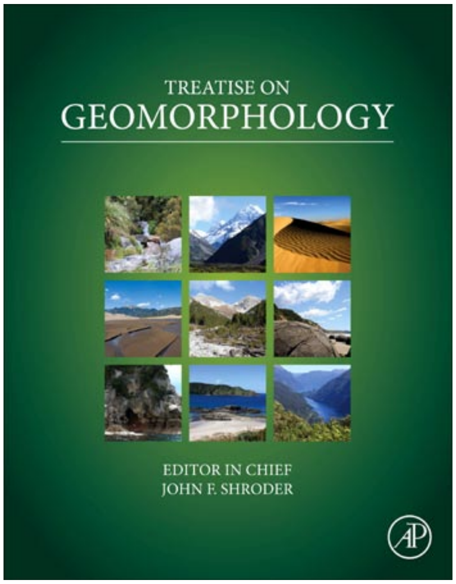

Frumkin A. New Developments of Karst Geomorphology Concepts. In: John F. Shroder (Editor-in-chief), Frumkin, A. (Volume Editor). Treatise on Geomorphology, Vol 6, Karst Geomorphology, San Diego: Academic Press; 2013. p. 1-13.

6.1 New Developments of Karst Geomorphology Concepts

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Glossary

Aggressiveness A measure of the relative capacity of water to dissolve rock material.

Confined A modifier that describes a condition in which the potentiometric surface is above the top of the aquifer.

Isolated caves Caves that developed without a breakthrough between input and output (surface to subsurface flow and vice versa) of groundwater flow.

Karren Superficial solution forms found on karst rocks, caused by dissolution. They vary in depth from a few millimeters to more than a meter and are separated by ridges or furrows.

Maze cave A cave with an essentially horizontal network of interconnecting and mainly contemporaneous passage loops. Three broad types of maze cave have been described – anastomotic, network, and spongework.

Palaeokarst A karstified rock or area that formed in the past under an earlier erosion cycle and often in remote geological times. It has been buried by later sediments; in some places, ancient caves have been completely filled by the later sediments.

Abstract

Karst terrains develop where chemical dissolution dominates over mechanical processes, commonly with well-developed secondary porosity. The karst system is unique, being truly three-dimensional, as it extends deep under the Earth surface. Karst geomorphology concepts have developed considerably during the last decades, mainly due to cave exploration and new research tools. Understanding of karst geomorphology concepts is a challenge particularly because much of the karst system lies below the surface, where direct observation is hardly possible. The unique subsurface morphologies, together with surface karst landforms, are distinct from other landscapes.

6.1.1 Introduction

Karst landforms, developing on evaporites, carbonates, and some silicate rocks, cover approximately 20% of global land surface (*see* Chapter 6.2). Carbonate rocks crop out at ~13% of the land surface, excluding ice-covered areas. About a quarter of Earth's populations live on such areas or are affected by their peculiar hydrology (Ford and Williams, 2007; De Waele et al., 2009). Understanding of karst geomorphology concepts has been a challenge both for classic and modern research, particularly because much of the karst system lies below the surface, where direct observation is hardly possible. The unique subsurface morphologies, together with surface karst landforms, are distinct from other landscapes. This chapter serves as a short introduction and summary to the karst volume, which may direct the interested reader to deeper, specific chapters.

The term karst originated in the Dinaric Classical Karst (Kras) region, today in Slovenia and Italy (Gams, 1993). Traditionally, karst terrains have been associated with subsurface drainage. Ford and Williams (2007) defined karst as ''terrains with distinctive hydrology and landforms that arise from a combination of high rock solubility and well-developed secondary (fracture) porosity. Such areas are characterized by sinking streams, caves, enclosed depressions,

Frumkin, A., 2013. New developments of karst geomorphology concepts. In: Shroder, J. (Editor in Chief), Frumkin, A. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 6, Karst Geomorphology, pp. 1–13.

fluted rock outcrops, and large springs." Such terrains are defined here as comprehensive karst systems. Old as well as new karst studies have shown that many types of karst terrains demonstrate well-developed surface drainage, combined with only few elements of the comprehensive karst system (*see* Chapters 6.13, 6.20, 6.27 and 6.31). Lauritzen and Skoglund (*see* Chapter 6.30); Wray (*see* Chapter 6.36); White and White (*see* Chapter 6.2) define karst as a terrain where chemical dissolution dominates over mechanical processes. In this definition, chemical dissolution should not be confused with chemical weathering and alteration, which are dominant in nonkarstic humid terrains. It is clear that in compact, impermeable, undeformed soluble rocks, dissolution alone does not produce many karst features; special rock properties, such as fractures, promote the development of comprehensive karst systems.

