Selected excerpts from 'Karst Hydrogeology and Geomorphology' by

Tanguy Racine

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1 Introduction to Karst

The following article summarises the influence of geology and geomorpholical processes on speleogenesis as outlined by the textbook 'Karst Hydrogeology and Geomorphology'.

Karst Karst is the term used to describe a special style of landscape containing caves and extensive underground water systems that is developed on especially soluble rocks such as limestone, marble, and gypsum. Large areas of the ice-free continental area of the Earth are underlain by karst developed on carbonate rocks (Figure 1.1) and roughly $20-25\%$ of the global population depends largely or entirely on groundwaters obtained from them. These resources are coming under increasing pressure and have great need of rehabilitation and sustainable management. The following figure 1

Definitions

- Karst: A karstified terrain has distinctive hydrology and landforms that arise from a combination of high rock *solubility* and well developed secondary (fracture) *porosity*. Such areas are characterised by sinking streams, caves, enclosed depressions, fluted rock outcrops, and large springs. Considerable rock solubility alone is insufficient to produce karst. Rock structure and lithology are also important: dense, massive, pure and coarsely fractured rocks tend to develop the 'best' karst.

- The comprehensive karst system: as shown in figure 2 comprehensive karst system is divided in two zones. A zone of primary erosion and a zone of primary deposition. The best known features of erosional karst are formed by rock dissolution by natural waters along pathways provided by the geological structure.

- Palaeokarst vs relict karst: Some karsts are buried by later consolidated rocks and are inert, i.e. they are hydrologically decoupled from the contemporary system. These are commonly referred to as *palaeokarsts*. Some

karsts are buried by later consolidated rocks and are inert, i.e. they are hydrologically decoupled from the contemporary system. They have often experienced tectonic subsidence and frequently lie under cover rocks. Occasionally they are brought to the surface and reintegrated into the active system, thus resuming a development that was interrupted for perhaps tens of millions of years. Contrast this with *relict* karst,ie: systems which, often, have been subject to a major change in baselevel. drowned karst on the coast is such an example. Drained upper level passages in multilevel cave systems are found in perhaps the majority of karsts.

- Exokarst vs endokarst: Exokarst refers to the suit of karst features developed at the *surface*. Endokarst concerns those developed *underground*.

- Other types of karsts

  vulcanokarst lava tubes and their mechanical collapse

  pseudokarst collapse and karst-like features produced by processes other than dissolution - ice caves in glaciers are an example because they involve a phase change and not dissolution.

  thermokarst topographic features found in permafrost due to the thawing of ice in soils.

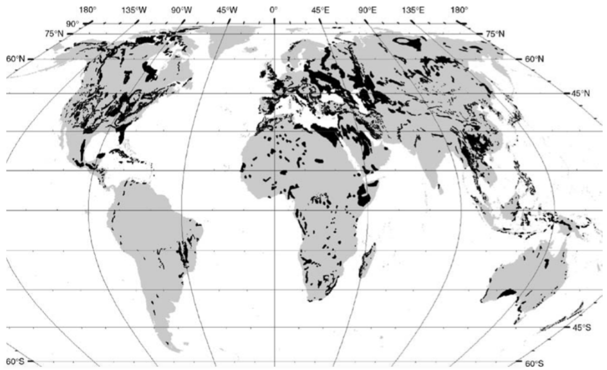


Figure 1: Global distribution of major outcrops of carbonate rocks. Accuracy varies according to detail of mapping. Generalization occurs in areas with interbedded lithologies and where superficial deposits mask outcrops. *(Map assembled using GIS on Eckert IV equal-area projection from regional maps, many of which were subsequently published in Gunn (2000a))*

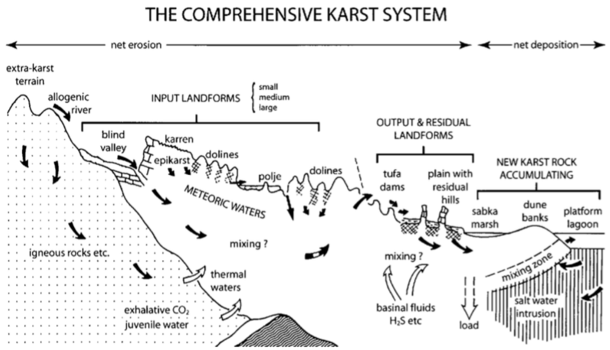


Figure 2: The comprehensive karst system: a composite diagram illustrating the major phenomena encountered in active karst terrains. Reproduced from Ford, D.C. and Williams, P.W. (1989) *Karst Geomorphology and Hydrology.*

