Internal Pressure Sculpting and Speleogenesis in Autogenic Karst

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Abstract: Understanding the ongoing speleogenic processes that produce sinkholes and control the vital drinking water supplies of Florida and much else of the world is necessary research. This article (and the associated poster presentation) discusses theoretical processes that may act in addition to mass dissolution kinetics in producing voids, conduits and caves in autogenic karst landforms. Possible theoretical factors that affect these speleogenic processes are: microscopic mixing corrosion (low constant flow, low constant flow against current, temperature-induced mixing corrosion, and pressure-induced mixing corrosion in karst matrix), random dissolution models, simulation of gravity-induced microscopic breakdown, and storm surge effects. Finally, a theoretical model is discussed that unifies these various microscopic processes into a macro-scale process, called internal pressure sculpting. Computer models were designed to illustrate these theoretical processes: (1) Non-calibrated computer models simulating each process discussed in this paper are presented for illustration, (2) as well as the preliminary results of calibrated models depicting random dissolution, mechanical breakdown, and storm surge effects. The theoretical processes discussed and simulated may have major effects on cave morphology. Computer simulations appear to accurately portray the shape and form of some cave features with dissolutional morphologies. Theoretical discussion concludes with a general discussion of possible improvements to the presented models as well as the ability to generalize theoretical processes to hypogenic, halogenic, and autogenic speleogenesis.

Key words: Cave development in limestone, mixing corrosion, karst, computer modeling, solutional widening rate, speleogenesis.

1. Introduction

There is a need to understand the ongoing speleogenic processes responsible for sinkholes and the provision of clean drinking water in the State of Florida, USA, as well as other areas in the world. The current theories of speleogenesis fail to account for the size, development, pervasiveness, and rate of growth of the vugs, voids, and conduits contained in autogenic karst terrain. Current speleogenic theories [1] explain cave development resulting from the aggressive dissolutional energy of allogenic waters entering a karst terrain of soluble rock [2], or by rising hypogenic waters [3], or by the halogenic mixing of saltwater and freshwater [4], or other types of mass-mixing corrosion [5], and are relatively well understood. Current computerized models of speleogenesis are based on simple chemical kinetics along lines of geologic faulting [6, 7], and neglect many of the other geophysical aspects that may by necessity effect morphological development. Certain assumptions made in dissolutional models, while necessary to model construction, may not accurately reflect actual speleogenic processes. One assumption reflects an attempt to mathematically quantify phreatic denudation dissolution rates which is expressed as solutional widening rates for conduits and fractures. White [8] assumes “The growth of cave height and width is symmetric throughout entire length from input to output as to height and width”. This is a modeling assumption made by assuming “that the rate of dissolution at the exit are active all along the entire fracture thus maintaining a profile of parallel planes”
This would result in series of uniformly connected voids (Fig. 1) or phreatic conduits enlarging evenly over time (Fig. 2), neither which seem to portray the actual morphology of autogenic caves (Fig. 3). Another model’s assumption (Fig. 4) is “that cave dimensions will assume a funnel-form from input to output” [10] due to water from inputs losing solutional aggressiveness (the ability to dissolve material) over time and space. This model, while applicable to input zones such as fractures or sinks, does not explain extensive conduit development that occurs at a distance from inputs or near output zones, nor does it explain the shape and morphology of conduit intersections or the sinusoidal roof heights typical of conduits and cave passages associated with autogenic passages (Figs. 3 and 4). That the assumptions in these models lower their predictive accuracy is demonstrated by the disparity between low predicted dissolutional rates and actual solute loads from aquifer outputs [11].

Factors other than dissolutional aggressiveness of water inputs may be especially important in understanding speleogenic processes that occur in autogenic karsts since the dissolutional aggressiveness of the involved waters is much less than found in other cave types when compared to the aggressive hypogenic waters or alloegenic streams tunneling into karst landscapes. Therefore, new factors that affect karst speleogenic development must necessarily be added to the basic dissolutional model in order to accurately account for the morphological development of autogenic karst. Factors such as gravity-induced breakdown, variations in hydraulic conditions, temperature effects, pressure-gradient forces, and fluid mechanics, as well as various mixing-corrosion regimes need inclusion for accurate computer modeling of autogenic karst speleogenesis. The purpose of this study is the preliminary development of these “other” processes both through logical discussion and simple computer models that demonstrate these possible additional processes associated with karst speleogenesis.

