Chapter 2
Karst Environment and Phenomena

Zoran Stevanović

In saxis ac speluncis permanant aquarum liquidus umor et uberibus flent omnia guttis.

Titus Lucretius Carus

(in: De rerum natura; around 70 BC)

(Water flows through rocks and caves and everything drips plentiful tears)

2.1 Past Karst as a Human Shelter and Mythic Understanding of Karst

A karst environment is something extraordinary. Other landscapes or rocks may be equally beautiful or remarkable, but it is only karst that often provides the opportunity to delve into its inner secrets to enable confirmation or revision of our ideas, theories, and engineering solutions.

How did this relationship with karst come to be? Caves were the first shelters of big animals, and then of Neanderthals and humans whose movement and settlements were chosen in accordance with the presence of caves as safe havens. Most archaeological evidence is found in the caves, giving us the chance to reconstruct human evolution and the kinds of life in ancient times. This is also how we know that caves served as sanctuaries or burial places as well.

For example, Shanadar cave in northern Iraq (Fig. 2.1), close to edge of the Mesopotamian basin built into massive Lower Cretaceous limestones, is one

Z. Stevanović (✉)
Centre for Karst Hydrogeology, Department of Hydrogeology,
Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia
e-mail: zstev_2000@yahoo.co.uk

Z. Stevanović (ed.), *Karst Aquifers – Characterization and Engineering*,
Professional Practice in Earth Sciences, DOI 10.1007/978-3-319-12850-4_2

Fig. 2.1 Shanadar Cave (northern Iraq)

of the world's archaeological treasuries well known for Neanderthal skeletons (c. 60,000 years ago). The Shanadar site was discovered in 1951 (Solecki 1955, 1975) when 14 m of stratified cultural layers were excavated from the cave along with stone tools associated with Neanderthals. But more importantly, analyses of pollen taken from soil samples and from around the skeleton of Shanadar IV revealed different plant species probably chosen for their medicinal purposes and possibly also providing evidence of Neanderthal funeral rituals (Maran and Stevanović 2009).

The famous *Petralonian Archantropus* of Petralona, Greece, discovered in 1960 is assumed to date back some 700,000 years (http://www.petralona-cave.gr). Findings as well as replicas and reconstructions are exhibited at the Anthropological Museum of Petralona along with animals' bones covered by $CaCO_3$ (Fig. 2.2).

Remnants of *Homo sapiens* are found in numerous caves. In fact, caves were their principal settlements. Caves such as Altamira in Spain, Chauvet and Lascaux in France, Zhoukoudian and Zengpiyan in China, and many others are famous for Palaeolithic paintings, skeletons, bones of mammals, or used tools. Later on, in the Middle Ages, when the caves became associated with devils and hells, people avoided entering them (Cigna 2005).

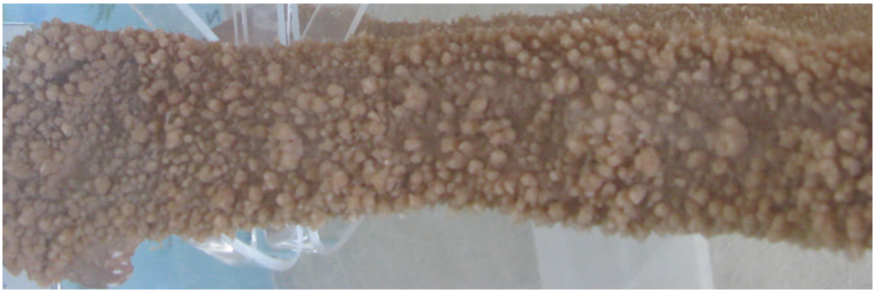

Fig. 2.2 Animal (panther) bone with stalagmitic cover. Details from exhibition in the Anthropological Museum of Petralona

2.2 Present—Man and Karst

Specific karst landscape and hydrographic networks as well as the high permeability of karstified rocks greatly influence both the distribution of flora and fauna and human life. Karstified rocks of different lithology cover more than 10–15 % of the continental ice-free surface of our planet (Ford and Williams 2007). In many places worldwide, where is karst, there are also limited natural resources. Of course, this depends greatly on climate conditions, and karst in arid areas is very different from karst in humid ones, or in zones permanently covered by ice (permafrost). Secondly, great differences for karst properties are powered by the altitude: Karstic terrains in high mountains often function as recharge zones with a shortage of water on their surface, while in littoral karst saltwater intrusion may disturb the freshwater supply (Fig. 2.3). One way or another, the karst environment is not always friendly and various kinds of intervention are sometimes needed to adapt the ambience to human needs.

Water shortage at high plateaus above erosional bases and drainage areas is well known in many places in the world. An extreme example is the mountain

Fig. 2.3 Glacial sinking lake at the Durmitor high mountains (Montenegro *left*) and littoral karst in direct contact with seawater (Zakinthos Island, Greece)

area above the Boka Kotorska Bay in Montenegro. Here, the annual average rainfall sum reaches 5,000 mm, but on account of fast infiltration, only collected rain water or no water at all is available at the surface, with the exception of small springs which drain rare perched aquifers.

The "fight for water" in such extreme conditions may result in migration of local inhabitants, reduction in the number of cattle and small ruminants, and limited cropping (Fig. 2.4). On the other hand, during periods of floods, many karstic poljes have been converted into temporary lakes, and people have had very limited cropping seasons (Fig. 2.5). Such situations and very limited available resources for normal life are well known in the Mediterranean region and in Dinaric karst in particular, and several anthropo-geographic studies describe the impact of current life conditions on human personality and psychology types. Although every generalization is relative, Cvijić (1914) highlighted the following as general

Fig. 2.4 Cisterns—specific reservoirs and intake wells for collecting rain water in high karstic mountains of Montenegro (Vilusi site *left,* and Grahovo village *right*)

Fig. 2.5 Channeled Trebišnjica River in mid of the Popovo polje, eastern Herzegovina. Previously the largest sinking stream in all of Europe, but also a cause of floods

Fig. 2.6 Villager in high Kurdistan mountains (Qandil Mts. northern Iraq, photograph courtesy of Alec Holm)

characteristics of Dinaric people: intellectual sensitivity, instinct to feel danger and to survive, great energy, and highly imaginative, often leading to mysticism. In addition, cheerfulness and a love of humor can be evident, but so too can vanity, pride, and, not rarely, stubbornness.

