6.2 Karst Landforms: Scope and Processes in the Early Twenty-First Century

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6.2.1 Introduction

The surface of the Earth is a dynamic place. Tectonic forces created by the constant jostling of crustal plates, driven in turn by deep circulation within the mantle, continually lift continents and thrust up mountains. Solar-powered water recycling from the oceans to the land and back to the oceans provides the mechanism for wearing down the rock masses lifted up by tectonic forces. Without tectonic forces, the Earth’s surface would be a featureless plain eroded down to sea level. Without the hydrologic cycle, the Earth’s surface would be a rugged mass of bare rock, devoid of life. The action of water on rock – rock weathering – has a chemical part and a mechanical...
part. Chemical reactions between water and the minerals that make up the rock loosen grains of mineral so that flowing water can sweep them away. Mineral grains and rock fragments in motion act as abrasives and grind off more rock material. Rock weathering and transport over time produce the mountains, hills, valleys, and other landforms that make up the Earth’s landscape.

Landscapes where chemical dissolution dominates over mechanical transport are known as karst. As suggested in Figure 1, the relative proportions of purely chemical weathering and mechanical transport vary continuously. The exact position on this continuum where the characteristic karst landforms begin to appear depends on details of rock lithology but as a rough approximation, rocks that contain more than 15–20% insoluble components rarely develop karst landforms. By far the most important of the soluble rocks are carbonate rocks. According to estimates by Ford and Williams (2007), such rocks, and therefore karst, occupy 12.5% of the Earth’s land surface. If evaporites, which often develop karst dissolution features at depth but which have less outcrop at the surface, are included, the number increases to about 20%.

The transport of rock weathering material in solution allows the development of underground drainage systems and subsurface landforms not usually occurring in nonsoluble rock environments. Thus, karst has both a characteristic suite of surface landforms – closed depressions, deranged drainage, and sculptured bedrock – and a characteristic suite of underground landforms – caves.

A highly genetic scheme for the development of karst landscapes is given in Figure 2. A specific geologic substrate (meaning the sequence of rocks, their lithologies, and structure) is acted not only by the dissolutional attack of rainfall and circulating ground water, but also by other processes such as fluvial action, glaciation, wave action, and others. These interactions take place within a specific climatic regime that itself will vary with time. Thus, both total elapsed time and the times during which various climatic regimes were active all impact the final assortment of landscape features that present-day observers call karst.

It is the objective of this chapter to present a very broad-brush description of the karst-generating processes sketched in Figure 2, thus providing a background against which more specific aspects of the subject can be placed. It follows, roughly, an earlier attempt to construct such a generalization (White, 2008).

6.2.2 Historical Background

Karst landscapes are intrusive on the lives of humans that occupy them and have, therefore, attracted the attention of humans for a long time. Attempts to understand these landscapes date back several centuries, although Europe in the mid-1800s might be a good starting point. In large part, caves and surface landforms were treated separately. Adolph Schmidl in Austria/Hungary and Eduard A. Martel in France were the pioneers in the scientific exploration of caves (Shaw, 1992). Early systematic study of surface landforms is usually credited to Jovan Cvijic in Serbia (Roglic, 1972).

Not surprisingly, early classifications of karst were based on the external morphology of the landforms. This approach focuses on the final product – the landforms – as sketched in Figure 2. Thus, one may distinguish:

- Doline karst: Dominated by close-spaced closed depressions on a wide range of size scales.
- Pavement karst: Dominated by wide expanses of exposed, sculptured carbonate bedrock.
- Cone and tower karst: Remnant steep-sided hills separated by either chaotic gorges or closed depressions. The original distinction between Törmkarst (tower karst) and Kegelkarst (cone karst) is not a real distinction. Likewise, cockpit karst is a variant on the same theme. These landforms have been generalized as polygonal karst (Williams, 1972).

![Figure 1](image1.jpg)

Figure 1 Sketch showing continuum between mechanical weathering and chemical weathering in the development of traditional karst.

