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Interactive comment

Interactive comment on "Dynamics of wormhole formation in fractured karst aquifers" *by* Wolfgang Dreybrodt and Franci Gabrovšek

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This is a carefully prepared paper on a highly technical topic, and it sheds light on a common problem of interpretation of groundwater flow through soluble rock. None of my comments suggest errors or misunderstanding by the authors. They are only suggestions for enhancing clarity. Nearly all comments are simply to enhance the clarity of the text (English is not the primary language of either author).

PAGE / LINE 1/1 – Wormhole formation in fractured "karst aquifers" may be misleading, because it suggests mature aquifers that have already acquired solution conduits and related geomorphic features. Perhaps "fractured limestone" would be more appropriate. Karst can also develop in other lithologies, but the dynamics discussed in

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this paper refer only to calcitic limestone. 2/6 – The measurements demonstrating this switch was that of Plummer and Wigley (1976) Geochimica et Cosmochimica Acta v. 40, p. 191-202. White (1977) based his suggestion on the data and interpretation in this paper. Wigley is (or was at that time) a karst scientist with specific interest in the kinetics of cave origin, although the 1976 paper did not pursue details on that topic. 2/25-26 – I agree with the authors (Dreybrodt and Gabrovsek) on this statement. 4/3 – Specifying these two concentrations assumes that calcite (limestone) is the soluble medium, as noted in line 4/17. 4/20 – Assuming standard temperature is maintained in system. 5/3 – ".. in a fracture i. . .." – In line 4/10, "i" is used to define the position of a node in one of the two dimensions, rather than a fracture. Meaning is clear, however. 6/18 – This is an important point, because a tiny penetration of water at zero c concentration through a very narrow opening will appear to drive the fluid to supersaturation in the model. This has given some modelers the wrong impression that no further dissolution can take place in the fissure. The authors are aware of this problem, although readers and other modelers may come to incorrect conclusions (for example, that there is a minimum aperture below which no dissolution can take place). It may be appropriate to make brief mention of this point. 7/6 – "Periodic" conditions = unclear. Would "variable" be more appropriate (i.e., varying with time)? 8/1 – ". . ..which occurs in some fracture in the net at that time." This is unclear – does "some fracture" refer to "any fracture"? Both authors are fluent in English, but some word usages in the language are difficult even for native speakers. (See next item.) 8/4 – "transversal flow" = transverse flow (widely preferred version). Also elsewhere in paper. 9/4 - . . .flow into the latter. . . 9/6 - . . . also retarded and eventually stop growing. (The 'retarding' continues.) 10/22 – "Comparison between the case with no seeds (. . ..) and. . ... 12/2 – "competition between two wormholes (for clarity). 12/14 – ". . . the vertical outflow increases and, consequently, the input flow rises." The rate of inflow is the result of greater overall efficiency of the conduit, rather than the result of increasing vertical outflow. (Both depend on continuity of flow and are the result of greater efficiency.) So a minor change in wording is suggested. Figure 8b – Are the ∼harmonic fluctuations in the lines caused by instability in the calculated values as the result of steps in the finite-difference calculations? They may be misleading to those unfamiliar with this kind of calculation. Would a brief explanation be appropriate? 14/7 – "….all remaining fractures… are insoluble." The meaning is clear, but of course it's the fractured medium that is insoluble (i.e., the walls of the fractures), not the fractures themselves. See also 14/18 and 15/6. Figure 11 – caption - …. "function of time distance to the breakthrough" is unclear. Apparently this should be "time minus breakthrough time", or (t – Tb). 15/2 – As soon as one wormhole…." 15/3 – "…emits transverse flow that increases its input flow." Here also, it appears that the increased inflow (and outflow) is in response to increasing overall efficiency of the conduit, rather than the result of increasing outflow at the tip. On the other hand, if water in the growing tip is being attracted by the porous medium that it is invading, as when water enters a dry sponge, then my statement is less appropriate. 15/14 – "…. and the wormholes develop at different rates. The transverse flow patterns, both upward and downward from the upper wormhole, are symmetric……, the transverse hydraulic gradients…. 15/18 – inflow of aggressive water into the upper wormhole… 15/19 – add comma after "faster". 16/Fig 12 – This looks complex, but anyone reading it carefully should understand it. 17/Fig. 14 caption – Labels correspond to those in Figure 12. 17/10 - ….crossed by transverse flow. 18/10 – domains of upward and downward flow from the…. 18/13 – "horizontal" flow on graph is probably not horizontal in the real aquifer. Perhaps best to say "parallel", or "parallel to the horizontal axis". 18/18 - … growth in Fig. 12a 20/2 – change "even" propagation to "uniform" propagation. 20/3 – "equivalent fractures breaks down and… 20/8 - … starting at individual seeds, …. 20/15 - ….to the output boundary are expected (?) 21/8 – channel, input flow is greater than… (for clarity) 21/18 – From our findings so far, … 21/23 - …a few tenths of a cubic centimeter per second. 22/1 - .. almost uniform rate of penetration… 22/2 – If the net is insoluble…. – clarify to show how wormholes can develop in an insoluble net. 22/7 – for clarity, would it be better to write "…. development of a uniform dissolution front retards breakthrough"? 23/6 – add space: …2005b; Szymczak…. 24/16 – "horizontal" in this case means parallel to the "X" axis. 25/16 – Meaning of uniform "compact" dissolution front = ? 26/8 – Perhaps clearer = ". . .fracture that has just been reached by the wormhole." 26/10 – Clarify "dimensions of 1 cm by 1 cm and a width of 1 cm." Should "width" refer to the larger block outlined in black, and therefore is greater than 1 cm? Or does it refer to thickness of the model? 26/14 – downstream resistivity – should this be "resistance", to distinguish it from the geophysical property of electrical resistivity? However, its meaning is clear. 27/19 - . . .dissolution along them penetrates. . .. 27/25 – "seed" fracture presumably has an initial width advantage (rather than increasing its width uniformly with time) –? Note: Because this is a simplified model used for explanation, perhaps add a comment that reference to "years" does not necessarily correspond to conditions in real aquifers.

Additional comments The value of this paper is that it shows how minor variations in initial fracture network and recharge/discharge boundaries can affect breakthrough time in an incipient karst aquifer. It shows the importance of scale in numerical modeling of such a system. The criticism of Szymczak and Ladd shows the importance of scale in these models. As we look more closely at the system, as is done in this present paper, it appears that the same concepts and functional relationships remain valid, even at a tiny scale. In conclusion, it appears that an understanding of the functional relationships of the many variables is the most valuable tool. In a real aquifer it is impossible to predict the exact initial conditions – but by recognizing the importance of heterogeneities it is possible to anticipate the controls on development of conduits within it. Or, working backward from a mature karst system, it is possible to reconstruct the initial conditions that governed the distribution of conduits. In this way, the nature of the initial aquifer and its evolution can be inferred. I am confident that the two authors have a full understanding of karst systems and of their modeling. They are the leaders in this field. However, questions posed by other authors are helpful in directing attention to potential mis-interpretations, and this exchange of ideas is healthy.

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