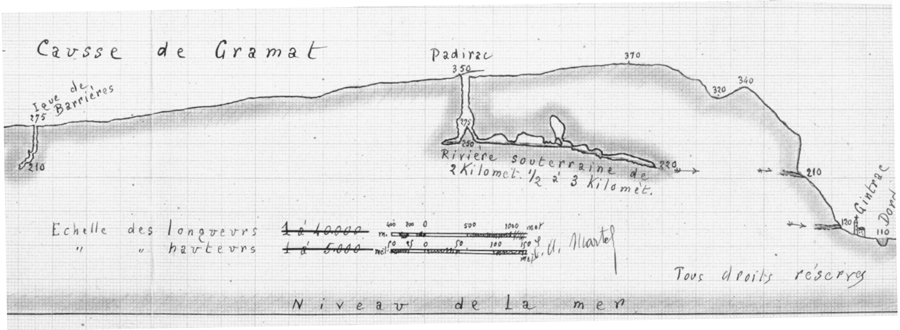


Figure 6. Simplified cross-section of the Padirac Cave by E.A. Martel, father of French speleology.

The complicated, heavy, and costly equipment used in the 19th century was gradually simplified over time. Scientific speleology, carried forward by E. Fournier, F. Trombe, B. Géze, Ph. Renault, P. Dubois, H. Paloc, J. Choppy, and many others, contributed to understanding the link between surface karst and the endokarst.

Understanding of karst as a whole has benefited greatly in the past few decades from the development of speleology and its techniques. For example, the advent of nylon rope and of single-rope climbing techniques (SRT) enabled significant advances in exploration in the second half of the 20th century. This opened access to the endokarst to anyone motivated by research interests or exploration. France is now home to approximately 20000 spelunkers, including many institutionally affiliated researchers and many self-taught practitioners.

Similarly, our understanding of submerged areas has expanded thanks to the constant progress being made in cave diving and in current technology, including rebreathers and gas mixtures, which now allow divers to explore for several kilometers into aquifers up to depths of 300 m!

The democratization of speleology and of travel and the search for new territory to explore have led speleologists into most of the karst areas on the planet, often paving the way, thanks to their observations and publications, for new areas of research in karstology. Today, resting on the shoulders of several generations of karstologists, speleologists, and hydrogeologists, karstology benefits from a global understanding of the processes associated with karstification. Interdisciplinary research is also making forays into biology, and it is likely that the next few decades will yield surprising information on the role of microorganisms in cave formation and in the concretion processes responsible for the formation of stalagmites and stalactites.

2.3 French Karstology and the Climate Paradigm

There is long-standing debate in the karstology community (Renault, 1992) concerning whether karst topography is shaped by climate, or instead by a cyclical erosional model described by Davis (1899), beginning with orogenesis and ending in a peneplain. This model shaped the evolution of French geomorphology (De Martonne, 1909) and was applied to karst by Cvijic (1893) and Chabot (1927). For karst systems, Davis (1930) described speleogenesis and outlined a bi-cyclical model that was then taken up by British geomorphologists. A French school of karstology arose following in Corbel's (1954) footsteps and based on the creation of climatic geomorphology by Tricart and Cailleux (1955), with a particular emphasis on climate. The leader of this school, J. Nicod, helped a number of karstologists begin their careers: R. Maire, J.N. Salomon, Ph. Audra, J.J. Delanoy, and J. Rodet, among many others, including the author.

Today, the debate seems closed, since according to Davis himself, the bi-cyclical model applies rather to tabular karst. And although climate plays a primary role in the formation of karst topography, since it determines the amount of water in the system and its physical and chemical properties, alone it cannot explain the extraordinary variety of landforms in existence, for example, the gigantic hypogenic voids found in New Mexico, independent of climate (cf. chap. 7). Modern karstology, as it becomes more interdisciplinary, appears to be moving away from paradigms and towards a more fluid conception of karst, in which karst landscapes can be attributed to a number of different mechanisms, in highly variable natural settings. The different models proposed are in fact complementary.

In France, karstology is a dynamic field, although, for several reasons, including the attachment of physical geography to Humanities and the fact that speleology is considered as a sport, it has encountered difficulties in establishing itself as a separate field, like oceanography or volcanology. The various aspects of karstology are taught separately in the academic world, and there is no institution specifically dedicated to karstology, as there are in Guilin (China), Postojna (Slovenia), and Carlsbad (USA). And yet it is a field that concerns a significant portion of the French landscape.

The Davis bi-cyclical model (after Chapuis and Nardy, 1986)

In geomorphology, the classic Davis model (1850–1934) states that a landscape evolves as water cuts into a terrain undergoing tectonic uplift, with a juvenile phase where the hydrographic network incises into the landscape and results in deeply entrenched rivers, a mature phase with regressive erosion, captures, and concentric erosion, and finally a peneplain phase where the topography has become totally flat.

In karst areas, however, Davis suggests a bi-cyclical model, with a first cycle in which caves form below the water table in the karst aquifer, followed by a second, either synchronous or subsequent cycle, where tectonic uplift lowers the water table. The caves, emptied of water, then evolve sub-aerially with the deposition of speleothems.

Davis, aware of the impossibility of applying this model to all karst, considered it valid only in tabular karst.

3

Carbonate Rocks

3.1 Definition

Carbonate rocks are composed of minerals characterized by the presence of the CO_3^{2-} ion. The most common of these minerals are calcium carbonate, $Ca^{2+} CO_3^{2-}$ (calcite and aragonite) and calcium and magnesium carbonate, $(Ca, Mg)^{2+} CO_3^{2-}$ (dolomite).

Calcium carbonate is found primarily in one of two mineral forms:

- calcite (rhombohedral), is the more stable form,
- aragonite (orthorhombic), commonly found in animals where it forms the shells of many invertebrates, is less stable and usually gradually transforms into calcite.

An important feature of carbonates is how common they are compared to other minerals such as silicates. Carbonate rocks comprise a vast family including limestones, marls, and dolomites, and make up approximately 20% of the sedimentary rocks found on the planet. Most sedimentation occurs in submarine environments, and the presence of carbonates is therefore dependent on the physical and chemical properties of the surrounding seawater.

Table 1. carbonate rocks.

Rock type	Pure limestone	Marly limestone	Marl	Calcareous clay	Calcareous sandstone	Conglomerate
% $CaCO_3$	> 95%	95 to 65%	< 65%	< 50%	variable	variable

3.2 REVIEW: The Origins of Carbonate and Calcium

Calcium carbonate formation requires water, and it is usually a byproduct of living organisms. The Mars exploration missions therefore included scientific protocols intended to confirm the presence of water and of life on the Red Planet by looking for carbonates. The rock samples analyzed by the robot Phoenix in 2008 (Boynton et al., 2009) contained 3 to 5% calcium carbonate, suggesting that water was present in the past.

Ca^{++} is one of the most common ions in ocean water, with a current concentration of 400 mg.L^{-1}. It enters the system from the leaching and hydrolysis of minerals in basalt (anorthite, $CaAl_2Si_2O_8$, and augite, $(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$).

Atmospheric $CO_{2(g)}$, emitted by volcanic degassing, dissolves in water ($CO_{2(aq)}$) where it is hydrated and forms carbonic acid, which dissociates into H^+ and HCO_3^- (hydrogen carbonate) ions, then into the carbonate ion CO_3^{2-} which, combined with Ca^{2+}, forms calcium carbonate.

This reaction can written as follows:

$$Ca^{++} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_{2(aq)} + H_2O.$$

Note that $CaCO_3$ precipitation releases CO_2.

Carbonate rocks could therefore have been present on Earth only once water, basalt, and CO_2, were all present, something that would have occurred only after the temperature dropped below 100°C, around 4 billion years ago.

Calcium carbonate can form by simple chemical precipitation, which is what appears to have been the norm until the Precambrian (Ridgwell and Zeebe, 2005), but the vast majority of carbonates form with the assistance of biological processes. Living organisms in the water take up CO_2 in carbonate form (dissolved and ionized into CO_3^{2-}), as well as Ca^{2+} ions in order to build their tests, shells, or skeletons. It should be noted that the oceans are currently supersaturated in $CaCO_3$ (Morse and He, 1993) given that, in order for calcite or aragonite to form, precipitation must be initiated by a nucleus.

The equilibria described above are dependent on temperature and pressure. Solubility increases as temperature decreases or as pressure increases. There is therefore a certain depth, called the “carbonate compensation depth” (CCD) or lysocline, beneath which carbonates dissolve rapidly unless the sedimentation rate is high enough to bury them quickly and isolate them from water. The CCD is currently estimated to be between 1000 m in cold waters and 5000 m in the tropics.

Figure 7 shows present-day carbonate deposits under the oceans.

The oldest known biogenic carbonates are the Warrawoona stromatolites, which have been dated to 3.5 billion years. They are made up of successive layers of carbonate sediments, presumably built up by bacteria or cyanobacteria (blue-green algae) extracting CO_2 from the water.

The organisms responsible for the creation of stromatolites were very common up until the Cambrian, building thick limestone beds (3000 m in the Anti-Atlas in Morocco). Today, they have been replaced by other species of builders. Their closest living relatives are now found only in a few places, primarily in Australia.

3.2.1 The Carbonate and CO_2 Cycle

The formation reactions for $CaCO_3$ show that it is a stable form of CO_2. This stabilization is not permanent, since the reaction as a whole relies on several equilibria that can shift either towards the consumption or the degassing of CO_2 (cf. dissolution chapter).

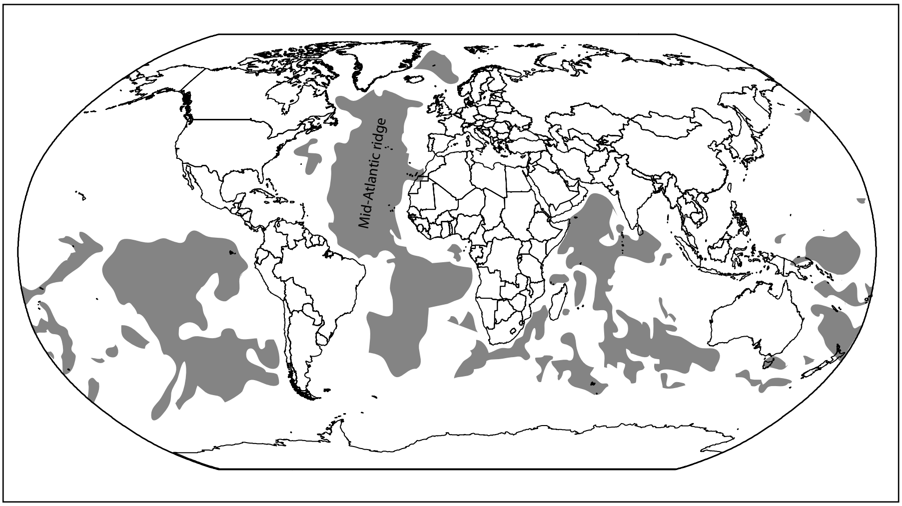


Figure 7. Deep marine sedimentary deposits with more than 40% calcium carbonate (after Archer, 1996). The largest deposits are found in the warm waters of the southern hemisphere. The presence of sediments in the north Atlantic is due to the mid-Atlantic ridge, which has an elevation higher than the carbonate compensation depth.

Figure 8. Stromatolites in Shark Bay (Australia).

3.3 Limestone

Limestone can contain up to 65% $CaCO_3$, it effervesces when it comes into contact with HCl (10%), and it can be scratched by steel. Limestones are immensely variable, and several classification schemes have been proposed based on the origins or the structure of the rock, which often consists of distinct fragments, or allochems (shells, grains, debris) held together by a fine-grained matrix (micrite) or crystalline cement (sparite).

The nature and thickness of the deposits are highly variable, from small, thinly bedded limestones to massive, poorly stratified blocks such as, for example, the Urgonian-facies Cretaceous limestones of France.

3.3.1 Limestone Classification Based on Origin

3.3.1.1 Detrital biogenic limestone

The allochems are bioclasts, tests, shells, or skeletons from marine organisms that, once dead, settle to the ocean floor. The smaller particles are often rapidly dissolved once they reach the carbonate compensation depth.

These are classified based on what type of fragments they are made up of:

- *Lumachels*: contain a significant accumulation of bivalve or gastropod shells.
- *Nummulitic limestones*: made up of giant foraminifer tests, common in the Tertiary.
- *Crinoidal limestones*: made up of crinoid debris.
- *Lithographic limestones*: very fine-grained, and as a result were used in the past as printing plates.

3.3.1.2 Bioconstructed limestone

These are limestones built by colonial organisms like corals. The rock may be highly porous if construction was recent. Corals build at shallow depths, since the zooxanthellae that they shelter in a symbiotic relationship to provide part of their sustenance, require sunlight. The creation of coral reefs depends on variations in sea level (isostasy, glacial rebound, glacioeustasy, tectonics, etc.). As soon as the reef rises above sea level, karstification begins. This makes for an ideal setting in which to study juvenile karst.

Certain types of coral form limestone at great depth, but little is known about them.

3.3.1.3 Limestone of chemical origin

This type of limestone forms as a result of $CaCO_3$ precipitation in a supersaturated solution. It is primarily found on continental masses (cf. 3.3.3).

3.3.1.4 Limestone of chemical and detrital origin

This type of limestone forms by concentric chemical precipitation around a nucleus (sand or bioclast) that is periodically lifted into suspension by currents. When many of these grains accumulate, the result is a carbonate rock with a granulated appearance, made up of many small spheres, termed either an oolitic or a pisolitic limestone.

3.3.2 Limestone Classification Based on Structure

3.3.2.1 Folk (1959)

Folk categorizes allochems as follows:

- intraclasts, angular rock fragments;
- ooids, spherical structures (ooliths or pisoliths);
- bioclasts, fossils or animal debris;
- peloids, ovoid structures (fecal pellets, algae bundles…);
  and orthochems as follows (the matrix binding the grains together);
- micrite, fine-grained microcrystalline base;
- sparite, crystals.

Rocks are named according to the matrix type preceded by prefixes characterizing the allochems. For example: oosparite, or biomicrite.

3.3.2.2 Dunham (1962)

Dunham takes into account the relative proportions of allochems and of the matrix:

- *crystalline limestone*: the sedimentary structure is not visible,
- *mudstone*: primarily made up of micrite with less than 10% of fragments,
- *wackestone*: at least 10% fragments (but not grain-supported) floating in micrite,
- *packstone*: grain-supported, with pore spaces filled with micrite,
- *grainstone*: grain-supported, with pore spaces filled with sparite,
- *boundstone*: original organic structures remain.

3.3.3 Continental Limestone and Limestone Crusts

The vast majority of limestone deposits form in marine environments, but deposition does occasionally occur on the continents.

3.3.3.1 Lacustrine limestone

In areas where carbonate rocks are abundant, lakes can serve as a depositional environment for calcareous mud formed by the precipitation of $CaCO_3$ caused by CO_2 consumption by algae during photosynthesis. This process can be observed in the present day in Annecy Lake and Bourget Lake (France) (Vatan, 1967).

3.3.3.2 Tufa and travertine

These are chemical deposits downstream of springs or in shallow streams, where precipitation caused by CO_2 degassing is made possible by high-turbulence zones. They can form thick, stratified deposits as in the Antalya region (Turkey), where they can be up to 270 m thick (Burger, 1992) (cf. chap. 9). As they are deposited, tufa and travertine usually trap vegetation, giving them a high porosity.

3.3.3.3 Limestone crusts

In arid regions, precipitation or capillary action can mobilize carbonates and result in their deposition within certain soil horizons or at the top of the water table, creating crusts of varying thickness, which can then be secondarily affected by karstification.

Figure 9. Limestone crust that was first exhumed then subjected to karstification (Southern Tunisia).

3.4 Chalk

Chalk is a soft porous rock formed by the accumulation of coccoliths, granules 2 to 10 µm in diameter created by planktonic algae, coccolithophores and foraminifers. It is generally very pure (over 90% $CaCO_3$). Chalk is characteristic of shallow depositional environments (< 300 m).

Figure 10. The chalk cliffs of Etretat (Normandie, France). The arch is a vestige of a karst system running parallel to the coastline.

3.5 Dolomitic Rocks

This is a family of carbonate rocks containing a more or less significant proportion of dolomite, a calcium and magnesium carbonate (Ca, Mg)CO_3. In outcrops, these rocks often look like elephant skin. They do not fizz in the presence of 10% HCl. When altered, dolomites result in a characteristic ruined-castle-like topography, while producing sand made up of dolomite crystals, which are less soluble than calcite crystals.

Dolomitization can be primary, when carbonate rocks form in an evaporitic environment, or secondary, during diagenesis, due to the circulation of magnesium-rich fluids. Dolomites may comprise only one part of a limestone unit.

The family of dolomitic rocks includes everything between pure limestone and pure dolostone, depending on the percentage of mineral dolomite.

Since dolomitization is only rarely complete, the dissolution of $CaCO_3$ in a dolomitic rock results in voids that may give the rock a very high porosity.

Table 2. Dolomitic rocks.

Rock	Limestone	Dolomitic limestone	Calcareous dolostone	Dolostone
% (Ca,Mg)$C0_3$	< 10%	10 to 50%	50 to 90%	> 90%

4

Limestone Dissolution

4.1 The Water Cycle, the CO_2 Cycle, and the Carbonate Cycle

The three primary agents of karstification are water, rock, and carbon dioxide gas (CO_2). The latter plays an important role in the overall dissolution reactions for limestone.

The study of atmospheric CO_2 sequestration in oceans, living organisms, and rock is a highly relevant subject today, due to its importance in the study of climate change. Over the course of geologic time, the composition of the atmosphere has varied considerably. The appearance of life caused a drop in CO_2 due to carbonate precipitation and an increase in O_2 due to photosynthesis, while creating organic matter. These variations are only long-lasting if the resulting materials, carbonates and organic matter, are buried. Changes in equilibrium can result in movement in the opposite direction. Anthropogenic actions such as burning fossil fuels (coal and petroleum) and decreasing global photosynthesis can therefore alter the composition of the atmosphere.

In this time of concern over the role of anthropogenic CO_2 in climate change and in the greenhouse effect, the role of carbonate rock, a stable form of CO_2, takes on particular importance. Oceans play a major role in trapping and releasing this gas, and as a home for organisms that can draw calcium, oxygen, and CO_2 from the water in order to synthesize calcite and aragonite, the two crystalline forms of $CaCO_3$.

Qualitative element: Foraminifer and echinoderm tests and skeletons, bivalve and gastropod shells, and polyp exoskeletons are primarily made up of $CaCO_3$.

Quantitative element: 1 metric ton of $CaCO_3$ corresponds to 430 kg of trapped CO_2. Tests are under way in Icelandic basalts and in peridotites in Oman, with pressurized water and CO_2 being injected at depth in order to cause a reaction with the rock, turning it into $CaCO_3$.

4.2 The Solubility of Limestone

4.2.1 Solubility of Calcium Carbonate, $CaCO_3$

The two crystalline forms of calcium carbonate, calcite and aragonite, are water-soluble only in small amounts: 14 mg.L^{-1} at 25°C, however, other chemical mechanisms involving CO_2 allow a considerable increase in the amount of $CaCO_3$ that can be dissolved.

4.2.2 The Role of CO_2

The overall reaction depends on the formation of calcium hydrogen carbonate (or calcium bicarbonate), which has a high solubility. This reaction involves CO_2, which is highly water-soluble. It is present in the natural environment in varying concentrations:

Table 3. CO_2 concentration in different environments.

Environment	**CO_2 concentration (% volume)**
Atmosphere	0.03
Organic soil	2
Confined cave atmosphere	10

4.2.3 Formation of Calcium Hydrogen Carbonate

Several steps can be described in a simplified manner:

- *Ionic dissociation*: $CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$
- *CO_2 dissolution*: CO_2 (g) $\leftrightarrow$ CO_2 (l) cold-favored reaction
- *CO_2 (l) hydrolysis*: CO_2 (l) $+ H_2O \leftrightarrow HCO_3^- + H^+$
- *Calcium hydrogen carbonate formation*:

$$HCO_3^- + H^+ + Ca^{2+} + CO_3^{2-} \leftrightarrow (HCO_3)_2Ca^{2+}$$

Calcium bicarbonate is approximately ten times more soluble in water than calcium carbonate. Thanks to this intermediary step, it is therefore possible to dissolve 300 mg.L^{-1} of $CaCO_3$ at room temperature.

This reaction, however, depends CO_2 going into solution in water according to Henry's Law, $[CO_2]_{aq} = K_o pCO_2$

where K_o is the temperature-dependent coefficient of solubility, and pCO_2 is the partial pressure of CO_2.

CO_2 can therefore be divided into dissociated (or aggressive) CO_2 and CO_2 in equilibrium.

Most of the above reactions are chemical equilibria dependent on temperature and on the presence of other ions in the solution. These reactions can therefore shift either in the direction of carbonate dissolution or in the direction of carbonate precipitation, depending on the environmental parameters and particularly on the partial pressure of CO_2.

4.2.4 Roques' Curve

Roques' curve (1964) describes whether or not a calcium bicarbonate solution is saturated or not as a function of pH.

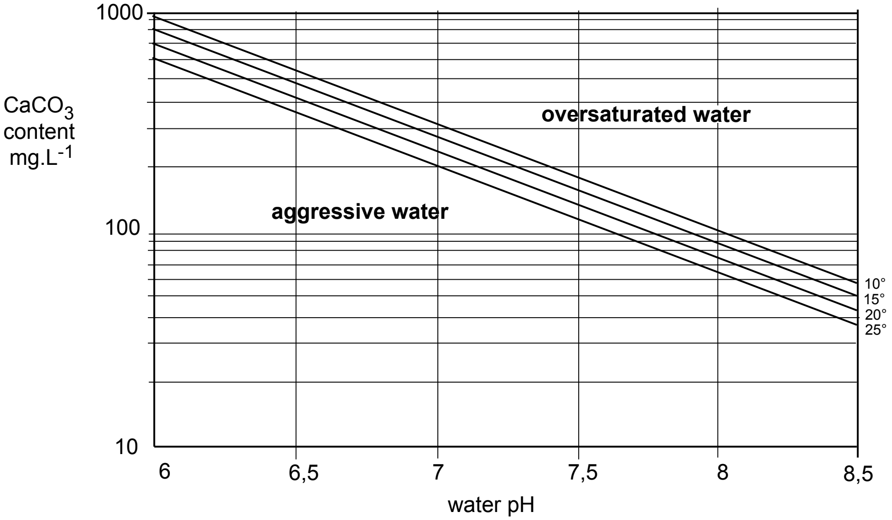


Figure 11. Roques' curve.

4.2.5 Dissolution Kinetics

Some steps in the overall reaction are slow, and the three components, rock, water, and atmosphere, must be in contact for a long enough time to allow the entire dissolution reaction, the slowest reaction determining the speed of the overall reaction. It is rapid at the water/atmosphere interface and slow at the water/rock interface.

For example, equilibrium between CO_2(g) and HCO_3 is established in only a few seconds (Dreybrodt, 1988), while the release of CO_2 is slower (Roques, 1964).

Equilibrium between water and calcium carbonate, on the other hand, is very slow to occur, ranging from a few hours to several months depending on the nature of the rock (Bakalowicz, 1979).

4.3 Factors Affecting Karstification

4.3.1 Theoretical Factors

Understanding the evolution of the properties of water percolating through a limestone structure is indispensible to understanding speleogenesis. From its formation in the atmosphere to its exit from the system through a spring, a single droplet of water interacts with many different environments: the atmosphere, the soil and the biosphere, the rock, the subterranean atmosphere, the water in the aquifer, and the water from other aquifers.

The following table (Table 4), based on the reactions described above, shows the factors that favor and that inhibit dissolution, as a function of the temperature and partial pressure of CO_2. From these one can deduce the geographic areas favorable to karstification.

Table 4. Factors favoring dissolution and precipitation.

Factors favoring dissolution	**Factors favoring precipitation**
Cold	Heat
Acidic environment	Basic environment
High CO_2	Ventilation
Abundance of water	Aridity
Long contact time	Short contact time

Gombert (1995) undertook a theoretical description, defining the MPD (maximum potential dissolution in mm/1000 yrs) based on effective precipitation, the partial pressure of CO_2, and the various constants for calcium-carbonate equilibrium. His analysis considered 226 climate stations. The resulting theoretical values were lower than the specific ablation calculated or measured through different methods (Table 5, Table 6). Tropical and equatorial zones showed the highest MPD.

Table 5. Maximum potential dissolution based on climate zones, after Gombert, 1995.

Climate type	**MPD mm/1000 yrs**	**Surface covered (%)**
Desert	3.4	23
Mountainous	50.9	5
Polar	42.5	15
Cold	29.4	19
Cold temperate	36.6	6
Warm temperate	31.9	4
Mediterranean	8.8	2
Subtropical	21	9
Tropical	92.7	8
Equatorial	88.2	9
Average	40.6	100

4.3.1.1 Favorable geographic regions

- *Intertropical rainy zones*: Abundant vegetation favors the production of CO_2 and of humic acid. Thick soils increase the contact time between the three phases. Rainfall is high.
- *Mountainous or periglacial zones*: Low temperatures are favorable for the dissolution of CO_2. Water is abundant during snowmelt, and the snowcap favors long contact between the three phases.

Table 6. Relationship between climate, calcium carbonate concentration, and karstic ablation.

Region	Rainfall	$CaCO_3$ concentration in springs ($mg.L^{-1}$)	Specific karstic ablation ($m^3.km^{-2}.yr^{-1}$ or $mm.ka^{-1}$)
Periglacial zones			
Lapland	7000	200	400
Mountainous regions			
Arres d'Anie (France)	2500	120	95
Vercors (France)	1700	190	120
Temperate regions			
Kentucky (USA)	1000		25
Dorvan (France)	1600	220	81
Mediterranean regions			
Vaucluse (France)	1500	200	45
Gran Sasso (Italy)	950		93
Vence (France)	1000	200	35
Dry tropical zones			
Ankarana (Madagascar)	1400	187	110
Humid tropical zones			
Papua New Guinea	6000	183	320
Mulu (Sarawak)	10000	110	520

4.3.1.2 Unfavorable geographic regions

- *Arid zones*. Rain is rare, vegetation is minimal, and high temperatures favor evapotranspiration. CO_2 is quasi-nonexistent.
- *Arctic zones*. The temperature prevents water circulation, vegetation is absent, and CO_2 is therefore rare.

4.3.2 The Concept of Karstic Potential

The amount and aggressiveness (as a function of dissolved CO_2) of water infiltrating into limestone is highly variable. This defines a potential for karstification (Mangin, 1975), where the amount of water and the hydraulic gradient, which is set by the morphology, determine the mechanical energy of groundwater flow, and where dissolved CO_2 determines the available chemical energy. In their absence, the potential for karstification is non-existent. Pure water can only dissolve a small amount of $CaCO_3$. Similarly, without an outflow, the solution would quickly become saturated.

This karstic potential is closely linked to climatic conditions, which determine the amount of available water and CO_2. Opposing this potential is the resistance of the environment, which is a function of the rock type and of the openness of discontinuities, and therefore is dependent on lithology and tectonics.

One question in particular divides karstologists: which factor, climate or structure, plays the primary role in the development of karstification. The primary factor is in fact water, the availability of which determines the amount of $CaCO_3$ leaving the system, as shown in Table 5.

Figure 12. Dolomitic stumps indicate several meters of ablation in the Caussols (Alpes-Maritimes).

Figure 13. Corrosion of a limestone slab. A trail blaze in waterproof paint has protected the underlying limestone from dissolution of about 1 mm over 30 years. Photo taken on a trail midway up a mountain in a Mediterranean climate.

4.3.3 Speed of Dissolution and Karstic Ablation

Dissolution carries $CaCO_3$ out of the system. Erosion is barely perceptible to humans, on the order of a few 1/100ths of mm by year at our latitudes. Its intensity can be determined by weighing slabs of limestone that are placed on the surface, or buried in the soil, in order to measure the amount of weight lost, or by using stainless steel markers and thickness gauges. Examining the rate at which dates carved into tombstones disappear is another method of quantifying dissolution.

Specific karstic ablation is the relationship between the volume of limestone taken out of the system and the surface area of the affected region. It is expressed in m^3/km^2/year or in mm/ka. It takes into account all dissolution, at the surface and at depth, and its value is therefore greater than that calculated from the single sheet of limestone that is eroded at the surface.

It can be estimated based on the amount of $CaCO_3$ exiting the system at springs, simply by taking the product of the total runoff and of the average $CaCO_3$ concentration. A precise result, however, must take into account variations in concentration as well as the magnesium present in dolomite.

It should be noted that some of the limestone exits the system as a solid, and that some of it may also come from the leaching of soils bordering the karst area under study. This calculation is therefore quite complex, and the resulting values are generally significantly higher than the MPD.

4.3.4 Specific Factors

The overall reaction involves a series of reactions and equilibria, such that various factors can shift the reaction in either direction.

4.3.4.1 Presence of pyrite: FeS_2

The hydrolysis and oxidation of pyrite create sulfuric acid.

$$FeS_2 + H_2O + 2O_2 \leftrightarrow FeO + H_2SO_4$$

The presence of H_2SO_4 in the solution results in the appearance of H^+ ions, shifting the reaction in the direction of dissolution.

4.3.4.2 Presence of hydrogen sulfide: H_2S

As with pyrite, the hydrolysis and oxidation of H_2S enables sulfuric acid formation.

$$H_2S + 2O_2 \leftrightarrow H_2SO_4$$

$$H_2SO_4 + H_2O + CaCO_3 \leftrightarrow CO_2 + CaSO_4\ 2H_2O \text{ (gypsum)}$$

Limestone, when subject to this acidic attack, undergoes neoformation and becomes gypsum. The consequences of this process in speleogenesis are explained further in chap. 7.5.

4.3.4.3 Presence of OH^- ions

Many types of cement used in construction cause an increase in the pH of water, shifting the reaction in the direction of precipitation. This can result in the formation of stalactites or of crusts on the cement in areas where water circulates.

4.3.4.4 Dissolution by mixing

Different environments with different physical and chemical parameters shift the equilibrium of the reaction towards either dissolution or precipitation. When two different bodies of water, both saturated in $CaCO_3$ but each with its own unique chemistry, come together, they can become aggressive by increasing the ionic strength of the solution (Bögli, 1980).

The ionic force, I, expresses the overall ion concentration of a solution:

$$I = \frac{1}{2}\sum_i C_i z_i^2$$

from which $I = 2\,[(Ca)+(Mg)+(SO_4)] + 0{,}5\,[(Na)+(K)+(Cl)+(HCO_3)+(NO_3)]$

The solubility of calcite is a function of the square root of the ionic strength (James, 1992).

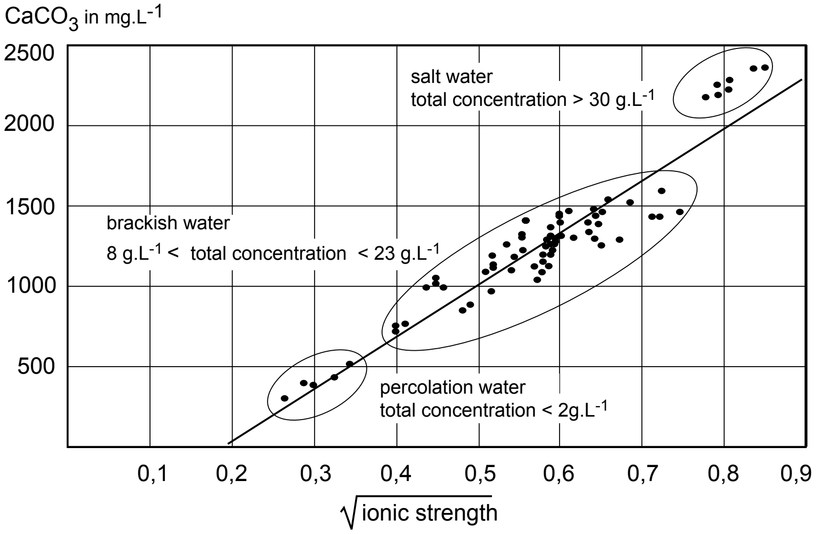


Figure 14. Variations in $CaCO_3$ concentration as a function of the ionic strength for the caves of Nullarbor (Australia) (after James, 1992).

Everyday karstification

Calcium carbonate dissolution/precipitation reactions can be found in everyday life:

The white spots that appear on glasses as they dry are rings of calcite precipitated as water evaporates.

The white ring that often forms around faucets is a calcite deposit formed when the tap water, carrying $CaCO_3$, emerges into a better-ventilated environment, allowing CO_2 (pressurized at 10 bars in the pipes) to degas. The deposits are thicker on hot-water taps, as the heat favors precipitation. The scale that forms on heating elements or on the inside of hot-water pipes forms by the same mechanism.

Marble or limestone floors losing their polish, although partially due to foot traffic, is also a result of successive washings, which gradually dissolve the surface. Carbonated beverage spills accelerate the process, since the CO_2 increases the water's acidity and the floors therefore dissolve even more quickly.

Similarly, the rugosity that develops on marble statues and monuments is the beginning of karstification.

5

The Surface Components of Karst

5.1 The Epikarst

All carbonate rocks exposed to the elements are subject to erosion by water, which can carry varying amounts of CO_2. In coastal intertropical zones for example, karstification begins on coral reefs as soon as they emerge due to eustatic (Bourrouilh-le-Jan, 1992) or tectonic (Gilli, 1995a) variations.

The rind along the surface and edges of a rocky massif are characterized by the rock decompressing and creating discontinuities (bedding or unloading joints). This distinct part of the landscape forms the epikarst. Its development can be assessed via the study of talus slopes and quarry walls, as well as by the use of ground-penetrating radar (Al Farhes, 2002). The bedrock in this zone may be exposed, or it may be covered with a variable thickness of soil. The degree of vegetative cover may vary as well. Water-driven erosion will therefore occur both on the rock surface, but it can also penetrate several meters into the rock as water filters in through discontinuities. The water can come into contact with the rock either through direct runoff, or by saturating the soil which forms a compress on the rock.

The resulting weathering and erosion create a great variety of shapes, sculpted by various factors:

- *Structural factors*: the nature of the rock, the number of discontinuities.
- *Topographic factors*: elevation, relief.
- *Pedologic factors*: the nature and thickness of the soil.
- *Meteorological factors*: temperature, and the type, quantity, and distribution of precipitation.
- *Biological factors*: the nature and density of vegetation, the presence of micro-organisms.

This list highlights the importance of climate, which determines the significance of most of these factors.

The general appearance of a limestone outcrop depends on the relationship between dissolution and other types of surface weathering: frost wedging, thermoclastic weathering, gravity, pressure release,...

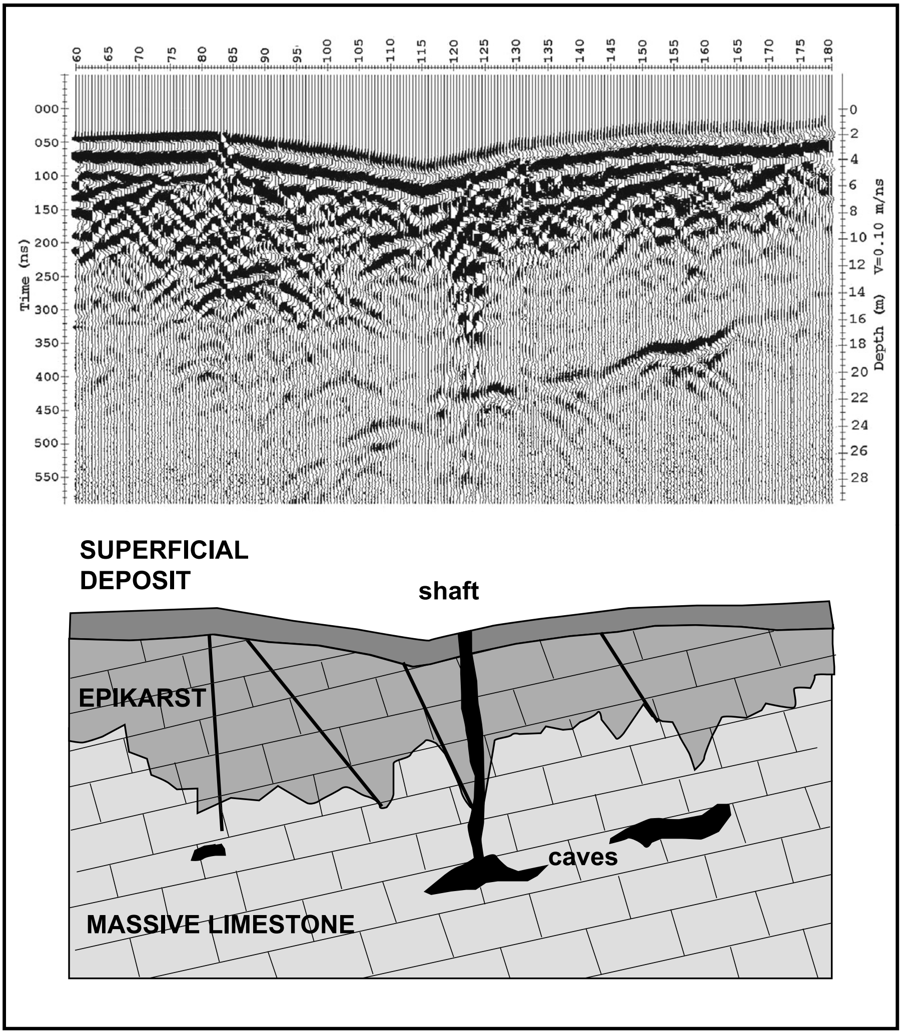


Figure 15. Radar cross-section showing the development of the epikarst on the Hortus Causses (after Al Fares et al., 2002).

5.2 Lapies

5.2.1 Ordinary Lapies

Lapies or karren, are small-scale (millimeter to several-meter) weathering formations found at the surface or beneath the soil cover. The resulting shapes vary greatly, and include acorn cups, bowls, flutes, clints and grikes, perforations, needles, blades, etc. They range in scale from a simple roughening of the rock surface to rocky needles several meters tall, such as the pinnacles of Mulu (Malaysia) or the Tsingy of Madagascar. Areas with a high density of lapies are called lapies or karren fields.

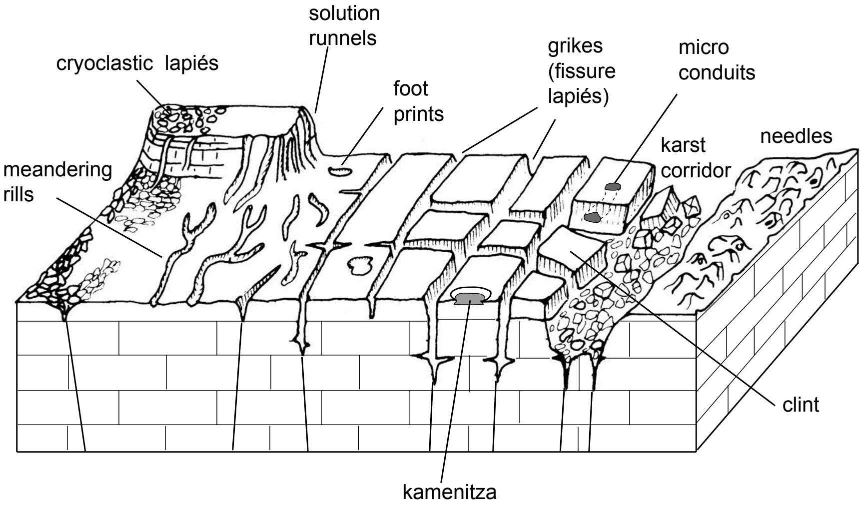


Figure 16. A few examples of common lapies formations (after Collignon, 1988 and Nicod, 1970).

Lapies have been the subject of several studies (Cvijic’, 1893; Bögli, 1980; White, 1988) and have given rise to several classification systems depending on their shapes. Nicod (1972) and Salomon (2000) proposed a classification based on what processes created the lapies, creating distinctions between sub aerial lapies, covered lapies, and biological lapies.

5.2.1.1 Sub aerial lapies

These are a result of the direct action of rain or snow.

- Lapies caused by runoff over solid rock
  These consolidate runoff channels, which then develop in different ways based on the steepness of the slope, forming sinuous meanders called runnels in low-relief area, and verticals flutes often called rillenkarrens on limestone walls. They can also be caused by snowmelt and form “footprints”, a process involving laminar water flow beneath a cover of snow, described by J. Choppy (1992a).

- Grikes
  These fracture lapies form when water and snow, by widening pre-existing cracks, sometimes down to a depth of several meters, emphasize the underlying tectonic canvas.

Figure 17. Meandering runoff karren on a subhorizontal Urgonian limestone slab (Platé plateau) (photo M. Delamette). The runoff, fed by snowmelt at 2250 m, is channeled towards a joint in the rock, where it trickles downwards.

Figure 18. Grikes. Discontinuities in the rock are widened by dissolution. The snow trapped in these fractures is protected from sunlight, which limits how much it sublimates.

- Limestone pavements
  In areas with a high concentration of cracks and joints, dissolution along joints and cracks can produce slabs called clints. It may forms karst features that look like man-made pavements.

- Snow pits
  These form in topographic depressions, where snow is partially protected from incoming solar radiation. The accumulation of snow forms névés, and their slow melting can create wells at their base, which favor even more accumulation. The resulting residual snow accumulation can dissolve the underlying rock, forming cylindrical wells with vertical solution flutes caused by snowmelt runoff.
- Humus pits.

These are a result of downward weathering by accumulations of organic material rich in humic acid.

5.2.1.2 Lapies formed beneath a cover (humus, soil, or permeable geologic formations)

These are sometimes called rundkarren. The overlying cover becomes saturated with water and forms a kind of "compress" that allows for long time contact with the bedrock. If in addition the cover material is partially organic, it produces CO_2 and humic acid, both of which accelerate weathering. This type of lapies is generally characterized by gentle, rounded forms.

5.2.1.3 Lapies formed by biological processes

Kamenitzas, or solution pans, are small, flat-bottomed depressions with an overhanging lip and an overflow channel. The overhang around the edge of the solution pan is a result of microbial action by communities of microorganisms that develop on the bottom of the depression. Additionally, sediment deposition can make the floor of the solution pan, halting vertical growth and encouraging lateral expansion instead.

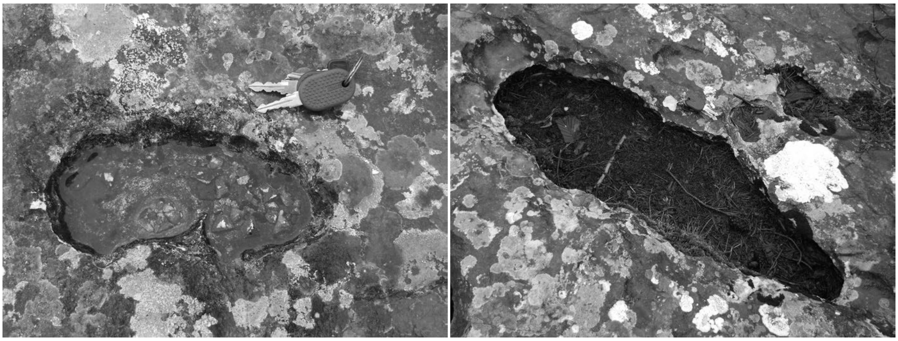


Figure 19. Juvenile (left), and mature, organic material-filled (right) solution pans in Caussols (Alpes-Maritimes).

5.2.2 Superimposed Lapies

In most cases, the features described above occur superimposed over each other. For example, when a karst surface that had previously been evolving beneath some sort of cover is suddenly denuded, the rundkarren will quickly be sculpted into a different shape as sub-aerial sharpened features form on the rock surface. Rundkarren at the surface therefore indicate recent denudation.

5.2.3 Lapies and Climate

Lapies shape the bedrock to different degrees of intensity in different climatic zones. It is easy to observe that the rate of incision is essentially tied to the amount of precipitation. At middle latitudes, the most striking relief is generally found in mountainous regions where there is greater precipitation and where the snow cover permits longer contact times between the bedrock and the cold snowmelt water. The most spectacular karren are found in humid intertropical zones. In these areas, karstification was constant over the course of thousands of years, since rainfall remained high even during glacial phases. At higher latitudes, the advancing ice prevented water circulation and in some cases destroyed pre-existing lapies.

5.2.4 Megalapies, Tsingy, and Stone Forests

In areas of intense karstification, the bedrock can be incised to depths of several meters to several tens of meters, creating a landscape where lapies reach spectacular dimensions. This is referred to as megalapies. They can also be found in dolomitic zones, where the sandier components of the rock are washed away by runoff, leaving behind the less soluble rock. Montpellier le Vieux, on the edge of the Causse Noir (or Black Causse), is a region of massive, ruiniform dolomites that includes picturesque megalapies like the "Gate of Mycenae". The area has been developed for tourism with the construction of a walking trail, a via ferrata, and a small train.

Figure 20. The "Gate of Mycenae" (or of the Elephant) at Montpellier le Vieux (Aveyron, France).

The stone forests (shilin) of southern China are another example of megalapies, areas where the landscape consists of deep, closely spaced towers, occasionally pierced by winding tourist paths. Often, these are landforms that initially formed beneath a protective covering, but were subsequently exposed by denudation. Precipitation then sculpted these crypto-lapies with secondary wall-lapies. In certain touristic locations, people have scraped away the overlying soil to reveal the lapies beneath.

Figure 21. Tourist path in the Shilin stone forest (Kunming, Yunnan, China) (photo Zhuosi Lu).

A similar process, coupled with intense fracturing of the limestone bedrock, is responsible for the Tsingy de Bemaraha and the tsingy in Ankarana (Madagascar). These are rocky needles several meters high, made up of stratified limestone sculpted by closely spaced vertical flutes, separated by ridges of extremely sharp rock. This combination makes traveling through the tsingy dangerous to virtually impossible. Rossi (1978) showed that the tsingy develop in very pure limestone (96% $CaCO_3$), with low porosity (< 2%). This is because pure limestones have a high rigidity, resulting in intense fracturing under tectonic pressure.

Figure 22. Tsingy of Ankarana (Madagascar).

With 10 m of rainfall per year, Gunung Mulu National Park (Sarawak, Malaysia) is one of the wettest places on the planet. The reason behind the park's creation is a feature on the southeastern side of Mount Mulu: a spectacular karst landscape that draws tourists from all over Southeast Asia. It is home to the largest underground chamber in the world, and to an extensive network of caves and subterranean rivers (cf. chap. 7.7). The landforms at the surface include a group of pinnacles that reach as high as 45 m (Figure 23).

Figure 23. Pinnacles in Gunung Mulu National Park (Sarawak, Malaysia).

5.3 Karst Corridors

Significant widening of pre-existing grikes or of runoff channels can create deep slot canyons wide enough for humans to explore. Spectacular examples exist in Madagascar, in the Bemaraha and Ankarana regions, where the karst corridors are several tens of meters deep. Some of these canyons may be the result of a cave roof collapse, while others are created by basalt dikes cutting across the limestone and creating paths for preferential dissolution.

5.4 Dolines

Dolines or sinkholes are an essential feature of karst landscapes, both in terms of hydrology and morphology. They are more or less circular closed depressions, varying in appearance and size. They dot the surface of karst regions, and they sometimes occur at such high densities that they coalesce. They form a multitude of small endorheic basins that collect rainwater and act as natural funnels.

Dolines also can accumulate soil cover in their flat bottoms. In Mediterranean karst, they are often the only places that can be cultivated amidst fields of lapies where the bare rock is sterile.

Figure 24. Subalpine doline in the Mediterranean (Calern plateau, France). The bottom of the doline has been cultivated. Note the presence of suffosion sinkholes, which indicate the removal of arable land by the endokarst.

Due to their ubiquitous nature, dolines have been the subject of numerous studies and have given rise to various classification systems based on their appearance, their genesis, or their hydrologic function.

5.4.1 Primary Types

Dish-like dolines: Characterized by low-angle sides and a flat bottom. The most common type of doline in temperate or semi-arid climates. The bottom may be marshy or hold an ephemeral lake or ice cap.

Bowl-like dolines: Crescent-shaped in cross-section. Primarily found in chalky areas or in karsts covered by a thick layer of soil.

Funnel-like dolines: These have steep sides, and large rocky blocks often obstruct the bottom. They often end in swallets, and are common in tropical regions with rapidly evolving karst.

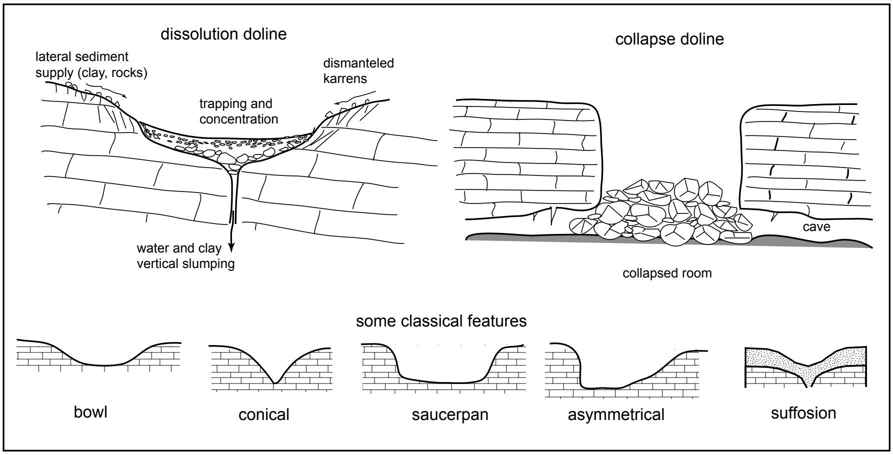


Figure 25. Doline structure and common forms.

Collapse dolines: Caused by the inward collapse of the roof of an underground cavity. They can reach impressive sizes, at which point they are called mega dolines. Among the largest are the Xiaozhai Tiankeng and the Dashiwei Tiankeng (China), the Minyé sinkhole (Papua New Guinea) (Figure 26), and the Sotano de las Golondrinas (Mexico).

The roof of a cavity collapses once the breadth of the arch exceeds a certain threshold (based on the rock type) the thickness of the bedding, and the degree of fracturation in the overlying rock. Collapse generally occurs once the thickness of the roof is less than the width of the cavity (Gilli, 1984).

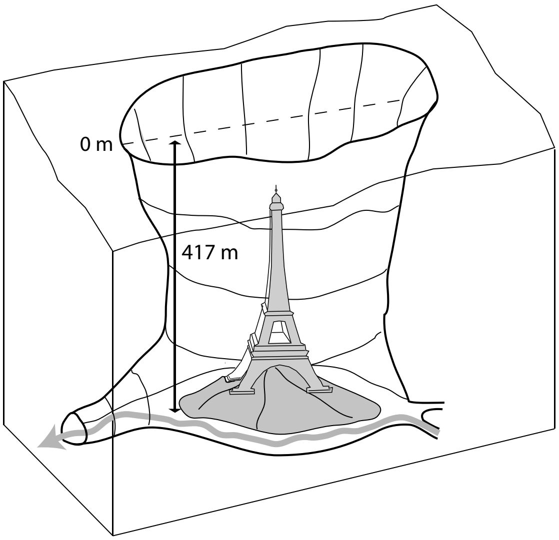


Figure 26. Minyé sinkhole (Papua New Guinea).

Cylindrical dolines: Characterized by vertical sidewalls meeting a level floor, they can evolve as a later stage of the collapse dolines mentioned above, due to infilling.

Suffosion dolines: These form in the unconsolidated material covering a karst area. In their early stages they are generally basin-shaped or cylindrical, but they can evolve quickly, collapsing into a steep-sided sinkhole and revealing the underlying bedrock.

5.4.2 The Structure and Formation of a Doline

A doline is a point of preferential water absorption, which concentrates runoff towards its center. It grows by dissolution, as well as through the classic mechanical processes of erosion, decompression, landslides, and frost wedging. When a thick soil cover is present, the doline can also grow through solifluction. As it evolves, the doline fills with colluvium, which is also subject to dissolution and is sometimes transported below the surface. All this colluvium disappearing into the doline's swallet usually indicates the presence of a vertical outlet. Similarly, speleological explorations often discover narrow karst fissures that open suddenly into large pits below the dolines. Ground-penetrating radar can provide imagery of these vertical drain holes (Figure 27), illustrating the classical structure of a doline: a rocky funnel filled with colluvium, leading into a vertical drainage outlet.

The sediment fill in dolines can create a natural filter, trapping soil and making agriculture possible. Human use of a doline changes its appearance: stones are removed from the fields, and terraces and retaining walls are put into place to prevent soil erosion. Despite these efforts, the soil cannot be entirely kept in place, and its eventual migration into the endokarst often causes small suffosion sinkholes.

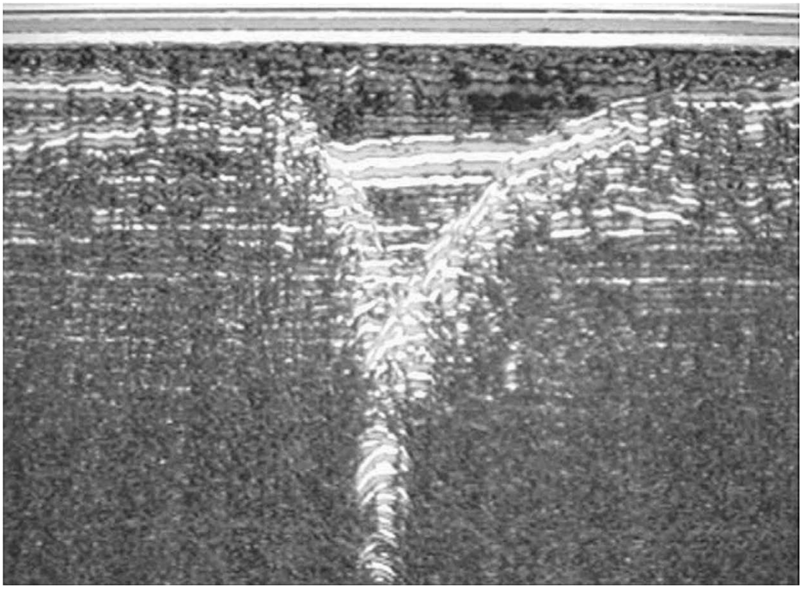


Figure 27. Ground-penetrating radar image of a doline (doc. A. Szynkiewicz). The imaging covers a depth range of approximately 25 m. The vertical karst conduit and the sediment fill are clearly visible.

5.4.3 Factors Affecting Shape and Distribution

Like lapies, dolines emphasize the underlying structure of the surfaces they occur on. They are generally aligned with major faults or fractures. In highly developed karst they can coalesce into uvalas and "polygonal karst", very common in tropical regions. In these regions, concentrated, frequent rainfall with high surface runoff cuts talwegs into the sides of the dolines. From a bird's-eye view, the dolines become star-shaped, rather than classically circular or ellipsoid. This is called cockpitkarst, after the Cockpit Country of Jamaica where it was first described (Birot et al., 1967).

A comparison between the density and depth of dolines in temperate regions (France, USA) and tropical ones (Puerto Rico, Santo Domingo) reveals that while the density is comparable, the depth and lateral extent of the dolines are far greater in tropical areas (Troester et al., 1984).

5.5 Poljes

The Slavic word polje means plain. Poljes are an important component of karst, where, aside from the bottoms of major dolines, they are one of the rare formations that can support large-scale agriculture. First used by Cvijic', the term has come to describe endorheic basins where surface runoff disappears into the heart of the karstic bedrock, though caves or chasms called ponors, swallow-holes or swallets.

This hydrologic system functions in its own particular ways, which results in the characteristic landforms common to poljes. When the discharge of a stream, swelled by abundant precipitation or snowmelt, exceeds the absorption capacity of the ponor it flows into, a semi permanent lake forms. This can also occur if the ponor becomes clogged with sedimentary and organic debris, with ice, or with various anthropogenic detritus (tires, barrels, etc.). The lake will persist as long as the blockage holds up against the water pressure. In inhabited poljes, where the economy of the area depends on the amount of arable land, ponors are carefully monitored in order to avoid clogging (cf. chap. 15). A lake can also form if the aquifer that normally receives water from the ponor overflows. The direction of flow through the ponor reverses, and it then acts as a source rather than a sink. These ponors are termed estavelles or inversacs.

Depending on the climate and the geologic context, a lake may form only rarely, it may appear year after year during the rainy season, or it may even become permanent. Even without maintaining a permanent presence, the lake gradually smoothes out the topography, while also laterally expanding the area of limestone that it alters (Roglic', 1964). A lacustrine morphology is therefore gradually emplaced within the karst landscape.

The presence of poljes depends on three main factors:

- A particular geologic context such as a fault network or a lithologic limit, which allows contact between a low-permeability unit, where water circulates at the surface and feeds streams, and a high-permeability limestone unit into which these streams can disappear;
- A strong hydraulic gradient driving the hydrographic network downwards, such as, for example, in areas with strong eustatic variations or significant tectonic uplift;
- Or, inversely, a high water table that can overflow easily. This last type of polje is often found in tropical karsts and is associated with tunnel-shaped caves providing drainage pathways.

Poljes are common around the Mediterranean (Figure 28), where they have been well described by J. Nicod (1972). Their abundance is probably linked to the Mediterranean's dramatic sea level drop during the Messinian salinity crisis (cf. chap. 14), which would have induced a strong hydraulic gradient and therefore encouraged surface circulation to migrate downwards.

Major poljes are also found in Turkey. The polje lakes in Eğirdir, Beyşehir, and Suğla are fed by surface circulation over the impermeable Anatolian plateau, butting up against the limestone barrier of the Taurus Mountains. The level of the lakes is set by the amount of drainage into ponors, directing the water through the limestone mass of the Taurus and out to massive springs such as the Dumanlı, which, with an average annual discharge of 50 m^3s^{-1} is one of the largest springs in the world. These hydrologic connections can stretch over tens of kilometers, such as the link between Beyşehir Lake and Manavgat, which has been followed via tracers over a distance of 80 km (Bakalowicz, 1970).

Poljes are also very common along the edges of tropical karsts, where their presence is a sign of the system's late evolutionary stage (cf. 6.4).

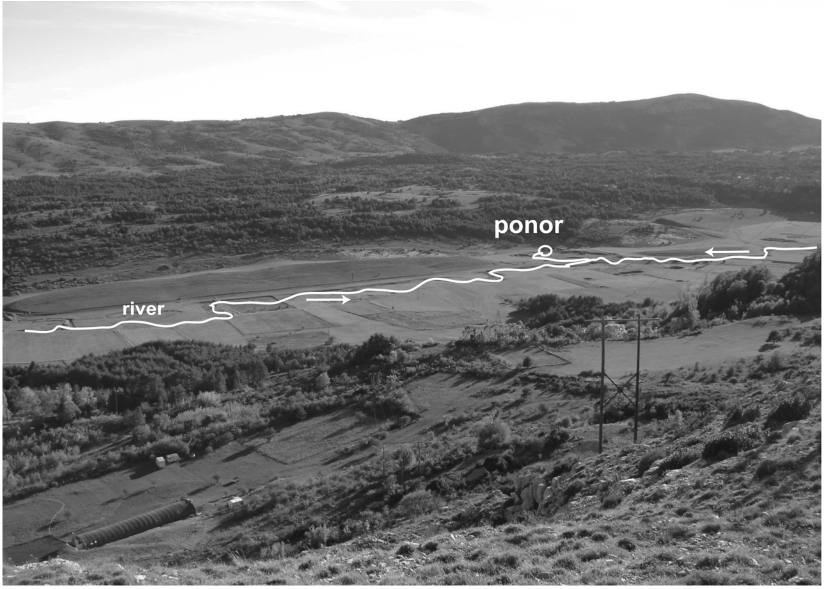


Figure 28. Polje in Caussols (Alpes Maritimes).

5.6 Dry Valleys

Holdovers from times when the climatic or structural conditions favored surface drainage, for example during periods of high precipitations, or during which permafrost was present, dry valleys with no surface circulation can be found on the surface of karstic massifs. They occasionally channel runoff during precipitation episodes, but the water quickly makes its way below ground. In late-stage karst landscapes, dolines may punctuate the valley, forming characteristic alignments.

5.7 Canyons, Pocket Valleys, Blind Valley and Karst Windows

Streams and rivers can be found running across the surface of karst regions, where they are connected to varying degrees with the subterranean drainage network. This results in a variety of landforms.

Canyons, such as the Verdon or the Tarn (France), are narrow gorges cut into the limestone bedrock. They are usually carved by powerful bodies of water, of allochthonous origin, which can incise the limestone without completely disappearing into it. A canyon may intersect groundwater flow paths, at which point it becomes the base level for groundwater circulation, but canyons can also be perched above the karst aquifer, which they then supplement with their diffusive losses.

Pocket valleys originate in limestone cirques with springs emerging at their bases, such as the Loue, the Fontaine de Vaucluse or the cirque d'Archiane in Vercors (France).

A blind valley is a gorge that terminates abruptly at a point where the stream sinks.

Karst windows are essentially the combination of a pocket valley and a blind valley. In thin limestone units, where water flows close to the impermeable substratum, sections of active river valley alternate with stretches where the water flows below ground, like in Rakov Škocjan Park (Slovenia). These valleys form when long stretches of cave roof collapse.

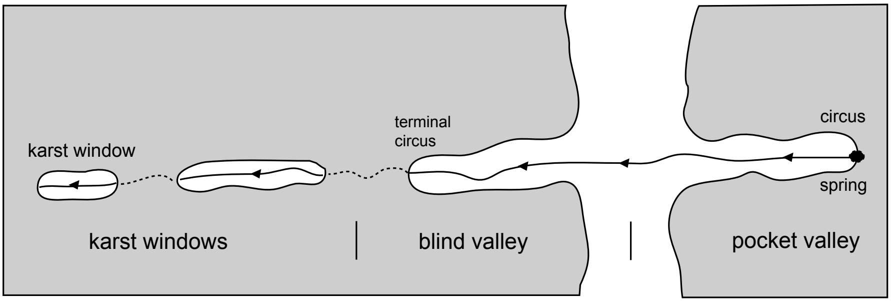


Figure 29. Surface flows in karst regions.

5.8 Springs, Tufa, and Travertine

Precipitation in karst regions is quickly absorbed into the ground, resulting in relative aridity across karst plateaus, coupled with small numbers of high-discharge springs along the edges of these limestone plateaus.

These springs commonly have discharges of several tens of $m^3.s^{-1}$. Many cities in Ancient Greece and Rome were dependent on these abundant water sources to sustain their growth. For example, the port city of Side (Turkey) was supplied by a 50 km aqueduct carrying water from the Dumanlı spring. Today, this spring lies hidden beneath the waters of the lake created by the Oymapınar dam, on the Manavgat River. Similarly, the Zaghouan springs in Tunisia fed the city of Carthage, via an aqueduct over 100 km long, parts of which remain functional to this day.

Springs are generally found where the base level (river, lake, sea) and the lowest point of a limestone unit intersect. Regressive erosion can then create pocket valleys retreating from this point.

The water may emerge inside a cave, like at the Loue (Doubs), or it may come from a submerged vertical conduit, such as at the Fontaine de Vaucluse (Figure 30), after which Vauclusian springs are named. Myriad smaller outlets are present beneath the principal spring, due to fractures that appear as the limestone unit decompresses along its edges.