![Figure 2](image2.jpg)

Figure 2 Flow chart showing processes involved in the development of karst landscapes.
Polje karst: Mainly the gigantic closed depressions that occur along the Adriatic Sea from Montenegro to Slovenia, although a few depressions of comparable size are found elsewhere.

The above limited list can be extended to any other aggregate of landforms that may be of interest. In the mid-1950s, there was an extensive effort to relate karst landforms to climate and thus a climatic classification of karst was developed, promoted especially by Jean Corbel in France (Corbel, 1957). Thus, one might distinguish:

- arctic karst,
- arid karst,
- temperate karst, and
- tropical karst.

Although climate and its variation over time are certainly important, attempts to establish a one-to-one relationship between specific karst landforms and specific climatic regimes has proved elusive.

Karst landforms can also be classified according to their cover (or lack of cover). This classification, developed extensively by the late James F. Quinlan, unfortunately appears in detail only in his unpublished dissertation. The outline that follows is based on a published abstract (Quinlan, 1967):

1. Covered karst.
   - Subsoil karst: rock surface covered with soil, usually insoluble residue (regolith) from the karstic rocks.
   - Mantled karst: rock surface covered with a relatively thin veneer of post-karst sediment, typically loess, glacial till, or volcanic ash.
   - Buried karst: karst surface entirely covered by a relatively thick cover of post-karst rock, which is older than its cover but not part of the contemporary landscape, and is often called “paleokarst”.
   - Intersstral karst: karstic rock covered by, but developed beneath, other rocks, which is younger than its cover.

2. Subaqueous karst.
   - Drowned karst: karst submerged by rising sea or lake levels.
   - Sub-fluvial karst: karst developed beneath rivers.
   - Submarine karst: karst developed below the tidal zone.

3. Exposed karst.
   - Naked karst: karst developed without cover, except possibly seasonal snow pack.
   - Denuded karst: subsoil, mantled, or intersstral karst, which has been exposed by the erosion of the cover.
   - Exhumed karst: buried karst which has been divested of overlying cover rock – a re-exposed portion of a former karst landscape.

6.2.3 The Geologic Substrate and Chemical Weathering Mechanisms

Many details go into the description of the geologic substrate including the lithology of the soluble rocks, the stratigraphic sequence of beds of differing lithology, the overall thickness of karstic units, and large- and small-scale structural features such as the nature of the fracture system and the arrangement of large-scale folds and faults. Of these, most important is the type of karstic rock. Karst can be classified by rock type into three main categories:

- carbonate karst: limestone and dolomite;
- evaporite karst: gypsum and salt; and
- silicate karst: quartzites, granites, and other igneous and metamorphic rocks.

The chemistry of limestone and dolomite dissolution has been intensively studied (Langmuir, 1997). Although details are much more complicated, the overall reactions are:

\[
\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + 2\text{HCO}_3^- \\
\text{CaMg(CO}_3)_2 + 2\text{CO}_2 + 2\text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + \text{Mg}^{2+} + 4\text{HCO}_3^- 
\]

The solubilities of the carbonate minerals in pure water are very low, about 7 mg l\(^{-1}\), but the solubility increases rapidly in the presence of dissolved CO\(_2\) (Figure 3) or other acids. The solubilities of calcite (limestone) and dolomite are very similar but the rates of dissolution are greatly different. The source of CO\(_2\) is primarily from overlying soils with some contribution from atmospheric CO\(_2\). The process is somewhat temperature dependent as displayed by the displacement of solubility curves calculated at 10 °C from the curves at 20 °C.

![Figure 3](image-url) Solubility curves for calcite and dolomite at two temperatures as a function of carbon dioxide partial pressure. Concentrations are calculated on an equimolar basis, calcite as CaCO\(_3\) and dolomite as Ca\(_{12}\)Mg\(_9\)CO\(_{17}\) in units of mg l\(^{-1}\). Reproduced from White, W.B., 2010. Springwater geochemistry. In: Kresic, N., Stevanovic, Z. (Eds.), Groundwater Hydrology of Springs: Engineering, Theory, Management and Sustainability. Elsevier, Amsterdam, ch. 6, pp. 231–268.
Many karst landforms, especially caves, can be interpreted in terms of the kinetics of the various carbonate reactions, rather than by their equilibrium states. Chemical kinetics forms the basis for some quite elaborate computer models of cave system development (Dreybrodt et al., 2005).

