Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2020-473-RC2, 2020

Hydrology and Earth System Sciences
Open Access
Discussions

Interactive comment on "Early hypogene Carbonic Acid Speleogenesis in unconfined limestone aquifers by upwelling deep-seated waters with high CO_2 concentration: A first modelling approach" *by* Franci Gabrovšek and Wolfgang Dreybrodt

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Received and published: 25 November 2020

This study simulates the development of solution porosity in specific settings where unconfined limestone aquifer recharged from the surface also receives the localized input of CO2-rich ascending deep waters at the bottom. The initial permeability structure in the highly idealized aquifer is represented by a rectangular net of fractures with apertures selected from a truncated log-normal distribution. The study focuses on

scenarios where both waters (that from the surface recharge and that from the deep source) are saturated with respect to calcite when they interact in the phreatic zone and dissolution is caused by their mixing, although scenarios are also modeled where one or both waters retain the aggressiveness.

Modeling hypogene karstification (speleogenesis) is highly relevant as its regularities and peculiarities are much less studied than those of more familiar epigene karst. This is especially true considering the great variability of settings and processes of hypogene karstification. This study models speleogenesis in particular settings (as outlined above) by the particular processes (mixing dissolution by carbonic acid) and provides insight into the regularities and peculiarities of speleogenesis in the modeled situation. The modeling part of the work is excellently realized for the chosen settings and conditions.

There are, however, some questions regarding the general presentation of hypogene karstification (Comments 1a-1c below), proper appraisal of previous modeling studies (Comment 2), and how representative is the modeled setting for hypogene karstification (Comment 3a-3c).

1a. Some statements regarding hypogene karst are inadequate and misleading due to the overgeneralization of specific situations. The authors state in Abstract (lines 9-10) that "Hypogene caves originate from upwelling deep-seated waters loaded with CO2 that mix with meteoric waters in a limestone aquifer." This, however, defines only one specific mechanism and situation of hypogene speleogenesis, modeled in this study. It is neglected that hypogene caves originate from a number of processes, including those in which CO2 and mixing are not involved, and in different lithologies, not only in limestones.

1b. In line 54, the authors open the listing of "various agents active in hypogene speleogenesis" but the subsequent list includes only two of those considered in the relevant literature: (A) dissolution of limestones by sulfuric acid (aka sulfuric acid speleogenesis

– SAS) and (B) dissolution of limestones by carbonic acid (aka carbonic acid speleogenesis – CAS). This listing ignores other agents active in hypogene speleogenesis, for instance in evaporite rocks or in silicate rocks, and therefore it should not be introduced in this general form.

1c. It is argued in Discussion (line 446) that “CAS is similar to sulfuric acid speleogenesis (SAS)”. In the subsequent paragraph, this statement is reasoned by that SAS and CAS similarly develop in unconfined aquifers from mixing of water from the surface with water rising from the depth. This, again, is an inappropriate generalization of the modeled situation to carbonic acid speleogenesis in general. For instance, carbonic acid speleogenesis in deep settings due to retrograde solubility of calcite in rising and cooling CO2-rich thermal waters (aka hydrothermal speleogenesis) is regarded to be one of the most common types of hypogene speleogenesis but it is in no way similar to SAS.

2. In several places in the text, this study is inappropriately presented as the first step in numerical modeling of hypogene speleogenesis whereas a number of works exist where it has been modeled in other settings and with other chemical processes (see references in the S.Birk’s comment). At least one study (Gong et al., 2019) has modeled hypogene karstification in settings similar to that explored in this work. Thus such general claims of priority must be avoided and appropriate citation of other modeling works is needed when the authors refer to hypogene speleogenesis in general (lines 10, 50-51, 459). I agree with the other referee (S.Birk) that comparison with other modeling studies and more discussion of other related works should be recommended.

3. How realistic and common in natural conditions is the modeled situation? Some discussion is needed why this particular modeling domain and setting are chosen to model hypogene karstification and how representative is the modeled situation. In my opinion, it seems to be of rather limited importance in nature. Some of the reasons for this appraisal are outlined below.

3a. The input of the deep waters from below is designed in this study as a region (a “window”) at the otherwise impermeable bottom, through which this rising water enters in a dispersed way into numerous “common” fractures in the limestone, forming the separate flow domain in the unconfined aquifer. In reality, a much more common mode of the input of deep waters into a shallower aquifer is through highly localized cross-formational tectonic disruptions such as faults and large fractures (so called “through-going” fractures) that cross both, the confining unit at the bottom and the shallower aquifer. The deep water remains largely canalized in a large fracture during further ascent and mixing occurs in and around it through the interaction with flow in the net of “common” fractures.

3b. From the perspective of geological evolution, a limestone aquifer commonly becomes unconfined as the result of uplift and denudation of the stratified formation, i.e. through the removal of the upper confining unit. This means that the now unconfined aquifer was once part of a confined aquifer system in which localized cross-formational hydraulic communication occurred. Such vertical communication (and hence the ascending input into the given aquifer) commonly occurs during long time spans on the way of the given formation from burial to the shallow subsurface and is particularly intensified when the upper confining unit is getting thinner and eventually locally breached. Thus, the inputs of the deep waters from below are usually inherited in the active state from the confined situation but not open after unconfined conditions have established.

The expected result would be (using the same chemical properties of two waters - the aquifer water and the rising deep water) that prior to the complete unroofing the given aquifer has experienced some hypogene karstification due to mixing dissolution so that substantial heterogeneity of the permeability structure would be present. In other words, the initial condition of a non-karstified aquifer that once starts receiving the localized input of the deep waters at the bottom seems to be unrealistic. It is worth to mention that the authors shown through their modeling exercises the great role of initial heterogeneities in the development of karstification patterns and emphasized as the finding that "the early state of cave evolution determines its final pattern" (line 470).

There may exist unconfined limestone aquifers that have not experienced burial yet, e.g. eogenetic limestones in young carbonate platforms. The modeled domain and setting may be relevant to this situation although (1) the fracture networks in eogenetic carbonates are commonly less regular and certainly differ from that inserted in the model, and (2) syngenetic karstification is likely to create considerable heterogeneity in the beds which, upon burial beneath younger beds, host the phreatic zone of the modeling domain.

3c. Two interacting waters (the aquifer water and the rising deep water) are taken in this study as of equal temperature and density, which is not common in such situations. The density differences between the two sources, if accounted for, would certainly have an impact on the flow pattern, mixing, and karstification.

In summary, this study provides insight into the mechanism of karstification in the chosen type of settings. However, revision is recommended with regard to the following aspects: (1) more adequate general presentation of hypogene karstification and clear acknowledgment that this study characterizes only one specific situation of it; (2) recognition of other modeling studies of hypogene speleogenesis; (3) discussion explaining why this particular setting is chosen to model hypogene karstification and how representative is the modeled situation.

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