3.1. Types of Karst and Evolution of Hydrogeologic Setting

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Abstract

Karst is treated as a specific kind of fluid circulation system capable of self-development and self-organization. Active karst may evolve at a wide range of geologic environments, from deep-seated (without any apparent relation to the surface) to subsurface, and be represented by confined and unconfined circulation systems. Extrinsic factors and intrinsic mechanisms of karst development change regularly and considerably within the general cycle of geologic evolution of soluble rocks, or more specifically, within a hydrogeologic cycle. The latter encompasses a period of exposure between major marine transgressions and is characterized by progressively expanding meteoric groundwater circulation.

A broad evolutionary approach is therefore needed to differentiate between karst types, which concurrently represent distinct stages of karst development. This is also a means to adequately classify speleogenetic settings. Evolutionary typology of karst considers the whole cycle of a geologic formation's life, from deposition (syngenetic karst), through deep burial, to exposure and denudation. The group of intrastratal karst types includes deep-seated, subjacent, entrenched, and denuded karst. The latter also overlaps into the group of exposed karst types. Exposed karst also includes open karst, which represents the unmixed exposed development, that is, karst evolved solely when soluble rock is exposed to the surface. Exposed karst development can be interrupted by subsequent burial (buried karst), with paleokarst formed as a result, and also can be rejuvenated by exhumation.

The types of karst are marked by characteristic associations of:

- Structural prerequisites for groundwater flow and speleogenesis.
- Flow regime.
- Recharge mode and recharge/discharge configurations.
- Groundwater chemistry.
- A degree of inheritance.

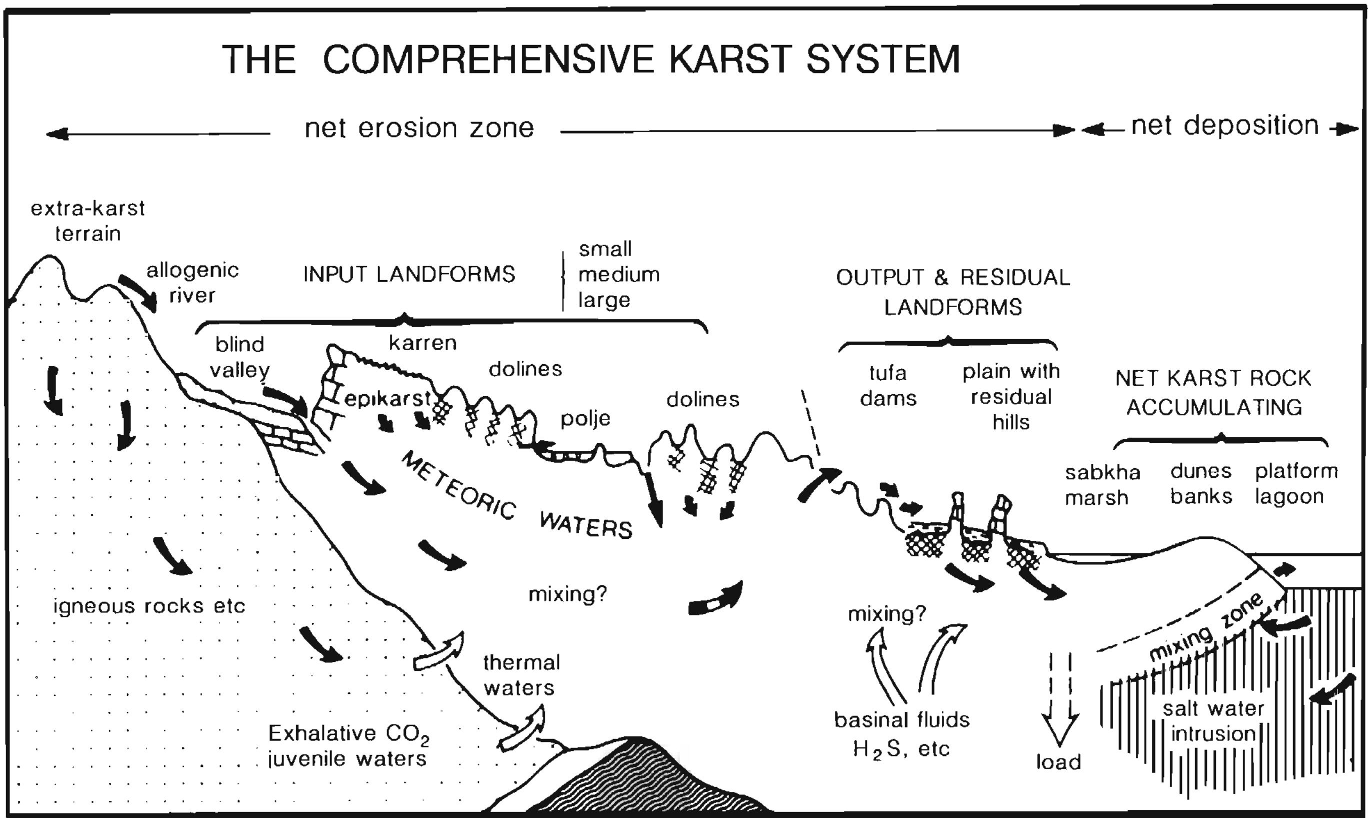
Consequently, these associations generate particular types of caves.