The attack by carbonic acid on carbonate rock surfaces can be interpreted as corrosion on a large scale. The aggressive solutions attack at geological weaknesses, usually fractures and fracture intersections, and remove the bedrock differentially at these points. The result is that closed depression depths are exponentially distributed (Figure 4) and can be fit to an equation of the form

\[ n = N_0 e^{-\frac{d}{d_c}} \]

where \( n \) is the number of closed depressions of a given depth; \( N_0 \) the fitting coefficient dependent on the number of closed depressions in the population counted but not equal to it; \( d_c \) a characteristic depth descriptive of the particular karst region; and \( d \) is the closed depression depth in meters. The distribution of closed depression depths bears a curiously close similarity to the distribution of corrosion pits on steel, although these, of course, are on a size scale of micrometers (Macdonald and Urquidi-Macdonald, 1992).

Gypsum dissolves by simple ionic dissociation

\[ \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + \text{SO}_4^{2-} + 2\text{H}_2\text{O} \]

Salt (halite) also dissolves by simple ionic dissociation

\[ \text{NaCl} \leftrightarrow \text{Na}^+ + \text{Cl}^- \]

The solubility of gypsum is about 10 times that of limestone and halite has a saturation concentration of 35.5 wt.% depending on temperature. The kinetics of gypsum and salt dissolution are also quite different from the kinetics of carbonate rock dissolution. Because of the higher equilibrium solubilities, rates are mass-transport controlled rather than surface-reaction controlled. In spite of these differences, karst landforms on gypsum have a physical appearance quite similar to landforms on carbonate rock. Likewise, caves in gypsum and salt have similar morphologies to limestone and dolomite caves. Because of their high solubilities, gypsum and salt are usually exposed at the surface only in semi-arid regions but regardless, gypsum karst is widely distributed throughout the world (Klimchouk et al., 1996).

Silicate minerals generally have low solubilities, although many are unstable in the presence of water and will gradually break down yet not actually dissolve. Using quartz (SiO$_2$) as an example, the solubility is about 6 mg l$^{-1}$ in pure water. Further, the kinetics of dissolution is extremely slow. The solubility increases in the pH range of 10 and above but waters with pH in this range very seldom occur in nature. In spite of these limitations, minor karstic landforms occur on exposed quartzites, granites, and other silicate rocks, especially in tropical weathering regimes. The solubility of quartz increases in organic acids (Bennett et al., 1988) and it is very likely that organic complexing plays an important role in silicate rock karst.

### 6.2.4 Types of Karst

Karst landscapes depend on both the chemical processes operating on the geologic substrates on which they operate and the flow paths of the fluids that carry active solvents to the site of karst development and carry away the reaction products. These concepts produce several broad categories of karst types which are coming into use in the literature (Figure 5). Karst, in its earliest concept, is a near-surface phenomenon. Precipitation within a local watershed creates surface landforms. Precipitation recharges the local groundwater system and groundwater circulation creates the underground landforms. The suite of surface landforms is referred to as exokarst and the underground landforms as endokarst. Together, these make up epigenetic karst.

Old carbonate rocks have usually undergone deep burial and tectonic deformation before uplift and present-day exposures. They tend to be well compacted with very low primary porosities. Groundwater moves only through joints, fractures, and bedding plane partings and these provide the pathways which develop into conduit systems. Young limestones in many island and coastal regions have never undergone burial or tectonic deformation and are still in the process of diagenesis. Primary porosities are large and fracture systems are often poorly developed so that karstic and diagenetic processes are combined. Thus, there is a distinction between karst in well-compacted carbonate rocks – telogenetic karst – and karst in immature, highly porous carbonate rocks – eogenetic karst.
Because eogenetic karst occurs primarily in coastal regions, freshwater–seawater mixing provides an additional aspect to the chemistry.