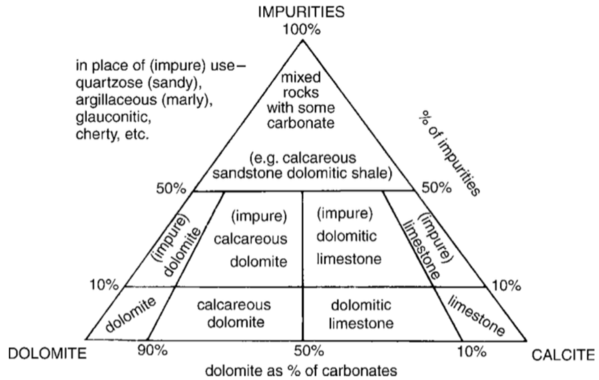


Figure 3: A bulk compositional classification of carbonate rocks. Reproduced with permission from *Leighton, M.W. and C. Pendexter, Carbonate rock types, Mem. 1, 3361. 1962 American Association of Petroleum Geologists.*

2 The karst rocks

Carbonate rocks and minerals Figure 3 gives a basic classification. Carbonate rocks contain > 50% carbonate minerals by weight. There are two common, pure mineral end-members, limestone (composed of calcite or aragonite) and dolostone (dolomite). Carbonate rocks are distinctive from other sedimentary rocks because their rate of accumulation is highly dependent upon organic activity and they are more prone to post-depositional alteration than other sediments.

In carbonate structures the CO2 anions can be considered as three overlapping oxygen atoms with a small carbon atom tightly bound in their centre. In pure calcite, the anions are in layers that alternate with layers of calcium cations. Each Ca^{2+} ion has six CO_3^{2-} anions in octahedral co-ordination with it, building hexagonal crystals. Divalent cations smaller than Ca^{2+} may substitute randomly in the cation layers; larger cations such as Sr^{2+} can be accepted only with difficulty.

Aragonite is only metastable. In the presence of water it may dissolve and reprecipitate as calcite. Aragonite is 8% less in volume than calcite. Inversion to calcite therefore normally involves a reduction of porosity. Aragonite crystals display acicular (needle-like), prismatic or tabular habits; there is frequent twinning.

In ideal (or stoichiometric) dolomite, equimolar layers of Ca^{2+} and Mg^{2+}

ions alternate regularly between the CO_3^{2-} planes. The reality is more complex. Some Ca atoms substitute into the Mg layers and trace quantities of Zn, Fe, Mn, Na and Sr atoms may be present in either Ca or Mg planes. Most dolomites are slightly Ca-rich so that the formula is properly written: $(Ca_{(1-x)},Mg_x)_2CO_3$. In addition, because Fe^{2+} is intermediate in size it fits readily into either Ca or Mg layers.

Environmental control of deposition Limestones are the most significant karst rocks. he nature and environmental controls of their deposition determine much of the purity, texture, bed thickness and other properties of the final rock. While today, karstic rocks can form in almost every environment from high mountain to deep oceans, most of which survives in the rock record is formed in shallow tropical waters, especially carbonate platforms and ramps.

- **facies**: is a body of rock with specified characteristics,which can be any observable attribute of rocks such as their overall appearance, composition, or condition of formation, and the changes that may occur in those attributes over a geographic area. Such facies are represented in figure 4.

The building blocks of carbonate rocks

- Carbonate mud (or micrite) is the most important bulk constituent. It can compose entire beds or formations, or serve as matrix or infilling. Much originates as aragonite needles from algae, some is precipitated directly, the rest is the finest fragmentary matter produced by abrasion, faunal burrowing, excretion, microbial reduction etc...

- Carbonate sand is formed mainly of faecal pellets, ooliths and fragments of skeletons and shells. It may accumulate in higher energy environments (beaches, bars, deltas) and build to sand ripples or dunes. More frequently it is dispersed within carbonate mud.

- Reefs make only a small volumetric contribution to the worlds limestones but they can be spectacular. They range from those having a complete framework tens to many hundreds of metres in height built of successive generations of coral or algae (framestone) to carbonate sand, silt or mud piles containing scattered, but unlinked, corals, fragments and algal or microbial mats. Modern coral grows chiefly between 30^o N and 25^o S in the photic zone (upper layer of the sea where photosynthesis occurs). Growth rates are commonly 1-7 mm.yr^{-}1

- Conglomerates are debris mounds or fans of pebble-, cobble- and/or boulder-sized clasts that have been rounded or partly rounded during transport by flowing water, waves or glaciers. Where the clasts are largely or entirely carbonate and the cement is calcite, they may function like other pure carbonate rocks. An example is the Dolomitic Conglomerate of the

