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Introduction to Karst

1.1 The Term Karst. Definition and Origin

Karst is a widely accepted term in the scientific community referring to a special type of landscape with distinctive landforms and hydrology, mainly arising from dissolution of various types of rocks. Karst terrains commonly display enclosed depressions, sinking streams, caves and major springs, and are characterized by prevalent subsurface drainage. Aquifers developed in karst rocks typically have a well-developed secondary porosity, mainly resulting from the solutional enlargement of discontinuities. Groundwater circulates through these interconnected subsurface channels much more rapidly than in aquifers with intergranular and fracture porosity, and may reach turbulent flow regime, which contributes to enhance dissolution rates and mechanical erosion processes. Karst geomorphology and hydrogeology are closely interrelated. Surface water tends to infiltrate preferentially through enclosed depressions and swallow holes, which are connected to integrated networks of solutional conduits, caves, and ultimately springs. The long-term evolution of these complex karst systems is controlled by changes in the regional or local base level of erosion. Moreover, underground channels may be responsible for the formation of the typical surface landforms (e.g., sinkholes generated by cave roof collapse).

Descriptions of karst phenomena date back to the antiquity, but the term karst has been used since the nineteenth century. In the seventh century BC, the Greek philosophers, who lived in a region largely underlain by karstified carbonate rocks, proposed two novel explanations for the hydrological cycle. One group, including Thales, Plato, and Pliny, sustained that sea water penetrates into the rocks and is driven upward losing its salts, until it reaches the ground surface through springs. The other group, among them Aristotle, proposed that springs are related to water condensation in caves. The Greek geographer Strabo (60 BC to 28 AD), in the second book of his 17 volumes *Geographica*, described various karst features such as caves, underground streams and springs. The Roman philosopher Seneca (4 BC to 65 AD), in his book *Naturales Questiones,* explained solution processes, cave development, as well as disappearance and resurgence of streams. The Peutinger's Tabula, a thirteenth century parchment copy of a previous Roman map, ascribed to Marcus Vipsanius Agrippa (died 12 BC), reports "Fonte Timaus", the famous karst spring of the Reka-Timavo River (Figure 1.1). This is probably the first known map locating a karst feature. A review on historical references to karst phenomena can be found in LaMoreaux (1995).

The capitalized word "Karst" is the German form of the regional place names "*Kras*" (Slovenian) or "*Carso*" (Italian), derived from the pre-Indo-European words *karra* (*gara*), *krs* or *kar*, meaning "stone" or "barren stony ground" (Roglić 1972; Gams 1973b; Kranjc 2018). This is the region in the northwestern sector of the Dinaric area around Trieste (Slovenia and Italy) traditionally regarded

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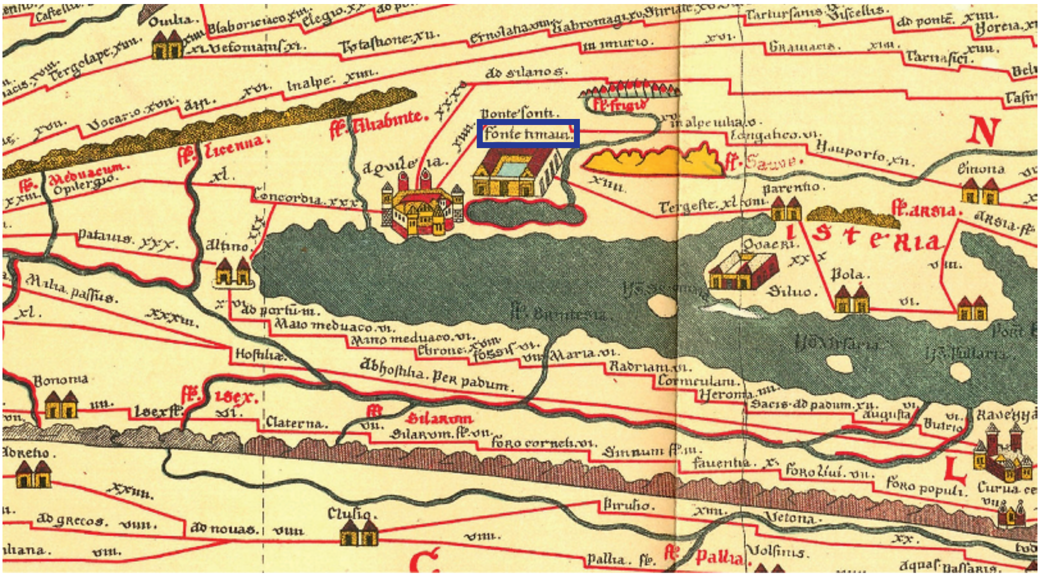


Figure 1.1 Detail of Peutinger's Tabula representing the karst region between Trieste (Italy) and Slovenia and locating the spring "Fonte Timaus," on the northern coast of the Adriatic Sea. *Source:* Own work/Wikimedia Commons/CC0 1.0.

as the Classical Karst, where much of the pioneering karst investigations were developed. In the second century BC, during the Roman occupation of the region, the maps reported the name "*Carsus*", subsequently transformed into "*Karstia*" in Valvasor's famous book (1687) (Figure 1.2). The area became part of the Austro-Hungarian Empire in the second half of the nineteenth century. In this period, geographers of the University of Vienna, including Albrecht Penck, focused their attention to this limestone area and the word was germanized into "karst," gaining popularity among the scientific community. Jovan Cvijić, a pupil of Albrecht Penck, published a comprehensive review of karst landforms entitled "*Das Karstphänomen*" (Cvijić 1893). This pioneering monograph is believed to mark the beginning of proper karst studies in the Western world (Sweeting 1972). von Sawicki (1909) expanded Cvijić's work to a global scale, describing tropical karst landscapes.