Introduction: Definition and Classification of Karst

The purpose of Chapter 3.1 is to place the subject of dissolutional cave development within the broader context of the karst system processes and forms, and to introduce the particular approach that will be emphasized in the following chapters. A schematic picture of the system as it has been described in general karst textbooks is shown in 3.1 Figure 1 (see page 46).

Karst extends from the newest limestone, dolomite, gypsum, and salt accumulating around the margins of seas and lakes to very ancient rocks deep in continental interiors. The waters may be meteoric, marine, expelled from deep sedimentary basins or from magmatic rocks, or mixtures of two or more of these in differing proportions. It is true that some types of karst landforms are entirely superficial erosional features—for example, rillenkarren on bare rocks. But the essence of the system is that water circulates underground, creating caves or breccias there, because the rocks are soluble. Surface features such as sinkholes and poljes (if they occur), develop to supply water to the underground or to drain it; they are not essential to the fundamental circulation.

The term *karst* itself means "stony ground." It came to be adopted as a place name for a limestone region encompassing western Slovenia and the hinterland of



3.1 Figure 1. The comprehensive karst system. A composite diagram illustrating the major phenomena encountered in active karst terrains (From Ford and Williams, 1989).

Trieste. Here, historically, the land was stony and barren because deforestation and overgrazing had led to the loss of most soil into sinkholes and caves (Gams, 1993). Poljes with deep alluvium on their floors were the best agricultural lands remaining.

This geographic association—plus until the middle of this century, the lack of cave maps, extensive groundwater tracing, or information from deep drilling for oil or mineral exploration—led to a principal focus on karst as a specific surface landscape with distinctive hydrology and landforms (Sweeting, 1973; Jennings, 1985; White, 1988; Ford and Williams, 1989; Lowe, 1992; EUR 16526, 1995).

Today we have become increasingly aware that dissolution features originate at deep-seated horizons without any apparent relationship to the land surface. This awareness, plus a desire to extend the historical analysis to the earliest possible phases of karstification in a given rock formation, make it desirable that the speleological definition of karst be broadened and separated from a strict association with surface landforms. It should focus on the most universal and essential characteristics of the phenomena and be applicable to any environment where these may develop.

From the perspective of hydrogeology, karst flow is a specific kind of fluid circulation system capable of self-development and self-organization due to its capacity to mobilize and transport matter by dissolution of host rocks.

Adapting a proposal of Huntoon (1995), karst may be defined as follows:

> 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 does not require that the rocks have a specific lithology, nor is one specific dissolutional process called for. The circulating fluid is not limited to water, although that is overwhelmingly predominant in known karsts. The definition is sufficiently broad to encompass circulation systems in unconfined and confined geologic settings, in the shallow subsurface and deep underground.

Whether karst is expressed at the surface is then not relevant. A karst system can operate in the subsurface without any relation to the surface, being represented exclusively by underground forms that draw their input water and discharge their output water from other nonkarstic rocks.

Many criteria can be used to distinguish the different types of karst that exist. In this volume, we attempt to approach the problem of karst types from the perspective of the geologic evolution of a bedrock formation—more specifically, from its hydrogeologic evolution. Such an approach seems promising for a better understanding of:

- genetic and functional relationships between numerous types and styles of karst forms,
- factors and mechanisms for their origin and development,
- and eventually for describing the average conditions of the evolution and functioning of karst circulation systems.

With this approach, certain types of karst can be viewed as successive stages in development. In each stage, major boundary conditions and the overall structure of the system may differ considerably from those of the preceding and succeeding stages. Despite the many local variations that may occur, on a global scale the major boundary conditions change between stages in a quite regular way over the course of geologic evolution. Therefore, such an evolutionary typology can also be used to classify karst and speleogenetic settings.

Speleogenesis can be viewed as the creation and evolution of organized permeability structures in a rock that have developed as the result of dissolutional enlargement of an earlier porosity. It is, therefore, an essential part of the concept of karst defined above. One can assert that:

karst is a function of speleogenesis,

a statement for which the validity is particularly evident in cases where there is no surface landscape component, the karst consisting solely of underground forms.

Hydrogeologic Structures

A clear scale hierarchy of water-bearing structures can be recognized in karst rocks. The smallest structures are the four types of elementary water-containing spaces:

- pores in the rock matrix—tiny intergranular or intercrystalline voids.
- fissures—planar discontinuities such as bedding planes, joints, and faults in which the opening (the aperture or width) is negligible in scale when compared to the length.
- conduits—elongated planar or tubular openings where width is a significant proportion of the length.
- vugs and caverns, that are seemingly isolated voids of irregular shape and with diameters several orders of magnitude greater than those of average matrix pores.

At a second scale, these several elementary types of voids combine in various proportions to form groundwater bodies termed *aquifers.* These are categorized by the predominant types of voids contributing to the overall porosity, such as porous aquifers, fissure aquifers, matrix-fissure aquifers, and fissure-conduit aquifers.

The third scale is the important hydrogeologic consideration as to whether these elementary aquifers are arranged in accordance with the sedimentary layering. That is, are they stratiform, intrastratal, or interstratal. Are they distributed across sequences of rocks with no respect to bedding and other layering. Are they within nonstratified rocks. In the stratified case, individual aquifers and their flow systems may correspond to individual stratigraphic units, such as geologic formations or members.