There are many karstic regions with rugged reliefs which result in the isolation or limited movement of the local population (Fig. 2.6). Although Papua New Guinea is not a purely karstic country, it is an excellent example of diversity and a variety of islanders. This country, with its glacier-capped mountains that reach 4,500 m asl and with the deepest caves in the Southern Hemisphere, is the most linguistically diverse region in the world. The isolation of local inhabitants has resulted in some 800 languages on the same island.

The karst terrains and their underground world are also an ideal place for tourism and extreme sports. Despite opposition from the "green" society which objects to tourist (show) caves as destructive of nature, they are ideal sites for learning about karst processes and the variety of nature. It is estimated that 150 million people visit show caves each year. Cigna (2005) assumed that with this figure the total amount spent to visit caves is around 3.2 billion USD annually and that around 100 million people worldwide earn salaries from show cave business. Beautiful canyons carved in limestones or evaporitic rocks also attract many visitors, while the wild rivers which created them are good places for rafting or canoeing.

There are many geoparks or reservation areas linked with karst (Fig. 2.7). The Nahanni National Park in Canada, the national park Plitvice in Croatia, the Lascaux cave in France, and Grand Canyon National Park, USA, were the first four sites containing karst features inscribed onto the UNESCO World Heritage list in 1978/1979. Today, the list contains 45 world heritage sites which "contain karst of outstanding universal value" (Williams 2008). The largest number (five) is in China and in Australia.

UNESCO is also an umbrella for geoparks as another cluster of protected outstanding geoheritage sites. As of January 2012, there were 90 Global Geoparks spread across 26 countries but mainly concentrated in Europe and in China. Many of them are pure karstic or include karst features. Some of the typical karstic are

Fig. 2.7 Tower in deltaic quartz conglomerate, fluvio karst in Meteora (World Heritage Site in Greece) *left*; Brenta Dolomites in Adamello-Brenta Geopark (northern Italy) *right*

the Carnic Alps (Austria), the Réserve Géologique de Haute Provence (France), the Swabian Alps (Germany), the Sierras Subeticas (Spain), Dong Van karst geopark (Vietnam), and Shilin geopark (China).

Speleology is a science, but it is also one of the most attractive disciplines open for wider purposes. When one declares himself a speleologist, the first impression is that he is caver or cave lover who visits and explores caves and potholes but who is not necessarily going to explain their origin or functioning or collect paleoenvironmental records. Many Web sites today are polygons for the race for the longest cave or deepest speleoobjects or for photographs showing the most beautiful speleothems. The Mammoth Cave system with the connected Flint Ridge Cave system in Kentucky, USA, is the world's longest natural cave network with more than 590 km of explored passages. Another world record for the deepest shaft in the world is Voronja (Krubera) Cave in the western Caucasus Mountains, Georgia, which is 2,190 m deep (Williams 2008).

Furthermore, diving in caves is a discipline which is becoming more and more prevalent in aquatic sport and may provide excellent information for engineering projects aiming to control karstic groundwater flows (Fig. 2.8).

Diving may be supported by the use of remote (autonomous) underwater vehicles for smaller passages. In contrast, for large underwater cave systems, it is common even to ride dive scooters as in the case of karst of Yacatan, Mexico, or Florida, USA.

2.3 Water and Karstic Rocks

No karst landscape or small karstic feature could be created without water. Water is the main agent for the destruction and dissolution of rocks. But when we consider that despite their voids or cavities, volcanic rocks such as the basaltic type do

Fig. 2.8 Diving in large karstic channels of Buna Spring (Bosnia and Herzegovina) (*photograph courtesy* of Claude Touloumdijan)

not belong to the karst group, we see that the sedimentary rocks are practically an exclusive media in which karstic processes take place. Thus, karstic rocks always deal with water: They were produced from water; later, again under the influence of water, they were modified at the surface; and today, they are "drinking" rain or stream water and store this water in the ground.

Sedimentary karstic rocks can be generally classified into the two major groups:

- carbonate rocks and
- evaporite rocks.

The carbonate rocks are formed from calcium and magnesium minerals—calcite, dolomite aragonite, and magnesite—and include the two major groups:

- limestones ($CaCO_3$) and
- dolomites ($CaCO_3$ x $MgCO_3$).

With a wide range of varieties, it is conventionally recognized that pure limestones contain 90–100 % of calcite (Fig. 2.9), pure dolomites (often called as dolostones) 90–100 % of dolomite mineral, while dolomitic limestones have 50–90 % of calcite and 50–10 % of dolomite.

The classification of carbonate sediments and facies is given by Dunham (1962), Folk (1965) and Wilson (1975).

Fig. 2.9 Calcite minerals (*left*) and banks of marly limestones (*right*) (*photographs courtesy* of Aleksandra Maran)

Discussing the origin of dolomites, Benson (1984) stated that some dolomite may primary precipitate, but mostly, it is formed through the replacement of original aragonite or calcite. This process of *dolomitization* has several driving mechanisms, and no consensus among specialists as to which is the primary one has yet been reached. The pure limestones are usually younger than dolomites, while dolomitic complexes prevail among Paleozoic and older, Pre-Cambrian formations.

Most carbonates are of organic origin. The constituent components of carbonate rocks are the following:

- allochemicals,
- micrite,
- cement, and
- non-carbonates (impurities).

There are six allochemical constituents: skeletal grains, ooids, oncoids, peloids, intraclasts, and aggregate grains (Benson 1984). The term micrite is proposed by Folk (1965) and explains microcrystalline lime mud which is common in slowly transported carbonate masses. This is an equivalent of detrital matrix in terrigenous deposits. The cement (connection material) resulted from saturated solutions and can be calcitic, aragonitic, or dolomitic. Non-carbonate material is terrigenous detritus, and its content in carbonates is usually minor.

Due to the dominant presence of the same basic minerals, cherts, conglomerates, breccias (Fig. 2.10), and finally marbles as metamorphosed sedimentary complex also belong to this carbonate group.