Some springs emerge in riverbeds, where they can be detected by observing variations in discharge, or by examining the physical and chemical properties of the water. For example the Var River (France) shows an increase in discharge of several hundreds of liters per second, as well as an increase in mineralization, as it passes through karst units downstream of the gorges of Daluis (where the river cuts through

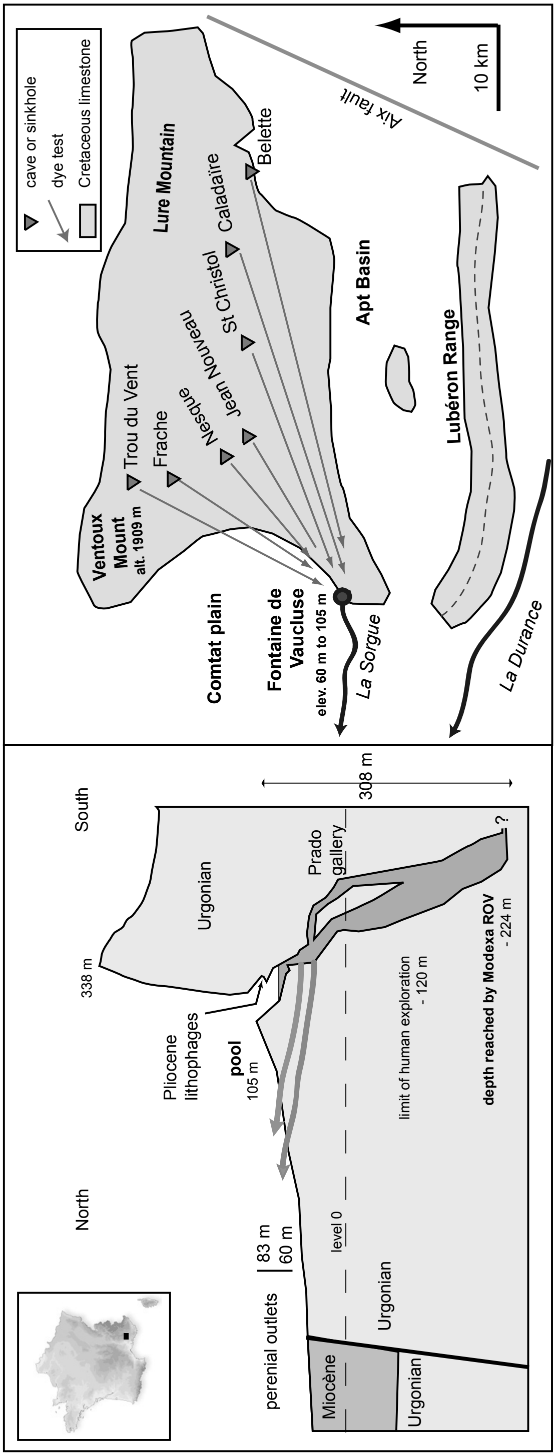


Figure 30. Cross-section of the Fontaine de Vaucluse. Only a remote-controlled robot could reach the bottom of the 308-m well, 224 m below sea level.

pelitic Permian rock). This type of spring can also be covered over by permeable alluvium or by scree slopes, in which case the spring can create a bump in the level of the water table. This phenomenon occurs on the Var River as well, near Carros. Lastly, springs can occur in sea or lakes, and form clearly visible concentric ripples on the water surface, due to the differences in density between the spring water being discharged and the surrounding lake or sea water (cf. chap. 14).

Springs can be perennial, with a high degree of variability in discharge over the course of the year. They may also appear only temporarily, when they are recharged by a yearly rainy season, by particularly intense precipitation events, or after several years of inactivity. Seasonal springs are generally found near perennial springs, but may scattered over several kilometers in the same valley, or may even emerge in a neighboring valley. Whether they are present and how they behave is a function of the landscape's degree of karstification (cf. chap. 8).

Historically, this variability of discharge, which is often accompanied by high turbidity due to leaching from underground deposits of red clay, was considered supernatural, giving rise to cults and to distinctive place names such as Fonsante or Fuon Santa (holly spring) in southern France. Chapels were occasionally built over emergences, such as Notre-Dame-des-Fontaines (Alpes-Maritimes) or Sainte Fontaine de Bellevaux (Savoie) in France. Some of these local cults are still very active: for example, in Lourdes, where the Massabielle cave and its miraculous waters attract millions of pilgrims.

Downstream of a spring, the $CaCO_3$ saturating the water can precipitate out and form deposits of calcareous tufa. Tufa terraces, which can reach impressive thicknesses, are common in Mediterranean regions, such as Cotignac (Var). They may house primary cavities sheltering secondary water outlets, and they may be subject to secondary karstification. Tufa precipitation may be uniquely linked to variations in physical and chemical conditions (decrease in pressure and CO_2 degassing, increase in temperature, variations in pH, changes in the ionic strength due to the presence of sulfates, etc.). It may also be tied to plant activity extracting CO_2 from the water. Tufa is generally highly porous, and consists of a mixture of calcite and plant debris. It can create highly picturesque landscapes, for example, in Plitviçe (Croatia) where the tufa forms a series of small lakes and waterfalls that have been developed for tourism.

The calcite may precipitate differentially, leading to the formation of a succession of dams across the river, several hundreds of meters downstream of the spring, like at Agua Azul (Chiapas, Mexico) where the water, carrying precipitated calcite, becomes bright blue and flows through a series of dammed basins, each pouring out into the next. On a smaller scale, numerous small natural dams often also punctuate the rivers in Basse Provence.

Inversely, precipitation may instead be immediate, covering up hydrothermal springs and forming travertine. Pamukkale, the Cotton Castle (Turkey), is a vast series of calcite tables precipitating spontaneously around hydrothermal springs. The site, an attraction even in Antiquity, receives millions of tourists.

Figure 31. Hydrothermal travertine basins at Pamukkale (Turkey).

This type of calcite deposit can build up stratified sedimentary units spanning vast areas, such as those in Antalya (Turkey), deposited downstream of powerful karst springs draining the limestone Taurus Mountains. The older parts of these deposits have been subject to dissolution and show the classic landforms associated with karstification (karren, dolines, caves, etc.).

6

Landscape Types

6.1 The Role of Climate

The factors affecting karstification are the amount of available water, the temperature, and the presence of CO_2, all of which are dependent on the climate. It is therefore possible to define a climate-based zonal classification for karst landscapes. However, such classification is made more difficult by the superimposition of different climatic conditions, since it is uncommon for a geographic area to have been subjected to only one type of climate. The succession of several different climates results in a landscape where each type of karstic feature imprints itself onto a pre-existing one. It is nevertheless possible to define some general tendencies according to climate zones, the key factor being the amount of rainfall (cf. chap. 4) and therefore the availability of liquid water. Deep hypogenic karst systems (cf. chap. 7.5) are, however, completely independent of climate.

6.2 Karst in Temperate and Mediterranean Regions

Temperate karsts display classic karst landforms: circular dolines of varying depths, rarely connected; thick soil and well-developed vegetation cover; surface drainage systems that disappear into swallets.

In Mediterranean regions, deforestation and an arid climate have led to soil erosion, frequently exposing bare rock. Dolines and poljes are therefore the only sites suitable for agriculture, and large-scale construction projects to create terraces are common in order to prevent soil erosion.

6.3 Karst in Cold Regions

6.3.1 Karst at High Latitudes

Landforms in high-latitude karst vary according to the availability of liquid water. In permafrost regions, water can flow across the surface, laterally, or beneath the permafrost layer. Research in Spitzbergen shows that beneath the ice sheet, water was able to trickle down into the karst due to the absence of permafrost.

In cases where an area with a pre-existing karst system was subjected to later periods of glaciation, the glaciers alter the landscape mechanically, hydrologically, and sedimentarily (Ford, 1992). There are several effects of this alteration:

- Glacial abrasion of lapies,
- Cavities are dissected,
- Moraines fill in depressions,
- Limestone is covered with sediment and thus protected from dissolution,
- Fine particles clog drainage networks,
- Ice blocks drainages and prevents the flow of water,
- High discharges due to snowmelt travel through preexisting channels,
- Valleys deepen and the water table drops.

These effects overlap and superimpose themselves onto the existing topography, creating a wide variety of new landforms.

6.3.2 Karst in Alpine Regions

As with high-latitude karsts, high-altitude karsts were covered by ice during periods of glaciation, partially or completely halting karstification.

The retreat of ice sheets since the Würmian has been gradual and geographically variable. It began in the Alpine arc 18000 years ago, in the regions farthest from the poles and at the lowest elevations. It reveals now a jumble of glacial features (moraines, roches moutonnées, striations, etc.) as well as recent karstification, due to the removal by glaciers of the impermeable unconsolidated cover that had been protecting the underlying limestone. The karsts of the Platé Desert (Haute Savoie), the Arres d'Anie (Pyrénées), or the Marguareis (Alpes Maritimes) are French examples of young, yet spectacular, landscapes.

High-mountain karsts are characterized by a strong hydraulic gradient, high precipitation, and the existence of a snow or ice pack that feeds the spring snowmelt. The slow melting of névé in protected topographic hollows provides a quasi-permanent water supply. Water circulation can, however, come to a halt during the winter, allowing speleological exploration without fear of the violent floods that often occur during precipitation episodes in other seasons. Such floods occur quickly due to the lack of soil cover that would normally slow infiltration.

Ice may have played a significant role in speleogenesis (cf. chap. 7). In some cases, the ice is still present. There are in fact a number of recently formed or still active underground accumulations of ice. These are not usually left overs from the last glacial maximum (Maire, 1990), but instead are a result of the compaction of névé inside natural pits, or of the refreezing of water from the fusion of ice, in areas with a cold environment (snow-filled pits or well-ventilated tunnels). The ice in these locations appears stratified, and creates underground glaciers. In Europe they can be found in many mountainous regions between elevations of 1500 to 3000 m. Examples include the Casteret cave (Huesca, Spain), the chasm of Scarasson (Marguaréis, Italy), Snezna Jama (Mount Raduha, Slovenia), or the Eisriesenwelt (Werfen, Austria).

In caves where ice was present, it has left characteristic underground features: moraines, broken speleothems, corroded walls. The weight of the ice and its intrusions can also deform the rock (fractures, bedding-plane slip). These features have occasionally been interpreted as seismic in origin (cf. chap. 19).

6.4 Karst in Tropical Regions

6.4.1 Specific Landforms

The richness of karst landforms in and around the intertropical zone was confirmed first by the exploration of Papua New Guinea and Borneo in the 1980s, then by the opening of China. Stone forests, pinnacles, giant dolines, gushing springs, cave networks stretching over tens of kilometers, enormous underground caverns and passageways, all stand as testimony to the intensity of karstification in these areas.

This is explained by several factors: rainfall that can reach extreme intensities (10 m in Mulu), lush vegetation that can store CO_2, and especially, the long time periods over which karstification has been taking place. These areas, being located near the Tropics, remained warm and humid while glaciers covered the rest of the world.

Tropical zones also allow for the existence of speleothems on the exterior of limestone surfaces.

6.4.2 Evolution

The durability of the karstification process allows for significant incision into the landscape. Dolines deepen, merge, and give rise to a cockpit karst landscape. When karstification nears the base level, it expands horizontally, and the gradual destruction of the ridges between dolines carves out conical stand-alone or contiguous limestone hills (mogotes or haystack hills), which then evolve, as their sides steepen and their bases are eaten away, into isolated forms (towers, peaks, fungling) (Figure 32).

In southeastern China, the constant uplift caused by Himalayan tectonics results in more accentuated verticalisation and relief.

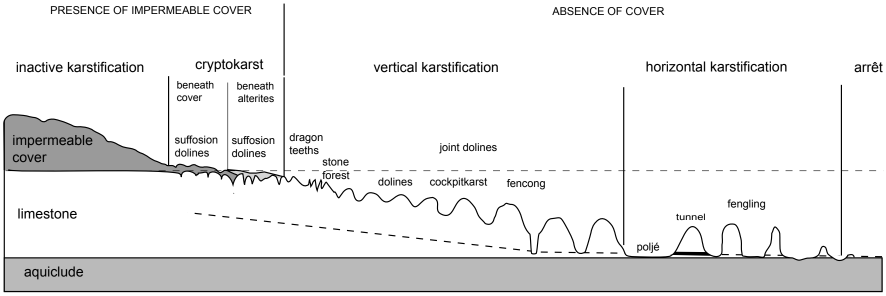


Figure 32. Evolution of tropical karst (after Salomon, 2000).

Figure 33. Fungling landscape (Guilin, China) (photo E. Gaschat).

Gunung Mulu National Park

Located in Sarawak (Malaysia) on the island of Borneo, Gunong Mulu National Park is home to the Melinau limestone, riddled with over two hundred kilometers of underground passageways. The intense karstification is due to the presence, east of the limestone outcrops, of a clayey sandstone unit, the Gunung Mulu, which concentrates the precipitation (10000 mm/year) and injects the water directly into the limestone, thereby excavating significant voids, such as Deer Cave or the Sarawak Chamber, the largest subterranean chamber in the world.

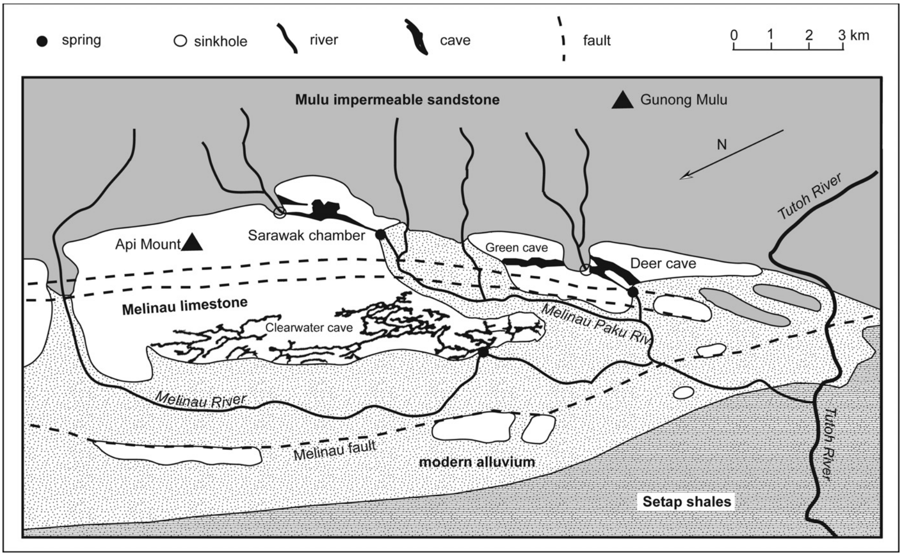


Figure 34. Geologic sketch of the Mulu region (Sarawak, Malaysia). The vast underground spaces of the Sarawak Chamber and of Deer Cave are located at the contact between the Melinau limestone and the Mulu sandstone, which collects large quantities of water (after Waltham and Webb, 1982).

6.5 Karst in Arid and Semi-arid Regions

Karst in desert regions (precipitation under 400 mm/year) is rare given the scarcity of water and vegetation. The features that do exist are usually inherited from times when the climate was more favorable. Limestone outcrops are usually devoid of the classic surface features found in other karst regions, such as dolines and lapies. These features are not, however, completely absent (Figure 35) since rainfall is not entirely non-existent. Solution pans (Figure 36) are common, and can occur at surprising densities. They form temporary watering holes, and the largest are sometimes crudely modified by humans to limit evaporation.

Figure 35. Juvenile lapies on a limestone slab in the process of being exhumed (Jebel Tebbaga, southern Tunisia). The lapies on the upper portion of the slab are more developed than those on the freshly exhumed lower portion. The intensity of the features can also be accentuated by the action of wind-borne sand grains.

Figure 36. Solution pans in the Jebel Tebbaga (southern Tunisia).

The wind can also sculpt eolian lapies, which are reminiscent of dissolution karren (Figure 37).

Figure 37. Eolian lapies in the Timbaïne limestone (southern Tunisia).

7

Speleogenesis and the Endokarst

The Endokarst

The endokarst is the part of a karst system that is underground, and therefore not visible from the surface. The endokarst is nevertheless closely linked to the exokarst. The endokarst can be subdivided into two parts: the carbonate matrix, and the open spaces within it. The underground spaces accessible to speleologists fall into this latter category. For hydrologic purposes the endokarst can be divided into the unsaturated (or vadose) zone, the phreatic zone, which is saturated year-round, and the epiphreatic zone, which varies with the vertical fluctuations of the water table.

7.1 The Infiltration of Aggressive Water

If water that is not saturated in $CaCO_3$ trickles down into a limestone unit, dissolution can take place at depth. Water that is initially saturated can also become aggressive if the physical and chemical conditions change. Dissolution can then take place, carving out subterranean spaces.

The high mechanical resistance of limestone allows these underground cavities to remain stable, and water can then flow through them, both widening them and leaving sediment deposits behind. This is how the subterranean karst landscape, the endokarst, takes shape.

Caves and caverns are only the parts of the endokarst that humans can visit. The network of underground passageways and cavities also includes a high percentage of spaces that are inaccessible and can only be indirectly studied.

In order for water to carve out subterranean spaces, three main conditions must be met: the presence of pre-existing openings (pore spaces or discontinuities), the presence of aggressive water, and the existence of a strong hydraulic gradient.

7.2 The Spatial Organisation of Discontinuities

7.2.1 The Nature of Discontinuities

Primary porosity (the spaces between grains) can occasionally be quite high, particularly in chalk or in limestone formed from coral reefs, which can have porosities of up to 30%. Most of the time, however, limestone is impermeable (and is often used in construction for that very reason). Water flowing through a limestone unit must therefore pass through discontinuities, joints, and faults, present as artifacts of sedimentation or of mechanical stresses.

Sedimentary rocks generally form through the deposition of successive layers. Variations in climate can result in layers with varying amounts of clay minerals, or in gaps in deposition. During diagenesis, the pre-existing layer boundaries can become discontinuities as joints (sometimes called interstrata) appear along the stratification planes. The types and magnitudes of these joints are highly variable, ranging from simple color variations to entire layers of clay or marl that water can leach away.

7.2.2 Diagenesis and Mechanical Forces

From their initial deposition in sedimentary basins to their eventual outcropping at the surface, rock units are subject a number of syn- or post-diagenetic stresses, resulting in the formation of fractures. The stresses acting on a rock (weight of overlying units, tectonics, fluid pressure, etc.) can be described by three primary perpendicular vectors: $\sigma1$, $\sigma2$, and $\sigma3$, where $\sigma1 > \sigma2 > \sigma3$.

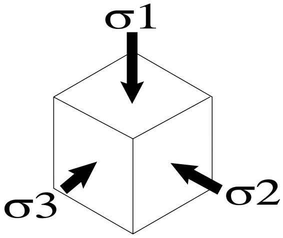


Figure 38. Mechanical stresses, σ1, σ2, σ3. Where $\sigma1 > \sigma2 > \sigma3$.

When subject to weak stresses, the rock will deform elastically, but as the stresses increase in magnitude, the rock will deform inelastically, first undergoing ductile deformation, then, as the stresses increase further, switching to brittle deformation (Figure 39). The point at which brittle deformation occurs and the rock ruptures is a function of the pressure and temperature, and can be empirically determined by laboratory testing. Figure 40 illustrates the behavior of a marble cylinder subjected to triaxial stresses at variable confining pressures (after Paterson, 1978).

From its diagenesis to its current state, every sedimentary rock has undergone a number of stresses that resulted in brittle deformation, creating joints (sets of ruptures where no displacement occurs) or faults (ruptures where one side moves with respect to the other).

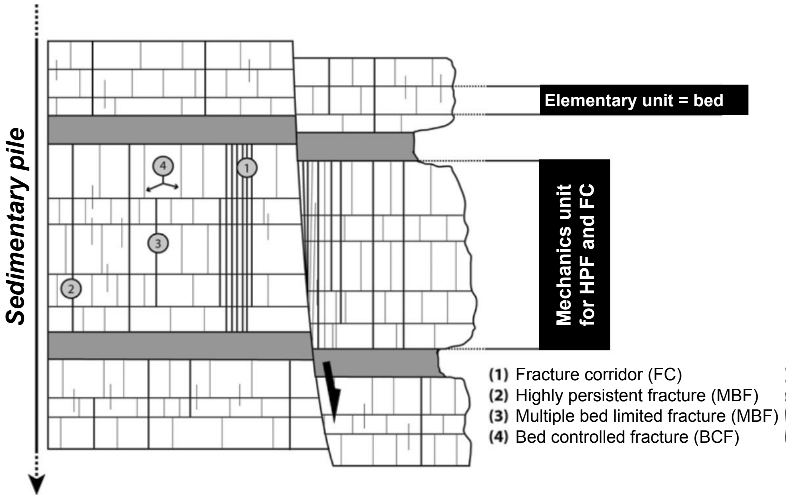


Figure 39. Different families of fractures in a stratified unit (after Bazalgette, 2004).

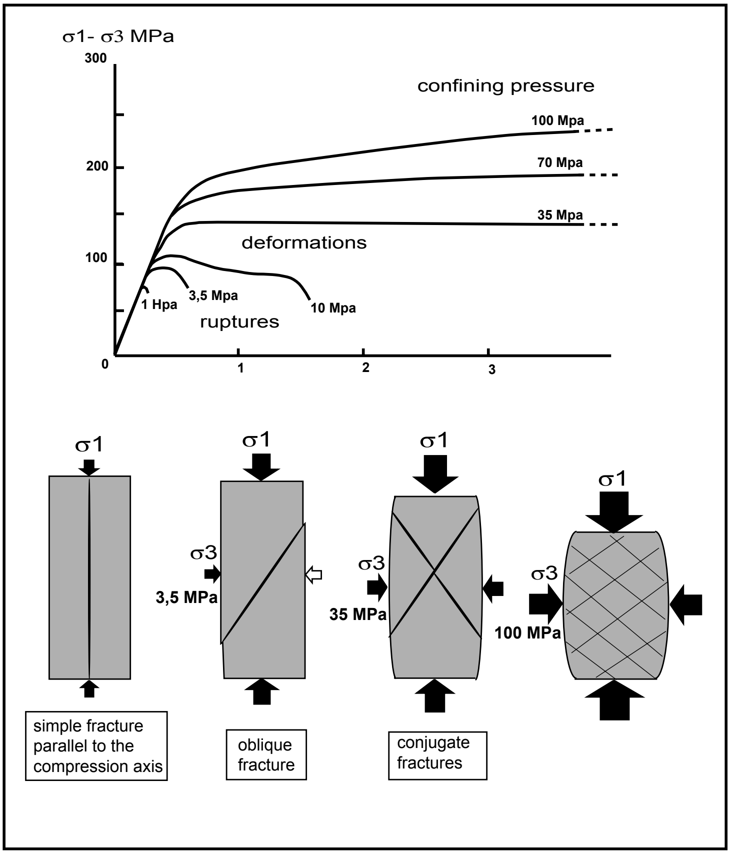


Figure 40. Triaxial tests on a marble cylinder.

Joints are a result of the processes that form sedimentary rocks (burial, diagenesis, and denudation). Rocks form under high pressure deep in sedimentary basins, and subsequent uplift and erosion results in unloading fractures as the compressive load on the rock decreases.

Many studies and models aim to analyze joint distribution and orientation, often for the purposes of exploring groundwater or hydrocarbon reservoirs (Bazalgette, 2004; Jorand, 2007).

Joints are generally thought to be a result of extensional periods, and are therefore expected along the extrados of a fold or in rift zones, but recent studies have shown that joint sets can also be generated by stresses perpendicular to sedimentary bedding planes, and that the distribution and geometry of these joints is dependent on the nature and depth of the affected layers.

With the exception of very deep formations (>10 km) where lithostatic pressure can be considered to be isotropic ($\sigma_1 = \sigma_2 = \sigma_3 = \rho gz$), the internal structure of outcropping limestone units, which are often hundred of meters thick, is determined by past and present stresses, which dictate where discontinuities will open or close. It is often assumed that stress perpendicular to the plane of fracture closes discontinuities. However, the closure is not total, since laboratory tests show that there is a limit determined by the surface roughness and the geometry of the fractures (Jorand, 2004).

In outcrop, a carbonate unit might be compared to a pile of variably spaced, more or less porous bricks, between which water can circulate. However, the initial fracture geometry cannot be the only factor, since the water saturating the unit exerts pressure, which also has an effect. Hydrostatic pressure causes fractures to open, a hydro mechanical phenomenon that has been analyzed by numerous authors (cf. chap. 20).

7.2.3 Determining Outflows

Karst aquifers are a very particular type of fractured aquifer. Water can circulate in the matrix when it is porous (like chalk). But more often the matrix is impermeable and infiltration occurs only through discontinuities (fractures, joints, etc.). The general permeability in a fractured medium is anisotropic and depends on the direction and interconnectedness of the fracturation (Figure 41).

Various tectonic environments favor the opening of fractures, and theoretically facilitate the infiltration and circulation of water at depth, for example, the upper surfaces of anticlines or the lower surfaces of synclines. The latter also form natural gutters as well (Figure 42).

It is useful at this point to recall two important requirements for karstification to occur:

1. $CaCO_3$ laden water must be flushed from the system through an outflow of some sort, otherwise it will prevent dissolution because it is saturated,
2. In order for there to be an outflow, there must be a hydraulic gradient.

The water collected by a catchment area filters into the bedrock unit, filling the fracture network above an impermeable layer (aquiclude). It then flows out to an exit point, which corresponds to the lowest point at the intersection between the aquiclude and the local base level (river, lake, sea). This creates a current from the

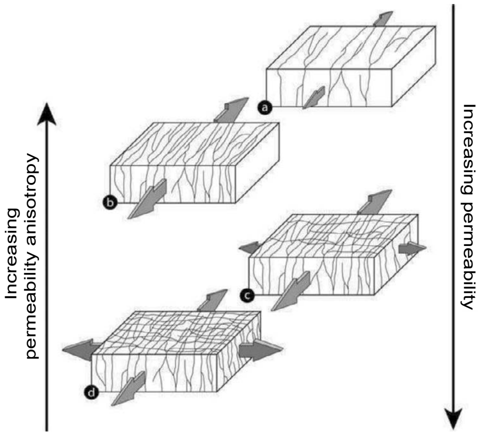


Figure 41. Variations in permeability as a function of fracturation (after Bazzalgette, 2004). The degree of fracturation increases, the permeability increases and well, and its anisotropy decreases, allowing water to circulate in different directions.

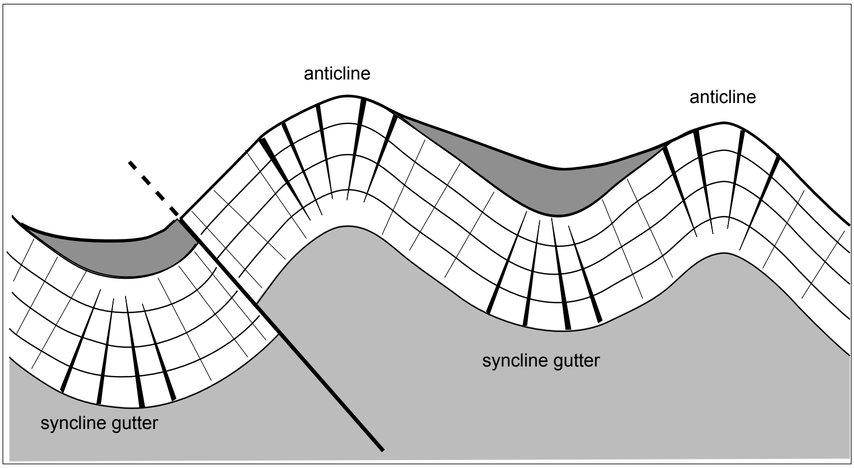


Figure 42. Spatial organization of open discontinuities in a fold zone.

entry point towards the exit point. Its specific characteristics depend on the resistance of the medium (porosity, degree of fracturation). Subterranean flows can thus be compared to an electric current that establishes itself in a circuit due to a difference of electric potential. The current preferentially follows the path of least resistance. Water circulation therefore favors zones with high transmissivity.

The distribution of these zones is a result of several factors:

- Lithologic (cavities in coral reefs, areas of high porosity, facies variations, gaps in sedimentation),
- Tectonic,
- Historical, when previous karstification has already created open spaces within the rock unit.

7.2.4 The Role of Structure

This question is the source of much debate. Structure actually only has an effect in allowing the circulation of water between an inflow zone and an exit point along the path of least resistance and on the shortest distance. If the structure is homogeneous, the flow path will appear to be independent of structure. If the structure has created a strongly anisotropic permeability, it will direct the flow path.

In mountainous regions, where the general drainage is often determined by the bedding dip, an analysis of geologic maps and cross-sections can uncover the important role of structure in the formation of conduits (Choppy, 1992c). Fractures oriented along the dip are preferentially used as drainage, but only if they are oriented roughly in the same direction as the general flow direction, which is determined by the base level.

Major faults, termed "highway faults", for which the loss of head is minimal, can locally divert water flow from its theoretical direct path to the outflow point. Similarly, the presence of conduits inherited from older karstification can channel water into drainage axes with very small to nonexistent losses of head.

Attempts to model speleogenesis therefore run into difficulties in trying to include all of the various factors determining the locations of highly transmissive zones within a limestone unit. This is made even more difficult due to the fact that variations, such as changes in the local stress field, can occur during the formation of water passageways.

7.3 Speleogenesis, or Cave Formation

7.3.1 Tectonic Cavities

Karstic cavities are spaces created by dissolution, overlaid onto the fracture network, but certain limestone cavities, such as the Cassaïre chasm (Figure 148), though they may contain speleothems, are simply tectonic cavities, created by the opening of a joint or the shifting of a fault. The formation of most cavities begins with a tectonic phase, since the opening of joints is a necessary prelude to the infiltration of water. At depth, circulation is determined by hydromechanical linkages, high pressures causing joints to open (cf. chap. 20).

7.3.2 Dissolution Cavities

When the water circulating through a joint comes into contact with rock, as long as it is not saturated, it will initiate the dissolution of $CaCO_3$. Without flow, phase equilibrium is reached and the saturated water can no longer dissolve the rock. As soon as circulation is established in the aquifer, dissolved ions are flushed out and saturated water is replaced with aggressive water. Dissolution can then proceed, and the joint widens. A conduit forms gradually, within which head losses decrease as the passageway becomes more excavated. This initiates a feedback loop favoring higher flow and thus increased excavation rates. In this context, certain discontinuities become preferred circulation channels, orienting and hierarchizing the general drainage system. Flow paths become organized between the infiltration zones of varying diffusivity, transit zones, and the aquifer, which contains reservoirs and drainages, converging towards one or more springs. This assemblage makes up the karst system.

7.3.3 Ghost Rock Karstification

Ghost rock karstification is a result of isovolumetric *in situ* alteration of limestone by the very slow infiltration of water. Water circulation, enabled by the presence of joints, takes place at a microscopic scale, within the matrix, gradually increasing the porosity of the rock via dissolution of its most soluble components. The resulting formations are large regions of altered, porous rock where only the insoluble framework remains, and where the initial structure of the unit, such as stratification, joint sets, faults, and fossils, is conserved. Pseudo-passageways may form, where the space between the healthy enclosing walls is filled with residual decayed rock. When the altered formations are evacuated a classic karstic cavity remains.

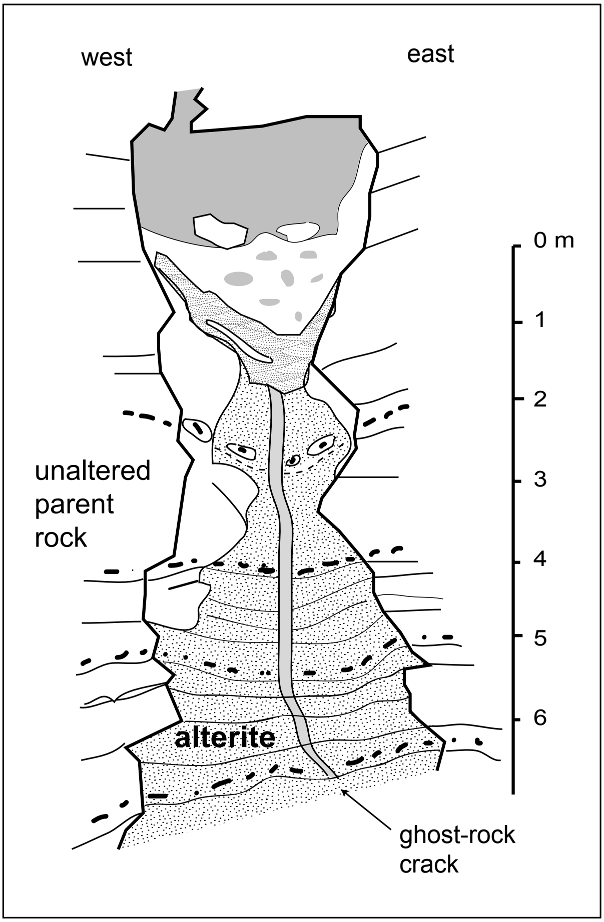


Figure 43. Ghost rock formations in the Pic à Glace cave (after Vergari, 1998).

Ghost rock karstification is an intermediate phenomenon, between karstification *stricto sensu* and the alteration of fractured rock, for example like in granites, where the action of water occurs only as it filters in through fractures. Interstitial flow carries away the more soluble ions while a less soluble mineralized fraction remains in place. It is possible that biological processes play a role as well.

7.3.4 Zonation of the System

Generally zones are listed from uppermost to lowermost:

- **The epikarst**—The rock unit is decompressing over a depth of several meters, karstification can be occurring beneath an overlying soil layer where corrosion is important. Water can accumulate in perched aquifers (epikarst aquifers), allowing the growth of vegetation. Although in certain cases horizontal conduits can lead to the formation of subcutaneous caves, the aquifer is largely vertically drained by fractures, which have been enlarged to varying degrees by dissolution.
- **The vadose zone, or unsaturated zone**—The vadose zone receives the water percolating down from the epikarst, or from precipitation when the epikarst is saturated. It is a zone for the transit of water in vertical conduits. It can be assumed that the major conduits are located beneath dolines, which concentrate water received from precipitation. The largest conduits are shafts explorable by speleologists, which can continue downwards into deep chasms. Water circulated very rapidly within them (with a residence time ranging from a few minutes to a few hours), which allows water not saturated in $CaCO_3$ to arrive at depth during large precipitation events.
- **The phreatic zone, or saturated zone**—This is the deepest part of the system, in which all openings (pore spaces, fractures, conduits) are filled with water. Its upper boundary, the **epiphreatic zone**, is the area within which the surface of the water table fluctuates, allowing exchanges between the three phases: solid, liquid, and gaseous.

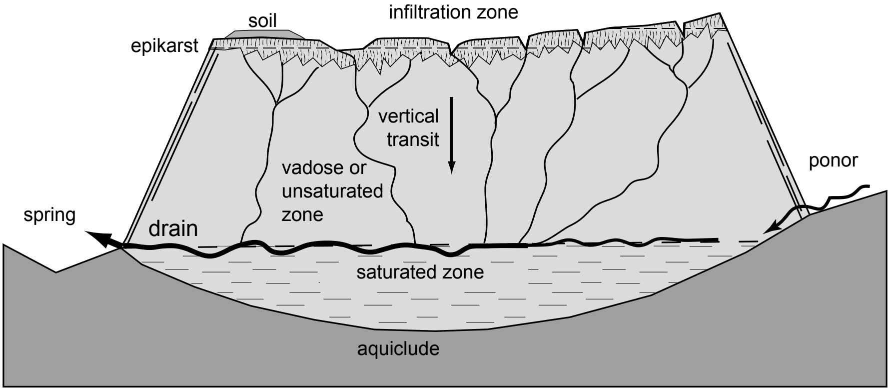


Figure 44. Spatial organization of a karst system.

- **Springs**—The saturated zone is drained by springs, points at which the system overflows, determined by the geometry of the unit and the elevation of the hydrologic base level.

7.3.5 Distribution of Dissolution

Dissolution and the widening of joints take place in a heterogeneous manner, depending on the zone they are located in:

- In the epikarst, dissolution occurs rapidly and homogeneously.
- In the unsaturated zone, dissolution is less rapid and is heterogeneous due to the rapid transit of water.
- In highly transmissive drainages in the saturated zone and in the epiphreatic zone, dissolution is significant but heterogeneous.
- In the capacitive saturated zone, where water becomes saturated in $CaCO_3$, dissolution is slow but homogeneous.

This leads to an irregular distribution of openings within the limestone unit.

7.3.6 The Formation and Evolution of Conduits

Speleogenesis can be examined at the conduit scale and at the system scale.

At the conduit scale, there are two types of excavation:

- In saturated systems, water fills the conduit and weathering occurs across its entire section. Dissolution generally highlights the fracturation and the lithology, but in some cases excavation is isotropic, giving the passageway a circular shape often termed a phreatic tube by speleologists (Figure 45).
- In unsaturated systems (or when water can flow freely), water only flows through the lower part of the passageway, and dissolution occurs below the water level forming vadose passages. The conduit can become deeply vertically incised, creating sinuous passageways with parallel vertical walls, called vadose canyons. Often, originally phreatic, tubular passages, are modified by vadose streams to create a typical keyhole cross-section.

In both cases, the presence of sediment deposits can protect the floor of the conduit, resulting in lateral erosion. A slow flow rate that cannot transport fine particles can still displaces ions, such that excavation occurs only by dissolution, which, paradoxically, favors the creation of cavities in the most mechanically resistant areas. The sedimentary deposit can clog passageways, resulting in preferential dissolution along their roofs. This type of dissolution, called paragenetic dissolution (Renault, 1970), can result in channels or pendants along the passage's roof.

At the system scale, it is useful to distinguish vertical conduits, which allow the passage of water from zones of infiltration in the epikarst down to the aquifer, and horizontal conduits, which drain the aquifer towards the springs.

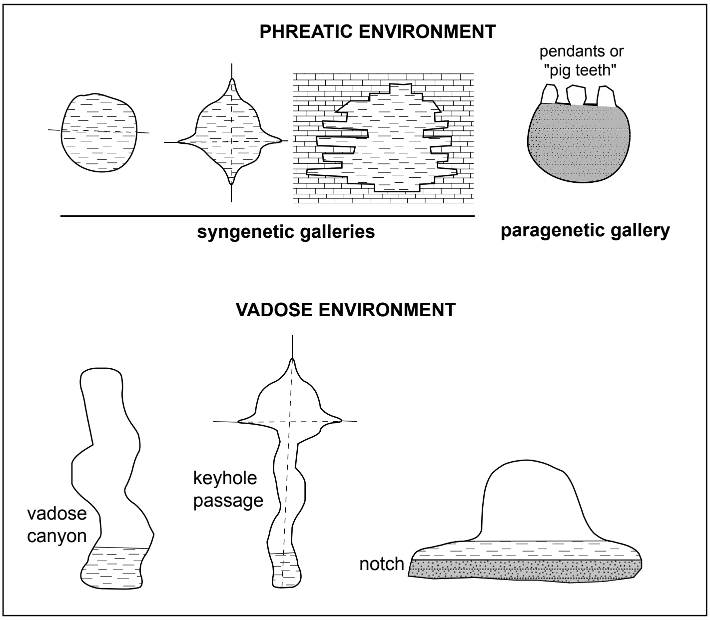


Figure 45. Examples of cross-sections of karstic passageways in saturated and unsaturated zones.

7.3.7 Drainage of the Unsaturated Zone

Between the epikarst, which can be saturated to varying degrees, and the deep karstic reservoir and drainage zones, water filtering downward passes through the unsaturated zone, where it can exchanges gases with the atmosphere. Water passes quickly through this zone, generally moving downward.

Ponors and losing streams feed subterranean flows, that form underground rivers perched above the aquifer, whose beds are determined by the underlying structure. These pathways consist of a succession of underground streams, waterfalls, lakes with sometimes totally submerged parts called sumps or siphons. It was in fact Martel's 1888 exploration of such a river, between the Bonheur River ponor and Bramabiau Spring that led to the longstanding misconception that karst systems could simply be reduced to a series of underground rivers.

Precipitation also provides water to the system, as it falls on the epikarst and then trickles down through it. The vertical transit of water occurs via slow percolation at the base of the epikarst, into a fracture network that then feeds stalactites (cf. 7.7.3). The influx from percolation varies with the amount of precipitation, the saturation of the watershed, and the amount of vegetation. The Edytem laboratory (University of Savoie, France) traced the discharge from stalactites in Choranche Cave (Vercors, France), approximately 200 m below ground, and found short response times, ranging from 4 to 7 hours, depending on precipitation intensity.

Water also travels through vertical conduits large enough to be accessible to humans, where the transit time is very brief. These areas, termed avens, shafts or pit caves, can have several origins: tectonic cavities, collapse sinkholes, dissolution pathways, etc. The rock structure in large part determines the flow paths taken by water (Figure 46).

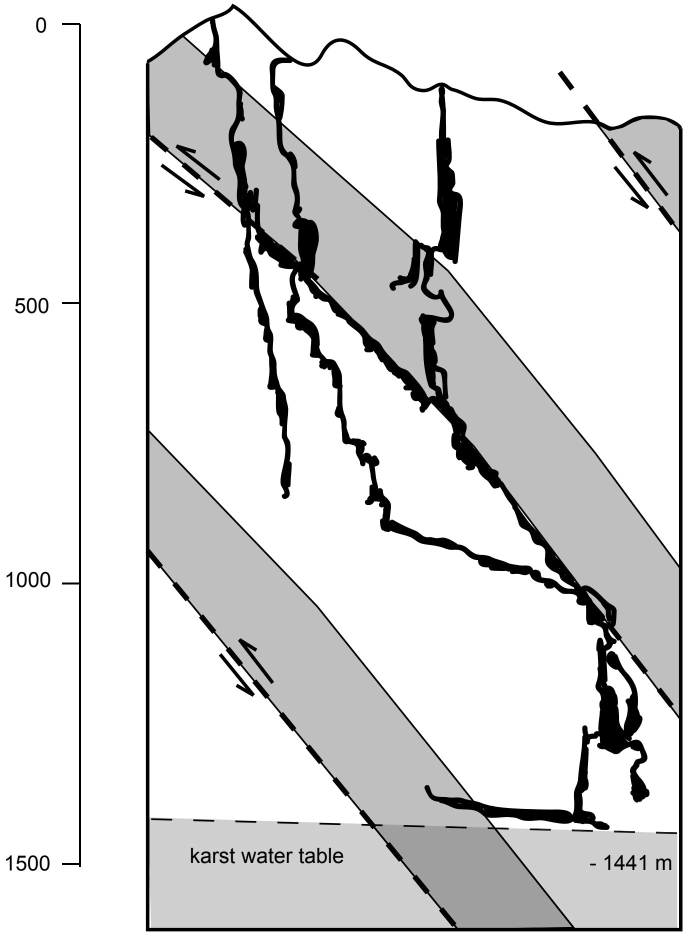


Figure 46. Trave System (Picos de Europa, Spain). The system is superimposed on major tectonic features, which in some cases control the shape of the passageways (Fernandez et al., 2000).

Shafts like the Cassaïre chasm (Figure 47) or the Barrenc du Haut Paradet (Figure 148), although they contain speleothems, are not karstic cavities *stricto sensu* but are instead tectonic cavities created by displacement along a fault. They nevertheless provide passageways for water transit, and can therefore be partially reshaped by karstification.

It is easy to understand the processes that lead to the formation of tectonic pits, or collapse sinkholes. Dissolution pits, however, are less well studied, and often exhibit surprising depths or diameters. They are generally vertical shafts located below dolines, demonstrating the importance of features that concentrate precipitation. These pits are often wider at the base, and exhibit vertical fluting, suggesting that they are carved by runoff flowing downwards.

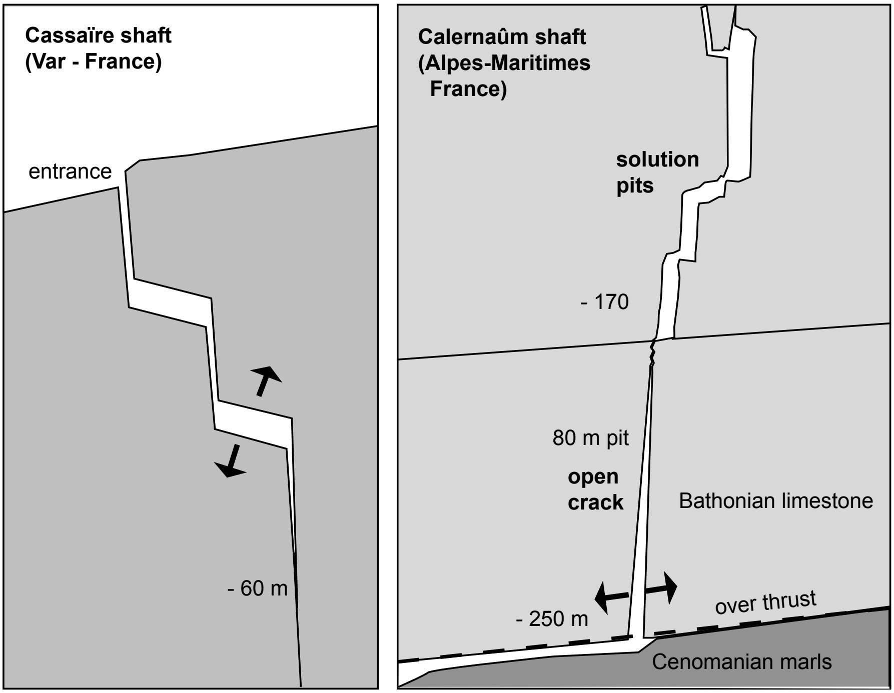


Figure 47. Partially or completely tectonically shaped cavities. In the Cassaïre aven (Var, France) underground chambers were created by fault motion. In the Calernaum chasm (Alpes-Maritimes, France), the terminal well is a large joint opened by unloading over a thrust plane.

Water splashing onto the walls, condensation, and downward flow along the walls can explain most of the formations seen in these vertical pits, but in some cases, the walls are perfectly smooth and cylindrical. This could indicate that the well was formed by residual snow or ice, melting slowly at the contact between ice and rock, and therefore producing only small amounts of water at a time (Figure 48). Underground glaciers still exist in mountainous regions such as Snezna jama (Slovenia), or the Scarasson chasm (Marguareis, Italy) (cf. chap. 6.3.2).

The transit direction of vertically percolating water can change if the water meets a perched aquiclude. The flow direction will then be more or less horizontal until the water finds a vertical discontinuity allowing it to pass through the aquiclude.

7.3.8 Horizontal Drainages

Horizontal drainages direct water in the aquifer out towards springs. In map view, the architecture of drainage networks (as we can observe them in dry caves or in water passageways large enough for diving) is determined by the hydraulic gradient, by porosity, fracturation and paleokarstification, and by the topography of the impermeable bedrock (Palmer, 1991). For example, synclines act as preferential drainage channels or gutters, while anticlines act as barriers. The geometry of drainage networks is

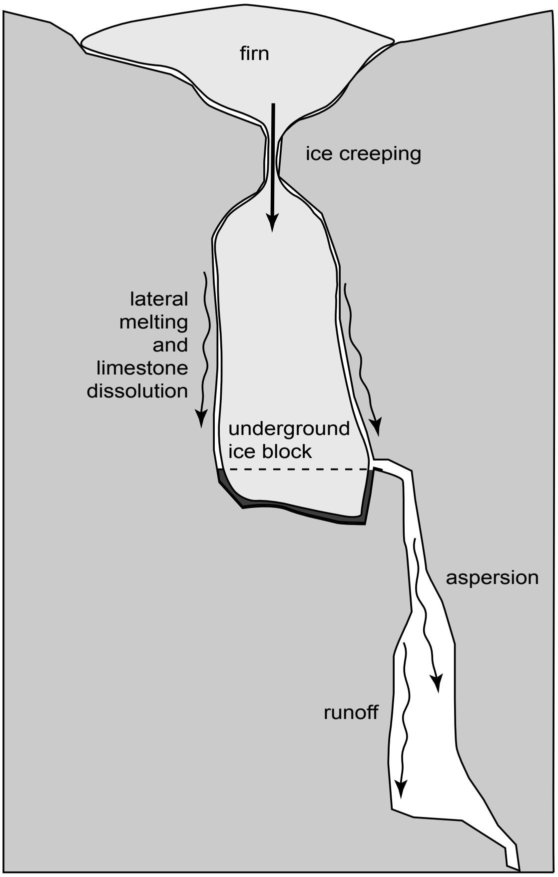


Figure 48. Possible role of ice in the formation of a vertical shaft.

therefore highly variable, ranging from simple underground rivers flowing along the steepest slope of an impermeable substratum, like the Berger chasm (Figure 49), to the labyrinthine anastomosing networks that can form in a vadose zone with very slow flow rates (Figure 50, Figure 51).

Their emplacement is different when water flows directly atop an aquiclude, as compared to an aquifer developing below the level of its springs.

In the first case, drainage passageways form at the contact between the limestone and the impermeable bedrock. If the flow rate is high, water can carve into the bedrock, and the conduit forms partially in the impermeable substrate and partially in the limestone. Under certain conditions, this can result in the formation of large chambers (cf. chap. 7.6). The subterranean rivers of the Pierre-Saint-Martin massif circulate this way, at the base of a thick Cretaceous carbonate unit discontinuously overlying folded Paleozoic basement. Similarly, in the Berger chasm, much of the circulation occurs at the contact between the limestone and the Valanginian marls (Figure 49). The layout in map view of the passageways is determined by the topography of the impermeable basement and the cracks network.

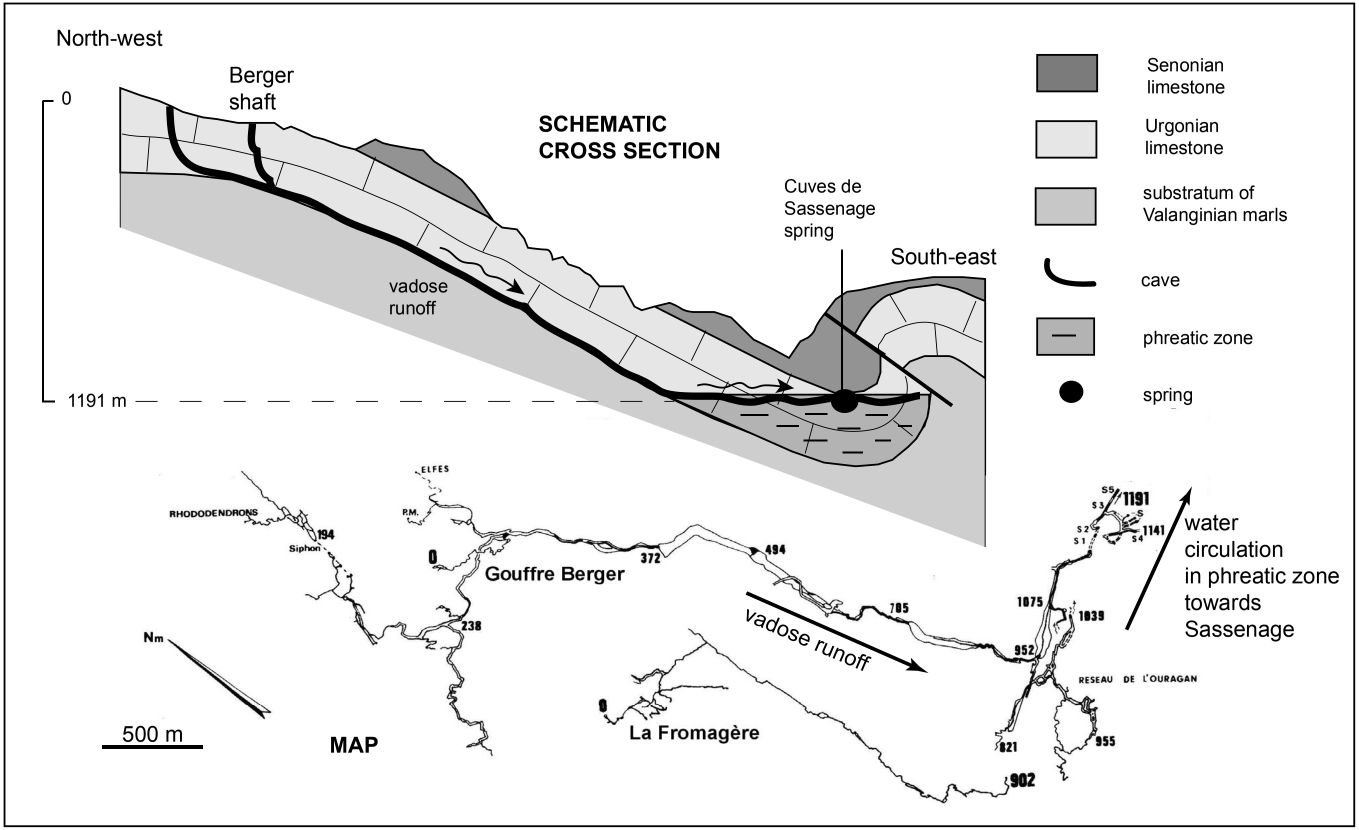


Figure 49. Map and cross-section of the Berger chasm (Isère) (after Courbon and Chabert, 1986).

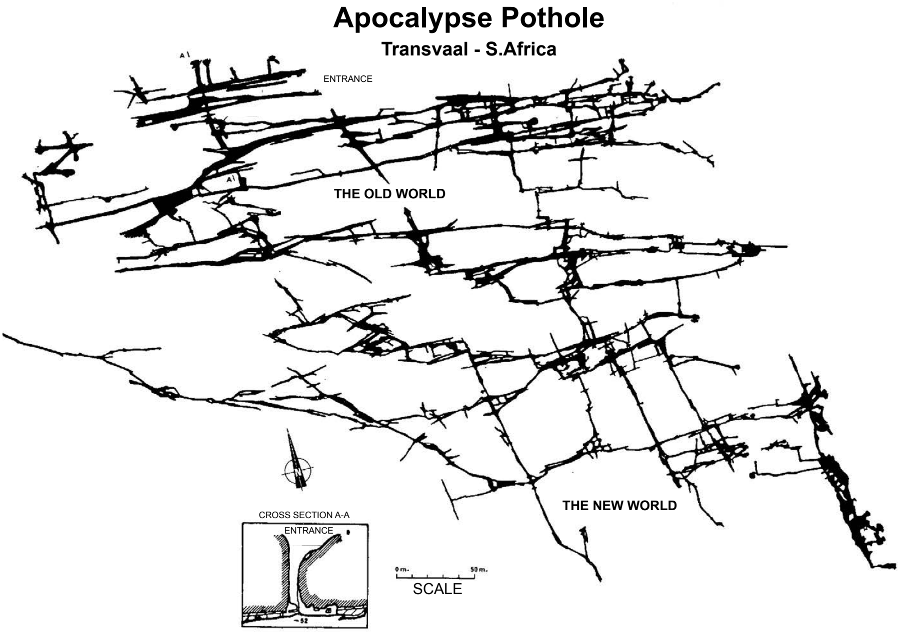


Figure 50. Map of the passageways in Apocalypse Pothol (after Courbon and Chabert, 1986).

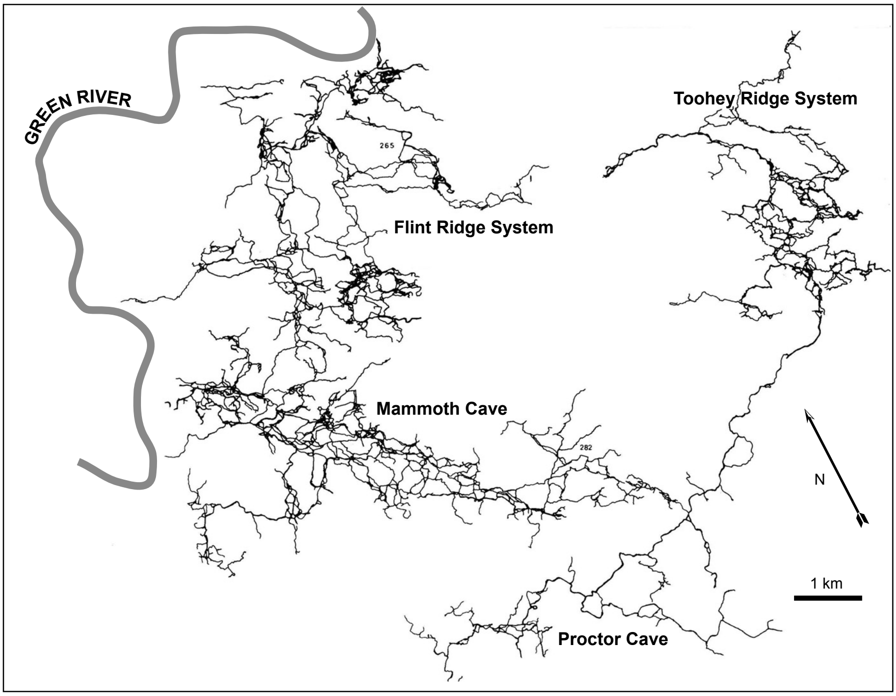


Figure 51. Map of Mammoth Cave (Kentucky, USA) (after Courbon and Chabert, 1986).

In the second case, Choppy (1992c) confirmed, based on numerous and varied examples, that when the springs draining a system are located at a higher elevation than the aquiclude, creating a significant saturated zone, the karstic drainages are preferentially located at the top of the phreatic zone, following the most direct path towards the spring. This is due to the fact that discontinuities generally form a dense enough network for the rock can be considered homogeneous.

7.3.8.1 Epiphreatic zone

The epiphreatic zone is the level of the karst system where the water table fluctuates. It is a favorable area for the excavation conduits, since CO_2 is abundant and facilitates the dissolution of the limestone. Choppy (1992c), then Audra (1994) demonstrated that part of the excavation of these conduits occurs not while they are submerged, but while they are being drained, due to the outflow of water. In mountainous regions, this often creates a rollercoaster-like topography, where confined conduits formed when the area was submerged alternate with passages with the fluting and meanders characteristic of unsaturated flow. The following figure is a simplification of the mountainous Siebenhengste system in Switzerland (Hauselmann, 2010).

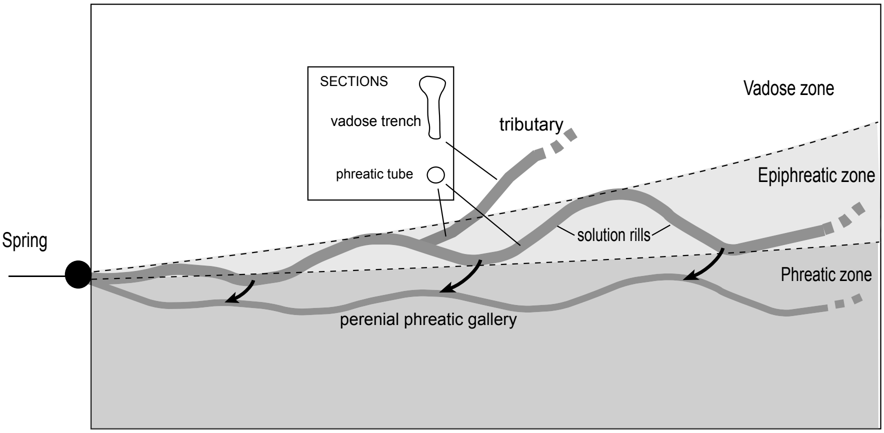
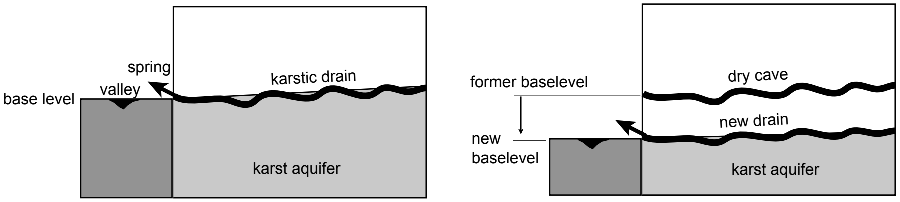


Figure 52. Cross-section of a rollercoaster system (after Hauselmann, 2010). The limit of the epiphreatic zone is characterized by the transition, at the tributaries, from flow conduits, with key-hole shape, to phreatic galleries.

7.3.8.2 Base level variations and inactive levels

When a valley forms, either because the sea level drops, or because of tectonic or isostatic uplift, the spring at the lowest point in the karst system can relocate to a lower elevation as long as the aquifer is not blocked by an aquiclude. The water table drops and new karst drains form at depth. The original water-carrying conduits then run dry, and become classic dry caves which are the realm of speleology. These drainage conduits occasionally go back into use during floods, and are then termed semi-active caves. If the difference in elevation is too great, however, the original conduits fill only under exceptional circumstances, and are called dry or relict caves.



Establishment of a drain

Lowering of the baselevel

Figure 53. Creation of an inactive level in a karst system due to the lowering of the base level.

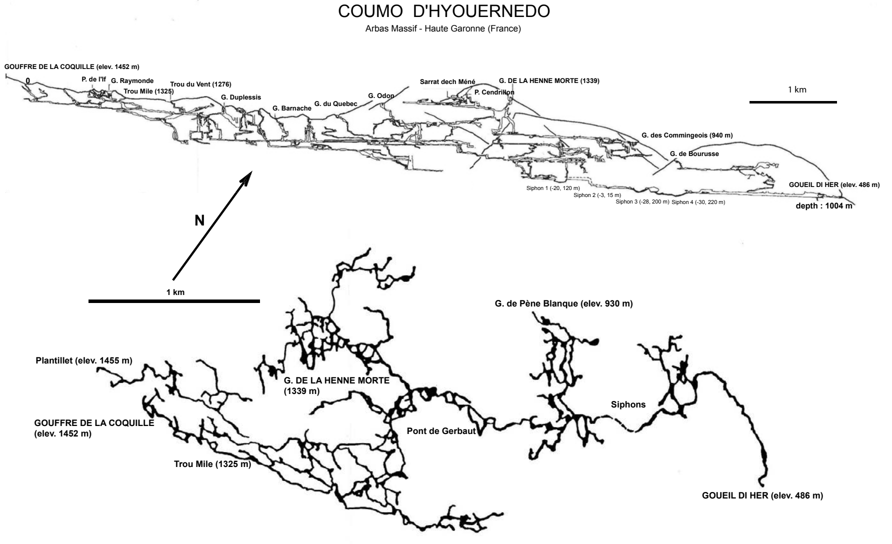


Figure 54. Trombe or Coume Ouarnede network (after Courbon and Chabert, 1986). The longest network in France, with 117 km of passageways and a depth of 1001 m. Note the staging of the horizontal passages, indicating the progressive lowering of the base level, and the capture by neighboring valleys.

7.3.8.3 The role of ice

Glaciers, because they exert a large amount of pressure, and because they can flow, can intrude into karst networks. This phenomenon can be observed in the Castelguard Cave (Alberta, Canada), 300 m beneath a glacial sheet.

Glaciers can either feed subterranean circulation or block it. The network at the Dent de Crolles (Isère, France) (Figure 55, Figure 56) was partially excavated by melt water from the Isère glacier, to the south. The subterranean circulation was flowing to the north, where a local glacier blocked the springs, creating a confined karst aquifer. The karstic drainages formed at the top of this aquifer (Audra, 1994).

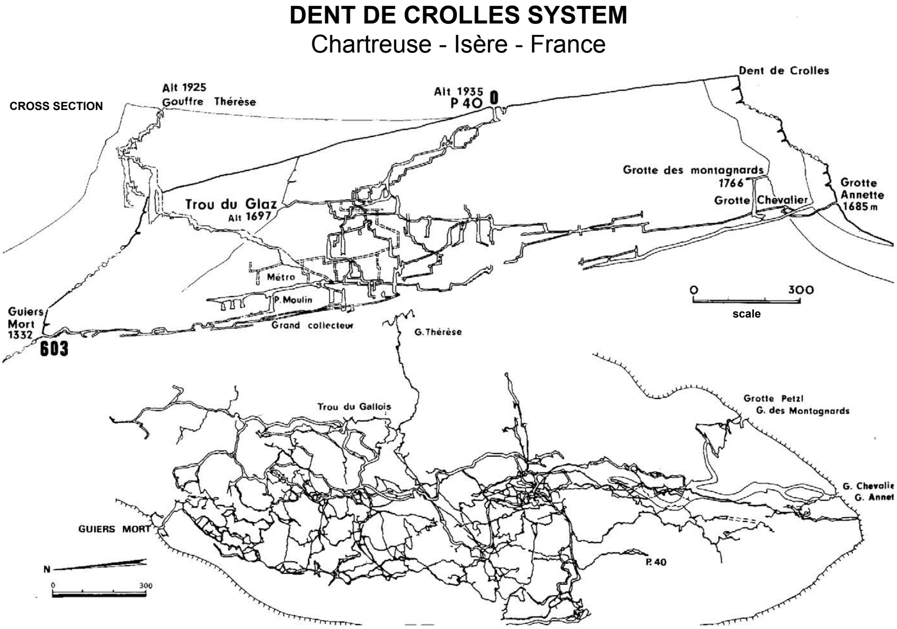


Figure 55. Map and cross-section of the Dent de Crolles (Isère, France) (after Courbon and Chabert, 1986). The system formed partially due to circulation through the rock of melt water from the Isère glacier.