In the crosscutting case, the aquifers are commonly confined to individual tectonic blocks, or between lithologically determined boundaries such as between a lava flow and a coral reef. Various structural controls of cave development at this scale are considered in more detail in the following sections.

At a fourth and largest scale there are regional hydrogeologic structures. These are principally *artesian basins.* Here rocks are prominently layered and contain stratiform groundwater bodies (layered aquifers), and *hydrogeologic massifs,* where groundwater bodies are of the tectonic-block type, with an overwhelming prevalence of crosscutting fissure-conduit permeability (Zajtzev and Tolstikhin, 1971; Pinneker, 1977).

Transitional types include *disrupted basins* (layered structure prevails but is complicated by block and crosscutting structures) and *layered massifs,* with layered structures of lesser importance. The succession *artesian basins—disrupted basins and layered massifs—hydrogeologic massifs* can correspond to different stages in the evolution of sedimentary basins. Artesian basins are modern or ancient basins displaying only minor to moderate tectonic disturbance of the layered structure. Disrupted artesian basins contain considerably deformed strata in tectonically active and uplifted parts of cratons, or in folded regions. Hydrogeologic massifs are common in highly deformed and uplifted highland belts. These categories may display significant differences in the boundary conditions for groundwater circulation systems and speleogenesis.

Karst Evolution within the Hydrogeologic Cycle

The development of groundwater circulation systems is broadly cyclic. The hydrogeologic cycle begins with marine sedimentation that is succeeded by tectonic subsidence and the formation of connate waters (trapped seawater with further minerals dissolved in it). It then encompasses uplift, with denudation and the progressive invasion of meteoric waters into the reservoir. It may include the intrusion of magma with release of juvenile waters. It closes with a new marine transgression and sedimentation (Pinneker, 1982).

Groundwater history in sedimentary rocks can be considered as a part of the diagenetic history of the deposits. Diagenesis is the progressive alteration of a sediment by processes of compaction, expulsion of water, and cementation, with or without dissolution. In karst rocks it is closely linked with, and largely operates through, groundwater processes. Creation and loss of solutional porosity is treated by sedimentologists as a diagenetic process (Choquette and James, 1988).

Choquette and Pray (1970) divided carbonate diagenesis into three stages:

- *eogenesis* when the shallow marine sediment is first laid down and may be altered by the effects of periodic drying or exposure to rainwater.
- *mesogenesis* when this sediment is buried, compacted, and altered under later rocks.
- *telogenesis* when later uplift and erosion thin or remove the cover rocks and permit meteoric water to invade and overwhelm any remaining connate or juvenile waters.

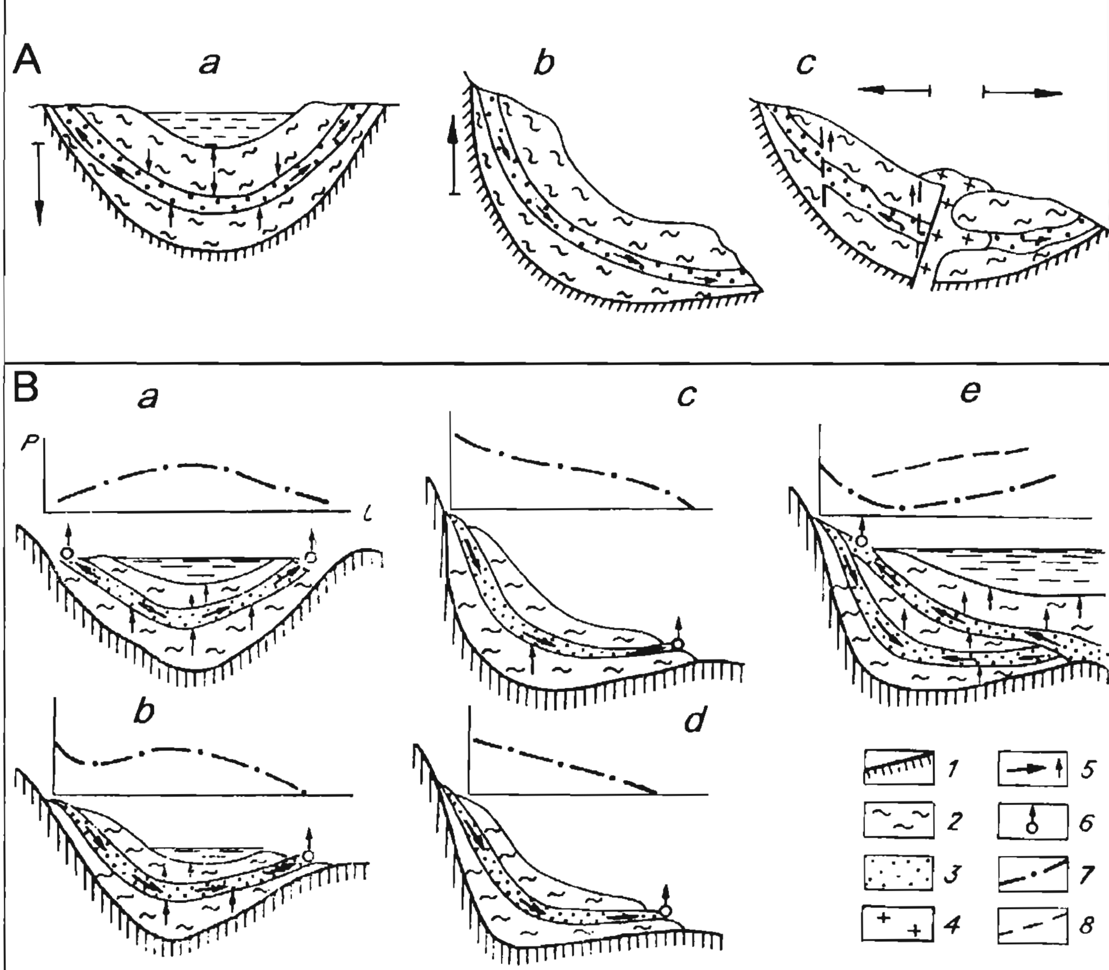
With increasing burial, connate waters are expelled from clayey sediments into coarser grained (sandy) reservoirs, the fluid potentials (pressure fields) being guided mainly by compaction. With burial to depths greater than 1 to 2 km, the increasing temperature may cause dehydration of minerals containing combined water and the consequent release of liquid resurgent waters that partially replace connate waters in the sediments. Groundwater movement is directed from areas of greatest subsidence to the margins of basins where the rocks are at shallower depths. This type of circulation is termed *expulsion* circulation (or *elision* circulation in the Eastern European literature; Kartzev et al., 1969).

