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Evolution of isolated caves in porous limestone by mixing of phreatic water and surface water at the water table of unconfined aquifers: A model approach

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SUMMARY

When water from the surface, e.g. from a lake flows through porous carbonate rocks down along some region with high hydraulic conductivity and encounters the water table of a phreatic aquifer both waters mix by diffusion along their boundary. In a carbonate aquifer, where both surface and phreatic waters are saturated with respect to calcite, mixing corrosion causes renewed dissolution of the carbonate rock in the diffusional mixing zone extending from the boundary separating the phreatic water from the surface water encountering it. A numerical model is presented from which the initial change of porosity in such a diffusional mixing zone is obtained. The initial change of porosity $d\Phi/dt_{/0}$ is proportional to $|\vec{\nabla} m(x,y)|^2$ and $d^2\Delta c_{eq}(m)/dm^2$. $m(x,y)$ is the spatial distribution of the mixing ratio, $m = V_{sur}/(V_{sur} + V_{phr})$, and the Vs assign the corresponding volumes of surface and phreatic water. $d^2\Delta c_{eq}/dm^2$ is the second derivative of Δc_{eq}, the renewed dissolution capacity of the mixed solution. It has been calculated for three geochemical scenarios with differing CO_2 concentrations of surface and phreatic water by use of PHREEQC-2. The spatial distribution $m(x,y)$ is obtained by using MODFLOW and MT3DMS in a modeling domain with constant hydraulic conductivity for various flow velocities of the phreatic aquifer. From the results the time scale of cave evolution is estimated. Passages of dimensions of about one meter in width and several 10 cm in height, extending in length along the border line, where surface and phreatic water meet, can be created in time scales of 10 000 years. These caves are horizontal with blind ending passages and resemble closely to the isolated caves observed in Central West Florida. For more realistic modeling we have used a geostatistical local distribution of hydraulic conductivities in the modeling domain. For a correlation length of 1% of the length of modeling domain the spatial distribution extends deeper into the flow direction. When the correlation length is increased by a factor of 10 flow focusing distorts the diffusional mixing zone and enhances the creation of porosity.

Introduction

Caves in young porous rocks are remarkably different from those in ancient fractured rocks. In the latter speleogenesis is governed by flow along fractures, such as bedding planes and joints, and the matrix conductivity is negligible. Consequently conduits develop along the flow directions in these fractures and their walls are solid rock without any porosity. The speleogenesis of these caves was the focus of research for two decades (Dreybrodt et al., 2005; Dreybrodt and Gabrovsek, 2003; Palmer, 1991, 2007; Ford and Williams, 2007; Kaufmann, 2005).

Caves in porous rocks, where the flow is not guided along fissures but where water is transported as Darcy flow through the matrix of the rock are well known from young carbonate islands. Here mixing of saltwater with freshwater creates flank margin caves along the rim of the island. These isolated caves at the freshwater lens originate as chambers of moderate size without entrances and exits, as reported by Mylroie and Carew (1990, 2000, 2003), Romanov and Dreybrodt (2006), and Dreybrodt and Romanov (2007).

In the porous rocks of Florida isolated caves are also common. Florea (2006) and Florea and Vacher (2006), and Florea et al. (2007) have described caves of moderate passage length with blind ending passages. Most of these are aligned along NW–SE and NE–SW regional discontinuities as revealed from photo lineament features on the surface. The cave passages are not longer than several hundred meters and do not represent an integrated system of passages between inputs and outputs of the aquifer. The walls of these caves consist of porous rock with many small-scale solution features.

The principal horizons of cave development appear between 3 m and 5 m; 12 m and 15 m; and 20 m and 22 m above present sea level. These horizons of cave development are related to prior

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phreatic water tables (Florea, 2006; Florea et al., 2007) of an unconfined aquifer. When water from the surface above, e.g. a lake, reaches such a water table it has become saturated with respect to calcite. It is mixed with the phreatic water, also in equilibrium with respect to calcite. When the CO_2 concentrations of both waters differ, mixing corrosion boosts up the dissolutional capacity (Dreybrodt, 1988). Due to the low hydraulic gradients and the slow flow velocity v_y between 10^{-7} m s^{-1} and 10^{-6} m s^{-1} (Hanshaw et al., 1965; Davis, 1996) the mixed solution again becomes saturated after several tens of centimeters. Therefore initial changes of porosity are restricted to a region close to the border line where surface water and phreatic water encounter and voids originate vertical to the flow of the phreatic water.

Fig. 1 gives a highly idealized hydrogeological set up of this situation. The water in the phreatic aquifer is driven by low hydraulic gradients with velocity v_y between 10^{-7} m s^{-1} and 10^{-6} m s^{-1}. It is entirely saturated with respect to calcite because of its low velocity and the huge reaction surface in the pores of the rock. Flow follows the Darcy rules in porous media.

