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Dynamics of cave development by allogenic water

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Abstract

Streams that drain from non-karstic surfaces tend to have great discharge fluctuations and low concentrations of dissolved solids. Where these streams encounter karstic rocks they can form caves with hydraulic and chemical dynamics quite different from those fed by autogenic recharge (e.g. through dolines). In either case, caves form only along those paths in which the discharge can increase with time. Only a few favorable paths achieve this goal, while the others stagnate with small and diminishing enlargement rates. Caves in carbonate rocks that are fed by allogenic streams have a relatively short inception period, after which the mean-annual rate of dissolutional wall retreat is typically about 0.01 cm/yr. Most of the annual growth takes place during a few major floods that occupy only a small fraction of the year. Local growth rates can be enhanced by abrasion from sediment.

During floods, highly aggressive water is delivered rapidly to points deep within the karst aquifer. As flood discharge increases, cave streams become ponded by constrictions caused by detrital sediment, insoluble beds, or collapse material. The head loss across a constriction varies with the fifth power of the diameter ratio under pipe-full conditions. Head loss also increases with the square of the discharge. Because the discharge during a flood rises by several orders of magnitude, the head loss across constrictions can increase enormously, causing water to fill parts of the cave under considerable pressure. This highly aggressive water is injected into all available openings in the surrounding bedrock, enlarging them at a rapid and nearly uniform rate. Depending on the structural nature of the bedrock, a dense array of blind fissures, pockets, anastomoses, or spongework is formed. Many such caves develop traversable mazes that serve either as bypass routes around constrictions, or as "karst annexes", which store and later release floodwaters. Many features that are sometimes attributed to slow phreatic flow or mixing corrosion are actually generated by ponded floodwaters. In caves that experience severe flooding, adjacent fissures or bypass routes with initial widths at least 0.01 cm can grow to traversable size within 10,000 years.

Keywords: speleogenesis, allogenic recharge to karst

Introduction

Allogenic drainage into ponors from non-karstic rocks tends to be highly aggressive toward carbonate and also varies greatly in discharge. Caves formed by this water have a much more dynamic developmental history that those formed by autogenic recharge from a karst surface. They represent the underground aspect of "border corrosion" described by Gams (1965). Not only does allogenic recharge tend to enlarge caves more rapidly than autogenic water, but it also can determine their entire passage pattern. Solution pockets, anastomoses, blind fissures, and crude mazes are commonly superimposed on the primary cave passages. Some caves formed in this way consist entirely of network or anastomotic mazes. Severe flooding is characteristic of most of these caves. Cave enlargement by floodwaters can therefore be considered epiphreatic. However, floodwater inundations are quite different from the slow water-table fluctuations typical of other hydrologic settings. Floodwater is the most dynamic member in the broad spectrum of epiphreatic conditions.

Dissolution rates and conduit competition

Rates of limestone dissolution have been measured by various researchers (e.g. Rauch and White, 1979; Plummer and Wigley, 1976; Plummer et al., 1978; Sjöberg, 1976; Sjöberg and Rickard, 1984; Buhmann and Dreybrodt, 1985a, 1985b). At normal groundwater temperatures and CO_2 partial pressures, dissolution rates remain high over a broad range of calcite concentrations but drops rapidly to very low values beyond about 70% saturation (see Fig. 1). Using rates recalculated from the experimental data of Plummer et al.

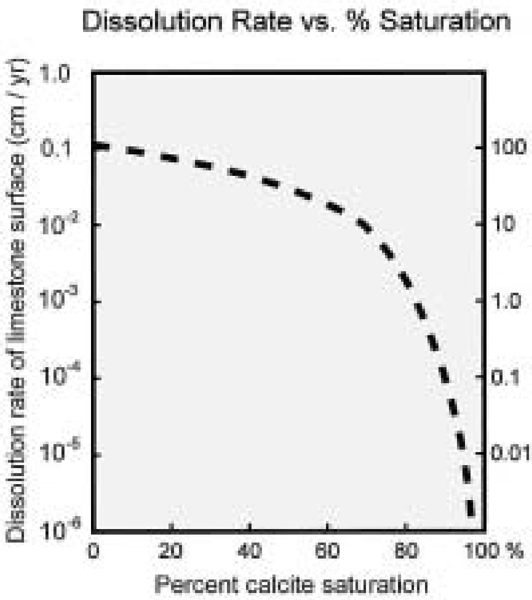

Fig. 1. Rates of limestone dissolution vs. percent calcite saturation at 10^{o} C and 0.01 atm CO_2 partial pressure (calculated from references in text).

(1978), Palmer (1981, 1991) used finite-difference analysis to show how the mean enlargement rate in conduits responds to passage size, discharge, flow distance, and water chemistry (Fig. 2). Discharge (Q) and flow length (L) have identical but opposite effects on rate of wall retreat and can be combined as a ratio (Q/L) on the graph. Enlargement rates are proportional to Q/L, and the only way for a specific passage to increase its enlargement rate is to gain discharge. However, there is a limit to the solutional growth rate, determined by kinetics, beyond which the discharge has little effect. This is because in carbonate rocks the rate is limited by the reaction rate at the solid surface, rather than by mass transport within the water (see Plummer and Wigley, 1976). The maximum rate is typically about 0.01-0.1 cm/yr, depending on the local water chemistry. These figures are compatible with field measurements in cave streams (e.g. High, 1970; Coward, 1975; Lauritzen, 1990) and with the results of recent numerical and analytical modeling (e.g. Dreybrodt, 1996; Gabrovšek, 2000).