No karst concept can be transferred automatically from one region to another. The modern global network of information and transportation allows better flow of ideas that supports better geomorphologic concepts. Some new developments in karst research are those driven by technological advances such as geophysics, computer modeling, and dating techniques. These methods try to address old and new questions, such as conduit and sinkhole development mechanisms, denudation rates or dating of landscape evolution, cave deposits, and cave levels.

6.1.2 Processes of Carbonate Karst

One of the main current (albeit not entirely new) concepts is that chemical aggressiveness of the karst water can be derived from various complex sources, in addition to the classic carbonic acid. Additional acidity may be provided by processes that involve hydrogen sulfide, mixing of solutions with different degrees of saturation, temperature effects, and microbiological agents (*see* Chapter 6.3). In particular, greater emphasis has been given (since mid-twentieth century) to sulfuric acid. Its role turns out to be more important than earlier workers appreciated. Being a strong acid, sulfuric acid is extremely more aggressive than the weak carbonic acid, giving rise to major caves under specific subsurface settings (*see* Chapter 6.4). Palmer (*see* Chapter 6.20) suggests that most cave enlargement by sulfuric acid occurs at or above the water table. At this setting water films and droplets can absorb gaseous hydrogen sulfide and oxygen and become highly aggressive (**Figure 1**).

Figure 1 Highly aggressive droplets on a 'snotite' developed under gypsum deposits in a limestone sulfuric acid cave. Villa Luz Cave, Mexico. Finger for scale (photo: A. Frumkin).

Until recently, the classic concept of epigene (also termed hypergene) karst, gaining its acidity from soil CO_2, has dominated in karst studies. Although epigene caves are commonly impressive, it has been recently observed that many caves are actually isolated, or genetically disconnected from surface features. The concept of isolated caves suggests that a breakthrough (*sensu* Ford and Williams, 2007) between input and output (surface to subsurface flow and vice versa) of groundwater flow is not a prerequisite for speleogenesis (Frumkin and Fischhendler, 2005). Many isolated caves are attributed today to local rejuvenation of aggressiveness under hypogene conditions, gaining the aggressivity from deep-seated sources (e.g., Frumkin and Gvirtzman, 2006; *see* Chapter 6.19). Restricted input/output and/or isolation from surface morphology can suppress the normal positive feedback between flow and dissolution. Speleogenetic competition seen in the development of initial flow path is reduced, allowing the development of maze-like morphology (**Figure 2**). Isolated caves are more easily recognized under arid or semiarid settings, where they are not overprinted by epigene processes. In such regions, for example, Guadelupe Mountains, USA, isolated caves of hypogene origin dominate the subsurface relict landforms, but the present surface demonstrates fluvial morphology rather than typical closed depressions of classic karst (Ford and Williams, 2007). Hypogene water ascending through nonkarstic beds into karstified rocks seems to be the main cause of isolated caves formation, although the global distribution of hypogene caves remains unclear. Caves can also form in an input or output setting, whereas the other portions of the flow path remain diffusive without a breakthrough.

It is clear today that microorganisms play an important role in karstification, particularly in carbonic and sulfuric acid biospeleogenesis (**Figure 3**). However, much remains to be understood about their role in these and other systems, such as iron and silicate minerals environments (*see* Chapter 6.5).

6.1.3 Rates, Dates, and Evolution of Carbonate Karst

Estimations of karst denudation rates are traditionally based on hydrochemical measurements at a spring or at a catchment outlet, on weight-loss of limestone tablets, and direct measurements using a microerosion meter and height of limestone pedestals (*see* Chapter 6.7; Plan, 2005; Häuselmann, 2008). A fascinating new development is estimating denudation using cosmogenic isotopes that can provide longer-term rates, but have only rarely been applied to karst. Theoretical equations allow prediction of maximum erosion rates from runoff, temperature, and carbon dioxide concentrations.