It became recognized during the final few decades of the twentieth century that karst as a near-surface phenomenon is not the whole story. There are also deep-seated processes that produce karst. The near-surface, groundwater circulation, landforms are now distinguished as epigenetic karst. Solutional landforms – mainly caves – developed by upwelling deep-seated fluids are hypogenetic karst (Klimchouk, 2007). These fluids are usually at temperatures well above surface ambients so the term “hydrothermal karst” is sometimes used. Some of these fluids have mainly a carbonate chemistry but with very high CO₂ pressures (here termed “type I”). Other fluids contain H₂S among other gases (here termed “type II”). Type II hypogenetic karst develops by chemical processes different from the well-established carbonate/carbonic acid chemistry.

6.2.5 Telogenetic Karst and Ancillary Processes

As indicated in Figure 2, the final forms of karst landscapes depend not only on the karstic process operating and the geologic substrate on which they operate, but also on other geomorphic processes operating on the same substrates at the same time.

6.2.5.1 Fluvio-karst

Karstic rocks are rarely pure calcium and magnesium carbonates and karstic outcrops are rarely large enough to encompass entire watersheds. Fluvial processes, not different from fluvial processes on any type of rock, compete with karst processes to sculpture the landscape. Groundwater inputs can be identified as sinking streams (allogenic recharge) and closed depressions (internal runoff). Groundwater outputs occur at springs where the water returns to surface streams. Flow paths can often be determined by tracer tests and by direct exploration and mapping of cave systems. From this information it is often possible to define drainage divides and thus the concept of a groundwater basin (Figure 6).

6.2.5.2 Alpine Karst

The term “alpine karst” carries connotations of the high mountain environment where many different processes are operating. Karstic rocks are likely to be highly deformed and fractured. Local climates are extreme with cold temperatures and thick snow packs in winter, hot sun and intense rains in the summer. High relief implies high hydraulic gradients and extensive development of deep caves. It is not surprising that most of the world’s deep caves are in alpine locations not only because of the high gradients but also because of deep vadose zones that permit deep air-filled shafts and caves. Mountain glaciation may have been active. Soils are sparse to nonexistent so that bare bedrock sculptured by rain and snowmelt is the dominant surface landform (Figure 7).

6.2.5.3 Glacio-Karst

Many karst areas in high northern (and southern) latitudes were impacted by the advances and retreats of the Pleistocene glaciations. Glacial scour removed soil and regolith to expose the carbonate bedrock. Many of the areas of pavement karst owe their existence to previous glaciations. Movement of
glaciers often shifts large quantities of till into karst areas. Later action of streams and meteoric water has flushed the tills into caves, clogging them.

Speleothems in caves provide an excellent record of the comings and goings of the Pleistocene glaciations. In northern latitudes, speleothem deposition may completely shut down during glacial advances. Uranium series dating provides an absolute chronology, whereas oxygen and carbon isotope profiles provide temperature and vegetation records. Age limitations on the U/Th technique to the past 400 000–600 000 years mean that most information is available for the past few glaciations (McDermott, 2004; Fairchild et al., 2006).

6.2.6 Coastal Karst/Eogenetic Karst

The term “coastal karst,” like the term “alpine karst,” refers to an environment. Coastal karst may be either telogenetic karst or eogenetic karst depending on the age and lithification of the rock exposed along the coastline. Processes include the effects of wave action, rising and falling tides, and, over long time periods, the rising and falling sea levels as the Pleistocene glaciations advance and retreat. The acting processes also include a different aspect of carbonate chemistry due to freshwater–saltwater mixing.

A factor in limestone weathering near coastlines and in the intertidal region is the near-continuous wetting of the rock from tidal rise and fall and from spray due to wave action. In tropical regions, this permits the growth of boring organisms which produce a ragged surface in contrast to the smooth, sculptured surfaces in other karst regions. Also, algae bore into the limestone where organic acids dissolve a lacy structure known as phytokarst (Figure 8) (Folk et al., 1973). Biogenetic processes are an important part of the development of coastal karst.