Fig. 2 shows a few representative points during the early development of a karst aquifer, when small amounts of water pass through narrow openings. The solutional enlargement rate differs greatly among the various flow routes (zone 1 in Fig. 2). This holds true whether the recharge is allogenic or autogenic. It is clear that the growth rate of any given conduit can increase only if the discharge increases. As dolines and ponors develop, the paths fed by them enlarge rapidly (e.g. paths A, B, and C), while other routes stagnate with low or even diminishing enlargement rates (e.g. D and E). Only those paths that gain discharge with time are able to grow into caves. The favored ones reach the maximum enlargement rate (zone 2 in Fig. 2), after which all passages with similar water chemistry grow at roughly the same rate. Enlargement rates vary with discharge (e.g. on a seasonal basis), because the water entering the aquifer tends to be more aggressive during high flow.

This process is accelerated where the karst aquifer is fed by allogenic streams. Only a few major flow routes reach the maximum growth rate, and they enlarge rather rapidly because the water feeding them tends to be more aggressive. Also, a steep hydraulic gradient is maintained by the large flow of water from ponors. Maximum growth rate in mature conduits is not limited by dissolution, since mechanical erosion aided by coarse sediment load can approach or even exceed the effect of dissolution during floods (Newson, 1971; Smith and Newson, 1974).

The flow distance (L) in Fig. 2 needs some explanation. This is the distance from where aggressive water first enters a particular conduit or other opening. In Fig. 2 an initial saturation ratio of zero is assumed (i.e. no dissolved carbonate). However, the saturation ratio is usually considerably higher, even in streams that drain relatively insoluble rocks. The shape of the diagram is still valid for water of any aggressiveness, but the maximum dissolution rate is smaller if the saturation ratio is greater than zero (see Palmer, 1991).

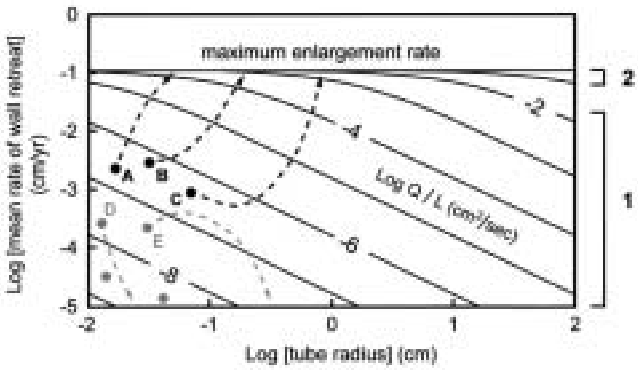

Fig. 2. Mean rates of solutional wall retreat in limestone conduits (from Palmer, 1991). Q/L = ratio of discharge to flow distance. Early stages of karst aquifer development are represented by zone 1, which includes a great variety of dissolution rates. Q increases with time in only a few conduits, allowing them to grow at a faster rate (A, B, C), while others stagnate at low and usually diminishing enlargement rates. Only those that reach the maximum rate (zone 2) grow into traversable caves. Graphs are similar for conduits with non-circular cross sections, but the lines have gentler slopes.

Fig. 2 applies mainly to relatively pure limestones. In dolomites the disparity in enlargement rates is even greater, and although the maximum rate in zone 2 is still valid, the rates in zone 1 are lower. The figure does not apply to evaporites, because their dissolution rates are higher and are proportional to flow velocity.

Floodwater dynamics

In the early stages of conduit development by allogenic streams, subsurface flow is limited because floodwaters simply overflow onto the surface. The impact of allogenic streams on cave patterns is greatest when the conduits have enlarged sufficiently to carry all (or most) floodwater. By this time the caves are partly air-filled, because the low-flow discharge is unable to keep them filled with water. Initially most such caves consist of only a few passages, owing to the limited number of inputs.

During floods, the caves carry highly aggressive water deep into the karst aquifer (Fig. 3). Floodwaters tend to pond behind constrictions in the stream passages. This is typical where there has been collapse, accumulation of sediment, or a narrowing caused by relatively insoluble rock. In turbulent flow, head loss is proportional to the fifth power of the passage diameter. Therefore, if one water-filled passage has only half the diameter of another, the smaller one will require a hydraulic gradient about 32 times greater to transmit the same discharge. The head loss also increases with the square of the discharge. During low flow there is generally very little ponding at constrictions. However, the discharge rises by several orders of magnitude during a typical flood, and so the head loss across constrictions increases enormously, causing water to back up and to fill parts of the cave under great pressure (Fig. 4). Rises in water level of more than 100 m are common in some caves fed by allogenic streams.

This water has been carried in from the surface very rapidly and is highly aggressive. In areas of ponding it is injected into all available openings in the surrounding bedrock. Because of the steep gradients and short flow distances, these openings are enlarged at a rapid and nearly uniform rate at the top of the growth-rate graph (Fig. 5). Cave enlargement by allogenic floodwater is considerably faster than nearly all other speleogenetic processes. In caves that experience severe flooding by aggressive water, fractures with initial widths at least 0.01 cm can grow to traversable size within 10,000 years (Palmer, 1991).