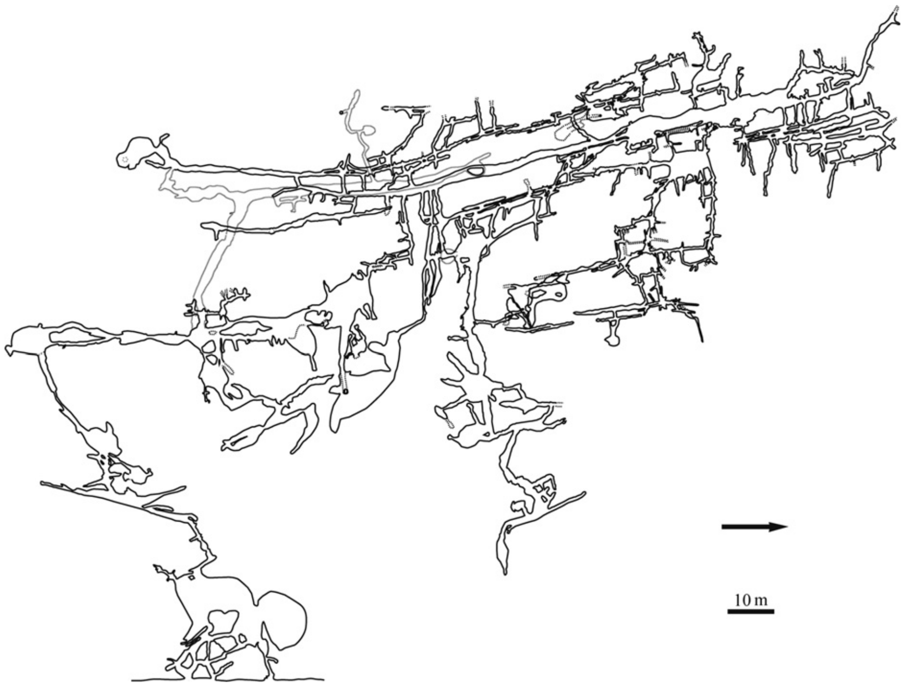

Figure 2 Plan of an isolated maze cave, formed under hypogene, confined conditions (Hariton Cave, Israel; survey by Israel Cave Research Center). Surface morphology above the cave is fluvial.

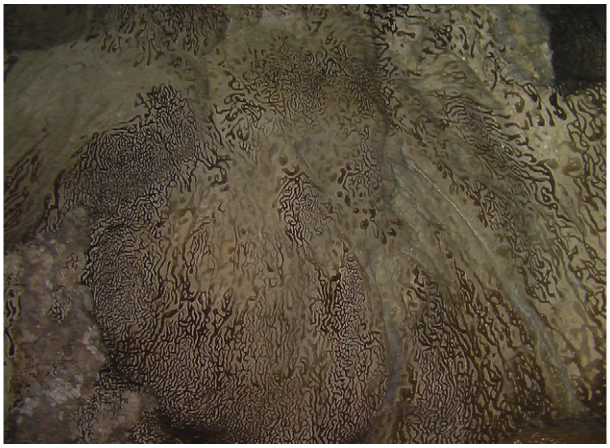

Figure 3 Vermiculations formed by microorganisms. Length of displayed area is ∼1 m. Grotte del Fiume Vento, Frasassi, Italy (photo: A. Frumkin).

Erosion rates vary spatially and vertically, with most dissolution concentrated in the epikarst, just below the soil.

Caves act as traps to various types of deposits, some of which can be dated by radiometric and paleomagnetic techniques. Combining dates, levels, and associated morphology may allow reconstruction of landscape evolution (Frumkin 2001; *see* Chapter 6.8). As caves and many other karst landforms are negative features, they are prone to filling by a range of materials, rendering cave sediments and palaeokarst deposits quite diverse (**Figure 4**). Caves and their internal deposits can be much older than the present surface above the caves (Osborne, *see* Chapter 6.9). Entire karst terrains can be buried and later exhumed, thus preserving ancient landscapes.

6.1.4 Surface Processes and Landforms in Carbonate Karst

The size of karst landforms can vary from millimeters scale (microkarren) to tens of kilometers (poljes). Small-scale dissolutional landforms, generally termed karren (**Figure 5**), are controlled by the physical and chemical properties of the water and the rock. The wide spectrum of multifactorial forms presents a challenge for global understanding. This challenge is met by an extensive classification scheme that considers various known genetic factors, and contains useful descriptions of form and size from millimeters to meters scale (*see* Chapter 6.12).

Groups of larger rock pillars may be termed 'pinnacle karst' or 'stone forests' (*see* Chapter 6.13). They reflect long-term geologic and climatic conditions favorable for dissolution, coupled with limited physical weathering. The largest stone forests occur under tropical and subtropical settings (**Figure 6**).

A quantitative method to analyze large-scale landforms is presented by Day and Chenoweth (*see* Chapter 6.14). Recent innovations in remote sensing and GIS have resulted in a renaissance of surface roughness research, as a component of digital terrain modeling (DEM). The combination of low-cost, high-quality DEMs, geospatial software, and desktop computers has brought new understanding to poorly mapped landscapes such as tropical karst regions analyzed here.

Figure 4 (a) Profile and (b) entrance of Cave of the Letters, Israel. The wall of Hever canyon has cut through the cave and its 11 m thick underlying fill, composed of laminar dolomite, collapsed rocks, and fluvial detritus. The burial of the topmost fluvial fill is dated to 3 million years by cosmogenic isotopes. Persons for scale (photo: A. Frumkin).

Figure 5 Two sets of karren embedded into one another on a formerly glaciated surface, Montenegro. (photo: A. Frumkin).

Figure 6 Stone forest developed under subtropical setting. The main pinnacle is ~10 m high. Xingwen, Sichuan, China (photo: A. Frumkin).

