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ESSAY

# Topical Collection: Progress in fractured-rock hydrogeology

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**Abstract**
The development of hydrogeology with respect to hard-rock and fractured-rock aquifers is described. The differences between porous aquifers and karst are explained, as well as the groundwater flow regimes in the different fractured rocks. A position is taken on numerical modeling, from the beginning of modeling to the present day, with focus on particular challenges. Because of the importance of fractured-rock aquifers, the tools for groundwater exploration and future resource management are mentioned. The essay introduces a topical collection of articles.

**Keywords** Fractured rocks · Groundwater flow · Fracture rock models · Groundwater management

## Background

Hard-rock aquifers were the general topic of the 17th Congress of the International Association of Hydrogeologists (IAH) in Tucson, Arizona (USA) in 1985 ("Hydrogeology of Rocks of Low Permeability", in Struckmeier et al. 2016). Prior to that, issues surrounding the hydraulic conductivity of these low-permeability rocks had become important due to proposals for nuclear waste disposal in hard rocks in various European countries. In 1993, the theme of the 24th IAH Congress was "Hydrogeology of Hard Rocks", which brought these relatively impervious rocks into the field of groundwater resources (Krasny and Mls 1996). This focus followed especially the popularization of the down-the-hole hammer drilling method of the 1970s and 1980s, which is particularly appropriate when drilling such hard rocks. Within Europe, various workshops on the Bohemian Massif and the Fennoscandian Shield followed. The main findings were from the Äspö Hard Rock Laboratory in Sweden, which was established in 1996 (Bjurnström 1996). The IAH working group on hard-rock hydrogeology was founded in 1994 by members of the Bohemian Massif subgroup (Krasny and Mls 1996) and is now the active IAH Network on Fractured-Rock Hydrogeology. The first international workshop of the Iberian subgroup on hard-rock hydrogeology was in 1997, with experiences from the Iberian Peninsula and Bohemian Massif (Yélamos and Villaroya 1997). The first meeting of the Fennoscandian subgroup was in 1998 (Rönkä et al. 2005) and the Middle and East Mediterranean Regional Group held its first meeting in Hellas, Greece, in 2002 (Rönkä et al. 2005). International congresses followed, notably in Prague (Czech Republic) in 2003 and 2012, and in La Roche sur Yon (France) in 2015, along with symposia and regional workshops, and the progress in research and development on hard-rock hydrogeology was documented in two IAH Selected Papers series, known as green books ("Groundwater in Fractured Rocks", Krasny and Sharp 2007 and "Fractured Rock Hydrogeology", Sharp 2014). The study of hard-rock aquifers was renamed as 'fractured-rock hydrogeology', to include soft rocks and other aquifers. A network of fissures and fractures is common to all consolidated rocks and is the dominant transport route for groundwater. The last regional international workshop was held in Chaves, Portugal, in 2017 ("Groundwater in Fractured Rocks" or GwFR) by the Portuguese and Spanish IAH Chapters (Iberian subgroup).

Because of their complex structure, fractured rocks are still an important field for research, especially since these aquifers are becoming increasingly important on all continents. This essay is part of the topical collection "Progress in fractured-rock hydrogeology", which describes advances in the various fields of fractured-rock hydrogeology.

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## Fractured rocks basics

In hydrogeology, fractured rocks correspond to all kinds of rocks that are sufficiently hard to break when subjected to strains. This is particularly the case in hard rocks such as plutonic or metamorphic rocks. The geological definition of a fracture is any kind of break in a rock formation, for example joints and faults. Fractures are important for groundwater flow, as they can favor water flowing inside impervious rock bodies. This is what is called "secondary porosity", in contrast to other kinds of rocks where "primary porosity" (pore porosity) is dominant. Fractures can also originate from lithification (diagenesis), such as in marlstones or lime marl where dissolution processes do not take place.

Fractured rocks are represented by all the lithologies where secondary porosity is more important for water storage and flow than primary porosity. This is mostly a characteristic of igneous and metamorphic rocks but fractures occur in sedimentary rocks too and play an important role in water transport. Thus, some sedimentary rocks are considered fractured rocks when their porosity is mainly represented by fractures (secondary porosity).

Groundwater flow in fractured rocks is almost always enabled by the network of fractures. In weathered hard rocks, (mostly vertical) flow also occurs in the porous unconsolidated part of the weathering profile, called the saprolite. Then, the aquifer is constituted by both the saprolite, which mostly exhibits storage properties, and the underlying fractured layer that mostly exhibits transmissive properties. In these types of rock, scale is an important factor; if at a given scale—greater than a few hundred meters—the flow can mimic a porous medium, and at a very local scale, the flow can be almost totally directional.