Sea levels have varied by more than 100 m during the Pleistocene, which means that some coastal karst features that formed near the surface are now drowned. Divers have found caves containing stalactites and stalagmites at depths of 100 m. Conversely, some halocline features that formed during sea-level maxima are now 10 m or more above sea level.

The state of chemical saturation of carbonate groundwaters can be described by a saturation index given by (see Langmuir, 1997, for details)

$$ S_{IC} = \log \frac{\gamma_{Ca^{2+}} m_{Ca^{2+}} \gamma_{HCO_3^-} m_{HCO_3^-} K_2}{10^{-pH} K_C} $$

The state of saturation depends not only on the pH and the concentrations, \( m \), of \( Ca^{2+} \) and \( HCO_3^- \) but also on the activity coefficients, \( \gamma \), of these ions. The activity coefficients, in turn, depend on other ions present in the water. A unique set of karst landforms appear in coastal environments because of
this quirk in the carbonate chemistry. Fresh groundwater moving from inland toward the coast may be at saturation with respect to calcite (S_C = 0) and seawater is also near saturation with respect to calcite. When freshwater and saltwater mix, the resulting mixture becomes undersaturated and can dissolve the limestone to produce karst landforms. The process was recognized as responsible for the development of lagoons and coastal reefs along the eastern edge of the Yucatan Peninsula (Back et al., 1979). The same mixing process at depth, just inland from coastlines, is responsible for what are called flank-margin or halocline caves (Mylroie and Carey, 1990).

Groundwater flow in telogenetic karst can be mainly described by a two-porosity model in which the interaction is between flow in fractures and flow in conduits. Eogenetic karst can also be described by a two-porosity model in which the groundwater flow is through proto-conduits originating as touch vugs and the generally high primary porosity of the poorly lithified carbonate rock (Vacher and Mylroie, 2002).

6.2.7 Hypogenetic Karst

Epigenetic karst, both telogenetic and eogenetic varieties, is a "top-down" phenomenon. Meteoric water migrates downward along hydraulic gradients to discharge points at springs. Depending on lithologic and structural constraints, the flow may be near base level or may descend in deep phreatic loops below base level. The dissolutional processes involve either direct dissolution (in the case of gypsum and salt) or chemical reactions in the CaO-MgO-CO_2-H_2O system (in the case of carbonate rocks). Hypogenetic karst is a "bottom-up" phenomenon. Deep-seated solutions rise through the soluble rocks. The circulation loops for hypogenetic karst are typically much longer and deeper than those for epigenetic karst. Because the sources of the attacking solutions lie at some distance from the site of dissolution, hypogenetic karst is almost entirely subsurface with little surface expression.

The chemistry of the deep-seated solutions that generate hypogenetic karst is complex and, in reality, relatively little is known about it. Pressures will be well above atmospheric, temperatures likely above surface ambients, and bulk compositions are poorly known. Because fluid flow rates are very low, the fluids will be in chemical equilibrium with the wall rock and changes in pressure and temperature or fluid mixing are required for dissolution to take place. There are some springs which display the chemistry of hypogenetic waters after they have reached the surface and other clues may be found in the mineral deposits formed in hypogenetic caves. The dissolution of calcite and dolomite (and sometimes gypsum) involves very complex fluids, which, taking into account both oxidized and reduced species, lie within the system CO_2-H_2S-SO_3-H_2O.

Some deep-seated karstification involves mainly CO_2, but CO_2 at high pressures (here called "type-I" hypogenetic karst or hydrothermal karst). The solubility of CO_2 at high pressures and temperatures is well established (Portier and Rochelle, 2005). The solubility increases with pressure, thus with depth. These waters are sometimes observed as carbonated springs such as those at Saratoga Springs, New York, where CO_2 pressures reach 2–4 atm (White, 2010). The solubility of calcite, however, rises with decreasing depth to a maximum in the range of a few hundred meters. Calcite solubility then falls precipitously to surface pressure values (Dublyansky, 1995). As a result of this behavior, calcite dissolution may occur at depth whereas the rising waters may precipitate calcite when CO_2 pressures fall as the waters rise toward the surface. Field evidence for caves formed by hot, CO_2-rich waters are linings of scalenohedral calcite and other minerals. There is evidence that the caves of the Black Hills, South Dakota, USA, were formed by this mechanism (Bakalowicz et al., 1987), although more detailed evaluation of the mineral coatings suggests a more complicated solutional and depositional history (Palmer and Palmer, 2008). The caves beneath Budapest, Hungary, are another well-known example (Dublyansky, 1995).