Since the initiation of karst geomorphology, negative surface landforms (closed karst depressions) have been considered as typical diagnostic karst landform, comparable to a stream in fluvial terrain. The terminology originates mainly from the Dinaric karst, and the full array of negative landforms are commonly regarded as indicators of a well-developed karst terrain. Kranjc (*see* Chapter 6.10) presents a classification of closed depressions, referring to their specific morphology and present understanding of their development. Of these, dolines, which are possibly the most typical and earliest studied karst features (Cvijić, 1893), may develop by several processes, such as dissolution (**Figure 7**), collapse (**Figure 8**), suffosion, and subsidence. Their morphology may vary accordingly.

The largest karst landform is the polje, reaching up to tens of kilometers in length and width (**Figure 9**). Poljes commonly develop at structural basins, and display complex hydrogeological features, which highly impact people living in their vicinity. These features include permanent and temporary springs and rivers, losing and sinking rivers, swallow holes, and estavelles (*see* Chapter 6.11). Today, the hydromorphological regime of many poljes is modified by anthropogenic interference. The complex morphology and hydrology of karst depressions is closely associated with the subsurface system of voids.

6.1.5 Subsurface Processes and Landforms

In the first half of the twentieth century, researchers attempted to attribute caves to a single zone, such as vadose, water table, or phreatic setting. The accelerating cave exploration and

Figure 7 Dissolution dolines in limestone at Akiyoshi-Dai, Western Honshu, Japan. (photo: A. Frumkin).

Figure 9 Dabarsko Polje, formed along a well-defined tectonic basin. Houses for scale. Bosnia-Herzegovina (photo: A. Frumkin).

Figure 8 A recently collapsed doline (also termed sinkhole) above salt, Dead Sea shore, Israel (photo: A. Frumkin).

Figure 10 Epikarst and terra-rossa filling on dolomitic limestone, exposed in a roadcut. Length of displayed area is ~1 m. Ofra, Israel (photo: A. Frumkin).

research during the recent decades have shown that there is a large array of cave formation processes and associated morphologies. Subsurface geomorphology must be studied at local and regional scales and only then can be generalized.

Although surface terrains are basically two-dimensional and well exposed, the three-dimensional subsurface is much more complex and elusive (e.g., Klimchouk et al., 2000; Palmer, 2007). Given enough time, computer modeling shows that caves tend to evolve toward water table systems (Gabrovšek and Dreybrodt, 2001). However, complex cave systems develop above and below the water table; these are shortly discussed below.

The epikarst is the interface between surface karst features (including the soil), where atmospheric and biospheric processes are dominant (**Figure 10**), and the deeper mass of the karstified rock. It demonstrates a more porous and permeable zone overlying the massive carbonate rock. The massive underlying rock is crossed by only few bedding planes and fractures (**Figure 11**), in some places enlarged by dissolution (*see* Chapter 6.15).

The vadose zone extends from the top of the epikarst to the water table. It is characterized by free-surface gravitational flow of water along the steepest available fractures, filling only a small part of the void (**Figure 12**). Conversely, within the phreatic zone (under the water table), water tends to flow at the most efficient paths allowed by the hydraulic gradient, filling the conduits entirely and enlarging them over all exposed surfaces (**Figure 13**). Water table passages tend to have gentler gradients, and passages cross sections tend to be lenticular. Fluctuations in the water table define the transitional epiphreatic zone, in which passages develop mostly by floodwater flow (*see* Chapter 6.17).

A huge number of dissolution channels are too small for humans to enter and so do not qualify as 'caves' in a dictionary sense. They are, however, formed or created in the same way as those that are enterable and thus should be considered to be the same thing. These embryonic conduits can be either epigene or hypogene, and can be studied by indirect methods such as modeling, tracing, boreholes, and geophysics.

In the past, it was assumed that water must pass through the karst rock in order to form caves. Recent observations show that water can create caves also by touching the karst mass without crossing it (*see* Chapters 6.19 and 6.32).

Figure 11 A fracture enlarged by dissolution in limestone just under the epikarst. Height of displayed area is ~10 m. Jerusalem, Israel (photo: A. Frumkin).

Figure 12 A vertical active shaft developed along fractures is probably the most common vadose karst feature. The wall displays dissolution by films of descending water, condensation corrosion, and speleothems. David Cave, Ofra, Israel. Person for scale (photo: A. Frumkin).

Hypogene water is commonly hydrothermal, due to deep circulation. Hydrothermal caves characteristically involve speleogenetic mechanisms such as free convection (both subaqueous and subaerial) and condensation corrosion (*see* Chapter 6.6). The hydrothermal water commonly flows upward from depth through smooth rising shafts (**Figure 14**).

