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**Groundwater in Fractured Bedrock Environments: Managing Catchment and Subsurface Resources**

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ACCEPTED MANUSCRIPT

Hard rocks, including crystalline igneous, metamorphic and strongly cemented sedimentary and carbonate rocks cover about 50% of the earth's land surface (*Singhal and Gupta, 2010*). Globally, the volume of groundwater contained in hard rock aquifers is not well constrained (*Comte et al., 2012*), but locally they can be important aquifers (*MacDonald et al., 2012*), albeit with low groundwater storage and poor primary porosity and permeability. Groundwater flow in these hard rocks is commonly observed to be associated with water bearing discontinuities, such as fractures, joints and faults (*Berkowitz, 2002; Mazurek, 2000; Font-Capo et al., 2012*) and in the weathered regolith (*Wright 1992, Chilton and Foster 1995; Deyassa et al., 2014*). Structural elements such as fault zones also strongly govern the behaviour of these systems (*Forster and Evans, 1991; Lopez and Smith, 1995, Bense et al., 2013*). The nature, abundance, orientation and connectivity of these water-bearing features are largely governed by the history and nature of structural deformation of the bedrock and commonly impose strong anisotropic flow and transport parameters on these bedrock aquifers (*Hsieh et al., 1985; Bour and Davy, 1997; Mortimer et al., 2011*). Weathering processes furthermore lead to an alteration of bedrock composition and associated aquifer properties resulting in enhanced fracture connectivity and an overall vertical stratification/zonation of bulk aquifer properties, ranging from highly altered shallow regolith horizons to more competent sparsely fractured bedrock at depth (*Dewandel et al., 2006; Krasny and Sharp, 2007; Lachassagne et al., 2011*).

Aquifer parameters governing flow and transport behaviour in these complex bedrock aquifers exhibit specific depth-dependencies (*Davis and Turk, 1964; Snow, 1968; Marechal, 2012, Comte et al., 2012; Sandford, 2017*) linked to weathering processes and the nature, orientation and connectivity of water bearing discontinuities with depth. Uplift processes commonly impose additional sub-horizontal stress-relief joints leading to higher degrees of connectivity between more steeply dipping fractures and thus increasing the degree of storage and water circulation at shallow depths (*Raven, 1977; Cruchet 1985, Martel, 2017*).

Characterising the flow regime and hydrogeological parameters for these fractured bedrock aquifers poses particular challenges due to their heterogenous and anisotropic nature across varying scales of observation (*Clauser, 1992; Bonnet et al., 2001; Oxtobee and Novakowski, 2002*). A variety of characterisation and monitoring techniques find their application in fractured bedrock environments, ranging from traditional hydrogeological techniques such as well hydrograph monitoring and time-series analysis (*Molénat et al., 1999; Chae et al., 2010; Jimenez-Martinez, 2013*), hydraulic well testing (*Marechal et al., 2004; Neuman, 2005*), active tracer experiments (*Gelhar et al., 1992; McKenna et al., 2001; Maldaner et al., 2018*) and hydro/geochemical and environmental isotope studies (*Ayraud et al., 2008; Ofterdinger et al., 2004*) to multi-scale geophysical surveying techniques such as well-logging, ground-based and airborne geophysical surveys (*Rubin and Hubbard, 2005; Vereecken et al., 2006; Cassidy et al., 2014, Binley et al., 2015*) and other air- and satellite-borne remote sensing techniques (*Becker, 2006; Meijerink et al., 2007*).

Various conceptual approaches have been developed in the past decades to describe and model the groundwater flow through fractured rock masses (*NRC, 1996*), ranging from equivalent continuum models (*Carrera et al., 1990; Bear, 1993; Hadgu et al., 2017*) to discrete fracture network simulation models (*Dverstorp and Andersson, 1989; Cacas et al., 1990a, b, c; Davy et al., 2006; Makedonska et al., 2015*). Numerical simulations have been employed to investigate flow and transport processes from the local to the field and catchment scale (*Janos et al., 2018; Jaunat et al., 2016; MacQuarrie*

and Mayer, 2005), reconciling scale-specific monitoring data or aiming to integrate multi-scale surveying data. Numerous case studies have been performed in fractured crystalline rock in the framework of the safety assessments for nuclear waste repositories (Herbert *et al.*, 1991; Neretnieks, 1993; Joyce *et al.*, 2014), investigating flow and transport phenomena on the small scale and on a regional scale (Voborny *et al.*, 1991; Voborny *et al.*, 1994). Observations in subsurface galleries have been used to investigate groundwater flow systems within fractured crystalline rocks on a regional scale (Kitterod *et al.*, 2000; Marechal and Etcheverry, 2003; Walton-Day and Poeter, 2009; Marechal, 2012). Over recent years modelling efforts have focussed on developing robust thermal-hydrodynamic-mechanical models to characterise more comprehensively the behaviour of fractured bedrock environments at depth, for example in the context of geothermal installations and carbon capture and storage schemes (Hudson *et al.*, 2001; Rutquist *et al.*, 2014, Bandilla *et al.*, 2015, Kolditz *et al.*, 2016).