When meteoric water invades the system following uplift, it is driven by the hydrostatic head. This is *meteoric* (or *infiltration) circulation.* During the continental regime, meteoric groundwater increasingly flushes out connate and resurgent waters from a basin, although expulsion circulation may still predominate in deep environments. The full hydrogeologic cycle may thus include replacement and expulsion, meteoric and magmatic (endogenous) circulation (3.1 Figure 2A, see p. 48), although the latter often does not occur.

If there is a second hydrogeologic cycle the new marine waters may enter any surviving older lithified rocks, replacing meteoric or hypogene waters in them that were inherited from the interrupted previous continental regime. At the same time, in the deeper parts of the basin expulsion of connate and resurgent waters from the first burial stage may be continuing (3.1 Figure 2B).

Consequently, the composition and circulation of groundwater in a large basin may be quite complicated where several hydrogeologic cycles are superimposed. The situation is further complicated where an originally unified groundwater basin is deformed and subdivided by differential tectonic movements, especially where time lags in the adjustment of the flow systems to the changing conditions mingle groundwaters of differing ages (Tóth, 1995).

In contrast to groundwater reservoirs of the stratiform class (artesian and disrupted artesian basins that predominate on continental platforms and along passive margins), massifs in orogenic regions are characterized by the overwhelming predominance of contemporary meteoric groundwater. This groundwater has almost entirely replaced waters of previous stages. Episodes of



Upper diagrams:
Stages:
a. *expulsion circulation (sedimentation).*
b. *meteoric circulation.*
c. *magmatic (endogenous) circulation. Large arrows indicate directions of tectonic movements.*

Lower diagrams:
a *through* ***d***—*Stages of the 1st hydrogeologic cycle:*
a. *expulsion circulation*
b. *meteoric circulation with inherited features of expulsion circulation.*
c. *meteoric nonsteady regime circulation.*
d. *meteoric steady regime circulation.*
e. *expulsion circulation, with inherited features of meteoric circulation in the lower aquifer and expulsion circulation in the upper aquifer of the 2nd hydrogeologic cycle.*

Key: 1–basement (the lower aquifuge). 2–clay. 3–sandy sediment (aquifers). 4–magmatic rocks. 5–groundwater flow direction. 6–discharge points. 7 and 8–potentiometric surfaces of the aquifers: 7 of the lower aquifer, 8 of the upper aquifer

3.1 Figure 2. Diagram A illustrates the full hydrogeologic cycle (after Pinneker, 1982). Diagram B, the hydrogynamic evolution of groundwater systems (Kudrjakov, 1970).

magmatic groundwater invasion and circulation are often important during the deformation that creates such regions. It may still be occurring in tectonically active areas.

Baskov et al. (1996) have emphasized that on the continents, (especially in the little disturbed stratiform regions), the hydrogeodynamic circulation discussed above often can be described as displaying two distinct stories. The upper story has active meteoric water circulation signified by the presence of significant amounts of dissolved oxygen and nitrogen of meteoric origin. The lower story is dominated by connate and resurgent water lacking such gases. During uplift and denudation, sedimentary formations move progressively into the upper story.

Ezhov and Vdovin, 1970; Ezhov and Lysenin, 1986; and Ezhov et al., 1991, 1992, have enlarged our thinking about water in the crust of the Earth by introducing the further concepts of *exokarst* and *endokarst*. The hydrogeodynamic circulation (both stories, meteoric and expulsion groundwater systems) constitutes an upper exokarst zone of the continental hydrosphere. This is one in which fluid pressures are close to the hydrostatic pressures, not exceeding them by more than 10-15%.

Below it is the deepest zone where fluid pressures are created chiefly by the lithostatic load (the weight of overlying rocks) plus any tectonic forces. In between is a transition region, the mesozone, where pressures can be highly irregular in both space and time. This is marked by maximum compaction of rocks and serves as an isolator between the upper and lower zones. Local releases of pressure in it allow fluids from below to break through into the exokarst from time to time. In the lithostatic zone and deep mesozone there may be a high degree of dissolution and fluid rupturing of rocks—the endokarst. Besides dissolving carbonates, the strong thermo-baric conditions there may make fluids highly aggressive with respect to silicate and aluminosilicate minerals that are of low solubility under exokarst conditions. For example, the solubility of quartz at temperatures of 300°-350°C and pressures of 200-250 MPa is comparable to that of gypsum at the surface of the Earth. The endokarst is discussed further in Chapter 5.2.5.