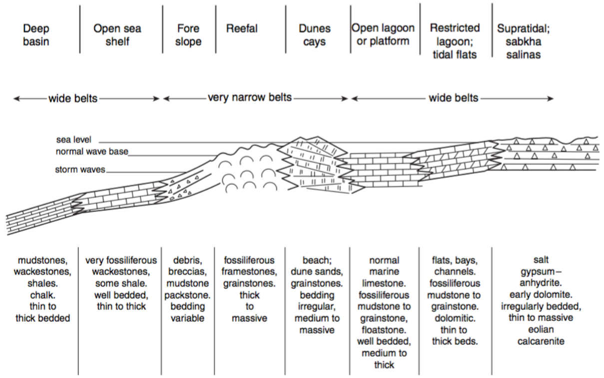


Figure 4: A composite facies model to illustrate deposition of limestone, early dolomite and evaporite rocks on a rimmed shelf and ramp. This is a generalised, simplified picture. Not all facies will be present in any given transect. Narrow belts range from a few metres to a few kilometres in width, whereas wide belts range from hundreds of metres to more than 100 km. Modified with permission from *Wilson, J.L. (1974) Characteristics of carbonate platforms margins, Bulletin, 58, 81024. 1974 American Association of Petrologists.*

Mendip Hills, England: the clasts (up to boulder size) are from platform limestones of Lower Carboniferous age that were eroded from steep desert scarps during Permian times and swept down canyons to accumulate as fanglomerates that then became submerged. In tourist caves such as Wookey Hole solutional forms in the passage walls can be seen to pass smoothly from the undisturbed Carboniferous Limestone to the Permian conglomerate.

- Terrestrial carbonates: the most widespread types are tufa and travertine. *Tufa* are grainy deposits accreting to algal filaments, plant stems and roots at springs, along river banks, lake edges, in cave entrances. It is typically dull and earthy in texture, and is highly porous once the vegetal frame rots out. In contrast, *travertine* is crystalline, dense calcite that is often well layered, quite lustrous and lacks framing plant content. That formed underground or at hot springs is largely or entirely inorganic.

Evaporite rocks and their minerals Salt karst landscapes are limited to small patches in deserts. Dissolution of these rocks (with or without some surface expression) is widespread and very important. The rocks are formed by homogeneous or heterogeneous precipitation in marine, lake or ponded waters that have been concentrated by partial evaporation, or as residues left by complete evaporation. Seawater is quantitatively the most important source: restricted lagoons, plus sub-, inter- and supratidal salt flats (known collectively by the Arabic term sabkha are the chief depositional environments. Gypsum precipitates at about three times seawater strength and salt at eleven times strength; gypsum is thus the more widespread evaporite deposit because lagoonal, sub- and intertidal waters are generally renewed before there can be much deposition of salt. In contrast to the carbonates, all of these rocks are wholly inorganic in origin and composition.

Silica rich sandstones Massive Precambrian quartzite scarp-lands of the Roraima Formation in Brazil and Venezuela are perhaps the greatest example, with corridors and deep shafts drained by caves that may be several kilometres in length. There are three principal requirements for substantial development of solution features: (i) high mineral purity, so that initial surficial pits or underground dissolution channels do not become filled or blocked by grains of the insoluble aluminosilicates, etc. that are present in a majority of sandstones; (ii) thick to massive bedding with a few penetrable planes intersected by strong but widely spaced fracturing; and (iii) absence of strongly competing geomorphological processes such as frost shattering or wave attack. The absence of effective competition permits the comparatively slowly developing solution landforms to become dominant.

3 Lithological factors affecting karst development

rock purity Clay minerals and silica are the most common insoluble impurities in carbonate rocks. It is a widespread finding that limestones with more than 2030% clay or silt (argillaceous limestones) form little karst. In a series of computer models Annable (2003) found that medium- grained silt was very inhibitive because it clogged protoconduits. The best karst rocks are ¿70% pure carbonates. Studies of local limestone and dolomite specimens have been made in many countries. They have established that laboratory dissolution rates in carbonated water may vary by more than a factor of five. Fastest dissolution has been recorded where the percentage of insolubles is nil and where it was as great as 14%, although most investigations show a clear positive correlation between percentage CaO and dissolution rate.

grain size and texture The finer its grain size the more soluble a rock tends to be because the area of exposed grain surfaces is increased. Many studies have found that micrites or biomicrites are most soluble and that solubility decreases substantially where sparite (coarse crystals) becomes greater than 40 50% by volume (e.g. Sweeting and Sweeting 1969; Maire 1990). In a discriminant analysis of ten different purity, grain size, texture and porosity measures applied to

cavernous limestones and dolomites in Missouri, Dreiss (1982) found grain size to be the most significant, the finer grained rocks being more soluble. However, the finest grained limestones are sometimes less soluble if the grains are uniform in their size and packing because surfaces are then smooth, with exposed grain areas being reduced; such rocks are termed *porcellaneous* in texture. The Porcellaneous Band is a distinctive, very fine-grained micrite that obstructs cave genesis and perches passages in Gaping Ghyll Cave, England (Glover 1974).

porosity

- **Porosity**: variation in the nature, scale and distribution of voids within the rock

Sedimentologists define *primary* porosity as that created during deposition of the rock (i.e. created first) and secondary porosity as that produced during diagenesis. For hydrogeologists, all types of bulk rock porosity are primary. Fracture (or fissure) and channel (or conduit) porosity are considered to be *secondary* and *tertiary* respectively. In general it is true to write that karst hydrogeology and geomorphology are concerned largely or entirely with large-scale, interconnected, non-fabric-selective porosity (penetrable bedding planes and fractures, dis- solutional channels and caverns in rocks where the fabric-selective porosity is low (¡15%). This is because the hydraulic pressure gradients experienced also tend to be low, insufficient to drive significant quantities of fluids through the tiny throats separating poorly connected pores within the rock fabric itself.