Fig. 1  Random dissolution model connecting three rectangular voids of varying sizes.
Fig. 2  A computer model of a narrow aperture entering an open phreatic void that is widened by random dissolution of surface units.

Fig. 3  A sketch of “typical” cave found in autogenic karst with multiple arched roofs, offshoots of dissolutional channels, openings to passages at smaller ends of chamber.

Fig. 4  Theoretical shape of single fracture dissolutional channel after 10,000 years of water input beginning at atmospheric CO₂ source; size of cavity much larger at input due to the unabated dissolutional aggressiveness of incoming water. Dimensions decrease with distance due to time constraints and loss of aggressiveness of water over distance.
2. Method

Mylroie [12], who has studied speleogenesis and mixing corrosion in carbonate islands, has stated that “micro-feature development mirrors macro-feature development”. Postulating that similar processes may be responsible for similar topologies, the macroscopic processes of mixing corrosion, gravity breakdown, and hydraulic flows have been applied on a microscopic scale using MATLAB-7 software [13]. Simple paradigms were developed to demonstrate (1) mixing corrosion regimes, (2) gravitational micro-breakdown, and (3) contra-flow microconduit development. The simulations used a “Monte-Carlo” method [14] which reevaluates each of the 10,000 cells of the 100 × 100 matrix for the paradigm values such as pressure, flow, structure, and aggressiveness of each simulation at every iteration of the program. Water flow is simulated by vectored movement and averaging of adjacent cell values while the rock matrix is simulated by fixed arrays of values. Values used in these initial conceptual models are only approximations of real attributes and time steps have not been calibrated. The following assumptions are made in each model: (1) initial total saturation of the involved waters with the concomitant inability to dissolve calcite, (2) a phreatic environment typical of endokarst on level with the active water table just below the percolation zone, (3) the purity of the karst carbonate-rock structure are made in each model, and (4) water moves by means of primary porosity through the rock matrix of karst providing an internal flow that effects secondary porosity development. This last assumption of primary porosity provides description of the temperature and pressure differences of matrix-bound waters in comparison with free waters; this allows study of the morphological effects of the boundary interactions between the two waters. Boundary conditions are steady state with a wide modeling field to escape boundary effects. Each separate process developed will be qualitatively examined by computer simulation to discover its ability to portray actual morphological features similar to those found in autogenic karst caves.

3. Results and Discussion

3.1 Mixing Corrosion Regimes

Mixing corrosion is the re-energizing of two saturated and nonaggressive waters producing a new zone of aggressive water; it becomes aggressive, unsaturated water again due the mixing [5]. There was general belief that mixing corrosion had no effect on cave network genesis, except in the limited cases of halogenic caves (saltwater), hypogenic caves (heated groundwater), or large allogenic caves caused by the mixing of two large volumes of water [10]. However, if one considers the horizontally flowing water of an aquifer as one flow of saturated water and the vertically percolating water from the vadose zone as a second body of saturated water, then the parameters for mixing corrosion are present. Since the volume of water percolating downwards would be much less than the mass waters of the water table the mixing corrosion models explored all involve very small quantities of incoming water which is quickly neutralized by the larger water body, thus keeping dissolutional processes localized at the rockface near the incoming aperture.

3.1.1 Small Constant Flow Mixing Regime

The simulations (Figs. 5-7) are of a small volume of saturated water constantly escaping from the rock matrix, representative of vertically descending water from vadose zone, which is then mixing with a large volume of saturated free water (in a conduit or void). Where the flow mix reaches a 1:1 ratio is where the greatest “un-saturation” of the water occurs causing these “packets” of water to be temporarily aggressive in dissolving karst. Dissolution of the model rock matrix occurs when the mixing water both becomes aggressive and intersects exposed rock surface. In these initial simulations of a constant flow volume the initial width of the corrosional pitting is determined.
Fig. 5  Beginning of mixing corrosion simulation with small constant flow entering phreatic void.