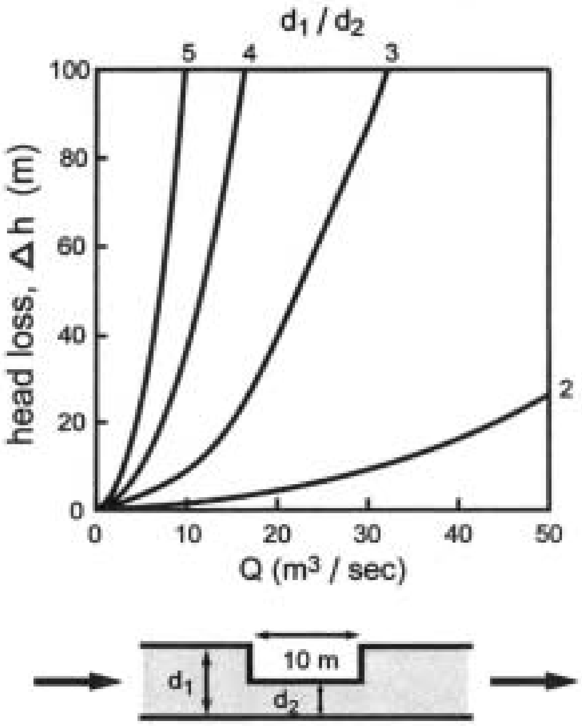

Fig. 3. Head loss across a 10-meter-long constriction in a water-filled conduit, at various discharges (Q) and diameter ratios (d_1/d_2). During floods, water can pond to great depths in the upstream parts of a cave because of such constrictions.

Because the floodwater retains most of its aggressiveness as it passes through the cave, the factor L in Fig. 5 applies essentially to the distance into the surrounding fissures that receive the injected water. The maximum enlargement rate will be slightly smaller than that shown in Fig. 2, because the saturation ratio is not zero.

Effects on cave morphology

Cave enlargement by floodwater can be recognized by a variety of features, even in relict cave fragments where the original hydrologic context is unclear:

- Diversion routes around constrictions. These typically have irregular profiles and ungraded intersections (i.e., the passage floors and ceilings of intersecting passages are at different levels). They may have a maze pattern, but often consist only of a few alternate routes.

- Blind fissures and network mazes. These are typical of highly fractured bedrock, especially at shallow depth below the surface. Such passages may serve as "karst annexes" (Mangin, 1975), which receive floodwaters during rising flow and release it more slowly as the flood subsides.

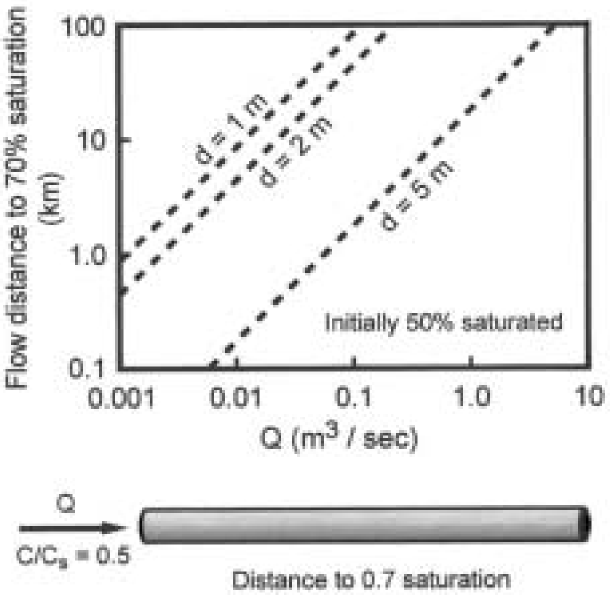

Fig. 4. Distance of penetration of highly aggressive flow into water-filled conduits. In this example, incoming allogenic water is assumed to be already 50% saturated (concentration / saturation concentration = 0.5). The graphs show the distance required for the water to reach only 70% saturation, beyond which the dissolution rate begins to decrease rapidly. Variations with discharge (Q) and passage diameter (d) are shown. A typical cave stream can penetrate a great distance while retaining most of its initial aggressiveness.

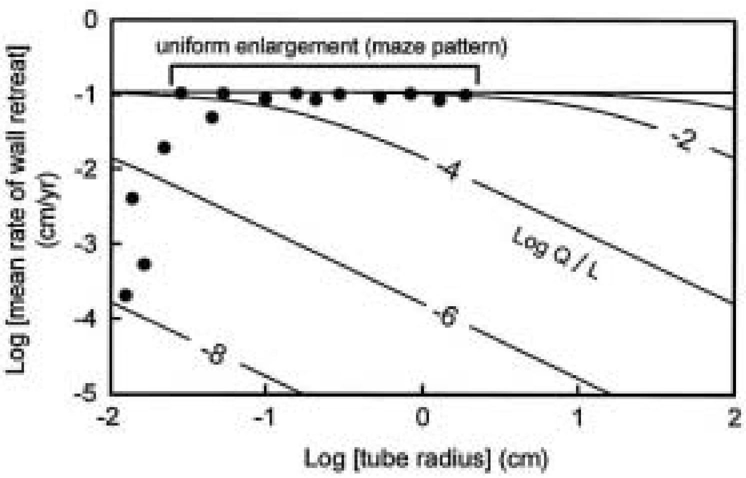

Fig. 5. Same as Fig. 2, but under floodwater conditions, when aggressive water is injected into many openings for short distances with steep hydraulic gradients (i.e. large Q/L ratios). All openings larger than a certain minimum size are enlarged at similar rates near the top of the diagram, producing maze patterns.

- Anastomoses and anastomotic cave patterns. Anastomoses are common where bedding-plane partings are the dominant openings, and where there have been frequent fluctuations in water level. Not all anastomoses are formed by floodwater, however: some are remnants of the initial flow paths that eventually developed into conduits (see Ewers, 1966). Anastomoses of this second type are common only in the upstream ends of flow paths, where the water is aggressive and the flow distance is short. In this way their origin is chemically identical (see Fig. 5). Anastomotic passages form either two-dimensional or three-dimensional arrays of tubes, in which many or all can be simultaneously water-filled and enlarged during floods. For this reason these systems are sometimes called “underground deltas” (Maire, 1990).

