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Effect of fracture network geometry on density-driven flow in fractured porous rock

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Density-driven flow can be a highly efficient transport mechanism in hydrogeological systems, especially if head gradients as a driving force for groundwater movement are absent. Unstable density layering may lead to variable-density, free-convective flow. Convection cells may form whose number and shape depends on the prevailing concentration and temperature gradients. The presence of open fractures may complicate the free convective flow pattern because fractures represent preferential pathways where water flow velocities can be considerably larger than in the rock matrix. Therefore, the purpose of this study is to provide insight into the structural properties of fracture networks that determine flow and transport patterns and to make a statement on the applicability of the equivalent porous medium approach (EPM).

We systematically study free convective flow in continuous, discontinuous, orthogonal and inclined fracture networks embedded in a low-permeability rock matrix. Layer stability and convection patterns for different fracture networks are compared to each other and to an unfractured base case representing an EPM. We examine rates of solute transport by monitoring the mass flux at the solute source and relate it to the critical structural properties of the fracture networks. Simulations are performed using the numerical variable-density groundwater flow and transport model HydroGeoSphere. Fractures are represented as discrete fractures, whose geometric properties are explicitly defined. Fracture permeability is calculated using the cubic law. Results show that for free convective flow, the EPM approach is not able to reliably represent a fractured porous medium if fracture permeability is more than 5 orders of magnitude larger than matrix permeability. Nonetheless the EPM approach can be a reasonable approximation if the fracture network (i) evenly covers the simulated rock, (ii) is of high fracture density, (iii) is well-connected, (iv) contains fractures whose length is close to the domain size. Fractures tend to destabilise the system and promote convection if fracture spacing is large, if fracture aperture is high and if fractures form closed circuits. In that case the fracture network provides continuous high-velocity flow paths throughout much of the domain. Closed circuits are most effective in terms of mass transport if they cover a large area and have a large vertical extension. Simulations of discontinuous fracture networks show that a continuous fracture path between solute source and sink is not necessary for free convection. Therefore, knowledge of the equivalent permeability of a fractured porous medium is not sufficient for the prediction of free convective flow. In addition, the geometry of the fracture network has to be considered.