To the *evaporite group* belong rocks and minerals which contain SO_4 or Cl anions:

- anhydrite ($CaSO_4$),
- gypsum ($CaSO_4 \times 2H_2O$)
- halite (HCl), (Fig. 2.11), and
- sylvite (KCl).

Fig. 2.10 Carbonate breccia (*photograph courtesy* of Aleksandra Maran)

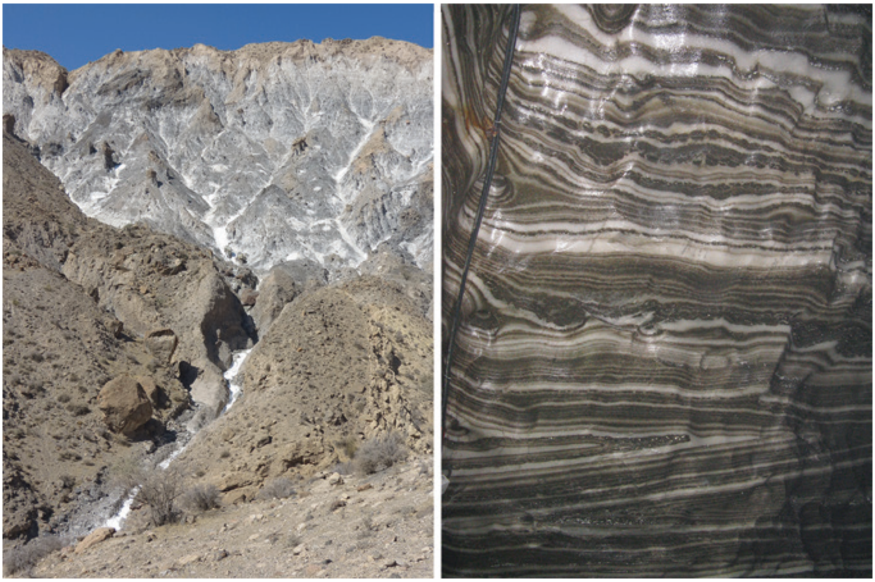

Fig. 2.11 Halite deposits, Konarsiah salt diapir (central Iran *left*), and laminated impure salty sequences, Ocnele Mari, Romania (*right*)

The quartzites and quartzitic rocks (SiO_2) can be distinguished as an additional group, but due to the structure of these rocks and their texture, karstified parts can be totally absent, or only surficial forms such as karrens may be developed.

There are the two main karstification forces: *mechanical* and *chemical*.

Mechanical erosion usually starts with surface water flows. The primary porosity of most carbonate sedimentary rocks does not allow for fast decomposition if it is created only by the pressure of water flows. As illustrated on Figs. 2.12 and

Fig. 2.12 Karstification over horizontal bedding plane of Hamanlei Fm. (limestones of Doggerian age) in eastern Ethiopia (a small coin is to a scale)

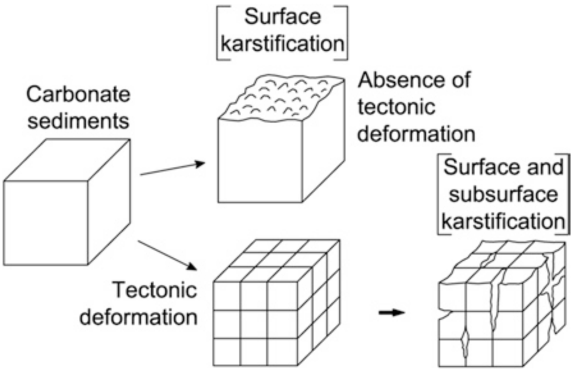

Fig. 2.13 Karstification mechanism (modified from Drogue 1982): Degradation and limited surficial karstification take place in compact carbonate blocks without tectonic deformation, while mechanical and chemical erosions as geodynamical factors create secondary porosity in the rock interior when tectonic deformation exists

2.13, in the case of the absence of tectonic deformation, karstification stays on the rock surface. Thus, small fissures and joints at the surface of the rocks or rough bedding planes are needed to have the process initiated in the rock interior.

When deeper thermal flows exist, the situation is quite different: Hypogenic karstification inside the rock mass takes place, and the process is activated, but again it starts along the deep faults as privileged paths. Mechanical erosion causes the expansion of the small, even microfissures, but during geological times, larger voids, caverns, and finally caves can be created. However, the process of mechanical erosion cannot be separated from the chemical process, and as a rule, they are integrated and function mutually. Which prevails is a matter of local conditions and many other factors.

Chemical erosion or *corrosion* is the process of rock dissolution. But not all rocks are equally soluble. The ranking list established by Freeze and Cherry (1979) for some representative minerals shows that calcite is six times less soluble than gypsum, but even 1,000 times less than halite. However, carbonate minerals are among the most reactive on the earth's surface. According to Wollast (1990), the calcium and magnesium bicarbonates are the most abundant ions present in freshwaters and when exposed to weathering result in roughly 50 % of the chemical denudation of the continents.

The dissolution of calcite (2.1) and dolomite (2.2) is expressed by the following equations:

$$CaCO_3 + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2HCO_3 \tag{2.1}$$

$$CaMg(CO_3)_2 + 2H_2O + 2CO_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3 \tag{2.2}$$

Similarly, dissolution of gypsum (2.3) is as follows:

$$CaSO_4 \times 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \tag{2.3}$$

Solubility also depends on temperature and pressure. When the dissolution process is endothermic (heat is absorbed), solubility increases with rising temperatures, but when the process is exothermic (heat is released), solubility decreases with rising temperatures.

The concentration of carbon dioxide enhances solubility. CO_2 is present in the air, in the soil where it is produced mostly by biological activity, and in deep confined parts where it comes ascendantly with basinal fluids and other gases such as H_2S through open, hydrogeologically active faults. As dissolved CO_2 is driven by the temperature and partial pressure of the atmosphere (Bakalowicz 2005), climate is therefore one of the main factors which drives karst processes.

In conclusion, the karstification process is very rapid with respect to geological time. Bakalowicz (2005) affirms the statement that a few thousand years, generally less than 50,000 years, are required to develop an integrated karst network.