Krásny (1996) and Lachassagne et al. (2011) among others demonstrate that hard rocks have three to four layers of interest in terms of hydrogeological characteristics. Krásny (1996) describes three layers that represent the geological environment of a hard-rock aquifer: an upper weathered bedrock, a middle fissured bedrock, and an unweathered bedrock. Thus, the productivity of a well is dependent on the groundwater level, the thickness of the two first layers, the resulting weathering characteristics of the upper two layers, and the number, length, dip, fracture intersection, dilation, and composition and filling of the fractures in the second and third layers (Krásny 1996). Lachassagne et al. (2011) demonstrate that the two first layers (the saprolite, and the underlying fissured/fractured layer) both belong to the weathering profile, fractures appearing during the weathering process, just above the weathering front in the deepest part of the weathering profile.

Essential findings on the fracture network and the groundwater flow in deep layers of hard rocks were reported early on from the Äspö Hard Rock laboratory in Sweden (Knutsson 1998). The fractures are well connected, so that water-bearing fractures, although with a very low yield, far beyond the one required for a groundwater resource well, were also found at a depth of 1,800 m.

Sharp et al. (2014) undertook important laboratory research about the behavior and properties of fractures. Upscaling from cores to big blocks showed the discontinuation of fractures in vertical and horizontal directions. This real test showed the difficulty of predicting flow in hard-rock fractures. This also shows the challenge for successful drilling for water supply and when creating conceptual and numerical models.

## Conceptual and numerical models

The elaboration of conceptual models is particularly important for understanding the hydrogeological conditions (Kresik and Mikszewski 2013). Models are particularly important in fractured rock, and they require a very good understanding of the permeable and capacitive structures (e.g. the fractured layer and the saprolite) and their genesis, also the chronological order.

The network of fractures, or at least the presence and thickness of the transmissive fractured layer and the capacitive saprolite, is crucial so that groundwater can flow. The use of digital elevation models, most of them obtained by remote sensing, as well as field observations on outcrops and geophysical measurements, also enable mapping of the layers of the weathering profiles. Hanslik and Jhoda (1997) developed a representative elementary volume (REV) for a hard-rocks conceptual model to obtain a basis of groundwater flow for a numerical model.

Numerical models in fractured rocks were used early (Mls 1996) and have improved a lot over the years. The problems of validation are usually quite significant because the amount of data available is small. The density of fractures and their opening and interlinking are essential for the continuous movement of water within the aquifer.

Without a good structural model, defining the boundaries is also difficult. Finite element models are used because the cell size and shape are variable; however, the numerical modeling of such fractured rocks continues to pose great challenges for the modeler. Modelling the weathered layers (saprolite, fractured layer) of hard-rock aquifers is easier as these layers can be mapped, and REV more easily defined. The models are often viewed very critically, since with their support, a waterworks facility can ultimately estimate certain yields of the aquifer. Unfortunately, however, the simplification of numerical models often results in an expectation of greater productivity for fractured rocks.

## Groundwater management in fractured-rock aquifers, remote sensing and hydrogeophysics

Generally, hydrogeologists consider fractured-rock aquifers as being of low permeability and low productivity, due to the difference of these characteristics when compared with aquifers in porous, volcanic or karstic rocks. In Europe, these areas were considered, in the basin hydrologic plans, as low productivity sectors, not even recognized as a "water mass", due to their low productivity; however, at the global scale, the water stored in this aquifer type is much more important than this description indicates. Even in Europe, these aquifers largely contribute to sustaining the low-stage discharge of rivers in hard-rock regions, and many individual domestic supplies in more isolated areas, as well as gardens and cattle-drinking supplies are based on these waters. Oefterdinger et al. (2019) gave many literature references in an introductory article about managing fractured rock aquifers.

In some continents where fractured rocks are present in large areas (such as Africa, India, Australia, large regions of South and North America), the only source of water comes from these types of aquifer. Thus, groundwater in fractured aquifers is a significant resource for local populations, especially in arid to semiarid regions and where the surface water is contaminated. The fact that the groundwater resource is normally available at shallow depth in many areas makes the aquifer accessible using hand drilling methods, which is essential in more remote and less developed regions.