- Solution pockets and spongework. Spongework forms where no significant fractures or partings are present. Once formed, ceiling pockets can be enlarged by turbulent eddies (Slabe, 1995) or by elevated CO_2 partial pressure resulting from air compression by rising water (Lismonde, 2000).

- Large contrasts in the grain size and distribution of sediments. Floodwater conditions usually involve great variations in flow velocity, with the result that large cobbles and boulders occupy the main stream routes, and fine sediment fills regions of static flooding. In local areas, high-velocity floodwater can prevent sediment from depositing at all.

Many of the dissolution features described here are often attributed to slow phreatic flow or mixing corrosion. Maze patterns, solution pockets, blind fissures, and anastomoses have all been used by various authors as indicators of phreatic cave development. In a sense they are correct, but not in the way they envisioned. These forms are best explained as the result of intermittent flooding above the low-flow water table. For example, in the dynamic hydrologic conditions of alpine karst, many tubular conduits that are often assumed to be phreatic have been shown by Choppy (1991) and

Audra (1994) to be actually the product of fluctuations in water level within the epiphreatic zone.

Most floodwater enlargement of existing passages is upward and lateral if the floor is armored by sediment. Although periodically refreshed interstitial water within sediment can dissolve the underlying bedrock, the rapid dissolution that takes place during high flow is apparently exerted most vigorously on the bare bedrock surfaces. Some deep fissures can form below the general level of the main cave streams, but these are uncommon.

Although mazes are a typical result of cave development by allogenic floodwaters, most large maze caves do not share this origin (e.g. the large network caves of Ukraine and the Black Hills of South Dakota). But the simultaneous enlargement of many alternate flow paths shown in Fig. 5 is valid for these caves as well. The large Q/L ratio necessary for maze origin is the result of small flow distances (L), so all significant openings are enlarged simultaneously. These conditions apply to leakage from overlying or underlying insoluble rocks, and also to mixing or H_2S oxidation where aggressiveness is produced right within the aquifer, resulting in cave development at small L values.

Examples

Several examples from the USA are described here to illustrate the variety of patterns produced by allogenic recharge in contact-karst settings (see locations in Fig. 6).

Blue Spring Cave, Indiana, is fed mostly by autogenic recharge, but it can be used as a standard for comparison with the extreme floodwater examples that follow. It is almost entirely a joint-influenced branchwork cave, but it contains two prominent maze sections where blockage of its large main stream has caused local ponding and diversion of water (Fig. 7). The catchment area for the cave is at least 35 km^2, which provides enough flow that the hydraulic conditions in these two constricted areas are, in a modest way, similar to those in caves fed by allogenic recharge. Blue Spring Cave is located in the Carboniferous Salem Limestone in an extensive low-relief sinkhole plain. The Salem dips only about 0.3 degree to the west. In the main stream passage, at a junction with a large tributary, extensive collapse has triggered local flooding and development of a network diversion maze around the breakdown (Palmer, 1991). With less than 25 m of overlying rock, the collapse has opened subsidiary fractures in the bedrock that have orientations quite different from those that guided the main passages (see inset **a** in Fig. 7). Passages in the network are highly scalloped, indicating high-velocity flow. This maze is located in the typical massive facies of the Salem Limestone. Farther upstream, in a bedded facies, chert beds have caused local passage constrictions, resulting in an anastomotic maze (inset **b** in Fig. 7). These passages are also prominently scalloped by high-velocity water. Floodwater features are uncommon elsewhere in the cave. The relation between flooding and maze development is clear.

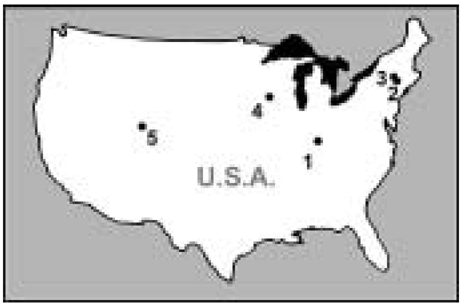

Fig. 6. Locations of caves described in this paper. (1) Blue Spring Cave, Indiana; (2) Onesquethaw Cave, New York; (3) = Skull Cave, New York; (4) Mystery Cave, Minnesota; (5) Big Brush Creek Cave, Utah.

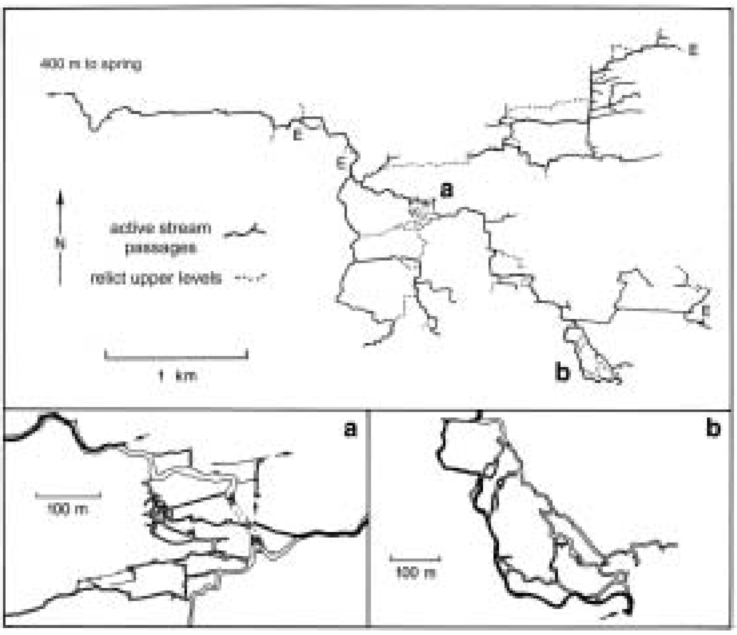

Fig. 7. Network and anastomotic mazes superimposed on the branchwork pattern of Blue Spring Cave, Indiana (from Palmer, 1991).