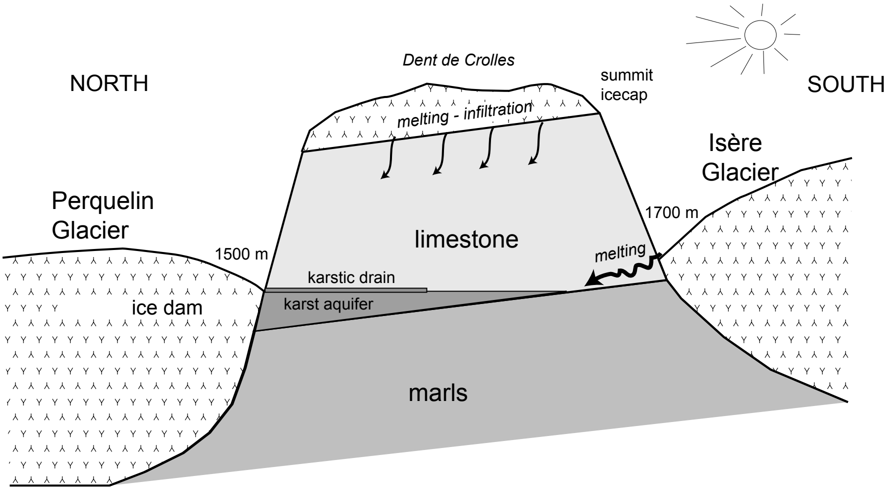


Figure 56. Glacier/karst interactions in the Dent de Crolles (Isère, France) system (after Audra, 1994). To the south, the Isère glacier provides melt water to supply the subterranean circulations, while to the north the Perquelin glacier blocks the karst aquifer.

7.4 Vauclusian Springs

At the Fontaine de Vaucluse (France), there is a spring emerging from a 308 m deep vertical conduit. Its origin is still subject to debate. Is it a drainage aligned on a fault that has been eroding upwards since its inception? Or is the vertical conduit an inherited form, secondarily put to use by water due to its small losses of head? Vertical fluting observed by divers is attributed to water running down the cavity walls when it was not completely submerged, supporting the second hypothesis (Gilli and Audra, 2004). This conclusion is also supported by observations of similar features around the Rhône's Pliocene ria (cf. chap. 8.1)

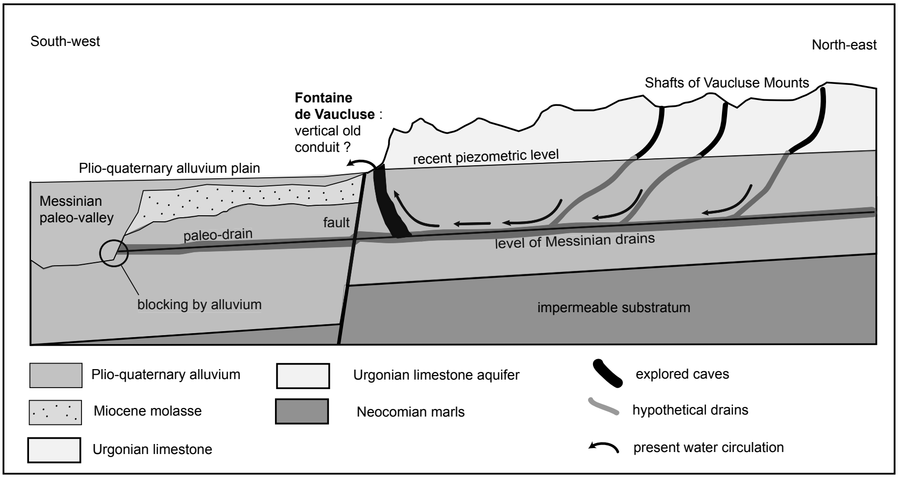


Figure 57. Messinian hypothesis for the emplacement of the Fontaine de Vaucluse.

7.5 Hypogenic Caves

The mechanisms described above depend on downward circulation fed by percolating water which forms an epigenetic karst. The presence of secondary gypsum formations in the giant caves of New Mexico like Carlsbad Cavern, or Lechuguilla (Figure 58) served as the basis for a model of cave formation that was quickly applied to numerous previously difficult-to-explain environments (Hill, 1987).

Excavation in these cases was not tied to an aquifer fed by percolating water or losing streams, but instead to fluid circulation *per ascensum* that forms a hypogenic karst. The water is still of meteoric origin, but it circulates at great depth and becomes laden with carbon dioxide or hydrogen sulfide. In France, the Grotte du Chat (Daluis) is an interesting example of hypogenic cave (Audra, 2007).

The cave was hollowed out in part by the effects of sulfuric acid. Subterranean degassing of hydrogen sulfide (H_2S) from a deeper aquifer led to the formation of

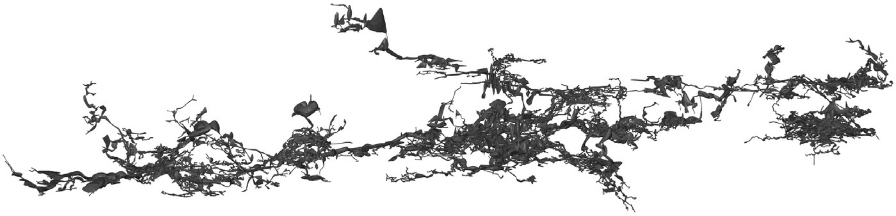


Figure 58. Cross-section of the hypogenic Lechuguilla network (doc. M. Heller. Uté de Zürich. Toporobot software). Upward excavation has resulted in a network of over 200 km of passageways.

sulfuric acid, then to the dissolution of the surrounding limestone and consequently to the formation of gypsum. The reactions involved are:

$$H_2S + 2O_2 \Rightarrow 2\,H^+ + SO_4^{2-} \text{ or } 2\,H_2S + O_2 \Rightarrow 2\,S + 2\,H_2O$$
$$\text{then } 2\,S + 3\,O_2 + 2\,H_2O \Rightarrow 2\,(2\,H^+ + SO_4^{2-})$$
$$H_2SO_4 \text{ in solution in the water} \Rightarrow 2\,H_3O^+ + SO_4^{2-}$$
$$CaCO_3 + 2\,H_3O^+ + SO_4^{2-} \Rightarrow CO_2 + (Ca\,SO_4,\ 2H_2O) \text{ gypsum.}$$

We note that CO_2 degassing, coupled with capillary water flow, creates an acidic solution, which also leads to limestone dissolution through a more classic series of reactions. The Grotte du Chat was recognized as having been formed in an unusual manner thanks to observations noting gypsum layers, dissolution humps and notches, and fine incisions (sulfuric lapies) on the walls of vertical conduits. The subsequent discovery of a sulfuric spring with high hydrogen sulfide emissions downstream of the cave in the Riou Valley, and of several abandoned karst conduits between the cave and the spring, confirmed this hypothesis.

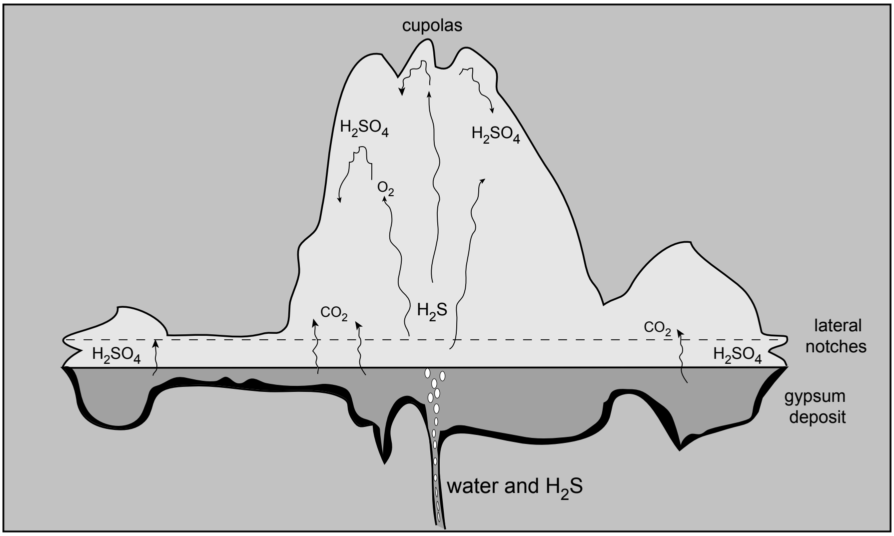


Figure 59. Hypogenic excavation of the Grotte du Chat main chamber (Daluis) (after Audra, 2007).

Hydrogen sulfide occurs naturally in petroleum, natural gas, volcanic gas, and hot springs. It can also be a byproduct of the bacterial degradation of sulfur. In this case, for the Riou spring and the Grotte du Chat, the H_2S could have come from the reduction of pyrite (FeS_2), which is common in the Barremian and in the Hauterivian marls, or, more likely, from the reduction of locally abundant Keuper gypsum. Water analyses of the spring show it to be rich in NaCl and in $CaSO_4$, which are characteristic of the Keuper. Recent work (Barton and Luiszer, 2005) shows that the production of H_2S also requires the presence of metabolically available organic carbon. In the caves of New Mexico it comes from hydrocarbon, but in Daluis its origin remains unknown.

Although some examples, such as the Grotte du Chat, are now dry caves and can be studied, active systems are much more difficult to access due to the water temperature.

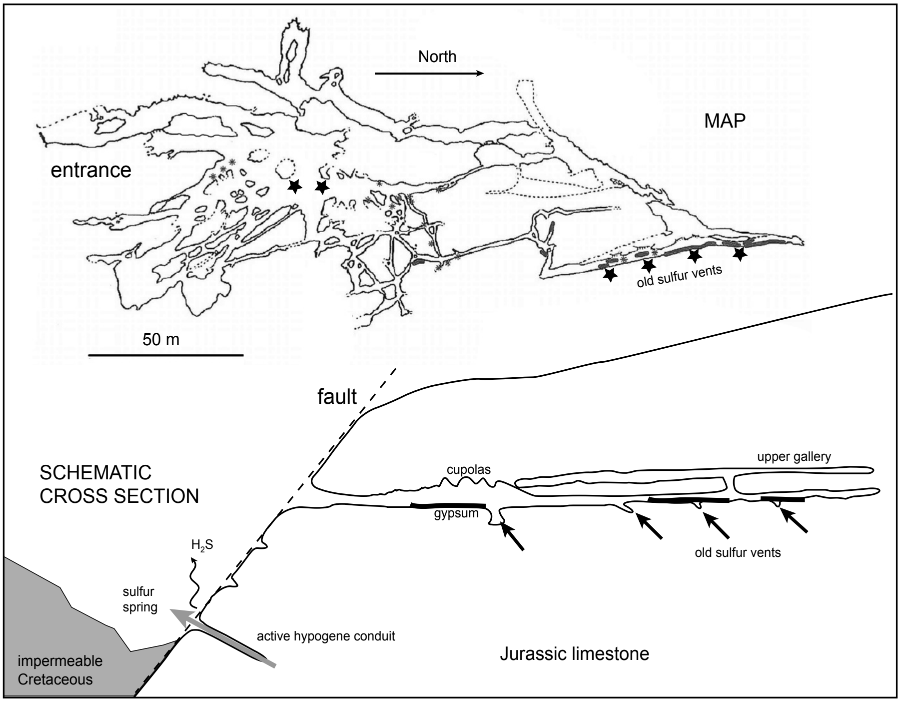


Figure 60. Map of the Grotte du Chat (Daluis). Note the labyrinthine shape of the cave network. H_2S sources are marked by stars.

7.6 Great Caves

Speleological explorations occasionally result in the discovery of gigantic subterranean cavities, giant galleries, or great chambers (this last term being reserved for the sudden widening of a passage in a cave system). Among these, we can cite in France the Verna chamber (Pierre Saint-Martin cave, Pyrénées-Atlantiques) with a diameter of around 250 m and a roof 150 m up, and in Borneo, the largest known underground space in the world, the Sarawak chamber (Mulu massif, Sarawak), of incredible size: 600 m long, 415 m across, and 100 m high.

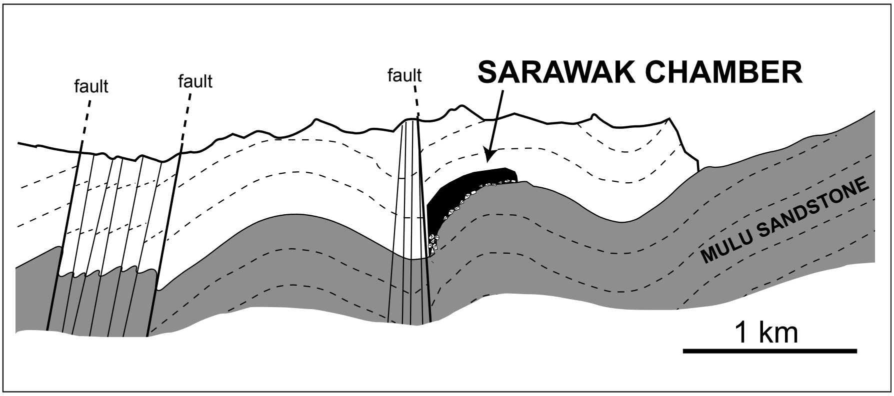


Figure 61. Structural context of the Sarawak chamber, the largest underground chamber in the world (Mulu, Sarawak, Malaysia).

7.6.1 Natural and Artificial Cavities

There is a large gap between human creations and natural examples. The largest human-made limestone cavity in France is the underground Sautet hydroelectric plant (36 m wide before the inner surfaces received their protective coating). The largest unsupported artificial excavations are the Tytyri mines (Finland), which extend for an entire hectare without any pillar. The Sarawak chamber is sixteen times larger. In an effort to determine the natural laws governing the existence and stability of such subterranean spaces, Électricité de France undertook a study during the 80s, examining thirty-odd caves in France, to see if some of these laws might be applicable to the construction of underground nuclear power plants (Gilli, 1984, 1986). The study found that most of the large chambers examined had the same formation mechanism.

7.6.2 Excavation Through Scouring and Draining

Large cavities can be found in a wide variety of geologic and structural contexts, although they often have a vaulted roof supported by thick limestone units. These cavities form as a result of repeated scouring and draining—they are not simply a result of the classic processes of dissolution and collapse in limestone like other caves. Their existence is linked here to erosion and to water transporting soft materials (marls, schists, etc.), all beneath a large mass of limestone providing a stable roof. One of the best examples of this phenomenon is the Poudrey chamber, a vast underground space near Besançon that has been developed for tourism. The roof consists of a massive Jurassic limestone slab, but most of the cave's volume is a result of erosion in the underlying marls, as the eroded particles are continually washed away into a karst network in the limestone below the marl (Figure 62).

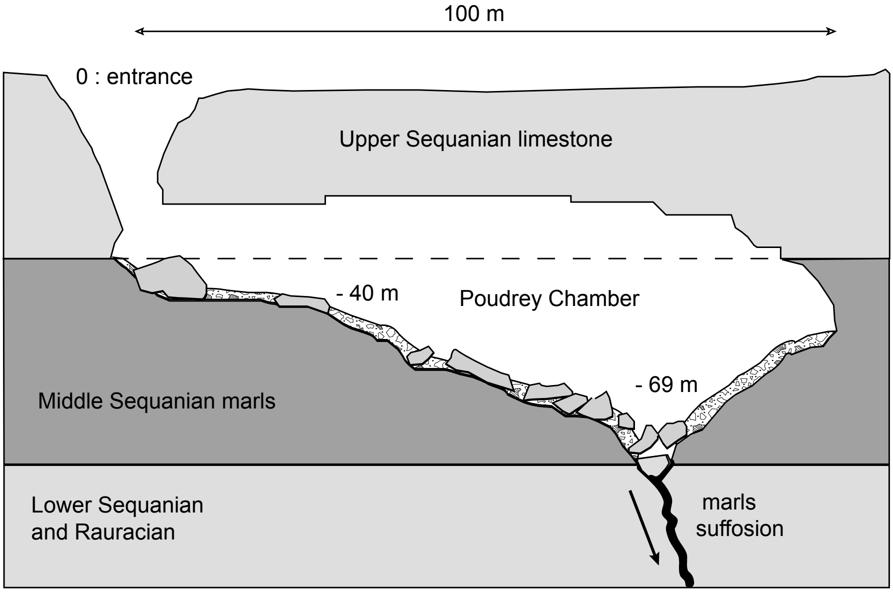


Figure 62. Cross-section of the Poudrey chamber (Étalans, Doubs, France).

La Verna, the largest underground chamber in France

In the Pierre Saint-Martin network, which contains several large chambers, water circulates at the base of the Cretaceous limestone found in the surrounding canyons, which discordantly overlies intensely folded Paleozoic basement. The basement is mostly impermeable, and the scouring of softer areas (schists, clayey sandstones, etc.) is what led to the formation of

Figure 63. La Verna chamber. Pierre-Saint-Martin cave (Pyrénées-Atlantiques). The people in the center of the halo of light give a sense of scale. In the foreground, a pile of scree rests on the Namuro-Westphalian basement schists. At its foot, the river disappears into the lower levels.

several chambers. For the largest of these, the La Verna chamber, the process was amplified by river water filtering in and flowing through basement to reach underlying limestone units. This led to the excavation of the Arphidia network, through which the particles eroded from the impermeable basement were washed away. Scouring of the Paleozoic basement thus occurred both laterally, as for the other chambers in the area, but also vertically, resulting in a chamber of immense volume (Figure 64, 2-3). The river capture is dated to 200,000 years, based on dating the sediments left in the Aranzadi passage, which was fossilized when the river was captured, and comparing them to deposits in the still-active upper passage (Quinif and Maire, 1998).

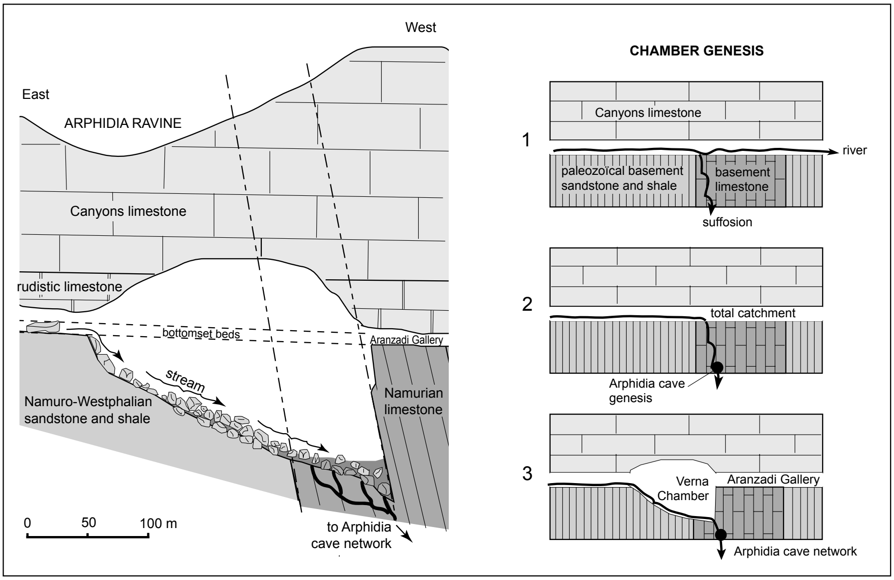


Figure 64. Structural context and genesis of the La Verna chamber. The chamber's large volume is in part a result of the impermeable Paleozoic schists and sandstones. Before the river was completely captured by the underlying Arphidia network, around 200 thousand years ago, it flowed through the Aranzadi Gallery.

Based on the mechanisms described above, it should be possible for humans to create large artificial caverns, by excavating soft materials under a thick slab of more resistant rock. The overlying unit could be reinforced and made more stable if it was naturally arch-shaped. The largest cavities could therefore be created by hollowing out the center of an anticline.

7.7 Underground Sediments

As it evolves, a karst system goes through periods of excavation, but also periods of deposition, when sediments, either autochthonous (rubble, dissolution residue, etc.) or allochthonous (terrigenous sediment carried underground by water, etc.) settles into the bottom of karst conduits. When water is not circulating, chemical precipitation in both submerged and sub aerial environments results in the formation of speleothems as well.

7.7.1 Clasts

Decompression along slopes and cryoclasty (freeze-thaw cycles) can result in rock units fragmenting and turning to rubble. Cave entrances are often subject to these processes and are thus filled with gelifracts and debris, which can in some cases completely obstruct the entrance.

Deeper into the cave networks, as dissolution widens discontinuities in the rock (joints, etc.), chunks of rock of various sizes are excavated and accumulate on the passageway floors. As the size of the passages increases, limestone beds, that can no longer resist being sheared, break. Similarly, when a passage crosses through a brecciated fault zone, large masses of rock can become destabilized and can fall into the conduits, sometimes completely obstructing them (Figure 65).

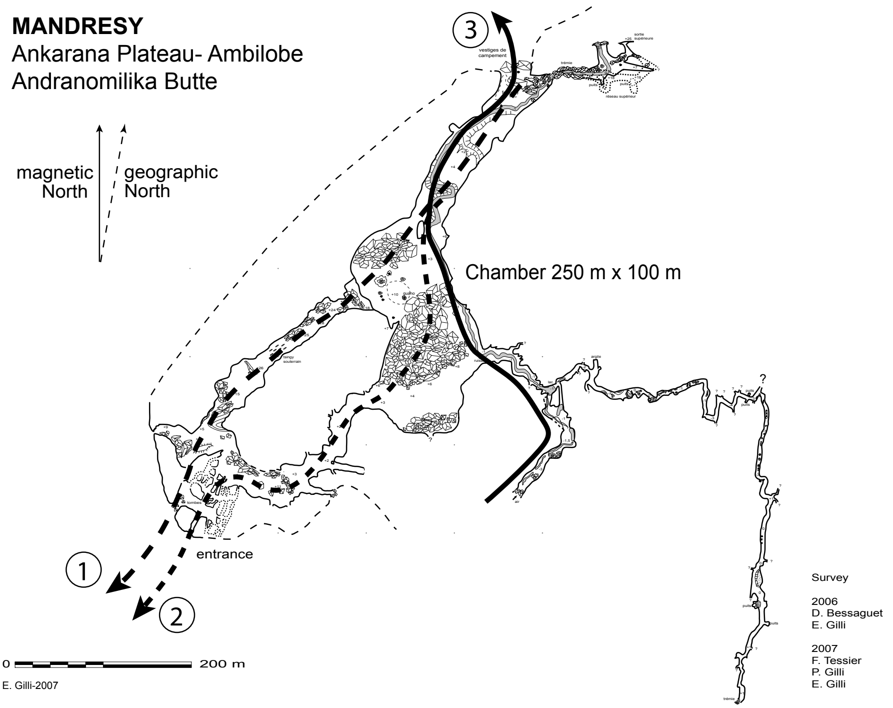


Figure 65. An underground network affected by collapsing chambers in Mandresy Cave (Madagascar). Widening of the primary conduit caused the roof to collapse, creating a first chamber and channeling water flow to the east. The new conduit created a second chamber, which also blocked the water flow with debris, shifting it eastward again.

7.7.2 Clay Deposits

Subterranean clay deposits are fed by residue left behind as impure limestone dissolves, but they come primarily from soil particles moving through the epikarst and from fine-grained sediment carried by allochthonous water flows or from glaciers. Karst system acts then as a sediment trap.

Soil erosion is a common agricultural problem in karst areas. Deforestation and soil tilling liberate fine-grained particles, which can then make their way through the endokarst. In the Mediterranean area, red soils (terra rossa) have in some cases completely disappeared into the endokarst, where they form substantial deposits.

Inside the drainageways, water-saturated clay deposits favor weathering, but the water they hold is not replaced and become saturated which limits corrosion. These clays form an impermeable coating that protects limestones from normal dissolution and favors paragenetic dissolution (cf. chap. 7.3.5).

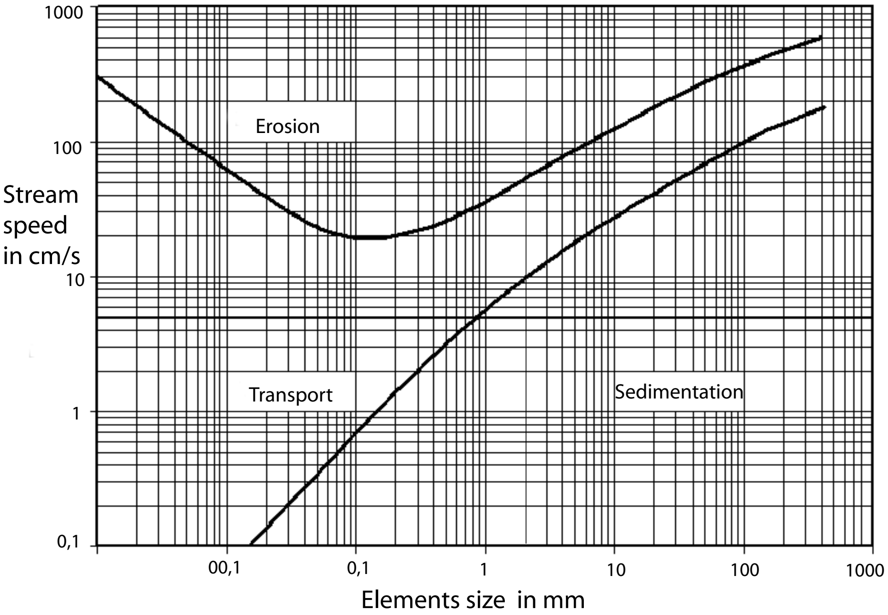


Figure 66. Hjulstrom diagram.

Subterranean deposits form much in the same way as they would in a classic surface stream, with sorted sedimentary sequences, where grain size decreases with water velocity: cobble, pebble, gravel, sand, silt, clay. As particles accumulate, they can completely clog conduits and stop circulation. A Hjulstrom diagram (Figure 66) delineates what water velocities can mobilize different particle sizes.

When a drainage dries up completely due to a lowered base level or during a dry period, various chemical deposits making up a large family of cave formations (or speleothems) can start and protect underlying series of detrital deposits.

7.7.3 Speleothems

Concretions, stalactites, stalagmites, flowstones, and so on, are an undissociable part of the world of caves. They form through the slow precipitation of calcium carbonate, and are dependent on many biological, physical, and chemical conditions. Precipitation can occur sub aerially, or in spaces filled with $CaCO_3^-$ saturated water. Speleothems grow as a succession of thin layers of calcium carbonate (laminae) are deposited. The presence of granules and filaments within these laminae suggests that microorganisms play a role in their formation, as is the case for other geologic features like stromatolites. However, it has thus far been difficult to identify any fossilized remains (Saint-Martin, 2010).

Each speleothem is the output of a biochemical system, the parameters of which are stored in the formation. Analysis of the order and characteristics of the laminae can reveal important information about the paleoenvironment they formed in (cf. chap. 19).

7.7.3.1 Principal forms

There is immense diversity in the forms speleothems can take. The most well known are stalactites and stalagmites, which ornament most caves.

Stalactites and sodastraws

Stalactites form from water percolating down through the limestone above a cave, and becoming saturated with calcium carbonate. Calcite precipitates around a water droplet, the crystals becoming distributed around its periphery. The precipitation and capillary action form a sort of cuff (Figure 67). The successive stacking of these cuffs creates a tube a few millimeters across, called a sodastraw. The sodastraws evolves into a stalactite as calcite precipitates around the tube, increasing its diameter and giving it a generally conical form. Stalactites therefore generally have a central channel.

Sodastraws are indicators of verticality that may be useful for stability studies.

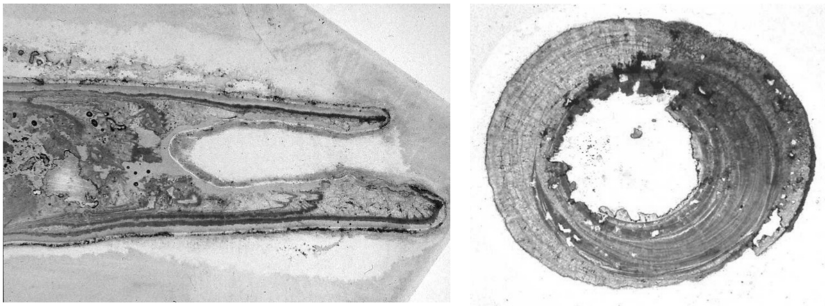


Figure 67. Longitudinal and transversal cross-sections of a sodastraw. The growth cuffs are clearly visible and consist of darker micrite laminae associated with clear sparitic laminae.

Stalagmites

Stalagmites are most often found immediately below stalactites, and form from the $CaCO_3$ remaining in the percolating water droplet. As the droplet falls, some of the water evaporates, liberating more calcite, which then forms a thin deposit. As these deposits accumulate on top of one another, they create a more or less vertical column. In stalactite-stalagmite pairs, when the stalagmite is large, the stalactite is generally small, and vice versa.

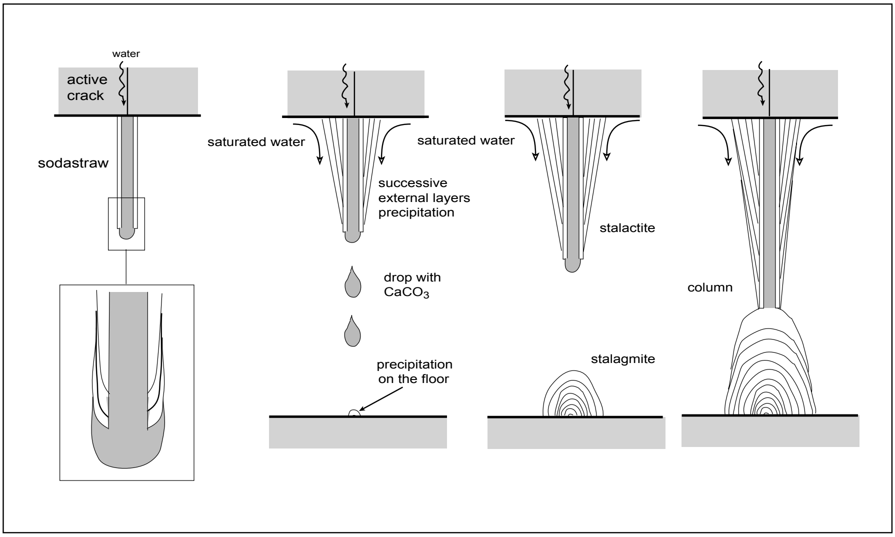


Figure 68. Birth and growth of sodastraws, stalactites and stalagmites.

Gours or rimstone dams

These are small basins, often superimposed. They form when the laminar flow of water leads to evaporation. When changes in slope thin the layer of water and favor evaporation, calcite precipitates. This forms a small dam, accentuating the phenomenon and causing the formation of a calcite dam tilted towards the center of the gour. As water evaporates from the surface of the gour, a thin film of calcite often forms, held on the surface by surface tension. This floating calcite accretes onto the sides of the gour and contributes to its growth.

Gours are indicators of horizontality that may be useful for stability studies.

The variety of speleothems

The description of the different forms speleothems can take would require an entire book. The following figure presents the most common forms. The reasons for such variation and for the location of different types of speleothems are still poorly understood. They are not randomly distributed, and it is likely that biological factors

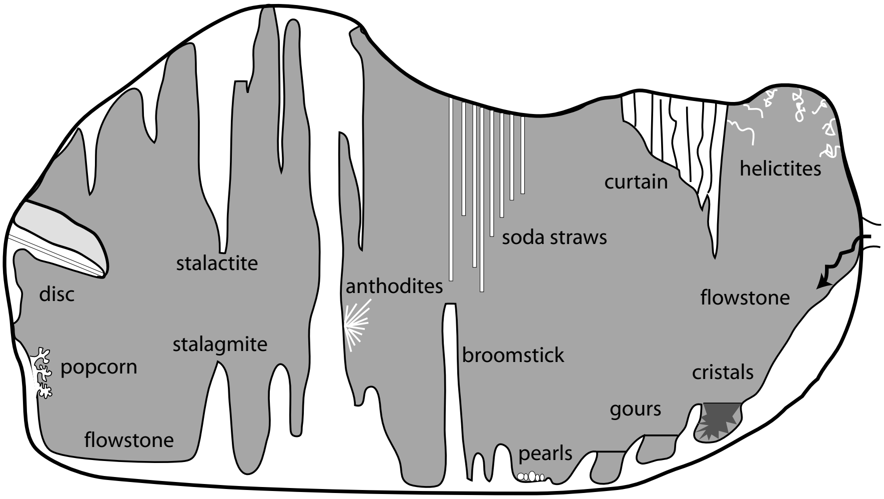


Figure 69. Different types of speleothems in a cave.

play a role. In nature, many types of $CaCO_3$ precipitation are linked to living organisms: test, shells, skeletons, stromatolites, algal crusts, etc. It would therefore be surprising if subterranean concretions were an exception.

7.7.3.2 Growth and evolution rates

Speleothems incorporate the elements found in the percolating water they are formed from (oxides, clays, humic acid), giving them a variety of colors. The rate of concretion is highly variable and depends directly on the climate. At European latitudes, they can grow several millimeters per year. Since they are made of calcite, they can dissolve when the cavity they are in is filled with water or ice. They can also halt their growth for several thousand years and then begin growing again without any noticeable morphological changes.

In warmer climates, speleothems sometimes degrade into onion-skin-like slices, as certain laminae become pulverulent or pasty. It has been hypothesized that this is due to some sort of bacterial process.

The crystal structure of a speleothem can also change, and in some cases systems of fine micritic or palisadic laminae have been observed to transition to a monocrystalline solid that keeps ghost traces of lamination. The cause of this phenomenon is unknown, and it creates a problem for the reliability of speleothem dating, which requires that the system be perfectly closed (Figure 70).

Figure 70. Calcite monocrystal with ghost laminae.

7.7.4 The Study of Sedimentary Deposits

The analysis of subterranean sedimentary deposits can inform our understanding of the evolution of the karst system and of regional climatic and hydrologic conditions (cf. chap. 19). Protected from exterior agents and from vegetation, sediments can be preserved for thousands of year, allowing for highly detailed analysis. The geometry of the deposits can be highly complex, due to successive phases of sedimentation and erosion below ground, resulting in nested deposits, where it is not uncommon to find younger deposits that appear to be below older deposits. A very careful analysis of the geometry of deposition is therefore crucial. Various dating methods are described in 19.2.

7.7.5 The Evolution of Subterranean Sediments

Karst is not only a trap for detritic material, but also an environment where these sediments can react and undergo diagenesis. Organic-rich clays can see the appearance of neoformation pyrite (FeS_2) and of sodium or potassium nitrates, which can prompt primitive resource extraction, such as in the Daxiao Dong cave (Luodian, Ghuizhou, China) where the sediments are washed and the resulting brackish water is concentrated and evaporated in underground ovens. The resulting nitrate is then used to manufacture gunpowder or fertilizer.

Such mineral resources, tied to a significant accumulation of material and to evolution over a long time period, can therefore be linked to karst. For example, limestones in Provence (France) hold bauxite accumulations, and phosphorites can be found in Quercy (France). A few examples of mineral deposits are described in chap. 17.

8

Evolution of Karst Landscapes and Paleokarsts

Like most natural systems, karst undergoes several stages of evolution. Given the rate of dissolution, this evolution is rarely noticeable on human timescales, unless the rock in question is highly soluble, as is the case for parakarsts in salt or in gypsum.

8.1 Variations in Climate and Paleogeographic Evolution

8.1.1 Variations in Base Level

The geometry and position of drainage channels are determined by the hydrologic base level. When the base level changes, the aquifer adjusts accordingly, and the

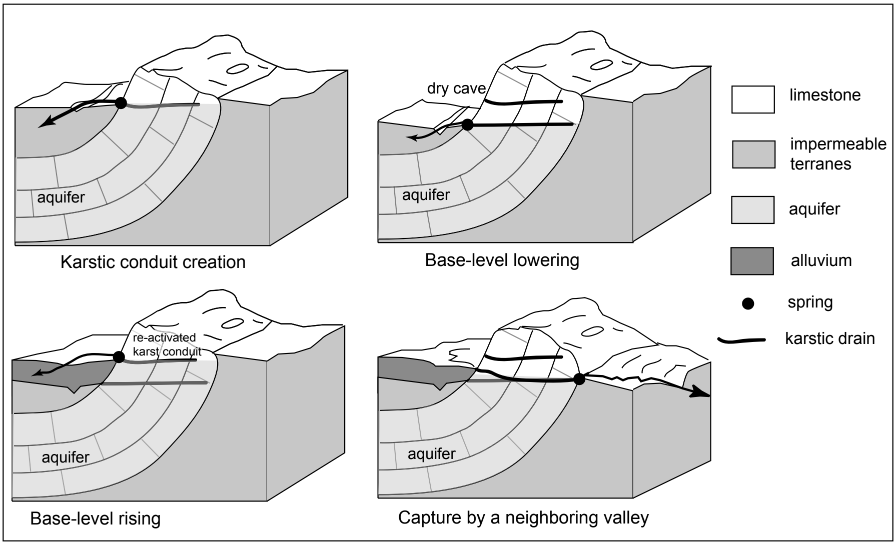


Figure 71. Changes in base level recorded by a karst system.

drainage system follows suit. These variations can be a result of either climatic or tectonic changes.

8.1.2 Glacio-eustatism

Milanković's work has shown that the amount of incoming solar radiation on Earth is a function of cyclical variations in the parameters describing Earth's rotation around the Sun: eccentricity, obliquity, and precession. These variations have a period of approximately 100,000 years. During the past four cycles, a strong correlation is apparent between the amount of incoming solar radiation and the extent of continental ice sheets. It is therefore an easy matter to infer that karst systems would have been regularly affected by alternating periods of excavation and infilling. In limestone units exposed for several million years, many oscillations have left their mark, and several successive karst features are superimposed making most of karst systems polyphase ones (cf. 8.2).

8.1.3 The Messinian salinity Crisis and its Effects on Karstogenesis in Southeastern France

During the Messinian, from 5.9 to 5.3 Ma a major event altered the recent sedimentary sequence in the Mediterranean zone: the Messinian Salinity Crisis (Hsü et al., 1977; Cita and Ryan, 1978). This crisis was a result of several successive drops in sea level, eventually decreasing to 2000 m below the present sea level. The Mediterranean maintained exchanges with the Atlantic through straights crossing through what is now southern Spain (the Baetian Mountains) and Morocco (the Rif Mountains) (Rouchy, 1999). Inflow from the surrounding rivers was not enough to counteract the high evaporation rates in the Mediterranean basin. The series of drops in sea level upset the depositional environment, resulting in the deposition of thick layers of evaporites in basin bottoms, as well as deep downcutting into the sedimentary layers along the continental shelf.

The major rivers, the Nile, the Pô, the Rhône, saw their beds cut downwards. The karst systems attached to these various hydrologic base levels (the sea, the rivers and streams) also incised downwards (Bini, 1994; Audra et al., 2005).

When the Mediterranean basin filled again at the beginning of the Pliocene (5.3 Ma), during the opening of the straight of Gibraltar, the subsequent deposition up until the present day was strongly influenced by Messinian paleogeography. The sea filled the Messinian valleys, up to 80–100 m of elevation, forming long rias (Mediterranean drowned river valleys) that were gradually filled with sediment, blocking karst water circulation. During the subsequent marine regression, these deposits were eroded down to their current level, resulting in yet more changes in the drainage networks.

Around the Rhône valley, these effects were felt along all the major karstic springs, resulting in the formation of very deep conduits, relict passageways, pits, chimneys, and Vauclusian springs (Mocochain et al., 2006).

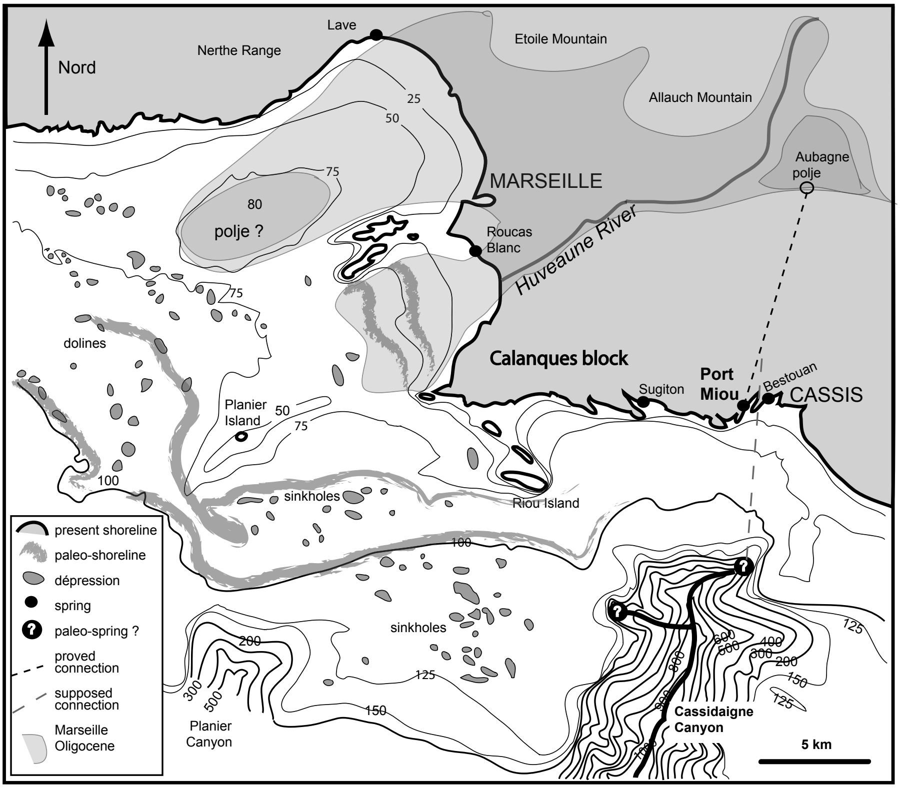


Figure 72. Submerged paleokarst off the coast of Marseilles (after Collina-Girard, 1994). The depth of the basins and the incision of the Cassidaigne canyon indicate a base level lower than that caused by the sea level drop during Plio-Quaternary glaciation.

8.1.3.1 Tectonics

Periods of uplift or of subsidence induce relative variations in base level. These can be regular and continuous, as in southern China, where the evolution of the topography and of speleogenesis are accentuated by the increasing hydraulic gradient caused by the Himalayan uplift.

They can also be sudden, such as changes caused by major earthquakes. During the magnitude 7.5 Limón earthquake in Costa Rica in 1991, the sudden uplift of the coastal region led to the exposure of a submarine carbonate platform, but also tilted the coastal karst systems that were already in place, resulting in the reversal of flow direction in some places, such as in the Gioconda cavern (Limón). This immediately affected sedimentation, and had more long-term effects on erosion as well (Gilli, 1995a).

8.1.3.2 Isostasy

When the mass of a continent changes, due to loading or unloading by glaciers, isostatic adjustments result in changes in base level, and therefore changes in the karst systems.

Post-glacial rebound due to the melting of continental ice sheets affected the karst systems in Patagonia (Chile) (Jaillet et al., 2008) and in Norway (Faulkner, 2005).

High erosion rates could also result in uplift due to isostatic adjustments (Molnard and England, 1990), a phenomenon that may have resulted in several hundreds of meters of uplift in the Pyrénées during the Cenozoic (Babault et al., 2005).

8.2 Polyphase Karst

In areas where a limestone unit has been uncovered for long periods of time, base level variations such as those described above can be seen in the rock record as the traces left by different phases of karstification. The Jurassic limestones of Provence, for example, have been subject to nearly continuous karstification since the Cretaceous (Blanc, 1993).

At the surface, this long history results in the gradual wearing away of limestone surfaces, such that it is not uncommon to find karstic cavities that have been exposed as slopes cut backwards and soil erodes away. Figure 73 shows a large stalagmite, a vestige from an older cave that was unroofed by erosion.

In the endokarst, successive adjustments to changing base levels can both create new conduits and fossilize older ones. The largest cave networks are often made up of numerous levels, remnants of different stages of karstification (Figure 54).

The systems in place today are therefore the result of an often-complex evolution, and the current landforms must be interpreted as the products of different phases of climate variation.

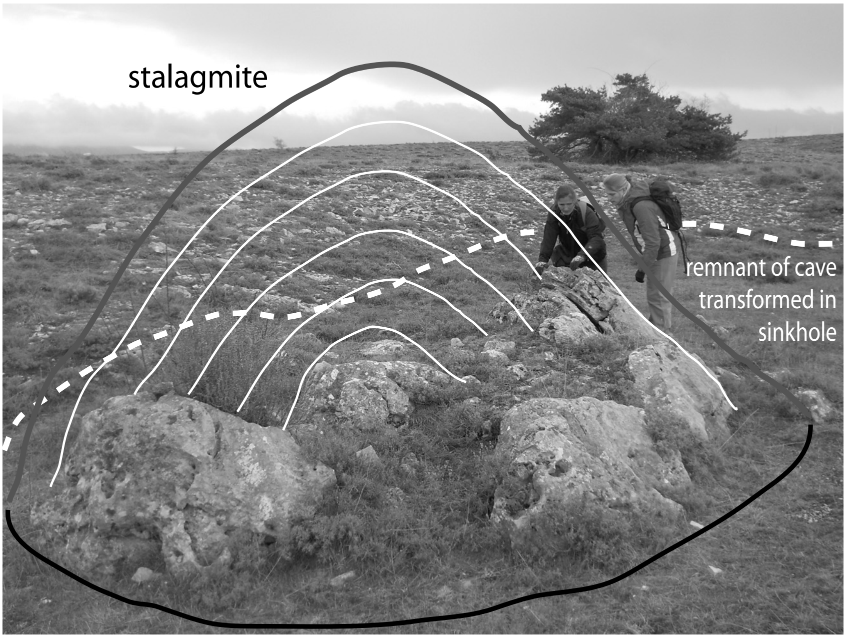


Figure 73. Vestiges of a large stalagmite, indicating the presence of a paleo-cave, on the Calern plateau (Alpes-Maritimes, France).

8.3 Paleokarst

It is safe to assume that, as long as the climate allows for the presence of water in liquid form, any carbonate platform exposed for a length of time, for example as a result of a marine regression, would have been subject to karstification. The evolution of the karst system can be completely halted by subsequent sedimentation during, for example, a marine transgression, resulting in preserved karst topography, or paleokarst with fossil caves. The deposits found in these systems can shed light on the paleoenvironment (cf. chap. 19). For example in the carbonate units in the sedimentary ring around the Maures-Tanneron massif (Alpes-Maritimes, France), paleokarst is common, because those sediments underwent frequent phases of exposure. In the town of Valbonne the Bajocian limestones were exposed during the Bathonian, when a karst network formed. The karstic cavities then filled with Bathonian clays, and were sealed off by another period of limestone deposition, during the subsequent marine transgression. This Bathonian paleokarst is responsible for the Vallauris pottery industry that flourished during the 19th century, thanks to the fire-resistant properties of kitchen utensils made from the clays found there. An examination of the road cuts in the same area reveals cross-sections of fossil shafts filled with Eocene red sand, or Oligocene marl or andesite (Figure 74). Karstification in this area has been almost continuous from the Cretaceous to the present day, making it difficult to determine the precise age of the caves that hold these deposits. They may be either primary deposits in pre-Eocene

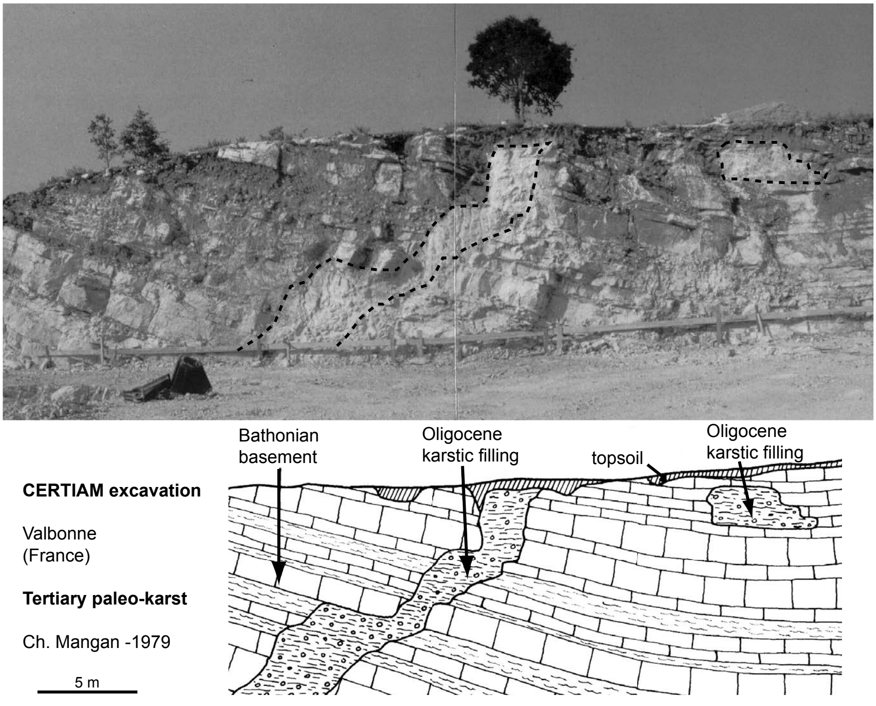


Figure 74. Tertiary paleokarst in Valbonne (Alpes-Maritimes) (doc. Ch. Mangan).

caves (in the case of sandy fill) and pre-Oligocene caves (in the case of andesite fill), or secondary deposits in more recent caves or dolines, which could have trapped reworked primary deposits.

Sediments below ground can undergo diagenesis and transform into economically important ores, such as the bauxites of Provence, trapped in Cretaceous paleokarst, or the iron ores of Kisanga (Zaire), found in an Upper Proterozoic karst (cf. chap. 17).

9

Parakarsts and Pseudokarsts

9.1 Parakarsts

Parakarsts are landforms that develop as a result of dissolution in non-carbonate rocks, and that can have karst-like features such as lapies, dolines, underground rivers, and caves. This often occurs in gypsum or in salt. The word karst is also commonly used for gypsum in particular. Gypsum karsts are highly problematic for development, as they evolve rapidly and the effects of dissolution can be felt after only a few years.

9.1.1 Evaporites

Evaporites are rocks deposited as a result of precipitation in confined bodies of water such as lagoons, isolated seas, and endorheic continental basins. Major evaporite minerals included anhydrite ($CaSO_4$), gypsum ($CaSO_4.2H_2O$) and salt (NaCl).

These minerals have high solubility, and karst features can develop very quickly.

Salt karsts exist only in arid regions; elsewhere the salt deposits they might have formed in are too quickly washed away by precipitation. Examples have been found in Iran, in Israel, and in the Atacama Desert in Chile (De Waele et al., 2009) as well as at the Rock of Djelfa in Algeria (Salomon, 2000).

Gypsum karst is common. It evolves differently than karst in carbonate, because of gypsum's different mechanical characteristics. Gypsum is fairly weak, so large caverns are unusual, and cavities have a tendency to collapse in on themselves.

Gypsum systems can be unary (ponor/resurgence) like at the Gébroulaz cave (Savoie, France) or the Suès cave (Sospel, France), but often karstification occurs when there is an inflow of unsaturated water, coupled with an outflow of water saturated in dissolved gypsum, through lateral or underlying karstic conduits in limestone units adjacent to the gypsum.

There are enormous subterranean networks in Ukraine (Klimchouk, 2000), where gypsum units are protected from surface erosion by an impermeable cover. Limestone units bracket the gypsum, providing support and stability for caverns like the Optimistic cave, and serving as passageways for the inflow of unsaturated water and the outflow of dissolved gypsum (Figure 75).

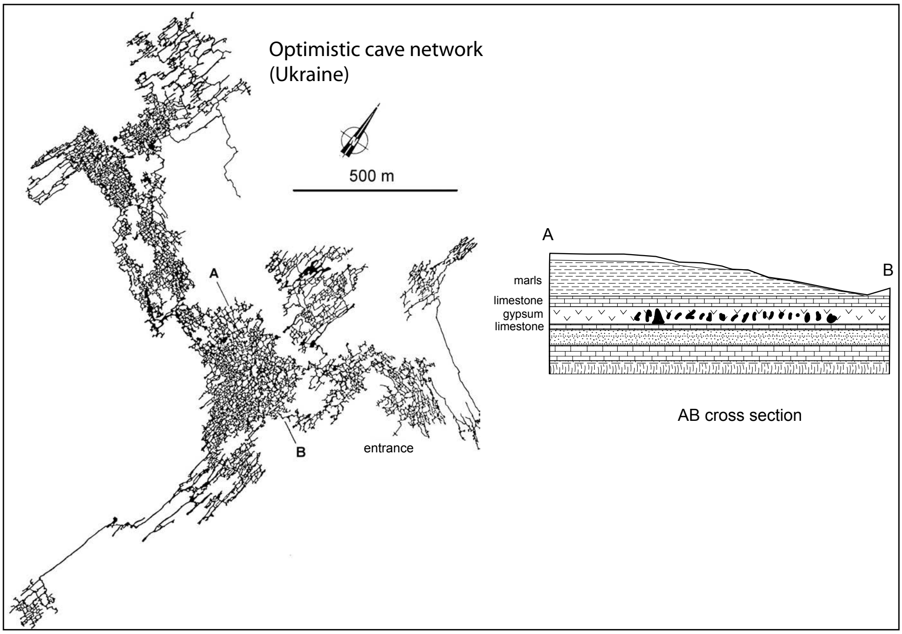


Figure 75. Optimistic network (Ukraine) (after Courbon and Chabert, 1986). This cave network, entirely carved out of gypsum, reaches over more than 100 km.

In France, gypsum layers are common in the Ludian (Uppermost Eocene, Parisian Basin) and in the Keuper (southern France). Deep karstification in these layers often creates significant problems due to soil movement and particularly sinkholes, which can be disastrous when they reach the surface. Occasionally, caves are discovered fortuitously during mining operations, such as those in Denis-Parisis (Béthemont-La-Forêt, France) where an underground gypsum mine perforated a 3-km-long cave network.

Given gypsum's rapid dissolution rate, ten times faster than limestone, gypsum karsts can be entirely anthropogenic. Leakage from water pipes, pumping, septic tanks, and poorly designed gutters can all be responsible for the formation of large cavities underneath built-up areas, and therefore require significant work to shore up foundations, or even force residents to abandon the area.

9.1.2 Quartzite and Arenite Sandstone

Siliceous rock units, while considered generally insoluble, occasionally show well-developed karstic formations. These have been found in basement quartzites in Africa (Martini and Marshall, 2002), and in Brazil (Willems et al., 2004). The largest examples are found in Venezuela in Precambrian quartzite (1600 Ma) from the Roraima formation (Poullyaud and Seurin, 1985), where gigantic collapsed dolines were discovered in Sarisariñama and in Aonda. Their exploration revealed an access point to a network of passageways comparable to those found in limestone.

Karstification mechanisms in these rocks are poorly understood, and hydrothermal processes have been suggested. However, these formations are some of the oldest on earth, and the low solubility of silica (5 to 10 mg.L^{-1}) may be compensated simply by the amount of time the rock has been wearing away.

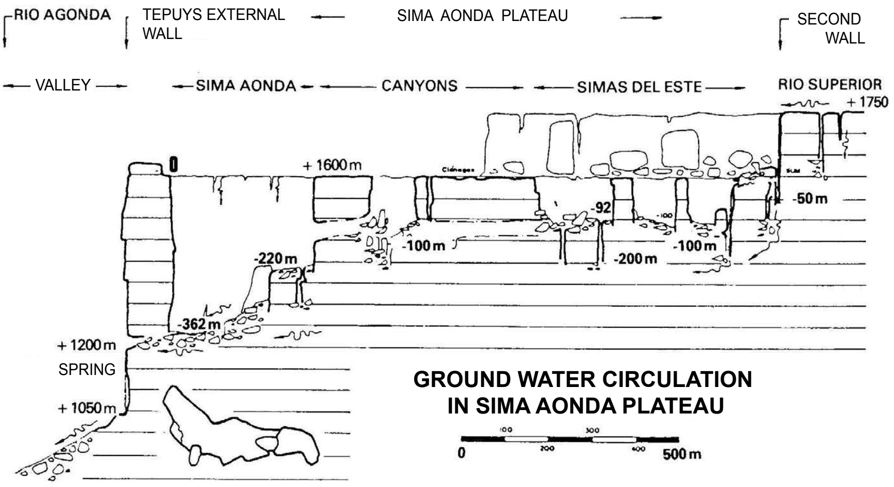


Figure 76. Caves in the Sima Aonda quartzite (Venezuela) (Courbon and Chabert, 1986).

9.2 Pseudokarst

They are landforms similar to those found in karst regions, but created by mechanisms other than dissolution.

9.2.1 Suffosion Dolines

Non-carbonate outcrops such as the loess plateaus of northwestern China are often dotted with numerous dolines. These are not a result of karstification, but of suffosion, a mechanism where interstitial water circulates through pore spaces between larger grains, carrying finer particles. The removal of these particles creates voids, which collapse in on themselves and cause settling and compaction. This process propagates upward to the surface, where it creates closed depressions. Examples have been found in many places, including the Campania, Apulia, and Calabria plains in southern Italy, regions where seismic activity can cause soil liquefaction, which speeds doline formation (Del Prete et al., 2010).

9.2.2 Thermokarst

Thermokarst refers to areas where dolines form due to the effects of snowmelt and of water circulation in the periglacial zone. Water can come from melting ice caps, or from liquid water flowing beneath frozen soil or permafrost. Interstitial water circulates and carries away fine-grained sediment, leaving behind underground cavities help up by the frozen soil above. When the roof melts, the cavities collapse, creating suffosion dolines.

The classic components of a karst system are still present:

- an environment with high mechanical strength,
- an energy vector, although in this case the energy is thermal, not chemical,
- a hydraulic gradient enabling the transport of material: either unsaturated water or water carrying fine sediment.

9.2.3 Water Flow in Ice

Where the climate allows it, ice on the surface of glaciers can melt as a result of incoming solar radiation, creating rivers and streams along the surface of the ice: a supraglacial stream. Tectonic openings such as crevasses or zones where the glacier is not attached to the underlying bedrock allow liquid water to flow through the interior of the glacier, carrying heat and melting the ice inside, thereby widening cavities within the ice. Ponors can form, like the Moulins in the Mer-de-Glace (Chamonix, France) where water has carved vertical shafts in the glacier that are accessible to speleologists. Similarly, rivers are common below the ice, between the glacier and the bedrock, where they often feed powerful rivers. At the Argentière glacier (Chamonix, France), these rivers have been diverted into passageways carved in the rock, where they generate electricity.

When fractures in the ice are interconnected and make it possible to link areas with contrasting elevations and amounts of solar radiation, air currents can have the same effect. Finally, in volcanic areas, geothermally heated water and fumaroles can excavate large cave networks, such as those in Kverkfjöll in Iceland.

Water flows in glaciers can also transport sediment. The cavities they flow through are then partially filled with sediment deposited by the stream, which, when the ice melts, leave long winding berms, called eskers, forming a raised imprint of the sub-glacial stream network.

9.2.4 Lava Caves

When lava is still fluid, it can, as it cools, form a solid crust underneath which the hot lava continues to flow. As the outflow slows then stops, the crust remains, forming caves called lava tubes. These can extend for several kilometers, and are often marked at the surface by sinkholes or collapse dolines.

9.2.5 Martian Pseudokarst

The various Mars exploration missions have revealed and/or confirmed the presence of two types of pseudokarst on the planet: lava tubes and sub-glacial streams.

Sinkholes aligned following certain lava flows are thought to be lava tube cave-ins (Battistini, 1985).

Figure 77. Buri lava tube (Iceland) (photo M. Detay). Molten lava flowed out beneath a hardened roof that it partially remelted. Note the lateral flow marks and the ropy lava floor of the cave.

Paleo-eskers observed along the periphery of the ice caps, talwegs, valleys, and lakes, show that liquid water must have existed, or still exists, on Mars, either beneath the permafrost or under the polar ice caps.

With the possibility of manned missions to Mars in mind, these underground features are of importance as potential sources of shelter and water.

10

Speleology and Study of the Endokarst

Speleology (also known as spelunking or caving) is the exploration or the study of caves. Although generally considered a sport, it is also a science, like any type of exploration. It is the only way of directly observing and studying part of the endokarst, with the result that advances in scientific understanding are directly dependent on improvements in caving techniques and equipment.

10.1 Precursors to and Origins of Speleology

The exploration of caves is undoubtedly as old as the invention of fire, and therefore of artificial light. Many caves still conserve evidence of the sometimes far-reaching explorations of our ancestors. Visits to the subterranean world were prompted by the need for shelter, for water, for game or natural resources, by religious ceremony, or perhaps even by simple curiosity. What differentiates speleology from simple underground excursions is the end goal of exploration, with specialized transportable and reusable equipment. The French caver E.A. Martel is considered the inventor of speleology by this definition, with his exploration of the Bramabiau cave in the Camprieu causse at the end of the 19th century. By following Bonheur Creek, he was able to pass through the mountain, from the point where the creek disappeared all the way to its re-emergence.

It has been estimated that since Martel, approximately 60,000 caves and 15,000 km of passageways have been explored and mapped in France.

10.2 The Speleology Community

The world of caving, although it is made up of members with various different backgrounds and interests, is nevertheless a very well organized microcosm. Exploration is a team effort, and it brings together people who have more in common than simply their interest in being underground. Programmers, topographers, scientists, engineers, and genius tinkerers, now connected via the Internet, have slowly built a community that takes the initiative to self-regulates almost all of its activities, from organizing underground rescue operations to managing databases. If a problem related to speleology arises, for example the discovery of a cave during a construction project, the caving community is quick to respond. There is a multitude of speleology clubs and organizations, some as many as 60 years old (Spéléo Club de Paris), with large libraries of area-specific documentation.

The FFS (French Federation of Speleology), founded in 1963, unites almost 8000 members and over 500 organizations. It edits a magazine, Spelunca, which publishes thematically related and region-specific articles, and contributes to the academic journal Karstologia. Website: www.ffspeleo.fr.

In the US the National Speleogical Society (NSS) with 10,000 members is the largest organization in the world working to further the exploration, study, and protection of caves. Website: caves.org.

On an international level, the UIS (Union Internationale de Spéléologie, or International Union of Speleology) was founded in 1965 and counts 59 member countries. Website: uis-speleo.org.

10.3 Methods in Speleology

10.3.1 Subterranean Travel and Speleometry

Methods and techniques for underground exploration are taught in a few specialized books, but are primarily learned through speleological organizations. It should be noted that since the advent of single-rope techniques, vertical drops are no longer an obstacle to human exploration (Figure 78).

Several barriers to exploration still remain:

- Narrow passageways. The concept of a cave is an anthropocentric one, based on the dimensions of the human body.
- The length of time spent below ground. Some cave networks extend over 100 km in length, and their exploration requires setting up camps to rest, and therefore transporting sustenance and light.
- High discharge rates in some subterranean rivers.
- Drowned passageways. These can only be explored using diving techniques.
- Disease (histoplasmosis).
- Heat and noxious gases in some hydrothermal or volcanic areas.