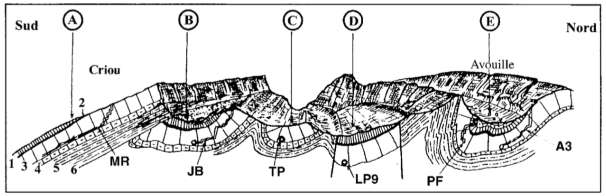
Rock strength At small scale the strength of a rock is a function of its interparticle bonding. Such strength can be measured in the laboratory by compression, shear or hammer tests. At larger scale in sedimentary rocks strength is more obviously a function of the density of fissures such as joints or bedding planes. This kind of strength is not amenable to machine testing. A majority of carbonate rocks are quite strong and will support vertical cliffs and cave roofs for long periods unless they are thinly bedded and highly fissured. Some chalks are too weak to support big cliffs or caves of enterable dimensions.

Interbedded clastic rocks Many carbonate, sulphate and salt formations are without significant clastic interbeds for thicknesses of tens, hundreds or even several thousands of metres. These strata generally yield the best karst development. However, the geological record contains many more examples of formations with frequent beds of clay, shale, sandstone or coal between the soluble strata. These grade to shales, etc., with limestone interbeds, etc. and the geomorphological and hydrological systems grade from wholly karstic to non-karstic. Groundwater penetration to initiate karst is often easier at the contact between limestone and shale than it is at bedding planes, joints, etc. within limestone.

Bedding planes, joints and faults

- **Bedding planes** Bedding or parting planes in sedimentary rocks are produced by some change in sedimentation or by its temporary interruption. The change may be minor, e.g. from one size of carbonate grain to another a little larger. Major changes are represented by large differences in grain size and, more often, by the introduction of clay by a storm or flood, etc. that leaves a paper-thin or thicker parting between the successive regular carbonate layers.
- **Joints** Joints are simple pull-apart breaks in previously consolidated (or partly consolidated) rocks. In shear fractures there is some lateral or vertical displacement but it is too small to be recognized in hand specimens (Barton and Stephansson 1990). Fracturing occurs during diagenesis, later tectonism, erosional loading and unloading. It is caused by tensional or shear forces.
- **Faults** Faults are fractures with some displacement of rock up, down and/or laterally. Where this is less than about 1 cm they may be considered to grade into shear fractures or joints. At the greatest, vertical displacement extends several kilometres while lateral displacement may amount to $10^2 - 10^3$ km. The hydrogeological and speleogenetic role of faults and fracture traces varies with their type, size, and the diagenetic record since they were formed. At one extreme they may direct the predominant flow in a groundwater basin, like a trunk river channel on the surface, or have sinkholes aligned along them. Large normal and reversed faults often have low permeability, however, due to clayey crush fillings (mylonite) or precipitated calcite in them, and thus serve as barriers.

Folding of the strata Rock folding requires plastic deformation and so tends to occur at great depth where lithostatic pressures are high. The amplitude of folds ranges from a few centimetres to several kilometres. High folds may extend for hun- dreds of kilometres along the strike. Tensional forces tend to create strike-aligned master joint sets at the crests of anticlines and in the troughs of synclines. Differential slipping of the bedding planes is often more important on the flanks. Where karstic beds or formations are mingled with siliciclastic strata, tilting and folding often create conditions of artesian confinement. Meteoric recharge water entering the karst rock becomes trapped beneath impermeable seals and may circulate slowly to remote springs. The longest karst groundwater flow systems that are known are created in this manner.