Passages in the network maze (Fig. 7a) are narrow fissures that are concentrated at the same level as nearby cave streams, and extending an average of 2 m both above and below the present streams. Many contain deep pools. Since the streams in nearby passages are now entrenched about 7 m below the initial passage ceilings, the concentration of maze passages at the stream level indicates that the maze developed rather recently within the zone of floodwater fluctuation. A few maze passages extend up to 5 m above the present water table, and as much as 10 m below (as shown by depth measurements in pools that contain outflowing water). Floodwater dissolution can apparently extend not only above the low-flow water table, but below it as well.

Onesquethaw Cave, in New York State, was used by Palmer (1972) as an ideal example of cave development by allogenic runoff (Fig. 8). It is fed by a single sinking stream with a steeply sloping 3.5 km^2 catchment area of shale and sandstone. The cave extends through the Devonian Onondaga Limestone, which is locally folded with considerable folding and faulting, and with local dips up to 25 degrees. The cave reaches no more than 20 m below the overlying land surface. Chert beds up to 20 cm thick have created many abrupt constrictions, which cause the cave to fill completely with water during high flow (approximately once every 2-5 years). Fig. 8 shows the contrast between low-flow and high-flow conditions, with the pressure head and velocity head indicated for the high flow. Many blind fissures extend laterally and upward from the main passages, and long sections of sub-parallel anastomotic tubes have developed around the main stream passage (Fig. 9). Most passages are strongly scalloped, showing high-velocity flow, but scallops are absent in the narrowest passages because of abrasion by suspended sediment. During a single flood in 1969, more than 3 m of gravel and sand accumulated in the cave, filling some of the low-level fissures and blocking some of the flow routes.

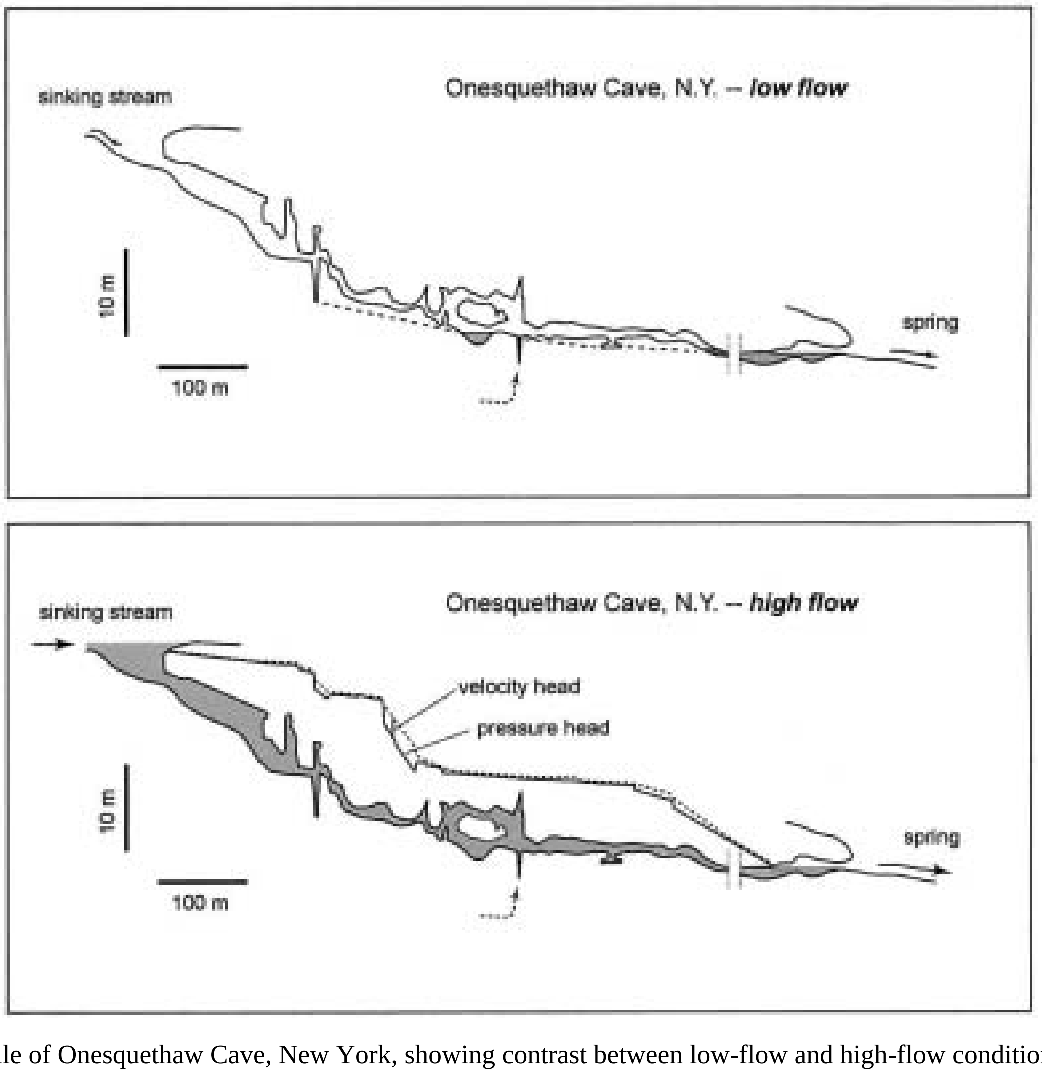

Fig. 8. Profile of Onesquethaw Cave, New York, showing contrast between low-flow and high-flow conditions. Note large variation in passage size anirregular hydraulic gradient. Head-loss calculations by M. Palmer (1975); profile from A. Palmer (1972).