Type-II hypogenetic karst is both more important and the result of a more complex chemistry involving reduced carbon species and both oxidized and reduced sulfur species. The upwelling fluids carry concentrations of H_2S. When these highly reduced fluids mix with shallow oxidizing groundwater, the H_2S is oxidized to H_2SO_4 which in turn attacks the carbonate host rock creating solution cavities of substantial size. The caves of the Guadalupe Mountains, New Mexico, USA, especially Carlsbad Caverns and Lechuguilla Cave, are spectacular examples. However, hypogenetic influence on the early stages of cave development seems to be a very widespread phenomenon (Klimchouk, 2007).

The sources of the fluids that create hypogenetic karst are varied. Some are derived from oil fields where the source of H_2S may be the reduction of gypsum by methane. In other regions, the fluids may have a volcanic source. In all of these reactions, microbial processes are thought to be an important part (Engel, 2007). Most hypogenetic cave systems have a long and complex history dating well back to the Tertiary or even earlier. The reactions take place at depth but cannot be investigated until the resulting features are exposed at the surface. Evidence for the fluid-mixing hypothesis is provided by the Guadalupe Mountains caves where ^40Ar/^39Ar dates range from 3 million years (My) for Carlsbad Caverns (the lowest and youngest) to 12 My for Cottonwood Cave (the highest and oldest) (Polyak et al., 1998). The oxidizing meteoric

Figure 8 Phytokarst. San Salvador Island, Bahamas.
component of the mixing zone moves deeper as the surface landscape is eroded away.

6.2.8 Conclusions

Until the latter decades of the twentieth century, karst was considered to be a rather specialized set of landforms – typically caves, closed depressions, and deranged drainage – that occupied only a minor portion of the science of geomorphology. With the extension of karst concepts to other environmental settings and with the improved understanding of the range of karstic processes, the subject has taken on greatly expanded importance.

References


Biographical Sketch

Dr. Elizabeth L. White holds a BS degree from the University of Pittsburgh and MS and PhD degrees from The Pennsylvania State University, all in Civil Engineering. She is a registered professional engineer in Pennsylvania. Her research work has been in storm water management and surface water hydrology, the properties of cement and concrete, and the hydrology of karst aquifers. She is the author of 44 technical papers and the co-editor of the book Karst Hydrology: Concepts from the Mammoth Cave Area. She was formerly a research associate at Penn State but is presently a private consultant. She has visited many karst areas throughout the world.
Dr. William B. White is a professor emeritus of geochemistry at The Pennsylvania State University where he is affiliated with both the Department of Geosciences and the Materials Research Institute. He holds a BS degree in chemistry from Juniata College (PA) and a PhD in geochemistry from Penn State (1962). He is a registered professional geologist in Pennsylvania. Dr. White has been engaged in research on karst for more than 50 years. The work includes both laboratory investigations and field studies. The field studies include the Mammoth Cave area, Puerto Rico, and the Appalachian karst of Pennsylvania, Virginia, West Virginia, and Tennessee. This karst work has resulted in more than 100 papers in peer-reviewed scientific journals. His books include *Geomorphology and Hydrology of Karst Terrains*, *Karst Hydrology: Concepts from the Mammoth Cave Area*, *Encyclopedia of Caves*, and *Benchmark Papers in Karst Science*. Dr. White has taught graduate and undergraduate courses in cave geology at Penn State and has supervised 18 MS and PhD theses on karst subjects. He has traveled widely to examine karst regions in the United States, the Caribbean, Europe, and China.