2.4 Karst Classifications and Distribution

2.4.1 Classifications

There are many classifications and regionalizations of karst. The classification principles include karstification factors and driving mechanisms, but also lithology types, morphological forms, and genetic or climatic conditions.

Sweeting (1972), by accepting Cvijić's basic classification of *holokarst*, *merokars*t, and *transitional karst,* distinguishes as follows:

1. Holokarst (fully developed),
2. Fluvio karst,
3. Glacial–nival karst,
4. Tropical karst, and
5. Arid and semi-arid karst.

Gvozdeckiy (1981) classifies several morphogenetical types of karst in the territory of the former USSR. Among them are paleorelief (buried) karst, covered karst, relict tropical karst, permafrost karst, and seashore karst. In addition, based on lithology, Gvozdeckiy makes the following divisions:

1. Limestone karst,
2. Dolomite karst,
3. Marble karst,
4. Chalky and marly karst,
5. Gypsum–anhydrite karst, and
6. Salty rocks karst.

Herak et al. (1981) categorize orogenic and epiorogenic karst based on tectogenetic factors. To the first group belong the following:

1. Lenticular karst (lens in orogenic structure),
2. Folded karst (system of anticlinoriums and synclinoriums formed before karstification, e.g., Alpine orogenic belt, Figs. 2.14 and 2.15),
3. Dissected karst (intensive tectonic disturbance, faulting, erosion, and dissolution, Fig. 2.16),
4. Accumulated karst (development of large forms as poljes, deep karstification often below erosional base, Fig. 2.17).

According to Herak et al. (1981), epiorogenic karst includes epicontinental rock sequences which overlie older platforms and orogens (e.g., Russian or Arabian Pre-Cambrian platforms, Paris basin, etc.). The group comprises tabular, homoclinal, folded, basinal, and deep types of epiorogenic karst.

In accordance with the main genetic factors of the creation of caves, i.e., speleogenesis, Klimchouk et al. (2000) differentiate the two main groups which may be identified as karst typology:

1. *Hypergene* or (*meteoric*, *unconfined, phreatic*) *karst*.
2. *Hypogene* (*deep*, *confined*) *karst*.

While in the first group karstic features are created by infiltrated meteoric waters, juvenile waters and gases are the main dissolution agents of hypogene karst. In addition to the two main groups, there are younger coastal caves developed in rocks which have newly appeared.

Several other classifications recognize the karst types in accordance with some specific developments or forms created by karstic or other mostly tectonic and

Fig. 2.14 Highly folded limestones at bank of Dokan Lake (north Iraq)

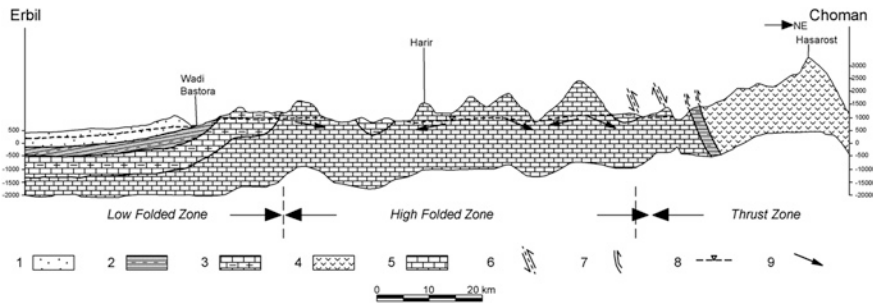

Fig. 2.15 Typical folded karst: The system of anticlines and synclines in Alpine orogenic belt: cross section from Zagros Mts. to Erbil plain and Mesopotamian basin, northern Iraq (after Stevanović and Iurkiewicz 2009)

erosional synergetic processes, as well as those formed under specific climate conditions. Below are explanations of some of these types.

Exokarst is a surficial type of karst, while *endokarst* considers internally developed forms inside unconfined karstic rocks. *Cryptokarst* refers to confined karst

Fig. 2.16 Dissected karst: Tectonically disturbed limestones and subvertical residual strata of Pila Spi Fm. (Darbandikhan area, northern Iraq)

Fig. 2.17 Accumulated karst: Small karstic polje Nava de Cabra, Sierra Subeticas Mt. Spain (*left*), and one of the submarine springs in the Boka Kotorska Bay, Montenegro (*right*)

and forms developed beneath the blanket of soil, till, residual clays, or similar sediments (Ford and Williams 2007).

Buried karst, paleokarst, and *fossil karts* are synonyms for covered karst, while *exhumed karst* is covered, but its actual status and exposure to the surface is different than in the creation phase.

Bare karst is a term commonly used for karst which either developed, or exists now, with a lack of vegetation. However, the same name is often applied to the karst which consists of big blocks with fast vertical karstification but without *epikarst*. The late term is used for the net of small fissures and a destroyed subsurficial part of karst. The synonym for bare karst is *naked karst* and is commonly used to explain either both a lack of vegetation and a lack of *epikarst*, or just one of them.

Barré karst or barrier karst is an isolated karst bordered by generally impervious rocks (Herak et al. 1981) or karst where the process has been interrupted due to the transgression of sea or lake waters. The latter may cause secondary plunging and dislocation of primary discharge outlets.

Pseudo karst represents landscape similar to karst and created karst-like forms but which has been created by other processes (Ford and Williams 2007).

A huge number of books and papers have been written on different aspects of karst hydrogeology, geomorphology, speleology and other karst-related disciplines over the last hundred-plus years. LaMoreaux PE and co-authors made a great effort to collect as many of them as possible and by 1993 he had edited five volumes of the Annotated Bibliography of karst terranes, three of them being published by the International Association of Hydrogeologists (1986, 1989, 1993).

2.4.2 General Distribution

Ford and Williams (2007) stated that surface and subsurface outcrops of potentially soluble karstic rocks occupy around 20 % of the planet's ice-free land, but as previously mentioned probably not more than 10–15 % is extensively karstified. The same authors found that probably more than 90 % of the evaporitic rocks anhydrite and gypsum do not crop out, while this percentage in the case of salty rocks is almost 99 %: Salt is remarkably soluble (360 g/l at 20 °C) and highly ductile, and the salt deposits as a rule quickly erode after precipitation (Zarei and Raeisi 2010, Fig. 2.18).