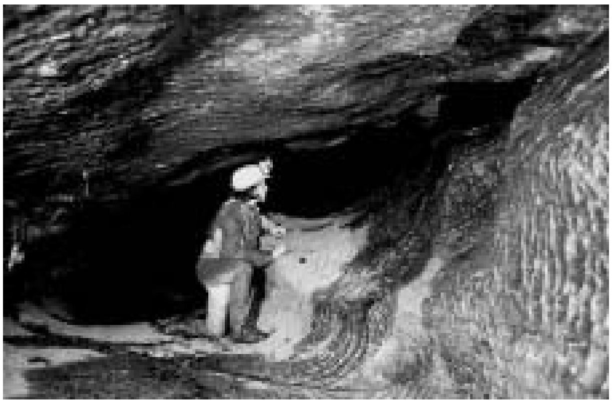

Fig. 9. Anastomotic passages in Onesquethaw Cave, which developed simultaneously by periodic floodwaters.

Skull Cave, in the Devonian Helderberg limestones of New York, is fed by two small sinking streams that drain shaly limestone capped by glacial till (Fig. 10). The stratal dip is SSW at about 2 degrees. The cave extends no more than 60 m below the overlying surface. Its spring is very inefficient because of blockage by glacial deposits, as well as trapping beneath poorly soluble shaly and dolomitic beds. Except for the upstream part of the entrance passage the entire cave floods to the ceiling nearly every year. Conspicuous fissure networks have formed in the two areas of most intense flooding (Fig. 11). Blind fissures also extend as much as 20 m upward from the main passages (Fig. 12). Armoring of the floors by sediment encourages upward dissolution during floods. In contrast with Onesquethaw Cave, anastomotic passages are not present, because jointing is much more prominent in the Helderberg limestones. Flooding is also rather static, with high pressure but little velocity. The networks contain no scallops, except in the sections near the main stream. In some areas their walls are coated with clay up to two centimeters thick. Delicate differential solution of the bedrock fabric behind the clay shows aggressiveness by periodically renewed interstitial floodwater. The fissure networks receive water during every flood and release it from storage as the flood subsides. They are good examples of “karst annexes” as envisioned by Mangin (1975).

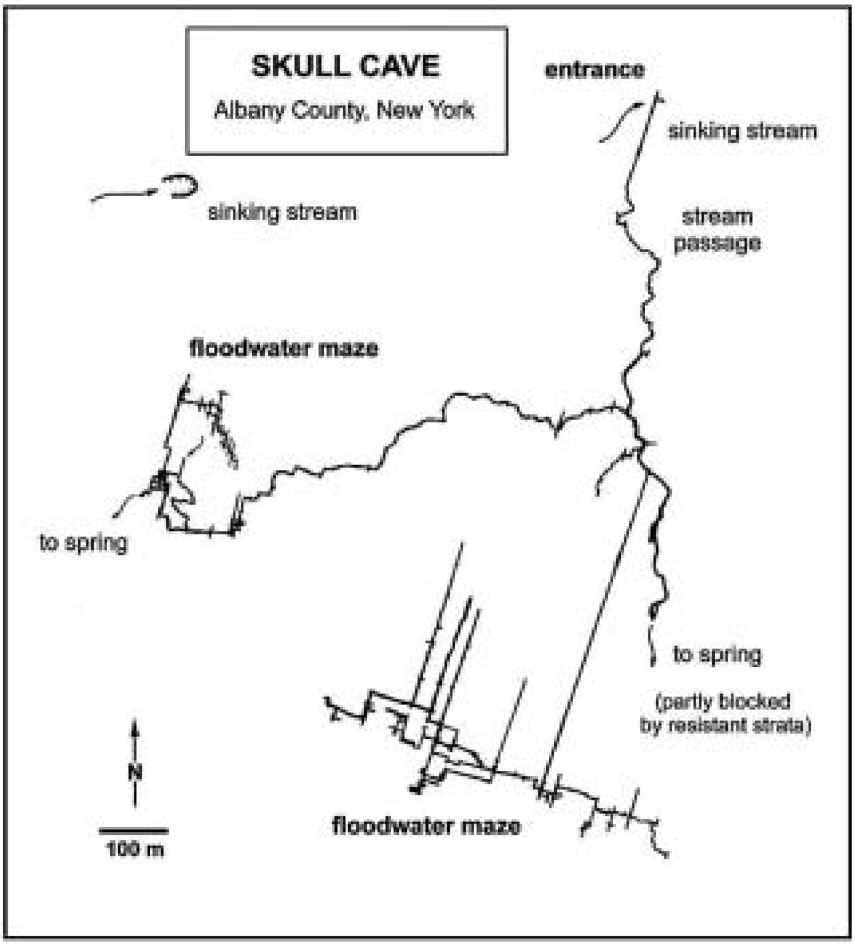

Fig. 10. Map of Skull Cave, New York, showing network mazes formed by static flooding (from Palmer, 1975).

Fig. 11. Typical floodwater passage in Skull Cave. Note irregular floor profile.