The Hydrogeologic Cycle and Perspectives on Speleogenesis

Most of the karst development that has been well studied is known to be associated with continental subaerial exposure and meteoric groundwater circulation. Conventional karst and speleogenetic theories are concerned mainly with shallow unconfined geologic settings, supposing that the karstification is ultimately related to the surface and that dissolution is driven by downward meteoric water recharge.

The possibility of karstification in deeper environments (although still within the exokarst) has been neglected for a long time. So the quite numerous instances of karst features found at significant depth have usually been interpreted as buried paleokarst (as defined below).

However, some recent studies reflect increasing recognition of the importance to speleogenesis of processes operating earlier in the hydrogeologic cycle or deeper underground:

- Some of the features formed during sedimentation and eogenesis (changes during shallow burial) can influence subsequent speleogenesis. Caves of enterable size can be formed penecontemporaneously with carbonate sedimentation or dune formation in the littoral environment and freshwater/seawater mixing zone (Jennings, 1968; Ollier, 1975; Esteban and Klappa, 1983; Lowe, 1992; Mylroie and Carew, 1995, and many others. In this volume see Chapters 3.2, 3.3, and 5.1).

- Deep dissolution during mesogenesis or telogenesis can play an important role in the earliest phase of speleogenesis, preparing potential flow paths for later selective exploitation. A shortcoming of many studies of modern caves has been the lack of recognition of possible inheritance from earlier stages. Moreover, there can be full scale cave development (macroscopic conduit porosity and cave systems) in the deep environment due to hypogene processes (Klimchouk, 1994, 1996b, 1997; Lowe, 1992; Lowe and Gunn, 1995; Mazzullo and Harris, 1991, 1992; Palmer, 1991, 1995; Smart and Whitaker, 1991; Worthington, 1991, 1994; and Worthington and Ford, 1995; in this volume see Chapters 3.3, 3.4, and 5.2).

Further important points to emerge from cave studies of the past three decades are these:

- That no one speleogenetic model can be applied to all geologic and hydrologic settings.
- That a number of different dissolution mechanisms may operate in the different settings to produce organized karst permeability.

This makes it necessary to categorize speleogenetic settings (environments) in order to evaluate genetic theories and mechanisms. As settings change regularly during the hydrogeologic evolutionary cycles outlined above, an evolutionary approach again is a helpful means to order the theories and models and to clarify their relations.

A Hydrogeologic Evolutionary Typology for Karst

The sequence of karst settings that a given formation could experience during its history is outlined in 3.1 Figure 3. These are:

- Syngenetic to penecontemporaneous karst.
- Intrastratal (interstratal) karst.
  - Deep-seated karst.
  - Subjacent karst.
  - Entrenched karst.
- Exposed karst.
  - Open karst.
  - Denuded karst.

  (The subtypes open karst and denuded karst are not sequential categories. They are characterized by similarly exposed geomorphic settings but differ in their previous karstification history. The true denuded karst is a former intrastratal karst)
- Mantled karst.
- Buried karst.
- Exhumed karst.

In actuality, no individual karst is known that displays all of its possible sequence, but many have experienced several of the components. Karstification need not begin syngenetically. Many limestones, gypsums, and salt deposits are buried without suffering significant earlier dissolution. Where buried, karstification may be initiated at any of the stages of intrastratal development that are shown in the figure. Or they may be delayed until the rock is exposed by stripping of the cover (open type). The karst may be completely destroyed, along with its host formation, within the same stage that its development commenced. This is more common for karst in sulfates than in carbonates and is the fate of most salt. At the other extreme, carbonate karst can survive through several cycles of burial-exposure (and the accompanying hydrogeologic cycles), being repeatedly fossilized and rejuvenated.

Syngenetic Karst

Most limestones, dolostones, and gypsum deposits are laid down on shallow oceanic or coastal platforms experiencing slow subsidence or uplift. Eustatic and glacioeustatic changes of sea level may result in alternating deposition and intermittent subaerial exposure on them. Freshwater vadose and phreatic, and freshwater-marine mixing environments can cause substantial and rapid cave development in the young rocks. Jennings (1968) categorized this as *syngenetic karst*. Its occurrence is not very widespread at present, because global sea levels are exceptionally high. But its importance in the past—and hence its role in generating features that will fall into the paleokarst category after subsequent burial—is underlined by the fact that a majority of limestones were deposited in less than 10 m of water. Thus they were vulnerable to even minor changes in sea-level and the related meteoric diagenesis (Wright, 1991). Speleogenesis in oceanic and coastal settings is treated in detail in Chapter 5.1.

Where carbonate rocks are frequently exposed and acquire considerable diagenetic maturity without being buried, this type of karst may pass directly into the open type. It is more common, however, that any syngenetic karst is buried to various depths, becoming paleokarst. Karstification then may be restarted at any stage of the intrastratal or later sequence (see 3.1 Figure 3, p.50). But any inheritance is commonly of the posthumous type.