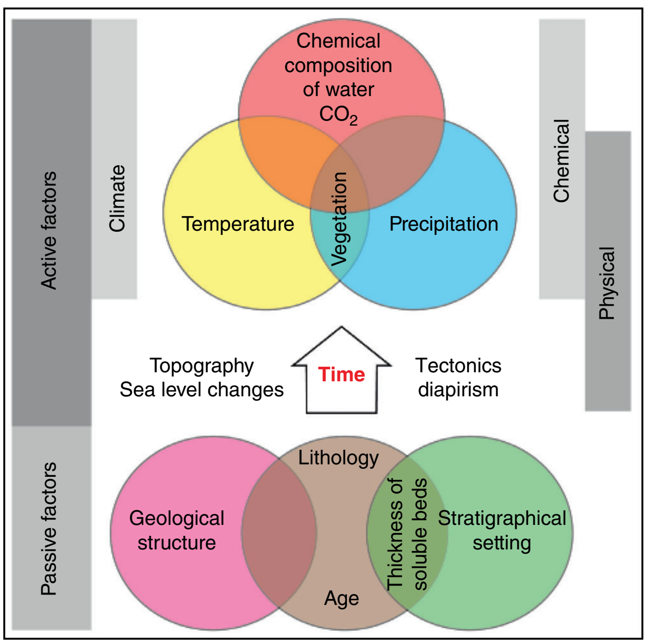
Ford and Williams (2007), in their second edition of the book *Karst Hydrogeology and Geomorphology,* defined karst as "*a terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well developed secondary (fracture) porosity*." A more general definition of karst is proposed in the book *Speleogenesis* (Klimchouk et al. 2000, p. 46), adapted from a previous definition by Huntoon (1995): "*The karst system is an integrated mass-transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organized to facilitate the circulation of fluid*." This definition is sufficiently broad to include any kind of rock, fluid, dissolution process, and geological context, and is not restricted to the classic karst landforms.

1.2 Classification of Karst

The evolution and characteristics of karst systems are controlled by a number of factors, notably: lithology, stratigraphy, geological structure, topography, precipitation, temperature, chemical composition of the water, and base level changes, which may be governed by various processes such as sea-level variations, tectonism, or diapirism (e.g., White 1988) (Figure 1.3). Karst has been classified in multiple ways, mainly using criteria related to the factors indicated above.

Figure 1.2 Historical map of the Kras region between Trieste (Italy) and Slovenia indicating the name "Karstia". *Source:* From Valvasor (1687).

Figure 1.3 The factors that control the development of karst landscapes.



Probably, the first attempt to classify karst was made in the early works of Jovan Cvijić, inspired by his studies in the Dinaric karst (Sweeting 1972). He used the term holokarst for a perfectly developed solutional karst landscape lacking river valleys. This type of situation mainly occurs in thick successions of soluble rocks (normally pure limestones) extending well below base level.

Merokarst is an imperfect or partial karst landscape in which fluvial activity and mechanical erosion still play an important role. It mainly develops in areas underlain by successions of soluble rocks with interbedded insoluble or less soluble lithologies. In later works, Cvijić realized that this classification worked well in the Dinaric and Moravian karsts, but he was forced to add a third "transitional" class for the many examples he encountered in France, Greece, and Cuba (Ford 2007). Nowadays, the concepts of merokarst and transitional karst have been substituted with fluviokarst, referring to landscapes and hydrological systems in which fluvial activity, mechanical erosion, and surface drainage play a significant role. The terms autogenic and allogenic fluviokarst are used to specify the source of the water, either the in situ karst aquifers or external areas with insoluble rocks.

Karst features can be grouped, according to the position in which they form, into exokarst and endokarst, developing at and beneath the surface, respectively. One of the most commonly used classifications is based on the main lithology in which the karst system is formed (e.g., limestone karst, evaporite karst, and quartzite karst) (Figure 1.4). Most karsts are developed in carbonate rocks, including limestone, dolostone, chalk, and marble (Figure 1.5a–c). Evaporite rocks, such as gypsum and rock salt (halite), much more soluble than carbonate rocks, also display well-developed karst systems, although generally with a smaller preservation potential and a lower degree of exposure due to their lower mechanical strength and higher erodibility (Figure 1.5d–f, h). The importance of dissolution in the formation of karst porosity in quartz sandstones (quartzites) has been confirmed in recent years (Wray and Sauro 2017) (Figure 1.5g).