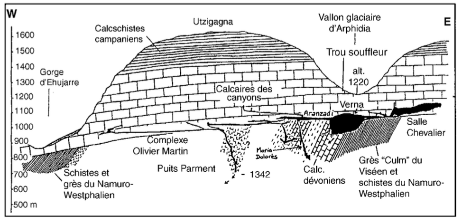


Figure 5: Two examples from France of karst development in complex geological structures. (Upper) The folded Alps at Samoens. Numbers identify individual formations, from lower Cretaceous (6) to mid-Cretaceous (1) in age; number 3, Urgonian, is the principal karst limestone. Letters identify individual homoclinal and synclinal structures. Re seau Mirolda (MR) and Re seau Jean Bernard (JB) are two of the worlds deepest explored caves (see Figure 7.1). TP, LP9, PF and A3 are other prominent springs or shaft systems in the other structures. (Lower) Re seau Pierre St Martin is another deep system that is entered in the Alpine zone on the Franco-Spanish border in the Pyrenees. It passes through a thick, gently dipping limestone formation of late Cretaceous age, to ramify along and penetrate below a grossly unconformable contact with underlying Devonian and Carboniferous strata. Salle Verna is one of the largest known cave chambers. Reproduced with permission from *Maire, R, La Haute Montagne Calcaire. Karstologia, Memoire 3, 731 p, 1990.*

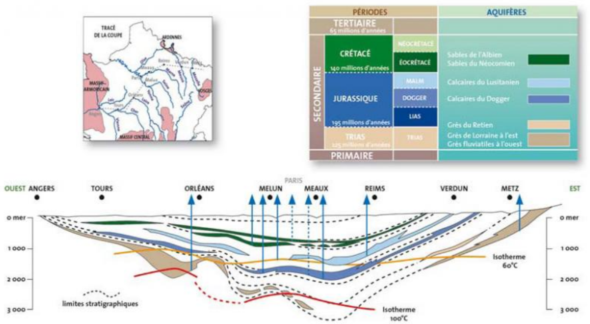


Figure 6: The deep karstic aquifers of the parisian basin are of predominantly from the Jurassic period: they are confined under early Cretaceous sandstones in green. Several artesian wells drain this karstified aquifer over the basin. Reproduced from *http://www.geothermie-perspectives.fr/article/aquiferes-profonds-bassin-parisien*.

4 Hydro-geological concepts

Definitions

- aquifer: A rock formation is regarded to be an aquifer when it can store, transmit and yield economically significant amounts of water. Karst aquifers like those of other rocks may be confined, unconfined and perched (Figure 5.1).
- aquiclude: Other rocks such as clay and mudstone, may absorb large amounts of water, but when saturated are unable to transmit it in significant amounts. These are termed aquicludes.
- aquitard: A relatively less permeable bed in an otherwise highly permeable sequence is referred to as an aquitard; a calcareous sandstone in a karstified limestone sequence could provide such a case.
- porosity: A distinction is made between the porosity n of a rock and its effective porosity ne. Porosity is defined as the ratio of the aggregate volume of pores Vp to the total bulk volume Vb of the rock. Effective porosity refers only to those voids that are hydrologically interconnected. For a fully saturated rock, it can be expressed as the ratio of the aggregate volume of gravitation water that will drain from the rock Va to the total bulk volume of the rock Vb. Effective porosity is influenced by pore size.

  Finally porosity is affected by reference volume considered: clearly caves are not found in hand specimens or boreholes.

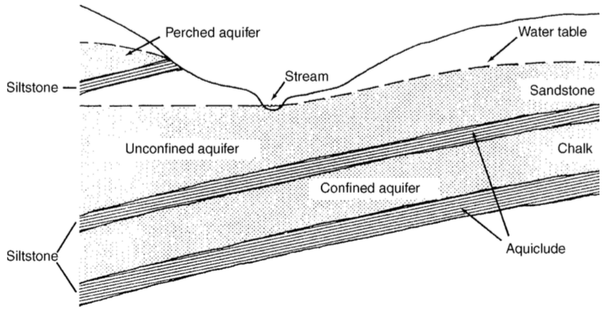


Figure 7: Confined, unconfined and perched aquifers. Reproduced from *Dunne, T.R. and L.B. Leopold, Water in Environmental Planning, San Francisco 1978 Freeman..*

	Proportion of storage (%)		
Location	Matrix	Fracture	Channel
Smithville, Ontario, Canada	99.7	0.3	0.05
Mammoth Cave, Kentucky	96.4	1.2	2.4
The Chalk, England	99.9	0.03	0.07
Nohoch Nah Chich, Yucatan, Mexico	96.6	0.6	2.8

Figure 8: Fractions of storage contributed by matrix, fracture and channel (conduit) porosity in four carbonate aquifers. Reproduced *from Worthington, S. R. H., Ford, D. C. and Beddows, P. A., Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (Eds.), Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, 220223, 2000*

5 Controls on Karst aquifer development

homogeneity karst aquifers can have a complex porosity that is difficult to describe. This contrasts with well- sorted sand and gravel aquifers that have comparatively consistent values for porosity and permeability through- out their extent.

Under these latter conditions in a simple porous medium hydraulic conductivity K is independent of position within the formation and the aquifer is then considered homogeneous. But if K varies with location within the formation then it is considered heterogeneous.