Water from a lake or a river on the surface leaks down to the phreatic aquifer, preferentially along some discontinuity, with higher hydraulic conductivity of the porous rock. This water joins the water table along the *z*-axis and floats as a layer on the phreatic water. Since both bodies of water exhibit Darcy flow, mixing of the phreatic water with the surface water can only be affected through the dividing streamline (DS) by molecular diffusion and transversal dispersion. The diffusional mixing zone between surface water and phreatic water zone extends along the *z*-axis where the surface water enters. For $y > 0$ a fan of mixed waters of width $W_x = 2\sqrt{D \cdot y/v_y}$ centered along the *y*-direction develops due to transverse dispersion with dispersion coefficient *D*.

Mixing corrosion is active in this region and causes increasing porosity along the *z*-axis where the surface water enters and down the *y*-direction along the dividing streamline. This way an isolated cave passage could originate, similar to those passages observed in porous rocks in Florida. Its conduits are directed normal to the flow direction of water, which has created them. This is similar to the concept of transverse speleogenesis as first suggested by Klimchouk (2007), although flow is through the matrix of the rock and horizontal along the water table in contrast to the flow ascending through fractures from below in Klimchouk's concept. In this paper we will investigate how and in which time scale caves can originate in such a hydrological setup.

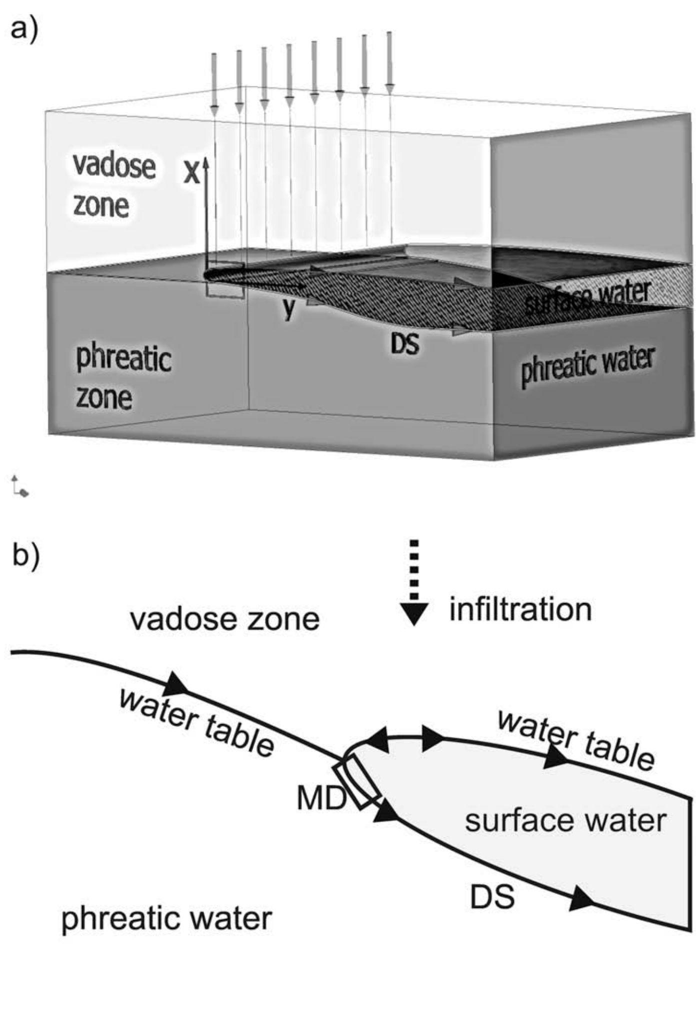

Fig. 1. (a) Geometry of the hydrological concept: water from a lake at the surface flows along some discontinuity with high hydraulic conductivity down to the water table of an unconfined aquifer. The surface water encounters this water table along the *z*-axis and floats with some depth on the phreatic water along the streamline (DS), dividing the two domains of water. Both waters are saturated with respect to calcite, but have differing CO_2 concentrations. A diffusional mixing zone is created along the dividing streamline (DS) of both water bodies. Therefore mixing corrosion becomes active creating porosity along the *z*-axis close to the dividing streamline. The small rectangle close to the origin of the coordinate system represents the region where the modeling domain is located. (b) Close up view of a transect showing the rectangle in the *x*–*y* plane of Fig. 1a. Due to the infiltration a mound of surface water builds up. Its upper boundary creates the new water table. Its lower border is the dividing streamline (DS) separating phreatic water from surface water. Black triangles indicate the flow directions. The rectangle MD represents the modeling domain, shown in Fig. 2.