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'Looping caves' versus 'water table caves': The role of base-level changes and recharge variations in cave development

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ABSTRACT

The vertical organisation of karst conduit networks has been the focus of speleogenetic studies for more than a century. The four state model of Ford and Ewers (1978), which still is considered as the most general, relates the geometry of caves to the frequency of permeable fissures. The model suggests that the 'water table caves' are common in areas with high fissure frequency, which is often the case in natural settings. However, in Alpine karst systems, water table caves are more the exception than the rule. Alpine speleogenesis is influenced by high uplift, valley incision rates and irregular recharge. To study the potential role of these processes for speleogenesis in the dimensions of length and depth, we apply a simple mathematical model based on coupling of flow, dissolution and transport. We assume a master conduit draining the water to the spring at a base level. Incision of the valley triggers evolution of deeper flow pathways, which are initially in a proto-conduit state. The master conduit evolves into a canyon following the valley incision, while the deep pathways evolve towards maturity and tend to capture the water from the master conduits. Two outcomes are possible: a) deep pathways evolve fast enough to capture all the recharge, leaving the master conduit dry; or b) the canyon reaches the level of deep pathways before these evolve to maturity. We introduce the Loop-to-Canyon Ratio (LCR), which predicts which of the two outcomes is more likely to occur in certain settings. Our model is extended to account for transient flow conditions. In the case of an undulating master conduit, floodwater is stored in troughs after the flood retreat. This water seeps through sub-vertical fractures ('soutirages') connecting the master conduit with the deep pathways. Therefore, the loops evolve also during the dry season, and the LCR is considerably increased. Although the model is based on several approximations, it leads to some important conclusions for vertical organisation of karst conduit networks and stresses the importance of base-level changes and transient recharge conditions. It therefore gives an explanation of speleogenesis that relies much more on the dynamic nature of water flow than on the static fracture density.

1. Introduction

For most of the last century, the question whether caves originate above, at, or below the regional karst water table was unsolved (see detailed discussion in Gabrovšek, 2000; Dreybrodt et al., 2005; Audra and Palmer, 2013). Field evidence and calculations did not give priority to any one of the conceptual models. Martel (1921) argued that cave enlargement is most intensive in the vadose zone where the infiltrating water is still aggressive, and because the high flow velocity enhances erosion. Davis (1930) and Bretz (1942) concluded from field studies that caves developed along Darcy flow paths below the water table. Swinnerton (1932) contended that caves are more likely to form where the density of groundwater flow is highest, that is, at and just below the water table (Fig. 1). Therefore, he considered the zone of water-table fluctuation to be the most favourable for cave origin. All the theories were partially supported by field observations.

The four state model (Ford, 1971; Ford and Ewers, 1978) relates fissure frequency and cave pattern in the dimension of length and depth (Fig. 1): Deep phreatic loops evolve when fissure frequency is low (e.g. few and widely spaced penetrable fissures), and 'water table caves' originate in cases of high frequency of permeable fissures. All the intermediate cases are also included in the model. The model was later expanded to six states (Ford and Williams, 1989), with one end-member being an isotropic rock with no fissures and thus no caves (for example a well-recrystallized marble) and the other one an isotropic highly porous rock where the porosity is so large that no distinct caves are formed (for example chalk). The four state model therefore answered

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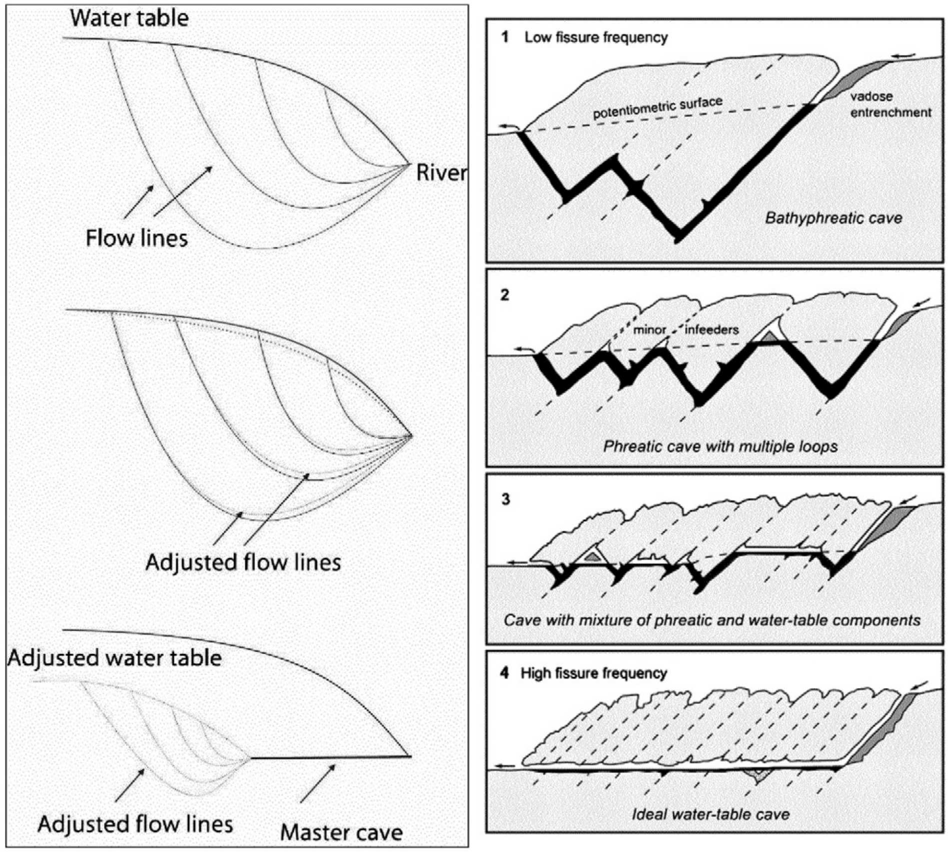