The sketch maps showing regional distribution of carbonate rocks are presented in Ford and Williams' book *Karst Hydrogeology and Geomorphology* (2007). The same map with a somewhat better resolution is available at the Web address of the University of Auckland, New Zealand http://www.sges.auckland.ac.nz/sges_research/karst.shtm.

Based on the experience of the creation of the Hydrogeological World Map (WHYMAP, BRG and UNESCO, http://www.whymap.org/whymap/EN/Home/whymap_node.html), the project World Karst Aquifer Map (WOKAM) was established in 2012. The ultimate goal of this project is to create a world map and database of karst aquifers. The new map will be based on the detailed Global

Fig. 2.18 Salt spring and deposits in the foothill of Konarsiah diapir (Iran)

Lithological Map (GLiM) but will show not only carbonate rock outcrops, but also deep and confined karst aquifers, large karst springs, including thermal and mineral springs, drinking water abstraction sites, and selected caves (Goldscheider et al. 2014).

The statistics concerning areas of carbonate rock outcrops are also available at the Web address of the University of Auckland, New Zealand. The total surface of carbonate outcrops on the continents, excluding Antarctica, Greenland, and Iceland, is around 17.7 million km^2 or 13.2 %. The largest portion is in Central and North America, with around 4 million km^2, but the largest contribution of carbonate rocks in the total surface coverage is in the Middle East and Central Asia, where they occupy around 23 % of the total land.

2.4.3 Regional Distribution

Previously presented classifications of karst also include regional and climatic factors. Although we have to agree that mixing classification criteria is not a scientifically correct approach, for practical reasons, we may distinguish several basic

Fig. 2.19 The littoral karst (Zakinthos, Greece *left*) and high alpine karst (St. Moritz, south Switzerland)

regional types of karst in accordance with their geographical position and dominant karstic occurrences:

1. Geosynclinal carbonate karst,
2. Platform carbonate karst,
3. Tropical karst,
4. Hypogenic and evaporitic karst,
5. Glacial karst.

Geosynclinal carbonate karst was formed in large sedimentary basins later exposed to epirogenic uplifting and to intensive orogenic folding. The typical example is the Mediterranean karst which was created in the Tethys sedimentary basin and includes the three subgroups: *littoral, hilly-mountains,* and *high alpine karst*. To the first group belong islands, shorelines, and adjacent coastal areas of northern African and Near East countries, Turkey, Greece, Albania, former Yugoslavia, Italy, France, and Spain as well as of some other smaller countries (Fig. 2.19). The second group encompasses mountain chains of the Atlas, Pyrenees, Provencale Mts., Apennines, Dinarides, Pindes, Hellenides, and Taurides, with hilly and mountain karstic relief dissected by numerous karstic poljes and wide valleys. High alpine karst extends over the central Alps (Austria, south Germany, south Switzerland, north Italy, and north Slovenia, Fig. 2.19) and is characterized by rough relief, steep slopes, and highly folded rocks. The climate conditions in the Mediterranean basin are quite diverse: from glacial karst at the tops of the Alps to the semi-arid and arid karst in North Africa and the Near East. The alpine systems extend further to the Caucasus and Zagros as well as to the Himalaya Mts., all specific by their altitudes and climate varieties which influenced karstification intensity and resulted in the creation of different karst landscape and forms.

The “classical” Mediterranean holokarst is mostly orogenic (folded) and hypergene, containing all forms typical of karstified carbonate rocks. The following text contains descriptions of main karstic forms typical of the Mediterranean, but also other similar, dominantly carbonate karstic environments worldwide.

Fig. 2.20 Karrenfeld on the shore of Skadar Lake (Montenegro) and in Ponoarele Mehedinti (SW Romania)

Fig. 2.21 Doline in karst of Kučaj (east Serbia): Cvijić photograph from 1895 and Stevanović photograph of the same area in 1985 (from "Cvijić and Karst," Stevanović and Mijatović (eds.) 2005, reprint with permission)

Karrens (German term, or *lapiés* in French) are small, dissolutional, and regularly linear forms of cm dimensions formed over rock surfaces (Fig. 2.20). When karrens are assembled, they create *karrenfeld* (Ford and Williams 2007). Many other similar small forms such as *solution channels* (*rillenkaren*) or *pans* (*kamenitze*), *pockets* (*tafoni*), or *microrills* are regularly present in holokarstic areas.

Dolines (*sinkholes*) are small to intermediate enclosed depressions in karst (Ford and Williams 2007). They are circular or elliptical and can be created by dissolution, subsidence, or collapse, but based on many in-field case studies, Cvijić (1893) recognized the solutional origin as the dominant one (Fig. 2.21). He also classified dolines as (1) bowl-shaped (Fig. 2.22), (2) funnel-shaped, and (3) shaft-like dolines.

Dry valley is the term employed for a completely dry riverbed which has been created by surface streams in the initial or previous karstification stage. It should be distinguished from a *sinking stream* which has a temporary flow throughout the year.

A blind valley is created by perennial or temporary streams and ends at some usually lithological (rocks of lesser permeability and solubility) barrier. It is

Fig. 2.22 Several very small and shallow bowl-shaped dolines at the karst plateau of Rax Mt. (Austria)

Fig. 2.23 Spectacular stone bridges carved in Jurassic and Cretaceous limestones in Carpathian karst of eastern Serbia (Velika Prerast *left*, and Valja Prerast *right*)

therefore a closed basin with an active or fossil ponor (sink point) at its end. *The stone bridge* may be opened after long "digging" of sinking water. Stone bridges are sometimes of spectacular dimensions because the process continues to deepen and erode the rock mass, causing the distance between the riverbed and the top of the bridge to expand quickly on a geological timescale (Fig. 2.23).

An *uvala* is elongated depression, a fossil valley (Fig. 2.24). The bottom can be rough with numerous dolines, but also filled with deluvial sediments.

Fig. 2.24 Uvala in Dinaric karst (Pluzine, Montenegro)

In many cases, the orientation of the uvala indicates fossils or the actual direction of groundwater flow underneath.