Fig. 6 Continuance of mixing corrosion simulation with small constant flow entering phreatic void; magnitude of aperture widening determined by incoming flow, while angle of declivity is a function of main current flow [void has no current].
quickly, and is maintained throughout. However, as the smaller flow is quickly neutralized by the larger volume of the water present in a conduit or void, dissolution of the karst only occurs near the aperture opening, causing the corrosion to tunnel back along the aperture into the rock matrix.

3.1.2 Small Constant Flow Mixing Regime into Current

Another simulation shows the results of the same small flow regime entering into a constantly flowing body of water such as found in an active conduit (Fig. 8). In this case, the mixing of waters is vectored in direction of the current resulting in increased corrosion on the downstream portions of the aperture opening. This results in the upstream aperture wall defining one side of a growing funnel which is elongated and oriented to the downstream flow. The angle of the funnel is dependent on the speed of the major water flow with a wider angle at higher velocity flows.

3.1.3 Small Intermittent Flow Mixing Regimes

When the incoming flow is intermittent, or very weak, the larger body of water extends its influence into the aperture and precludes mixing corrosion from spreading by quickly diluting and assimilating the new waters. The method used in the models to simulate incoming water flow was also used to simulate storm surge and water table-pressure variations. The resulting morphology of this process is similar to a series of linked voids. When current variability is added, the resulting funnel-shaped morphology created by high current speed is partially erased by normal mixing regimes during low flow periods, but the process will return to the growing funnel-form when flow is increased (Fig. 9). This results in a series of inset declivities in the widened aperture pointing in the downstream direction with softened curves on upstream aperture walls.
Fig. 8  Mixing corrosion resulting from small constant flow of percolating water entering active conduit with constant current from right to left. Magnitude of widening controlled by aperture flow volume.

Fig. 9  Mixing corrosion resulting from small constant flow of percolating water entering active conduit with variable current flowing from right to left; the direction or bias of developing morphological declivity is determined by the direction of main water flow in the conduit.
3.1.4 Temperature-Induced Mixing Regimes

The formula for the dissolution of karst (calcite in CO₂ system) is dependent on temperature, CO₂ concentrations in the solution, and the dissolution rates forward and backward for calcium [15]. As water reduces temperature its ability to hold solutes increases, thus becoming increasingly under-saturated and aggressive (Fig. 10). Since the groundwater water held and released by the rock matrix is at the mean annual temperature it will almost always vary from temperature of meteoric waters from surface inputs. If micromixing of phreatic and vadose waters does occur this would lead to increased corrosion from micromixing temperature differences during solstice seasons of winter and summer when the temperatures of water inputs varies greatest from the mean annual temperature of rock matrix-bound waters. Temperature corrosion effects would decrease during equinoxes when mean temperatures and surface generally coincides. The general morphology of temperature-induced corrosion would be limited to input zones where water temperature vary and would be dependent on the various flow regimes present, but with an enlarging of dimensions or speeding of denudation rates due to increased aggressiveness of mixing waters.

3.1.5 Pressure-Induced Mixing Corrosion

High-pressure water can hold more dissolved solids than low-pressure water. It is possible that mixing corrosion occurs where primary and secondary apertures conducting water through the rock matrix intersect with a water-filled void or conduit. In this simulation the movement of water via primary porosity (intecellular spaces of matrix) has effect on a vertical aperture leading into a water-filled void (Figs. 11-13). The pressure differential changes at the water/rock interface much more quickly than other factors leading to mixing corrosion. In the simulations the greatest pressure differential occurs just inside the rock matrix along lines of primary porosity. The rock seemingly crumbles, sometimes bypassing and isolating surface units, by cause of underlying corrosion and removal of rock matrix cells. Note in simulations how the pressure differential is greatest just inside of the rock matrix rather than at the interface surface (Fig. 13). This results in a symmetrical, cylindrical cone with increasing slope as aperture ascends into rock matrix due to corrosion and dissolution of karst. Adding a small component of random dissolution at the beginning of

![Dissolutional Opportunity by Temperature Degradation](image_url)

**Fig. 10** Theoretical histogram of model rock matrix units dissolved due to decreasing temperatures of flowing water (zero on graph corresponds to annual high temperature of water at input and each 10 steps is equal to a 1°C decrease in temperature); as temperature decreases the dissolutional aggressiveness of the water is enhanced.
of the process causes a variety of resulting dissolutional forms (Fig. 14).