Fig. 1. Left: the water table cave hypothesis proposed by Swinnerton (1932). Right: The four state model of Ford and Ewers (1978). See text for discussion.

the main question in an easily understandable and quantifiable way. It therefore quickly became the main speleogenetic model, and is still regarded valid by many researchers: "The argument concerning whether caves formed above, at, or below the water table that so preoccupied researchers of the classic period, was definitely put to rest by Ford and Ewers (1978). The answer was, "yes"" (White, 2000).

However, continuing research on speleogenesis revealed several questions that were not compatible with the four state model. Worthington (2004, 2005) questioned the validity of the Ford–Ewers model by noting the development of sub-horizontal caves as much as 100 m below the water table. He also showed statistically that the depth of phreatic cave development is proportional to the overall length of flow paths and angle of the stratal dip.

The main point is that tectonised and fractured Alpine rocks should show many more water table and near water table caves than, for example, the relatively undisturbed limestones of the Mammoth Cave Plateau (USA). But in the Alps, there are very few water table caves or caves of State 3 (see Fig. 1 for an illustration). For example, the folded and thrusted Vercors massif (French Prealps) contains 277 large caves (from Lismonde and Frachet, 1978, modified), of which 190 are vadose and 15 unrecognizable (speleothems, breakdowns, etc.). The other 72 caves of phreatic origin are composed of 6 water table caves (8%) and 66 'looping caves' (92%). Another example is Hölloch cave (Switzerland), which by Ford and Ewers (1978) is considered as the type locality for State 2, although it is located in steeply dipping and densely fractured limestone. This topic was discussed in some length in Jeannin et al. (2000), where Derek Ford states in a public comment after the article: "The Four State Model … does not attempt to predict what will be the effective fissure frequency and aperture in any particular topographic or geologic setting …". In other words, the four state model cannot be used as a predictive model explaining "why did that particular cave form in this state at that location".

Ford and Ewers (1978) stipulate that fissure frequency increases with geological time, causing multilevel caves to evolve from State 1 to near State 4. However, even if the increase in fissure frequency over the lifespan of a karst seems reasonable enough (erosional unloading of the surface, tectonic release when valleys are deepened, continuous karstification of pre-existing small fissures, etc.) such effects are usually localized near the surface (creating the 'epikarst') or constrained to well-defined fissures. Thus, the implied time-dependency of the four state model induced confusion among many karst researchers who had troubles matching the model to the observed reality.

Palmer (1991) suggested that the plan pattern of caves is also controlled by discharge fluctuations, a view that is now widely accepted and also cited by Ford (1999). However, Ford (1999) does not take into account possible recharge variations while explaining the cave pattern in length and depth. During the last two decades, it has been found that recharge variations have a huge influence on speleogenesis. Water chemistry measurements as well as direct observations in caves have shown that floodwaters are much more corrosive and erosive than low waters (Palmer, 2000). Scallop size depends on flow velocity, and the velocity back-calculated from scallops also reveals that erosion mainly occurs during flood events (Lauritzen et al., 1983). Audra (1994) emphasized the influence of the epiphreatic (floodwater) zone for speleogenesis of passages of apparent phreatic origin, and Häuselmann et al. (2003) subsequently refined the model, explaining the speleogenesis of Bärenschacht (Switzerland) on the basis of floodwater fluctuations. We thus can ascertain that floodwater effects are very important in speleogenesis.

Furthermore, karst in orogens is subjected to rapid base-level changes which result in time-varying boundary conditions for the development of karst networks. The existence of cave levels has been related to stillstands of base level, however we still lack some basic understanding of how karst systems adopt to changes of erosional base level.