A polje is the largest landform on the karst surface. It is a tectonical–erosional depression filled by lacustrian, deluvial, or fluvial sediments or a combination thereof and is dissected by perennial or temporary streams. Commonly, on one side of the polje edge, there are drainage zones marked with springs and estavelles, while on the other margin there are ponors (Fig. 2.25) which transfer percolated surface waters to the other lower-positioned poljes or regional erosional bases (sea or basin or riverbed; see also Sect. 16.4). A small polje may have an extension of a few km^2, or even less, but the largest forms can extend over a hundred square kilometers.

The karstic plateau or karstic plain is a flat or subhorizontal surface consisting of karstified rocks either naked or with a thin soil cover, usually positioned at higher altitudes. Residual plateaus are often left after the paleostream incises a deep canyon (Fig. 2.26).

Canyons and gorges are deep-incised landforms very frequent in carbonate karst (Fig. 2.27). If the bottom is reached and cut in impervious bedrock, which is very common, this means that karstification was completed in the studied vertical section.

A shaft (*pit, aven, abyss, pothole, jama*) is a vertical or subvertical cavity, usually tectonically formed and additionally adapted by percolated water. The majority of shafts are fossil or still active ponors. Some of the deepest single vertical

Fig. 2.25 Alluvial ponors at the margin of Dasht Arjan karstic polje (Zagros Mt., south-central Iran)

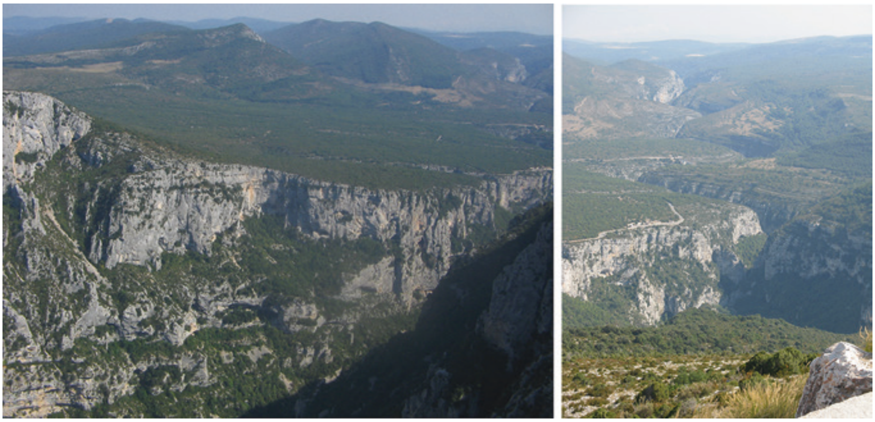

Fig. 2.26 High abandoned plateaus and meanders on the *left side* of the Verdone canyon (Provençale karst, France)

shafts ("pitch") which may reach a depth of 500 m are explored in the Slovenian Alps (Vrtoglavica, Kanin Mt.) and in Croatia (Lukina jama). In the "Stone Sea" area in the Montenegrin karst above the Boka Kotorska Bay, there are more than 300 vertical shafts within an area of only 8 km^2 (Milanović 2005).

Caves are mostly explored karstic and speleological forms (Figs. 2.28 and 2.29). A cave is a subhorizontal or slightly inclined cavity or developed system of cavities and galleries, created by a combination of mechanicals and chemical erosional factors. In principle, the term is used when cavities are completely, or at least partly, passable for humans, although for smaller forms, the term *cavity* or *channel* or *cavern* could be adequate. The conventional hydro(geo)logical classification of caves includes still active (with perennial flows), temporary active,

Fig. 2.27 Lazarev Canyon (east Serbia)

Fig. 2.28 Gigantic entrance into the Potpeć cave (Dinaric karst, western Serbia)

and dry (with percolated water), while in hypergene (unconfined) karst, they are genetically *ponor cave*, *spring cave*, or a combination of both, *ponor–spring cave* (groundwater *passage* or *tunnel*). An additional group are hypogene caves created by thermal fluids and water containing H_2S and other specific microconstituents which stimulate corrosion of karstic rocks.

Fig. 2.29 The stalagmite (*left*) and stalactite with water drips (*right*). Speleothems from Cloşani cave (SW Romania)

The Glossary of karst hydrogeology (Paloc et al. 1975) includes definitions of the terms above and other terms from karstology, speleology, karst hydrogeology and geomorphology, and karst sciences in general. Another important glossary, *A Lexicon of Cave and Karst Terminology with Special to Environmental Karst Hydrolog*y (EPA/600/R-02/003, 2002, EPA: Washington, DC. Speleogenesis Glossary), is available at the Web site http://www.speleogenesis.info/directory/glossary/.

Platform carbonate karst is generally characterized by thick sedimentary complex formed in large platforms, and less folded in comparison with geosynclinal karst. It can also be exposed to the surface as *exhumed karst* or *paleokarst,* or still *buried karst* overlain by younger rocks.

The four typical representatives are the following: *Russian platform, Yucatan—Floridian karst, Edwards Aquifer,* and *Chalky aquifers* of Great Britain and France.

Russian platform karst is one of the largest world karst systems extending over the Russian Plain to the east and comprising also the Pre-Ural (Ural Mt. Foreland) and Ural. With the exception of a few basins, it developed in a platform depositional environment and has a very long geological history, from Pre-Cambrium until Neogene, with Paleozoic and Miocene sediments encompassing the largest portion. Both carbonate and evaporitic facies developed, and they are often covered by younger moraines or fluvio-glacial sediments. This type of karst Maksimovich (1963) called "Russian karst."

Yucatan—Floridian karst was created in younger Tertiary carbonate deposits under the strong influence of the Caribbean Sea water fluctuation during Pleistocene. The tectonic subsidence also caused an impermanent submergence of the carbonate rocks. These highly karstified rocks are widely exposed to the surface with large nets of underground channels and specific karstic features such as *cenotes* (vertical shafts with groundwater formed mostly by cave roof collapse), distributed all over the Yucatan Peninsula (Mexico) or large karstic springs such as the Wakulla discharge system in the Floridian karst which, along with the two neighboring systems, consists of 50 km of underwater caves.