Soluble sediments may be affected by karst processes during or soon after their deposition leading to syngenetic or penecontemporaneous karst. These early dissolution processes are generally related to subaerial exposure phases of soluble sediments in marine and lacustrine basins. Dissolution of young, poorly lithified carbonate, and evaporite sediments is often called eogenetic karst, which displays features similar to the ones created by syngenetic karst (Grimes 2006). Intergranular porosity in these rocks with limited compaction, cementation, and fracturing, offers the principal paths for water flow. These types of karst can be considered as the opposite to the so-called telogenetic karst, developed in fully lithified hard rocks, in which flow mainly occurs along discontinuities.

Climatic factors have a profound impact on the intensity of dissolution processes and the resulting landforms (Figure 1.3). This is why karst is often classified from a climate perspective. The following climatic types of karst are often identified (e.g., Jennings 1985): temperate, Mediterranean, tropical, humid, arid, semiarid, glacial (or alpine), and periglacial (or nival). This classification has significant limitations, since similar landforms can form in different climates, and the role played by litho-structural factors and time can be much more important than climate. Other classifications and definitions are based on topographic or environmental factors. The distinction between mountain karst and lowland karst, although readily understandable, is probably too trivial. The term coastal karst is often used for dissolution occurring in carbonate rocks in the seawater–freshwater mixing zone (Lace and Mylroie 2013). Biokarst refers to karst landforms created or influenced to a significant degree by biological processes (Viles 2004a, 2004b).

Another way of classifying karst is based on the stratigraphic position of the soluble rocks and their degree of exposure (Figure 1.4). The terms exposed or bare karst are used where the soluble rocks crop out at the surface (Figure 1.5a, b, f). Open karst typically refers to areas in which soluble rocks are exposed extensively. Mantled or covered karst refers to dissolution of soluble rocks overlain by unconsolidated deposits, either transported allochthonous sediments (e.g., alluvium, loess, volcanic ash), residual soils related to bedrock dissolution (e.g., terra rossa), or plant litter (Figure 1.5c–e). Some European geomorphologists use the terms subsoil karst (Gvozdeckij 1965) and cryptokarst