10.3.2 Cave Diving

Since caves drain karst aquifers, it is common for diving to be necessary in order to explore submerged cavities. In France, the first such explorations took place in the Fontaine de Vaucluse, with heavy-footers diving suit and helmet, by Ottonelli in 1878, but the breathing tube required for the suit prevented any significant exploration of the passageways. It was not until the invention of the autonomous “Le Prieur” then

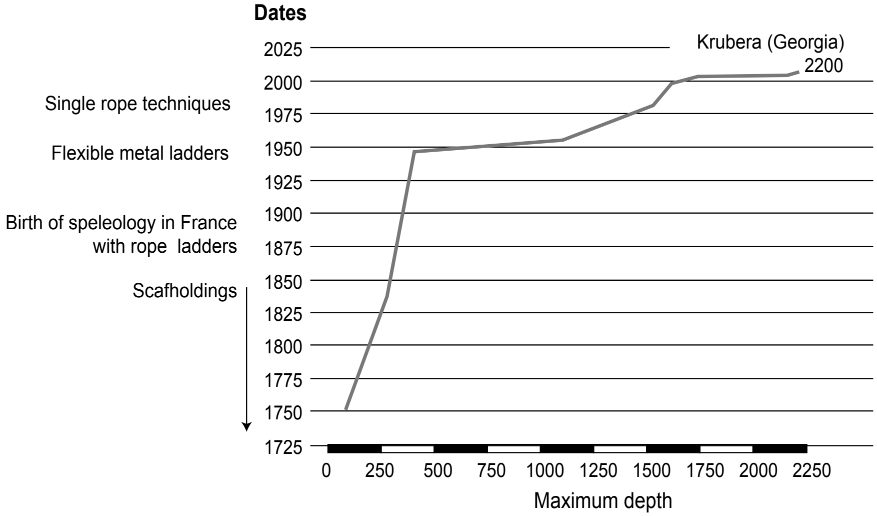


Figure 78. Evolution of underground exploration since 1750.

"Cousteau-Gagnan" diving equipment with regulator and compressed air tanks that significant exploration was possible. It should be noted that J.Y. Cousteau tackled the Fontaine de Vaucluse in 1946, reaching a depth of 46 m, only a part of the cave's total known depth of 308 m (Figure 30).

The distances and depths accessible to humans are highly dependent on technological advances. The greatest discoveries were a result of using gas mixtures, with helium in the 80s and with hydrogen by the pioneer J. Hasenmayer, an innovation that allowed him to descend alone to a depth of 200 m in the Fontaine de Vaucluse. Today, the use of rebreathers is becoming more widespread, allowing divers to explore distances of over a kilometer: 5900 m at the Doux de Coly (Dordogne), and 3000 m in the Bestouan (Calanques de Cassis), as well as depths of over 100 m, the French record being 240 m at the Goule de la Tannerie (Ardèche).

However, human exploration has its limits, and continued efforts can quickly become out of the question. For example, at Port Miou, the current record is a dive of more than 2 km from the entrance; at a depth of 223 m. Continued exploration is possible only with the help of submarine robots. Beyond certain depths, ROVs (Remote Operated Vehicles) take over from humans, and have been able to travel down into the Fontaine de Vaucluse to a depth of 308 m, and into the Pozzo del Mero to a depth of 320 m. However, although a ROV can easily work completely submerged when equipped with a tether cable of neutral buoyancy, horizontal displacement over any significant distance is impossible. Current ROVs can therefore only explore near-vertical shafts. For horizontal passages, the only known exploration technology is the specially designed ROV used during the exploration of the Titanic (Cameron Ltd.), which was piloted via a fiber-optic cable that unspooled as the robot made its way through the wreckage, and which was abandoned on-site once the project was over. It was built out of material that would gradually dissolve over time, so that after a few months no trace of the cable remained.

10.3.3 Underground Topography of Karst Systems

10.3.3.1 Objectives and methods

Topographic surveying is inextricably tied to the work of exploration, and accurate mapping of cave systems is at the foundation of any fundamental or applied research in the endokarst. The classic tools of the topographer (theodolites, total stations, etc.) can be used for the more accessible caves, but in most cases specializes equipment that is light and sturdy must be used. This generally includes a compass, a clinometer, and a laser distance-meter. The most up-to-date tools are entirely electronic, and can record and store data.

Data analysis is done with the help of specialized softwares, which have been developed, tested, and improved by the speleology community (Compass, Visual topo, Toporobot, Cyber topo, GNU Hades topo....). These softwares can create 3D models of caves and their surroundings (surface topography, other caves, fault planes, etc.).

Angle measurement errors can be significant, and can result from imprecise instruments, possible magnetic disturbances, or reading errors. The quality of the measurements can be tested when a passageway being surveyed cuts across a previously mapped location. The XYZ offset observed between different measurements for the same location gives the measurement precision, which is sometimes less than 2%. Softwares can automatically compensate for this type of error. When it is not possible to intersect with a pre-existing survey marker, surveyors can do a round trip, taking measurements in both directions (Courbon, 2002). For better precision, classic methods with a theodolite should be used.

10.3.3.2 Precision of existing surveys

It can be risky to use an existing cave map for professional purposes if the map's precision is not known. The degree of precision is a function of the mapmaker's goal: a simple exploratory sketch, a highly detailed description of the cave walls for an archaeological dig, a morphological analysis of speleothems, and so on. It is also a function of the original surveyor's attention to detail and of the equipment they used. Estimates made using different surveyors' maps of the same area (Aucant et al., 1971) that varied by as much as 100%! The use of laser telemetry starting in the 90s slightly increased the accuracy of topographic maps.

The BCRA (British Cave Research Association) put forward a precision scale, which is now included on some maps, and which estimates their precision. The numeric part of the scale indicates the precision of the location and route of the passageways, while the letter indicates the precision of the height and width measurements used to draw the map. Speleological surveys usually have a BCRA rating of 4C.

Table 7. Precision scale for subterranean topographic surveys (after the British Cave Research Association).

Degree	Tools	Measurement precision
1	None	Variable
2	Graduated rope, compass	Length to ± 1 m; angles to ± 5°
3	Decameter, compass, clinometer	Length to ± 0,5 m; angles to ± 3°
4	Compass, navigational compass, decameter, clinometer	Length to ± 0,1 m; angles to ± 2°
5	Compass on tripod, Laser range meter, total station	Length < 10 cm; angles to ± 1°
6	Compass on tripod, Laser range meter, total station	More accurate position of stations than grade 5
X	Theodolite, total station	Length to ± 5 mm; angles to ± 10^{-2}°

Precision of the cave dimensions

- Class A: drawn from memory.
- Class B: widths and heights estimated on-site.
- Class C: widths and heights measured at each station.
- Class D: details measured and notes on-site at each station and between stations.

The La Verna tunnel

During the exploration of the Pierre St. Martin shaft, speleologists following the river underground found an enormous chamber, almost 200 m in diameter, which the river flowed into over a waterfall. Since this occurred near a steep-sided valley, EDF (Electricity of France) proposed a project to generate hydropower by diverting the water. Based on the survey maps created by speleologists (BCRA rating 3B), a tunnel was dug along the side of the valley near Saint Engrace, to reach the chamber. When the tunnel did not hit the chamber where it was expected to be, a team of geometers undertook a second survey (BCRA rating 6C). They found the chamber 400 m away from where it was thought to be. Once the error had been corrected and the chamber finally reached, a second surprise awaited the engineers: the river's discharge had been significantly overestimated, and the project had to be abandoned. Fortunately, the construction was not a complete loss, as it led to the discovery of the Arphidia cave network (cf. chap. 7.6).

Currently, thanks to the increased development of renewable energy projects, the diversion has been realized a few years ago.

10.3.4 Automated Cartography

Combining the use of video equipment and lasers enables precise cartography and 3D rendering of caves. In France the Cosquer cave, the La Verna chamber, and the Chauvet cave have all been very precisely mapped thanks to these techniques.

LIDAR can automatically acquire thousands of spatial data points with a laser beam, and is also used to create DTMs (Digital Terrain Models) of the passageways and their fill level. This allows, for example, the study of paleo-flow levels that may be responsible for nicks on the cavern walls. This type of work is currently underway at the Chauvet cave (Ardèche) in order to study the relationship between prehistoric humans and their environment.

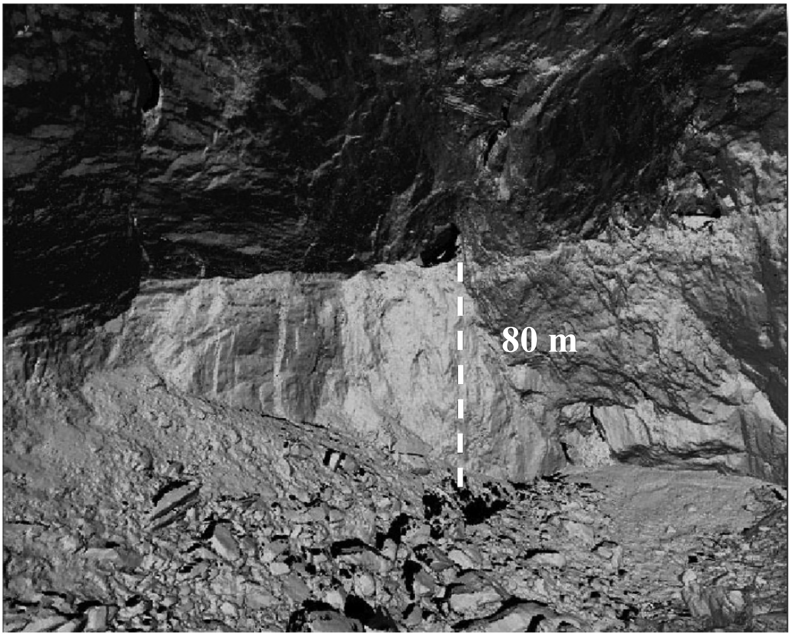


Figure 79. Automated LIDAR cartography in the La Verna chamber (document ATM3D).

Speleothems in the Orgnac sinkhole

In order to analyze the external morphology of the stalagmite forest in Room 1 of the Orgnac sinkhole (Ardèche, France), a high-resolution (average grid spacing of 19 mm) survey was undertaken using terrestrial LIDAR.

This data was used to create a model of the speleothems, by defining series of overlapping ellipses. An analysis of 134 stalagmites, taking into account the geometric floor measurements, identified breaks in the stalagmites' growth linked to activity in a karstic drain.

This type of 3D analysis using a dense numeric model allows for the study of fragile or difficult-to-access objects.

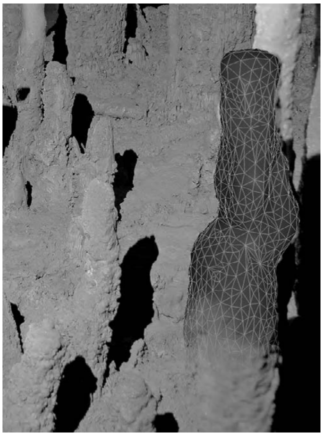


Figure 80. Digital envelope around a stalagmite in Orgnac (Ardèche) (Hajri et al., 2009).

10.3.5 Locating Caves

When a cave is already known to exist, it can be useful to precisely position a section of the cave, to install a water well for example. The precision of speleologists' topographic surveys depends on a number of factors: the nature of the material, the availability of reference markers, and the surveyor's attention to detail. Generally surveys have a 1% precision. For instance, in the case of a 300 m deep shaft, with passages extending over 2 km, and in which someone wishes to drill a well to reach a gallery that is 3 m in diameter, the survey precision would be ±3 m of elevation and ±20 m of map extent, which would not be enough.

Two courses of action are then possible:

- Increasing the precision of the topographic survey using better cartographic methods,
- Guiding the drill by using a magnetic or electromagnetic beacon.

10.3.6 Radiolocation

Radiolocation involves finding the depth and position of an emitter located underground, using a radio receiver array at the surface. The beacon can be hung from a cavern ceiling, attached to a tripod, or left on a buoy in a body of water in the area to be located.

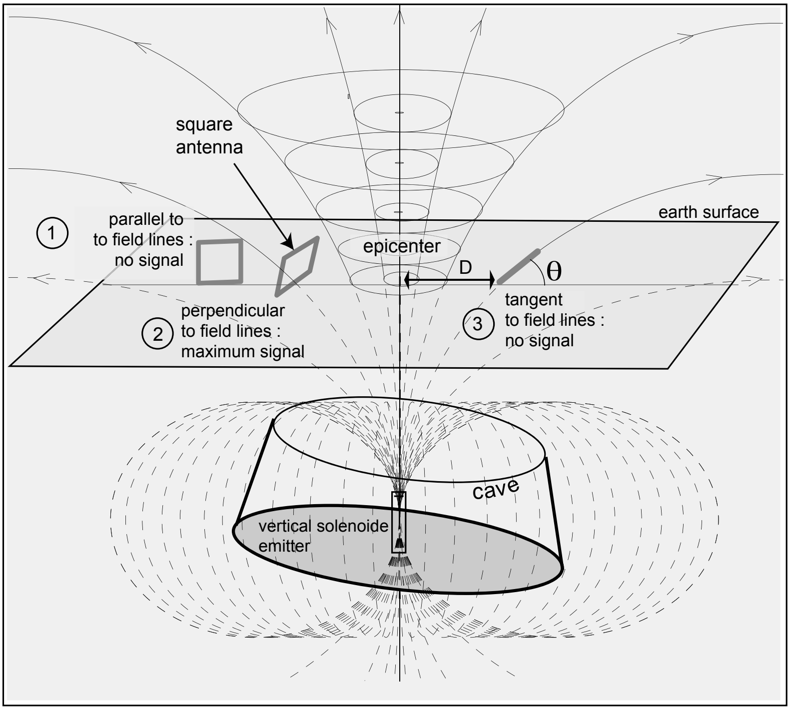


Figure 81. Principles or radiolocation by Hertzian beam.

The receiver array is then transported at the surface above the cave, and reports the strongest signal when it is perpendicular to the field lines. The signal cancels itself out when the receivers are parallel to the field lines. The different cancellation directions observed are drawn along the ground, and the emitter can be located at the intersection of these lines.

In order to find the depth, the receptors are placed perpendicular to the field, at a distance D from the epicenter, and is tilted at an angle θ until the signal cancels out. The receiver is then tangent to the field lines. The depth can be found using the following formula.

$$P = D \cdot \frac{3\tan\theta\,\sqrt{9\tan^2\theta + 8}}{4}$$

This method has been used to find underground rivers in order to pump water from them through wells (Table 8).

Table 8. Examples of wells drilled based on radiolocation.

Location	Depth in m	Purpose
Vitarelles network, Lot, France	120	Water supply
Qattine Azar, Lebanon (Courbon, 2002)	280	Water supply
Trou qui Souffle, Vercors, France	300	Water supply
Ressel Spring, Lot, France	95	Water supply
Labeil cave	26	Cabling

10.3.7 Magnetometry

Magnetometry involves placing a carefully oriented magnet in the cave whose location is to be determined. This method is useful in submerged passageways that are accessible to divers. It was used to drill water wells in the Lez spring (cf. chap. 13) and the access well to the “Cloche 500” in the underground river at Port Miou (Marseille, France), at the respective depths of 880 m and 46 m below the surface (cf. chap. 14). This technique was also used in 1987 to choose a location for the 250 m long well drilled into the Trou du Garde in Féclaz (Dévoluy, France), using nuclear magnetic resonance magnetometers developed by CEA-Leti (a French research and technology organization).

Because locating the magnet in the cave is a complex operation requiring costly technology, radiolocation is often preferable. This is particularly true now that waterproof beacons exist that can be used in submerged caves (Figure 82).

10.4 The Impacts of Speleology on Water Quality in Wells in Karst Aquifers

Although speleologists are the primary source of direct observations of underground water sources, they are also considered by some professional hydrologists as potentially harmful to water quality. Caving is therefore prohibited in certain caves used as sources of drinking water in France (Brudour Cave, Embut de Caussols, Trou du Garde), a

Figure 82. Waterproof beacon (photo M. Douchet, Valade-minage).

decision that prompted a study on what the real effects speleologists have on water quality (Hobléa and Picollier, 2007). The study was done on caves in the mountains around Vercors (Brudour cave) and Bauges (Trou du Garde at Féclaz), and showed that visits by groups of cavers significantly increased turbidity only in one case, and that they had no significant effect on the water's bacterial content. Based on this study, and in response to pressure from speleologists, who discovered the water resource in the first place and had a hand in tapping it, the regulations at the Trou du Garde were revised to allow access to all but a few critical passageways near the pumping station.

11

Karst Aquifers

11.1 Particular Characteristics

Karst aquifers are a particular type of fractured aquifers. Unlike other fractured aquifers, in karst the water circulating through the network of discontinuities dissolves the surrounding rock, creating a very anisotropic aquifer. Dissolution favors further circulation of water, creating a hierarchically structured system, from the catchment basin down to the point of outflow. A karst system is therefore similar to a surface hydrographic system, where small streams high in the watershed converge downstream, flowing together into progressively larger, but less numerous, waterways. Karst evolves rapidly as a function of climate, which determines when the system will downcut and when it will fill in, resulting in a geometry that varies over time, and therefore in complex functioning (Mangin, 2008). The study and modeling of karst aquifers is therefore complex, because unlike porous aquifers, they cannot be assigned a representative volume element (RVE), and their geometry and functioning can be understood only through the study of karstogenesis in the area.

A karst hydrosystem has 4 permeable aspects:

- A generally non-porous matrix, excepting certain carbonate rocks such as chalk or dolomite,
- Microfissures units that have a high porosity but a low permeability,
- Active drainages, which have less holding capacity, but through which water can flow rapidly (velocities of ten to a hundred meters per hour), which are more or less connected to the previously mentioned structures,
- Paleo-drainages and paleo-cavities from previous stages of karstification (which may have occurred a very long time ago), which may be more or less filled in, and more or less closely connected to the current drainages.

11.2 Geometry of the Aquifer and Surrounding System

The different zones of a karst system, outlined above, are of course the result of water, and therefore have hydrogeologic significance.

- The epikarst is a highly permeable, relatively homogeneous environment, able to store a non-negligible portion of inflow from precipitation, which creates an epikarst aquifer near the surface that percolates slowly down to the deeper karst aquifers or returns to the atmosphere through evapotranspiration. In Mediterranean karsts, the epikarst has easily recoverable reserves of 15 to 30 mm.
- The vertical transit zone is a generally unsaturated region, where perennial water flow fed by the epikarst or by losing streams, and temporary flow from precipitation events transits through. If the lithology and structure are favorable it can have perched aquifers within it.
- The phreatic, or saturated, zone makes up the primary karst aquifer and serves as the system's deep reserves. It is a permeable zone, generally with horizontal drainages along its top. It can include annex-to-drain systems, areas with a high water storage capacity that are nevertheless poorly connected to the drainage network.
- The epiphreatic zone is the range of depths between the highest and lowest levels that the water table fluctuates between. It plays an important role as the site of gas exchanges between the aquifer and the atmosphere of the unsaturated zone.
- Finally, at the lowest level of the system, there is the zone of emergence, which usually contains a small number of springs.

Multiple karstification can result in the superposition of these different zones, creating a system whose complexity reflects its history. As a result, different karst systems can behave in vastly different and sometimes disconcerting ways.

It should be noted that parts of the above description of a karst system are still subject to debate, particularly with respect to the nature of deep karst aquifers in the saturated zone. Is the water mainly held in the fracture network (Drogue, 1974) or in karstic voids (Mangin, 1994)? Completely dry areas must exist in the saturated zone, as evidenced by the number of wells drilled into the saturated zone that are nevertheless dry. Experiments that involve artificial waterhead augmentation in cave network or pumping from karst conduits have shown that the rock units around the karst conduits are generally impermeable. Coastal and submarine karst aquifers that remain uncontaminated by salt water serve as more examples of how impermeable the surrounding rock and fracture network can be (cf. chap. 14). This supports the idea that the majority of water reserves in karst aquifers are stored in karstic cavities. The available storage volume would then be dependent on the area's paleokarstification. Older areas, where there has been a great deal of karstification phases would be more likely to hold significant groundwater reserves. For example, the aquifers in the Jurassic limestones of Provence (France) may exist today because that area has been undergoing almost continuous karstification since the Cretaceous, and has seen significant variation in base level as a result of isostatic adjustments, tectonic activity, post-glacial rebounds, and the Messinian Salinity Crisis (cf. chap. 8).

The particular characteristics of any given aquifer are, however, a function of the type of discontinuities present, of the various constraints particular to the area, and of the hydrodynamic system (cf. chap. 20). For example, under high pressure conditions water can flow into discontinuities even if they would normally be closed. It is prudent to consider that there is not only one model for karst systems, and that each system will be differently shaped by the history and characteristics of the carbonate units it develops in. These characteristics will determine the shape of the fracture and drainage networks that will eventually hold the water in the saturated zone.

11.3 Behavior of a Karst System

The behavior of a karst system depends on the surrounding rock structure and its geologic history, and on the climate, which determines the amount of precipitation. Soil thickness above the epikarst and the importance of vegetation cover (which affects the amount of water percolating downwards) also have a significant effect.

11.3.1 The Epikarst and the Unsaturated Zone

During rainy periods, water infiltrates into the epikarst and also feeds rapid vertical flow down into the deeper parts of the karst aquifer. If the epikarst is saturated, precipitation will also flush water through the system, increasing the amount of water flowing to deeper areas. When vertical drainage paths can no longer accommodate the inflow, dolines and poljes fill with water, forming temporary lakes and streams as the epikarst overflows. The Lac de Rives (Hérault) and the lakes in the Hospitalet causse (Larzac) are two French examples of such features.

Water continues to move into deeper parts of the system even after the precipitation stops, sustained by percolation in the epikarst and by losing streams at the surface. During dry periods, the epikarst can become completely drained and surface streams run dry, slowing and then bringing to a halt the vertical transit of water. However, perched aquifers in the epikarst, although still poorly understood, appear to play a role in temporarily storing water within the unsaturated zone.

11.3.2 The Saturated Zone and the Drainage Network

During periods of precipitation, a rapid influx of water moving downwards feeds into the deeper karst. The system's behavior depends on whether or not it encompasses a saturated zone with deep reserves. If these reserves are absent, groundwater flows through the system in much the same way, as it would move through a surface drainage network. The discharge increases, then gradually decreases as a function of the amount of water flowing in.

When a deep aquifer does exist, precipitation creates an incoming wave that acts as a piston, flushing water through storage systems and prompting an immediate increase in discharge at the springs draining the system. The movement of water is therefore a result of pressure changes. In either scenario, the increased discharge may exceed the capacity of the drainage network. If this occurs, the water level in the epiphreatic zone rises, and water can flow back up into normally dry galleries, flooding fossilized levels and driving the water towards temporary perched springs. These changes in the height of the water table often exceed a hundred meters.

During the dry season, discharge gradually decreases as the water stored in compartments connected to the drainage network is used up. In some cases, the discharge can decrease to zero, but a lack of discharge does not necessarily mean that there is no water left in the system—some water can be stored at elevations beneath the springs, and so cannot exit the system.

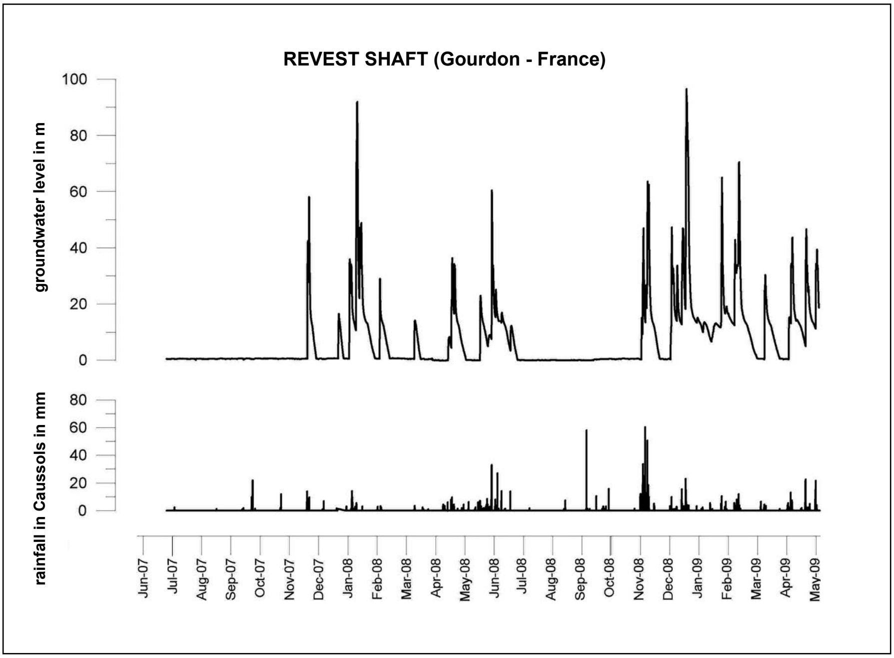


Figure 83. Fluctuations in the water table at the Gouffre du Revest (Gourdon, Alpes-Maritimes).

11.3.3 Springs

Springs are the endpoints for karst systems, and quality and quantity of water they discharge is therefore dependent on the state of the system it issues from. Monitoring stations set up at various springs, combined with individual measurements of three parameters: discharge, temperature, and conductivity, provide good information on how the system as a whole functions.

Periods of precipitation generally result in an abrupt increase in discharge that begins with the water that was already in the system being pushed out in a warm wave with a high dissolved mineral load, followed by decreasing discharge made up of colder rainwater with low amounts of dissolved minerals, and finally a return to the initial state of the spring (Figure 84).

Karst springs can have highly variable discharge, and the lowest and highest discharges in a year often differ by one order of magnitude.

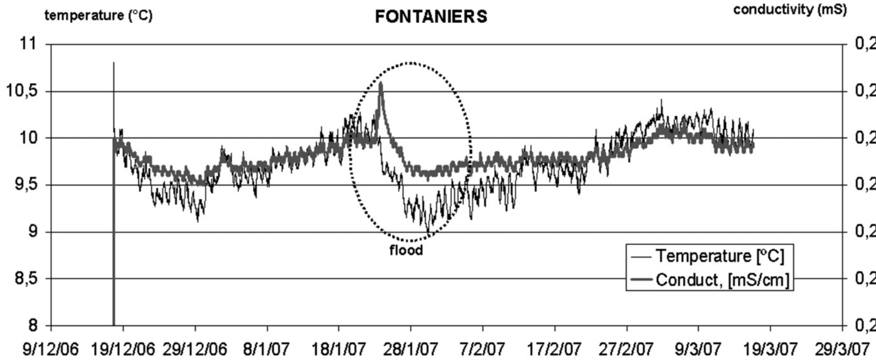
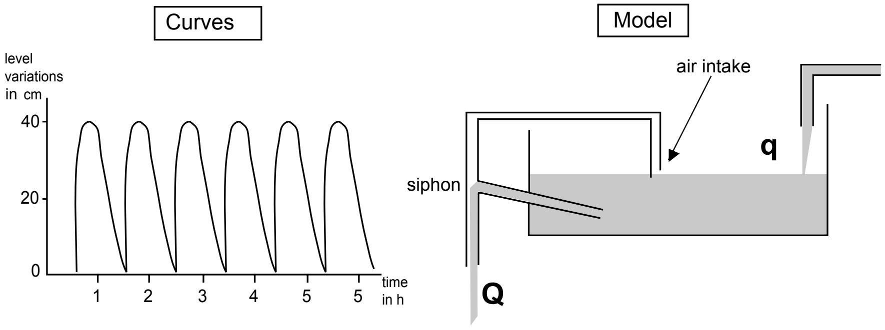


Figure 84. Salinity and temperature variations in a karst spring.

Fontesorbes: An intermittent spring

There are almost a hundred known intermittent springs like the one at Fontestorbes (Belesta, France), with a discharge that fluctuates regularly from a few tens of liters per second to almost 2 m^3.s^{-1} with a periodicity of 61 minutes. The spring is connected to the Caoujous Cave, through which runs an underground river. The cave also contains a sump where strong variations in the water level have been observed. The spring was originally interpreted as the result of a system where a reservoir filled up and then emptied through a siphon. However, later on A. Mangin (1969) attempted to model the spring's behavior and showed that a simple siphon was not enough to explain the fluctuations in discharge, and that an air intake was needed to create a functional model (Figure 85).



with **q** constant filling flow and **Q** variable discharge

When the air intake is active, Q is lower than q and the reservoir fills in.
When the water level reaches the air intake, Q becomes higher than q
and the reservoir empties

Figure 85. Intermittent spring at Fontestorbes (Bélesta, France). The constant discharge is represented by q and the variable discharge by Q. When the air intake is open, Q is less than q and the reservoir fills up until the intake is submerged. Q then becomes greater than q and the reservoir empties.

11.4 Quantitative and Qualitative Consequences

Karst aquifers are notably difficult to use as resources. Their highly variable discharge rates mean that only part of the theoretically available water supply is actually usable.

This is also problematic in designing catchment systems with appropriate capacities and security measures. Catchment structures that are too small are vulnerable to flooding and are unable to take advantage of periods of high discharge. Conversely, catchment structures that are too large become unusable during dry periods.

In addition problems of quantity, there are also problems of water quality, such as high turbidity and bacterial contamination, due to the lack of filtration as the water passes through a karst aquifer. There are two potential reasons for high turbidity: it can be a result of turbidity in the drainage basin, or it can occur when relict galleries are flooded, and the turbulent water flowing through stirs up old sedimentary deposits and becomes loaded with clay particles.

Bacterial contamination comes from the surface (from water flowing directly into ponors, or from wastewater being discharged into the ground), and because of the short residence time (often less than a week) and absence of filtration mechanisms in karst aquifers, the bacterial load is not much reduced by water's passage through the aquifer.

11.5 Circulation in Hydrothermal Systems

The existence of hypogenic caves has revealed aquifers that are drained *per ascensum*. Water in deep reservoirs becomes loaded with minerals and thermal energy, which it can conserve if it rises quickly enough to the surface.

A recent study (Thiébaud, 2008) on workings of the La Léchère (Savoie, France) hydrothermal system showed that water circulates in a low pressure area fed by both surface water circulation and by heated water from the deeper parts of the system. B. Blavoux (1995) demonstrated that thermal waters are primarily fed by infiltrated meteoric water. This is indeed the case at La Léchère, where, at the beginning of its journey, the water in the system reacts with dolomite, cargneule, and gypsum (Ca, SO_4, Mg), before following a different path from the surface water, travelling through the basement rock over the course of several thousand years, during which it picks up Cl, Si, K, as well as organic material and H_2S from Permo-Carboniferous rocks. When this deep water flows back up towards the surface, it mixes with the surface water near the springs where it finally emerges.

The Mescla cave (Malaussène, France) behaves in a similar way, and cave divers have observed deep isolated conduits that supply hot, salty water to the system. The water comes from deep circulations along the sides and bottom of a Jurassic limestone syncline, at the contact with the evaporitic Triassic substrate (Reynaud, 2000).

The movement of water back up towards the surface is in part a result of the hydraulic gradient between the springs where it emerges and the infiltration zone, but is also due to the water heating up and releasing CO_2 or H_2S, both processes that result in decreased density and allow the water to flow up through the upper levels of the karst aquifer, which contain colder and denser water.

12

Aquifer Characterization

12.1 Geometry of Karst Systems

12.1.1 Geologic Structure

One of the first steps in understanding a karst system is defining the aquifer and aquiclude geometry. This type of analysis requires a geologist's approach: surface mapping, exploratory wells, and geophysical surveys.

In areas with complex structure, in the Alps or the Pyrénées, it is not always easy to determine even the approximate relationships between permeable and impermeable units.

Figure 86 shows an example in the Préalps near Grasse (France). The Caussols unit forms a limestone reservoir that is partially drained towards the underlying Malle unit. To the north, the Calern thrust unit shows a similar structure. In such complex environments, speleological exploration and tracer studies provide precious information. For example, at Calern, the Calernaum Shaft follows the contact between the Calern limestone and the Caussols marl for several kilometers. Speleological exploration in the cave found that groundwater was flowing northwards, and tracer tests confirmed that it then turned to the south.

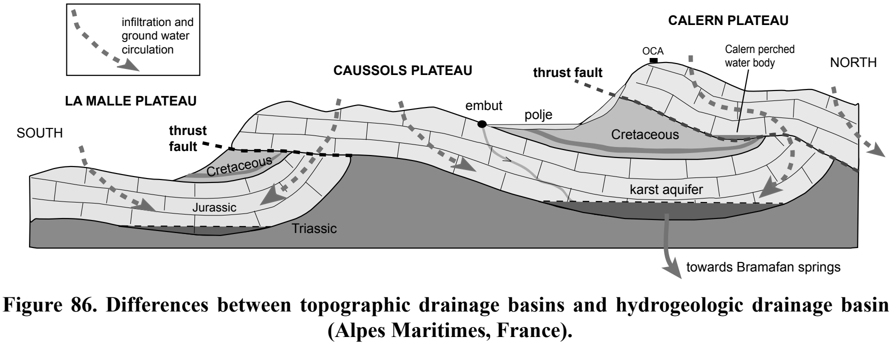


Figure 86. Differences between topographic drainage basins and hydrogeologic drainage basins (Alpes Maritimes, France).

12.1.2 The process of Karstification and of Spatial Organization in the Endokarst

Multiple phases determine the extent and the geometry of karstification. Areas that have been subject to several periods of uplift and exposure suggest the existence of highly karstified, and therefore high-capacity zones. The spatial organization and therefore the workings of an aquifer are a function of the paleogeography of the base level, which determines preferential flow axes.

Information provided by cavers is therefore important. For example, cave diving exploration revealed the extent and the geometry of drainage passageways in the south of France, and thereby led to our current understanding of the Messinian Salinity Crisis' important role in speleogenesis in the area.

12.2 Data Collection

"Better one person who knows than ten who are searching...."

12.2.1 Bibliography and Preliminary Data Gathering

Sources of information are numerous and varied: national databases, universities, drilling organizations, private consulting firms, naturalists' associations, caving clubs, etc. Even so, the study of karst is somewhat similar to a police investigation, where every tiny detail is important. It is therefore often useful to practice "bistrot geology": a day spent at the local bar or cafe where hunters and fishermen congregate often yields precious information, such as the exact locations of seasonal or hidden springs.

12.2.2 Fieldwork

Hydrogeologic analysis requires hydrometric, climatic, physical, and chemical data. To calculate a hydrologic budget for a basin, all the inputs and outputs need to be measured first.

12.2.2.1 Weather data and catchment basins

A main difficulty is to obtain reliable, well-distributed weather data covering the basin in question. The current trend is unfortunately towards fewer and fewer weather monitoring stations, but better technology is making it easier for individuals to set up small stations with very little effort. These cannot, however, provide older data from previous years. Additionally, it is important to avoid confusing topographic basins with geologic basins (Figure 86). Setting up instrumentation on a basin therefore requires an initial understanding of its geologic limits.

12.2.2.2 Hydrometry

Although it may seem a simple matter to measure karst springs, in fact several factors make it a complex operation:

- Highly variable discharge. Peak discharges are often not measured because the sensors in use are not equipped to handle such large volumes.
- Temporary springs, which are sometimes several kilometers away from the main spring, discharge some of the water exiting the system.
- Some springs are hidden (springs that emerge on the sea floor or that are covered by permeable alluvium).
- The aquifer can overflow into other aquifers or receive inflows from other aquifers, all below ground.

The total discharge is therefore often underestimated.

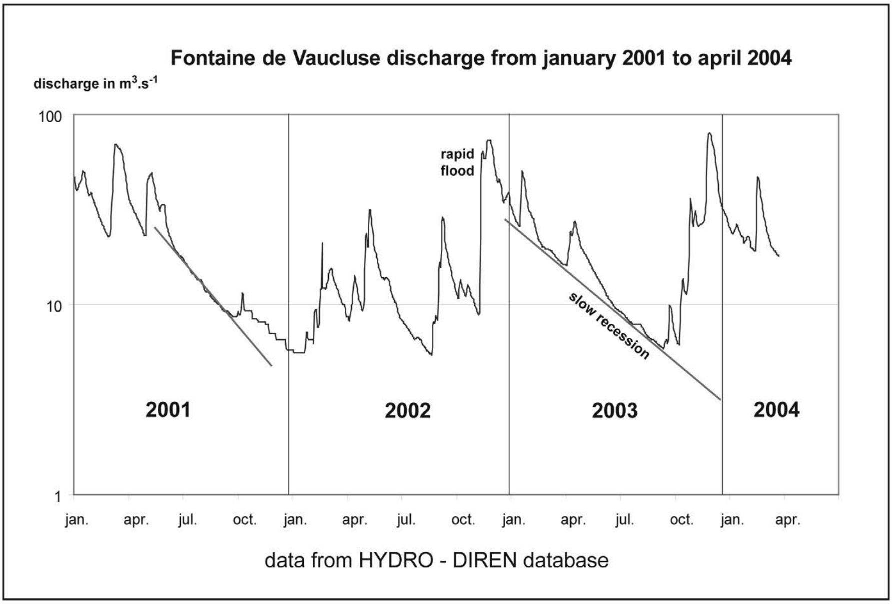


Figure 87. Fontaine de Vaucluse (France) hydrograph in $m^3.s^{-1}$ (2001–2004).

12.2.3 Piezometry

The geometry of an aquifer in a porous medium can be determined by using a network of piezometers. In karst regions, this process is more difficult for several reasons:

- the aquifers are often at great depth,
- there is a high likelihood that any boreholes that need to be drilled will pass through karstic voids or cave-ins, which requires a larger initial diameter and is therefore more expensive,
- there is a risk that a piezometer will be in an impermeable block, or in an area that is not connected to the aquifer.

The sumps seen in some caves can serve as natural piezometers, providing a view of the karst water table, and the water level can be monitored at minimal cost by installing an autonomous piezometric sensor that can store data collected over long periods of time (Figure 83).

12.2.4 Water Quality Analyses

12.2.4.1 Physical, chemical, and microbiological characteristics

Changes in the different physical and chemical characteristics of water reflect the conditions deep within the aquifer. For example, water saturated in $CaCO_3$ suggests a long residence time in the phreatic zone.

Natural tracers (physical, chemical, isotopic, or microbiological) are a powerful tool for understanding groundwater. Indeed, at every point where groundwater can be observed below the surface (piezometers, caves, etc.) or as it emerges (springs, man-made catchment systems, passageways, wells, or boreholes), water carries information about its provenance and the sources of its dissolved minerals, the overall hydrologic budget of its recharge zone, the different inputs from various parts of the hydrologic system, its residence time in the reservoir, and any natural or anthropogenic contamination. This information can be read and understood if the various components present in the water appear in detectable concentrations.

12.2.4.2 Isotopes

Isotopes provide essential information when the existing data is insufficient and traditional methods are inadequate. Table 9 outlines the major applications of the most common tracers: provenance, recharge volume and timing, water-gas interactions (CO_2, H_2S), and water-rock interactions (silicates, carbonates, sulfur, evaporites, etc.), residence time in the phreatic zone or in confined aquifers, pollution sources, etc.

Table 9. Major isotopes used in hydrogeologic surveys.

ISOTOPE	Stable	Radioactive
In water	**^{18}O** Recharge elevation. Seasonal phase shifts. Paleo-recharge.	
	^{2}H + ^{18}O Soil,vadose and phreatic zone evaporation. Carbonate/silicate exchanges. H_2S exchanges.	**^{3}H** dating: < 30 years
	^{13}C Vegetation type. Deep/biogenic CO_2 exchanges. Solid carbonate exchanges. Dating.	**^{14}C** dating: < 25,000 years
In solutes	**^{34}S** Sulfur origins: pyrite oxidation/evaporites	**^{36}Cl** dating: < 250,000 years
	^{15}N Nitrogen origins: fertilizer/livestock/wastewater	
	^{87}Sr Origins of dissolved minerals: basement/evaporites/carbonates	

Determining the catchment basin of an aquifer: the Fontaine de Vaucluse
(Blavoux et al., 1992; Malzieu, 1987)

In order to determine the average elevation of an aquifer's large, diffuse recharge zone (the Vaucluse system), samples are taken from springs with well-understood recharge zones in a similar geologic, geomorphologic, and climatic environment (Figure 88). Samples are taken simultaneously, during the dry season (when the aquifer's reserves are emptying out), from the reference springs and from the spring under study. The reference springs are then used to adjust the ^{18}O-elevation relationship curve (whether by using a linear function or, in the Mediterranean, where there is no linear relationship between effective rainfall and elevation, an exponential curve). Indeed the δ^{18}O changes with temperature (low elevation → hot → not very negative, high elevation → cold → very negative).

The following reference graph (Figure 88) is a guide to estimating the average recharge elevation for Mediterranean aquifers.

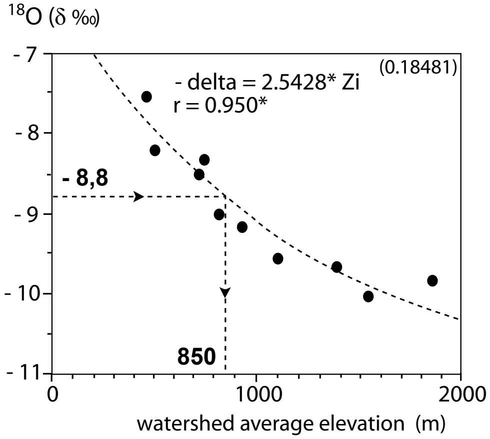


Figure 88. Average recharge elevation of an aquifer.

12.3 Data Analysis

12.3.1 Hydrometric Data

12.3.1.1 Discharge

A karst spring is the final exit point for water that has passed through a complex system of reservoirs and passageways. A simple examination of discharge curves, coupled with precipitation graphs, provides a great deal of insight into karstification. A very short response time indicates either a system with a well-developed drainage network or with a low storage capacity, while a longer, more softened response time indicates either a system with very high storage capacity or with a poorly developed drainage network. The following graph (Figure 89), where even the slightest precipitation event results in a spike in discharge, shows a system with a small storage capacity, as evidenced by the fact that it can be completely drained in two months. Additionally, the slope breaks visible during the dry period indicate that there are two compartments within the reservoir, a hypothesis confirmed by the system's geological and structural context.

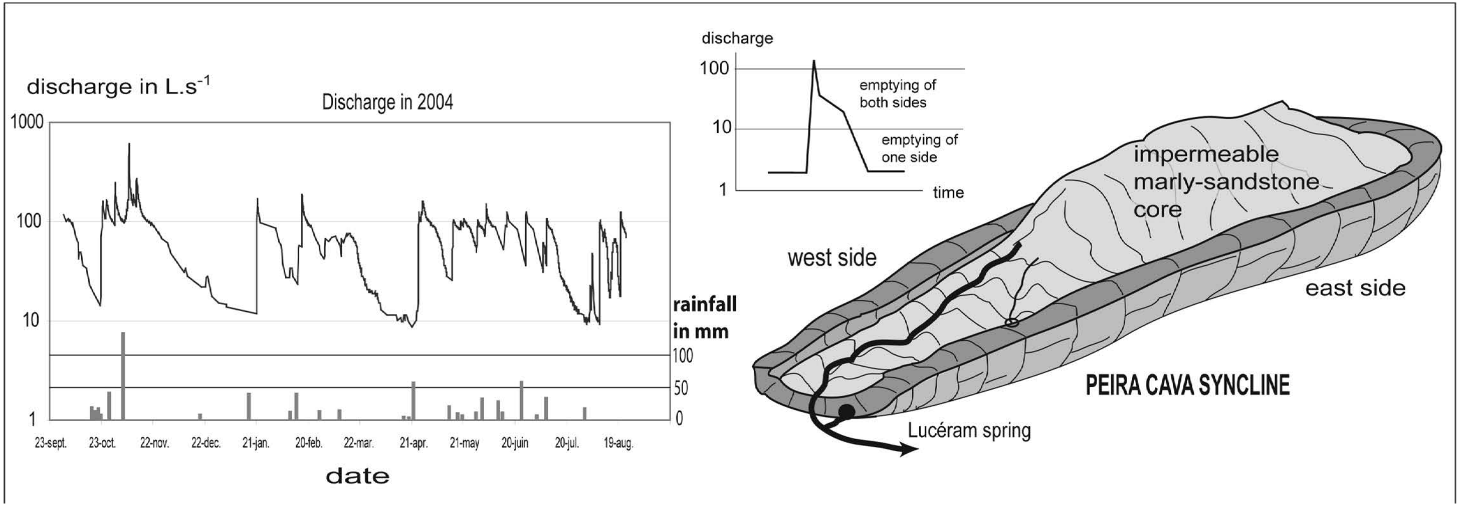


Figure 89. Discharge and structural context of the Foux de Lucéram (Alpes Maritimes). Data from HYDRO, DIREN.

12.3.1.2 Flow-duration curves

A more in-depth analysis of the discharge data can yield even more information about the system.

Specific events like a sudden outflow at depth, an influx of water, a seasonal spring beginning to flow, or a particular compartment emptying itself, can be identified by using flow-duration curves. These events show up as slope breaks or changes on a hydrograph (Mangin, 1975; Marsaud, 1997).

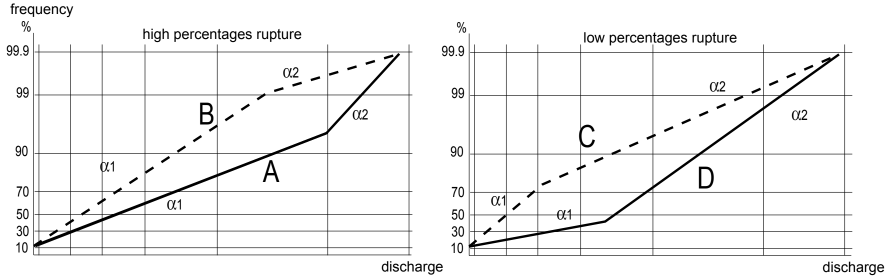


Figure 90. Flow-duration curves.

Table 10. The workings of karst systems, deduced from flow-duration curves (cf. Figure 90).

Example	**Slope**	**Position of the slope break**	**Interpretation**
A	$\alpha 2 > \alpha 1$	High percentages	- Activation of an overflow basin - Outflow to another system - Temporary storage - Leakage or overflow at the gauging station during high-water episodes
B	$\alpha 2 < \alpha 1$		- Inflow from another system - The gauging station is measuring flood discharge that includes water from another system
C	$\alpha 2 < \alpha 1$	Low percentages	- Inflow from a reservoir that was created during a previous cycle
D	$\alpha 2 > \alpha 1$		- Water being stored in a reservoir
	$\alpha 2 > \alpha 1$ $\alpha 3 < \alpha 2$	Double break	- A reservoir being cut off as the water level drops, and then being reconnected during the low-water period

12.3.1.3 Hydrographic recession curves

Hydrodynamic parameters can be defined through the study of recession curves. For example, the curves can yield information about the coefficients for recession, infiltration, and flow heterogeneity, as well as providing a way to estimate the system's dynamic volume. This last value can be found from the discharge at the slope break (Q_i, t_i), when recession begins (Figure 91):

$$V_{dyn} = c \, . \, Q_i/\alpha$$

Where c is a time constant (c = 86400 when Qi is in $m^3.s^{-1}$ and α is in days)

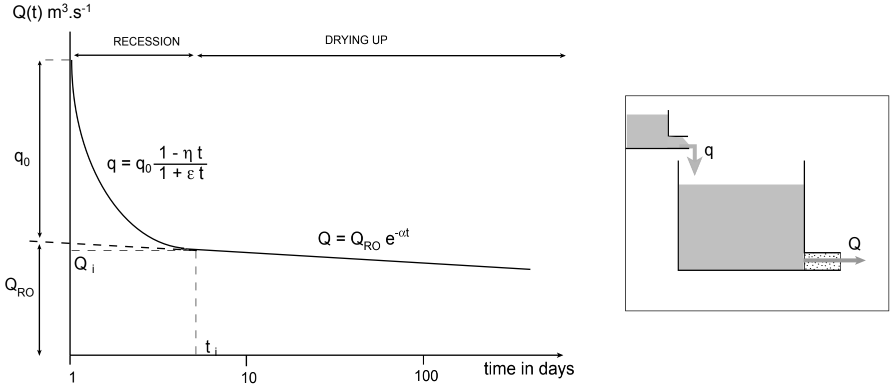


Figure 91. Recession curve (Mangin, 1975). This system includes a reservoir (epikarst and unsaturated zone) that empties into another reservoir, the saturated zone.

12.3.1.4 Classification of karst systems

Mangin (1975) created a classification for karst systems, based on the analysis of two coefficients, **K** and **i**.

- **K** (regulation coefficient) represents the average residence time for water in the saturated zone. It is equal to the relationship between the greatest dynamic volume over a long time period and the interannual transit volume (the volume discharged during the most cycles divided by the number of cycles) calculated over the same time period. In normally functioning karst systems, K is often under 0.5.
- **i** (infiltration delay coefficient: $0 < i < 1$) is equal to the discharge two days after a flood peak. A high i value indicates slow infiltration or strong influence from the epikarst. A low i value is the sign of short transit times to the saturated zone.

The different types of karst systems are as follows:

- Type 1: Highly developed drainage network and small saturated zone.
- Type 2: Well developed drainage network leading to a significant karst system in the saturated zone.
- Type 3: Karst systems that are more well-developed downstream than upstream, with delayed influxes.
- Type 4: Complex karst systems.
- Type 5: Systems with poorly developed or mostly inactive karstification (fractured aquifer, paleokarsts).

12.3.1.5 Systemic approach

Systemic approach (Mangin, 1975), takes into account the aquifer in its entirety, and defines the karst system as a sort of black box with definite inputs and outputs, that can

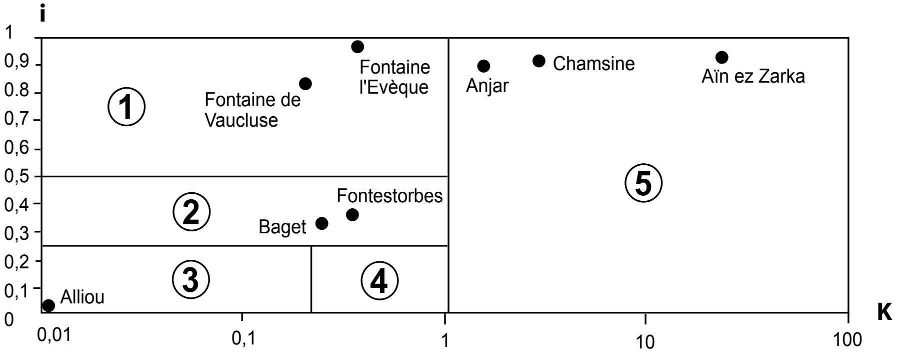


Figure 92. Classification of karst systems (after Mangin, 1975 and El Hakim, 2005).

be described using multiple parameters (rainfall, height of the water table, hydrometry, physical and chemical characteristics, etc.).

The signals that the system receives and transmits can be analyzed with many different methods: correlations, spectral analysis, wavelet analysis, fractal or multifractal analysis, and dynamical systems attractor analysis (Mangin, 2008). These analyses enable the identification of point-specific or recurring events (tides, snow fusion, etc.) within the overall system response.

12.3.2 Temperature and Conductivity

The transit time for water entering the system as precipitation is easy to find, based on the delay between the abrupt discharge increase that follows a precipitation event and the subsequent change in water temperature. The mass of incoming water displaces water already in the aquifer, resulting in an almost immediate increase in discharge at the spring, whereas the change in temperature of the water coming out indicates that new water has reached the spring. Using hydrographs and the delays between different responses, it is therefore possible to estimate the reservoir size and the system's response time.

12.4 Tracer Tests in Karst Systems

12.4.1 Objectives and Difficulties

Tracer tests (or dye tests) involve injecting some product that is not naturally found in the water at a point upstream, and then looking for it downstream, in springs, rivers, caves, or wells. This was how Norbert Casteret discovered, in 1931, the true source of the Garonne River, by pouring fluorescein into the Trou du Toro in Spain; the dye reappeared in the Goueil de Jouéou before flowing across the border into France.

In some cases, tracer tests happen by accident, as was the case in 1901, when a fire broke out at the Pernod distillery in Pontarlier (Doubs, France), and all of the alcohol and liquor stored nearby was dumped into the river to prevent it from catching fire and destroying the town. A few days later, the waters of the Loue spring began to smell like absinthe, proving that it was somehow connected to the water being lost from Doubs River.

When planning a tracer test, it is best to seek out locations where large amounts of water concentrate and move down into the system, particularly locations that have a year-round flow of water (ponors, natural caves with underground waterways, losing streams, etc.). This ensures that the tracer will be carried all the way into the deeper aquifer. In the event that no such entry points can be found, the tracer can be flushed into the aquifer by injecting a large amount of water with it, into areas likely to absorb both (dolines, karren fields, etc.), but there is always a risk that the tracer will remain trapped near the surface and never make it all the way into the aquifer.

In order to reduce costs, multiple tracer tests are often done at the same time, by injecting different tracers at different points in a karst system, and by simultaneously monitoring different potential exit points: springs, caves, wells, etc.

Tracer tests are always delicate and costly operations, requiring a careful operating protocol and rigorous interpretation. A few common problems that can lead to failure are listed below:

- Not enough tracer was used.
- The number of potential exit locations being monitored was insufficient.
- The tracer was injected into an impermeable part of the aquifer.
- The monitoring period was too short.
- The monitoring instruments were lost (because of flood or theft).
- The samplers were too worn down, or were saturated with organic material.
- The person collecting the samples did not wash their hands well enough and contaminated the samples.
- There was no circulation within the aquifer (deep drought). In this last case, the tracer will stay in the aquifer until it is replenished by rainfall, which can be extremely problematic, as it can then affect later tests.

12.4.2 Artificial Tracers

Many different substances can be used as tracers (salts, radioactive elements, bacteria, viruses, colored spores, etc.) (Table 11), but fluorescent compounds (fluorescein, eosin, rhodamine, and naphthalene) are the most commonly used in hydrogeology, because they are harmless, easy to detect, and can be measured using activated carbon samplers (particles of activated charcoal in a permeable container), which trap tracer particles and are easy to place in the locations being monitored.

These fluorescent tracers emit a very specific type of radiation when they are lit up by particular wavelengths of radiation. For example, fluorescein emits 515 nm wavelengths when it is excited by 475 nm incoming radiation.

These measurement methods convert a fluorescence signal into a concentration. However, many fluorescent organic materials (humic and fulvic acids) occur naturally in water. Activated carbon samplers have the same problem; they record the natural background levels of fluorescence. Quantitative tracer measurements should therefore always be confirmed with qualitative analysis of the tracers using radiation to excite them and then measuring the outgoing radiation's spectral signature. Generally, natural fluorescence creates peaks spread out over many wavelengths, because it reflects many different weakly fluorescent substances, whereas injected tracers create narrow, intense peaks. However, high background levels of fluorescence can sometimes mask a weak tracer signal. It is therefore wise to consider concentrations under a $\mu g.L^{-1}$ untrustworthy. The use of data loggers like the GGUN fluorometer, which continuously monitors the fluorescein levels *in situ* allows for a visual representation of the tracer's arrival (Figure 94).

Table 11. Primary tracers used in karst hydrogeology.

Tracer	Color	Analysis method	Detection threshold	Trapped by activated charcoal?	Disadvantages
Fluorescein	Green	fluorescence	few $\mu g.L^{-1}$	Y	Can be confused with naturally occurring fluorescence
Rhodamine	Red	fluorescence	few $\mu g.L^{-1}$	Y	Easily adsorbed
Eosin	Pink	fluorescence	few $\mu g.L^{-1}$	Y	Similar spectral signature to rhodamine and fluorescein
Duasyne	Blue	fluorescence	few $\mu g.L^{-1}$	Y	Not commercially available in Europe
Sodium Naphtionate	No color	fluorescence	few $\mu g.L^{-1}$	Somewhat	Can be confused with naturally occurring fluorescence
K iodide	No color	Ionic chromatography	10 $\mu g.L^{-1}$	N	Costly analysis
Lithium chloride	No color	Atomic absorption	10 $\mu g.L^{-1}$	N	Costly analysis
Na Cl	No color	Conductivity	1 $g.L^{-1}$	N	Requires large quantities
Radioactive tracers	No color	Counting the number of particles	_	N	Delicate handling required
Bacteria	No color	Microscope	_	N	Delicate handling required
Bacteriophage viruses	No color	Microscope	_		Deteriorate during pumping
Colored spores	Various	Microscope	_	N	Labor-intensive

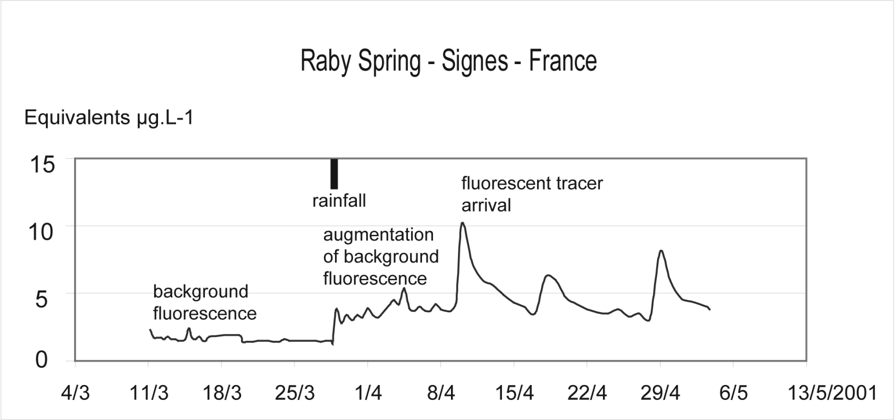


Figure 93. Example of sodium naphtionate restitution at the Raby spring (Signes, Var). The background noise is high and varies with rainfall. Concentrations before the 8/4 peak reflect the environment's natural fluorescence.

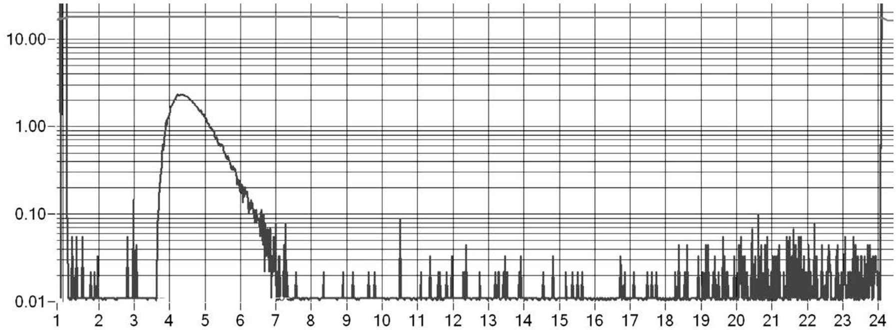


Figure 94. Example of rhodamine injection in the subterranean river beneath Port Miou (Cassis, Bouches-du-Rhône). Note the background levels right before the peak (0,14 µg.L^{-1}) compared to the maximum concentration (2,2 µg.L^{-1}) of rhodamine (time in hours on the x-axis, µg.L^{-1} equivalents on the y-axis).

12.4.3 Tracer Interpretation

Knowing transit times is useful in determining the velocity of the water flowing between the injection point and the exit point. However, this velocity can only ever be an average, estimated for a straight line, and generally the actual path that the water takes is unknown, as are the environments through which it passed (fractures, karst conduits, cave-ins, fissural aquifers, etc.).

In karst systems, water often travels several meters per hour, and can sometimes reach velocities of hundreds of meters per hour (Example: 400 m/h between the Caussols ponor and the Bramafan Spring).

Analyzing tracer breakthrough curves, the amounts of tracer that were recuperated, spring discharges, and rainfall data allow for a more precise understanding of the system.

- A tracer breakthrough curve with a sharp peak indicates highly developed karstification and low reserves. The tracer may have been injected into a drainage that flows directly into the spring (Figure 94).
- On the other hand, a very spread out curve, highly diluted, shows that the tracer passed through a poorly karstified area or an area with a large storage capacity.
- Successive spikes tied to rainfall events indicate that the tracer has become trapped in the epikarst or a compartment badly connected to the aquifer.
- Spikes that are not linked to rainfall may indicate that the aquifer has several compartments or that there are diffluences.

12.4.4 Hydrobiology and Biological Tracers

The karst system is home to a very specific flora and fauna. Each environment (drainage passageways, shores, fractures, caves, etc.) has its own characteristic assemblage of organisms, and each aquifer has its own ecosystem. Capturing and analyzing, with a plankton net, the organisms carried in water emerging at a spring, provides insight on the environment that water is emerging from (Gibert, 1986; Prié, 2009)

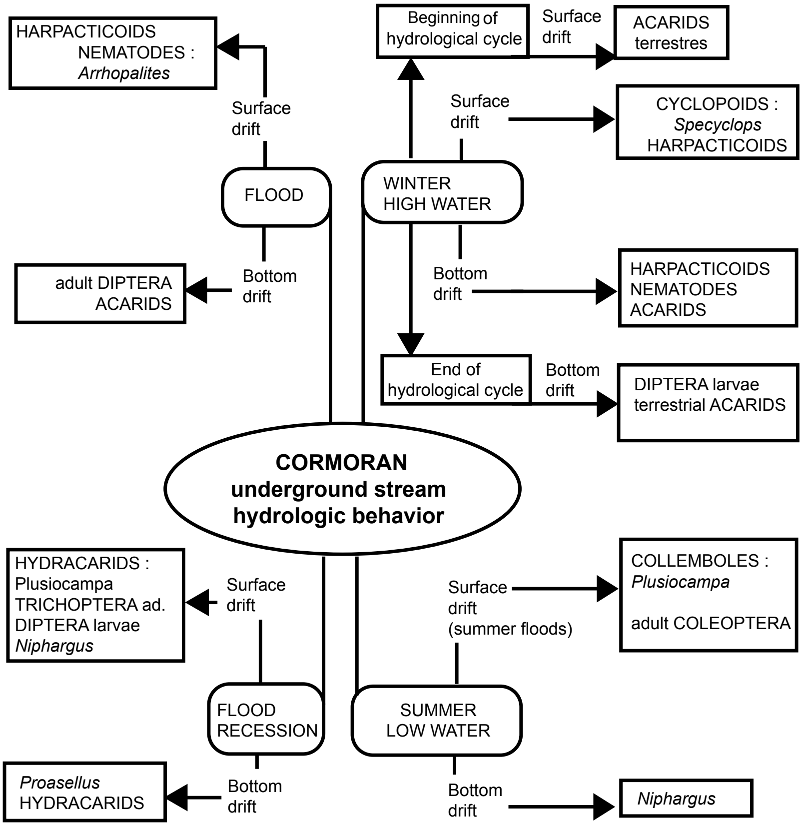


Figure 95. Ecology of the Cormorant cave (Gibert, 1986).

Subterranean fauna, once isolated from the outside world, evolves rapidly to create genetically distinct populations that can in some cases become entirely new species. Karst water fauna are characterized by a high level of endemism. Phylogenetic studies on stygophilic mollusks, which are confined to the subterranean world, show that in 97% of the cases studied, there were genetic differences between organisms that were putatively of the same species but that lived in aquifers separated by a vadose zone, even when the aquifers were geographically close to each other (Prié, personal communication). This can be useful in determining the precise relationships between the aquifers in question.

12.5 Modeling Outflows

Aquifer models can be deterministic, seeking to reproduce the various properties of the environment, or stochastic, seeking to find the relationship between an input (rainfall) and an output (discharge, dissolved mineral load, etc.). The problem will be different for a temporal model like a rainfall-discharge one, versus a spatial model (gridded model) which will require a solid grasp of the scaling involved—a complex problem given the heterogeneity of karst systems.

There are three types of models:

- Simple discharge models for springs, linking precipitation and spring discharge. These are based on surface flow models.
- Reservoir models (BEMER, CREG, VENSIM) where the different parts of a karst system (epikarst, drainages, annex drainage systems, saturated zone, etc.) are represented as nested conceptual reservoirs, with pre-defined flow relationships.
- Three-dimensional models using partial differential equations (PDE). These define a series of hydrodynamic behaviors and responses for the different components of the system: matrix, fractures, and drainages.

All of these methods run into problems with scaling, and with fully describing the polyphase system. To complicate things further, groundwater movement occurs both in saturated environments and in contact with air, and therefore water flows both monophasically and diphasically, which makes modeling more difficult.