Deep phreatic loops formed under the water table in epigene conditions have attracted some debate. The 4-state model of Ford and Ewers (1978) suggested that deep loops form where fissures, able to direct ground waters back up toward a water table, are widely spaced along the penetrated fracture or bedding plane in dipping strata. Worthington (2004) argued that deep phreatic loops are favored in large karst catchments with steeply dipping layers where faster flow is favored deeper because of geothermal warming of the water. Audra and Palmer (*see* Chapter 6.17) argue that vertical sinuosity is favored where discharge and consequent water levels are highly irregular. They also note that deep phreatic voids, if not hypogene, can often be associated with flooding by a base-level rise. Base-level rises commonly follow tectonic subsidence, filling of valleys, or sea-level rise. A major sea-level rise event followed the Messinian Salinity Crisis around the Mediterranean, with many associated deep voids being filled (*see* Chapter 6.17; Laskow et al., 2011). Ford (2000) argued that epigene artesian and epigene unconfined caves can also discharge from depths greater than 200–300 m following deep circulation in large-scale phreatic loops. The exact distinction line between epigene and hypogene caves is thus arguable (Klimchouk and Ford, 2009). A large spectrum of phreatic to confined loop dimensions exists. Where the loops are kilometer to tens of kilometers long, there is commonly some type of confinement, and the rising limb of the loop can be described as hypogene, particularly if additional evidence exists (Frumkin and Gvirtzman, 2006; *see* Chapter 6.19). Such supporting evidence can be indications of enhanced solute concentrations in the water – which will usually mean that they have H_2S or are thermal. The confinement can be caused by any impermeable rock, such as clays or even nonfractured carbonates.

Cave passage morphologies can be used to differentiate between free-surface flow in the vadose zone and full pipe flow in the phreatic zone. Identification of former vadose–phreatic transition zones allows reconstructing the position of former water tables and associated base levels

Figure 13 A relict phreatic tube developed along a bedding plane in chalk, entrenched by a vadose stream after lowering of the water table. Niqbot Cave, Bet Guvrin, Israel (photo: A. Frumkin).

Figure 14 A smooth-walled rising shaft, in which hydrothermal water was rising toward the water table. (photo: A. Frumkin).

(*see* Chapter 6.17). Over geological time scales, base-level changes may support stacked interconnected cave levels, forming the largest and most complex epigene cave systems (e.g., Mammoth Cave, USA). Base-level rise may produce deep voids and phreatic loops, where water flow or isolation from sediment sources can eliminate filling by deposition (Laskow et al., 2011).

In steeply sloping mountains, surface paleoenvironmental information may be rare because of the intensive erosional processes. Caves in such areas may be particularly important for understanding of the paleoenvironment and evolution of the surface morphology (Frumkin 2001, *see* Chapters 6.18 and 6.8).

Morphological characteristics of rock features in caves are essential for understanding the geomorphic evolution of the cave and its setting. Slabe and Prelovšek (this volume) evaluate the morphology and genesis of such rock features in epigene caves. These are affected by the flow of material and energy in caves and associated processes, particularly, water, sediments, air flow, ice, and organisms. In the complex cave settings, several factors may shape the rock features simultaneously or sequentially.

Maze caves origin has been debated for several decades. The modern concept seems to acknowledge various settings and flow directions, as long as pressurized aggressive water is injected into all available permeable voids (Frumkin and Fischhendler, 2005; *see* Chapters 6.19 and 6.20). The initial permeability features within the bedrock will thus be enlarged and emphasized (**Figure 15**).

Kempe (*see* Chapter 6.22) differentiates between 'primary' caves, also termed 'syngenetic', which are formed coeval with the rock surrounding them, and secondary caves, formed later, mostly even long after the rocks that contain them. The most common caves in other planets are probably lava tubes, which are also the most common primary caves on Earth. The study of such caves in other planets is premature but promising.

Speleothems in syngenetic caves can be primary, that is, composed of the rock that formed the cave, as well as secondary, that is, formed by later deposition of minerals (**Figure 16**). In contrast, secondary caves contain only secondary speleothems (Hill and Forti, 1997). Rock- and mineral-composed speleothems often have similar morphologies, commonly determined by gravity, for example, stalactites and stalagmites (**Figure 17**). However, other types of speleothems in both primary and secondary caves also display forms that are more specific (*see* Chapter 6.22).

Other cave deposits may resemble surface deposits, such as fluvial sediments of a stream that may retain its depositional features while passing from the surface to subsurface. The velocity of fast flowing water in a simple-geometry cave channel can be calculated from both fluvial pebbles and bedrock scallops (**Figure 18**). However, cave features are often more complex in terms of materials, evolution, and morphology, due to specific cave environments (**Figure 4**). A cave may stop functioning as a karstic entity when it fills with sediments completely. Cave entrances are even more susceptible to penetration and deposition of a wide range of natural and anthropogenic deposits, whose morphology and composition can be modified by speleological processes (Frumkin et al., 2009).