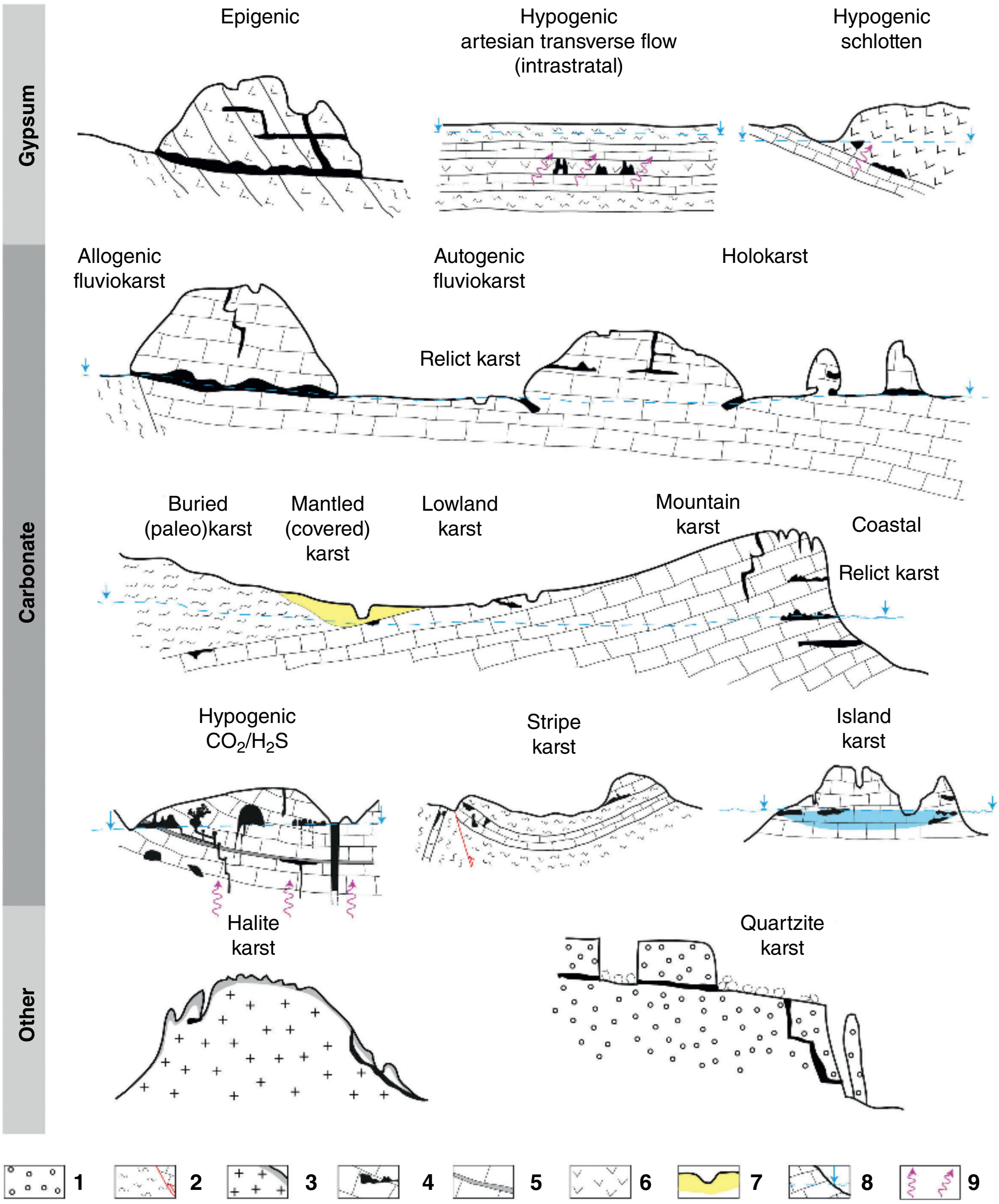


Figure 1.4 Different types of karst (see text for details): 1, Quartzites; 2, Fault that juxtaposes soluble rocks against less soluble rocks; 3, Halite with surficial insoluble residue; 4, Carbonate rocks with caves; 5, Less permeable bed within a carbonate sequence; 6, Gypsum; 7, Permeable unconsolidated sediments; 8, Carbonate rocks with local groundwater level or the mean sea level; 9, Ascending flow.

(Lacroix 2004) for describing the subcutaneous dissolution that occurs in the epikarst zone under a thin cover of surficial formations. The term interstratal karst is used when the karst rock is overlain by insoluble or less soluble rock formations, which are designated by some authors as caprock. This type of subjacent karst is particularly important in evaporitic formations, which may be affected by

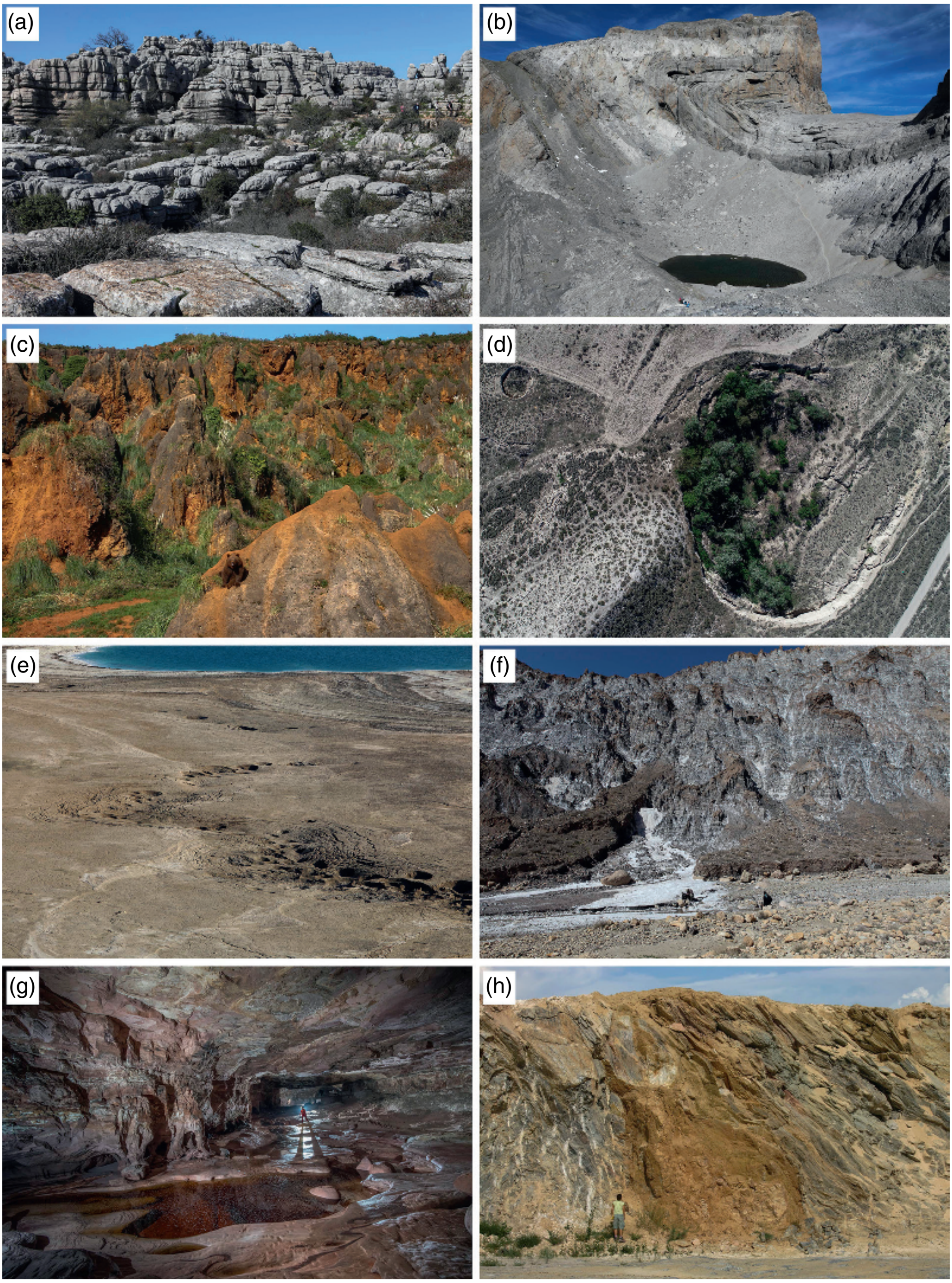


Figure 1.5 Images of various types of karst features developed in different lithologies and settings. (a) Bare karst landscape in UNESCO World Heritage Torcal de Antequera (Málaga, Spain) formed on subhorizontal stratified limestone showing well developed structural karren and lack of surface drainage network. *Source:* Francisco Gutiérrez (Author). (b) Partial view of an alpine carbonate massif, formed by the stacking of thrust sheets, that functions as the recharge area of a major spring. Note recumbent fold and lake in overdeepened glacial basin (Ordesa National Park, Spain). (c) Pinnacles and solutionally enlarged fractures in Early Cretaceous dolomitic limestones overlain and filled by iron-rich red clays.