Intrastratal karst

The concept that an evolutionary karst sequence can be linked to the relationships with insoluble cover beds has been considered by many geomorphologists. For example, Ivanov (1956) distinguished covered, semi-open, and open *stages* of karst development as an evolutionary succession for the neotectonic epoch in many regions. More detailed classifications were proposed by Quinlan (1978). There is also further discussion in Bozák, Ford and Glazek (1989), Palmer and Palmer (1989) and others for limestone, and Klimchouk (1996a) for gypsum.

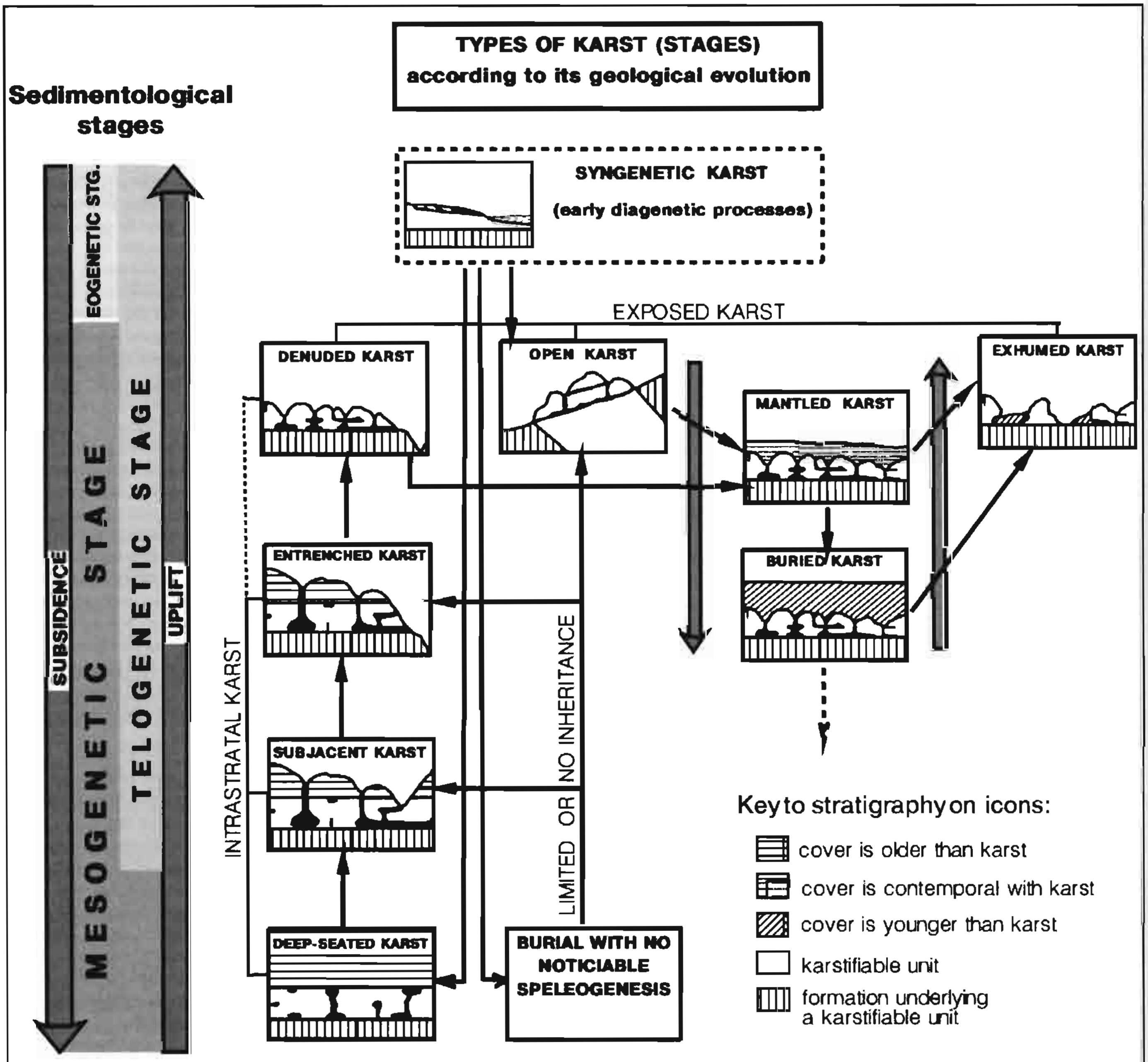
Quinlan (1978) originally proposed *interstratal karst* as the term to describe dissolution features that develop beneath cover rocks deposited before any karstification. Palmer and Palmer (1989) suggested that *intrastratal karst* is more appropriate, because most dissolutional processes at depth are not limited to the boundaries between different strata. Perhaps *interstratal* is better where a soluble stratum is being entirely removed (the fate of many salt beds) but *intrastratal* is used here as the more broadly applicable term.

On all continents the area of common karstifiable rocks that lie at some depth beneath insoluble sediments substantially exceeds the area of exposed karst. There is much evidence from exploration drilling and mining that karst features occur widely beneath cover rocks. But, as noted, these have generally been treated as inert paleokarst (*buried karst* in the classification adopted here) rather than actively evolving forms. However, the likelihood and mechanisms for intrastratal karstification to considerable depths are increasingly recognized, and occurrence of active deep-seated intrastratal karst is probably much greater than traditionally supposed.