Deposits filling karstic caves demonstrate a wide spectrum of sedimentary features, such as sorting, grading, clast orientation, lamination, intercalation, deformation structures, and porosity (*see* Chapter 6.23). These structures and

Figure 15 Smooth horizontal tube formed along two initial fractures by slow-moving hypogene water. Part of the Hariton Cave maze, Israel (photo: A. Frumkin; for plan see **Figure 2**).

Figure 16 Secondary calcite stalactites in a syngenetic cave: Khsheifa lava tube, southern Hauran, Jordan. Pencil for scale (Frumkin et al., 2008; photo: A. Frumkin).

others can be used to identify microfacies and processes such as lacustrine, slackwater, debris flow, slumping, sheet wash, hyperconcentrated flows, and solifluction. Micromorphological data derived from postdepositional

Figure 17 Calcite speleotherms in a limestone cave, truncated by condensation corrosion. Height of displayed area is ~1 m. Esh'har Cave, Galil, Israel (photo: A. Frumkin).

diagenetic trends allow reconstruction of climatic history and regional landscape evolution. In combination with paleoclimatic chemical and isotopic evidence from speleothems, which can be precisely dated (e.g., Li et al., 1989; Woodhead et al., 2006), it is possible to gain multiproxy, long-term paleoenvironmental and anthropogenic records (e.g., Frumkin and Stein, 2004; Karkanas et al., 2007). Combining several dating methods on chemical and detrital deposits in caves is particularly promising for landscape evolution research (Stock et al., 2005).

Some cave features such as vertical dripstones or horizontal deposits and notches formed by a body of water can preserve their known initial orientation. These oriented features can be measured to determine the magnitude of a regional or local tilt, helping to reconstruct tectonic or speleologic events (*see* Chapter 6.24).

In the past, the general concept was that flowing water is needed for speleogenesis. Today, the concept of atmospheric cave processes, including cave enlargement, is also gaining ground, being observed on a global scale at sites that had been formerly attributed to dissolution by water. The most important speleologic atmospheric process in terms of morphologic impact on caves is condensation corrosion (Dublyansky and Dublyansky, 2000; Dreybrodt et al., 2005; *see* Chapter 6.25). It etches carbonate bedrock and speleothems, which can result in microkarren, boxwork, cupolas, and bell holes (**Figures 17** and **19**). Ceiling cupolas demonstrate

Figure 18 Two features indicating the velocity of a fast-flowing cave river: size of pebble deposits (bottom), and size of bedrock (marble in this case) scallops (left). Sagelava river cave, Salangen, Norway (photo: A. Frumkin).

the change of concept: in the past, they had been usually attributed to phreatic or hypogene water. Today, many of these features are considered to be formed or enlarged by condensation corrosion above the water table (Figure 19). Palmer (*see* Chapter 6.20) suggests that abundant H_2S in the air above the water table for a long enough time can form large rooms in caves by this process.

6.1.6 Karst Variation over a Range of Environmental Settings

One of the most intriguing questions in karst geomorphology is the variation with climate. Climate (particularly precipitation) impact on denudation rates is generally well established, but karst landform variation with climate is complicated due to other effects, such as geology, which obscure the climatic effect. Daoxian (*see* Chapter 6.26) finds a way to overcome this problem, by introducing the karst feature complex concept. Using dissolutional and depositional features of various scales, on the surface as well as subsurface, Daoxian defines each environmental setting by its typical group of landforms. In this way he avoids the confusion of isomorphism (similar features that may result from different processes). The group of features defining a climatic regime

Figure 19 Ceiling cupola cutting through thin clay beds within limestone in a sulfuric acid hydrothermal environment. Zickron Anava Cave, Nesher Quarry, Israel (photo: A. Frumkin).

is also robust enough to overcome the geologic variation, by introducing geological modifications into the general concept.

Tropic and subtropic settings may sustain distinct karst terrains, under suitable geologic conditions (*see* Chapter 6.27). Within the various theories of their development, the karst cycle concept, originally based on W.M. Davis' theory, had an impact for several decades, but today it gives way to modern concepts. For example, tower and cone landforms are explained today by the concept of 'simultaneous system evolution,' where each terrain develops according to prevailing geologic, hydrologic, and climatic setting. Cone karst develops under meteoric infiltration, tectonic uplift in excess of local erosion rate, and well-developed vadose zone above a deep water table (Figure 20). In contrast, tower karst is favored by allogenic water flowing in a well-developed network of surface flow on the flat base of the towers (Figure 21), and a water table close to this surface (Xuewen et al., *see* Chapter 6.27). What happens to cone karst that erodes down to the level of the water table where there are no incoming allogenic streams may still be debated.