Edwards aquifer is an arch-like zone around 250 km long extending through south-central Texas. The Edwards massive and thick-bedded limestones and dolomitic limestones are between 100 and 250 m thick (Eckhardt 2010). The hilly and slightly undulated terrain is separated from the low-lying coastal plain by long and large escarpments. The aquifer outcrops at a large area covering more than 3,000 km^2, but large springs issue from a few outlets in the marginal confined–artesian part.

Chalky limestones are pure $CaCO_3$ in chemical composition and characterized by specific *vuggy* porosity. The presence of chert or flint nodules in *chalk* is also common. The chalk primary porosity is generally larger than in other carbonates. The largest extension of these sediments of Cretaceous age is in Great Britain, NW France, Denmark, and Germany. Along the shorelines where most of the chalky rocks are exposed, very high cliffs can be formed.

There are also other specific regional karst developments. Ford and Williams (2007) described *Nullarbor Plain* in SW Australia covering a surface of some 200,000 km^2. The *Guateng Group* and other dolomitic formations are well developed in central and northern South Africa but are often overlain by a relatively thin cover of younger rocks.

Tropical karst includes different subtropical varieties characterized by undulated relief with specific rough hills and residuals in topography. Although *Yucatan—Floridian karst* is also tropical and subtropical in terms of climate factors, it is added to the previous group because of other different properties such as flat relief and the absence of specific residuals.

Cockpit karst is typical of Jamaica and several other Caribbean Islands. *Cockpit* is of similar origin to *doline*, but its creation has been more influenced by humid tropical conditions. Cockpits are usually extended between small hills and may be connected and elongated (Fig. 2.30).

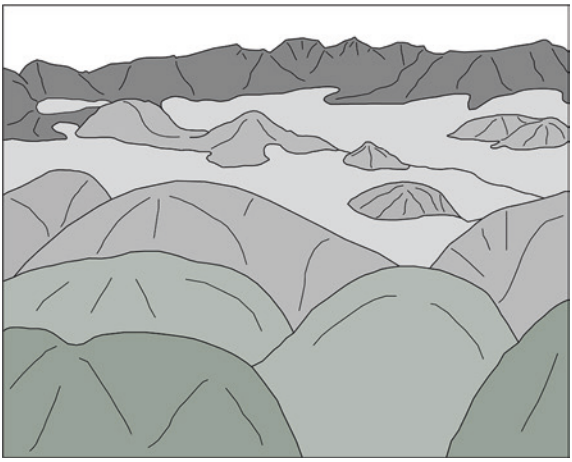

Fig. 2.30 Sketch of cockpit forms (elongated valleys between the hills)

Tower karst is famous due to its very specific residual landforms (Figs. 2.31 and 2.32) present in south China and in north Vietnam, as well as in several other countries of SE Asia (e.g. Indonesia, Philippines). The size and shape of the hills can be very different, symmetrical, or irregular. A very similar environment is also called *Pinnacle karst* or *Cone karst*. The terms *cupola* and *hum* are also used to describe the residuals which are rounded and conical. If residuals are very rare, such karst is often called *Relict karst*. *Fenglin* is the Chinese term indicating isolated forms (*teeth*), while *fengcong* is a group of hills from the same bedrock. *Fenglin* means "peak forest," and there are numerous wonderful geoheritage sites and parks in China, Papua, Malaysia, and Belize consisting of huge fenglins and karrens making the surrounding area almost impassable for visitors if corridors are not artificially opened. *Feng* means valley, and *fengcong* may be developed as an accentuated cockpit karst (Ford and Williams 2007).

Fig. 2.31 Tower karst—Fengcong along Li Yiang River (*left*) and in Xiangqiao geopark (Guanxi province, south China)

Fig. 2.32 Tower karst—Ha Long Bay (Vietnam) UNESCO World (geo) heritage site (*photograph courtesy* of Boris Prokić)

Fig. 2.33 Specific karst combination: platform (structure) and evaporitic (lithology), in Horn of Africa (Karkar Fm. near Boohodle, Somalia)

Hypogenic and evaporitic karst is also developed under specific climate conditions, mostly arid or semi-arid. Low rainfall rates and the absence of large paleostreams as main generators of mechanical karstification in humid karst have been compensated for by the presence of highly soluble evaporitic rocks deposited in a warm, often desert environment (Fig. 2.33). The hypogene karst and process of carving caves in confined conditions is well explained in the book *Speleogenesis* of Klimchouk et al. (2000).

The very large caves and long system of tens of kilometers of underground channels and labyrinths are created in gypsum (called also *maze*) and halite rocks. Such caves are well explored and studied in Ukraine, Poland, Hungary, Italy, and the USA (Klimchouk et al. 2000; Ford and Williams 2007). In addition, evaporitic and salty rocks are widely present in Central Asia, the Middle East, and the Arabian Peninsula, where many sulfuric caves and springs are recorded.

Glacial karst is characterized by the presence of both recent forms created by glacier actions and "paleoforms" developed in bedrock before Quaternary glaciations (pre-glacial karst). In addition to Antarctica and Arctic poles, permanently ice-covered areas (permafrost) are widely distributed in Greenland, Russia, and Canada and in high glacial mountains such as Patagonia (Argentina) or the European Alps. An excellent explanation of the glacier mechanism and creation of landforms can be found in Ford and Williams' book *Karst hydrogeology and geomorphology* (2007).