3.2 Gravity-Induced Microscopic Breakdown

In the random dissolution and the pressure-induced mixing corrosion simulations there were often units that rather than being dissolved became detached from the rock matrix (Figs. 1 and 2, Figs. 12 and 13). If this detachment without dissolution were to occur, by whatever means, on a downward slope the fragments would be pulled down and away from the aperture while an upwards vector would lead to a clogging of the aperture by excess fragments. A sideways or horizontal vector of the aperture where it exits the
rock face would result of in an accumulation of fragments on the lower slopes of the aperture forcing flow and corrosional effects upwards. A computer model was developed to determine if such detached fragments could be a significant factor in the morphology of cave walls. The model presents a horizontal ceiling exposed to random dissolution of surface cells and compares the amount of rock lost to dissolution as compared to the amount of single cells detached by corrosion. The model shows that the percentage of mass of karst that is lost due to undercutting by random dissolution and gravitational...
Fig. 13  Pressure-induced mixing corrosion due to release of high-pressure water at interfaces. (a) Water pressure on left, (b) rock matrix on right; the dissolution of interior rock cells indicates the rate and boundary conditions of this process depends on the primary porosity of the karst substance involved.

Fig. 14  Variations of dissolitional morphology caused by introducing random dissolution factor at start of pressure-induced mixing corrosion simulations.

breakdown can be significant (Figs. 15-17). The percentage of mass lost due to detachment ranges from under 3% at inception and increases over time to over 12% of total rock volume lost. In porous or impure karst rock this percentage may increase to above 25%. This would increase the resultant solute loads from dissolitional activities by the same factor over values expected by conventional kinetic equations.

Expanding upon this concept of an uneven karst surface resulting from random breakdown it was postulated that increased turbulence, such as caused by storm surge, would act to smooth the surface as
Fig. 15  Totally random dissolution of karst horizontally inverted surface with a digitalized count of the number of cells dissolved versus number detached by dissolution.

Fig. 16  Totally random dissolution of karst surface; number of cells dissolved versus number detached by dissolution. Note the varied depths of dissolutional penetration of karst surface in theoretical model (range of -1:-18). Also note the significant amount of rock removed from karst matrix without being directly acted upon by dissolution (+10%).
weakened and exposed portions of the karst surface were broken off and swept away by the increased force of moving water. A developed model, karst widening rates, shows that standard solutional widening rates can be increase from 1% to 15% to 300% depending on size and timing of storm surge events [16]. This process could easily cause accelerated development of aquifers, sinkholes, and other karst morphologies in areas such as Florida which have regular precipitation and hurricane events.

### 3.3 Internal Pressure Gradient Corrosion Model

These mixing corrosion scenarios are all dependent on the amount of water flowing to the mixing zone. It is known that over time porosity enlarges in the direction of hydraulic flow which follows the pressure gradients within the waters of the aquifer; in essence the flow follows paths of least resistance from high pressure input zones to low pressure output zones and widens those passages over time [11]. Apertures with stagnant or unmoving waters may become blocked by precipitated minerals such as calcite or gypsum [10]. Hence, over time flow networks become oriented along lines of maximal flow towards points of discharge. Inside an aquifer flow is towards conduits which act as an output focus of the system. In this computer model the pressure of the flowing water of the conduit creates pressure differentials which act to guide internal flow of descending, percolating waters. The most flow is pulled towards areas of low pressure and repelled near areas of high pressure. As water flows along a water-filled passage pressure increases at chokepoints and decreases as the volume increases (Fig. 18). Percolating water would be drawn to areas of low-pressure increasing force of the micro-mixing and breakdown processes in those areas. In the model the morphology of the cave is self-perpetuating due to feedback reactions between the dissolitional mechanisms and pressure-flow regimes (Fig. 19). Therefore, the conduit will maintain the same general shape as it enlarges. This process of increased flow leading to increased corrosion with water pressure
gradients internal to the karst matrix acting to direct the flow can be described by the term “internal pressure sculpting”.