Percussion drilling rigs provoked a revolution in the use and study of hydrogeology of hard-rock aquifers during the 1970s, as they enabled the underlying fractured layer to be reached with small-diameter boreholes, to increase the discharge of the wells. Such aquifers and boreholes largely enabled the Indian "Green Revolution", but not without drawbacks, as a large proportion of hard-rock aquifers is overexploited in India (Singh and Singh 2018). Good water management could ensure better security of supply, notably with the use of the modeling tools described in the preceding. However, drilling deeper and deeper when the piezometric level decreases is counterproductive in hard-rock aquifers as the specific yield decreases with depth (Maréchal 2010).

Takorabt et al. (2018) used remote sensing data and geophysical methods to explore groundwater recharge in a deep aquifer. Only large fractures were considered for this. The combination of the methods led to a successful detection of the flow paths in the deep aquifer.

The use of modern remote sensing methods is becoming increasingly important for groundwater exploration and management, for undeveloped areas difficult to access.

Geophysical methods in fractured rocks are extremely useful tools. One book worth mentioning is *Hydrogeophysics* (Rubin and Hubbard 2005). GIS has made mapping in fractured rocks easier and more accurate. Hydrogeologic maps are particularly important in multilayer systems. The creation of hydrogeological conceptual and numerical models is the basis for groundwater exploration (Chaminé et al. 2015).

## Challenges in fractured rock research

In many areas of the world, supplying water from fractured rock aquifers is a major challenge. In arid to semiarid areas, where surface water is lacking, there is no alternative to this kind of groundwater resource. The main challenge is not only to appropriately site new water wells, but also to manage the groundwater resource for sustainable development. Lots of effort has recently been directed towards developing groundwater management tools in granite-type hard-rock aquifers, with highly valuable achievements. Metamorphic hard-rock aquifers have a much more complex structure and must also now be the focus of similar research activities. The aim will be to better characterize the aquifer structure, and in particular the structure of the saprolite and fractured layers, and their functioning, and to develop appropriate management tools.

In humid climates, management of fractured rock aquifers faces the challenge of preventing contamination from agriculture and industry, because runoff from these aquifers is a major contributor to surface-water quality. Whatever the climatic context, aquifer engineering techniques such as those developed in other hydrogeological contexts (e.g. artificial recharge) must also be applied to these complex fractured rock aquifers.

For optimization of groundwater management, multidisciplinary strategies are necessary. The structural geological evaluation uses remote sensing options, since detailed onsite work requires great effort and is cost-intensive; nevertheless, remote sensing must strictly be validated with field checks. The development of hydrogeophysical methods will also surely contribute to the knowledge and understanding of fractured rocks. The challenge is now to distinguish, from the surface, water-bearing fractures in the fractured horizon from similar but clogged and then sterile fractures. This target, though still far from being reached, would dramatically enable an increase in the success rate of water wells.

Tunnel constructions pose special challenges. Unexpected groundwater inflows are usually the reason for delays in completion. Precise prediction of groundwater conditions is essential, as tunnels are expensive and engineering failures can therefore have serious consequences (Coli and Pinzani 2014). In fractured rocks in particular, the fracture behavior in the various stress states and the groundwater flow regime have not yet been sufficiently researched. The knowledge that Sharp et al. (2010) gained on tomography of large blocks needs to be deepened. The precise modeling of the whole cycle of weathering–fracturing–reweathering and clogging or fracturing, etc., at the scale of the sets of fractures from the saprolite and fractured horizon, is a more theoretical challenge. It may however lead to a better forecast of the geometry and hydrodynamic properties of fractured rock aquifers. A comprehensive summary of hydrogeologic problems in the engineering-geologic domain has been provided by Gustafson (2012).

Numerical modeling still encounters major problems when considering multiporosity. As the experiments by Sharp et al. (2014) showed, large variations in the fracture width in both horizontal and vertical dimensions are normal. Fractures can be from several centimeters to millimeters wide. A continuity of the openings across wide areas and the formation of a corresponding network is often not the case. From the results of hydrogeophysical and remote sensing investigations, several aspects of a large-scale solution to the flow simulation of fractured aquifers can arise.

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**Note** This topical collection brings together selected studies illustrating hydrogeologic problems that were presented and discussed at the international conference on ‘Groundwater in Fractured Rocks’, Chaves, Portugal, in 2017. The articles are: Lachassagne et al. (2021), Blake et al. (2021), Moore and Walsh (2021), Balvín et al. (2021), and Naves et al. (2021).

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