The fluid potentials that drive groundwater flow in deep normally confined settings originate from different sources, including gravity, compaction, compression, dilatation, and heating. The deep chemical processes that can generate acids for dissolution and speleogenesis are also various and include maturation of hydrocarbons, sulfate reduction, and metamorphism. Nonacidic aggressiveness with respect to carbonates can be caused by the cooling of ascending water (increasing the solubility of CO_2), and, for sulfates, by the reduction process.

Dissolution by mixing of waters with contrasting chemistries is of particular importance. Dedolomitization (dissolution of $MgCO_3$ with concomitant precipitation of $CaCO_3$) can contribute substantially to the creation of porosity in both sulfates and dolomites. Thus it can be important in interbedded sulfate-carbonate formations (which are very common). Settings and mechanisms of deep-seated speleogenesis are reviewed in more detail in Chapters 3.4 and 5.2.

Hydraulic continuity and vertical cross-



3.1 Figure 3. Evolutionary types of karst (modified from Klimchouk, 1996a).

formational hydraulic communication is of paramount importance for intrastratal karstification (Klimchouk, 1994, 1997b; Tóth, 1995). This is because it helps to activate different chemical mechanisms and reinforce mixing corrosion effects. In most deeply covered karst strata, the only source of recharge is from an adjacent formation. Whether the recharge is focused or dispersed depends largely on the structural situation. Particularly favorable conditions for speleogenesis are created where expulsion waters and meteoric waters can mix and the meteoric water begins to flush out basinal brines from the aquifers.

Deep-seated intrastratal karstification tends to be more diffuse and less selective than that of shallow settings, due to both hydraulic and structural controls. As a consequence of standard denudation and uplift on the continents, the deep-seated rocks are shifted with time into progressively shallower positions. They pass into the upper hydrogeodynamic level where meteoric circulation is driven predominantly by topographic differences of head. At some stage *en route* to the surface, erosional incision into the cover rocks locally breaches the hydrogeologic confinement, and the aquifer is brought into direct hydraulic connection with the surface.

Further incision causes inversion of the circulation system, drastic changes in recharge-discharge configuration, and establishment of a vadose zone and water table conditions within the karstic strata. At this point the unit is still commonly capped by some insoluble beds over most of its area. Progressive denudation may eventually expose the rock entirely.

Various stages of this evolution are represented by the sequence of intrastratal karst types. The boundaries between them are in reality transitional, but can be drawn in the following way:

- *Deep-seated karst* is not evident at the surface and the soluble rock is not exposed.
- *Subjacent karst* occurs where the soluble rock is locally breached by erosion over a minor part of its thickness. Karst features may already be expressed at the surface at springs or collapse features.
- *Entrenched karst* is where the entire thickness of the soluble rock is entrenched along valleys, but the insoluble cap remains over most of the interfluves.
- *Denuded karst* is where the cap rocks are removed.

Where continuous karst develops from the deep-seated stage to the denuded stage, the role of inheritance can be quite important.

In some cases deep-seated karstifiable rocks, particularly gypsum and salt, may be entirely removed by dissolution before any breaching and exposure. Such dissolutional removal leaves characteristic karst breccias composed of the insoluble or less soluble remnants of intercalated beds (commonly carbonates) and broken fragments of the overlying rocks.

The different intrastratal karst stages are marked by characteristic changes:

- In the geologic controls of speleogenesis (see Chapter 3.2).
- In the dynamics of the flow system, recharge mode, and recharge-discharge configurations (see Chapter 3.4).
- In groundwater chemistry (see Chapters 3.4 and 5.2).

For instance, the recharge mode (which largely determines the style of speleogenesis) tends to switch from a predominantly diffuse, steady flow from adjacent formations in deep-seated karst, to a highly focused and variable flow from the surface in subjacent and entrenched karsts where caprocks are poorly permeable. However, the occurrence of diffusely permeable caprocks may still maintain diffused recharge in these settings. Recharge becomes less focused and variable in denuded karst, but underground flow patterns are largely inherited from the earlier stages. Confined circulation systems give way to unconfined phreatic flow when passing from deep-seated to entrenched and exposed stages, with consequent development of water-table and vadose zones. Therefore, the cave patterns vary between these settings (see Chapter 3.4).

The concept of a succession of intrastratal karst stages applies to the evolution of artesian basins and disrupted basins. In highly deformed and folded highland regions (many of which contain thick karstifiable formations), stratiform groundwater circulation characteristic of basins is overwhelmed by fault block circulation. Individual stages may be recognized where there are cover beds but not the regular stratiform sequence of karst development suggested by the term "intrastratal."

Exposed Karst

When the surface extent of soluble rocks exceeds that of any remaining caprock, the karst can be considered exposed. There are three paths to this condition (3.1 Figure 3. The first two correspond to the open karst, while the third one generates denuded karst:

- The karst rock has never been buried by other rocks.
- The rock has been buried but then stripped of cover before there was any significant development of karst circulation or features. these are "open" karsts.
- Earlier intrastratal karst is exposed and becomes denuded.

There may be considerable differences in mechanisms of development and styles of karst landforms and caves between the open and denuded categories.