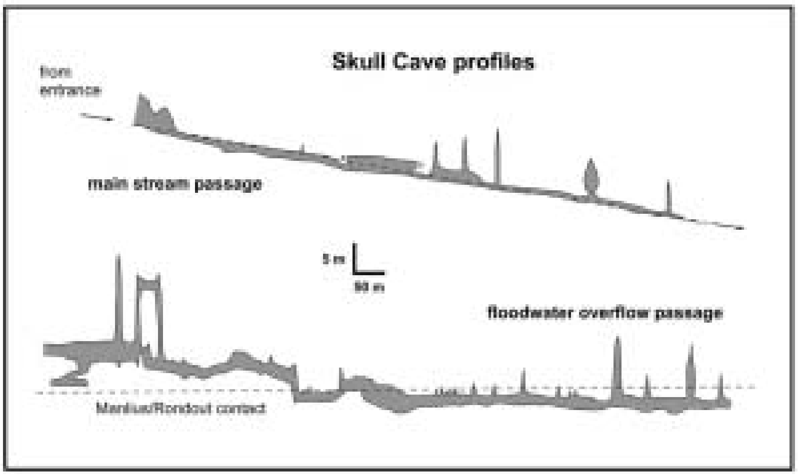

Fig. 12. Profiles of the main stream passage and the main east-west passage of Skull Cave, showing floodwater fissures in ceiling.

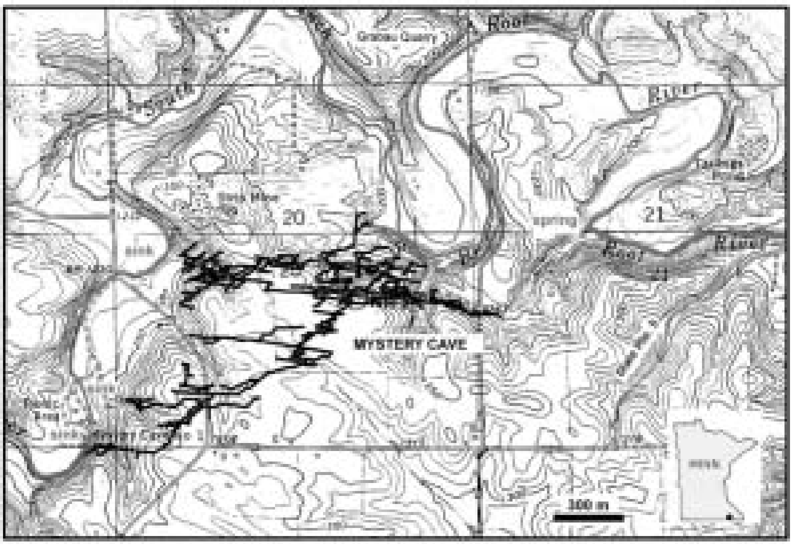

Fig. 13. Mystery Cave, Minnesota, a subterranean meander cutoff of the West Fork of the Root River Cave map by Minnesota Speleological Survey, reproduced with permission.

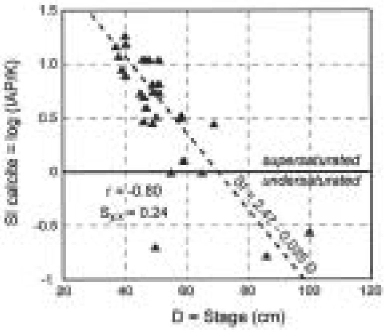

Fig. 14. Calcite saturation index (SI calcite) of allogenic water entering Mystery Cave vs. river stage on West Fork of Root River. Equilibria calculated by Palmer and Palmer (1993) from chemical data by Grow (1986). Approximate conversion from C/Cs in Fig. 4 is SI ~ log $[(C/Cs)^{2.86}]$.

Mystery Cave, in the highly fractured Ordovician Stewartville and Dubuque Formations of Minnesota, is a subterranean meander cutoff of the Root River (Fig. 13). The entire cave consists of a fissure network totaling 21 km of mapped passages at a depth of 20-40 m below the surface. The local dip is 0.3-0.8 degrees to the west, and the groundwater flow, which is to the east, is discordant to the bedding along fractures. Although it is not strictly an example of contact karst, as in the previous two examples, the hydraulic and chemical setting, as well as the resulting influence on the cave pattern, are similar to those of true contact karst fed by allogenic streams. Fig. 14 shows the variation in saturation index with stage in the river. Much of the riverbed is on carbonate rock, and only the floodwaters are solutionally aggressive.

Big Brush Creek Cave is located at an elevation of 2500 m in the Uinta Mountains of Utah in the Carboniferous Deseret and Humbug Formations (Fig. 15). Brush Creek drains about 65 km^2 of high-altitude metamorphic rock, mainly quartzites, and today has a peak discharge of about 30 m^3/sec. Much of the water is now tapped for irrigation, but there is evidence for larger flows in the past. Quartzite boulders up to 2 m in diameter have been carried into the cave (Fig. 16). There is still enough water today to fill the entire cave during high flow. The cave is fairly deep by American standards, extending to more than 250 m below the land surface. Its spring lies 650 m below the entrance. To reach the spring, the cave water must rise along fractures in an overlying sandstone formation, which presents a considerable impediment to floodwaters. Also, many constrictions in the cave have formed by sediment and rafted logs that have accumulated in large piles. The Humbug Formation is an intraclastic carbonate breccia with fragments up to half a meter in diameter. Fractures and partings are very sparse, and most openings are narrow interstices between