In tropical and temperate areas biological processes are relatively important, whereas at high latitudes and altitudes, as well as in deserts, physical processes become more important. De Waele and Furlani (*see* Chapter 6.28) demonstrate this generalization for the case of marine surface karst. They show that coastal karrens are multifactorial, formed by dissolutional, physical, and biological processes (Figure 22). Coastal karren assemblages can often be distinguished by form and processes along zones parallel to the coast, sometimes named after their prevailing organisms. The subsurface of young carbonates in coastal zones may display flank-margin caves (*see* Chapter 6.29). These caves form along coastal margin of fresh-water aquifers, where dissolution is enhanced by mixing zones at the top and bottom of the fresh groundwater body. Both flow velocities and organic decay at these boundaries enhance dissolution close to the coast. Flank-margin caves grow from isolated initiation points that may amalgamate,

Figure 20 Cone karst develops in a tectonic uplifted area with well-developed vadose zone (at the background). Caoping, Guangxi, China (photo: A. Frumkin).

Figure 21 Tower karst with a well-developed network of surface flow on the flat base of the towers and a water table close to this surface. Yangshuo, Guangxi, China (photo: A. Frumkin).

Figure 22 Coastal karren under temperate conditions. Note the biogenic cover (green and black), and the high water notch at the base of the rock. North-west Ireland (photo: A. Frumkin).

forming large complexes. Such caves and their deposits can be used to reconstruct sea-level position.

In cold, alpine, or high-latitude karst settings, glacial activity has various, sometimes contradicting, effects (Ford and Williams, 2007). Mechanical abrasion at the base of flowing ice may destroy preexisting surface karst landforms. Karst development may be impeded where carbonate bedrock is shielded from dissolution by overlying glacial till, which also buffers water acidity (**Figure 23**). However, karstification is often stimulated by glacial action. Karst features may be preserved and keep their hydrologic functions throughout glacial cycles, and glacial dissection gives rise to a peculiar morphology that includes new cave openings, unroofed conduits, and unwalled shafts (*see* Chapter 6.30).

Figure 23 Glacial till protecting a limestone pavement from dissolution. Burren, Ireland. Person for scale (photo: A. Frumkin).

Glacial processes within deeper parts of caves are normally restricted to high-latitude or permafrost areas (*see* Chapter 6.21). In contrast, many cave entrance zones are subject to seasonal freezing and therefore also show abundant evidence of cryogenic features, including cryoclasts associated with frost shattering and seasonal cave ice formation (**Figure 24**). Paleo-permafrost in caves can be identified by cryoclasts, solifluction lobes, sorted sediment patterns, cryogenic calcite, and broken speleothems.

Carbonate karst processes under dry settings are slow due to scarcity of water and biogenic activity. Carbonate karst is modified very slowly by desert processes, including dissolution and salt crystallization, which may break bedrock and speleothems (*see* Chapter 6.31). Surface fluvial networks may be better developed in semiarid to arid regions than in humid settings. Closed depressions and epigene karst features are rare under dry conditions, but isolated caves may be common (**Figure 25**).

Figure 24 Ice curtain at the entrance of a gypsum cave. At mean annual temperature of 0 °C, ice features occur at cave passages that are frozen most of the year. Width of displayed area is ~10 m. Person at bottom for scale. Golubinskiy Proval Cave, Pinega, NW Russia (photo: A. Frumkin).

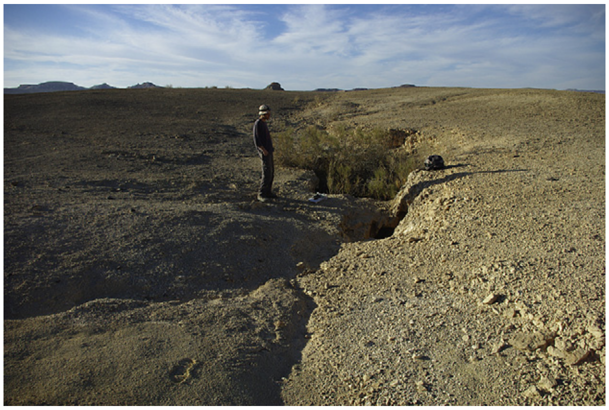

Figure 25 A rare ponor in a desert limestone wadi, possibly associated with the breeching of an old isolated cave. Govay Cave, Negev, Israel. Person for scale (photo: A. Frumkin).

Figure 26 A 50 m deep collapse doline in salt formed at a wadi ponor where the underground stream dissolved its way around a growing pile of caprock blocks, accelerating the continuous collapse of the cave roof. Malham Cave, Mt. Sedom, Israel (photo: A. Frumkin).