Given the problems described above, it is easy to understand why modeling karst environments is so difficult, and why it has yielded little useful information.

13

Water Use and Management

13.1 Water Management

Water management in karst regions must deal with several challenges:

- Flooding risks in depressions (dolines and poljes).
- Soil erosion and migration into the endokarst.
- Variable spring discharge.
- Difficulty in accessing deep reservoirs for catching water.
- Bacterial contamination and turbidity in the water.

Water laws written in France introduced the concept that water is all one entity and that it has value as natural heritage. The new legislation no longer treats surface water and groundwater separate entities, nor does it make a distinction between water resources and wastewater. Like any natural resource, water as an entity requires both qualitative and quantitative management.

Quantitative management of a groundwater resource involves maintaining long-term equilibrium between the outflow to other aquifers or to human consumption, and the inflow recharging the aquifer. Another concern is prioritizing use of the aquifer to ensure that drinking water supply needs are met first.

The European Union's Water Framework Directive introduced the legal concept of "good qualitative status." This means a healthy biological, physical, and chemical state, defined by certain maximum acceptable concentration limits for specific contaminants (nitrates, pesticides, etc.). For surface water (for example in rivers), this also takes into consideration the ecological state of the body of water as a potential habitat.

13.2 Surface Water Management

13.2.1 Poljes and Flood Zones

Poljes, due to the way they are formed, have their own unique workings. They flood periodically, either when the water table rises or when the conduits leading downwards fill up. If a ponor becomes clogged with debris, the polje may flood significantly more and for a longer time period.

In the Peloponnesian region (Greece), projects to drain swallow-holes (or katavothrons) and poljes were undertaken as early as the classical Antiquity, by protecting ponors and preventing them from getting clogged, and by channeling water towards more absorbent areas. For example, in Tripoli, water was directed into the Mantinea and Tegea ponors, or into Lake Copais and the Vinya ponors. Pausanias relates the legend of Hercules draining another lake, Lake Phenea, by digging a canal 50 stades (10 km) long to carry the water into a chasm. Today, Lake Phonias fills the area, fed by the Olbios and Aroanios rivers, which used to be drained by ponors. The ponors were obstructed by debris, flooding the ancient city of Phenea (Beulée, 1875).

In France, the Cuges polje (Var) was drained and turned into agricultural land around 1475, by cleaning and widening the ponor to the west of the polje, then later in 1860 by building a surface drainage system to direct water into areas where it would be easily absorbed (Nicod, 1972).

On a smaller scale, dolines that receive clayey sediment are also prone to flooding, which can damage buildings that were imprudently placed in the bottom of the depression. In the Mediterranean, as the collective memory of such events fades, an illusory impression of aridity takes shape and leads to construction in seemingly safe locations. When a particularly rainy year comes along, poorly placed buildings can be affected.

In poljes, this type of risk can be managed by directing water into the ponors with the greatest absorption capacity, and increasing infiltration rates by cleaning out ponors, preventing them from clogging up by stabilizing the surrounding embankments, and regularly cleaning and widening surface drainages.

Boreholes can serve as artificial infiltration pathways in dolines and poljes, if they are drilled deep enough to get past the clay filling the bottom of the depression. The wellhead is usually protected by a half-sphere of wire netting to prevent debris from clogging it.

The Caussols polje

In the Alpes-Maritimes (France), the access road leading to Caussols passes through a vast polje, and is sometimes cut off when a lake fills the depression.

Located at the base of the Calern limestone, thrust upwards to the south over the Caussols unit, the Caussols polje is a nice example of a typical Mediterranean polje. It is mostly located in Cenomanian marl. Water flows into it from its catchment area: the plain and its surroundings, and particularly the scree slopes off the Calern unit, resting on impermeable marl. Several small springs feed a small stream that meanders across the marl. At the southern edge of the plain, the stream reaches Jurassic limestone, where it disappears into a ponor. It can be followed underground for a few hundred meters, until it reaches a 40 m vertical siphon that has not yet been successfully explored by divers. Beyond the siphon, the water theoretically flows through a series of cascading passages until it reaches the base of the Caussols limestone, where it is stored in a deep reservoir in the base of the Caussols syncline, above the impermeable Triassic clays. Dye tests have shown that water travels very quickly (400 m per hour) through the system to the Bramafan springs, 6 km to the east, at an elevation of 460 m in the Loup River gorges.

During intense rains, the stream's discharge exceeds the ponor's absorption capacity, and a lake fills the polje. It generally empties out again in less than a day.

Figure 96. Lake formation in the Caussols polje (Alpes-Maritimes) after several days of heavy rains (photo M. Giovannini).

After a piezometer was installed, it recorded regular increases in the level of the water table, which occurred when discharge at the ponor exceeded 4 $m^3.s^{-1}$; however, precipitation events often lead to discharges of over 8 $m^3.s^{-1}$. Flooding of the polje is therefore a function of the system's geometry, and not an event that occurs only in response to the ponor becoming clogged, as had previously been thought (Tennevin, 2010, personal communication).

The 1994 Frayère flood

In 1994, the village of Auribeau–sur-Siagne was devastated by a flood that took everyone by surprise, as the Frayère River's bed normally held only a thin trickle of water. The damage was considerable because, following a change in municipal governance, the zoning regulations had been modified to allow construction on a lot in the floodplain, which had until then been, for good reason, considered unsuitable for development. A survey of the karstic catchment basin that fed the river showed that a first wave of rain fell when the grasses in the area had reached their maximum growth. The grass flattened and created a layer like a thatched roof over the underlying karren field, shedding water and preventing it from reaching the epikarst. When a second wave of rain arrived, most of it flowed into the river as runoff instead of infiltrating into the epikarst.

13.2.2 Runoff Concentration

Runoff from roads and paved surfaces is sometimes collected and driven to ponors or caves. Although these openings can be useful in capturing rainwater, they can also lead to contamination by allowing water carrying hydrocarbons from the pavement into the aquifer. This phenomenon therefore requires an impact study.

13.3 Using Water Resources

Because of the size of the subterranean voids that exist in karst (10 to 30%), this type of landscape's economic value lies primarily in its abundant water resources. Karst aquifers have been used as resources since classical Antiquity, and they enabled the growth of many cities around the Mediterranean, such as Rome, Nîmes, Fréjus, Carthage, etc.

Today, drought and pollution require us to better understand the aquifers in order to properly manage our water resources (delineating catchment basins, exploratory drilling in deep karst reservoirs, drawdown optimization, underground dams, etc.). The 1992 French "Law on water" led to the creation of protection perimeters around water catchment structures, and the European Union's Water Framework Directive requires that the state of European aquifers be well understood by 2015. These regulations prompted a large number of karst hydrogeological studies.

13.3.1 Spring Catchments

Humans have been using water from springs since the dawn of our species. In Classical Antiquity, major projects were built, like the 3-km-long aqueduct in Nîmes (France), which includes the Pont du Gard. It carries water from the Eure spring in Uzès. In Tunisia, the Zaghouan aqueduct supplied the city of Carthage with water from a spring 100 km away.

The advantages of diverting water right from the spring are the concentration of discharge at one point, the ability to immediately estimate the resource, and the absence of effects on the aquifer when water is collected. Only the water exiting the system is used. The disadvantages are the distances water must be transported over using only gravity, the variability of discharge, and the turbidity of the water during floods. Additionally, there can be problems with bacterial contamination.

The invention of the steam engine in the 19th century, and later on the invention of electric pumps, meant that water could be lifted, and that springs could supply even regions that were at a higher elevation than the spring. The optimizations methods described below (cf. 13.4) can help to compensate for the irregularity of the discharge.

13.3.2 Water Wells

Drilling wells into an aquifer means that water can be drawn near where it will be used. Down-the-hole drilling techniques enabled rapid drilling to great depths, although without eliminating the risk of passing through caverns or areas of crushed rock. It is therefore important to plan on starting the drilling with a large diameter, so that difficult passages can be stabilized with injected cement and drilling can continue at a smaller diameter.

13.3.2.1 Choosing borehole location

The depth to the water table is generally easy to estimate based on the elevation of nearby springs, the structural context, and the information gathered by speleologists. The more difficult task is in choosing a location in a conductive zone that actually holds water. Often, boreholes that are drilled down to the water table stay completely dry because they never cut across a discontinuity that water can flow through (a fracture or a karst conduit). To avoid such a scenario, it is necessary to allow for a significant margin of depth (at least 100 m below the top of the water table).

Ideally, the borehole would be drilled directly into a drainage conduit, but there is currently no technology that can detect passages more than a few tens of meters below the surface. When speleological reconnaissance is possible, a suitable location can be found using careful topographic surveys or electromagnetic location methods (cf. chap. 10). The Féclaz Ski Station (Savoie, France), for example, draws its water from a borehole drilled down to the Trou du Garde, 300 m below the surface.

In the Guizhou and Yunnan plains, when the water table is near the surface, ponors and vertical shafts punctuate the course of subterranean rivers. A river's path can be inferred from the locations of these features, and then used to choose drilling locations. The drilling depth is estimated based on the depth of the ponors, shafts, and uvalas (Mengxiong, 1988).

13.3.2.2 Pumping tests

These are used to evaluate the reservoir capacity and the characteristics of the well. There are several different methods (Detay, 1993), some of which work well in karst aquifers. The Collignon method (1986) for example, consists of slowly draining the aquifer through a long period of steady pumping, while carefully monitoring the water table through a network of piezometers. This allows for a simple, rapid, and precise evaluation of the available reserves in a karst aquifer. The pumping should be done when it will not be influenced by rainfall, and must move a significant volume of water (several hundred thousand m^3).

Based on a large number of tests in Algeria, Collignon demonstrated that when large volumes of water are pumped from a well in a karst aquifer, the resulting graph of the water table, as a function of the volume being pumped, was both reproducible, and marked by three distinct phases (Figure 97):

- An immediate drawdown characteristic of the well, as the aquifer's drainage patterns adjust to the influence of pumping,
- A slow period of decline as the aquifer empties,
- A more or less rapid rebound once pumping stops.

The residual drawdown indicates the slice of the aquifer that was affected by the pumping tests.

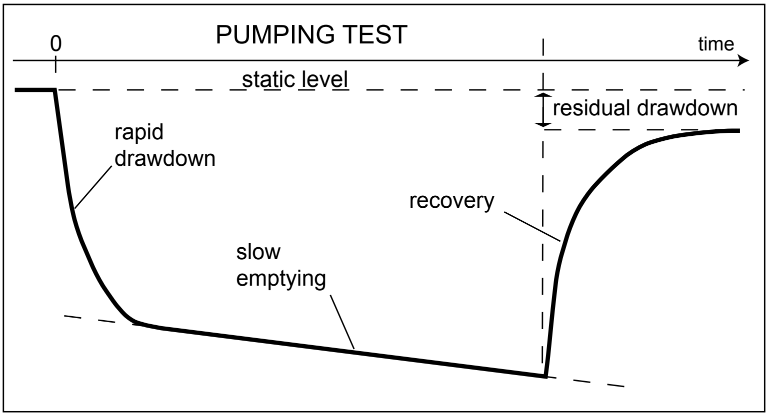


Figure 97. Typical pumping test drawdown curve (after Collignon, 1986).

A slow, linear decrease in the water table would indicate that the karst aquifer being tested had the same behavior as a cylindrical reservoir completely open to the well, with impermeable boundaries and a constant capacity as a function of depth (at least in the cross-sectional area being tested). The proportional relationship, between the drawdown and the volume of water being pumped out, can be used to easily calculate the specific storage of the aquifer (S_s) which refers to the volume of water extracted per meter of drawdown. In the example shown in Figure 98, the specific storage S_s is given by the ratio $\Delta V/\Delta h$ and has a value of 220,000 m^3/m.

This type of test can also be used to estimate the permanent reserves that can be pumped from (which represent the average volume of water stored in the aquifer), by multiplying the specific storage by the usable height of the borehole being pumped from.

Drawing down the aquifer through pumping, during periods where there is no influence from rainfall, is compensated for by recharge from effective rainfall. This recharge can be quantified graphically as the vertical distance between two drawdown curves, or it can be calculated by multiplying the specific storage S_s by the recharge height ΔH. In the example in Figure 98, the 1986 recharge volume reached 1.1 million m^3.

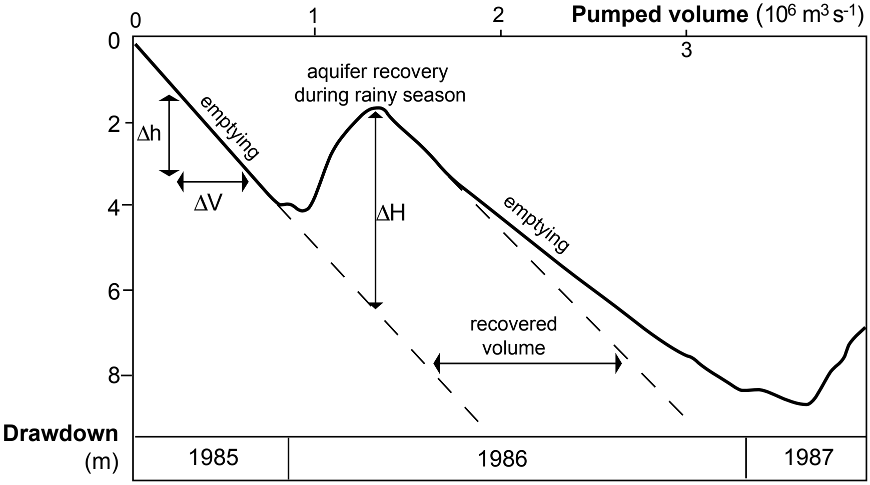


Figure 98. Example of a well being monitored over several years of use (after Collignon, 1986).

Alternating between periods of drawdown from pumping and periods of recharge from rainfall is also useful in order to evaluate the amount of renewable reserves available. These correspond to the volume of water that flows into an aquifer every year, through the direct and indirect effects of precipitation.

Finally, these types of test can show changes in the drawdown curve over time, indicating changes within the aquifer, or the delayed effects of environmental changes. For example, an increase in slope is characteristic of a limited specific storage, and can be a result of decreased permeability in the reservoir at a certain depth, or of a lateral inflow (a losing stream, an exchange with a neighboring aquifer) stopping suddenly. The inverse, a decrease in slope, is characteristic of an increase in the specific storage, and can be a result of having reached a more capacitive layer of the aquifer, by a sudden inflow from a lateral reservoir, or by decreased leakage (if, for example, nearby springs run dry).

13.4 Quantitative Management

13.4.1 Goals

13.4.1.1 Problem and goals

In regions with sharply contrasting dry and wet seasons, karst aquifers are characterized by their irregularity. They alternate between discharging high volumes that can lead to violent floods, and supplying only a trickle of water or even drying up completely. It would therefore be useful to be able to store water during the wet season, to be used later when the discharge decreases, particularly since the water supply dries up during the summer, just when demand is highest. This is especially true in the south of France, where the population increases during the summer due to an influx of tourists. The following diagram shows an example, a spring with a dry season discharge of 10 L.s^{-1}, which could provide double that amount if water were stored during the rainy season.

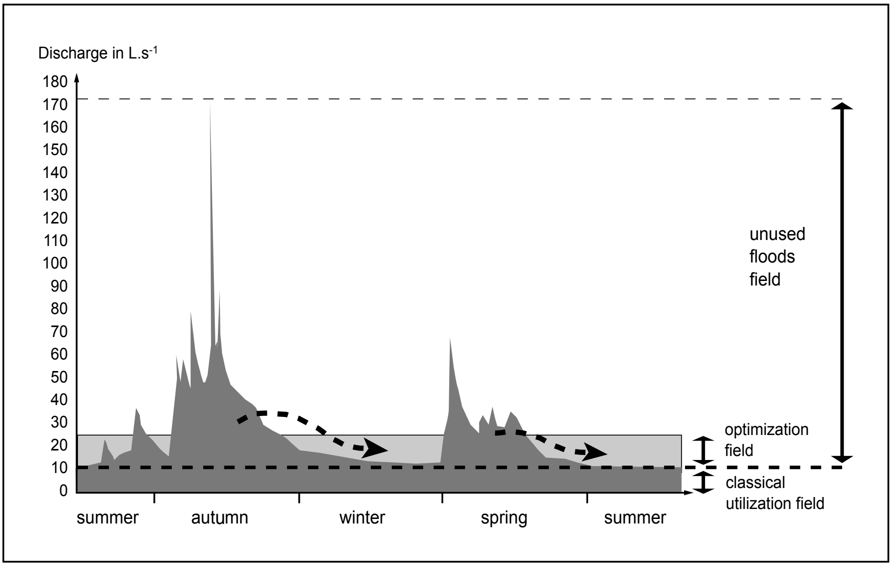


Figure 99. Optimization example for a karst spring.

The goal of a successful water management program is to regulate this type of resource, something that can be achieved through a number of different strategies. However, putting any of them into place requires a solid understanding of the system and of how it works, as well as a comprehensive monitoring system (piezometers, gauging stations, etc.).

13.4.2 Optimization at Spring Catchments

When karst is bounded by an impermeable layer, and the saturated zone is thick enough, water can be pumped out from the karst aquifer, below the spring. The idea is to overexploit the aquifer, drawing the water table down to below the level of the spring. When precipitation occurs, instead of causing increased discharge and flooding, it recharges the aquifer back to normal levels again. In order to do this several solutions exist:

- inclined drainage boreholes drilled below the spring,
- vertical wells into the deep aquifer,
- pumps installed in the karst conduit.

One of the first installations of this type was at the Bou Merzoug spring (Algeria), where water was pumped from the aquifer in 1953–54, in 40 m boreholes near the spring, with a total discharge of 500 then 800 L.s^{-1} over almost 100 days, during which the natural discharge was 450 L.s^{-1}. This resulted in 2,200,000 m^3 more water being made available for use. The water table remained low for three months after pumping stopped. The immediate yield varied from 20 to 43%. The apparent capacity of the karst reservoir was therefore evaluated to 700,000 m^3 per m of height (Margat, 1981). In this example, it was therefore possible to temporarily overexploit the karst aquifer, by counting on natural recharge to return the water table to its previous level.

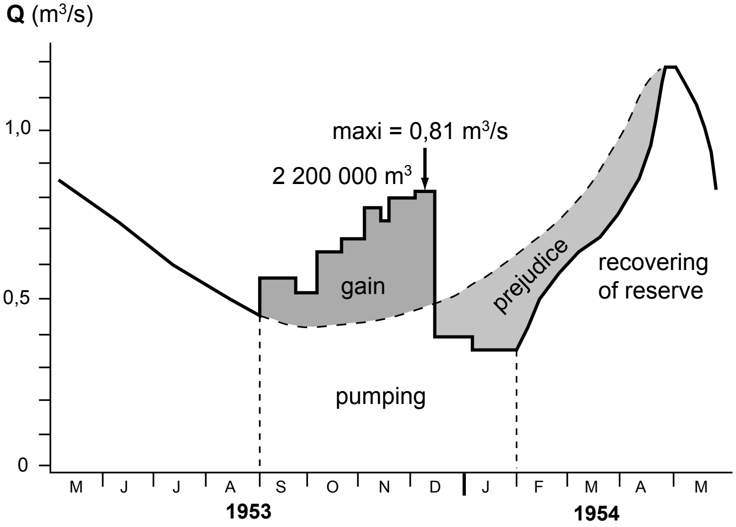


Figure 100. Pumping in the Aïn Bou Merzoug (after Margat, 1981).

This method was used at the Lez spring in Montpellier, under the direction of J. Avias, by installing a pump directly in the submerged karst conduit which had been explored to a depth of 75 m by cave divers.

The installation took place in 1981. An underground station was built, and four 1.8 m in diameter boreholes were drilled into the conduit. Three pumps were installed, each with a maximum pumping capacity of 1000 L.s^{-1} (Figure 101). The aquifer is carefully managed so that it recharges completely during the autumn rains. Currently, the system is still in place and working perfectly. At the end of the summer, the water table is drawn down by 38 m, extracting 1700 L.s^{-1}. Part of this water is sent to Montpellier, and the rest is diverted into the Lez River, in order to maintain a minimum flow of 160 L.s^{-1}, thereby maintaining good surface water quality. A network of sensors distributed over the spring's catchment basin monitors the piezometry and the water quality of the aquifer.

The advantage of pumping directly from an underground conduit is that it is, by definition, connected to the aquifer's drainage network, whereas a well drilled into the limestone unit might end up in less permeable rock, or even in a completely impermeable area.

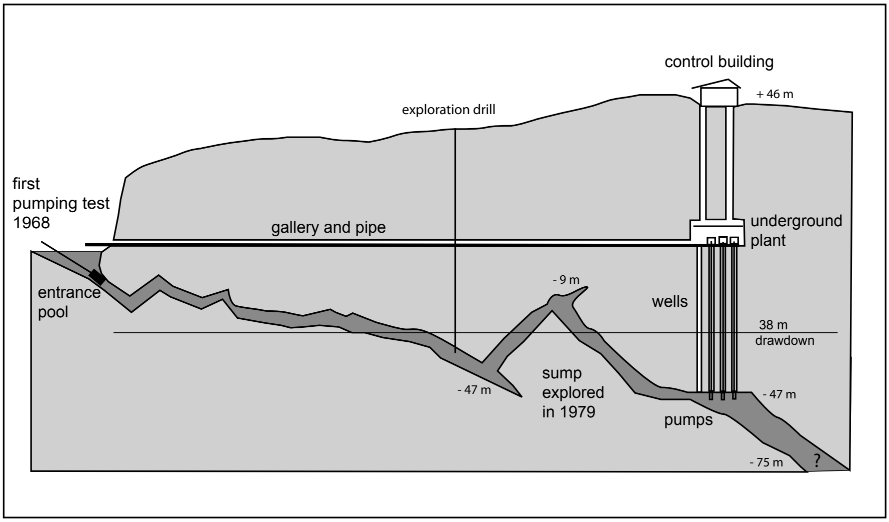


Figure 101. Example of pumping at a spring in order to optimize the karstic resource (Source du Lez, Montpellier, France).

There is a similar example in Montenegro, in Opacica near Kotor Bay, where the karst aquifer was drawn down to 20 m below sea level, thanks to a favorable geologic context that protects it from saltwater intrusions.

Blocking springs or karst conduits

Completely blocking springs can make the water table rise, and thereby create large reservoirs both below and above ground. One of the first times this was tried was in Syria (Detay, 1997), in the Orontes valley. Slightly raising the level of various springs resulted in more water being stored in the aquifer. Gates installed on the springs were then opened during the dry season in order to increase discharge. Many similar projects were undertaken in China (cf. infra), and a prototype was built in France in Coaraze (Gilli and Mangan, 1994).

The largest problem is of course leakage through the fracture network and through small karst conduits. In Uganjska Vrela (Croatia), this was mitigated by covering the limestone slope by an anchored concrete blanket (Mijatovic, 1993). A larger project is in the works in Ombla, also in Croatia, where a grout curtain will be built by drilling boreholes and injecting liquid cement into the rock from a grouting gallery (Breznik, 1998).

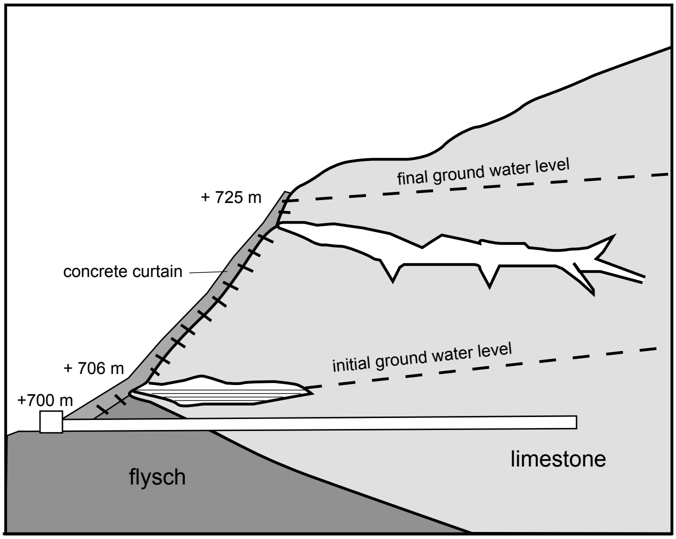


Figure 102. Uganjska Vrela dam (Montenegro) (after Mijatovic, 1993).

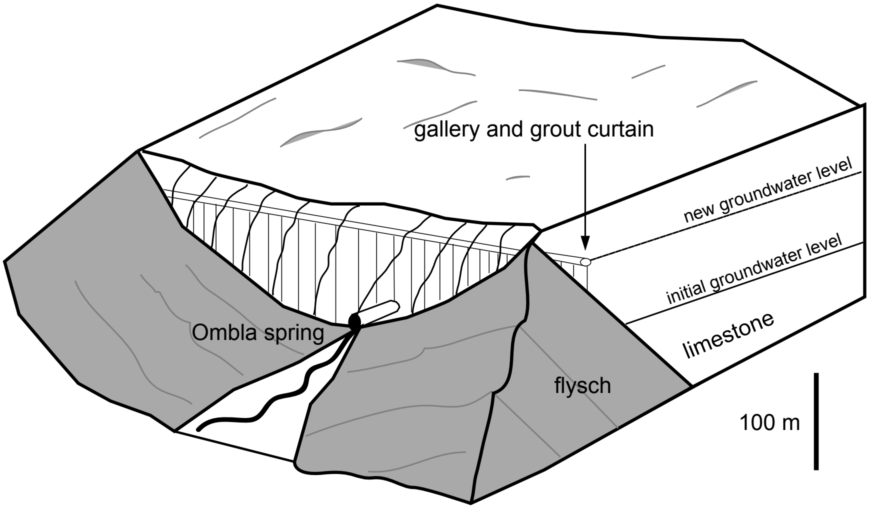


Figure 103. The Ombla dam, a project being considered in Croatia (after Breznik, 1998).

Numerous examples of underground dams can be found in China, in regions where the karst systems quickly became more entrenched, and water flows near the geologic base level. The cockpitkarst terrain results in streams that go in and out of the ground, flowing at the surface in poljes and disappearing into tunnel-caves that link one polje to the next. Dams built inside these caves are meant to store water by using the underground voids already available, as well as using the depressions formed by dolines and poljes upstream of the dams. These dams come in a range of geometries. They can block the entire gallery or part of them. They can be located in the caves, or at springs (Mengxiong, 1988; Daoxian, 1991).

Table 12. Examples of subterranean dams.

Name	**Location**	**Purpose**	**Height**	**Storage capacity (m^3)**	**Reference**
Coaraze	France	Experimental	9 m	-	Gilli and Mangan, 1986
Port Miou	France	Preventing saltwater intrusion	3 m	-	Potié, 1973
Kiveri	Greece	Preventing saltwater intrusion	1 m	-	
Almyros	Greece	Salinity reduction	6 m?	-	Arfib, 2001
Yidong	Guangxi, China	Irrigation	10	-	Daoxian, 1991
Yuzhai	Guizhou, China	Irrigation	6	96000	Daoxian, 1991
Longwangdong	Sichuan, China	Irrigation	62	17 millions	Daoxian, 1991
Jijiao	Guangxi, China	Irrigation	30	-	Daoxian, 1991
Yuhong	Hunan, China	Electricity	115	-	Daoxian, 1991
Beilou	Guangxi, China	Electricity	24	-	Daoxian, 1991
Wanger	Guizhou, China	Irrigation	9	100,000	Yuan Daoxian, 1991
Neiwan	Hunan, China	Irrigation	70	700,000	Daoxian, 1991
Uganjska Vrela	Cetinje, Montenegro	Drinking water supply	20	3 millions	Mijatovic, 1993
Ombla (projected for 2015)	Dubrovnic, Croatia	Electricity and drinking water supply	60	8 millions	Milanovic, 2004
Daxiao	Guizhou, China			-	Mengxiong, 1988

Installation of this type of system requires a detailed understanding of the drainage network's geometry, and therefore necessitates careful speleological exploration. In order to avoid hydraulic short-circuits and leakage through newly cleared karst conduits, the sedimentary deposits around the construction sites and across the subterranean drainage basin must be carefully mapped and described. Flowstone floors cannot be considered adequate natural barriers, as they may have been deposited on top of easily erodible clayey sediments. At the site of the Solue underground dam (Bama county, Guangxi, China), the conduit is 13 m across, but the subterranean alluvium is over 18 m thick. The twenty-foot underground dam at Port Miou (Cassis, Bouches du Rhône) (cf. 14.2.6) was meant to prevent saltwater intrusions while raising the height of the water table in the karst aquifer. It was built directly on alluvium, and the first flood destabilized it, requiring submarine construction efforts to shore it up (Potié, 1974).

13.4.3 Artificial Recharge

Catchment system optimization has been described above. Artificial groundwater recharge is also possible, but so far it is not common in the karst regions of France. Artificial groundwater recharge has been practiced in Israel for over 30 years, in the Yarkon-Taninim aquifer, by injecting 75 to 100 million m^3 of water from the Jordan River every year (Detay, 1997).

The concerns commonly associated with artificial groundwater recharge include the eventual clogging of the aquifer's pore spaces, and the poor quality of the water being injected. In karst regions, even more problems arise. Recharge effectiveness depends on the aquifer's spatial organization. In fact, although the high transmissivity of limestone might initially appear to favor artificial recharge, it also heightens the risk of concentrating recharge near drainage paths, thereby increasing spring discharge without re-establishing the aquifer's reserves (Mijatovic, 1993). In such cases, artificial groundwater recharge produces only short-term benefits.

In addition, the absence of filtration mechanisms means that water passing through the aquifer retains high turbidity levels, and is not naturally cleaned. It is therefore important that water being injected is carefully monitored for quality, or even treated before being used.

Another problem can occur in recharge wells when air in the well is subject to pressure, and then escapes violently up the well, causing serious damage to the equipment (Sternaut, 1967).

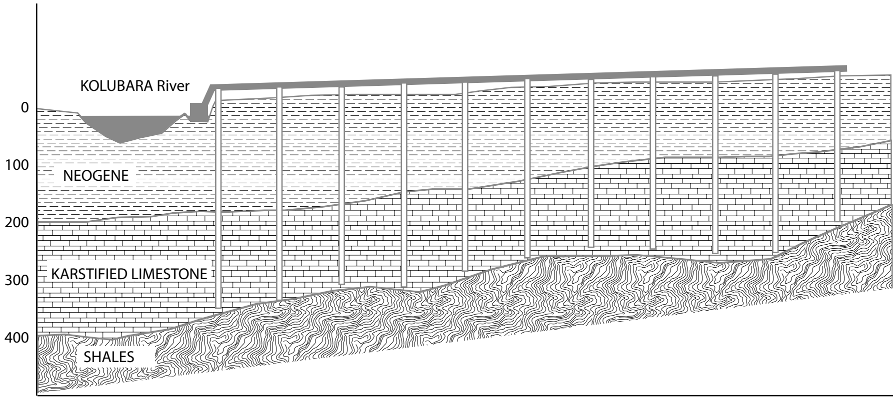


Figure 104. Water catchment system and injection wells on the Kolubara River (after Mijatovic, 1993). The catchment diverts 1 m^3.s^{-1} of water from the river, which is then treated preventively (filtration, denitrification, iron removal) before being injected through boreholes.

13.5 Qualitative Management

13.5.1 Drinking Water Catchment Vulnerabilities and Protective Measures in Karst Environments

Circulation in karst environments, where drainage passageways have been enlarged through dissolution, does not filter water at all. In addition, water can travel through these systems very rapidly, and residence times are generally shorter than pathogen lifespans. If part of the watershed is contaminated, that contamination can spread quickly to the springs, which may appear misleadingly limpid. For example, a person who had been drinking spring water for years at the Siagne (Alpes-Maritimes) became almost fatally ill with a severe bacterial infection after the spring became contaminated. Later, a tracer test found that a defective wastewater treatment plant had been collecting and concentrating wastewater from a nearby village, and then directly injecting the untreated water into a swallow hole that led to the spring. The water emerging downstream was therefore little more than diluted sewage!

13.5.1.1 Tracer tests

Defining a spring's catchment area is a necessary first step in qualitative water resource management. The methods used to define and study aquifers are covered in Chapter 12. These include tracer tests, which are of great value in estimating the potential transit times of introduced pollutants, which are then used to delineate protective perimeters around springs.

13.5.1.2 Protection perimeters

In France, the regulations governing the protection of drinking water sources are based around a system of concentric perimeters:

- An immediate protection perimeter around the catchment system,
- A tight protection perimeter that allows for a reasonable response time in case of contamination,
- A loose protection perimeter on the whole aquifer.

In the tight protection perimeter, qualitative and quantitative restrictions are in effect in order to preempt any actions that could contaminate the water. However, water quality and quantity are related, because a karst aquifer that drops below its normal drainage point, reversing the hydraulic gradient, is at risk of absorbing contaminated surface water. In such cases, water quantity problems lead to water quality problems.

These perimeters were initially designed for porous aquifers and surface waterways. They are based on the idea that the farther a contamination source is from the catchment, the longer is will take for the contamination to reach the water source. The perimeters are usually designed to allow for a 50-day transit time, with the water flow velocity being defined by the permeability and the hydraulic gradient. However, in karst systems, where favorable drainage axes can rapidly carry water to a spring, with velocities of several hundreds of m/h, transit times can be very short. A 50-day limit would therefore require enormous perimeters, extending over the entire basin.

Defining protection perimeters in karst regions is therefore a complex task, and is often divorced from the physical appearance of the watershed. In order to tailor the perimeters to offer the best protection, it is allowable to delineate satellite perimeters, protecting potential points where rapid infiltration occurs (ponors or dolines). Some licensed hydrogeologists even include subterranean rivers, restricting or forbidding access to cavers (cf. 10.4).

However, these measures are often subjective, and more targeted strategies are recommended, such as detailed preliminary efforts to map and quantify vulnerability.

13.5.1.3 GIS

GIS (Geographic Information Systems) are useful tools in studying aquifer vulnerability. They can superimpose layers of physical information (topography, hydrography, geology, pedology, karstic networks, karstic surface indicators, etc.), and anthropological information (land use, human activity, agriculture, etc.). The intersection of these different data sets facilitates the delineation of vulnerable areas.

Various cartographic methods (EPIK, RISKE, RISK) have been developed in Switzerland and in France, using 4 or 5 parameters to characterize the sensitivity of karst aquifers to anthropological pressure, with the goal of defining a global vulnerability index (Doerfliger et al., 1999). The vulnerability maps generated in this way are useful in defining primary protection perimeters, as well as eventual satellite perimeters.

One example of a collaborative effort on an aquifer scale is the Aqui Brie association, which manages the qualitative and quantitative management of the Champigny limestone aquifer (Seine-et-Marne, France). This was prompted by a

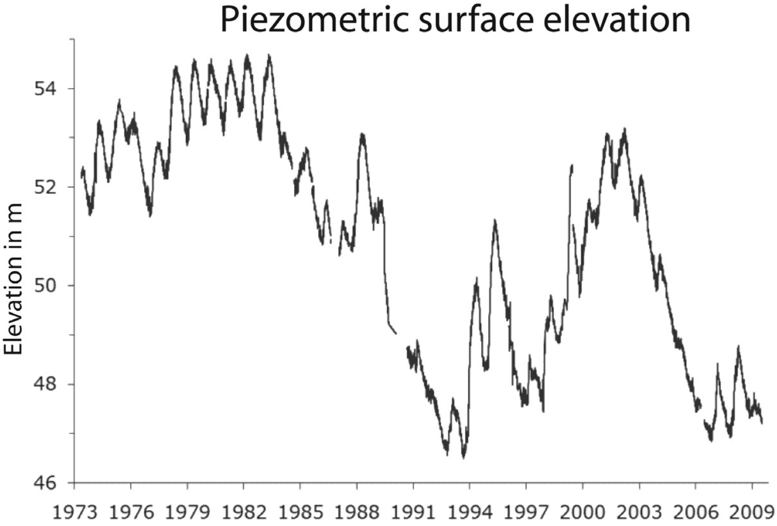


Figure 105. Drop in the water table in the Champigny limestone aquifer (doc. Aqui'Brie).

dramatic drop in the water table during the 1990s, resulting in problems with supplying enough drinking water to the nearby communities, and in persistently dangerous atrazine levels over more than 200 townships.

A GIS model of the aquifer was built, and is now used to manage the aquifer. It is used to integrate hydrogeologic data with anthropogenic, agricultural, transport, industrial, and recreational data. The organization also has an outreach and education branch, in order to educate users, both private and institutional, about the importance of rehabilitating the aquifer to a good hydrologic condition.

13.5.2 Agriculture and Soil Erosion

During phases of rhexistasy, infiltration of surface water into the epikarst is facilitated, and can lead to the movement of fine-grained particles. In agricultural regions, this can result in the disappearance of all arable land, while also increasing the turbidity of water emerging at springs. Preventing soil erosion is one of the priorities of the Guilin (China) Institute of Karst Geology.

A similar problem exists in areas where deforestation has led to fragile soil conditions.

14

Coastal and Submarine Karst Aquifers

Many of the world's large limestone units border coastal areas. This type of geography has consequences for the morphology and evolution of karst, as well as on the workings of coastal aquifers.

14.1 Morphology

When limestone units come into contact with the sea, they form very particular features. This occurs because, although sea-water is normally saturated in calcium carbonate and does not dissolve limestone, brackish water, which is a mix of freshwater and seawater, can and does favor dissolution. The process of weathering through mixing is described in Chapter 4. The increased ionic forces in the solution can shift equilibrium to favor dissolution. In coastal areas, the contact between karst water saturated in $CaCO_3$ and seawater can lead to more weathering. This mechanism also explains the formation of giant caves in the Nullarbor Plain (Australia) (James, 1992).

Several coastal environments are therefore favorable for dissolution:

- Areas subject to sea spray.
- River estuaries.
- The area around undersea springs.

These areas often display sea notches or visors, which cut horizontally the base of a sea cliff. They are being created when freshwater, which is less dense than seawater, forms a layer at the surface. Weathering occurs where the waters mix and is assisted by the organisms living in these areas. In intertropical zones, where precipitation is greater and creates a semi-permanent film of freshwater, sea notches occur all along the coast (e.g., Ha Long Bay in Vietnam, and Phang Nga in Thailand). The notches can extend for several meters, and were used to hide junks during the Vietnam War.

14.2 Coastal and Submarine Karst Aquifers

14.2.1 Saltwater Intrusion

Karst aquifers are by definition in contact with seawater, which can flow into the heart of the limestone unit. Freshwater, being less dense, floats on top of seawater. The geometry of the contact between fresh and salt water follows Ghyben-Herzberg Laws (Figure 106). The depth of the interface, the plane separating fresh and salt water, is located at a depth below sea level of approximately 40 times the value of the hydraulic gradient. The interface is more or less diffuse and is a zone of high corrosion rates (cf. chap. 4.3.4.4).

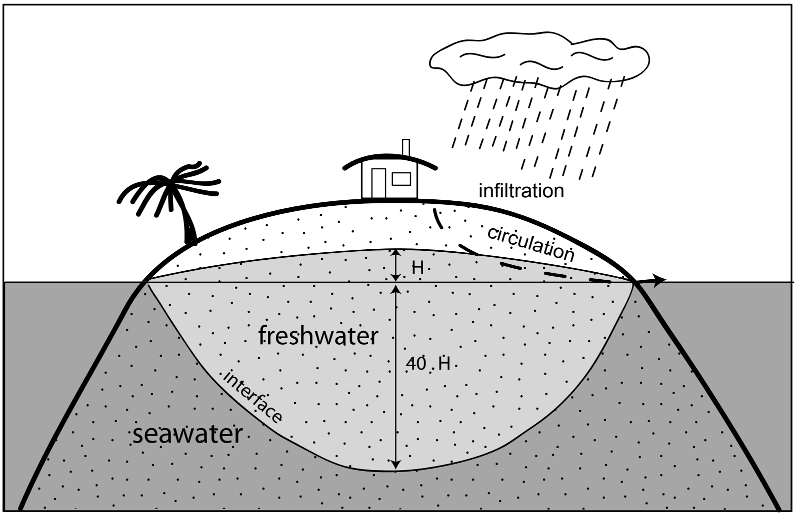


Figure 106. Ghyben-Herzberg lens in an island aquifer.

Anthropogenic pressure is generally high in coastal areas, and overexploitation of an aquifer can result in saline contamination. Understanding and managing coastal karst aquifer therefore requires a careful analysis of the contact.

14.2.2 Submarine Springs

There are many known submarine karst springs along the coastal limestone areas around the Mediterranean, as well as in Florida and in Cuba, where they have been carefully studied. They are almost all brackish, even when they are located a few meters above sea level.

The existence of such springs is a result of decreases in sea level, which leads to downward excavation of karstic passageways, and to the formation of new springs at low elevations draining these conduits. When sea level rises again, freshwater can no longer circulate in the deep conduits, and reuses older passageways. However, in some cases where there is a strong hydraulic gradient and favorable lithology, the deep

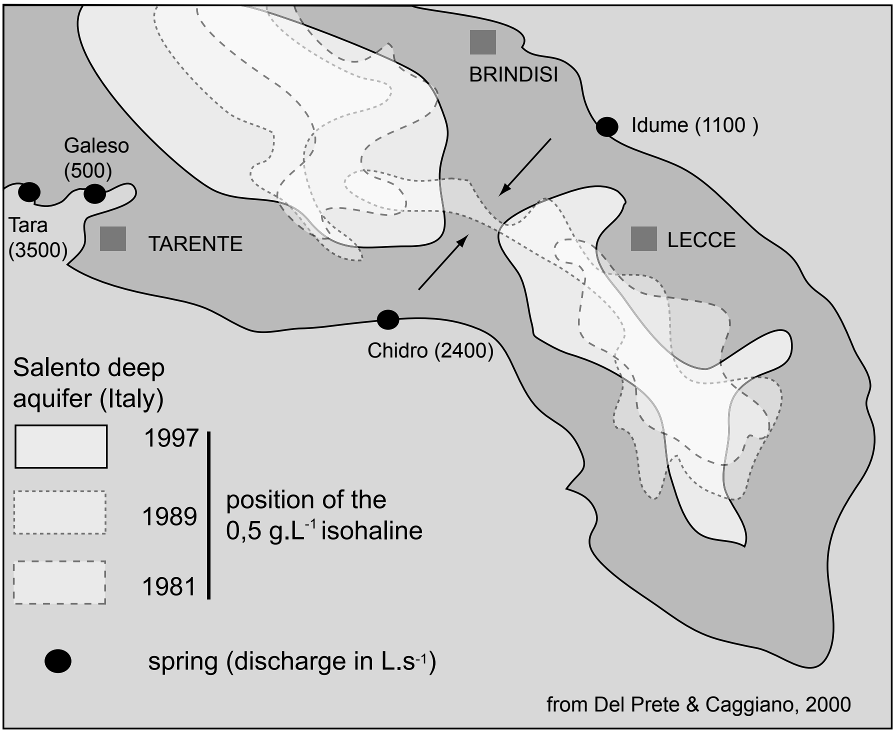


Figure 107. Variation in saline intrusions in the Salento aquifer (Southern Italy) (after Del Prete and Caggiano, 2000).

conduits can remain in use, feeding brackish submarine springs. These springs can form large caverns, accessible to humans, as is the case in Port Miou (Bouches-du-Rhône, France) and in Cabbé (Alpes-Maritimes, France), or they can emerge in alluvium, as is the case in the Vise, in Thau Pond (Hérault, France). In the areas humans can access, like Port Miou, undersea speleothems have been observed, confirming that the passage was once above sea level.

The presence of submarine or coastal springs is an indicator of important coastal aquifer systems. They are not generally directly usable, since they pick up salt upstream, but the signals they provide (variations in discharge, temperature salinity, etc.) are a source of precious information about the aquifers that feed them, and this data can be used to better manage the resource.

14.2.3 Effects of the Messinian Regression on Mediterranean Coastal Karst

The Messinian Salinity Crisis resulted in a considerable drop in sea level around the Mediterranean Basin, which affected the karst systems upstream. The drop in hydrologic base levels resulted in lower karstic water tables, moving water downwards until it reached impermeable structural units (the Keuper or the crystalline basement rock for example) (cf. chap. 8).

This period was followed by a sudden, synchronized rise in base level that occurred when water flowed back into the Mediterranean Basin from the Atlantic Ocean. It has been estimated that this took place over only a few decades, and can therefore be considered instantaneous. Seawater flooded the valleys, forming deep rias, blocking deep karstic circulation, and prompting a rise in hydrologic base level. The effects of the subsequent stable high sea level conditions were accentuated by sediment infill in the rias and alluvial deposits in the valleys (Audra et al., 2004).

14.2.4 Saline Contamination

Almost all coastal or submarine karst springs are either permanently or periodically brackish. Generally, when the discharge increases, the salinity decreases, which means that source of the salt cannot be related to the Venturi effect. There are two hypotheses explaining the contamination:

- **Diffuse contamination:** the karst conduit passes through a rock unit permeated with salt water, and the spring water becomes saline when it comes into contact with the rock. This mechanism is observed at the Almyros of Heraklion (Arfib, 2000).
- **Concentrated contamination:** secondary karst conduits take up seawater and carry it to the principal drainageway. This mechanism is observed at Argostoli (Greece) and in Port Miou (Marseille) (Gilli, 2001; Cavalera et al., 2010).

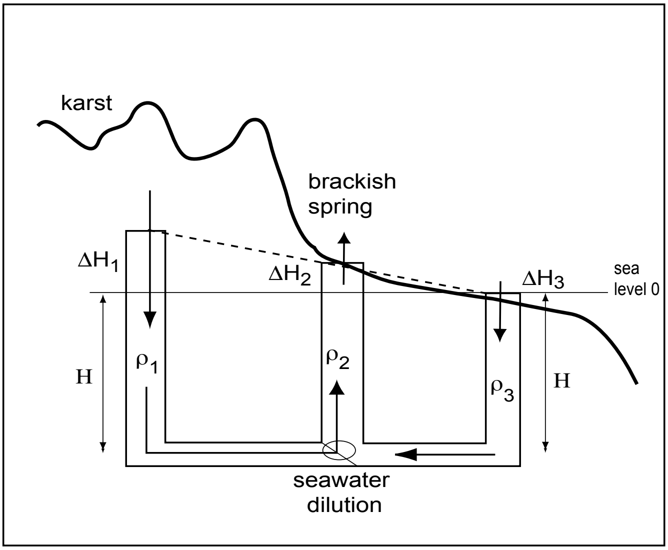


Figure 108. Saline contamination via a seawater conduit, with a brackish spring located above sea level. At equilibrium: $(H+\Delta H_1)\rho_1 = (H+\Delta H_2)\rho_2 = (H+\Delta H_3)\rho_3$. With depth H in the drainages; ΔH_1 hydraulic gradient in the karst; ρ_1 density of water in karst (considered a constant); ΔH_2 elevation of the brackish spring (constant); ρ_2 density of brackish water (variable); ΔH_3 sea level variation; ρ_3 density of sea-water (considered a constant).

In the first mechanism, diffuse salt-water intrusion can be limited by increasing the pressure in the freshwater conduit. In the second mechanism, the situation is more complex, but it can be modeled using a system of 3 connected tubes.

A laboratory model shows that when the amount of freshwater increases (when precipitation feeds into the karst aquifer), a current forms moving towards the brackish spring. The density ρ_2 in the brackish water tube decreases due to dilution, which creates disequilibrium in the seawater column and allows a negative ΔH_3. Since sea level remains constant (in the Mediterranean), there is salt-water intrusion into the conduit. This occurs in the Argostoli Moulins (Greece).

This model works if there is a great deal of dilution (and therefore of freshwater discharge) without significantly increasing pressure (ΔH_1). This implies large conduits, where losses of hydraulic head are minimal.

The motor driving salt-water intake is therefore the freshwater current, although geothermal fluxes can also have an effect, by inducing convection currents and the vertical migration of seawater. This mechanism was suggested to explain saline contamination of springs in Florida (Henry and Kohout, 1972; Sanford et al., 1998).

14.2.5 The Almyros of Heraklion (Greece)

This high-discharge (8 $m^3.s^{-1}$) spring has been defying attempts to use it for several decades. It has been the subject of numerous studies, because it has the potential to be an important water source for a region that, despite abundant precipitation, suffers from droughts that limit its economic development. It is located 6 km from Heraklion, at the foot of the Keri plateau, and 1 km from the coast, at an elevation of + 3 m. Unfortunately, it has very high salinity (5 $g.L^{-1}$) during the dry season.

Several diving teams explored the conduits for 500 m; reaching a maximum depth of –51 m. Recession curve analysis shows a well-regulated aquifer with significant reserves.

Between 1968 and 1971, the F.A.O. (Food and Agriculture Organization) and the Greek government undertook a significant hydrogeologic study in order to solve the salinity problem. An 8 m dam was built around the spring; in an effort to increase the hydraulic head for freshwater, thereby shifting the saltwater/freshwater contact, according to the Ghyben-Herzberg Law. Unfortunately, the project did not have the desired effect (Soulios, 1987; Maire, 1993).

Arfib (2000) demonstrated, based on salinity/discharge hysteresis curve analysis, that the contamination came from a porous rock unit saturated with seawater. When the discharge increases, the pressure prevents seawater entry. The contamination zone was estimated based on the delay between variations in discharge and variations in salinity. It is located at a depth of approximately 400 m. Theoretically, a dam over 10 m high would be required in order to create enough pressure in the conduits to prevent saline intrusions.

14.2.6 The Port Miou System

The submarine springs at Port Miou and Bestouan (Marseille and Cassis) are both exit points from the same aquifer, with submerged karst conduits that have been explored over several kilometers. They were described as early as the Classical Antiquity. These brackish karst springs, despite having a total discharge of approximately 7 $m^3.s^{-1}$, are not currently being used. They feed the largest waterway in the southwest between the Rhône and the Argens rivers.

They have been under study since the 1970s, and an experimental catchment system was put in place, with an underground dam meant to increase the hydraulic head (SRPM, 1978). Despite these efforts, the residual salinity remained high, near 3 $g.L^{-1}$, and the project was abandoned. The salinity is entirely marine in origin (Blavoux et al., 2004), and at Port Miou the water remains brackish 2 km in from the entrance, in a shaft that has been explored to a depth of 223 m.

These springs have a higher discharge than would be expected given their supposed impluvium, which includes the Urgonian ring around the Beausset basin, as well as part of the Ste Baume, totaling approximately 300 km^2. A large portion of Basse Provence, on the other hand, has a water deficit. It is therefore plausible to imagine that part of the water infiltrating into Basse Provence feeds into Port Miou. The basin is estimated to cover between 500 km^2 (Cavalera, 2007) and 1000 km^2 (Gilli, 2001).

Some karst features, such as the depth of the Port Miou conduits, or the presence of a submerged karst paleorelief 150 m deep south of the Calanques (Collina-Girard, 1996), can be explained by the regional base level having once been much lower, more than 200 m below current sea level. Similarly, the Cassidaigne canyon, a submarine feature off the coast near Port Miou, displays a pocket valley morphology, without being attached to a large enough continental valley. The current hypothesis is that Cassidaigne may have been shaped by a paleo-Port-Miou-spring more than 250 m below current sea level, during the Messinian Salinity Crisis (Figure 44).

Given this context, the current spring may have become brackish due to saltwater flowing in through the Messinian paleo-conduit. The discharge is approximately 1 $m^3.s^{-1}$. This hypothesis is supported by the analysis of hysteresis curves, which do not indicate a diffuse contamination mechanism (Arfib et al., 2006). Additionally, a layer of red sediment was observed upstream of the dam in the Port Miou conduit. The sediment may have come from the terra rossa in the catchment basin, or from the red marine clays deposited in the Cassidaigne canyon. This second hypothesis is supported by the composition of the metallic elements in the layer, which is similar to that of the Cassidaigne muds (Cavalera et al., 2010). This is further evidence for saltwater contamination via a paleo-drainage, as depicted in the following diagram (Figure 110). In Port Miou turbulence in the terminal shaft explain the sea water suction (Gilli, 2015).

14.2.7 The Argostoli Sea-mills

The Argostoli sea-mills are one of the most surprising karst features on the planet. On the western coast of Cephalonia (Greece), in Livadi Bay near the town of Argostoli,

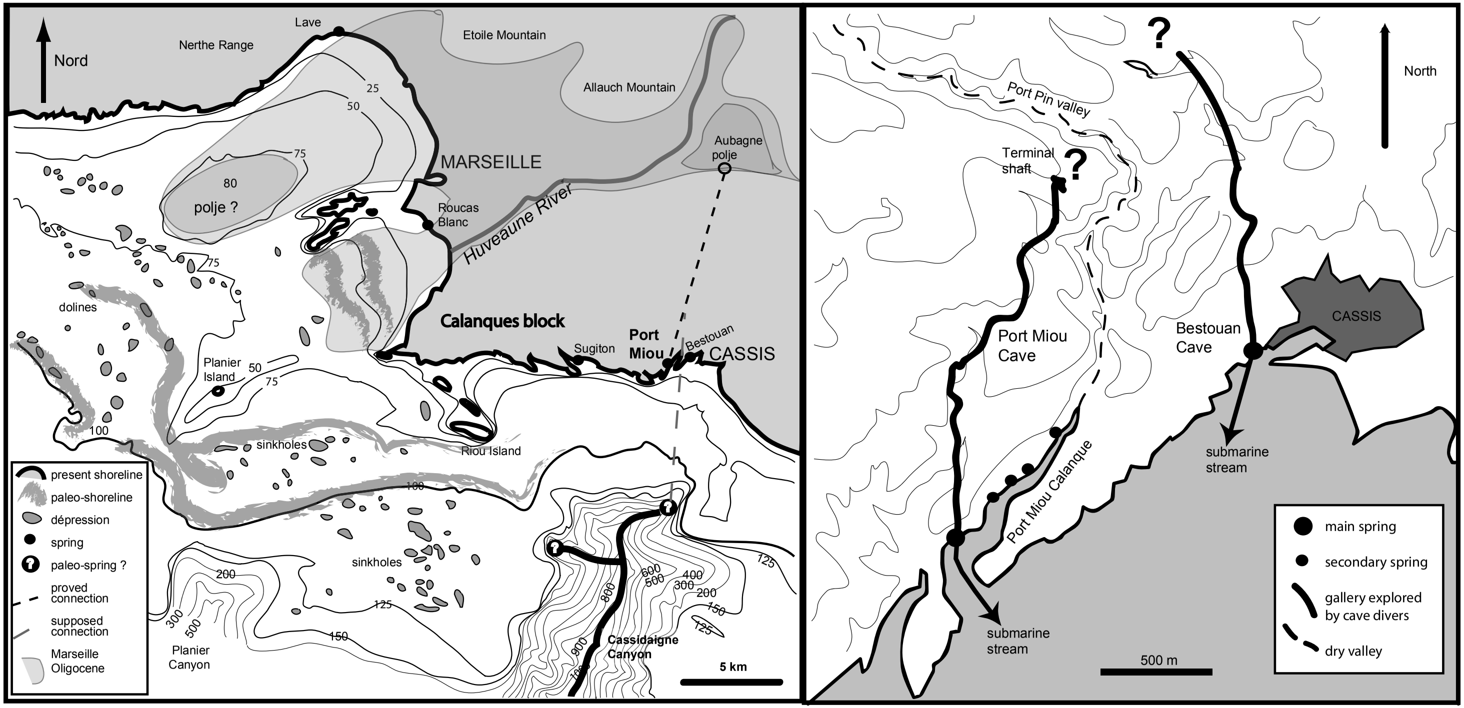


Figure 109. Submarine karst topography off the coast of Marseille (Collina-Girard, 1996) and Port Miou system off the coast of Cassis (Bouches du Rhône).

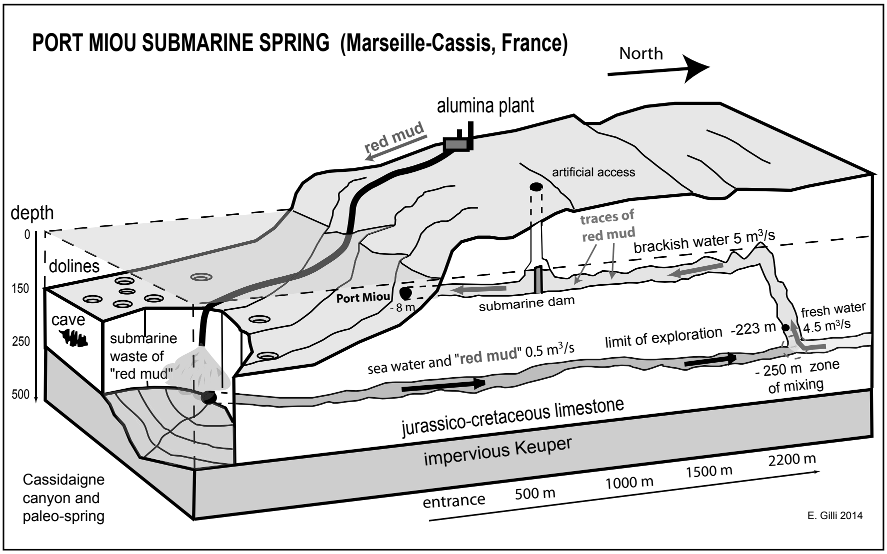


Figure 110. Potential model explaining the deep saline contamination of the Port Miou system.

swallow-holes draw in several tens of liters of seawater per second. A 1963 tracer test with 100 kg of fluorescein demonstrated that there was a connection, with a 16-day transit time, between the sea-mills and the brackish Karavomilos springs near Sami, on the eastern coast of the island, approximately 15 km from Argostoli (Maurin and Zötl, 1965) (Figure 111).

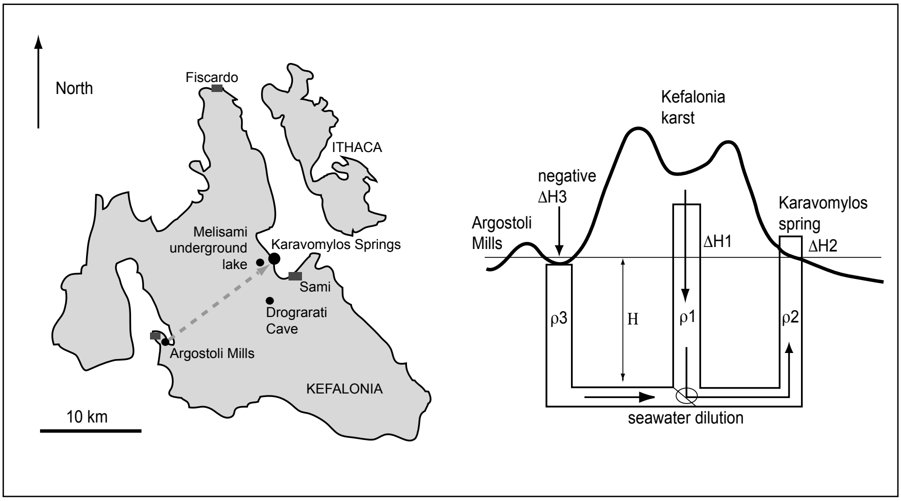


Figure 111. Map and model of the Argostoli sea-mills (Greece). A current forms between the western and eastern sides of the island. The system is driven by the karst aquifer's hydraulic gradient.

This area is therefore of exceptional interest, since the sea-water absorption mechanism described above is visible above ground, and there are known injection and restitution points, as well as openings into the karst aquifer at several different locations (Aggalaki, Melissani, Zerbati) where quantitative tracer tests could be undertaken.

14.2.8 Cenotes and Blue Holes

The Yucatan peninsula is scattered with coastal and submarine springs, as well as with cenotes, dolines that open directly into the aquifer, and that sometimes serve as access points to extensive networks of submerged cave. Several feats of technology were necessary for their exploration, particularly the use of diving bells that allowed explorers to rest during multi-day excursions. The cenotes were a source of water for the Mayans, and some of them were sacred sites used for sacrifice. Guided diving tours are available at the Dos Ojos cenotes (Tulum, Mexico), where tourists can explore a submerged cathedral-like chamber, with powerful lights illuminating beautiful underwater speleothems.

In coastal areas, divers generally pass through a layer of less saline water before reaching the underlying seawater. Divers have explored the Ox Bel Ha system (Tulum, Mexico), finding over 257 km of submerged passages reaching depths of 101 m. The halocline is, on average, 13 m below the surface. The neighboring Sac Actun system (Tulum, Mexico) is longer (333 km), and extends to greater depths, reaching a maximum of 130 m. There are many similar systems, with a maximum depth of 120 m (at Dos Ojos), which is consistent with glacio-eustatic sea level fluctuations.

Blue holes (Belize, Bahamas, Honduras, Yucatan) are submarine avens or sinkholes. They have also been interpreted as submarine cenotes. However, explorations have found that some of them are not connected to a cave network (C. Thomas, spoken communication). They are formed when an aggressive fluid dissolves per ascensum the limestone which forms a sinkhole when the phenomenon reaches the surface. This process is probably geothermally driven, as plumes of hot, less dense, water migrate through an aquifer (Sanford et al., 1998). This mechanism had previously been proposed to explain the behavior of coastal karst aquifers in Florida (Henry and Kohout, 1972). The rising plume enables dissolution as the waters mix and dissolved ions are evacuated.

14.3 Deep Submarine Karst

Many carbonate units that are currently submerged include closed depressions that can be attributed to a karst landscape (Florida, Corsica and outer shelf off the coast of Marseille in France). When such areas are an extension of a continental karst area, the features can be explained as being inherited from a period when sea level was lower and the limestone was exposed. When sea level rose again, due to glacioeustasy, tectonic uplift, continental flexure, or isostasy, the karst features were submerged.

Neoformation has also been considered, if freshwater circulation fed by continental sources dissolved the limestone, mixing with seawater could create a highly aggressive environment. This has been suggested, but not yet proven, as an explanation for the linear distribution of large submarine avens on the continental shelf along the coast of Florida (Land and Paull, 2002).

However, topography that looks like karst one has been observed in chalk deposits at depths of 1700 to 2600 m, along the Carnegie Ridge (Equator), east of the Galapagos. The depth and distance from any continent make this feature difficult to explain. It contains depressions that can reach depths of 300 m and diameters of 2 to 3 km, larger than the features normally found in tropical karstic limestones (Figure 112). Although several mechanisms have been proposed, the explanation currently being favored is that the features are being formed through dissolution at depth (Michaud, 2008). However, it is possible that classic karstification is responsible, during a period when the area was above sea level. The Galapagos Islands, located along the same ridge, are an example of an area that is currently uplifted. Such an explanation would require that at some point, the mechanics of subduction led to uplift of that area by several hundred meters, followed by 2500 m of subsidence.

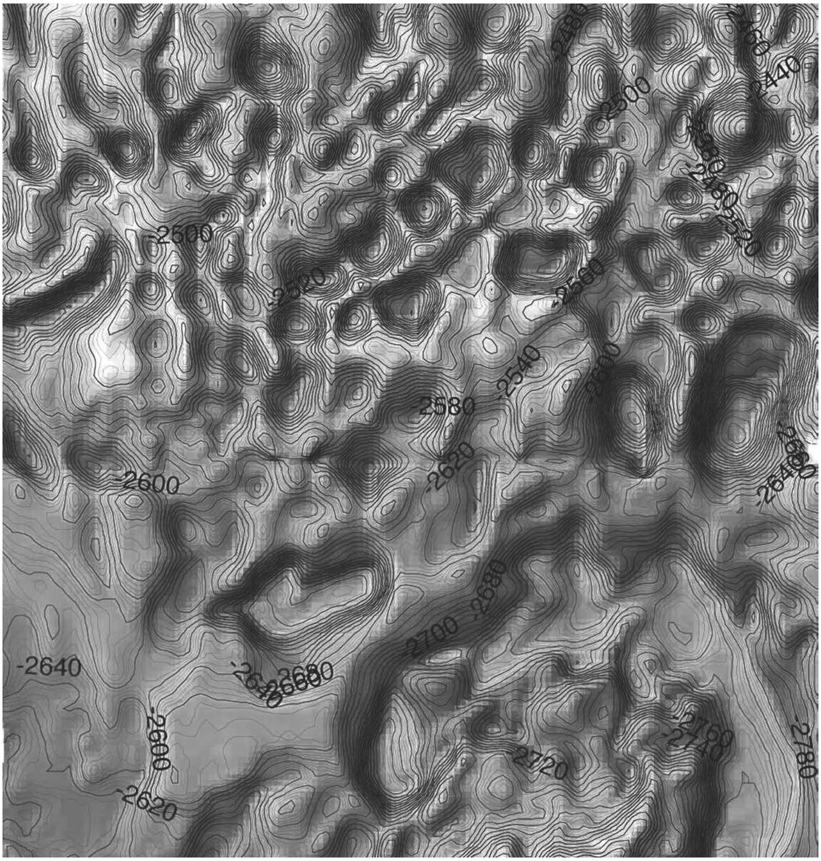


Figure 112. Topography along the Carnegie Ridge, at a depth of 2500 m, attributed to karstification (Pacific Ocean) (after Michaud, 2008).