Figure 1.6 Panoramic view of the Ojos Negros iron mine (Iberian Chain, Spain), which used to supply around 20% of the iron production in Spain. The iron exploited in this mine occurs in a deep paleokarstic weathering mantle related to the dissolution under oxidizing conditions of the underlying Mg-Fe-rich Ordovician dolomites and the concomitant concentration of iron oxides (gossan-type deposit). The irregular rockhead exhumed by mining shows pinnacles, tower-like features, and solutionally enlarged joints. *Source:* Francisco Gutiérrez (Author).

widespread deep-seated dissolution and generate large-scale dissolution-collapse breccias and subsidence structures (Warren 2016). Some authors propose the use of the term intrastratal karst where there is preferential dissolution of a particular bed or rock unit within a sequence of soluble rocks (Ford and Williams 2007). Buried karst indicates inactive karst features unconformably overlain by sediments deposited during or after the development of the karstification. Note that in an interstratal karst the karstification is younger than the capping rocks, whereas in a buried karst the karstification is older than the overlying sediments. Exhumed karst refers to a previously buried karst that has been exposed by erosion (Figure 1.6).

The term paleokarst, frequently used by stratigraphers and sedimentologists, is typically an inert karst of considerable age decoupled from the contemporary conditions (Figure 1.5h). A paleokarst may be buried or exhumed. Some paleokarsts hold valuable mineral deposits (e.g., James and Choquette 1988) (Figure 1.6). This is not to be confused with relict karst, referring to karst landforms that are now abandoned by dissolving waters, such as perched passages in multilevel cave systems or drowned coastal karsts. Some authors also use relict or inherited karst to describe essentially inactive features developed under past environmental conditions, for instance caves found in hyperarid regions formed during past pluvial periods.

Klimchouk and Ford (2000b) proposed several terms to describe the morphologic and hydrologic evolution of confined interstratal karst systems affected by fluvial downcutting and base level lowering. Their deep-seated karst occurs when the formation affected by dissolution is completely

Figure 1.5 (Continued) Dissolution beneath the karstic residue is enhanced by the oxidation of iron sulfides in the weathering mantle and the consequent acidification of the percolating waters. This subsoil karst has been exhumed by iron mining (Cabérceno Park, Santander, Spain). Bear in the central and lower part of the image for scale. (d) Drone view of active collapse sinkholes in the partially mantled gypsum karst of the Ebro River valley, NE Spain. Large doline with trees in the bottom is 75 m across. (e) Collapse sinkholes related to eogenetic dissolution of Quaternary salt deposits beneath an unconsolidated cover (mantled karst) in the Dead Sea, Israel. Salt dissolution has been induced by the anthropogenic decline of the water level in this terminal lake. The sinkhole alignments are controlled by concealed faults. (f) Saline spring in Jahani salt extrusion, Zagros Mountains, Iran. The salt exposure, locally covered by residual capsoils, corresponds to the flank of a namakier (salt glacier). (g) Golondrinas Cave developed in well stratified and vertically jointed quartzites in Auyan Tepui, Venezuela. *Source:* Photo by Vittorio Crobu, La Venta Esplorazioni Geografiche. (h) Example of paleokarst recorded by a clay-filled cave of probable pre-Quaternary age developed in Triassic gypsum (Chodes, Iberian Chain, Spain). *Source:* Photos except g by Francisco Gutiérrez (Author).

covered by the confining non-karst rocks. The subjacent karst stage starts when incision locally breaches the confining unit and the karst aquifer is brought into direct hydraulic connection with the surface. The entrenched karst phase starts when the fluvial systems incise below the karst formations, although it is still partially overlain by caprock. In the denuded karst, the insoluble overburden is completely removed and the karst formation is fully exposed.

Some terms are used to describe the cartographic distribution of the karst phenomena and their geometrical relationship with adjacent non-karst formations. The karst unit entirely surrounded by insoluble rocks is often called impounded karst or karst barré. A stripe karst is a narrow belt of soluble rocks bounded by non-karst formations. This type of situation commonly occurs in moderately to steeply dipping successions. Contact karst indicates areas of intense karstification associated with the contact between karst and non-karst rocks (Gams 2001). In these settings, unsaturated aggressive water coming from the insoluble formations may produce significant dissolution in the karst rocks along the contact zone (Figure 3.49). The contact between the different formations, either a stratigraphic discontinuity, a fault or an intrusive contact, may also act as a hydrogeological barrier forcing the convergence and upwelling of groundwater flow enhancing dissolution.