Denuded karst was proposed by Quinlan (1978) to identify former subjacent or entrenched karst exposed by removal of its cover. It is characterized by the coexistence of features formed during the exposed stage and those inherited from previous stages. The latter may be largely relict or adjusted in varying degrees to the new hydrologic and hydrogeologic setting. Inherited cave patterns greatly influence the development of the karst landscape and hydrology.

Open karst is that developed largely or entirely during the exposure stage. As such it is unmixed and controlled by surface and shallow subsurface factors without any inheritance from previous karst stages. It is dominant in the great cockpit and tower karst highlands of the tropics and subtropics. It is common where evaporites or any soluble lithology are exposed in areas of very low relief, with aquicludes such as shales prohibiting vertical interformational groundwater flow. It also predominates on tropical islands and coasts where recent carbonates have been continuously exposed. The Yucatan Peninsula of Mexico is the great example.

Exhumed karst is earlier karst exposed by the erosion of sediment that once buried it (Quinlan, 1978; Bosak, Ford and Glazek, 1989). It represents former exposed karst, once (or repeatedly) interrupted by burial but now returned to an active state by the exhumation. Exhumed karst exhibits complicated polyphase inheritance and is characterized by the presence of many paleokarst features.

Exposed karst settings characteristically generate branchwork cave patterns in carbonates, and branched to linear patterns in sulfates. As fissure patterns and the relief and thickness of the vadose zone may range widely, the profiles of invasion vadose caves can be quite varied. Denuded karst can exhibit a wide range of cave patterns inherited from the preceding stages, utilized to varying extents by the active systems.

Mantled Karst and Buried Karst

Mantled karst is that covered by significant thicknesses of unconsolidated sediment that accumulates as the karst develops. Most common are soils formed from the insoluble residuum of impure limestone and dolostone (locally derived or "autochthonous" deposits). An "allochthonous" mantle is one carried in from outside the karst terrain, such as the volcanic ash layers that mantle the karst at Waitomo, New Zealand.

Mantled karst should be distinguished from *buried karst*. Buried karst is a complete infilling and burial by later rocks such as transgressive marine sediments, surpressing or (usually) terminating the karstification. Buried karst should not be confused with intrastratal karst, where the karstic rocks were buried before any karstification occurred. Buried karst has only the direct meaning—a karst that was exposed and then buried. We suggest that minor syngenetic karst in diagenetically immature rocks should not be classified as buried karst where burial followed almost immediately after deposition. Only karst that has undergone the pronounced exposed development before burial should be treated as truly buried karst.

When karst is buried, it is generally the most unambiguous case of true paleokarst, as described below.

Paleokarst

Paleokarst does not imply any particular type of karst but rather refers to a condition, namely fossilized. From the definition of karst, a paleosystem is karst that lost its mass transport function. It is hydrologically decoupled from contemporary systems, in contrast to *relict* systems that exist within contemporary systems but are displaced from the environment in which they formed (Ford and Williams, 1989).

At the extreme, a karst rock can be entirely removed (dissolved). It is replaced in the geologic cross section or at the surface by residual sediments or by sediment that was emplaced within karst forms, such as sinkholes that have since been destroyed. This means that paleokarst can be recognized even when the host rock no longer exists. This is a point of particular importance for the interpretation of interstratal gypsum karst.

Karst systems, or their components, can be fossilized at any of the stages of development described above. Fossilization is almost inevitable when syngenetic karst is buried. In deep sulfate beds a karst system can develop fully and then disintegrate, possibly to the extent of total removal of gypsum beds from a cross-section, without having been elevated to the shallow subsurface. As noted above, karst-breccia horizons of minor insoluble intercalations and fragmented overlying rocks are common in sulfate and sulfate-carbonate sequences, where they represent intrastratal paleokarst. However, it is worth reemphasizing that the occurrence of deep-seated karst does not, in isolation, indicate a paleokarst condition. Active karstification also occurs commonly in this environment, where it may develop intermittently over long timespans, being repeatedly activated and deactivated. Distinguishing between intrastratal karst and paleokarst is often difficult, as pointed out by Palmer and Palmer (1989, p. 337).

Intrastratal features are considered paleokarst only if they are out of adjustment with the present geologic setting. This criterion is often difficult to apply, for intrastratal processes tend to operate over a long time span, and many features that qualify as intrastratal paleokarst were formed by processes still operating at a diminished rate today.

Even those intrastratal features that are filled with collapse breccia are not necessarily paleokarst. Breccia pipes or "geologic organ pipes"—Klimchouk and Andrejchouk (1996) have suggested the generic term vertical through structures to denote such forms—are common features of upward stoping through overlying formations, induced by dissolution of underlying salt or gypsum beds. Breccia pipe development is not merely a breakdown process, but is maintained by active groundwater circulation through the pipes, with partial mass-removal by dissolution. They become paleokarst features only when they are fossilized to the extent that groundwater circulation is interrupted.

When karst passes into the entrenched stage, most earlier conduits (artesian, phreatic, water-table) become relict. This is because circulation in the now dominant vadose zone is highly localized. Further evolution into the exposed karst stage may reactivate many of these relict features as they become integrated into a karst landscape where the dissolution is more dispersed. Should there be subsequent burial, different parts of one contemporary system can become separated hydrologically, some becoming completely fossilized, others not. In some situations such paleokarst can be exhumed and reintegrated into active systems. Further discussion of the problem of paleokarst, as it relates to speleogenesis, is provided by Osborne in Chapter 3.7.

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