14.4 The Study and Management of Coastal Aquifers

Drawing water from coastal aquifers is problematic due to the relationship between the continental aquifer and the marine environment. The use and management of such aquifers must take into account three major difficulties: evaluating discharge, understanding the mechanisms by which water becomes saline, and estimating the risk of saltwater contamination.

14.4.1 Measuring Discharge at Sea

Karst aquifers flow out into the sea, either in a diffuse manner, through fractures in the rock, like other aquifers, or through coastal or submarine springs. The water discharge is generally brackish, due to contamination upstream of the springs. Measuring discharge, which is already difficult (as explained in Chapter 12), becomes even more challenging, since it involves measuring fluxes of water of varying salinity in a liquid environment with constant salinity. Additional difficulties arise from the fact that in large conduits, like those at Port Miou, the water is stratified. Precise measurements are therefore impossible without completely isolating the spring from the surrounding sea-water, or taking measurements inside the conduit, as was done in Port Miou, where the SEM (Marseille Water Administration) dam was equipped with sensors.

Out at sea, a surface salinity map can be used for preliminary evaluations, by estimating the number of brackish springs. For example, in Port Miou and in Bestouan (Cassis, Bouches du Rhône) the surface salinity map shows isolated plumes, whereas a map of the surface around the Pissarelles Springs (Eze, Alpes Maritimes) shows multiple springs emerging from fractures around the main spring. In the latter case, the measured discharge must be increased by some factor, which is difficult to determine.

One method currently being developed relies on dissolved radon and radium isotopes to quantify groundwater fluxes in coastal regions. The isotopes are present in different amounts in freshwater and in seawater.

14.4.2 Characterizing Saline Contamination

Understanding contamination mechanisms is a necessary step in deciding how to exploit a resource. A terrestrial source can be excluded based on the Br/Cl ratio. A ratio (in mEq/L $.10^{-3}$), around 1.51 is characteristic of seawater while a ratio between 0.7 and 1.2 indicates the presence of evaporites.

If the marine contamination is diffuse, an increase in pressure could theoretically prevent salt-water intrusions, as is the case in Anavalos-Kiveri spring (Greece). If the contamination is occurring in the drainage network, one potential solution is to intercept the freshwater by drilling a borehole upstream of the mixing zone.

Analyzing hysteresis curves during periods of high discharge, with Q_{sea} (sea-water discharge)/C_T (salinity), can yield information about the mechanisms responsible for the salinity of the water (Arfib et al., 2006). The curve (Figure 113) is characteristic of a limited diffuse contamination during high-discharge periods, when the hydraulic head in the conduit increases.

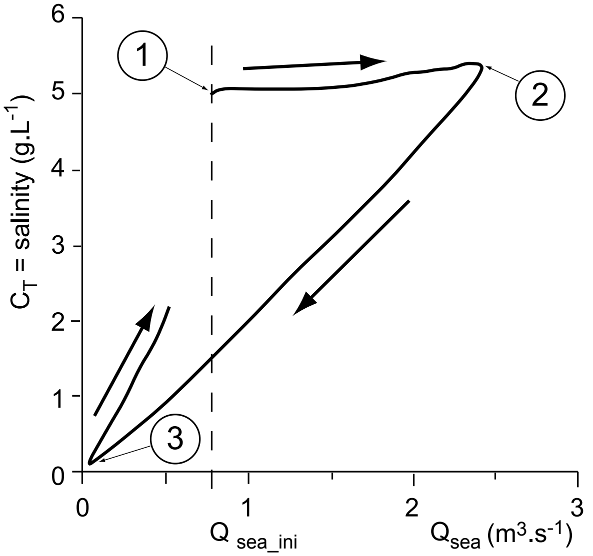


Figure 113. Hysteresis curve discharge/salinity, during the January 16th to 27th floods in 2001 at the Almyros spring in Heraklion (Greece) (after Arfib et al., 2006). The salinity (C_T) and intrusive seawater discharge (Q_{sea}) inducing the salinity are measured. The high-discharge period begins at 1, and the discharge increases without increasing the salinity until 2. Then from 2 to 3 the salinity drops and the seawater discharge decreases to less than the initial Q_{sea}, because the increased hydraulic pressure in the conduit prevents the entry of seawater.

14.4.3 Exploitation Methods

14.4.3.1 Catchments at the spring

Anavalos-Kiveri. This is one of the rare examples of a successful catchment system at a spring. A semi-circular dam with sluice gates was built around the spring, separating it from the sea, and maintaining enough freshwater pressure to prevent seawater from intruding. The salinity determines how much the sluice gates are opened and how much water can be drawn.

Tarento Springs (Italy). These are located on the Salentino Peninsula (Figure 107), in the Mar Piccolo at a depth of 20 m. They have been used since the Classical Antiquity, and Strabo described a catchment system involving copper and lead pipes. Out of the fifteen or so springs, the Galeso was chosen to be covered with a fiberglass bell, encompassing the entire opening (Figure 114). The catchment system includes a siphon, where the seawater freshwater interface is located. Conductivity probes monitor the location of the interface, and the discharge being pumped out is adjusted accordingly in order to avoid contamination. Nevertheless, the system has thus far not been able to adequately decrease the salinity.

Mortola Spring (Italy). This spring discharges approximately 100 L.s^{-1} and is located at a depth of 36 m off the coast of Menton close to the French-Italian bordure. An experimental catchment system was put in place during the 1960s, by placing a pipe in the conduit in order to feed a floating fountain out at sea. By isolating the seawater, the hydraulic gradient was strong enough to creating an artesian spring that rose above sea level. However, the spring remained brackish the entire length of the several-month trial period, leading to the conclusion that the spring could not be used (Stéfanon, 1972).

A more recent attempt, with a catchment system based on the one at Tarento, ended in resounding failure, when the system drew in seawater and actually increased the salinity at the spring.

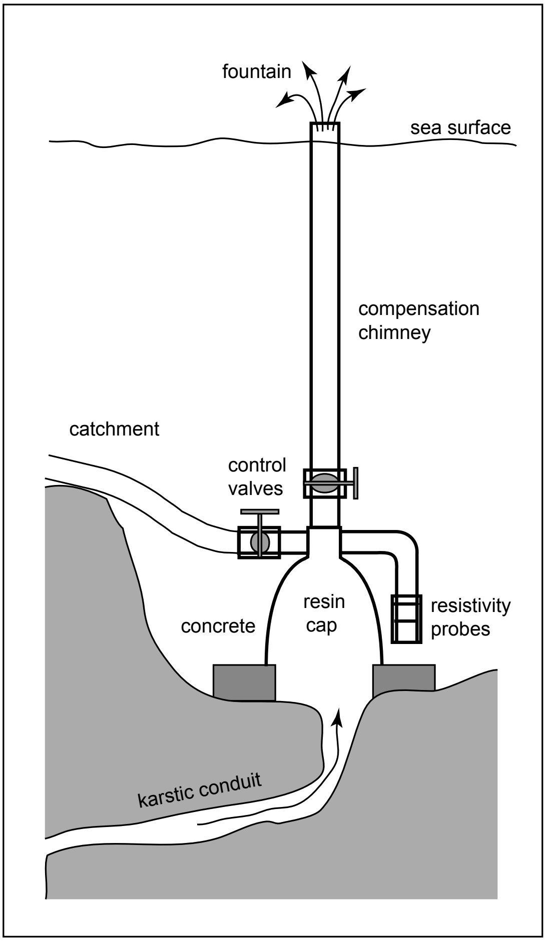


Figure 114. Catchment system at the Galeso Spring (Tarento, Italy) (after Stefanon, 1984).

14.4.3.2 Boreholes

The Chekka springs in northern Lebanon are a group of 17 springs, located between 20 and 1500 m from the shore, at depths of –25 to –45 m. Their discharge is of several m^3.s^{-1}. The salinity varies from 16000 mg.L^{-1} in the summer to 46 mg.L^{-1} in the winter. At Point C, on land, the salinity is 24 mg.L^{-1} year-round.

The springs are fed by a confined karst aquifer beneath a roof of impermeable marl. At Point C there is an artesian spring, and boreholes have confirmed that the aquifer can support artesian wells. The springs occur where there are faults through the marl (Figure 115).

The limestone aquifer is protected from salt-water intrusions by the marl, which forms a barrier. The springs are the only point of entry for seawater. When the hydraulic pressure is great enough, freshwater pushes the seawater back to point S12. If the discharge drops, seawater starts flowing in from S12, preventing freshwater from exiting the system at that point, and directing it all towards S1.

Given the low salinity of the system, the water is usable and is drawn from boreholes upstream of the springs.

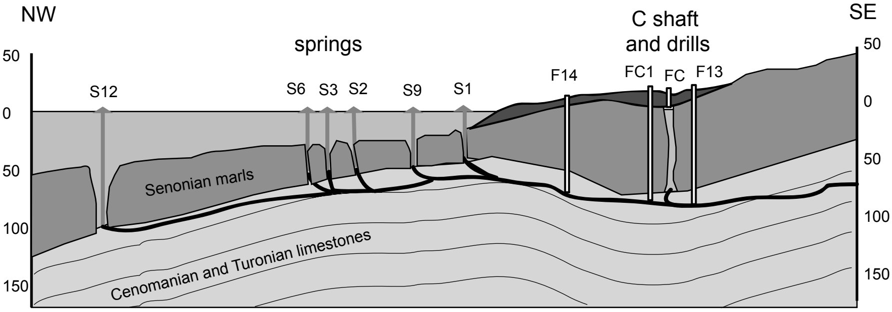


Figure 115. Chekka springs (Lebanon) (after Kareh, 1967).

14.4.3.3 Drainage passageways

In order to avoid disrupting the freshwater/salt water equilibrium, one method is to only extract water from the upper layer of the aquifer, using several shallow borewells, in order to minimize the drawdown.

Another option is to excavate subhorizontal drainage passageways at the top of the aquifer. Increased discharge is achieved by elongating the passage. There are numerous examples of such catchment systems, in Croatia, Cuba, and Malta (Breznik, 1998). One advantage of this method is that the active fractures can be blocked off if their salinity increases too much.

15

Development in Karst Regions

Construction projects in karst regions face two types of problems: those caused by anomalies or cavities below ground, and those caused by the hydrologic workings of karst systems, which can lead to water inflows during civil engineering projects, leaking dams, and flooding in urban areas.

15.1 Sub-soil Anomalies

Anomalies can include voids, or highly uneven topography, with lapies and dolines beneath an unstable soil cover. These induce the risk of uneven compaction across the site, which can cause buildings to fracture if, for example, one corner of the foundation rests on limestone and another on clay.

In Sophia Antipolis (Valbonne, France), one building project was planned for an area of Bathonian paleokarst, with a complex geometry of clay layers filling in dolines and caverns (Figure 116). This limestone paleorelief was gradually sealed off by clay

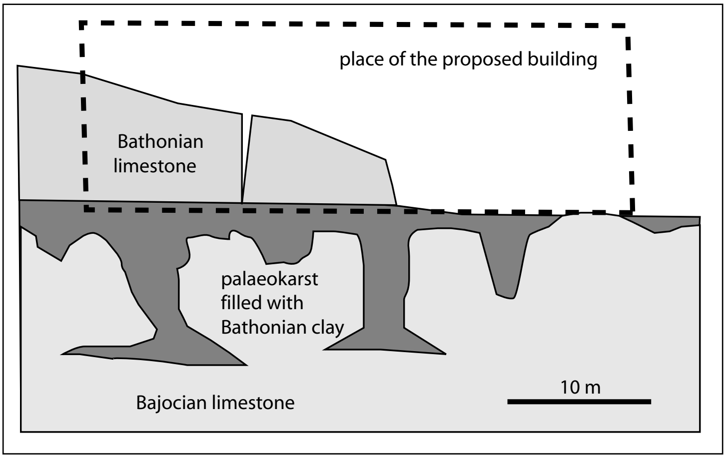


Figure 116. Projected construction plans disregarding paleokarst (diagram based on the Life Sciences building at Sophia Antipolis).

spreading out and then by Bathonian limestone sedimentation. Part of the building's foundation would rest on limestone, which can bear loads of over 1 MPa (10 bars), while another part rested on clay, which can have load-bearing capacities of less than 0.1 MPa. In order to prevent differential compaction, foundation wells were drilled down beneath the clay levels.

In the absence of preliminary reconnaissance work, such problems are revealed only after the soil is cleared from a site. They are often easy to work around, but require costly and time-consuming accommodations.

More difficult problems arise if there are voids or cavities beneath a proposed foundation. Such spaces are often discovered by chance during construction, and the overseeing company often fails to report them. When they are near the surface, or directly beneath part of a foundation (pile, isolated pad), the roof of the cavern may be considered too thin to support additional weight, and the construction plans must be modified accordingly, either by changing the footprint of the foundation or by taking site-specific measures. However, the mechanical strength of a cavern roof is difficult to estimate, and the rock may have been made less stable by the use of explosives nearby. In the following example at Sophia Antipolis (Alpes-Maritimes) (Figure 117) caverns discovered by chance were explored, and their stability analyzed. They could have simply been reinforced, but mining work had destabilized them, and the foundation had to be deepened to anchor below them (Mangan, 1985).

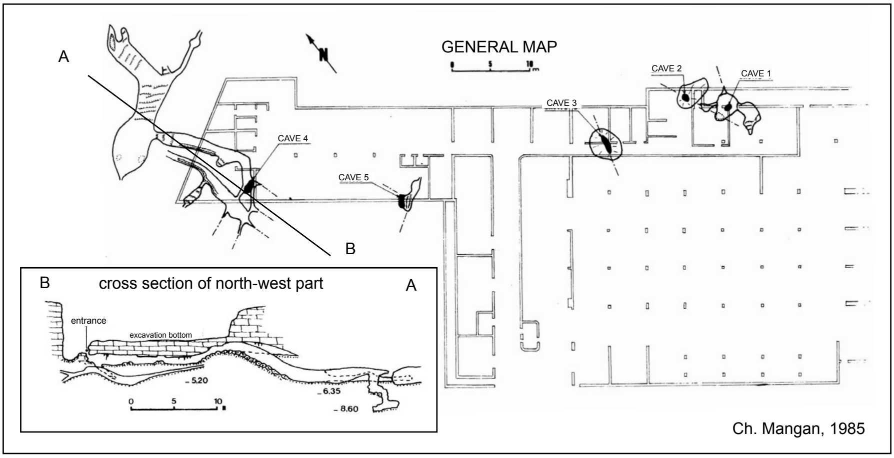


Figure 117. Caverns discovered during construction at Sophia Antipolis (Alpes-Maritimes) (Mangan, 1985). Significant excavation work had destabilized the cavern roof, requiring more than simple reinforcement structures.

When the cavern is smaller than the projected construction, the foundation can be modified to form a bridge over the weak zone. The building can also be protected against future slumps or landslides by drilling deep foundations that pass through the cavern and are anchored on its floor (Figure 118).

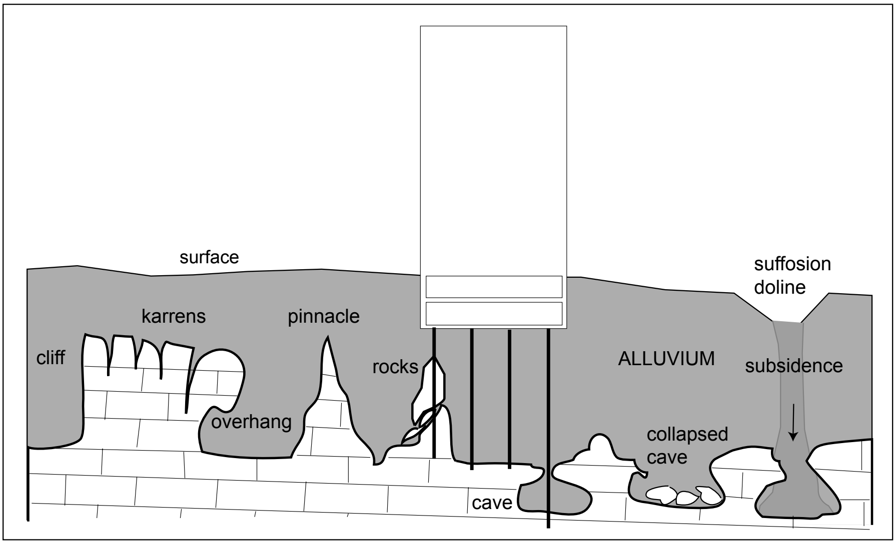


Figure 118. Schematic rendering of the civil engineering problems found in Kuala Lumpur (Malaysia) (after Chang and Hong, 1986). The town of Kuala Lumpur is partially built on alluvium that filled in over paleokarst.

15.2 Hydrologic Problems

15.2.1 Water Inflows

Dolines and poljes, which normally absorb all the water flowing into them, can occasionally become saturated and create temporary lakes, flooding any buildings in the basin. Construction projects with deep foundations can also cause flooding, by blocking groundwater circulation.

Groundwater circulation patterns, inherited from often-complex paleogeography, can sometimes behave in atypical ways as a result of the geometry and size of pre-existing conduits, which can only accept limited discharge. As a result, during rainy periods there can be sudden outflows due to the water table rising, sometimes over a hundred meters, which can lead to flooded buildings. This may be a yearly event, or it may be a rare occurrence, in which case it quickly disappears from collective memory. For example, in an industrial zone called Fuon Santa (La Trinité, France) a warehouse containing household electronics was suddenly flooded by water pouring from a temporary spring, whose existence had been completely forgotten. The aquifer feeding the spring had other exit points beneath a layer of alluvium from the Paillon River, which is the local hydrologic base level. Since all of the springs were hidden by alluvium, there had been nothing to suggest that the karst system was active. However, local toponymy provided clues as to the presence of a spring: Fuon Santa means “Holy Fountain”, a name commonly used for springs with mysterious behavior.

15.2.2 Aquifer Contamination

Civil engineering projects, quarries, and underground construction projects in karst areas can lead to significant groundwater contamination by hydrocarbons or by chemicals used in cement grouting. This leads to drinking water contamination or to decreases in discharge. For example, the Larvoto springs (Monaco), which were used as a source of drinking water, were highly negatively impacted by the construction of nearby buildings and their foundations.

15.2.3 Dams and Lakes in Karst Areas

In limestone areas the prevalence of narrow gorges in canyons and the high mechanical strength of the rock have favored dam construction [some as high as 105 m, in Oymapınar (Turkey)]. When the projected reservoir extends over limestone units as well, there is a risk that water will flow into underground passages and create a hydraulic short-circuit (Table 13). There are several examples of large dams that were never able to fill their reservoirs, both in France (Bouvante Dam, Vercors) and abroad, such as the Montejaque Dam in Spain (Thérond, 1973) (Figure 119).

The leakage generally flows out through pre-existing springs, or through empty or sediment-filled karstic conduits. When the influx of water clears out the sediment, there are sometimes very sudden increases in discharge. The water usually emerges back at the surface less than 2 km from the dam. Thérond (1973) demonstrated that the springs' natural drainage basin, when subject to an increase in discharge due to leakage, extends out to the reservoir. He estimates that a karstic conduit presents a significant risk if it is less than 150 m away from a reservoir. The size of a spring's drainage basin can be quickly evaluated if the specific infiltration modulus of the relevant areas is known (for example, with a modulus of 10 $L.s^{-1}.km^{-2}$, a 10 $L.s^{-1}$ spring corresponds to a 1 km^2 drainage basin).

In France, the Génissiat Dam on the Rhône (104 m), the Vouglans Dam on the Ain (130 m), the Castillon Dam (100 m) and the Sainte-Croix Dam (90 m) on the Verdon were built on karst terrain, and in some cases were faced with significant cave networks (Caborne de Ménouille, Fontaine l'Evêque Cave). Nevertheless, time-consuming studies and the emplacement of large grout curtains (44,400 m^2 in Castillon, 50,000 m^2 in Sainte-Croix) led to success for the dams.

Table 13. Examples of the magnitude of leakage from dams in karst areas.

Name	Country	Discharge in $m^3.s^{-1}$
Keban	Turkey	26
Vrtac	Yugoslavia	25
Iliki	Greece	13
Canelles	Spain	8
Camarasa	Spain	11.2
Lar	Iran	10.8
Marun	Iran	10
Mavrovo	Macedonia	9.5
Great Falls	USA	9.5

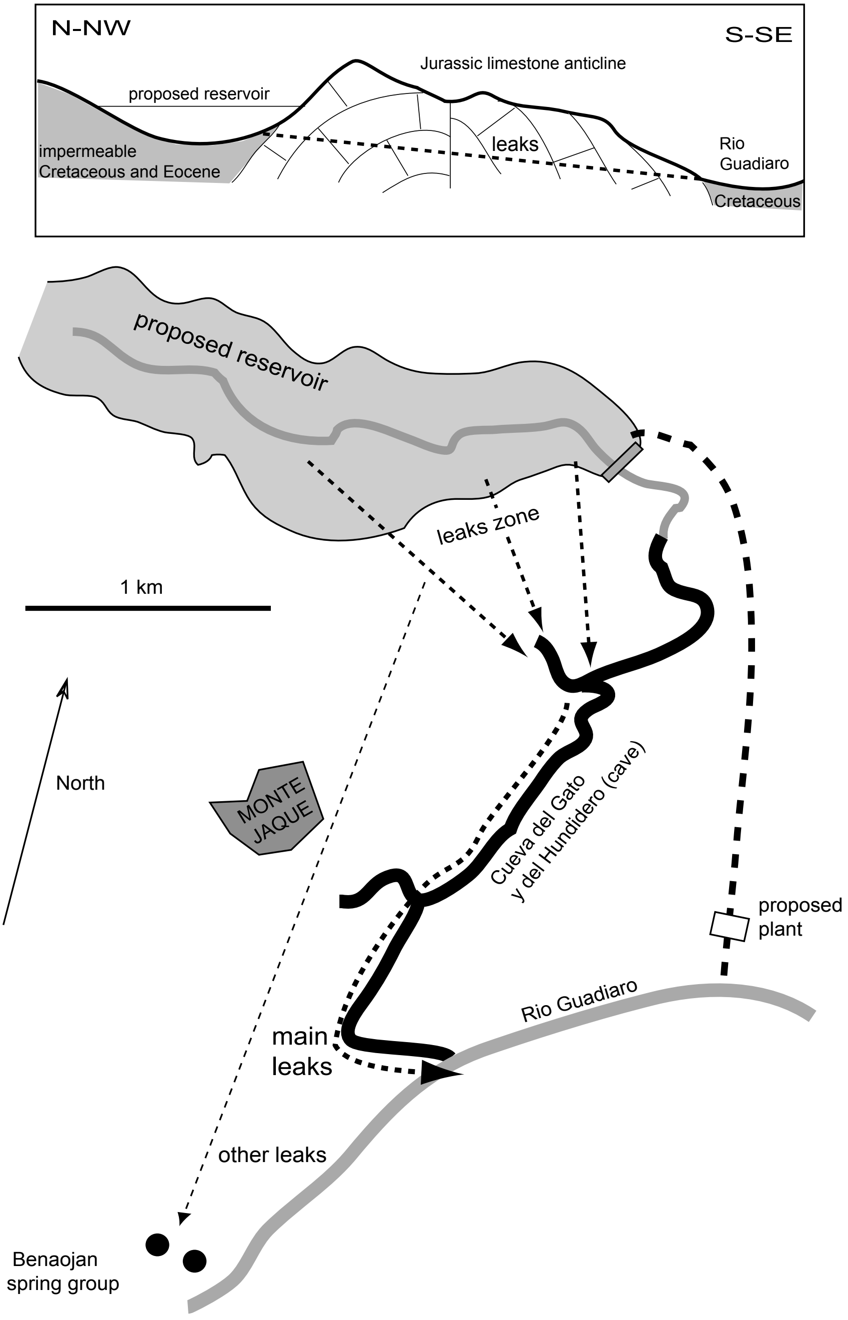


Figure 119. Leakage from the Montejaque Dam (Spain).

Cheurfas Dam (Algeria)

After it was rebuilt following partial destruction in 1885, this dam required significant waterproofing in order to mitigate losses from its reservoir, which was being drained through the underlying karstified Tortonian limestone. The infiltrated water re-emerged immediately downstream of the dam, at the level of several springs on the left bank of the Oued Mebtouh River. On the right bank, a grout curtain was easily built, stretching down to the underlying Helvetian sandy clays. On the left bank, the particular structure of the site (a faulted syncline) meant that a conduit had to be excavated slightly above the water level in the reservoir, to serve as a platform from which to build a grout curtain. The curtain itself required a total of 5,824 m of injection wells, and 2,631 tonnes of grout. The construction, once finished, decreased the reservoir's losses by 90%.

Keban and Atatürk Dams (Euphrates, Turkey)

Turkey undertook an ambitious development program along the Euphrates, consisting of several large dams. Completed in 1974, the Keban gravity dam, 185 high, was built on the Euphrates (which has an average discharge of 655 $m^3.s^{-1}$) on a marble unit, with the goal of creating a 30 billion m^3 reservoir to be used for irrigation and hydroelectric power generation. During construction, a 100,000 m^3 karst cavern, the Crab Cave, was discovered 300 m below the dam site. It was filled with cement, and the unit beneath the dam was waterproofed using a grout curtain. On the left bank, karst features were discovered during preliminary geologic surveys, as well as during the excavation of a diversion. A 250 m deep grout curtain was put in place in this area as well, although it appears to have been insufficient given the position of the Crab Cave. When the reservoir was filled, significant leaks appeared, creating a vortex on the lake's surface. Increasing leakage led, in 1976, to losses of 26 $m^3.s^{-1}$, compared to the initial 6 $m^3.s^{-1}$. The lake was partially drained, revealing an opening into a large cavern, the Petek Cave. This opening was surrounded by a concrete chimney, in order to decrease its absorption capacity, and was then filled with one million m^3 of material. Part of the left bank was also waterproofed with a 50 cm-thick curtain wall. These modifications brought the water losses down to 9 $m^3.s^{-1}$, which is only slightly over 1% of the Euphrates' total discharge, and its therefore economically viable.

An examination of the caverns led to the conclusion that they were hydrothermal in origin (Bozovic et al., 1972). This may explain why the risk of karst-related problems was underestimated. In fact, surface surveys during the preliminary studies for the dam did not find very evolved karst features.

A similar problem occurred during the construction of the Atatürk Dam downstream of the Keban Dam. The former rests on an area of dolomitic limestones interspersed with thinly bedded limestones. A few springs were known to exist downstream, but their temperature (24 to 26°C) suggested a hydrothermal source, tied to deep karstification estimated to extend down 300 m. The risk of reservoir losses through these rocks had been considered negligible. Nevertheless, when the dam was built in 1989, the discharge at the springs increased gradually to over 10 $m^3 s^{-1}$. The grout curtain that had been built extended down to 200 m but did not reach an impermeable substratum, and so water was able to flow around it (Ertunç, 1999).

15.2.4 Water Storage in Poljes

The sediments at the bottom of poljes are generally relatively impermeable, usually consisting of alternating layers of gravel and clay. It is therefore logical to use this natural impermeability to store water outside of the rainy season, by blocking up the ponors. Several examples of this type of use are known in the karst regions of the Dinaric Alps. Whether or not such a project succeeds depends on the type and on the thickness of the deposits that have accumulated in the depression, on the difficulty of effectively clogging the ponors, and on the risk of water finding other entry points into the epikarst. In addition, some flood occur through estavelles when the water table rises, which complicates waterproofing efforts. The rising water table exerts a force that comes from below rather than from above, which is what most reservoirs are built to handle. Rising water tables can also flush air out of the conduits. The Popovo polje reservoir (Bosnia-Herzegovina) was built with a waterproof membrane, and a relief valve in a borehole, through which air can escape when the rising water table pushes it out of the passageways beneath the polje (Breznik, 1998).

There are also numerous examples of failed attempts, since water often flows around structures meant to hold it in, and can clear out old karst conduits. The Slivje ponor, which drains the Nikšičko polje (Montenegro), for example, was surrounded in 1950 by a 50 m in diameter, 20 m high chimney, to create a reservoir. The chimney was built directly onto the limestone bedrock, under ten or so meters of clayey silt. As soon as water was put into the reservoir, new absorption points opened up around the chimney, and the water cleared out older passageways, resulting in major losses from the reservoir. Eventually, significant construction work involving grout curtains resulted in several functioning reservoirs on the surface of the polje (Breznik, 1998).

In Thorenc, a small tourist resort in the Alpes-Maritimes (France), a similar project was undertaken around 1900, with the goal of creating a lake. It was located in a small polje, at the contact between Cretaceous marl and Jurassic limestone, fed by a permanent stream and drained by two ponors at the lowest points of the depression. The polje is located at an elevation of 1,165 m, and tracer tests demonstrated a rapid linkage between the water absorbed at the ponors and the Mouna spring, at an elevation of 1,000 m. The ponors were isolated by structures anchored in the bedrock, concrete chimneys with valves to regulate the level of the lake and to accommodate overflows by directing them into the ponors. A lake did form when the project was first tested, but hydraulic short-circuits soon appeared in the immediate periphery of the chimneys, absorbing all of the accumulated water. The project was abandoned, but the two concrete chimneys remain, now standing in a grassy field, as reminders of this failed project (Figure 120).

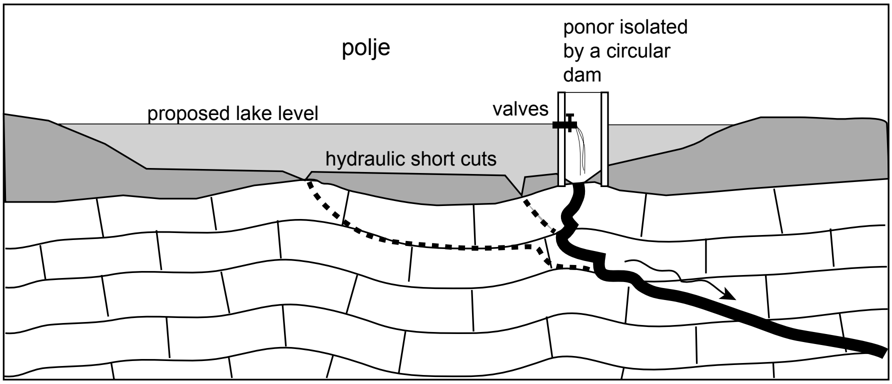


Figure 120. Thorenc polje (Alpes-Maritimes). Outline of the project.

15.3 Karstic Subsidence and Drawdown

On a human timescale, the effects of dissolution on limestone are barely noticeable. However, pumping in karst aquifers can, by transporting fine-grained sediment, clear out caves, which can collapse in on themselves. These collapses can have repercussions at the surface, resulting in significant damage to any buildings in the area. Same mechanism may also occur in non karstic areas (Figure 121).

Figure 121. Urban pseudokarst sinkhole in Guatemala.

In areas with gypsum units, given the high solubility of the rock, anthropogenic dissolution cavities can appear and evolve rapidly, as they did at the Kodak factories in Sevran (France), where large amounts of water had been pumped out to be used in processing photographic film (Toulemont, 1987). The Cannes-Grasse (France) highway collapsed suddenly for the same reason in 1998, due to pumping water to irrigate a golf course (Mangan and Gilli, 2002) (Figure 122).

A similar problem arose during the construction of the Toulon (France) highway tunnel, which collapsed in 1996. Construction of the tunnel, which was below sea level, required significant pumping over the course of several years. The pumping reactivated a paleokarst in the Keuper gypsum unit, which had originally formed when the Mediterranean was much lower, and had then been isolated and filled in when sea-level rose again.

Figure 122. Cannes-Grasse highway collapse (Alpes Maritimes, France) in 1998. The damage was a result of gypsum in the underlying rock being rapidly dissolved due to groundwater pumping to irrigate a golf course.

The 1996 collapse of the Toulon tunnel

Beneath the city of Toulon runs a highway tunnel, thirty meters below the surface and approximately ten meters below sea level. When the tunnel was designed, preliminary studies did not take into consideration the paleogeography or the state of the karst system in the coastal area. This had serious repercussions: during the excavation process in 1996, part of the tunnel roof collapsed, bringing construction to a halt. The accident, while it luckily did not cause any deaths, was observed by an eyewitness who reported that the side walls of the tunnel collapsed first, causing the roof to cave in. This suggested that a cave had collapsed beneath the tunnel, rather than that the roof had failed.

- Hydrogeologic analyses demonstrated that significant inflows of water had been noted in areas where the construction passed through karst. They were stopped up using grouting, without any investigation regarding what happened to the water that was thereby diverted.

- Following the cave-in, geophysical measurements indicated a significant negative anomaly in the area, which was attributed to a pocket filled with loose material.

- Bathymetric surveys nearby had found karst paleorelief at depths of 120 m. A bathymetric analysis was made in the study area, based on SHOM (Naval Hydrographic and Oceanographic Service) data, with an isobath spacing of 1 m. The analysis revealed the following features: closed depressions peppering the sea floor, and a narrow canyon approximately 12 m deep cutting into it. Both are characteristic of karst topography.

- On land, a few kilometers from Toulon, divers exploring submerged karst systems (Ragas) found passageways 90 m below sea level.

Deep karst systems are therefore present in the area, at least down to elevations of –100 m, and probably as far as –150 m. Karstification occurred in the limestone units, but also in the Keuper gypsum layers, which were probably affected by water rising up from the limestone.

Geologic surveys undertaken both before and after the accident revealed the existence, in the gypsum units, of a depression filled with weathering debris. Data archives, when analyzed, contained evidence that similar cave-ins had occurred in the past.

Based on all of this information, the following sequence of events was proposed to explain the accident:

The Mont Faron limestone massif, which drains to the south, funneled large volumes of water into gypsum-rich areas. During a period of much lower sea level, a strong hydraulic gradient led to a high degree of karstification in the Jurassic limestones and the Keuper gypsum units, as well as in the underlying Muschelkalk limestone. When sea level rose again, the sea flooded the karst area; gradually filling sediment into the spaces that had been carved out. When construction began, several years of pumping reactivated old circulation patterns, clearing one of the old passageways and leading to its collapse. The process was amplified by salt-water intrusion, which increased the gypsum's solubility (Mangan and Gilli, 1997).

15.4 Location, Detection, and Remediation of Cavities

15.4.1 Goals

During construction in karst regions, there are two essential questions to be asked: how to detect the presence of cavities, and how to work around them? Some preliminary reconnaissance work is necessary in order to choose the most appropriate strategy:

- Re-locating the construction project
- Modifying the foundation design
- Implanting specialized foundations
- Reinforcing the bedrock
- Reinforcing the cavity

15.4.2 Geophysical Detection Methods

Geophysical methods are useful during preliminary surveys, but they are limited by several factors: the cavity may be empty, or it may be filled with water, sand, or clay. The rock around it may be fractured, or completely solid. The space may be elongated or compact. Since the anomaly that is detected depends on the contrast between the cavity and the surrounding rock, it can be difficult to see a space if there is minimal contrast.

Numerous attempts to detect karst conduits from the surface have generally shown that it is impossible, unless the conduit is very large and close to the surface. However, these methods can shed light on the structure of the rock unit, which influences karstification (Guérin, 2004). This information can be used to determine which follow-up methods are appropriate, such as for example drilling boreholes.

15.4.2.1 Microgravimetry

This method entails measure the local variations in the gravity field, which indicates empty spaces as a mass deficit. This method requires very precise topographical mapping and corrections for elevation, and is generally used only in flat areas (for example the floor of an excavated area). It reveals any areas that are less dense than the surrounding rock, and can therefore detect empty spaces, pockets filled with water, and even cavities that were filled in by debris. Measurements are not affected by the electric grid, making this method useful in urban areas. It works particularly well for man-made cavities.

15.4.2.2 Electric resistivity

This method involves sending an electric current into the ground using two electrodes, and then measuring the resistivity at the surface. It requires a significant contrast between the rock and the hollow area. When a cavity is empty, it forms a zone with poor resistivity. On the other hand, if it is filled with clay, it will be more conductive than the limestone.

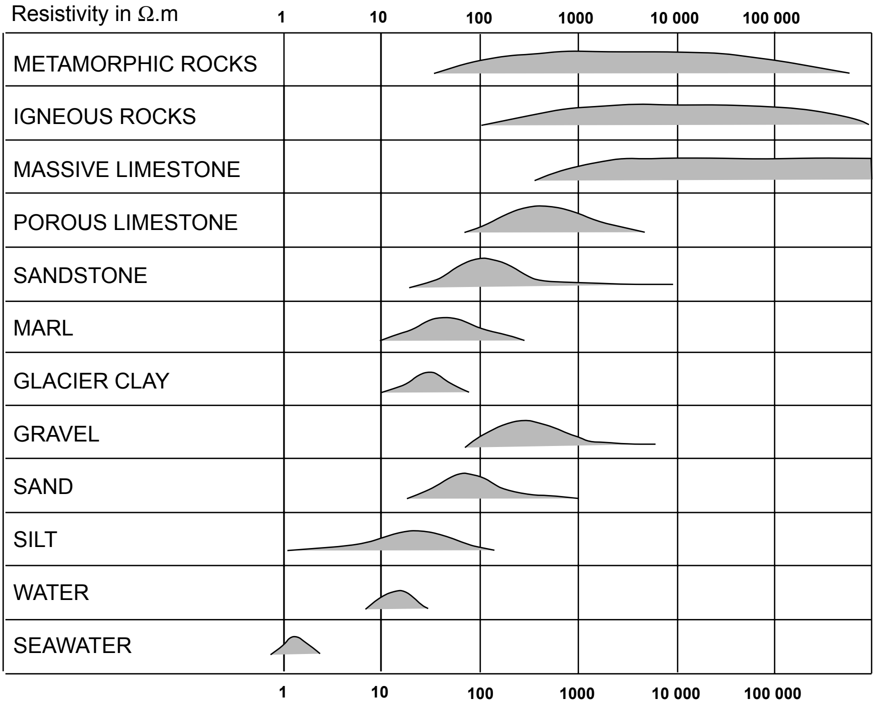


Figure 123. Average resistivity values in known contexts.

Various mechanisms and techniques are available:

Electric dipoles

The current is sent between two electrodes, AB, and the resistivity is measured between two electrodes, MN. The depth that is revealed corresponds to AB/4. Electrodes A and B are gradually spaced farther and farther apart to measure greater and greater depths, building up a cross-sectional image. A dry cavity is more resistive than the fractured limestone surrounding it. A cavity filled with clay will be wetter and therefore more conductive.

Electric panels

Measurements are taken by moving around a mechanism with a fixed geometry, which can then be used to compare the characteristics of different locations. Another option is to install a network of electrodes.

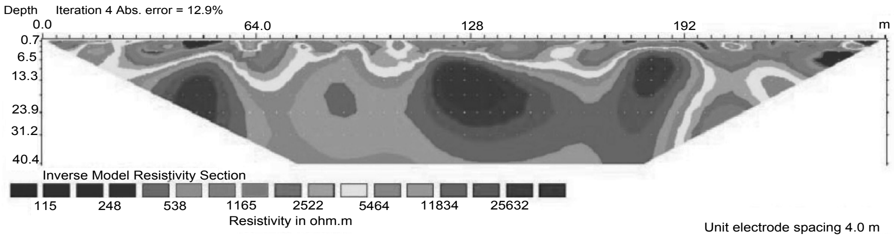


Figure 124. Underground cavities revealed by electric panels in Lamalou (after Guérin, 2004).

Color image of this figure appears in the color plate section at the end of the book.

Grounding

The primary conduit in the Port Miou cave, which contains a brackish underground river, was detected from the surface using an alternating current loop, with one electrode at the spring and one electrode on the ground 1 km upstream. The current flowed through the brackish water, which served as a natural conductor (Figure 125).

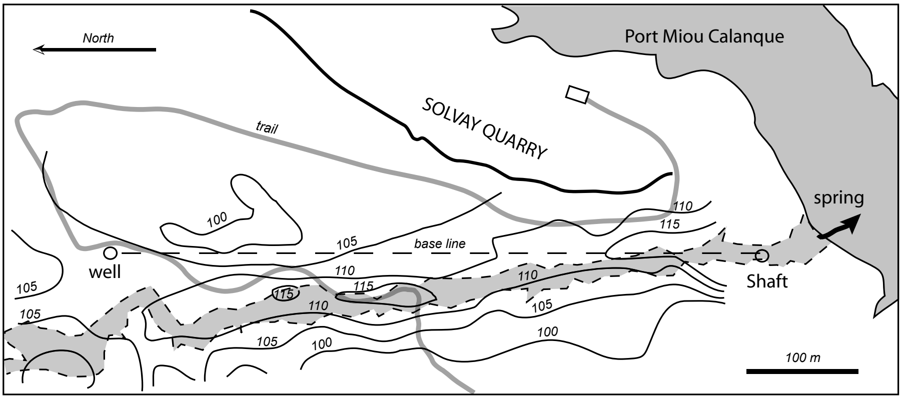


Figure 125. Geophysical detection of the Port Miou conduit (Marseille, Cassis) (after Cornet et al., 1963).

15.4.2.3 Magnetic and electromagnetic methods

These methods involve measuring natural or artificially induced variations in the Earth's magnetic field.

Georadar

An antenna sends high-frequency electromagnetic waves into the ground, as a series of very short pulses. The waves are reflected by flat surfaces and by anomalies in the subsurface. Georadar is primarily used in civil engineering to detect cavities a few meters below roads. In well-suited terrain, with low-frequency antennas (10 to 200 Hz), georadar can reach depths of up to thirty meters. Figure 27 depicts a doline, its sediment fill, and the vertical conduit that drains the area. Figure 126 shows one application of this method, in detecting cavities in an urban area in order to manage the risk of slumps and subsidence.

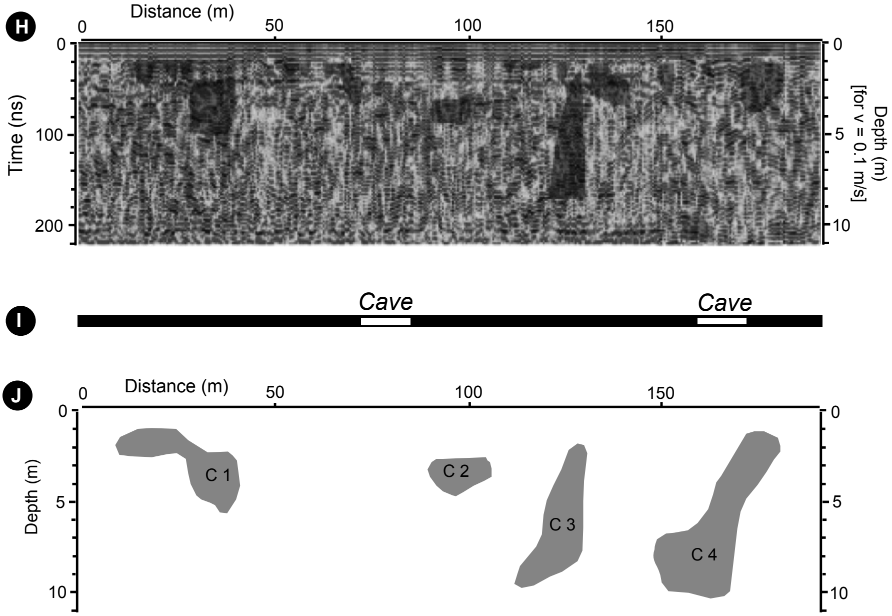


Figure 126. Georadar survey and cavity detection in the town of Zaouit Ech Cheikh (Morocco) (after El Khammari et al., 2007).

Magnetic resonance sounding

MRS, or Magnetic Resonance Sounding, works by exciting the hydrogen protons in water with an electromagnetic field, and then measuring their resonance signal after they are no longer being stimulated. An alternating current is used to generate an electromagnetic field, which excites the protons in water molecules. The current is stopped abruptly, and the protons emit a signal that can be detected at the surface. This signal is proportional to the amount of water present below ground. This method, which is used to measure the size of groundwater reservoirs, can only detect water-filled cavities. Tests on the Hortus Causses (Hérault, France) found that MRS could detect a karst conduit 40 m below ground, feeding the Lamalou spring (Gard, France) (Vouillamoz et al., 2002) (Figure 127).

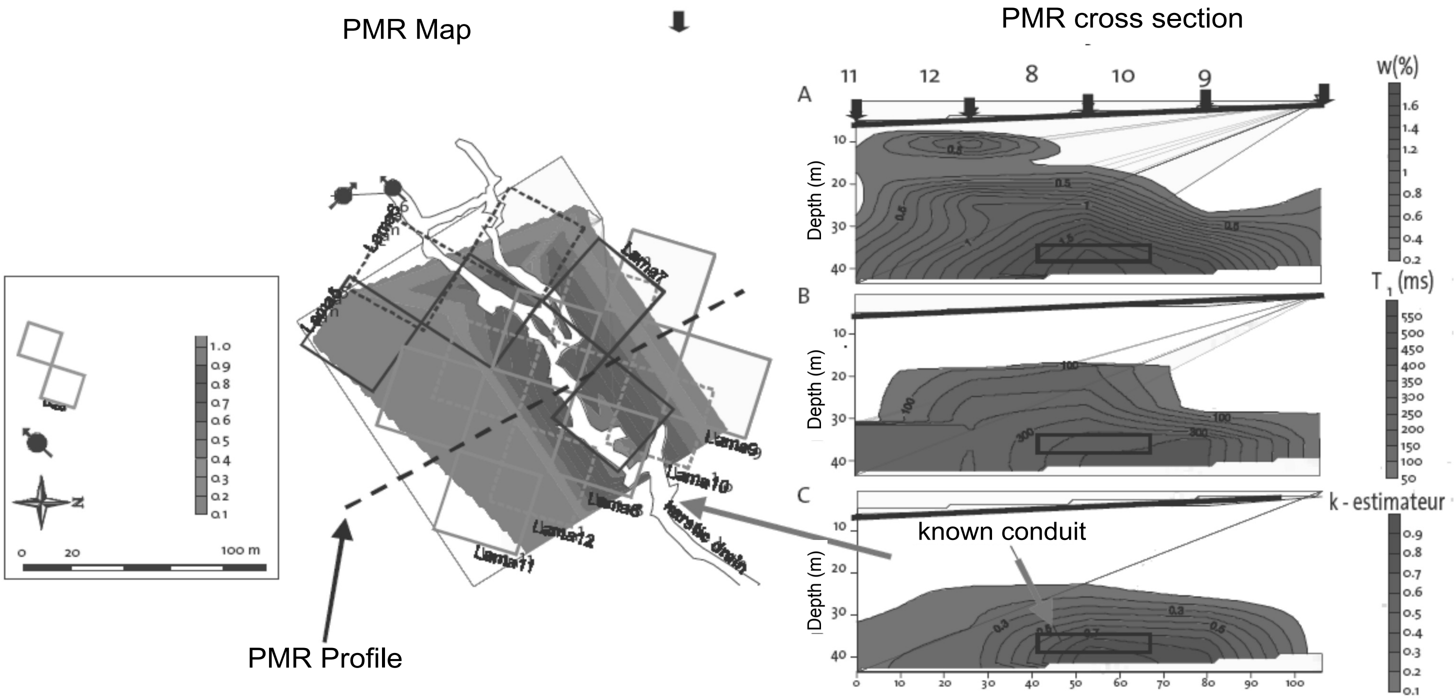


Figure 127. Detection of the conduit feeding the Lamalou spring (Gard) by MRS (BRGM file).

Very Low Frequency

VLF, or Very Low Frequency, sounding relies on the propagation of very low frequency hertzian waves, which can pass through bedrock and water. This type of wave is used by various military organizations to communicate with submarines. There are therefore stations constantly emitting these waves, which are modified as they pass through subsurface anomalies: mineral deposits, faults, etc. These variations can be measured at the surface with a simple receptor setup. Although this method is simple in practice, it is not often used in karst environments. It has, however, been used on occasion, for example, to locate a subterranean passage in Alcala (Spain) (Ogilvy et al., 1991).

15.4.2.4 Seismic and acoustic methods

These methods rely on the analysis of sound waves travelling through the ground, generated by some type of shock: a weight dropping, explosives, etc. Planar surfaces (bedding planes, faults) can be detected because they reflect or refract the waves. However, sound waves generally pass around cavities, so these are not visible unless they are very large or very near the surface.

It seems possible to pick up and locate, from the surface, the sound of subterranean waterfalls using geophones, but as yet there are no examples of this being done (N. Florsch, verbal communication). However, one interesting experiment can be noted, by Breznik (1998). In an attempt to locate the karstic conduit draining the Fatničko polje (Bosnia-Herzegovina), three "geo-bombs" were detonated at intervals. The 1 kg spherical bombs had a density similar to that of water, so that they would be carried along by the current after being thrown into a ponor. The explosions, spaced 1 hour apart, were detected from the surface by a network of geophones extending as far as 150 m from the insertion site.

15.4.3 Controlling for Geophysical Anomalies

Geophysical surveys can generally provide a good image of a known cavity, after adjustments and transformations, but creating an image of an unknown cavity is a more delicate operation. The various methods described above only reveal anomalies, which are often difficult to interpret. It is therefore prudent to consider that any single method is inadequate, and that only the intersection of information from several different methods, with convergent results, is enough to support the presence of a subterranean cavity.

Once this is done, the best method to determine whether or not a cavity is indeed present is to drill a borehole. As a result, cavity detection is often done directly by drilling a more or less closely spaced array of boreholes. Before the construction of the Besançon Hospital (France), in a karst area, a tightly spaced array of boreholes was drilled in order to detect any potential cavities. When no karstic indicators were found, construction began. However, during the construction process, several cavities and conduits were found. Upon comparing the locations of these anomalies and the borehole grid, it became apparent that, by unlucky coincidence, the cavities all fell in areas between boreholes.

The degree of precision achieved is therefore a function of the borehole spacing, and the survey team must therefore balance the high cost of careful reconnaissance and the need for adequate information. The combination of relatively cheap geophysical surveys over the entire area and more expensive borehole drilling in the potentially risky areas indicated by the geophysical surveys is a good way of optimizing costs. During drilling, recording the drilling speed can provide useful information. A sudden increase in drilling speed suggests a clay-filled pocket, whereas a large empty space can result in the drill bit dropping suddenly (Figure 128).

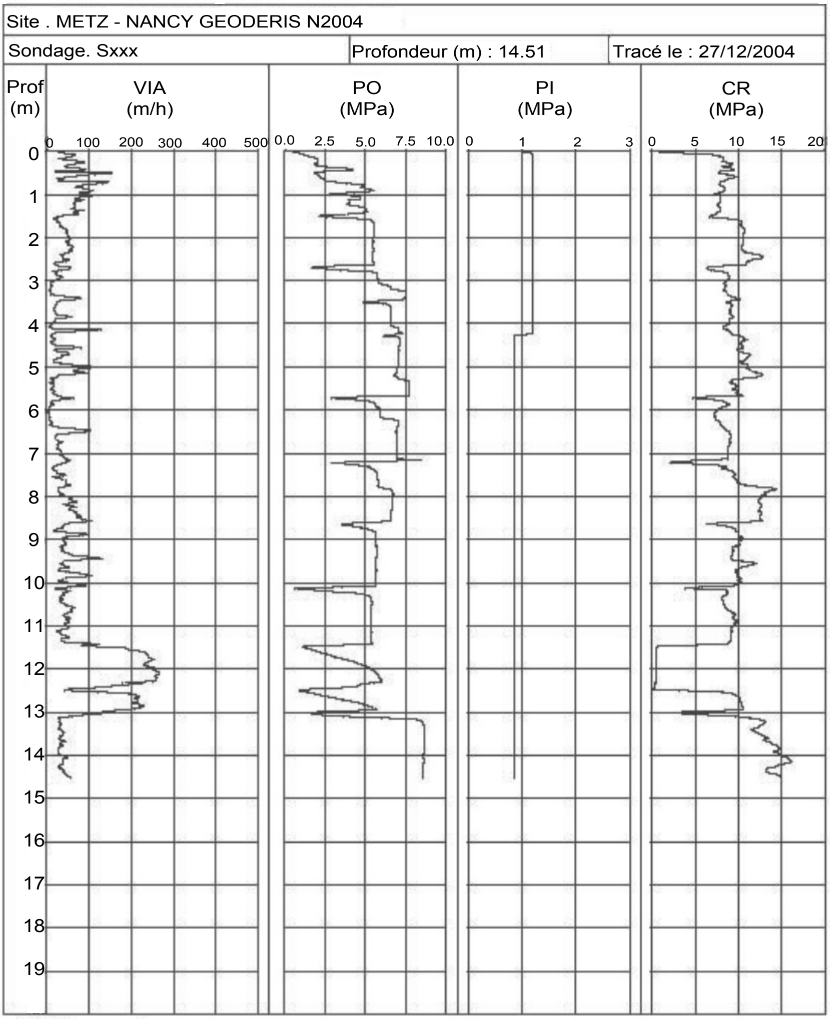


Figure 128. Borehole in which the drill bit dropped suddenly (GEODERIS file). The drop is visible on the VIA (instantaneous penetration velocity) and is accompanied by a drop in PO (bit pressure) and CR (torque rotation).

15.4.4 Examining Hollow Cavities

Once a cavity has been detected, the best option is firsthand exploration by speleologists (cf. Speleology chapter), which sometimes requires widening the entrance passageway. This is not possible if the cavity is located far below the surface, or if it was discovered by drilling. In these cases, it can be roughly mapped with equipment lowered through the borehole and controlled remotely from the surface: laser telemetry in a dry space, sonar if the cavity is submerged. These methods can be paired with video footage or stereo-photography.

Laser telemetry, with specially adapted setups for downhole measurements, can be used to directly map the visible areas of cavities. One such specialized setup, "La Taupe" (the mole) from Ginger-CEBTP firm, includes a laser telemeter and a rotating step motor, which are gradually lowered down a borehole, recording a three-dimensional array of data points that can then be used to calculate the volume of the cavity (Figure 129).

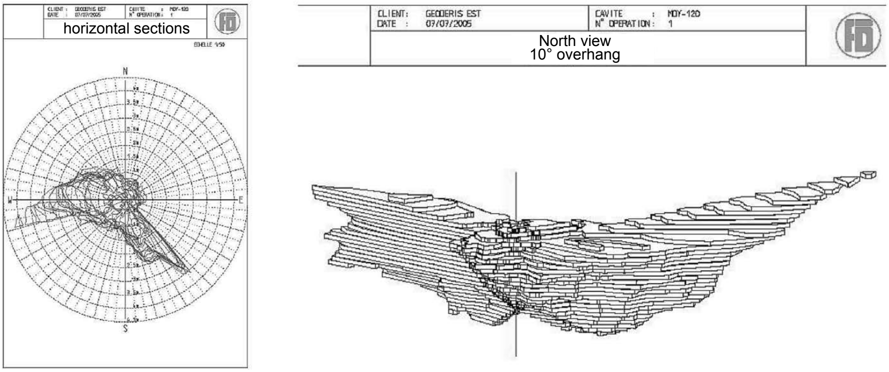


Figure 129. Laser measurements and 3D image of a cavity discovered by drilling (after GEODERIS, 2005).

15.4.5 Working with Cavities

When a hollow cavity is discovered on a construction site, the question becomes what to do about it. Are the geometry and the mechanical strength of the roof solid enough to support the building? If the building cannot be moved and the foundation design cannot be modified to create a bridge over the void, or to shift loads to the rock beneath the cavity, reinforcements may be necessary. When the cavity is accessible to humans, bricked support pillars can be built. Other methods, such as those traditionally used to reinforce cliffs and rock faces, can also be used in a subterranean context (shotcrete, bolting, anchors, injection, etc.) (Besson, 2005).

If the cavity is not accessible, it can be filled in from the surface by the injection of inert material from the surface, using hydraulic or pneumatic mechanisms. Vertical reinforcements can also be put in place: artificial stalagmites created by injecting successive layers of quick-setting grout (Figure 130) or by filling in geotextile sleeves. However, this requires a good understanding of the cave's geometry, and is dependent

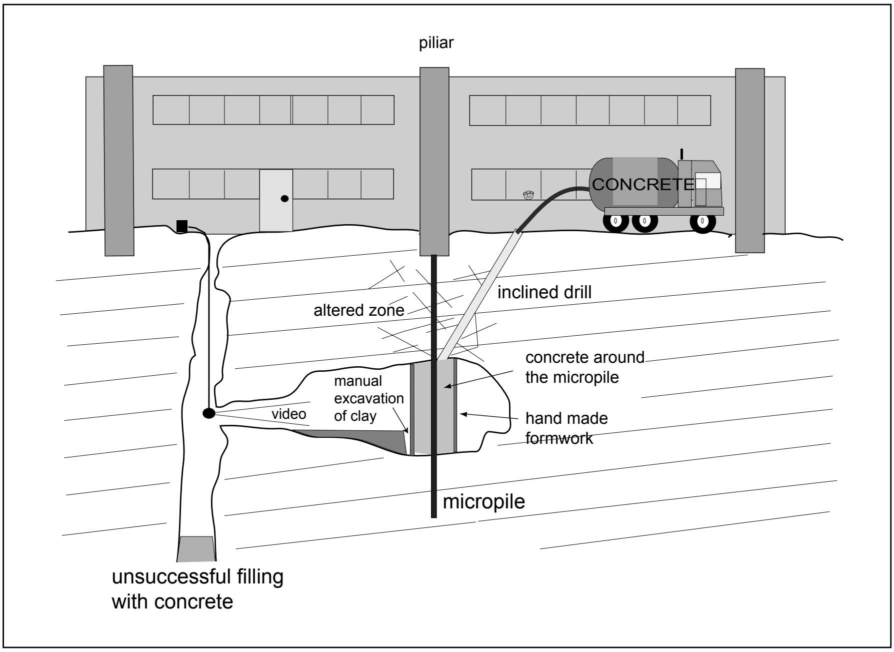


Figure 130. Cave underpinning by constructing a concrete pillar.

on the stability of the unit that the supports are being built upon. Hydraulic cleanings may be necessary to clear out clayey fill.

Unfortunately, there is a strong tendency to minimize the time spent in reconnaissance, and to simply fill the cavity with concrete before continuing construction. The problem is only considered complex if the required volume of concrete is unusually large! However, heedlessly filling in a cavity makes it completely inaccessible, and prevents any further monitoring. This can lead to problems such as:

- ineffective cavity treatment,
- uncontrolled spreading of the fill material,
- changes in the natural circulation paths of groundwater,
- destruction of an unknown underground heritage,
- needless costs, as the natural strength of the cave roof may be enough to support the building.

Examples of construction problems in Sophia Antipolis

Towards the end of construction work for a multi-story building in Sophia Antipolis (France), an inaccessible cave was discovered, by chance, very close to the building. The construction company decided to fill it with concrete. Three truck-mixer-drums of concrete were dumped into the cavity, without filling it. A video inspection was then undertaken, which revealed a cavern large enough to be explored by speleologists. The entrance was widened and the cavers noted that the lower parts of the cavern were blocked off by concrete, preventing further exploration. They did find a lateral passageway extending beneath the construction site, directly below one of the load-bearing columns supporting the building. More surprising still, they found two micropiles passing through the conduit. Preliminary geologic surveys had indicated that the limestone in this area was highly fractured, and recommended micropiles for stabilization. However, a micropile is useless if it is passing through a cavern and not anchored in rock. Underpinning was therefore needed. The clay covering the floor of the cavern was cleared away, casings were put in place around the micropiles, and a precise topographic survey was undertaken in order to choose a location for a directional borehole. Cement was injected into the casing through the borehole. Once the cement set, the casing was removed to verify that the micropiles were indeed solidly anchored all the way to the cavern roof.

This example demonstrates three major errors:

- Lack of preliminary surveys looking for cavities in an area well known for being highly karstified
- Lack of geologic monitoring and quality control while the micropiles were being put in place (the drill bit dropping suddenly during drilling for the micropiles could not have gone unnoticed)
- Lack of any examination of the cavity before injecting cement.

The problem of stabilizing the load-bearing pillar was therefore resolved, but the concrete that was haphazardly poured into the cavern blocked off further exploration, making it impossible to see if the cavern extends out below other parts of the building and if it has water flowing through it.

16

Tourism

Water resource management is the primary application of karstology, but karst-related tourism is also an important economic activity.

16.1 Touristic Regions

Karst landscapes have the power to attract large crowds. In France, the writing of E.A. Martel in the 19th century played a significant role in popularizing the karst areas of France. A few famous locations draw several million visitors every year:

- The Calanques near Marseille,
- The Fontaine de Vaucluse,
- The Loue and Lison Springs,
- The Gorges du Verdon,
- The Causses and the Cévennes,
- The Gorges in the Tarn and the Ardèche.

Notable sites in other parts of the world include:

- the Karst region in Slovenia,
- the Dalmatian Coast and islands (Croatia),
- the Stone Forests in the Yunnan Province (China),
- natural parks in many karst areas,
- the Guilin towers and the Li Jang River (China),
- Ha Long Bay (Vietnam),
- the Tsingy of Bemaraha and the Ankarana Reserve (Madagascar).

Among the 180 sites classified as UNESCO World Heritage Sites (2010) twenty or so are karst areas or caves:

- Shillin, Lubo, and Wukong karsts (Southern China),
- Vézère Valley caves (France),
- Carlsbad Caverns (New Mexico, USA),
- Mammoth Cave (Kentucky, USA),

- Pirin National Park (Bulgaria),
- Yagul Cave and Mitla Cave, prehistoric sites in Oaxaca (Mexico),
- Altamira Cave (Spain),
- Skocjan Caves (Slovenia),
- Plitviçe National Park (Croatia),
- Desembarco del Granma National Park (Cuba),
- Ohrid Lake region (Macedonia),
- Mont Perdu (Spain, France),
- Gunong Mulu National Park (Sarawak, Malaysia),
- Dolomites (Italy),
- Tsingy de Bemaraha (Madagascar),
- Durmitor National Park (Montenegro),
- Kotor region (Montenegro),
- Western fjords (Norway),
- Puerto Princesa Underground River National Park (Philippines),
- Aldabra atoll (Seychelles),
- Pamukkale Springs (Turkey),
- Ha Long Bay (Vietnam),
- Phong Nha-Ke Bang National Park (Vietnam).

Several historic sites in karst areas can be added to this list, including Tikal National Park (Guatemala), the Mayan site of Copán (Honduras), and various Mexican archeological sites.

16.2 Karstic Trails and Itineraries

There are numerous examples of sites that have been developed to accommodate visitors and show off the most spectacular aspects of the karst landscape.

The trails meandering through the Shilin stone forests, where visitors wander through mega-lapies on pathways carved into the rock and ornamented with pools and pagodas attract thousands of visitors (Figure 21). In Montpellier-le-Vieux (France) a little train runs through a ruiniform landscape; in Rakov Skocjan (Croatia) trails lead into eclipsed valleys. In Plitviçe (Croatia), tufa waterfalls are accessible via a network of suspended walkways. In the Gorges du Verdon (France), E.A. Martel oversaw the construction of a famous trail that now bears his name. In Ha Long Bay (Vietnam), junks carrying tourists float in and out of the limestone spires. In Guilin (China), a boat trip up the Li Jang River, through a landscape of limestone towers, is a must-see for tourists. In Turkey, the Pamukkale Springs, with its pools separated by white travertine, has been a tourist destination since the Classical Antiquity. In France the great springs, like the Loue or the Lison (Doubs) have been developed to accommodate visitors. At the Fontaine de Vaucluse, a recent discovery by a diving expedition found hundreds of coins, indicating that the site had been drawing visitors since Gallo-Roman times.