A notion that has received great attention in recent times is the distinction and characterization of karst systems according to the source of the dissolving water and/or aggressiveness. Epigene (or epigenetic) karsts are dominated by downward groundwater flow from an overlying or adjacent recharge area. Hypogene (or hypogenic) dissolution is related to groundwater coming from below (Klimchouk 2007) or renewed aggressiveness generated at or below the water table (Palmer 2007). Hypogenic caves can be generated by fluids enriched in CO_2 or H_2S, generally thermal, but also by undersaturated waters entering the soluble rocks (often evaporites) from below, giving rise to extensive maze caves or schlotten-type isolated cavities.

Pseudokarst refers to karst-like features produced by other processes than dissolution or dissolution-induced subsidence (Figure 1.7). These areas often host shallow caves and enclosed depressions similar to sinkholes, considered by some authors as the diagnostic features of karst. The term pseudokarst links to the geomorphological concept of equifinality or morphologic convergence, whereby different processes may generate identical or similar landforms. It would be advisable to abandon the term pseudokarst, since it does not provide any information about the genetic process, and use already existing specific terms instead (Eberhard and Sharples 2013). Examples are glacier caves generated by the melting and movement of ice or lava tubes produced by low viscosity lava flows. The use of “karst” in these cases is misleading and should be avoided. Similarly, thermokarst, referring to enclosed depressions resulting from thawing of ground ice or buried glacier ice and the subsidence of the overlying deposits, is an established term, but has nothing to do with karst (Figure 1.7a, b). The use of vulcanokarst, although less common, is highly discouraged (Figure 1.7c, d). Significant cave systems and dense fields of holes also develop in fine-grained detrital deposits such as loess or valley fills, but their genesis is related to subsurface water erosion of fine particles (piping) and the collapse of the resulting conduits (Bernatek-Jakiel and Poesen 2018) (Figure 1.7e, f).

1.3 Global Distribution of Karst

Karst, as described above, develops in soluble rocks under suitable geological, hydrological, and climatic conditions. This includes most carbonate rocks, evaporites and, in some cases, quartzites. The global distribution of carbonate and evaporite rocks at or near the surface amounts to approximately 20% of the Earth’s ice-free landmasses. Not all of these soluble formations are located in regions where karst can be active today. In some areas, the availability of liquid water is too scarce