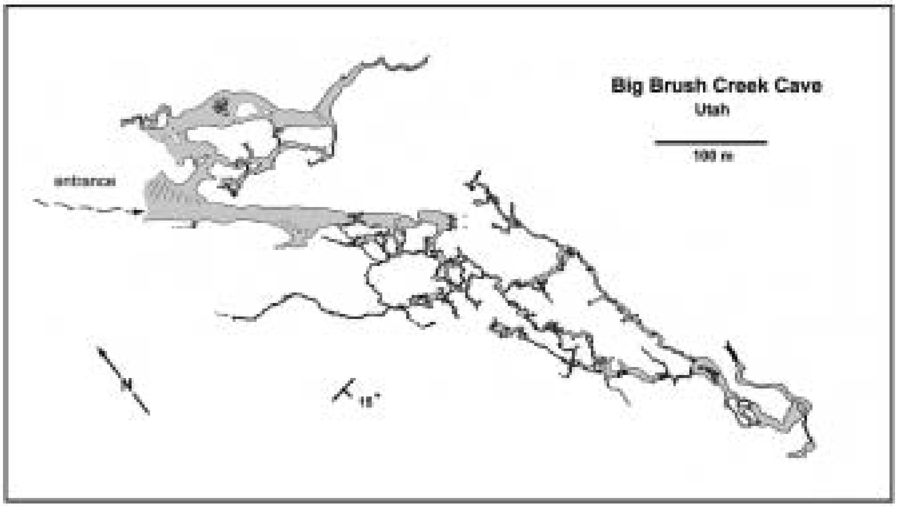

Fig. 15. Partial map of Big Brush Creek Cave, Utah (from Palmer, 1975).

Fig. 16. Entrance of Big Brush Creek Cave.

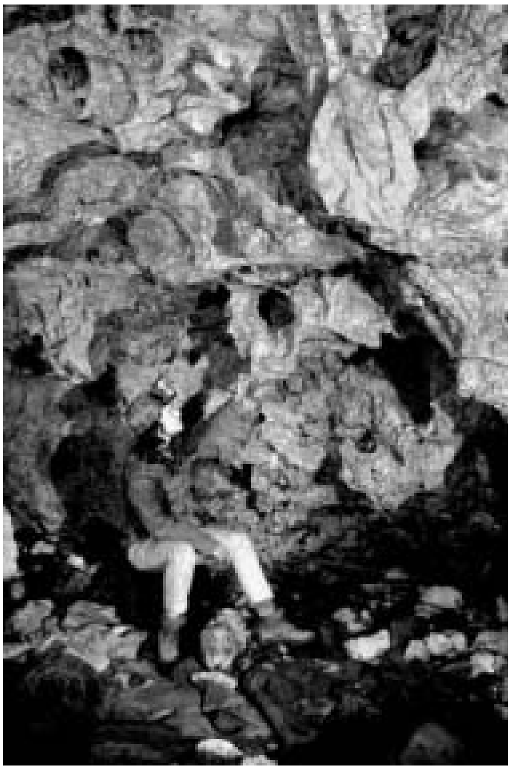

Fig. 17. Spongework in carbonate breccia, Big Brush Creek Cave. Note large quartzite cobbles on floor.

clasts. The earliest cave development followed the contact with the underlying dolomitic Deseret Formation, which dips about 15 degrees to the south, but most floodwater dissolution has been upward into the Humbug. Extensive spongework and 3-dimensional mazes have been dissolved in the Humbug (Fig. 17). Spongework and maze development is most prominent in the upstream part of the cave. A long, deep section not shown on the map contains unpleasant concentrations of carbon dioxide from organic decomposition. It is mainly a unitary passage with few of the floodwater features described above.

Conclusions

With the exception of Brush Creek Cave, all of these examples are located in thin, shallow aquifers, which are most susceptible to the development of floodwater mazes. In Brush Creek Cave the mazes and spongework are most conspicuous in the upstream parts, where the water is most aggressive and overburden pressures are least.

The effect of allogenic water on cave patterns is less conspicuous in well-drained, massive limestones. This is especially true for caves that lie at considerable depth below the land surface. Many of the important karst areas of the world fall in this category. Karst aquifers with few fractures and constrictions generally respond only with great enlargement of active cave passages and perhaps simple diversion routes around blockages. Some of the best examples of allogenic recharge are located in the classic Karst of Slovenia, including the well-known Škocjanske jama (Mihevc, 2001) and Postojnska jama (Šebela, 1998). In these caves the effects of flooding are expressed mainly as irregular patterns with solution pockets and blind fissures. Except for a few local fissure networks there are no extensive mazes like those in the shallower examples described above.

How can floodwaters create maze caves? As shown in Fig. 5, it is possible for all openings with sufficient Q/L to enlarge simultaneously at about the same rate. However, the graph also shows that openings below a certain size will not achieve this same rate. The exact threshold size depends on the hydraulic gradient forcing the water into the openings; but it is unlikely that openings less than 0.005 cm in initial width or radius will be competitive. This means that mazes are most likely in shallow aquifers that have experienced considerable erosional unloading, or perhaps also stress from the weight of continental glaciers. The New York caves described above, and possibly also Mystery Cave, have probably benefited from the latter. The network maze in Blue Spring Cave was clearly enhanced by the opening of new fractures around the collapse zone.

But why do mazes form, rather than simple parallel diversion routes? Mazes are so common because as the major flow paths enlarge, secondary fissures and tubes are formed by floodwaters injected into the walls of these new routes. The pattern of secondary passages therefore grows outward in a ramifying way until the various blind spurs intersect, forming a maze. In addition, water in the various diversion routes has highly irregular hydraulic gradients during flooding (see Fig. 8). As a result, adjacent flow routes tend to have disparate head values, resulting in the development of crossover passages between the main routes (see Fig. 7b).

Many of the smaller features described in this paper are also found to a smaller extent in caves fed by autogenic recharge. These include anastomoses, solution pockets, and blind fissures. Knowing how these features are formed in caves that undergo severe flooding, we can better understand the dynamics of how they are formed in caves fed by allogenic water as well.

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