References

Anthropological Museum of Petralona (http://www.petralona-cave.gr). Accessed 15 Jan 2014

Bakalowicz M (2005) Karst groundwater: a challenge for new resources. Hydrogeol J 13:148–160

Benson DJ (1984) Carbonate rocks and geological processes. Lithology. In: LaMoreaux PE, Wilson BM, Memon BA (eds) Guide to the hydrology of carbonate rocks. IHP studies and reports in hydrology, vol 41. UNESCO, Paris, pp 21–30

BRG and UNESCO. The world hydrogeological map. http://www.whymap.org/whymap/EN/Home/whymap_node.html. Accessed 12 Nov 2013

Cigna A (2005) Show caves. In: Culver DS, White WB (eds) Encyclopedia of caves. Elsevier, Academic Press, Amsterdam, pp 495–500

Cvijić J (1893) Das Karstphaenomen. Versuch einer morphologischen monographie, Geograph. Abhandlungen Band, V, Heft 3, Wien, p 114

Cvijić J (1914) Jedinstvo i psihički tipovi dinarskih i južnih slovena (Unity and psychology types of Dinaric and South Slaves). In: Lukić R (ed) Works of Jovan Cvijić, speeches and articles (1987) (Reprinted in Serbian). Serbian Academy Science and Arts, Belgrade, pp 237–294

Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Ham WE (ed) Classification of carbonate rocks. American Association of Petroleum Geologists, Memoires 1, pp 108–121

Eckhardt G (2010) Case study: protection of Edwards aquifer springs, the United States. In: Kresic N, Stevanović Z (eds) Groundwater hydrology of springs: engineering, theory, management and sustainability. Elsevier, Amsterdam, pp 526–542

EPA (2002) A lexicon of cave and karst terminology with special to environmental karst hydrology. EPA/600/R-02/003, Washington DC. Speleogenesis glossary. Also available at the web site http://www.speleogenesis.info/directory/glossary/. Accessed 12 Jan 2014

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Englewood Cliffs

Folk RL (1965) Petrology of sedimentary rocks. Hemphill Publications, Cedar Hill

Ford D, Williams P (2007) Karst hydrogeology and geomorphology. Wiley, England

Goldscheider N, Chen Z, WOKAM Team (2014) The world karst aquifer mapping project—WOKAM. In: Proceedings of international conference Karst without boundaries. Kukurić N, Stevanović Z, Krešic N (eds) DIKTAS, Trebinje, 11–16 June 2014, p 391

Gvozdeckiy NA (1981) Karst. Izdatelstvo Misl, Moscow, p 214

Herak M, Magdalenic A, Bahun S. (1981) Karst hydrogeology. In: Halasi Kun GJ (ed) Pollution and water resources. Columbia University seminar series, vol XIV, part 1. Hydrogeology and other selected reports. Pergamon Press, New York, pp 163–178

Klimchouk AB, Ford DC, Palmer AN, Dreybrodt W (eds) (2000) Speleogenesis; evolution of karst aquifers. National Speleological Society of America, Huntsville

LaMoreaux PE, Tanner JM, ShoreDavis P (1986) Hydrology of limestone terranes; annotated bibliography of carbonate rocks, vol 3. International contributions to hydrogeology, vol 2. Verlag Heinz Heise, Hannover

LaMoreaux PE, Prohic E, Zötl J, Tanner JM, Roche BN (1989) Hydrology of limestone terranes; annotated bibliography of carbonate rocks, vol 4. International contributions to hydrogeology, vol 10. Verlag Heinz Heise, Hannover

LaMoreaux PE, Assaad FA, McCarley A (1993) Hydrology of limestone terranes; annotated bibliography of carbonate rocks, vol 5. International contributions to hydrogeology, vol 14. Verlag Heinz Heise, Hannover

LaMoreaux PE, LaMoreaux J (2007) Karst: the foundation for concepts in hydrogeology. Environ Geol 51:685–688

Maksimovich GA (1963) Osnovii karstovedenia, vol I and II. Perm

Maran A, Stevanović Z (2009) Iraqi Kurdistan environment—an invitation to discover. IK Consulting Engineers and ITSC Ltd., Belgrade

Milanović P (2005) Water potential of south-eastern Dinarides. In: Stevanović Z, Milanović P (eds) Water resources and environmental problems in karst. Proceedings of international conference KARST 2005, University of Belgrade, Institute of Hydrogeology, Belgrade, pp 249–257

Paloc H, Zötl JG, Emplaincourt J et al (1975) Glossaire d'hydrogeologie du karst. Choix de 49 termes specifiques en Allemand, Anglais, Espagnol, Français. Italien, Russe et Yougoslave (Glossary of karst hydrogeology. A selection of 49 specific terms) In: Burger A, Dubertet L (eds) Hydrogeology of karstic terrains with a multilingual glossary. Publication of IAH and International Union of Geology Science, Paris

Solecki Ra (1955) Shanidar cave: a palaeolithic site in Northern Iraq and its relationship to the Stone Age sequence of Iraq. Sumer 11:14–38

Solecki Ra (1975) Shanidar IV, a Neanderthal flower burial in Northern Iraq. Science 190:880–881

Stevanović Z (2010) Utilization and regulation of springs. In: Kresic N, Stevanović Z (eds) Groundwater hydrology of springs: engineering, theory, management and sustainability. Elsevier, Amsterdam, pp 339–388

Stevanović Z (2012) History of hydrogeology in Serbia. In: Howden N, Mather J (eds) Hystory of hydrogeology. CRC Press and Balkema, Boca Raton, pp 255–274 (International contribution to hydrogeology)

Stevanović Z, Mijatović B (eds) (2005) Cvijić and karst/Cvijić et karst. Special edition of Board on Karst and Speleology, Serbian Academy of Science and Arts, Belgrade

Stevanović Z, Iurkiewicz A (2009) Groundwater management in northern Iraq. Hydrogeol J 17(2):367–378

Sweeting MM (1972) karst landforms. Macmillan Press, London

University of Auckland School of Environment, New Zealand. World Map of carbonate rock outcrops v3.0. http://www.sges.auckland.ac.nz/sges_research/karst.shtm. Accessed 15 Dec 2013

Williams P (2008) World heritage caves and karst. IUCN, Gland, p 57

Wilson JL (1975) Carbonate facies in geologic history. Springer, New York

Wollast R (1990) Rate and mechanism of dissolution of carbonates in the system $CaCO_3$–$MgCO_3$. In: Sturmm W (ed) Aquatic chemical kinetics; reaction rates of processes in natural waters. Wiley, New York, pp 431–445

Zarei M, Raeisi E (2010) Karst development and hydrogeology of Konarsiah salt diapir. Carbonates Evaporites 25:217–229

Springer

http://www.springer.com/978-3-319-12849-8

Karst Aquifers - Characterization and Engineering
Stevanovic, Z. (Ed.)
2015, XX, 692 p. 437 illus., 291 illus. in color.,
Hardcover
ISBN: 978-3-319-12849-8