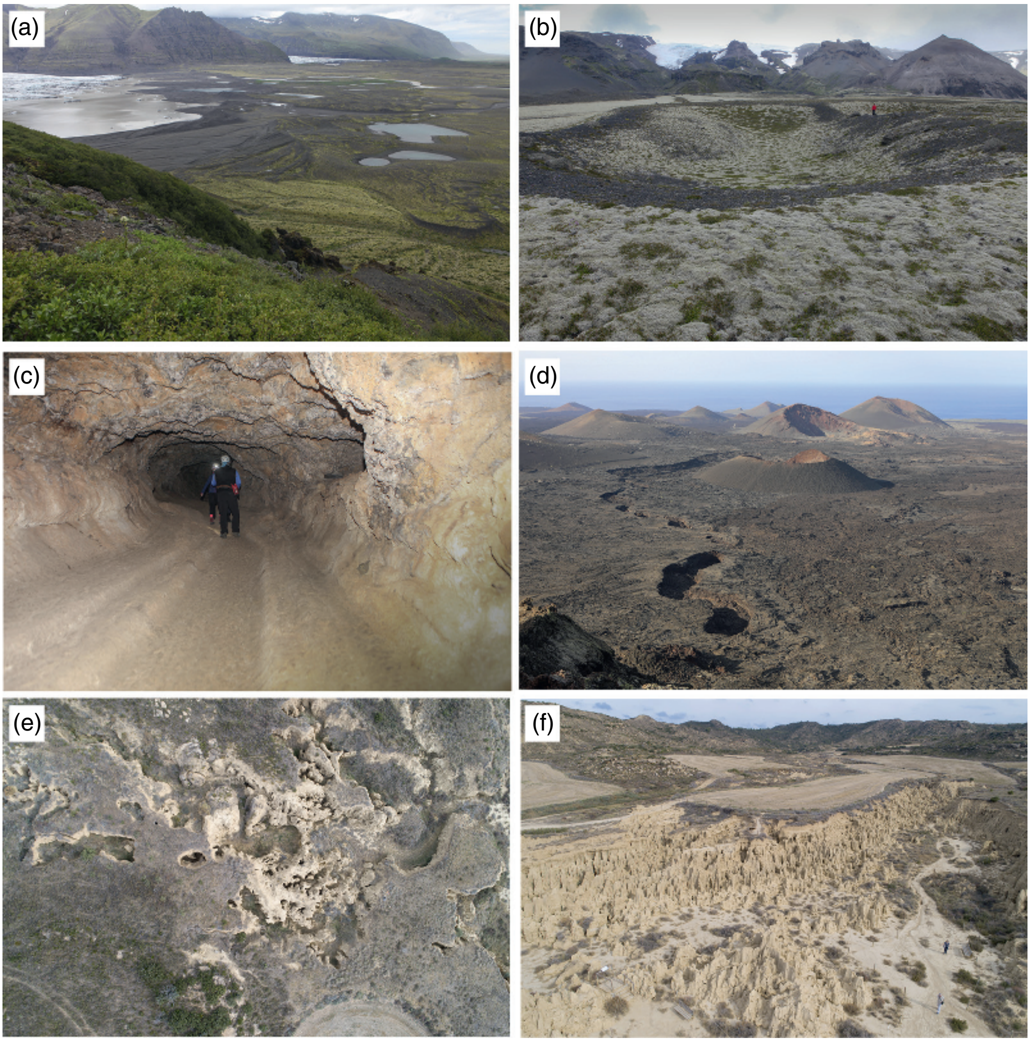


Figure 1.7 Images of different types of karst-like features not related to dissolution processes. (a) Water-filled enclosed depressions (kettle holes) beyond the frontal moraine of a glacier generated by the thawing of buried glacial ice and the subsidence of the overlying sediments. (b) Subsidence depression generated by the melting of a large buried ice block (thermokarst) accumulated by a flood (jökulhlaup) induced by the 1727 Oraefajökull eruption in Iceland. Note person for scale on the right edge. (c) Cueva del Viento lava tube generated by a basaltic eruption of the Teide Volcano (Tenerife, Canaries, Spain) at around 27 ka. (d) Collapsed lava tube in the eighteenth-century lavas of the Timanfaya National Park, Lanzarote island, Canaries, Spain. (e) Drone image of collapse depressions related to conduits and caves produced by subsurface water erosion in fine-grained valley-fill deposits (Aguarales de Valpalmas, Spain). The elongated depression on the left is 25 m long. (f) Valley fill dominated by fine-grained deposits with a dense network of conduits generated by piping, producing a peculiar terrain riddled by pinnacles and collapse holes (Aguarales de Valpalmas, Spain). Persons for scale in the bottom right. *Source:* Francisco Gutiérrez (Author).

for dissolution processes to occur, either because most of the water is permanently frozen (permafrost regions), or because precipitation is too low (hyperarid regions). In the current global warming scenario, the extent of karst is expected to increase at high latitudes in the near future due to the degradation of the permafrost. Wang et al. (2019) estimate that a global surface temperature rise of

2 °C may lead to the disappearance of one-third of the permafrost in the northern hemisphere. Recent estimates report 12–13% of the continental areas to hold currently active karst (Hollingsworth 2009). This estimate is very close to that reported by the most recent world karst map of Williams and Fong (2016) and differs little from the earlier assessments by Palmer (2007) and Ford and Williams (2007). Most of these maps are based on the available geological data, which are very heterogeneous and the documented presence or absence of karst caves. Obviously, these are rough approximations biased by the lack of data in many areas worldwide.

Dissolution of soluble rocks may occur in the subsurface by unsaturated groundwater flows. Deep-seated interstratal dissolution of salt and Ca-sulfate formations affects extensive and difficult-to-assess areas in large evaporitic basins, commonly by the migration of dissolution fronts (e.g., Devonian Prairie evaporites in Canada, Permian salts in the Delaware Basin in New Mexico, Hith Formation in the Arabian Peninsula) (Gutiérrez and Cooper 2013; Warren 2016). It is estimated that c. 25% of the continental surface is underlain by evaporitic formations (Kozary et al. 1968), and it is reasonable to believe that in a significant proportion of those areas karst processes are active today. If we take into account those karst areas with hidden deep-seated dissolution, the actual extent of karst in Earth's ice-free continental areas could be around or higher than 15% (Figure 1.8). Recent works document the production of digital nation-wide karst maps that illustrate the importance of karst. For instance, karst is found in more than 30% of mainland China (Lei et al. 2015) and 18% of the United States is underlain by soluble rocks (Weary and Doctor 2014). Several countries are dominated by outcrops of karst bedrock (e.g., countries of the Dinaric Alps).

To better understand the spatial and temporal distribution of soluble rocks in the stratigraphic record as well as the variable intensity and extent of karstification processes throughout geological time, it is essential to consider the climatic history of the Earth. The Quaternary and late Neogene are characterized by a relatively cold climate controlled by waxing and waning polar ice sheets. The cyclic transfer of water from the sea to the continental ice masses and vice versa (i.e., glacial and interglacials), with frequencies of c. 100 ka over the past 780 ka, were accompanied by sea level oscillations with amplitudes of around 100 m. The sea level drops during the lowstands involved the emergence of extensive platforms underlain by carbonate rocks and a substantial base level decline, creating adequate conditions for new or rejuvenated dissolution. The resulting karst features were submerged and/or covered by younger sediments during the subsequent sea level rise, becoming an inactive relict karst or a buried paleokarst, respectively. Today, some 10% of the world's surface is covered by glacial ice, representing about 80% of the total volume of surface freshwater, and an additional 20% is affected by permafrost. In the last glacial maximum (c. 20 ka), around 25% of the Earth's surface was covered by ice and the sea level was approximately 125 m lower than today. In contrast, during most of the Phanerozoic, especially between the Eocene and the Triassic, the Earth was a "greenhouse" planet with a CO_2-rich atmosphere and largely devoid of glacial ice. This warm climate and the relatively higher and more stable sea level favored the accumulation of extensive carbonate formations. These factors also explain why the extensive marine evaporites deposited during the Phanerozoic have no similar-scale counterparts in the Quaternary saline systems, developed under the current cooler "icehouse" climate. The greatest volumes of evaporites were accumulated from Neo-Proterozoic to Cretaceous times in marine basin-wide and platform settings. The earlier evaporites typically consist of halite-rich successions, hundreds of meters thick, whereas the more recent ones are dominated by Ca-sulfate units, 10–50 m thick associated with carbonates (Warren 2010, 2016). A world map showing the distribution of the main saline basins can be found in Warren (2016, figure 5.30).