If hydraulic conductivity is the same regardless of direction of measurement, then the aquifer is defined as isotropic, but if K varies with direction then it is anisotropic. A characteristic of karst aquifers is that they become increasingly heterogeneous and anisotropic with time. In an unkarstified rock, heterogeneity within the permeability field may be perhaps 1 to 50, whereas karstification may increase it to perhaps 1 to 1 million.

boundary conditions Boundary conditions are determined especially by geological, topographic, climatic and biological influences, which control sites and quantities of recharge and discharge, including altitude of recharge, altitude of discharge, rainfall and infiltration rate. Thus one may identify flow boundaries, where flow either enters or leaves the karst, as well as no-flow boundaries, such as provided by an aquiclude beneath the aquifer or a down-faulted impervious block along one side of the karst.

For a given set of boundary conditions, hydraulic gradient and specific discharge can be estimated. But in the long-term the very process of karst groundwater circulation modifies effective porosity, specific storage and hydraulic conductivity, and lowering of the outlet spring modifies hydraulic potential. Consequently, the karst circulation system undergoes more feed-back giving rise to

Location	Proportion of flow (%)		
	Matrix	Fracture	Channel
Smithville, Ontario, Canada	0.000003	3.0	97.0
Mammoth Cave, Kentucky	0.00	0.3	99.7
The Chalk, England	0.02	6.0	94.0
Nohoch Nah Chich, Yucatan, Mexico	0.02	0.2	99.7

Figure 9: Reproduced from *Worthington, S. R. H., Ford, D. C. and Beddows, P. A., Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In Klimchouk, A.B., Ford, D.C., Palmer, A.N. and Dreybrodt, W. (Eds.), Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, 220223, 2000*

continuous self-adjustment than occurs in any other type of groundwater system.

The most abrupt changes to boundary conditions are brought about by geomorphologically rapid events (often associated with climatic change) that culminate in major alterations to hydraulic gradient because of modifications to outflow conditions. For example, valley deepening by glaciation increases the hydraulic potential of the system, whereas submergence of coastal springs by glacio- eustatic sea-level rise reduces it.

input control When discussing input control in section 5.2 it was noted that recharge into karst can be autogenic or allogenic (Figure 4.1). Autogenic recharge is often diffuse and slow (although it is more concentrated and rapid when focused by dolines), whereas allogenic recharge normally occurs as concentrated, very rapid point inputs of sinking streams from adjacent non-karst terrains. It follows therefore that recharge is highly variable in space, and because of the changeability of weather and climate it is also highly variable in time.

output control 1. Free Draining Springs (Figure 5.17a and b). In these cases, the karst rock slopes towards and lies above the adjacent valley, into which karst water drains freely under gravity. The karst system is entirely or dom- inantly vadose, and is sometimes termed shallow karst (Bo gli 1980). Complications may arise where the underlying impermeable rock is folded or has an irregular surface, because then subterranean ponding can occur with the consequent development of isolated phreatic zones. 2. Dammed Springs (Figure 5.17ce). These are the most common type of karst springs. They result from the location of a major barrier in the path of underground drainage. Impoundment may be by another lithology, either faulted or in conformable contact, or be caused by valley aggradation, such as by glacio- fluvial deposits. The denser

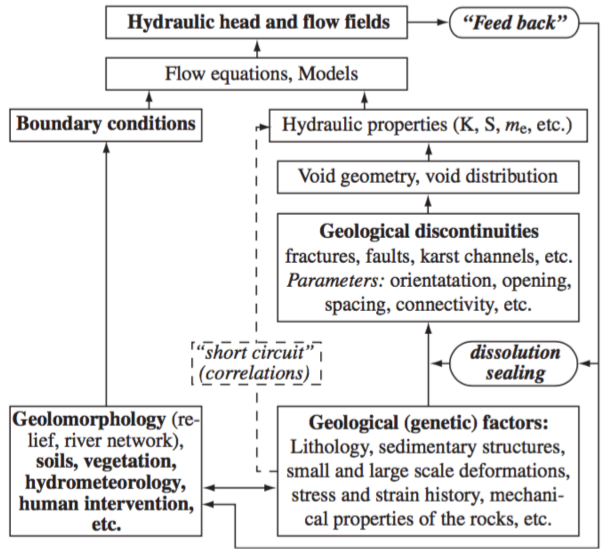


Figure 10: Schematic representation of the relations between groundwater flow field, hydraulic properties and geological factors in karst aquifers. Reproduced from *Kiraly, L., Karstifica- tion and groundwater flow. In Gabrovsek, F. (Ed.) Evolution of Karst: from Prekarst to Cessation. Postojna-Ljubljana: Institut za raziskovanje krasa, ZRC SAZU, 155190, 2002.*