Many similar sites exist all over the world. Often tourist accommodations consist primarily of facilitating access to the site, but the recent rise of eco-tourism and cultural tourism has led to the creation of discovery trails, where visitors are directed towards informational signs. For example, in the Grande Corniche Departmental Park (Alpes-

Maritimes, France), a trail leads visitors to signs explaining the general structure of the region, and guided tours into a small cavern are available upon request.

16.3 Tourist-accessible Caves

Caves and the subterranean landscapes they offer draw tens of millions of visitors each year. France is ranked third in the world after China and the United States (Pissard and Mantovani, 1997). It is home to hundreds of commercial caves, which receive approximately 4 million visitors every year. The oldest show cave in France is the Osselles Cave, which has received organized visits since the beginning of the 16th century.

When caves are located in areas that are struggling economically, tourism can be the starting point for regional development. The Padirac Chasm is often described as the "tourism lighthouse" of the Midi-Pyrénées region in France. Subterranean tourism began in the 19th century, with the advent of the railroad, the invention of electric lighting, and the rise in fashionability of taking the waters at hot springs.

Most developed caves are economically viable, but during the 1990s, the number of visitors began to drop, although it has now re-stabilized. The decrease was tied to discrepancies between the public's expectations and the actual infrastructure inside the caves, which was often very old. The problem was addressed by renovating some of these structures, and by enhancing the presentation of these natural wonders (Gauchon, 1997).

16.3.1 Tourist-accessible Caves in France

- Orgnac (Ardèche) (140,000 visitors per year),
- Padirac (Lot) (350,000 visitors per year),
- Aven Armand (Lozère) (150,000 visitors per year),
- Dargilan (Lozère) (120,000 visitors per year),
- Cocalière (Gard) (100,000 visitors per year),
- Grotte de Betharram (Pyrénées Atlantiques) (250,000 visitors per year),
- Clamouse (Hérault) (130,000 visitors per year),
- Choranche (Isère) (180,000 visitors per year),
- Grotte des Demoiselles (Gard) (120,000 visitors per year),
- Lascaux facsimile (Dordogne) (300,000 visitors per year).

However, the most heavily visited sites are those with religious significance, such as the Massabielle Cave in Lourdes, which receives 6 million visitors per year.

16.3.2 Tourist-accessible caves around the world

- Caves of Altamira (Spain) (UNESCO World Heritage Site),
- Grotte de l'Observatoire (Monaco),
- Han Caves (Belgium),
- Cueva del Drach (Balearic Islands, Spain),

- Grotta Gigante (Italy),
- Postojna (Slovenia) (900,000 visitors per year),
- Skocjan (Slovenia) (UNESCO World Heritage Site),
- Carlsbad Caverns (New Mexico, USA) (UNESCO World Heritage Site),
- Mammoth Cave (Kentucky, USA),
- Eisriesenvelt (Austria),
- Deer Cave (Sarawak).

16.3.3 Underground Safaris

Not all caves are heavily altered to accommodate visitors. Several sites offer underground safaris, where the necessary caving equipment is provided: "Couffin-Chevaline traverse" in the Choranche Caves (Vercors, France); "Orgnac 2 and 3 visit" in the Orgnac aven (Ardèche, France); "Subterranean Safari" in the Trabuc and Cabrespine Caves (Gard, France); "Adventure Caving" in Mulu Park (Sarawak, Malaysia); "Carlsbad adventure tour program" in Carlsbad Caverns (New Mexico, USA).

In some caverns, like the Via Souterrata (Caille, France) cables and ladders have been installed, mimicking mountain via ferratas (Figure 131).

Figure 131. Via souterrata in the Yvon aven (Caille, Alpes-Maritimes).

This type of experience, which is rooted in eco-tourism, is likely to become more and more popular. Other new concepts include “Obscuricole Events” (or LÉO, Les Évenements Obscuricoles), where visitors explore the cave in its natural state, with no light, and with an emphasis on the other senses. This type of experience is currently being offered in the Lacave Caves (Lot, France).

16.4 Developing Caves for Tourism

16.4.1 Current Trends

The ways that caves are developed for tourism have changed a great deal over the past several years. Large structures with bright lighting, trails, guardrails, stairs, and elevators have given way to structures with a lighter footprint, using materials that blend into the surroundings and discreet lighting, allowing visitors to get a better feel for the atmosphere inside a cave. The increasing use of LEDs to replace incandescent or fluorescent lighting should accentuate this trend. Quaint commentaries pointing out the ever-present stalagmite in the shape of the Virgin Mary, the Ghost or the Octopus have been replaced with descriptions more focused on natural science. Subterranean tourism is becoming more interested in the science and culture of sites.

16.4.2 Legal Difficulties

Under French law, private property extends down the center of the Earth, but natural resources (petroleum, mineral deposits) belong to the state. Caves are considered a part of the ground, not a natural resource. Water, however, is a shared resource.

The owner of the land above a cave therefore also owns the cave itself, and can do with it what he sees fit, unless it contains prehistoric or archeological artifacts. It is unusual for a cave to be contained to only one parcel of land, and so the development of a cave requires an agreement between all of the landowners concerned.

The Orgnac cave system in France

Conflict over a cave put into opposition two towns in Ardèche for many years. The Orgnac aven was explored in 1935 by Robert de Joly, who immediately saw the touristic value of the cavern. It was quickly developed. The entrance and the area accessible to tourists (Network 1) were in the district of Orgnac, but the cave network extended out under the neighboring district of Issirac. Magnificent areas were explored in 1965 in these further reaches (Networks 2 and 3), which could have been developed for tourism if a suitable access point could be found. However, access to the 2 and 3 networks was slowed and even blocked by the district of Orgnac, up until the creation of the Orgnac-Issirac SIVU (an inter-district syndicate). After significant renovation and construction, the Orgnac cave system was awarded the label “Grand Site de France” (Great French site). In the networks 2 and 3, visits have been allowed since 1998, but only accompanied by a specially trained guide, and in groups of no more than 8 people.

16.4.3 Technical Difficulties

The primary difficulties are changes in the subterranean climate, and vegetation growth that can cover walls and speleothems.

A cave is a carefully balanced environment. Speleothems, which are often the features that draw visitors to a cave, can be degraded if they dry out or if they are covered in vegetation. CO_2 and water vapor breathed out by visitors alter the composition of the air inside the cave, and can increase the acidity of the film of water covering the rock, causing changes in the rates of dissolution and precipitation that can alter prehistoric cave art along the walls.

Vegetation can grow inside a cave when artificial lighting enable photosynthesis, colonizing the area through spores and seeds carried in by visitors or by flowing water. In the past, this problem was dealt with by simply cleaning off the affected surfaces with soap or fungicides. Although it would be difficult to control contamination carried in by visitors, it is much easier to control the lighting situation, by choosing lamps that emit a spectrum of light that is not sufficient for photosynthesis, and by limiting the amount of time that the cave is illuminated. The following figure (Figure 132) shows that red and yellow light is not favorable for plant growth, whereas blue, green, and orange light is.

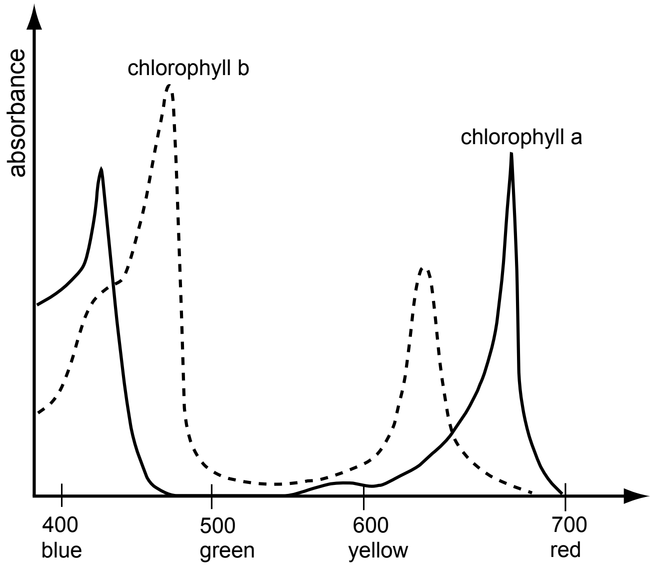


Figure 132. Parts of the light spectrum favorable to vegetation growth.

In order to limit the amount of time the cave illuminated, the lights can be turned on and off as visitors pass through a cavern, either manually or with an automated system. At the Souterroscope in Baume Obscure cave (Alpes Maritimes, France) visitors follow an automated tour, led by light and sound from speakers placed along the underground path, without a guide.

The example of Lascaux **(Dordogne, France)**

Following the discovery of the Lascaux cave, a landmark site for prehistoric cave art, unrestricted tourist access, with 1000 visitors every day for 15 years, put the prehistoric paintings at risk for serious damage. Significant changes were made, particularly the closing of the original cave and the creation of a facsimile, but conservation efforts are still inadequate. Lascaux has served as an important example upon which current strategies for preserving and displaying prehistoric caves are based. The timeline below outlines the major events in the Lascaux story:

1940—The cave was discovered by M. Ravidat, J. Clauzel, M. Queyroi, L. Périer and their dog Robot.

1948—The cave was developed to accommodate visitors.

1955—The first signs of damage appeared on the walls, caused by excess carbon dioxide from visitors' breath.

1957—A climate control system was put in place to limit the amount of CO_2.

1960—First appearance of the "green blemishes", caused by algae colonies on the walls, and of the "white blemishes", caused by calcite deposits on some of the paintings.

1963—Ozone filters are installed, and Lascaux is closed to the public.

1965—A new system to regulate thermal and hygrometric conditions is installed, to re-create the cave's initial condition.

1970—A facsimile of the cave is built, which opens in 1983.

2000—A new climate control system is installed.

2001—Black stains appear on the cavern roof and near the entrance, caused by a fungus. Emergency measures are taken (fungicide and antibiotic compresses, spreading lime along the cave floor, application of biocides).

2002—Creation of an International Scientific Committee to monitor the Lascaux Cave.

2007—Black stains reach the deeper zones of the cave.

2008—Biocide applications.

2008—The climate control system installed in 2000 is updated.

2009—Symposium on preserving the cave.

2009—The painted caves in the Vézère Valley, including Lascaux, are named UNESCO World Heritage Sites.

2010—A scientific committee is established, headed by Yves Coppens, to ensure the preservation of the cave.

17

Mineral Resources

17.1 Karstic Traps

Karst creates natural traps in the form of underground cavities. Paleokarst (cf. chap. 8.3) can therefore hold economically valuable ore bodies that have formed as clay minerals change over time or as detritus accumulates, such as, for example, the remains of iron-rich hardpans.

17.1.1 The Provence Bauxites

Bauxites are an aluminum oxide ore, used in the production of aluminum. They are named for the Baux-de-Provence (France), where they were first identified and studied during the 19th century. They are common in intertropical zones. They are variable by nature, composed of a mixture of clays, oxides, and hydroxides of various metals, including aluminum. They come primarily from the transformation of silicates when they are deposited in laterites in tropical regions. Oxides and hydroxides form aluminum-rich horizons of primary bauxite, which can become secondarily more concentrated when the laterite is eroded and the resulting sediment becomes trapped in karstic depressions.

Lateritisation can also occur directly in clay-rich limestone. The primary bauxites that form in the process are then carried into the underlying karst and accumulate in caves and sinkholes, combining with the terra rossa deposits already present.

The bauxite in Provence were deposited at the beginning of the Cretaceous, in a humid tropical climate, when the Durancian isthmus was exposed (where Languedoc and Provence are currently), between an Alpine sea to the northeast and a Pyrénéan basin, corresponding to the opening of the Atlantic to the southwest of Languedoc and Provence. This led to intense karstification in the Jurassic and Lower Cretaceous limestone, creating terra rossa deposits in the process. The lateritisation of the adjacent crystalline and metamorphic rock led to the formation of primary bauxites. Both the bauxites and the terra rossa were subsequently trapped in the sinkholes and caves of the underlying karst. This karst was then sealed off by Middle and Upper Cretaceous deposits (Guieu and Rousset, 1978), and then caught up in the various steps of the Provençal orogeny (Figure 133).

These bauxites form a discontinuous unit across a large part of Provence. In the process of exploiting the ore, disconnected underground pockets were cleaned out, revealing the original karstic terrain, which consisted of numerous depressions, in some cases featuring karren, as well as caves. The Provence bauxite is no longer being mined, having been replaced by more economically viable deposits in Guinea.

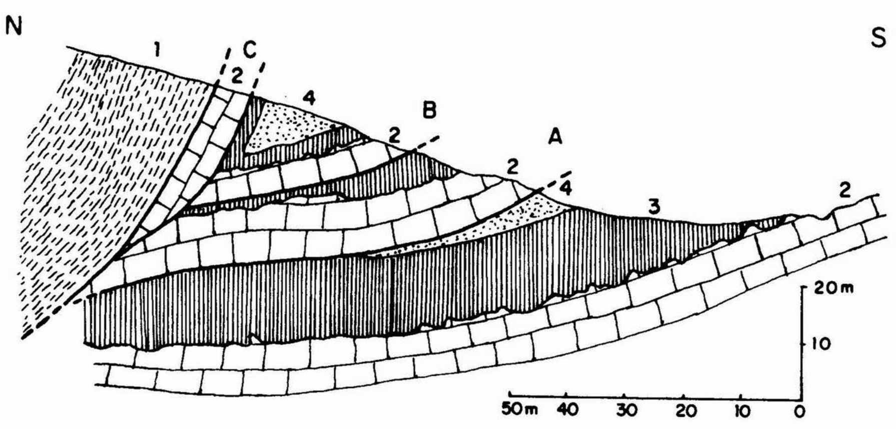


Figure 133. Bauxite deposit in Combecave-Pins Bâtards (after Gouvernet et al., 1979). 1—Middle Jurassic (Dogger) marly limestone; 2—Upper Bathonian limestone; 3—Bauxite; 4—Upper Cretaceous fluvio-lacustrine deposits (Campanian sand and sandstone); A, B, C—Bathonian limestone beds.

17.1.2 Kisanga Iron

The ferruginous products of lateritisation can accumulate in karstic pockets in much the same way as bauxites. They are eroded away and then re-deposited in karstic depressions, forming deposits of iron ore. The deposits in Kisanga (Zaire) are a result of one of the oldest known karstic cavities filling up with debris from iron-rich hardpans (Buffard, 1993).

17.1.3 Guano and Phosphates

Guano is primarily used in its raw state as fertilizer. It comes from accumulated bat or bird excrement. Phosphate deposits are also used to produce fertilizer. They contain mostly apatite ($Ca_5(PO_4)3(F,Cl,OH)$). They are primarily of marine origin, but some karstic deposits are in use.

Caves, particularly in tropical regions, can host large bat colonies reaching several million individuals, such as the colony in Deer Cave (Mulu, Sarawak). Excrement from the colony accumulates in thick layers, forming guano deposits that can be mined for fertilizer. Similarly, in karst regions, bird guano can be eroded and carried into the endokarst. As it is transported through the system, it turns into calcium phosphate. These deposits often contain fossils, reminders of their organic origins. Karst can also act a trap for secondary deposits of phosphates from a primary marine source. In most cases, karstic deposits do not exceed a few hundred or thousand tonnes. They are most commonly found in the Salomon Islands, in the Philippines, in Thailand, and in Mexico (Tournis and Rabinovitch, 2010). In France, the deposits in Quercy were heavily mined up until the 19th century, when they were gradually abandoned in favor of more abundant marine phosphates from abroad (cf. chap. 21.2).

17.1.4 Metal-bearing Mineral Formations

Karst can also contain mineral formations tied to hydrothermal speleogenesis. Aside from neo-formed gypsum deposits, which are not generally mined, metallic sulfur formations sometimes cover the walls of karstic caves. In France, the Oilloki Cave (Pierre Saint-Martin) was the site of galena mining. The Grande Vernissière mine (Cévennes) also contains accumulations of fluorite, barite, smithsonite, and galena (Audra, 2008).

In the Djebel Hallouf mines (Tunisia) sulfur minerals (blende, galena, jordanite, and microspheres of pyrite) are present (Rouvier, 1971).

17.2 Hydrocarbons

17.2.1 Distribution and Plays

Approximately half of the world's classical hydrocarbon reservoirs are located in limestone or dolomite. These include 30 to 50% of hydrocarbon production in the US. These reservoirs are often marked by low matrix permeability, problems with fluid control, and low hydrocarbon extraction rates. Karstification can play an important role in determining the overall porosity of deposits, such as Rospo Mare (cf. infra). Understanding and modeling karstic cavities is therefore key for petroleum geologists seeking better extraction methods.

Models are constructed based on well logs, but these do not always provide a representative data set. Petrographic analyses on core samples or during drilling do not generally take into account karstic cavities, and therefore only provide a partial representation of the heterogeneity in the subsurface. This makes any attempt to extrapolate volumes from point data fairly hopeless.

Aside from attempts to evaluate reservoir size, a good understanding of karstification is also necessary during the extraction process, in order to find better ways of recovering hydrocarbons (cf. 17.2.6—Rospo Mare) and of minimizing brackish water influxes during pumping. In order to select the best well locations, 3D seismic surveys are used to determine the heterogeneity of the rock; by estimating to what extent fractures influence the karstification.

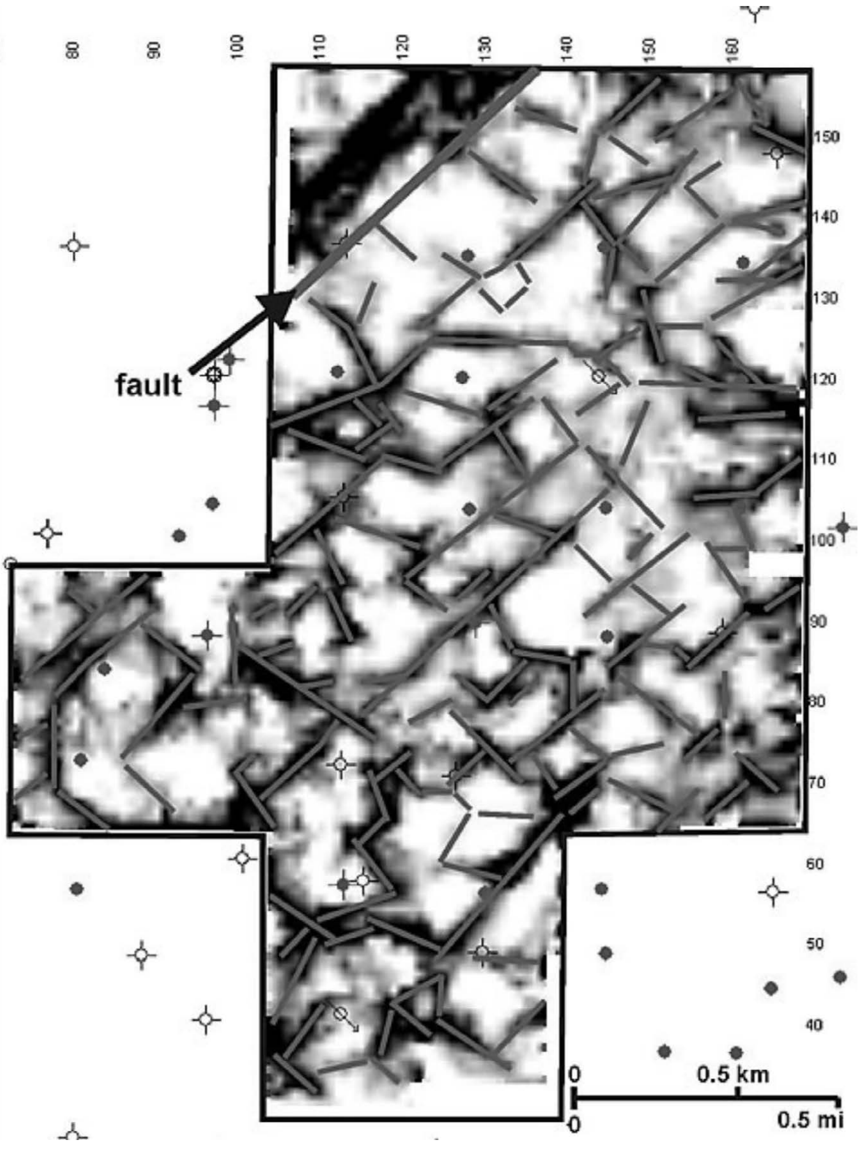


Figure 134. 3D seismic imaging of the Mississippian Reservoir (Colorado, USA) and structural interpretation (doc. Kansas Geological Survey & University of Houston Geophysical Lab).

17.2.2 Diagenesis in Carbonate Platforms and the Evolution of Organic Material

Hydrocarbons form naturally during sedimentation, when there is some organic matter in the sediment. This organic material is preserved in reducing environments (Vatan, 1967). Mud deposits and sedimentary features can incorporate a significant amount of organic material, which is then quickly altered by bacteria into a solid product called kerogen. Kerogen evolves into hydrocarbons through a process called maturation, which requires the sediment to be exposed to heat. This occurs as the sediment is buried deeper and passes through the geothermal gradient (approximately 1°/30 m), where it is exposed to higher and higher temperatures at greater depths. The heat cracks the kerogen and turns it into hydrocarbons (Durand, 1987). Tissot and Welte (1984) define three steps in the maturation process:

- *diagenesis*: sediment turns to rock through compaction and water loss, at depths of up to 2 km.
- *catagenesis*: kerogen turns into oil and gas, at depths of up to 5 km.
- *metagenesis*: oil, gas, and any remaining kerogen turn to methane.

The second important step in the creation of hydrocarbon reserves is primary migration; during which pressure drives the lighter oil and gas out of the rock that they formed in.

The third step is secondary migration of oil and gas towards geologic traps, reservoir-rocks where they accumulate in favorable structural features. These can include anticlines with a layer of permeable rock beneath an impermeable roof, or karst units sealed off by impermeable deposits. Finally, the petroleum and gas may also escape from these traps and migrate to secondary reservoirs.

The origins of carbonate rocks are described in Chapter 3, which highlights the importance of bioclastic sediments and of reef structures. Carbonate rocks that incorporate organic material during their formation can theoretically be subject to the processes described above, if they are buried rapidly enough. However, maturation requires low permeability in order to store the kerogen for a long enough period of time, over a million years, for maturation to occur. Carbonate rocks (limestone and dolomite) serve primarily as reservoirs during migration, rather than as sources.

17.2.3 Karstic Reservoirs

Carbonate units are triply porous:

- Primary microporosity of the rock, which is less than 1% for massive limestone (like Urgonian units), and can be up to 50% for chalk and limestone reefs,
- Secondary fracture-related macroporosity, caused by tectonic activity,
- Tertiary macroporosity due to karstification.

The following figure (Figure 135) shows, as an example, the heterogeneity of karstification in a limestone butte in the Ankarana (Madagascar). The caverns present today are the result of several phases of karstification, tied to changes in the flow of water through an ancient NE-SW-oriented system, which was cut down by erosion, and over which recent east-west circulation superimposed more recent conduits. The resulting heterogeneity is enormous.

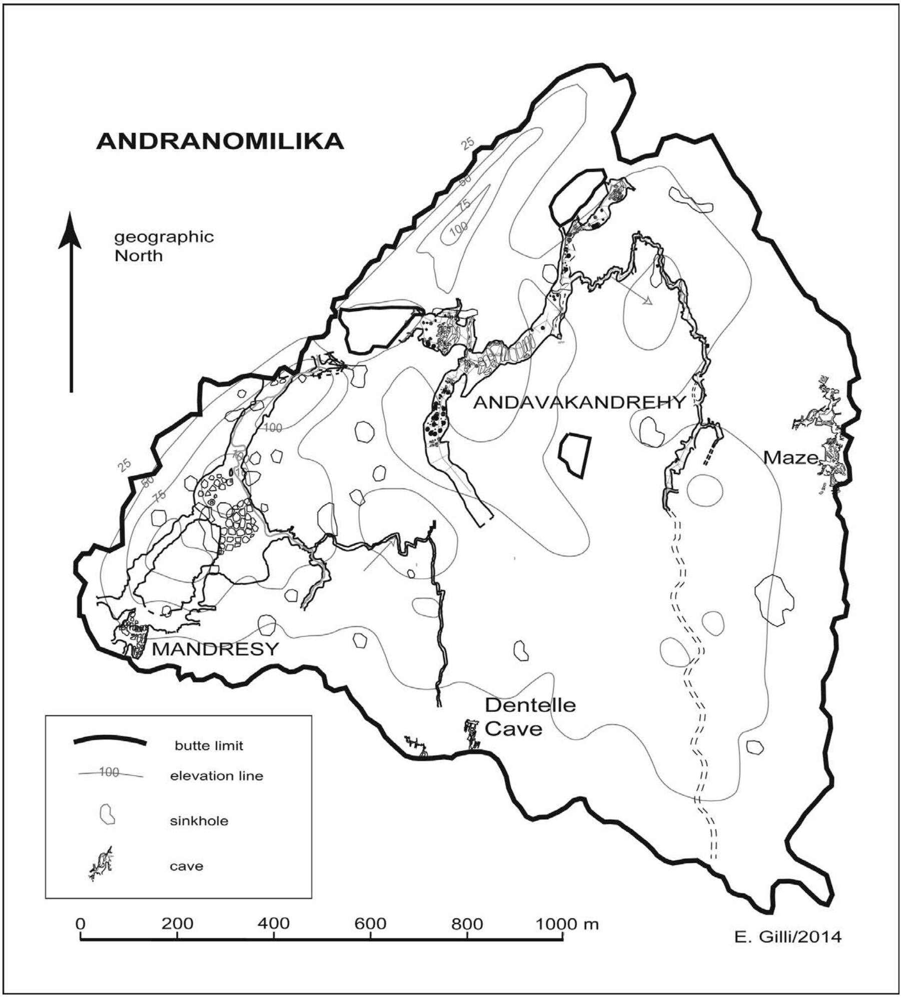


Figure 135. Analamisondrotra Butte (Ankarana-Madagascar).

17.2.4 The Capitan Reef (Texas)

The Permian Delaware Basin, which extends across New Mexico and Texas, is famous for its petroleum reserves, which lie in the dolomitic limestones formed by an ancient coral reef: the Capitan Reef. These limestones also contain Carlsbad Caverns and the Lechuguilla Caverns, which formed by hypogenic excavation, which was assisted by H_2S coming from hydrocarbon deposits (cf. chap. 7.5).

The basin, which covers approximately 30,000 km^2, is made up of a series of 500 to 600 m thick units of alternating limestones and clayey schists, accumulated over a long period of subsidence during the Upper Permian. When the subsidence stopped, the sedimentary basin was ringed by a 560 km-long coral reef, made up of sponges and stromatolites. The whole area was uplifted at the end of the Permian, which led to significant karstification. A marine transgression deposited a thick layer of evaporites (the Castille formation), which was followed by terrestrial deposits, effectively sealing off the karst.

Another period of uplift exposed the limestone again and led to further karstification. During the Tertiary, the Laramide orogeny lifted and folded the area, creating the Guadalupe Mountains, which thrust over the basin.

The petroleum that formed in the schist units migrated vertically into the different limestone units, which had different degrees of karstification, and included the thick Capitan reef unit.

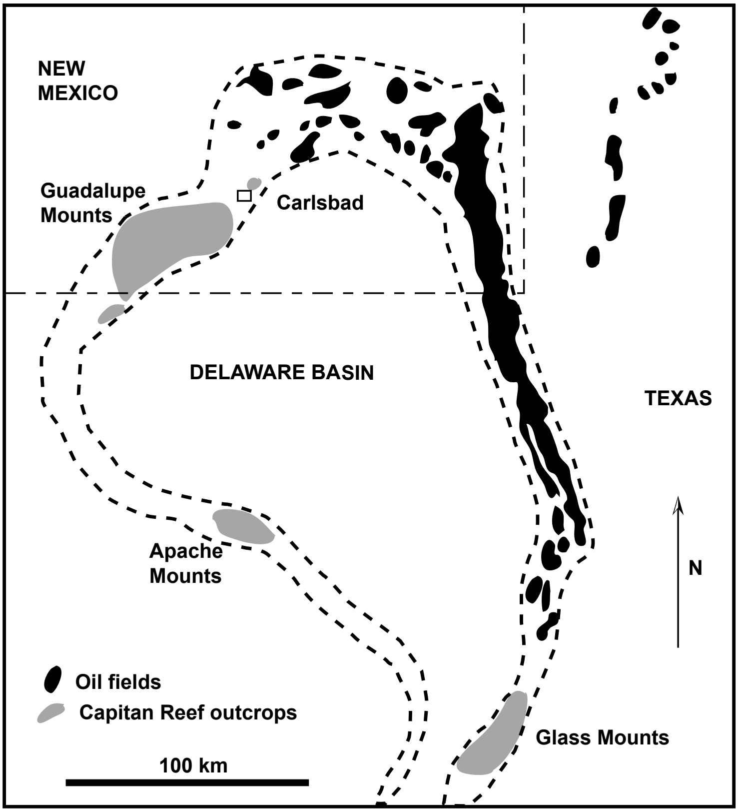


Figure 136. Hydrocarbon deposits in the Capitan reef (after Ward et al., 1986).

17.2.5 Reservoirs in the Middle East

These are thought to be the largest petroleum reserves in the world, but the actual amount of available petroleum is unknown. The deposits are found in limestone and in sandstone units.

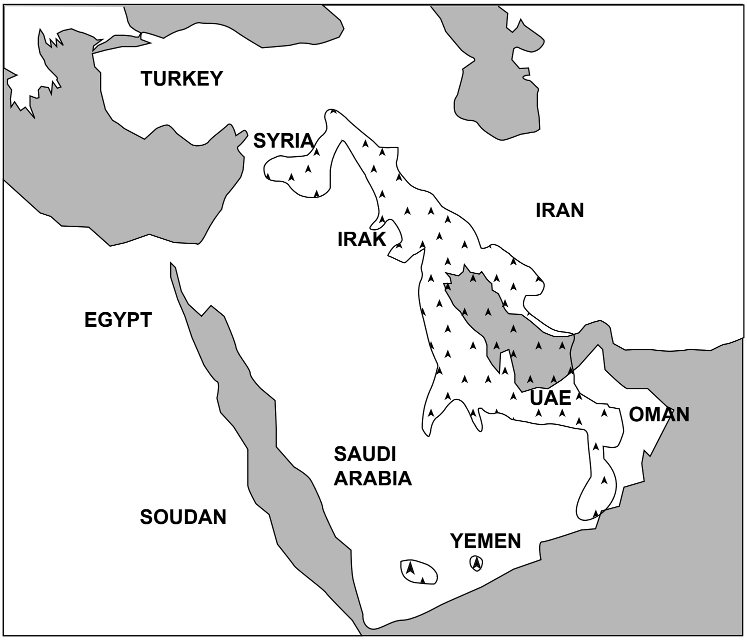


Figure 137. Extent of petroleum deposits in the Middle East.

The Rospo Mare deposits

Rospo Mare is a 75 million ton petroleum reservoir in the Adriatic Sea, 20 km off the coast of Italy. Wells have reached oil at 1500 m in Cretaceous limestone. These deposits have been exploited since 1988, based on careful interpretation of the area's paleogeography by Elf engineers (Dubois et al., 1993). The Cretaceous limestone was karstified during a period of tropical climate (cf. chap. 6), which led to the formation of a series of mogotes, which, once covered by a thick layer of impermeable Mio-Pliocene deposits, created numerous reservoirs. Petroleum is extracted through horizontal wells intercepting the summit of the mogotes.

The area's geologic context was described over the course of numerous complementary studies:

- A 3D seismic survey showing the locations of dolines and mogotes, which was used to make a precise topographic map of the paleokarst.
- A series of 7 boreholes, which yielded 1100 m of core, used to determine the spatial organization of the karst and which found vertical zonation characteristic of a highly evolved karst, with an epikarst, a vertical infiltration zone, a horizontal drainage zone, and a saturated zone.
- High-resolution well logs, used to determine the size of the underground spaces and what they were filled with.
- A comparative study of a different paleokarst of the same age, exposed at the Apricena rock quarry 40 km to the southeast of Rospo Mare, where the large quarry walls exposed the paleo-morphology both at the surface and at depth.

These studies demonstrated that karstification had affected the upper portion of a group of Jurassic and Cretaceous limestones and dolomites, more than a thousand meters thick. These units were exposed from the Upper Cretaceous to the Oligocene, during which time a highly developed karstic drainage network evolved. It was sealed off at the end of the Oligocene by marine sediments and evaporites, which fossilized the karst system and created an impermeable cap. Tectonic shifts bent the units into an anticline, and petroleum was trapped at its roof. These reserves are found in a layer approximately 150 m thick, beneath which the karstic cavities are filled with either fresh or brackish water.

The morphology of the top layer of karst, where the oil migrated to, was the object of intense scrutiny, in order to select the best drilling locations. The approach chosen involved drilling vertical boreholes that curved out horizontally at the bottom for 500 to 1300 m, in order to cut across the maximum number of fractures. The wells were drilled in the highest parts of the paleokarst, while remaining beneath the faulted or clay-filled areas in the epikarst.

The success of this endeavor, in an unusual context that was not initially easy to understand, was due to the efforts of karstologists. Other similar reserves are known in the Adriatic Sea, in Hungaria, and in Spain (the Ampostona field for example).

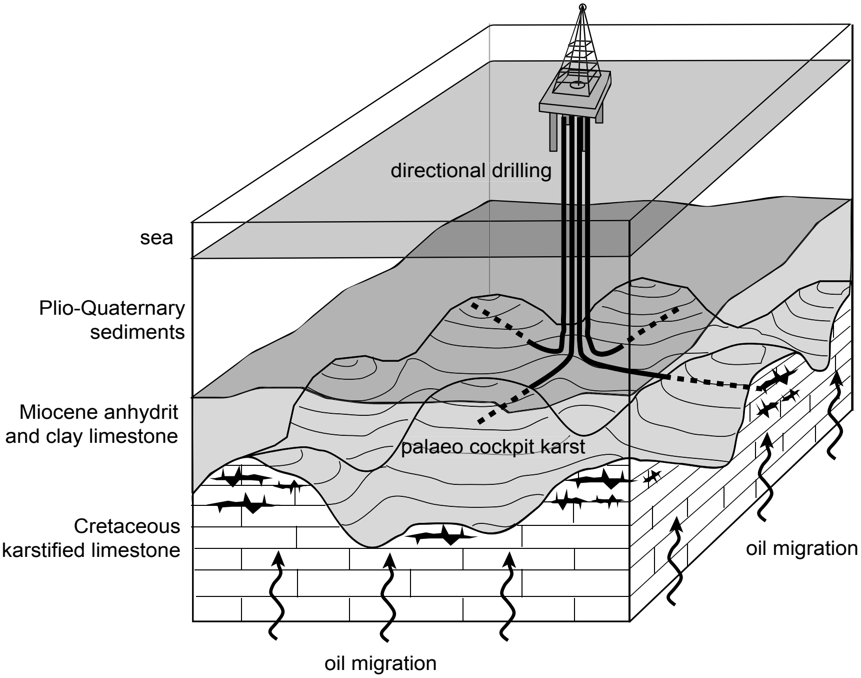


Figure 138. Simplified cross-section of Rospo Mare reservoir (after Dubois et al., 1993).

18

Hydrothermal and Geothermal Processes

18.1 Hot Springs

Hydrothermal karst speleogenesis is described in Chapter 7.5. Warm, mineral-rich karstic water makes karstic hot springs popular spa and bath destinations. There are several such locations in France:

- Aix-les-Bains (Savoie), with the 44°C Alun spring, the Gouffre Chevalley (42°C) and the Grotte des Serpents, which are all part of the same hydrothermal system. The Sulfur Spring has a temperature of 43°C (Hobléa et al., 2010),
- Salins-les-Thermes, with the 33°C Salins spring; whose waters carry carbonic acid and NaCl (12 g.L^{-1}), as well as iron carbonate and radioactive elements. The temporary Massiago spring is at 33°C and has an NaCl concentration of 35 g.L^{-1},
- Gréoux-les-Bains (Alpes de Haute Provence),
- Saint-Paul-de-Fenouillet (Eastern Pyrénées), the Fou spring is radioactive,
- Rennes-les-Bains,
- Ussat-les-Bains.

In the rest of the world, notable hot springs include the Cap Bon springs in Tunisia (Figure 139), the Buda springs in Hungaria, the Pamukkale springs in Turkey, and many others. The karst systems feeding these springs are often impassable, and have not been explored, due to the dangerously high temperature of the water. However, a few passageways have been explored by cave divers. One such example is the Salins spring, which was explored to depths of –70 m below the opening (Salins-les-Thermes, Savoie).

Often, hot springs only appear warm because they emit water at a constant temperature, while the surrounding air temperature fluctuates. During the winter, the springs appear warm by comparison, and they may even give off plumes of steam. True hot springs are generally defined as having a temperature of at least 5ºC above the neighboring springs.

Figure 139. Cap Bon hot springs (Tunisia). Water flows through the deep limestone units in the Tunisian mountain ridges.

18.2 Natural Climate Control

During prehistoric times, caves were often used as a natural shelter, because during the cold months they maintain a constant temperature warmer than the surrounding landscape. The temperature of a cave is generally near the average of the temperatures in the surrounding area. In the winter, they therefore tend to stay warmer than the exterior. This characteristic could eventually be used to create heat pumps.

The inverse situation also exists. For example, the Flying Tiger Cave Hotel in the Piduhe Valley (Hunan, China) was built facing the cave entrance, so as to benefit from the cold air currents flowing out in the summer and the warm air currents flowing out in the winter. However, the air coming from the cave has a very high humidity, which leads to a great deal of condensation in the hotel.

In Provence (France), in the Sainte Baume massif, some karstic shafts were used as natural iceboxes up until the end of the 19th century. Twenty or so sites are known to have been used this way. In the winter, water was set out to freeze in shallow basins and snow was collected, and both were then packed into the cave shaft. The ice could then be used to supply the naval dockyard of Toulon and the city of Marseille.

The karst in these cases was acting as a natural icebox. Cold, dense air accumulated in the shafts, and the ice was protected from incoming solar radiation. Occasionally an air current would evaporate some of the moisture and decrease the temperature even further. The thermal mass of the surrounding rock kept snow and ice frozen during the summer.

Figure 140. Flying Tiger Cave and Hotel in the Piduhe Valley (Hunan, China). The hotel (on the left) has natural air conditioning because of the air currents flowing out of the Flying Tiger Cave.

19

The Study of Paleoenvironments

19.1 Karstic Archives

19.1.1 Karstic Recording Properties

Karst is useful in several fundamental realms of research. Because of the number and complexity of factors that govern its development, it is a remarkable natural recording of paleo-environmental indicators. In addition, because sediment deposits in caves are protected from rain and other forces of erosion, they preserve objects and imprints for thousands of years.

The most well-known cave research has to do with prehistoric life. Primitive human life (tools, habitat, diet, artwork, etc.) was recorded over the course of several tens of thousands of years, through artifacts buried in sediment and kept safe from erosion. Paleolithic art has survived until the present day after having been protected for thousands of years in caves with remarkably stable environments, with no light or vegetation to degrade the paintings. But prehistoric life is not the only event recorded by karst. Others include:

- neotectonic activity, which is recorded in morphology and in speleothems (Gilli, 1986, 2005; Jeannin, 1990);
- past earthquakes, which can break speleothems (Gilli, 1995a; Forti and Postpichl, 1985);
- changes in the hydrologic base level (rivers, lakes, or sea-level), which determines the elevation of caves;
- paleoclimate, which shapes the landscape and the type of speleothems that form, and which is also recorded in stalagmite growth laminae;
- prehistoric fauna fossilized or preserved in sediment;
- many other types of information as well.

Karst, specifically the endokarst, can therefore be thought of as a vast library of information on the Earth's past environments, where only a few books have as yet been opened (Gilli, 1995b). It is a much richer source of information than ice cores or coral reefs when it comes to studying paleoclimate. In addition, karst regions are found across most continents, and are even present in some marine environments. However, the drawback to such a trove of information is that it is enormously complex, and therefore difficult to analyze.

19.1.2 Subterranean Sediment Deposits

These deposits reflect climate variations. Speleogenesis and speleothem formation occur in hot and temperate climates, and come to a halt during the ice ages when varved silt deposits form, or in arid climates when dust deposits form. The study of cave sediments can therefore reveal the sequence of climatic phases in a particular region.

The elements and the fossils found in cave sediments also provide information on climate variations. Megafauna bones indicate what climate they were deposited in. For example, bison and reindeer are characteristic of cold periods, while deer and aurochs indicate temperate periods.

Similarly, analyses of spring travertine with a large amount of vegetative debris, snail shells, charred wood, etc. can reveal information about the environmental conditions near where they were deposited. A detailed analysis of this type was done in Saint-Antonin (Bouches-du-Rhône, France) at the foot to the Sainte-Victoire range, and the results compared with the cycles of regional prehistoric human settlement and with global climate shifts (Guendon et al., 2003).

19.1.3 Speleothems in Caves

As they are growing, speleothems trap particles from their environment (dust, pollen, etc.), and undergo changes in growth rate or deformations, all of which provide information about the environment inside the cave (Figure 141).

The laminae that make up a speleothem also hold useful information. They can change color, luminescence, and reflectivity.

- UV luminescence is a function of the amount of humic acid in the rock, and indicates period of vegetation growth. In intertropical zones, luminescent laminae can be correlated to wet periods (Baker et al., 1998). Low luminescence correspond to dry periods.
- The color is a result of impurities. The greater the discharge flowing through the cave, the cleaner and clearer the calcite.
- Reflectivity is more complex to interpret.

Inspection of laminae under UV light, which highlights fluorescent humic acids, can yield very precise analyses. It is generally considered that alternating light/dark laminae indicate yearly wet season/dry season cycles. However, some authors have been able to detect individual precipitation events, by greatly magnifying the laminae (Shopov et al., 1994).

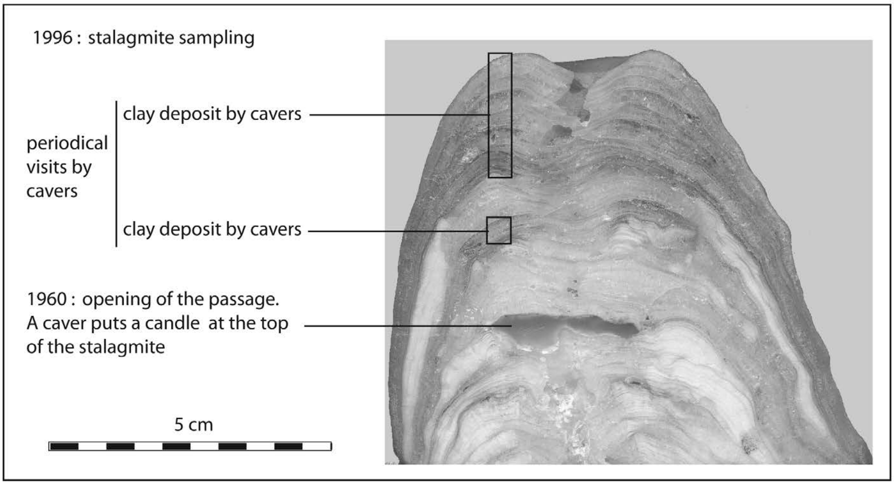


Figure 141. Waxy layer and traces of clay, indicating the presence of speleologists. The passage where this stalagmite was found was opened in 1960. Aside from the clay deposit, there is also a distinct color change, with several brown layers indicating clay tracked in by cavers as they passed through, which was then spread out over the speleothem by percolation. They gray tint of the calcite above the wax could be a result of blackening from carbide lamps smoke.

When paired with radiometric dating (U/Th or ^{14}C), laminae analysis can identify periods during which the speleothems stopped growing, which can be interpreted as very low precipitation episodes, such as dry periods or ice ages.

Thanks to technological advances, the sample size required for dating has decreased significantly, from a few grams in 1970 to a few centigrams today, which allows us to measure samples from within the speleothems.

Table 14. Evolution of dating methods.

Time period	Method	Calcite sample size (grams)
1970–1990	α counting	1–10
1990–2000	Mass spectrometry (MS)	0.1–2
2000–present	Multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS)	0.01–0.2

19.2 Dating Methods in Karstology

19.2.1 Relative Dating

The principle of relative dating is based on the premise that in a normal sedimentary sequence, the more recent units are deposited on top of the older units. For example, speleothems that formed on top of a clay layer are younger than the clay layer. Similarly, a lava flow that filled up a doline is younger than the doline. Certain stratigraphic markers of known age can then be used as reference points, such as volcanic tephra deposits from the 19th century (Tambora or Krakatoa eruptions).

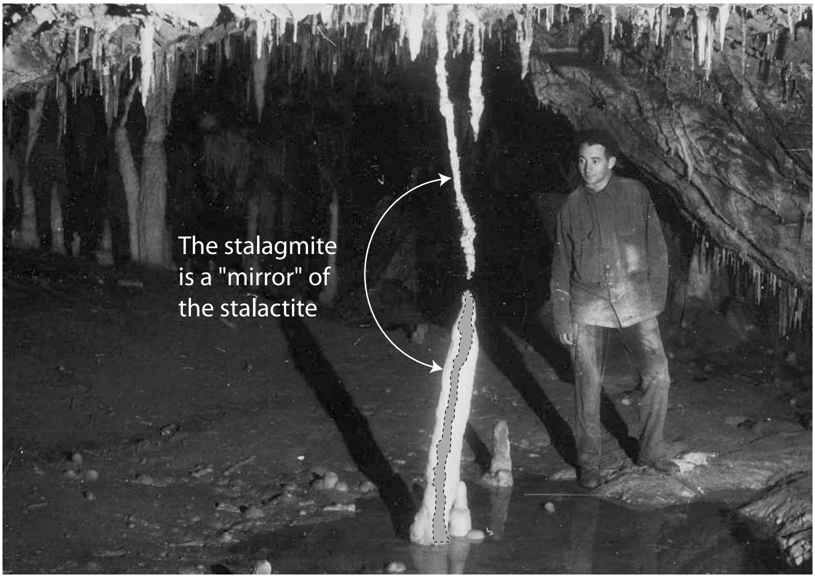


Figure 142. Pair of speleothems slanted by air currents (Folacci files). The stalagmite recorded variations in the growth axis of the stalactite, which was feeding it through percolation. In this example, the two speleothems grew at the same rate, and the stalagmite formed a mirror image of the stalactite.

Morphological features also follow chronological relationships, so that in a cave network, a canyon would *a priori* be considered younger than the cave floor that it is incising.

However, in practice it is often difficult to be certain of different features' relative ages, because karst landscapes are usually polyphasic. For example, subterranean alluvial deposits overlap one another as a result of variations in base level and in stream discharge, while being confined by the dimensions of their conduits (Figure 143). This can make a spatial analysis difficult, because younger deposits may be located underneath older ones.

19.2.1.1 Fossils and other objects trapped in sediment

Speleothems and other subterranean deposits can cover over or incorporate objects with known ages (prehistoric tools and pottery, ancient coins, etc.), which can be used to bracket the age of the sediment. While examining a stalagmite that had been cut and polished to reveal the laminae, we were surprised to find, 4.5 cm from the top, a layer of modern wax covered by young calcite (Figure 141). It was an old candle that had been left on top of the stalagmite by explorers at the entrance to a narrow passageway in the 1960s.

For older deposits, fossils can provide some age indications. For example, Ursus speleus remains indicate that the sediments are at least 10,000 years old, since that

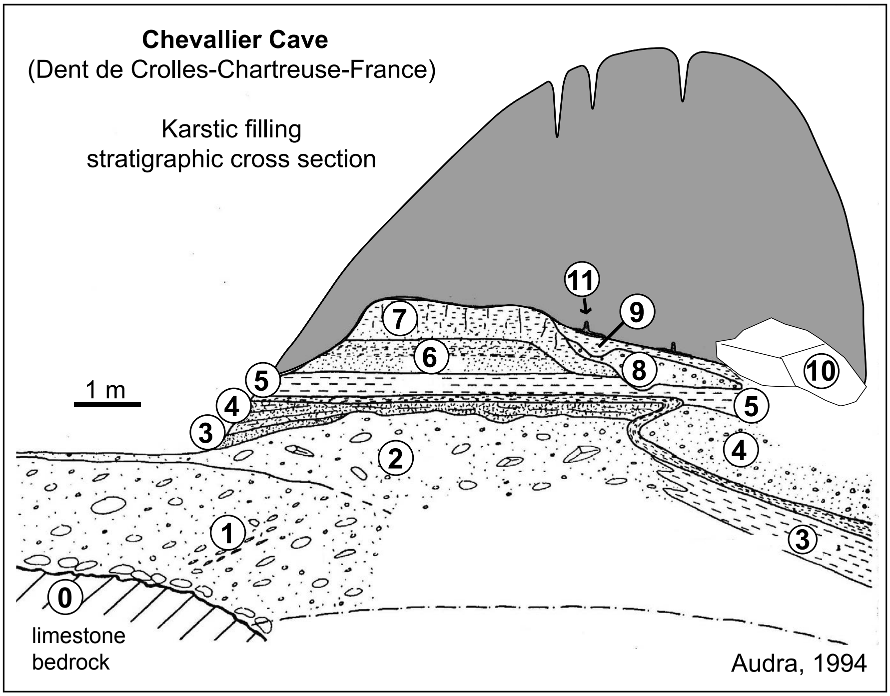


Figure 143. Stratigraphic cross-section of the Chevallier Cave (after Audra, 1994). The numbers indicate relative age, from 0 (oldest) to 11 (youngest).

species of bear had completely died out by then. Small rodents teeth are also useful, since they tend to evolve quickly. They are generally well preserved in cave sediments and are chronological indicators.

19.2.1.2 Paleomagnetism

Analyzing the orientation of iron oxide particles trapped in clayey sediment and in certain types of stalagmite coatings can indicate the inclination, declination, and in some cases the reversals of the Earth's magnetic field when the sediments were deposited. The variations in Earth's magnetic field over time are well known, and can therefore be used to date the sample (Thompson and Oldfield, 1986).

This method is often used to date subterranean clay deposits. The precise location and orientation of samples must be carefully noted. The easiest marker to look for is the most recent reversal of the magnetic poles, the Brunhes–Matuyama reversal (approximately 780,000 years ago). If the clay deposits show a normal magnetic orientation, they are more recent.

19.2.2 Absolute Dating

19.2.2.1 General concept

Absolute dating is done using natural chronometers, which can directly indicate the age of a sample (speleothem, clay, charcoal, etc.) when it is subjected to various technical operations.

Note: In order for speleothem dating to be reliable, the sample must come from a closed system with no possibility of dissolution and recrystallization, which is not always easy to determine. Recrystallization, which is described in Chapter 7.7, are therefore a problem in absolute dating.

19.2.2.2 Radioactive families

In one radioactive family, a parent element decomposes into a daughter element at a known speed. The parent/daughter ratio indicates the age of the sample. Mass spectrometers make it possible to date very small samples of material.

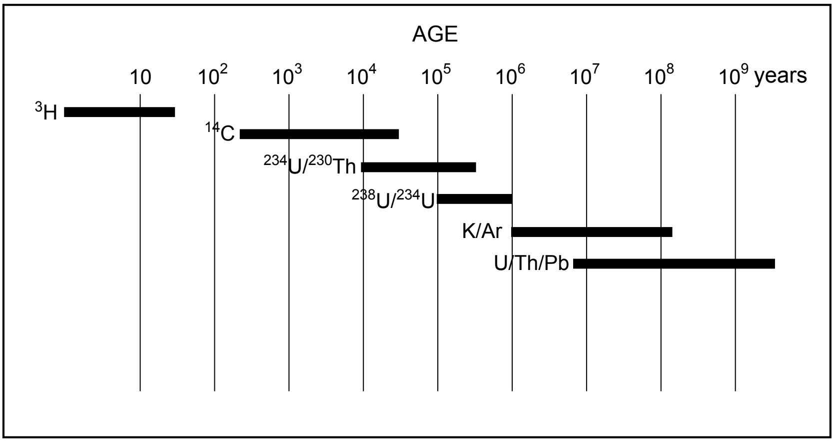


Figure 144. Dating ranges for the most common radioactive families.

19.2.2.3 Carbon-14 (^{14}C)

^{14}C forms in the upper atmosphere from ^{14}N being bombarded by incoming radiation. It is a part of all living organisms, at a roughly constant level, as long as the organism is alive. Once the organism dies, the amount decreases, and the remaining fraction indicates the age of the remains. ^{14}C dating is primarily used for organic material, which can be found in cave deposits (wood charcoal, bones, etc.), allowing the deposits themselves to be dated as well. This method can also be used to directly date speleothems made of $CaCO_3$.

However, dating speleothems is made more difficult by the presence of inorganic carbon. The carbon of calcite that makes up a speleothem comes both from limestone and from atmospheric CO_2, as described in the dissolution equations in Chapter 4. The measured age is therefore more recent than the actual age of the sample. Genty et al. (2001) found that the percentage of inorganic carbon is usually around 20%.

19.2.2.4 Uranium/thorium

Uranium-238, which is soluble, is transported by percolating water and incorporated into calcite's crystal structure, where it gradually decays into thorium-213. The ratio of the two elements therefore indicates when the calcite crystallized.

However, thorium-213 can also come from detrital sources, which can alter the ratio and makes the measured age appear older than the actual age of the sample. This makes it difficult to date younger speleothems. If the detrital thorium is carefully measured in order to correct the measurement, this method can be used for rocks as young as 500 years (Pons-Branchu, 2001).

19.2.2.5 Cosmogenic nuclide dating ($^{10}Be/^{26}Al$) in karst

Cosmic radiation creates different isotopes at the Earth's surface: hydrogen (^{3}H), helium (^{3}He), beryllium (^{10}Be), carbon (^{14}C), neon (^{21}Ne), aluminum (^{26}Al), and chlorine (^{36}Cl). Those found in quartz (^{10}Be and ^{26}Al) are of particular interest in dating cave deposits. These two isotopes are being produced at a constant rate at the surface. If quartz is carried into a cave, the sediments there are protected from the production of more cosmogenic nuclides, and the isotopes already present decay radioactively. ^{26}Al disintegrates faster than ^{10}Be, so the ratio of these two isotopes indicates the amount of time that has passed since the sediment was deposited in the cave.

This method was used to date the sediments in Mammoth Cave (Kentucky, USA), showing that the passageways they were found in were formed before the Pliocene (Granger et al., 2001).

This method was also used in the caves of the enormous Siebenhengste system, above Thoune Lake (Switzerland). The oldest sediments were 4.4 ± 0.6 Ma and therefore indicate that karstification happened during the Pliocene (Hauselmann and Granger, 2005).

19.2.2.6 Isotopes of anthropogenic origin

Some radioactive elements are of anthropogenic origin, and can therefore be used to date very recent events. ^{210}Pb comes from leaded gasoline, which has been outlawed since 1975 (in France). Cesium isotopes, ^{137}Cs and ^{134}Cs, were released during nuclear testing in the 1960s, and after the disaster at Chernobyl (Ukraine) in 1986. The Fukushima Daiichi (Japan) nuclear power plant catastrophe in 2011 had a similar effect.

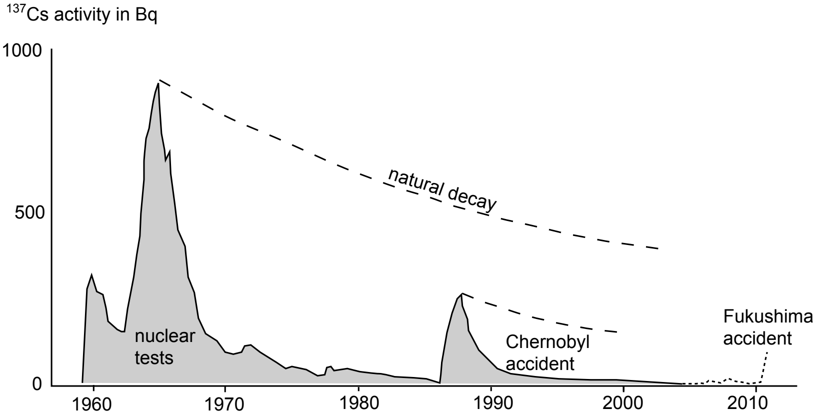


Figure 145. Cesium 137 peaks, from nuclear testing and Chernobyl.

19.2.3 Comparative Dating Methods

19.2.3.1 Concept

The idea is to look for clues indicating a climatic period of known age (ice age, dry period, etc.). The characteristics and appearance of clay deposits and of speleothems can provide clues as to what the climate was like when they were deposited. For example, speleothems grow in warm climates, and stop during ice ages, which instead deposit varved silt. Ice intrusion into a cave system will break the speleothems, which then serve as a record of the glacial event.

19.2.3.2 Paleotemperature correlation

If the climatic history of an area is known, the age of a speleothem can be found by looking at the amount of ^{18}O in the $CaCO_3$ molecules, which indicates the Paleotemperature (cf. infra) and can be used to estimate which climate period the speleothem was formed during.

19.2.3.3 Palynology

As a speleothem grows, it incorporates spores and pollen carried into the cave by percolating water. Theoretically, it is therefore possible to examine these spores and to determine what type of vegetation was present at the surface, which would indicate the climate and therefore provide a potential age range, in much the same way as oxygen 18 dating. However, the number of spores is very small, and this type of analysis would require very large samples (Bastin, 1978).

19.2.3.4 Counting laminae

Many authors have attempted to date stalagmites and stalactites by counting growth laminae, in much the same way that dendrochronologists count tree rings.

The results are disappointing since, although is seems possible that climate cycles are responsible for alternating layers, and that white or transparent layers correspond to rainy periods while brown layers rich in humic acid correspond to drier periods, it is much more difficult to assign absolute ages to these periods (Baker et al., 1998; Shopov, 1994; Railsback et al., 1994). Do the laminae record individual precipitation events or do they characterize the dry season versus the wet season? If the latter, are there two or four laminae per year?

Improvements in dating technology and methods, and the possibility of dating very small samples, now allow measurements of individual laminae, which bodes well for a more and more frequent use of speleothems as climatic markers.

19.3 Environmental Factors

19.3.1 Oxygen-18 (^{18}O) and Monsoon Tracking

Because stalagmite laminae are made up of $CaCO_3$, they contain oxygen, and the ratio of ^{18}O and ^{16}O may indicate the amount of rainfall at the time of deposition. Dissolved carbonate takes on the isotopic composition of the rainwater it is suspended in, and when the carbonate precipitates out, it records that composition. In the Wanxiang Cave (Gansu, China), for example, a single stalagmite recorded monsoons from the 190 to the year 2003. The $^{18}O/^{16}O$ ratio was measured in 703 samples taken along the length of the stalagmite. An intense monsoon was indicated by a decrease in ^{18}O, and vice versa. This analysis revealed that variations in the intensity of monsoons followed the temperature variations in the Northern Hemisphere, including the slight drop during the Little Ice Age (1550–1850), and that the monsoons were correlated with solar activity cycles and variations in alpine glaciers (Zhang et al., 2008).

19.3.2 Oxygen-18 (^{18}O) and Temperature

^{18}O is also useful in determining the temperature of the cave when speleothems were forming. For any given sample, the $^{18}O/^{16}O$ ratio (in number of atoms) is compared to a standard, and the resulting difference, $\delta^{18}O$, expressed in ‰, indicates the temperature. This type of analysis, like ice core or coral reef studies, can be used to re-create paleotemperatures by taking samples of $CaCO_3$ at different heights on a stalagmite.

19.3.3 Carbon-13 (^{13}C) and Vegetation

The $\delta^{13}C$ recorded in speleothems can be used to analyze changes in vegetation at the surface, which are indicative of climate. Analysis of speleothems in 3 caves in Guangxi and Guizhou (China) revealed monsoon patterns reaching back 15,000 years (Xiaoyan et al., 2006).

Plants can photosynthesize in two different ways, producing different initial molecules, which can have either 3 or 4 carbon atoms, with different amounts of ^{13}C, which indicate the type of environment the plants grew in. Forest plants produce C_3, while grasses produce C_4, which has higher amounts of ^{13}C. Speleothems are generally considered to contain only 20% inorganic carbon, as a result of exchanges between the air, soil, water, and rock (cf.19.2.2.3).

The amount of ^{13}C in a speleothem will therefore be highly dependent on the vegetative cover.

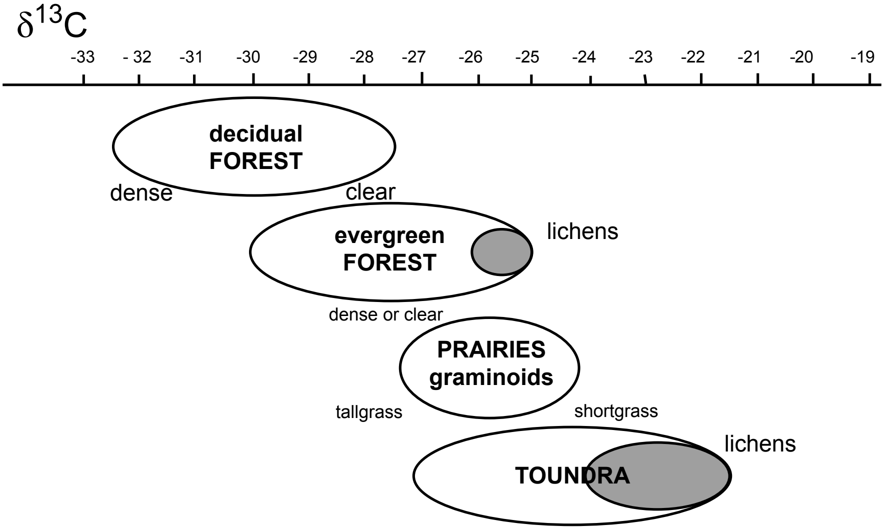


Figure 146. $\delta^{13}C$ in C_3 plants according to the type of environment (after Drucker and Celerier, 2001).

19.3.4 Spatial Organization of Karst Conduits

In a limestone massif, the process of karstification affects the pre-existing discontinuities, and is organized as a function of local hydrologic conditions. Karst systems, as they are being emplaced, record the fractures in the rock and the base level at the time. These records are being created throughout the process of karstification.

For example, if an area is uplifted, the base level becomes relatively lower, and the karst system adjusts by excavating lower conduits. The presence of several levels of dry galleries indicates several phases of uplift (cf. chap. 8). Conversely, when the area subsides, lower passageways fill in and the upper conduits are re-used, or new conduits are excavated higher up. In mountainous areas, large systems like the Dent de Crolles (Figure 55) were created by glacial meltwater, and as a result some passageways record the presence and geometry of the glaciers. Similarly, the perched caves in the fjords of Norway are indicators of post-glacial rebound.

19.4 Records of Deformation

19.4.1 Faults

The stability of large civil engineering projects (dams, nuclear power plants, etc.) depends on understanding the stability of the landscape over long time periods, by identifying active faults and evaluating the risk of future seismic shocks. There is a relationship between the length of a fault and the magnitude of the earthquakes it produces. The seismic risk can also be evaluated by looking for past evidence of activity along major faults. The study of damage to ancient architecture (archeo-seismicity) and geomorphologic studies (paleoseismicity) have long been used to provide this kind of information for delicate civil engineering projects that are generally expected to last 50 years. However storage facilities for radioactive waste must remain safe for several thousands of years making it necessary to estimate the seismic risk over very long periods. This makes caves an appealing location to evaluate the risk.