Summarizing, globally karst occurs over approximately 15% of the continental ice-free land surface (Goldscheider et al. 2020). These karst areas are especially abundant in the northern hemisphere (North America, Europe, and Asia), where outcrops of soluble rocks represent around 20%

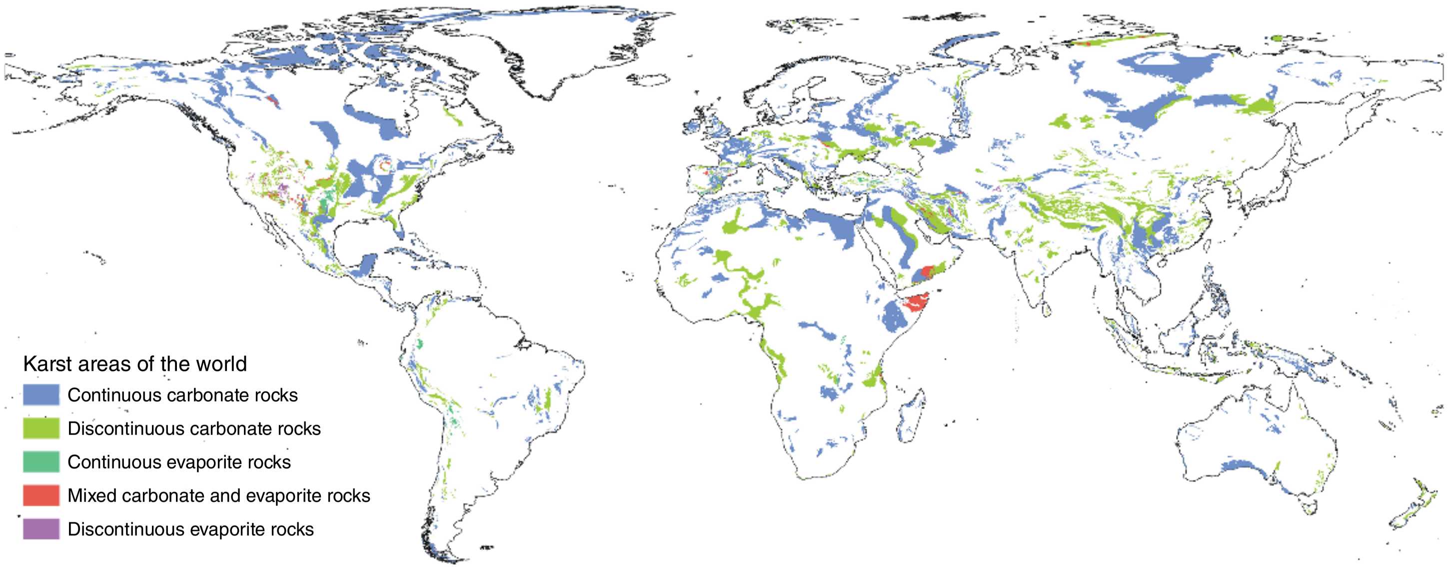


Figure 1.8 Global karst map, based on the WOKAM map. *Source:* Adapted from Chen et al. (2017) and Goldscheider et al. (2020).

of the land surface. In contrast, the landmasses derived from the Gondwana supercontinent (South America, Africa, and Australia) have sparser outcrops, except along their continental margins. For instance, the carbonate outcrop of the Nullarbor Plain in southern Australia covers an area almost as large as Great Britain (200 000 km^2).

1.4 Karst Terminology

Karst features have been known since prehistoric times, and since humans have developed languages in different cultures, several names have been used to describe similar karst landforms. This is why many different words are used to designate features such as caves, shafts, dolines, etc., even in the same language and region. The International Union of Speleology has a rather updated online multi-lingual dictionary of caving and speleological terms (UIS 2019). This glossary was based on earlier works in different languages, such as Trimmel (1965) (in German), Kósa (1967) (Hungarian-English), Monroe (1970) (for Northern America), Gèze (1973) (in French), Gams (1973b) (Slovene), Roglić (1974a) (Croatian), Jennings (1979) (for Australia), and many others. These were condensed in Kósa (1995/96) and Panoš (2001), then by Lowe and Waltham (2002) and ultimately by Field (2002b) for the English terms only. Nowadays, although certain words are widely recognized and used at a global scale (e.g., doline, polje), certain karst features have two different names (e.g., karren or lapiés), or even more (e.g., anemolite, anthodite, eccentric, and helictite). The international karst literature can sometimes be rather confusing indeed. Hopefully, this book will help readers to identify the most proper terms.

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