salt water of the sea also forms a barrier to freshwater outflow. In each case, temporary overflow springs may form in response to high water tables. The type of cave upstream of the spring will determine whether its discharge spills from a flat passage developed close to the water table or wells up from a great depth within the phreatic zone. Thus a dammed karst outflow site typically consists of a main low-water spring with one or more associated high-water relief springs; Smart (1983a, b) has termed these overflowunderflow systems. In some situations water escapes via a distributary system of several springs at about the same level, as described by Quinlan and Ewers (1981) in the case of the Sinkhole PlainMammoth CaveGreen River system. 3. Confined Springs (Figure 5.17f and g). Artesian conditions prevail where karst rocks are confined by an overlying impervious formation. Fault planes some- times provide exit routes for the water; elsewhere it may escape where the caprock is breached by erosion. Since the emerging water is usually under hydrostatic pressure, an updomed turbulent boil is particularly characteristic of spring pools in this class, although dammed springs that are semi-confined by a particu- larly thick bed may also boil, especially during flood. The discharge capacity of the artesian spring determines the elevation of the potentiometric surface in the aquifer and hence the depth of the phreatic zone.

5.3 ENERGY SUPPLY AND FLOW-NETWORK DEVELOPMENT
The development of flow paths in karst aquifers depends upon the energy supply available and its spatial distribution. This derives mainly from:

- the throughput volume of water;
- the difference in elevation between the recharge and discharge areas;
- the spatial distribution of recharge, i.e. on whether it is evenly distributed (as is characteristic of diffuse autogenic recharge) or is focused (as is characteristic of allogenic point recharge);
- the aggressivity of the recharging waters.

5.1 mechanical work

Most of this power is dissipated in overcoming fluid shear resistance to flow; so relatively little energy surplus is available for erosion and transport by the stream. The velocity of water flow in karst varies considerably both within a given aquifer and between aquifers. Within a given aquifer and for a given hydraulic gradient, it varies over several orders of magnitude between water movement in the matrix, fissures and conduits, as indi- cated by hydraulic conductivity values.

5.2 Other remarks on flow network development

. We may conclude from the above discussion that, given sufficient hydraulic potential, the style of recharge has a strong influence on the occurrence, density

and size of conduit permeability (although not on the process of conduit development). The following end-member con- ditions occur in the development of flow networks. 1. Diffuse recharge onto a carbonate rock with high primary porosity, e.g.rain on aeolian calcarenite or uplifted coral, when few or no karst conduits form until subaerial diagenesis (case hardening) focuses recharge; 2. Widely spaced, large volume, point recharge into a dense carbonate rock with well-developed fissures, e.g. recharge windows in a breached caprock over massive limestones, when a few very large diameter conduits form commensurate in size with their throughput discharge. Competition is limited to corridors down- stream of recharge points that are separated by unkar- stified rock beneath the umbrella of still intact caprock. Doline karst falls between these two recharge extremes because, although the recharge is autogenic in origin, the flow is internally focused through a large number of point inputs of modest volume

6 Karst aquifer analysis

defining the limits of the system

Water balance of the aquifer The two most important problems encountered in calculating the water balance in karst areas are, firstly, determination of effective precipitation and, secondly, determination of the catchment boundaries, not least because in karst the recharge area often varies in time depending on groundwater levels.

7 Speleogenesis

In this section we examine the principles that govern the propagation of solution conduits through the fissures (a term encom- passing bedding planes and joint and fault fractures) and down the gradient. Before dissolution begins, minimum apertures of connected voids in the fissures are small, 10mm to 1mm, and their aggregate volume is also small. Available runoff thus is readily able to fill them and the water table is consequently at or near the ground surface.

Annable,W.K. (2003) Numerical analysis of conduit evolution in karstic aquifers. Univ. of Waterloo PhD thesis, 139 pp.

In every experiment one tube chances to grow ahead of others. It deforms the equipotential field, reducing the gradients at the solution fronts of its competitors (sub- sidiaries) and thus slowing their rates of advance. When this principal or victor tube attains the output bound- ary, three important effects can occur in succession, and rapidly when compared with the slow advance of the proto-caves previously.

First, kinetic breakthrough is quickly achieved, accelerating the rate of enlargement of the tube (Chapter 3).

Second, there is hydrodynamic breakthrough if/when flow becomes turbulent, destroying Darcy flow conditions (Chapter 5).

Third, when suffi- ciently large the tube (now a regular karst conduit) can create a trough in the water table. The equipotential field is reoriented onto it, creating yet greater inhomogeneity.