3.4 Discussion of Results

In terms of the growth of conduit networks in karst none of the processes here discussed should compare in scope to the dissolitional power of unsaturated flowing waters moving through enlarged fracture and bedding planes. However, some of the similarities between the models developed and actual cave morphology are remarkable. The sinuous, undulating, quickly narrowing conduits along autogenic cave roofs and walls are very well portrayed by the mixing corrosion scenarios. The multiple-connected void shape and the elongated (fluted) funnel of the other mixing corrosion regimes are also reminiscent of commonly seen autogenic karst cave morphology such as: (1) The roughened surfaces of karst surfaces due to random dissolitional action; (2) The arching of dissolved apertures, conduits, and caves is similar to the morphology that is described by the gravity breakdown model; (3) The cross-sectional sinusoidal shape of many cave passages is adequately copied by the internal pressure gradient corrosion model. In essence, the preliminary results of these models seem to indicate that these models portray significant speleogenic processes. The mixing corrosion processes seem to be able to explain and replicate dissolitional morphology in localized settings and conditions. However, any impact on total network development from these mixing corrosion models
would require a restriction of allogenic water inputs, such conditions as can be found in the autogenic aquifers of Florida. The microscopic gravitational breakdown process that was modeled would have effect on any dissolitional process; downward vectors would show the greatest amount of denudation given the same dissolitional energy expenditure. Model results show that storm surge effects could have major effect on speleogenic growth rates in karst landscapes that are affected by major precipitation events. Mixing corrosion processes, though seen only in as yet non-calibrated computer models, may have some effect, but this is would be related to the development and porosity of the karst rock through which water moves; low porosity would reduce the flow that is the driving force enabling these processes. Finally, the internal pressure sculpting model can be used to demonstrate possible results of the interaction of matrix-bound waters moving via primary and secondary porosity with the freely circulating waters moving via tertiary porosity.

4. Conclusion

Computer models of various mixing corrosion regimes, as well as the microscopic gravity breakdown model, show results that seem to accurately simulate certain dissolitional features of caves and conduits in autogenic karst. The demonstration model shows that it is the internal hydraulic pressure gradients in the phreatic karst that drives the flow of mixing waters which has the greatest effect on cave morphology. The additional solute loads that would be added to outgoing karst waters by the gravity breakdown and mixing regime models could provide the source for the additional solute loads which are currently unexplained by dissolitional-denudation equations. There is a need to investigate, quantify, and model these processes in order to gain a greater understanding of the speleogenic processes responsible for the extensive development of autogenic karsts which for the most part contain saturated, nonaggressive waters. These models need to be developed in order to better simulate water flow and water mixing, as well as calibrating model components to provide time rate estimates. The first of these theoretical models has already been developed and some preliminary results are reported here. Once these models are fully explored they need to be integrated with an advanced fracture dissolitional model. In addition, there is the need to factor in other physical processes which may have impact on speleogenic processes; examples include hydraulic abrasion by suspended sediments (corrasion), eustasy and eostasy effects on hydraulic head, and teleogenic processes [17], water table variations, compositional variations of karst rocks, as well as the varied effects from biological sources in the karst [18]. These are all valid and established processes that may effect speleogenesis and need further investigation and modeling development. Further research is needed to combine the various processes into a single comprehensive model capable of accurately demonstrating and portraying speleogenesis in autogenic karst. Finally, actual physical analog models and field investigations need to be conducted to judge the veracity of computer simulations. However, this initial research has given positive support to the presence and significance of other processes of speleogenesis that act in addition to the major dissolitional-fracture control models. In conclusion, while minor processes of speleogenesis such gravitational breakdown, various mixing corrosion regimes driven by pressure gradients may not significantly impact the evolution of large-scale karst conduit networks, there is support from this study that they may have significant effect on the small-scale morphological development of autogenic caves.

References