Karst systems are formed when dissolution occurs along the discontinuities of a limestone unit, and the slightest tectonic shifts can readjust discontinuities and therefore the speleothems or conduits along them. The karst terrain can therefore provide clues about the past seismic and tectonic activity of a region, with records stretching back several tens of thousands of years.

In the endokarst, speleothems and clay deposits mark off the horizontal and vertical planes. If an area is tilted, that tilt will be recorded in the speleothems, which will change their direction of growth to remain vertical. For example, the Castellaras cave (Le-Tignet, France) is located into a limestone scree slope that is slowly sliding down the underlying bedrock. A record of this motion over 30,000 years was created by a sodastraw that curved as the limestone slid downslope (Gilli et al., 1994) (Figure 147).

When karstic conduits are aligned with active faults, the speleothems inside are modified by motion along the fault. This occurred at the Frassino Cave (Campo dei Fiori, Italy) (Bini et al., 1992), in Barrenc-du-Haut-Paradet (Eastern-Pyrénées, France) (Figure 148) or in the Cueva Corredores (Costa Rica) (Figure 149).

Given the absence of soil and vegetation, millimeter-scale displacement can be observed in a cave that would not be visible at the surface (Figure 150) (Gilli, 1986b).

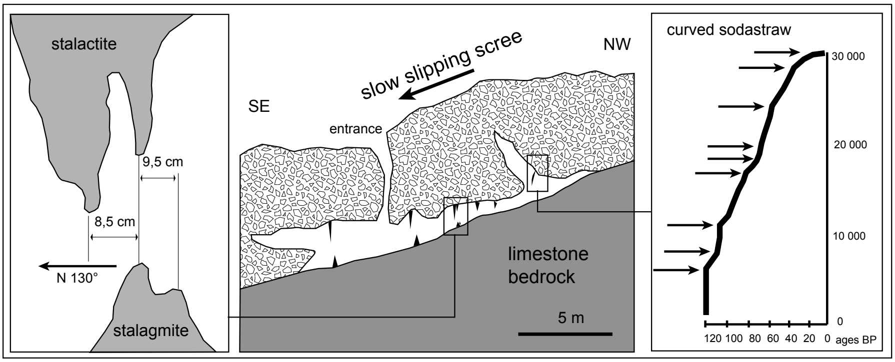


Figure 147. Broken and offset speleothems in the Tignet Cave (Alpes Maritimes).

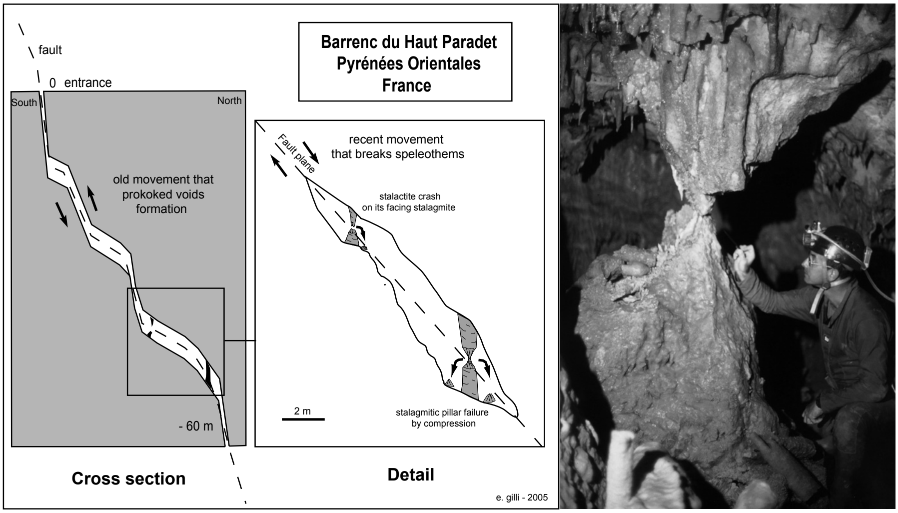


Figure 148. Record of fault motion in speleothems in Barrenc du Haut Paradet (Eastern Pyrénées) (Gilli et al., 1999).

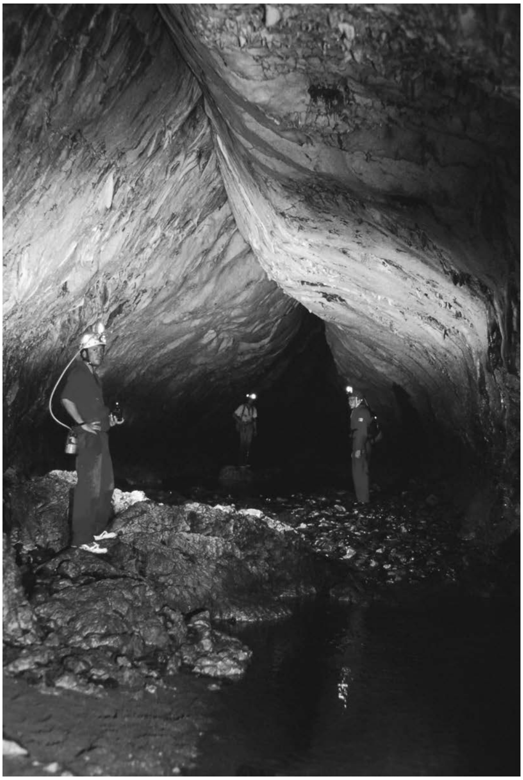


Figure 149. Offset of part of a cave in a subsiding region (Cueva Corredores, Ciudad Neily, Costa Rica) (Gilli, 1995).

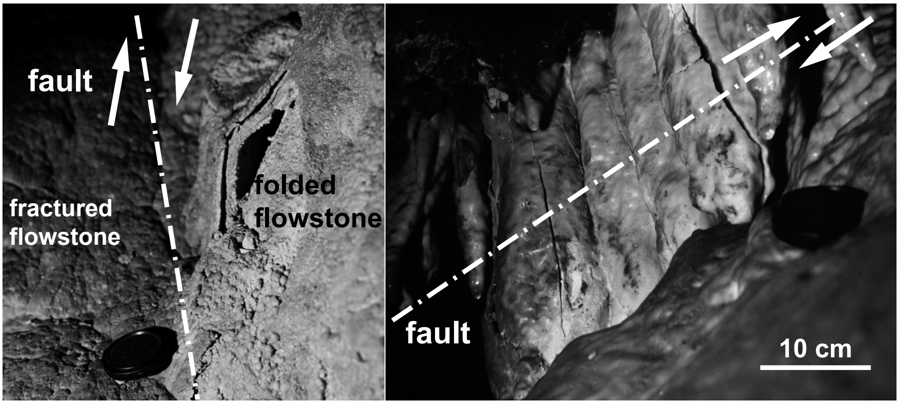


Figure 150. Record of fault motion in speleothems in the Deux Gourdes Cave (Alpes Maritimes) (Gilli, 1986b).

Cévennes fault in France

The Cévennes fault, which runs over almost 180 km at N 35°, separates the older terrain in the southern Massif Central from the Languedoc Meso-Cenozoic fold belt. Geologists from the IPGP (Institut de Physique du Globe de Paris) and from Montpellier university hold contradictory views of the fault. The Paris researchers suggested that the Cévennes fault was an active sinistral fault moving between 0.1 and 2 mm/year (Lacassin et al., 1998), whereas, for Montpellier geologists, the classical interpretation had been that the Cévennes fault was dextral, and had been formed during the Variscan orogeny, after which it reactivated sinistrally 40 Ma during the formation of the Pyrénées. Then it had been inactive since the Oligocene (30 Ma) due to the collapse of the Golfe du Lion mountain range responsible for the creation of normal faulting (Mattauer, 1998).

If the fault's Quaternary activity could be confirmed, it would, because of its length pose the risk of a magnitude 7 earthquake in a densely populated area. However, karstologic evidence supports the second interpretation. In fact, observations in the Garrel cave system, which cuts across one of the NE-SW parts of the fault, revealed that the karstic conduits were not offset by the fault, and that the speleothems inside have remained undisturbed for at least 466 thousand years (Camus et al., 2001).

19.4.2 Submarine Indicators

Along sea notches (chap. 14), living organisms like shells and seaweed build up a crust over the limestone, which means that Holocene platforms can be dated using ^{14}C. These sea notches are excellent sea-level markers, and can be used to calibrate models of sea-level change that incorporate eustasy, tectonics, and isostasy.

These submarine karstic markers were used by Collina-Girard (1999) to compare the relative motion of areas that were separated by active faults. By carefully mapping the submerged topography in southeastern France, he was able to identify a succession of benches and sea notches, records of past sea-level variations. At –55 m, which corresponds to 10,000 years ago, there are a number of submarine caves and overhangs. Differences in depth for the notches observed on both sides of a fault suggests it is an active one. In the area around Nice, the same sequence is present, but it is offset by two meters on either side of the Var River. This may indicate the presence of an active fault along the Var River.

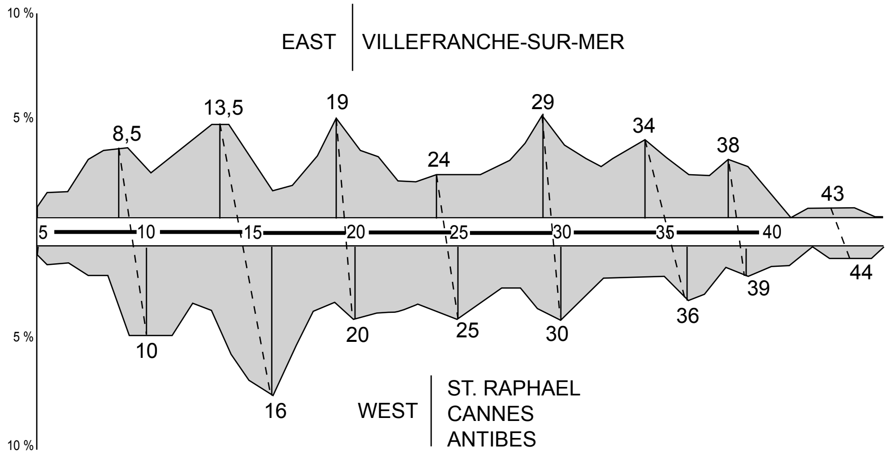


Figure 151. Comparative bathymetry for overhangs and the base of submarine cliffs on either side of the Var River (Alpes Maritimes) (Collina-Girard, 1999). The area to the east of the Var (Villefranche/Mer) appears to be 2 meters higher than the area on the western bank.

In Barbados, the Miocene cuesta is scarred with numerous sea notches, the highest of which is 300 m above sea level, indicating rapid uplift (Nicod, 1972). The Gulf of Bodrum (Turkey) is aligned along an east-west axis, and contains submarine sea notches to the west and perched sea notches to the east, indicating that the coast has tilted slowly to the west. A similar situation can be observed on the island of Cephalonia (Greece), where the sea notches are at different elevations on the eastern and western shores of the island.

19.4.1 Applications in Paleoseismicity

19.4.1.1 Seismically induced breakage of speleothems

Broken or tilted speleothems, which have been observed on the floors of many karstic or volcanic caves, are often interpreted as the result of seismic activity, and they have been studied in great detail (Becker, 1929; Gospodaric, 1977; Schillat, 1977; Forti and Postpichl, 1986; Agostini et al., 1994; Delaby, 2000). When the features that are observed are correctly interpreted, study of the endokarst can yield a great deal of information about the paleoseismicity of an area, as was seen in Switzerland with the PALEOSIS program (Becker et al., 2006).

However, recent work done in labs and *in situ* indicates that speleothems are more resistant to seismic shock than was previously thought. Only the more elongated formations (sodastraws and long candle-shaped stalagmites) are likely to break due to seismic activity. Other mechanisms, such as sediment creeping in caves (Gilli, 1999) or ice intrusions (Gilli, 2004; Kempe, 2004) have been identified, which could explain the majority of the damage that has been described by previous authors (Figure 153).

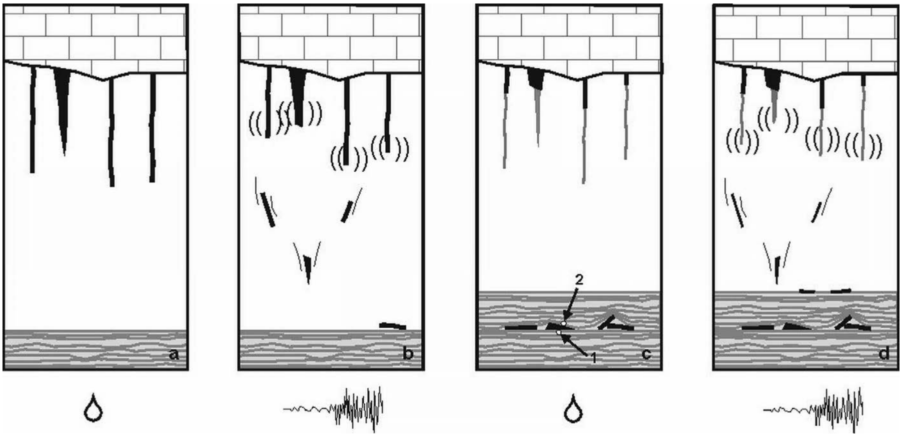


Figure 152. Seismic activity recorded by the speleothems in a cave (Gilli, 1999).

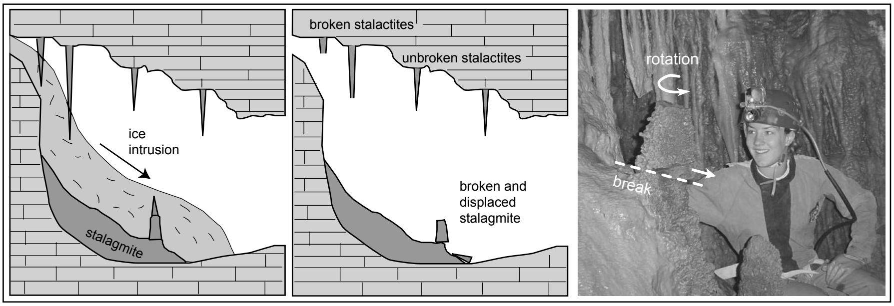


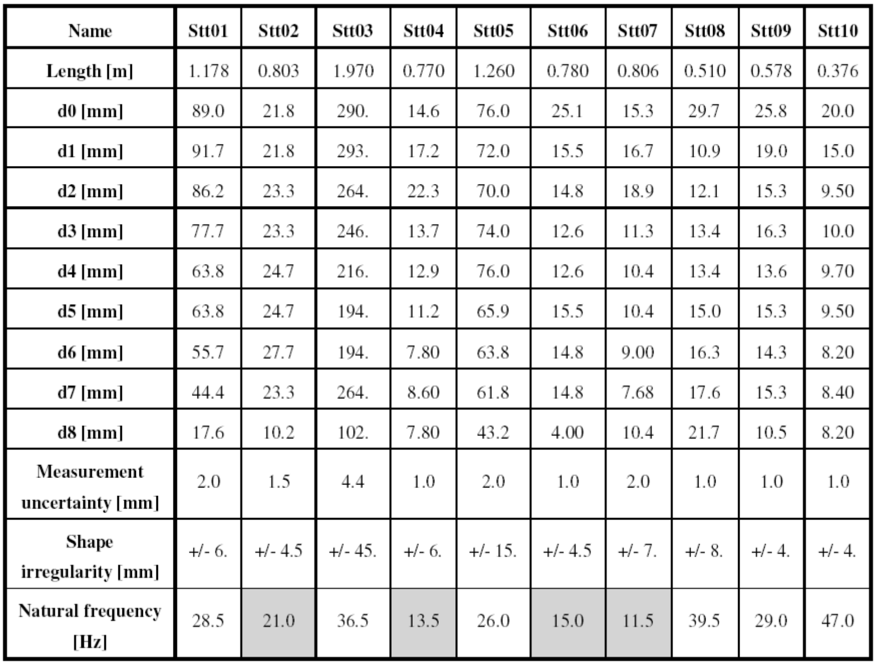
Figure 153. Effects of ice intrusions into karstic conduits (Gilli, 2004).

19.4.1.2 Mechanical tests on speleothems

In order to determine whether or not seismic shocks could damage speleothems, the mechanical properties of stalactites, stalagmites and sodastraws were studied, to find their static breaking point (Cadorin et al., 2000), as well as their resonant frequencies and their damping (Lacave et al., 1999).

These tests found not only the average mechanical strength of the speleothems, but also its variability, which makes it difficult to estimate the acceleration needed to break any one speleothem. A statistical approach is therefore needed. The speleothems thought to be potentially most vulnerable (whether they were already broken or not) were measured in Milandre Cave (Switzerland). Dynamic amplification, as well as the heterogeneity of each individual speleothem's potential strength were taken into account. This approach found that at least one medium-strength earthquake had occurred in the past, in this particular study area (Lacave et al., 2002).

Table 15. Geometry and eigenfrequencies for 10 stalactites measured in the Milandre Cave (Switzerland). The frequencies that fall within the range of seismic vibrations are highlighted in gray (after Lacave et al., 2002).



Name	Stt01	Stt02	Stt03	Stt04	Stt05	Stt06	Stt07	Stt08	Stt09	Stt10
Length [m]	1.178	0.803	1.970	0.770	1.260	0.780	0.806	0.510	0.578	0.376
d0 [mm]	89.0	21.8	290.	14.6	76.0	25.1	15.3	29.7	25.8	20.0
d1 [mm]	91.7	21.8	293.	17.2	72.0	15.5	16.7	10.9	19.0	15.0
d2 [mm]	86.2	23.3	264.	22.3	70.0	14.8	18.9	12.1	15.3	9.50
d3 [mm]	77.7	23.3	246.	13.7	74.0	12.6	11.3	13.4	16.3	10.0
d4 [mm]	63.8	24.7	216.	12.9	76.0	12.6	10.4	13.4	13.6	9.70
d5 [mm]	63.8	24.7	194.	11.2	65.9	15.5	10.4	15.0	15.3	9.50
d6 [mm]	55.7	27.7	194.	7.80	63.8	14.8	9.00	16.3	14.3	8.20
d7 [mm]	44.4	23.3	264.	8.60	61.8	14.8	7.68	17.6	15.3	8.40
d8 [mm]	17.6	10.2	102.	7.80	43.2	4.00	10.4	21.7	10.5	8.20
Measurement uncertainty [mm]	2.0	1.5	4.4	1.0	2.0	1.0	2.0	1.0	1.0	1.0
Shape irregularity [mm]	+/- 6.	+/- 4.5	+/- 45.	+/- 6.	+/- 15.	+/- 4.5	+/- 7.	+/- 8.	+/- 4.	+/- 4.
Natural frequency [Hz]	28.5	21.0	36.5	13.5	26.0	15.0	11.5	39.5	29.0	47.0

19.4.1.3 Paleoseismic indicators

The relationship between earthquakes and fallen speleothems is difficult to prove, and observations of caves shortly after an earthquake are needed to determine whether or not speleothems will eventually be useful in determining paleoseismic activity. This has already been done in a few locations, following recent earthquakes, and the following observations were made:

- Saint-Paul-de-Fenouillet (Ms5.2) earthquake in 1996 (France, Eastern Pyrénées), a few fallen sodastraws, blocks of fallen rocks and dust deposits (Gilli, 1999);
- Colfiorito (Ms6) earthquake (Italy) in 1997, rock fragments flaking off the cave walls;
- Limón (Ms7.5) earthquake (Costa Rica) in 1991, speleothem coating on the cave walls cracked, flow reversals in subterranean rivers, blocks of fallen rock (Gilli et al., 1995).

19.4.2 Tsunamis

The karstic record may also show traces of prehistoric tsunamis, in marine cave deposits or on cave walls. Some studies have been done in Thailand, on Koh Phi Phi Island, after the 2004 Indian Ocean tsunami (Gilli, 2010). They discovered that the sea waves, which reached heights of 8 m in places, had barely affected the underwater cave of Tham Phaya Nak, and only left a few pieces of coral debris near the entrance (Figure 154).

However, another layer of coral fragments, dated as being 6000 years old, was observed, which reached all the way to the bottom of the cave, and may have been deposited by a large wave (cyclone or tsunami). In the same area, along the limestone cliffs, the stalactites on the exterior walls are all broken below 10 m of elevation (Figure 155). This could support the hypothesis that large waves occurred in the past during a prehistoric tsunami.

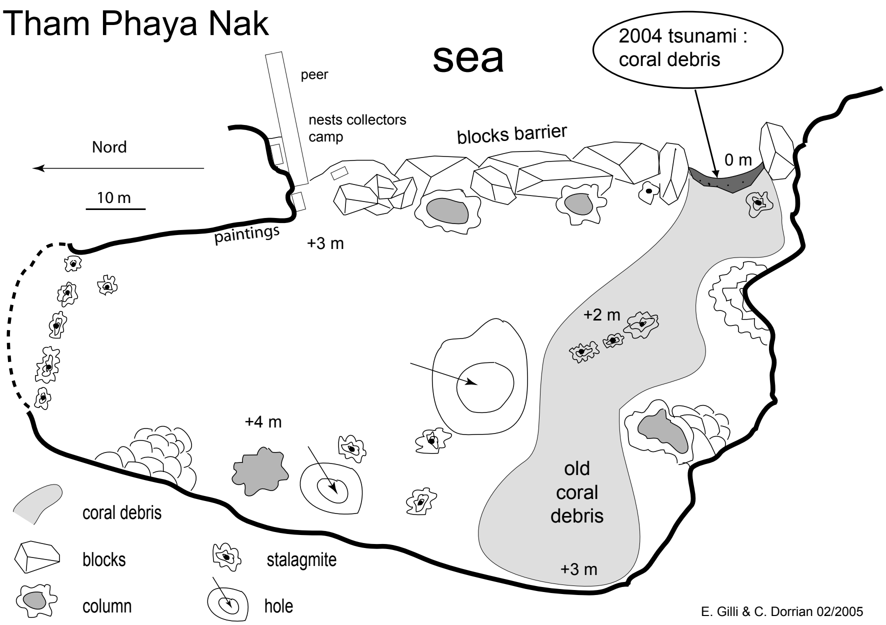


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Figure 154. Record of a paleotsunami in Tham Phaya Nak Cave (Thailand).

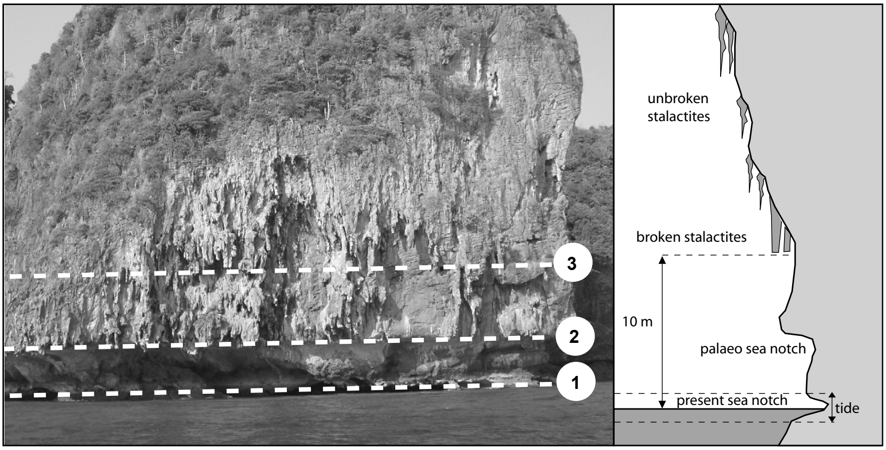

Figure 155. Wave-cut platforms indicating previous sea-level elevations. 1—current overhang, 2—ancient overhang, 3—broken stalagmites.

19.5 Applications in the Study of Paleoclimate

The role of climate in the evolution of karst systems and in the formation of speleothems opens up the endokarst as a place to study paleoclimate.

19.5.1 Climate Forcing

Monsoon analysis in China was described earlier (cf. 19.3.1). Interesting observations were also made in the Corchia Cave (Italy), going back to 1 Ma (Drysdale et al., 2009). By correlating very careful records of precipitation in northwestern Italy, oxygen isotope analyses, and U/Th dating, the end of the second-to-last ice age was dated to 141,000 years ago, confirming the influence of obliquity cycles on the Earth's climate.

19.5.2 Fall of the Mayan Empire

Archeologists have defined three periods in the Mayan Empire: the Pre-Classical period, the Classical period, and the Post-Classical period. The end of the Classical period, around the year 900, was marked by decadence from which the empire never managed to recover, leaving a civilization in disarray to the conquistadors. Various causes for the Mayan Empire's decline have been proposed: earthquakes, wars, overpopulation, famine, the disappearance of the elite, monoculture, and so on.

A stalagmite from the Macal Chasm on the Vaca Plateau, west of Belize, was the subject of careful examination, including laminae luminescence, ^{18}O and ^{14}C content. The luminescence of the laminae yielded interesting information. Luminescence occurs when humic acid is present, which indicates the density of vegetation at the surface. Paleoenvironmental information is therefore recorded in the laminae, in this case going back 3,300 years. Analysis suggests that significant droughts, which is characterized by decreased luminescence due to less production of humic acid, hit the Mayan Empire at least four times within a span of 1500 years (Webster et al., 2007) (Figure 156). These droughts coincided with the collapse of the Classical Mayan Empire. These findings highlight the Mayan civilization's dependence on water, and the impact that decreased resources had on a civilization that could not adapt to environmental change.

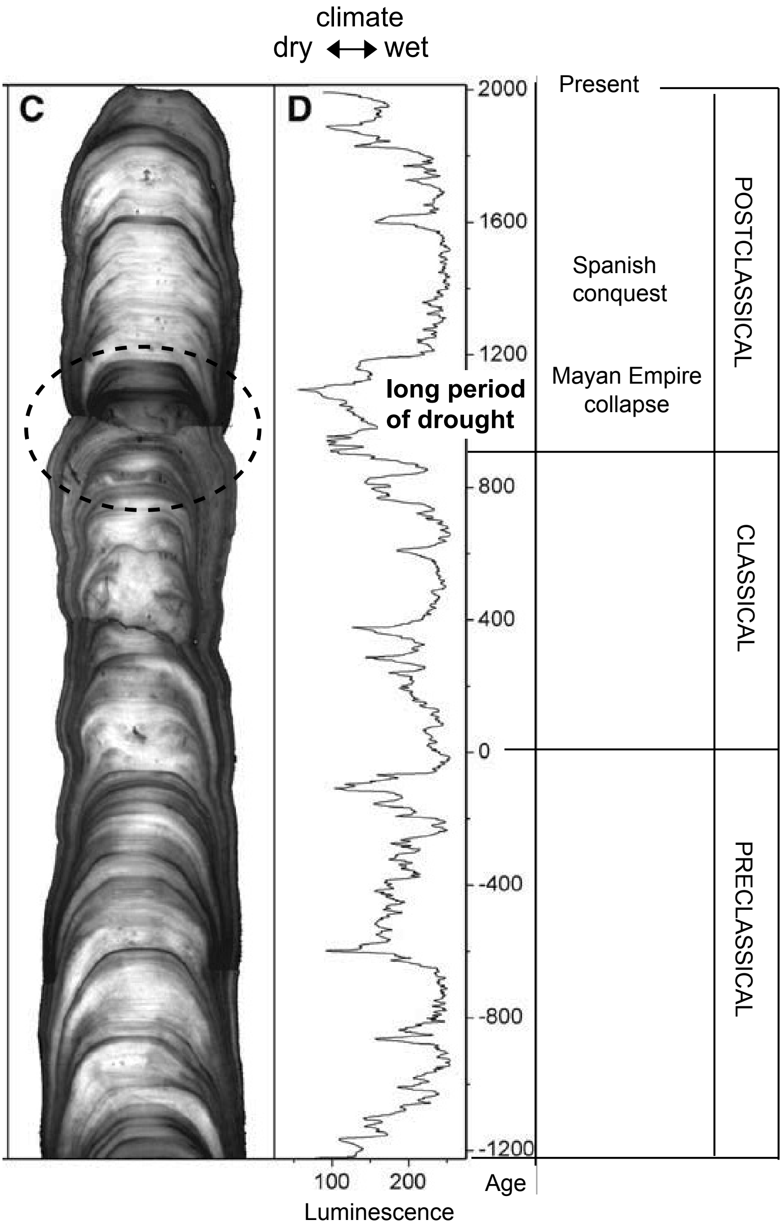

Figure 156. Luminescence in a stalagmite in Mayan territory in Belize (after Webster et al., 2007).

20

Geodesy and Rock Deformation

20.1 Value of Karst Systems

Karst systems are rigid environments within which structural deformation can be studied. Caves, which are protected from temperature variations, are well suited to hold sensitive monitoring equipment.

20.1.1 Tiltmeters

Long-base tiltmeters, which can have an angular resolution of 10^{-9} radians, can measure elevation changes of 1 mm over 1000 km. They are used to measure earth tides, tectonic and gravitational shifts, and deformation caused by hydrologic forces (Boudin, 2004).

They are useful in studying the behavior of subterranean bodies of water in karst.

20.1.1.1 The Calern karst plateau (Alpes-Maritimes, France)

The Calern karst plateau (Figure 157) is home to a geodesic observatory where geodesic variations that have long gone unexplained are now being measured. The plateau itself undergoes an annual vertical oscillation of up to 6 cm. In order to study the relationship between geodesy and hydrology, two long-base tiltmeters (5 m and 9 m) were installed in the Cipiernaum Chasm, and several other hydrogeologically relevant sites were equipped with CTD (Conductivity, Temperature, Depth) probes. The plateau drains to Bramafan Spring, above which the Revest Chasm is located, where there is an access point to the karst aquifer and where the water table has been observed to fluctuate by over 100 m.

Tiltmeter observations show a general loading of the plateau in the N100°E direction, beginning a month after the start of the rainy season, then an unloading in the N90°E direction during the dry season. The maximum clinometric gradient is 8 μrad.

There is a strong hydrologic/clinometric correlation in the karst aquifer near Revest-Bramafan. The first autumn rains have no effect, but starting in November there is a strong correlation between the water table and the incline, when increased precipitation provokes a water loading in the N100°E direction. The long-term tilting

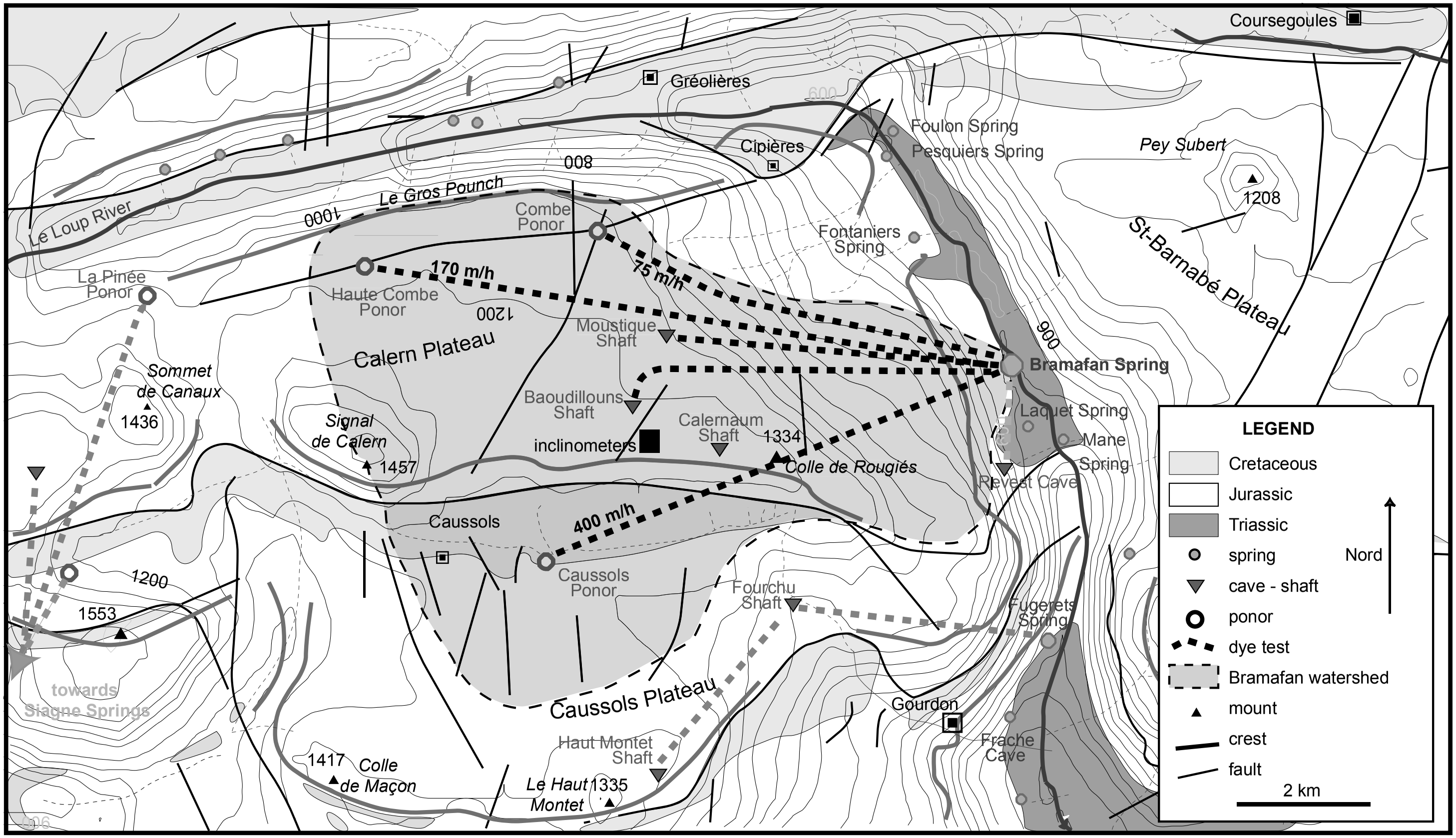

Figure 157. Geologic and hydrogeologic outline of the Calern Plateau (Alpes-Maritimes). The water collected in this drainage basin is concentrated on the eastern part of the plateau and flows out through the Bramafan Springs.

of the plateau seems to be tied to the lowering of the water table during the dry season. In the fall, the first rains recharge the epikarst aquifer that emptied during the dry season, without influencing the tilting of the plateau. The winter rains flush down the water towards the deep aquifer on the eastern side of the plateau. Occasional changes are then observed by the tiltmeter in the N320° direction (Figure 158).

A simple flexure model, based on the Boussinesq principle, can be used to calculate the clinometric effect of a water loading in a given location, with the direction of maximum tilting between 90 and 100°E. Based on a structural analysis of the catchment basin, it is estimated that following a precipitation event, 25 million m^3 of water accumulates in an 8 km^2 area between the tiltmeter and the Bramafan Spring. The corresponding flexure was calculated to be 4 µrad at the tiltmeter station, the same order of magnitude that had been observed by the tiltmeters (Gilli et al., 2010).

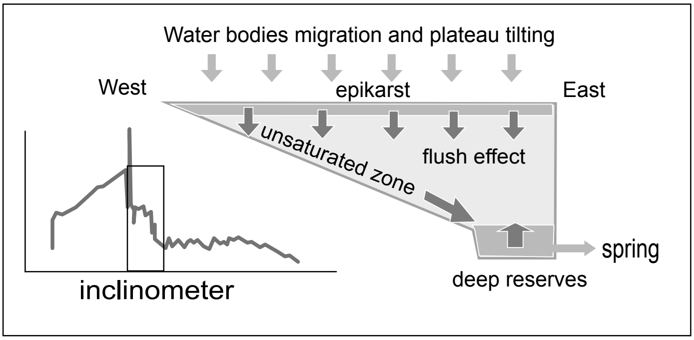

Figure 158. Clinometric variations on the Calern plateau, correlated with fluctuations in the water table of the Revest-Bramafan karst aquifer (Alpes-Maritimes).

20.1.1.2 Durzon Spring (Larzac, France)

The Durzon Spring drains approximately 100 km^2 on the Larzac Plateau. Geodesic observation stations (GPS unit and absolute gravimeter) were installed in Salvetat, La Blaquerie and Les Canalettes, and 4 tiltmeters were set up in avens 50 m below the surface.

The observed clinometric variations (Figure 159) were correlated with the variations in discharge at the spring. During the fall of 2006, the plane defined by the clinometers tilted towards the spring after each increase in discharge, then returned to its original position. Models showed that the measured tilt is also related to hydraulic changes in the fractures near the tiltmeter (Jacob et al., 2008).

20.1.1.3 Applications

Tilting of a karst massif appears linked to the hydrologic state of the aquifer it contains. It is therefore theoretically possible to estimate the size of karst aquifers using geodesy.

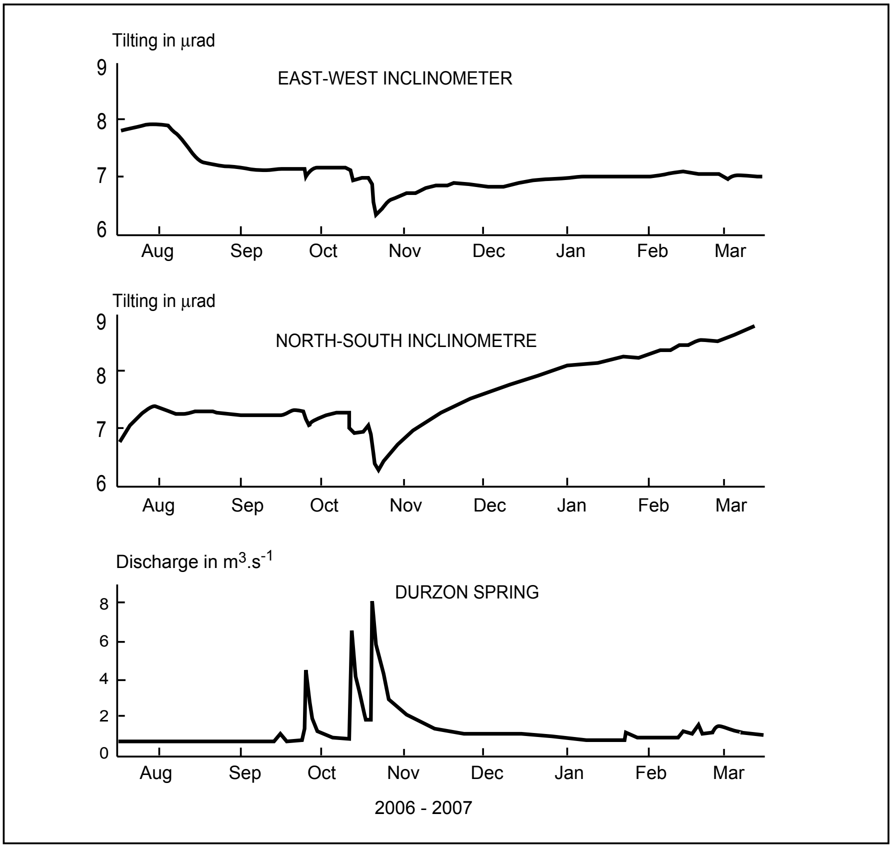

Figure 159. Surface tilting above the Durzon Spring (Larzac).

20.2 Rock Mechanics

An underground dam prototype was built in Coaraze on a karst spring (Figure 160) that drains a small Neocomian limestone unit. The spring was blocked off by a sluice gate, which can be closed to artificially raise the water table of the karst aquifer until it overflows through a perched outlet 8 m above the spring. When the sluice gate is open, water flows from the spring and drains the reservoir. Several tests demonstrated that closing the sluice gate would, on the one hand, flood karst conduits, and on the other hand, recharge the network of discontinuities in the limestone unit, thereby creating an underground reservoir (Gilli and Mangan, 1994).

This prototype was later modified to serve as an *in situ* laboratory for studying the hydro-mechanical coupling of rock discontinuities. The reservoir was equipped with monitoring probes that measured the water pressure and the mechanical strain on the rock at different points within the limestone unit, while under controlled hydraulic conditions. This arrangement was used to study the effects of fluctuations in the water table on the network of fractures.

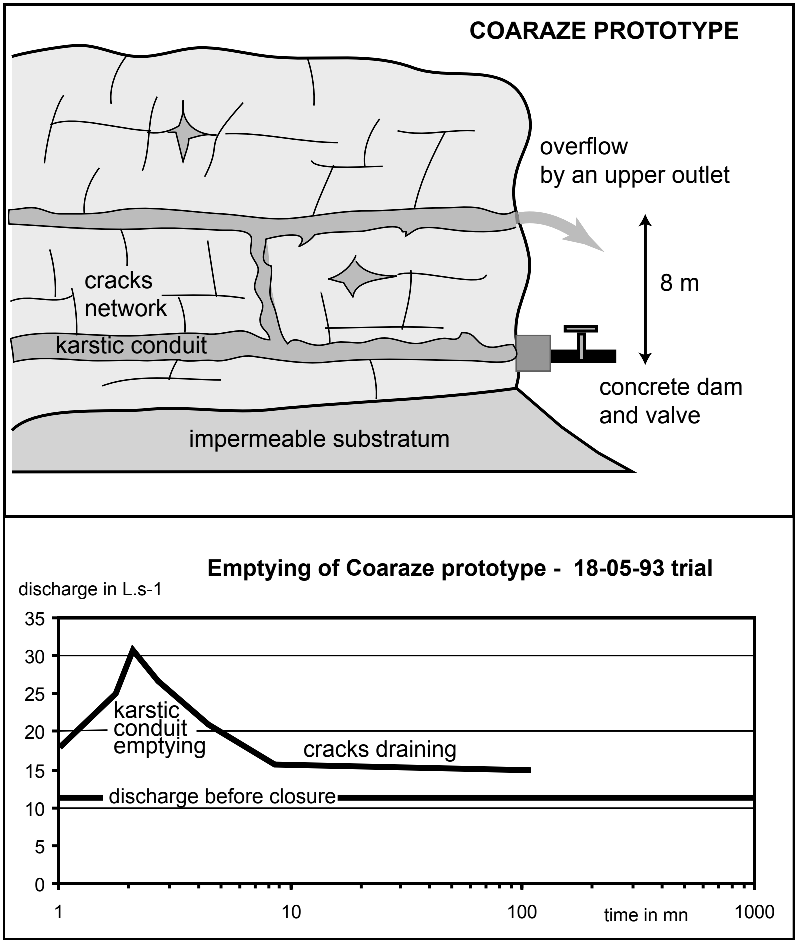

Figure 160. Drainage and interpretation of the Coaraze prototype dam (Alpes Maritimes) (Gilli and Mangan, 1994).

In fact, the hydrometric conditions inside a fracture are a function of both its hydraulic and mechanical properties, as well as its orientation, the magnitude of the stresses being applied, the degree of interconnectedness with other fractures, and the surrounding large-scale structural context (Cappa et al., 2005). A field laboratory like the Coaraze prototype is therefore useful because it enables the study of all of these parameters in the same place.

The fracture network can be subdivided into three distinct groups (Figure 161).

- 3 subvertical faults oriented N50/N70,
- 11 subvertical faults oriented N120/N140,
- 12 stratification joints oriented N40 with a 45° dip to the SE.

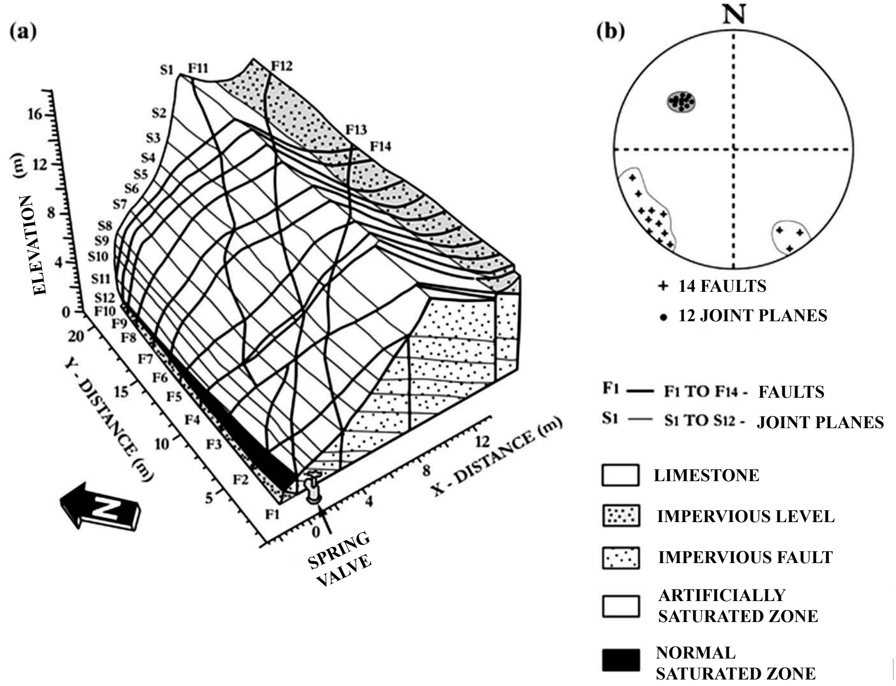

Figure 161. Fracture network upstream of the Para spring (Coaraze, Alpes-Maritimes) (after Cappa et al., 2005).

Measurements indicated that the limestone matrix is impermeable (k = 9,8 × 10^{-17} m^2) and has low porosity (0.2%), whereas the fractures are highly interconnected. The experimental setup also revealed differences in behavior between the faults and the stratification joints. Several experiments involving increasing and decreasing the hydraulic load found that faults have a high hydraulic conductivity (0.57 × 10^{-4} to 1.9 × 10^{-4} $m.s^{-1}$), while in joints it is much lower (0.9 × 10^{-6} to 7.6 × 10^{-6} $m.s^{-1}$). When the sluice gate was closed, the faults opened as soon as the pressure increased, and stabilized around 1.5 à 2 × 10^{-6} m in measured locations. When the sluice gate was raised, the system returned to its initial conditions after two minutes of hydraulic discharge (Guglielmi and Mudry, 2001; Cappa et al., 2005).

Further study is needed on the relationship between this behavior and speleogenesis (cf. chap. 7.2).

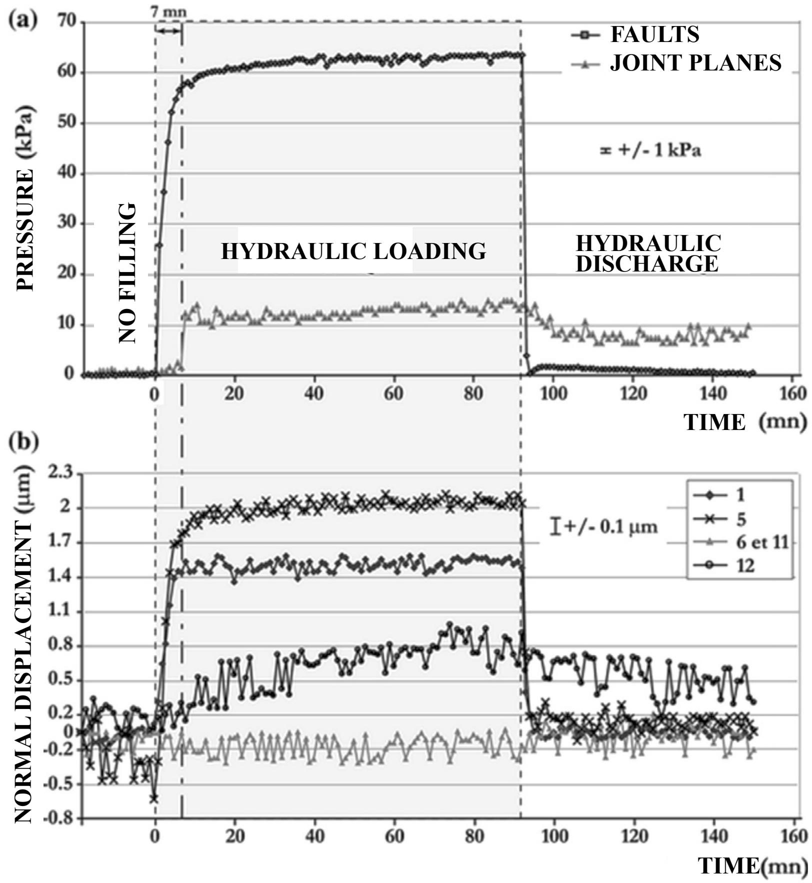

Figure 162. Coupled hydraulic and mechanical cycles in Coaraze (Cappa et al., 2005).

21

Paleontology, Archaeology, and Biology

21.1 Traps and Conserving Environments

The endokarst is protected from light and precipitation, has no vegetation, and remains at stable climatic conditions, with the result that it protects records of events for thousands of years. Cave deposits preserve traces of the animals that inhabited the cave (bears, cats, bats, rodents, etc.), or that fell into it. The following photograph (Figure 163) depicts a fossilized lemur skull that was preserved in a cave in Madagascar after it fell into a chasm. In addition to fossils, caves also preserve the traces of animal activity, such as bear claw marks or the hollows they excavated to hibernate in. Prehistoric humans also left behind numerous traces of their activity, in addition to their bones and tools.

21.2 The Quercy Phosphorites

In southwest France, the Quercy phosphorites are phosphate-rich sedimentary deposits trapped in a karstic paleorelief. During diagenesis, the sediment, through sorting, compaction, leaching, and possibly the circulation of mineral-rich fluid, turned into rock that could be mined and turned into fertilizer.

During the mining process, karstic depressions and caves were excavated, revealing a large number of fossils. This location, which contains 130 fossil beds and millions of exceptionally well-preserved individual remains, has provided source material for several significant paleontological discoveries (Pelissié, 2010). The species diversity that is represented is extraordinary, with more than 500 species of mammals alone.

Figure 163. Fossil lemur skull. Ankarana Massif (Madagascar).

21.3 "Cavemen"

The concept of cavemen is a misrepresentation, since early hominids actually spent only part of their time in caves. When they did choose to dwell in caves, they preferred south-facing entrances near a water source. Various types of habitations were found in caves: temporary hunting camps, nomadic encampments, religious or burial sites, sources of useful materials, or even simply traces left by curious explorers.

In Asia and in Madagascar, funeral rites that take place in caves are still practiced. In Central America, descendants of the Mayans also still use caves for ritual purposes, in order to communicate with their ancestors.

Early humans left traces of their passage, either intentionally or by chance, which were preserved for thousands of years, making caves a rich source of information for archaeologists and paleontologists, thereby leading to the "caveman" stereotype. Early humans lived outside caves, but the traces of their encampments have for the most part been erased by erosion and vegetation growth. The traces found in caves are varied: tools, paintings and graffiti, footprints, buildings, fireplaces, middens and graves. One set of 30,000 year-old prehistoric cave paintings in the Chauvet Cave (Ardèche, France) was preserved so well that they were thought to be fakes when they were discovered. Footprints and even fingerprints are visible in clay deposits in Niaux Cave and in the Tuc d'Audoubert cave, in French Pyrénées. Today also even the briefest human incursions leave traces: soot from carbide lamps, mud deposited over speleothems, boot prints on flowstones, etc. Although these may be of interest to future archaeologists, human traffic can then cause significant damage, and can obscure older clues. For example, in Niaux Cave, archeologists found that the footprints left by modern-day visitors have almost completely erased those of the cave's early hominid visitors!

The endokarst is not solely studied for the objects it has preserved. It also records information about the relationship between humans and their environment. Similarly, more and more studies have been focused on the relationship between humans and caves, in order to understand what would have motivated early hominids to begin exploring underground.

Studies in the greatest French archaeological cave sites, like Tautavel, Cosquer, Chauvet, and Lascaux can provide enough context to sketch a picture of primitive humans in their environment, which left records in the endokarst. For the Holocene and early human history, anthropogenic environmental changes (controlled burns, deforestation, soil erosion, etc.) left their marks on speleothems and in rhythmic detrital deposits, which can yield useful information when carefully analyzed.

21.4 Isolation and Genetic Divergence

The endokarst preserves information about organisms found there in the past, but it can also isolate and conserve living populations, which, due to their isolation, evolve along a different path and become genetically distinct from their parent population. Caves act as "islands", where divergent evolution can lead to the creation of new species, such as blind, colorless fish. As a result, one region may be home to several different species of the same genus, each living in isolated caves.

The same phenomenon occurs in aquifers, and the work of V. Prié (verbal communication) on gastropods shows that one species may encompass a great deal of genetic diversity across aquifers, which, although geographically near each other, are separated by an unsaturated zone. These differences could be used to better describe karst aquifers.

21.5 Extremophiles

Some plants and animals can survive in area once thought to be uninhabitable, such as ice, hot springs, and anoxic or acidic environments.

In karstic hot springs, bacteria colonies can be observed, floating in flakes through the water. They indicate the presence of life at great depths, where it survives without light or oxygen.

At the Pestera de Movile, discovered in 1986 in Romania, near Mangalia, there is an entire ecosystem of organisms that do not depend on sun for their survival. These 60-odd species live in an environment with very low oxygen levels (7–10%), but high levels of carbon dioxide (2–3.5%), methane (1–2%) and hydrogen sulfide. They survive by metabolizing sulfur.

Studies have been done on hypogenic or hydrothermal caves, such as Lechuguilla (New Mexico, USA) or Cueva de Villa Luz (Tabasco, Mexico), rich in hydrogen sulfide. On the roof of Villa Luz, they found filaments of bacteria called snottites. These colonies live in acidic environments and derive energy from metabolizing sulfur. The role they play in speleogenesis is as yet unknown. Studies of these types of organisms have led to new thinking about what conditions are necessary for extraterrestrial life, and about how life may have originated. This is particularly relevant for the Mars exploration missions, where water is known to exist below the surface.

22

Conclusion

Karst is an immense field, and vast parts of it remain almost completely unexplored, including hydrothermal karst, deep karst, and submarine karst.

It is a well-defined entity that cannot be fully understood without linking surface and subterranean features, nor without the concept of carbonate cycle. Karstology is a field in which an interdisciplinary approach is necessary, calling on a number of different areas of study. As with most scientific disciplines, general studies and specialized sub-disciplines exist side-by-side, each with their own problems, and often grappling with either a too-narrow focus or a too-broad superficial approach. Luckily, the karstologic community, which includes both speleologists and geologists, is working to bridge interdisciplinary gaps. In France, the Rencontres d'Octobre (October Meetings), Rik Raks, and speleological conferences are opportunities for fruitful exchanges, as are the Slovenian Karst Schools and numerous international conferences.

In terms of geographic understanding, the relationship between karstology and speleology has developed considerably thanks to technical advances, which have allowed humans to explore almost all of the known caves in the world, aside from those where water is still an obstacle, either because of its velocity, its temperature, or the important distances and depths to reach. As a result, further exploration of the greatest flooded cave networks in France, such as the Fontaine de Vaucluse or Port Miou, is dependent on specially adapted new diving techniques. As of yet, there are no systems that can support exploration over several kilometers within these underwater cave networks to discover their secrets. Technological improvements to support exploration could be a worthy challenge for the private sector, with immediate applications in water resources management.

On the conceptual level, there are many questions that have as of yet only partially been explained:

- What is the maximum depth at which karstification can occur?
- Where are karstic water reserves located? Are they only present in the deep saturated zone, or do comparable volumes also exist in the epikarst and in the unsaturated zone?

- What respective roles do fracture networks and drainage conduits or paleodrainages play in water storage?
- What is the role of microorganisms in speleogenesis?
- How do subterranean speleothems form and evolve?
- How can speleogenesis and karst systems be modeled?

Important goals in applied karstology remain out of reach as well:

- Surface detection of deep cavities and water conduits.
- Detailed analysis of the vulnerability of karst aquifers.
- Estimating and modeling cavities and the resources they contain (water, petroleum, etc.).
- Tapping coastal karst aquifers and submarine springs.
- Tapping deeper reservoirs.
- Water resource management, including, for example, artificial recharge in karst aquifers.

Thus many questions remain unanswered, and that can therefore serve as the focus of research and study. In addition to these questions, there is also a need for study of the catchment basins for most karstic springs. All of these areas are employment and study opportunities for generations of karstologists.

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Color Plate Section

Chapter 15

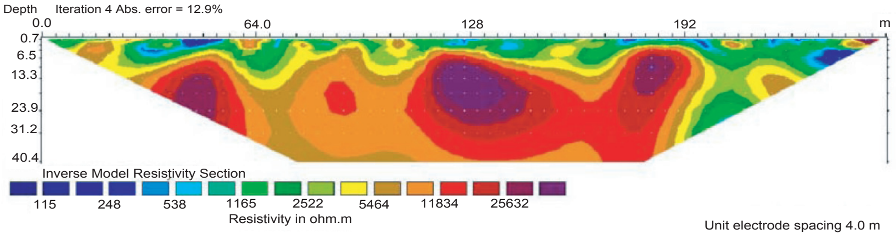

Figure 124. Underground cavities revealed by electric panels in Lamalou (after Guérin, 2004).

Figure 164. High-mountain karst in the Marguareis (Alpes Maritimes, France). This landscape is shaped by superimposed karstic and glacial features. Glacial polish and moraines were left behind when the ice melted in the Holocene. The melt water carved out deep karstic conduits, and exposed limestone surfaces, which were then incised by more recent lapies.

Figure 165. Saint Barnabé karst (Alpes Maritimes, France). Lapies forming under a layer of soil cover created rounded shapes (rundkarren) sculpted by water running down their surfaces.

Figure 166. Caussols ponor (Alpes-Maritimes, France). Water collects in Cenomanian marls, and disappears into the ground when it reaches the contact with Neocomian limestone. It re-emerges at the Bramafan Springs, 6 km to the east.

Figure 167. Dumanli Vauclusian spring (Turkey). The discharge ranges from 50 to 1000 m^3/s. Today, this spring is hidden beneath the waters of the Oymapinar Dam reservoir, which it feeds into. The water is used for irrigation and for electricity production.

Figure 168. Submarine lapies (Lérins Islands, Alpes-Maritimes, France). These features formed when sea level was lower.

Figure 169. Fluorescein tracer injection in the Cambario Valley (Alpes-Maritimes, France) (photo G. Tennevin). The tracer is poured into a body of water in the limestone, and flows into the deeper parts of the karstic reservoir before emerging at the submarine Cabbé Spring (Roquebrune-Cap-Martin, France).

Figure 170. Residual karstic butte. Ankarana Massif (Madagascar).

Figure 171. Manenjeba resurgence (Ankarana Massif, Madagascar) (photo F. Tessier). The presence of stalactites on the exterior walls, characteristic in tropical karst.

Figure 172. Clear Water subterranean river. Mulu Massif. A paragenetic platform is clearly visible on the right side of the photo, indicating a period of slower water circulation during which sediment was deposited, protecting the cavern floor from erosion.

Figure 173. Deer Cave tunnel, Mulu Massif. The vertical white streaks are waterfalls fed by water stored in the epikarst, flowing down into the unsaturated zone.

Figure 174. Méailles Cave (Alpes de Haute Provence). This cave was formed at the base of a sandstone and calcareous conglomerate unit, resting on marl that is visible on either side of the person in the image. A channel along the cave roof is clearly visible, left from the initial phases of cave formation when water flowed slowly across the marl at the base of the conglomerate. Increased discharge led to further erosion of the marl.

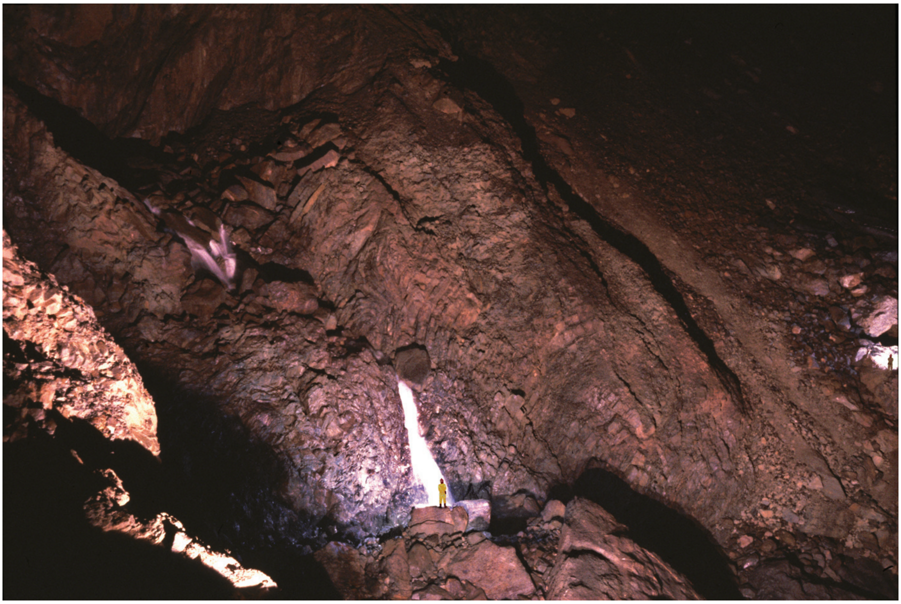

Figure 175. La Verna chamber in Pierre Saint Martin Cave (Atlantic Pyrénées). This chamber, the largest one in France (250 m diameter), formed at the contact between limestone and folded Paleozoic basement rock. The river eroded the impermeable substratum.

Figure 176. Overlook of the Sarawak Chamber (Mulu Massif, Sarawak, Malaysia) (photo P. Delange, Th. Gaschat, E. Gilli, R. Schejbal). This 600 m x 415 m chamber is the largest known underground space in the world. It formed along the side of an anticline, by eroding into clayey sandstone beneath a massive limestone roof, at the base of which thinly bedded limestone units collapsed, creating the boulder field on the cave floor.

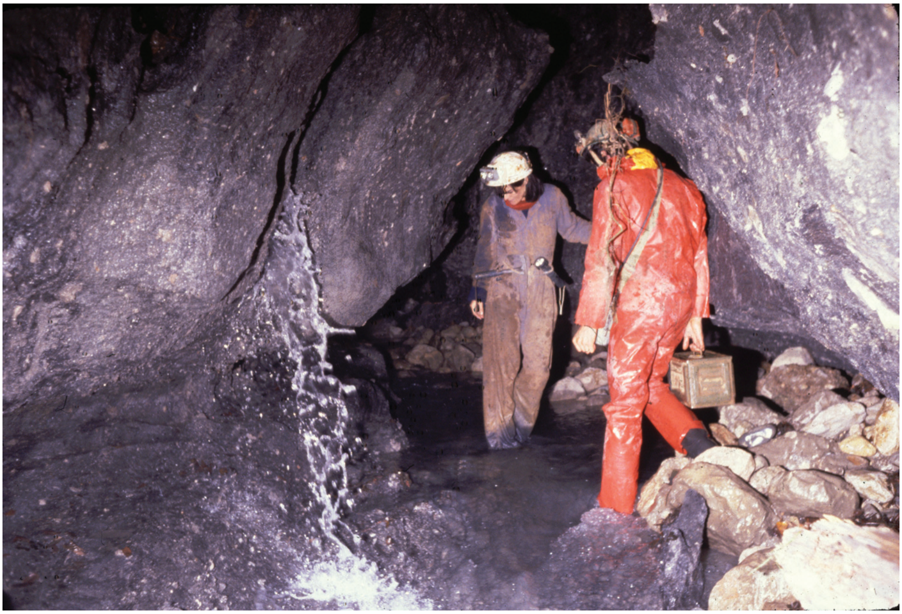

Figure 177. Suès subterranean river (Sospel, Alpes-Maritimes, France) in gypsum. The pebbles and boulders are limestone chunks carried into the cave by water.

Figure 178. Ice cave in the Gaumukh glacier (India). This thermo-karst formed as water from one of the springs that feeds the Ganges flowed along the base of the glacier. The boulders in the streambed are reworked moraine deposits. When the glacier eventually melts, these deposits will form long, snaking hills called eskers.

Karst landscapes are home to 25 percent of the world's drinking water supplies; in many countries water supply is highly dependent on karst aquifers. Their unique structures, containing many voids, are a particular problem for building corporations and land developers. This book, written by the well-known karstologist Éric Gilli, presents a diverse range of chapters on history of karstology, aquifers and their characterization, water supply management, coastal and submarine karsts, evolution of karst and paleokarst, paleontology, tourism, and oil and mineral reserves.

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