Pendants, half tubes Anastomoses may be independent forms or, with pendants or half-tubes, can constitute a gradational set of independent anastomoses are the subsidiaries of primary tubes. They may continue to extend throughout the phreatic history of a cave. The frequency of their divergence and convergence is a function of properties of the fissure and of its gradient. Vertical joints, steeply dipping bedding planes, etc. show relatively little anastomosing. Excellent anastomoses can originate late in the history of a cave where water from an established large passage opens up hitherto impenetrable bedding planes or fractures 252 Karst hydrogeology and geomorphology (i.e. effective fissure frequency is increased). This is best seen where stratal dip is low. Often it appears that the penetration is by floodwater, e.g. into bedding planes overlying the original ceiling in many places in Mammoth Cave, Kentucky. Pendants (Ger. deckenkarren) are residual pillars of rock between anastomosing channels. They can develop in bedding planes and joints, where they are gradational from anastomoses. They also appear on unfissured ero- sional surfaces such as cave walls where they developed at the contact with rather impermeable clastic fill. They may be as much as 1 m long and can cover tens of square metres of cave wall. They can be carved by water draining up, down or along the contact. Very diverse and complex patterns can be created.

solution pockets Solution pockets are one of the most attractive features of phreatic caves and one which most surprises geomor- phologists who are not cave specialists. They may occur in floors and walls but are best developed in the roofs (Figure 7.38). They are varieties of blind pockets that extend as much as 3040 m upwards. Many terminate in a tight joint or microjoint that they have followed during expansion. They may be single or multiple features, rounded like conventional cupolas, or elongated along the guiding fracture. Some are multicuspate and transitional to honeycomb structure; these develop particularly well in vuggy rock, e.g. reefs. Some pockets are complexly multicuspate but have neither vugs nor joints to guide them. Osborne (2004) gives a comprehensive review. It is now well established that pockets can be created by condensation corrosion in vadose conditions. These are considered in section 7.11. In relict phreatic caves, however, the majority of solution pockets will generally be of phreatic origin except, possibly, in periodically wet dry entrance zones or climatic chimney sites (section 7.11). Several different mechanisms have been proposed to explain these. Most widely accepted is dissolution by cellular convection in near-static waters, driven either by thermal gradients or by solute density gradients.

vadose shafts and canyons Shafts created by falling water are known up to 640 m in depth. Many of the deepest caves are of the primary or invasion

vadose types and consist of spacious vertical shafts linked by short sections of constricted meander canyon (Figure 7.17). The form of shafts ranges between two extremes. The first is that created by a powerful waterfall. The water mass itself will tend to create a simple circular or elliptical cross-section for its fall but this is often mod- ified. Breccia is swept out of any guiding fault, to form a parallel wall shaft. A plunge pool undercuts the walls which, therefore, tend to display irregular taper rather than parallelism near the base. Spray at all levels attacks weaknesses to produce local block fall. Many shafts are highly irregular in form as a result of these effects.

The other extreme is that of the domepit created by a relatively slow and steady flow (Figure 7.42). This may occur as leakages at the base of the epikarst (Figure 5.28) or below point-recharge depressions (Figure 5.16a), and is able to attack drained joints in the vadose zone. In the ideal condition the flow is never large enough to detach and fall free in the vertical plane. Instead, it is retained against the rock by surface tension. It disperses radially from an input point and carves a set of dissolutional flutings down the walls. The pit has a symmetric dome at the top (where the first dispersion occurs) and is circular below. This kind of pit is best developed where strata are flat-lying and joints are few and with high resistance. This is the case in the Mammoth Cave area of Kentucky, where the form was first analysed (e.g. Merrill 1960). There is a sandstone caprock there which functions as an additional regulator to maintain a steady, filming flow of aggressive water. Many shafts show a mixture of the two forms, with waterfall features down the fall line and fluting of farther parts of the perimeter.

dissolutional scallops Dissolutional scallops are spoon-shaped scoops (Figure 7.44). They occur in packed patterns so that individuals are usually overlapping and incomplete. They are common on walls, floors and ceilings in caves. Inspection shows that they are smallest where flow is fastest, e.g. in a venturi. Measurement reveals that their length is log- normally distributed, usually with relatively little statis- tical dispersion. Most scallops are 0.520cm in length but they range up to 2 m. Width is 50% of length. In the right conditions it is evident that patterns of scallops of characteristic length extend to colonize all available surfaces. They are the stable form of these surfaces in the prevailing conditions. It has long been recognized that many scallops are strongly asymmetrical in the direction of flow. The perimeter is steeper at the upstream end, i.e. facing downstream. Scalloping is common in limestone, gypsum and salt caves. However, not all limestone regions display it and it is quite rare in dolomite caves. This is because uniform rock grain size is necessary for good scalloping, and a lack of heterogeneities such as insoluble fragments or open pores. Many limestones and dolomites are too heterogeneous to develop scalloping, e.g. reef rocks.

Breakdown in caves The largest cave breakdowns are failures in the tension dome. These are most regular in form where strata are well-bedded and horizontal. As a consequence, this is the situation used in basic analysis. Bonding across bedding planes is presumed to be much weaker than strength within the beds; therefore, the beds sag elastically away from each other. Each bed then can be considered to function as a separate beam if it extends the full width of the passage, or as a cantilever where it is fractured through (e.g. by a wide central joint) or does not extend the full width. Fractured spans are usually much stronger than simple cantilevers. Cliffs at the surface most often fail as cantilevers.

References