6.1.7 Noncarbonate Karst

As climate becomes drier, evaporite rocks are likely to develop karst morphology without obliteration by excess water. Being more soluble than carbonates, evaporites demonstrate more dynamic features. The most soluble karst rock is salt, which may develop persistent karst landscapes particularly under dry conditions (*see* Chapter 6.32). Surface features include salt karren which tend to be sharper than their limestone counterparts. The concept of salt caves is somewhat new, as a few decades ago an important textbook noted that "Natural salt caves from inside salt domes are not known" (Bögli, 1980). Today, we know that salt caves are commonly formed on salt outcrops by sinking streams, but are very dynamic in terms of development and destruction (**Figure 26**). The surface above the salt is often dynamic too, with deformations and sinkholes that are hazardous to human activity (**Figure 8**).

Gypsum and anhydrite outcrops are more abundant than salt ones. Gypsum shares some dynamic characteristics with salt karst, but these are less pronounced, because gypsum is ~100 times less soluble than salt. Compared with limestone, gypsum is more soluble, has a lower mechanical strength, and more ductile rheology. On the surface, subsidence structures are common, as well as poljes, karren (**Figure 27**), tumuli (or 'tents'), polygons, and landslides controlled by gypsum dissolution (*see* Chapter 6.33).

Many surface features are closely related to subsurface evaporite karstification, both epigene and hypogene. Dissolution of evaporites may develop deep below the surface, where an evaporite bed sandwiched between less-soluble beds is dissolved by hypogene water (*see* Chapter 6.34). If the surface is further denuded, the resulting forms are highly related to the degree of connection between the hypogene voids and the surface. As this connection becomes well established, epigene speleogenesis becomes dominant, but it is greatly facilitated by the presence of earlier solution porosity, inherited from older intrastratal dissolution. Diverse karst landforms related to subsurface conduits evolve through different stages of the intrastratal karst development.

The rapid subsurface dissolution of evaporites, coupled with their common occurrence, creates environmental hazards,

Figure 27 Rillenkarren on anhydrite. Mt Sedom caprock, Israel. Finger for scale (photo: A. Frumkin).

particularly associated with subsidence and collapse of man-made structures. Understanding evaporite karst, and producing sinkhole susceptibility and hazard maps are crucial for development and public safety (*see* Chapters 6.32 and 6.35). Situations that change the local hydrogeology can artificially accelerate dissolution and subsidence processes, increasing the severity of the problems. Mitigation steps include careful survey as well as hydrogeological and geophysical investigation (Frumkin et al., 2011) followed by preventive planning, and construction incorporating sinkhole-proof designs.

Highly quartzose rocks, such as quartz sandstones and quartzite, represent the less-soluble end member of the karst rocks spectrum. Karst landforms on such rocks may include ruiniform towers, grikes, stone cities, caves, dolines, smaller surface karren, and silica speleothems (Martini, 2000; *see* Chapter 6.36). Where chemical dissolution is a critical component in the development of these features, they can be termed karst landforms. Dissolution of quartzose rocks is slow, so karst landforms occur mostly in stable cratonic settings, where weathering and weathering could take place over geological time scale (in the order of many millions of years).

In the context of hardly soluble rocks, the concept of combined processes (i.e., dissolution combined with mechanical erosion) is emphasized. In reality, mechanical processes are involved to some degree in all types of karst processes in any rock. Quantitative research methods allow better evaluation of the role of each process.

6.1.8 Conclusion

Karst terrain is a unique geomorphic system that extends not only on the surface but also to the subsurface, where research is not straightforward. Karst systems, particularly caves, preserve important records of past environments. These morphological and/or sedimentary records are commonly discovered by cavers, studied *in situ* by geomorphologists, and analyzed in various laboratories. Karst geomorphology is therefore a multidisciplinary science that often enables work in beautiful and remote areas of the world. Karst geomorphologists work in fragile and unique environments that should be preserved for future generations.

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Relevant Websites

The full CV and publications of Prof. Amos Frumkin can be found in the following websites:

http://geography.huji.ac.il/en/cmd=staff.108&act=read&id=21
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Biographical Sketch

Amos Frumkin serves as a full professor at the Hebrew University of Jerusalem. His interests cover karst and cave morphology, cave sediments as indicators of paleoclimate, paleohydrology, and the development of karst aquifers. He also studies geoarchaeology and ancient water supply systems using speleological evidence. The research is mostly associated with underground (speleological) features studied using earth-science methods, such as geomorphology, radiometric dating, and stable isotopes.

He has authored and coauthored some 100 refereed articles. Two of his coauthored publications are: 'Dating the end of the Lower Palaeolithic by Uranium series of speleotems from Qesem Cave' (*Nature* 423, 977–979) and 'Dating the Siloam Tunnel, Jerusalem' (*Nature* 425, 169–171). He has written several books and edited several collections of papers. As an active speleologist, he founded and directs the Cave Research Center of the Hebrew University in Jerusalem. Within this framework, an interdisciplinary and transdisciplinary view of the subsurface is achieved by wide-scale interaction and cooperation with scientists from various fields and institutions. He represents Israel at the International Speleological Union, and serves in several international committees.