Despite the commonly encountered low yields of these fractured bedrock aquifers, these complex bedrock aquifers play an important role in water resource management and are key to understanding the potential impacts from the competing demands for the use of the deeper subsurface. At shallow to intermediate depth, fractured bedrock aquifers help to sustain surface water baseflows and groundwater dependent ecosystems (Whiteman *et al.* 2017), provide local groundwater supplies and impact on contaminant transfers on a catchment scale. At greater depths, understanding the properties and groundwater flow regimes in these complex bedrock environments can be crucial for the successful installation of subsurface energy and storage systems, such as deep geothermal or aquifer thermal energy storage systems and natural gas or CO<sub>2</sub> storage facilities (Bricker *et al.*, 2012), for the siting of nuclear waste repositories as well as for the exploration of natural resources such as conventional / unconventional hydrocarbons. In many scenarios, a robust understanding of fractured bedrock environments is required to assess the nature and extent of connectivity between such installations and/or explorations at depth and overlying receptors in the shallow subsurface or above ground. Figure 1 illustrates some of the key hydrogeological contexts of fractured bedrock environments.

To this end, fractured bedrock environments have seen continued interest by researchers and practitioners, albeit with varying focus over the decades. An ontology-based search of the bibliographic indexing service Web of Science (WoS; Levine-Clark *et al.*, 2008; Chavarro *et al.*, 2018) indicates the shifting focus and interest of research in fractured bedrock environments. The WoS index was reviewed for publications published between 1990 and 2017 and matching specific search terms. Retrieved results were aggregated into two-yearly publication numbers (e.g. 1990/91, 1992/93, ..., 2016/17). Figure 2 illustrates the increasing research interest in fractured bedrock environments and the shifting background rationale for fractured bedrock studies and investigation methods applied.

In general, publication-rates in relation to fractured bedrock environments have steadily increased since the early 1990's, with a marked rate increase from the late 2000's. Publications on groundwater studies in fractured bedrock environments over the past three decades have seen an approximate 10-fold increase (Figure 2a). With regard to groundwater studies, water-supply and water quality-related publications have seen a steady increase over the past decades, with publications related to water resources showing more steeply increasing numbers from the late 2000's onwards (Figure 2b). Fractured hydrogeology studies related to geothermal, nuclear waste

repositories, hydrocarbons and Carbon Capture and Storage CCS have all risen over the decades (Figure 2c) with geothermal and hydrocarbon studies showing a dramatic increase since 2008. The major sector contributing to publications in the area of fractured bedrock environments are the geothermal and oil & gas sectors (Fig 2c). Publication rates for the latter sector show three distinct segments over the past three decades, with steady low increasing publication numbers from the early 1990s to the mid-2000s, a steeper rise in publication numbers between 2004/05 and 2010/11 and an even steeper increase since then. Bi-annual publication numbers for this sector have increased 4-fold since 2010/11, most likely associated with the increased research activity around the exploration of unconventional hydrocarbons.

With regard to methods commonly applied in the investigation of fractured bedrock environments, as reflected in published papers over the past three decades, publication numbers have seen some variations over the years (Figure 2d). Traditional hydrogeological methods such as Tracer Tests and Hydraulic/Well test have seen an increase in publication numbers over the decades. While publication numbers in relation to tracer tests increased during the 1990's, publication numbers in relation to this field method seem to have plateaued since. Publication numbers in relation to hydraulic/well testing have increased steadily at higher rates since the 1990's with a distinct increase in publication rates from the late 2000's onwards (Figure 2d). This may be related to the requirements for well testing in the context of increased geothermal applications and unconventional hydrocarbon exploration (Figure 2c). The application of geophysical methods for the study of fractured bedrock environments has produced a steadily increasing number of publications from a low base in the early 1990's. Similarly, numerical groundwater modelling studies for fractured bedrock environments have produced steadily rising numbers of publications over the decades. Recognising the limitations of an ontology-based review of publication numbers, the above nonetheless illustrates the continuing and rising interest in the research area of fractured bedrock environments over the past three decades and provides some insights into the changing focus of research activity in this area.

Responding to the continued interest in fractured bedrock environments, Queen's University Belfast hosted a 1-day conference on the 10<sup>th</sup> June 2016 entitled '*Groundwater in Fractured Bedrock Environments: Managing Catchment and Subsurface Resources*' as part of the Geological Society's '2016 Year of Water'. 16 talks and 11 posters were presented at the event from national and international authors to an audience of 80 delegates. The event was co-sponsored by the Hydrogeology Group of the Geological Society, the UK and Irish chapters of the International Association of Hydrogeologists (IAH), the Institute of Geologists of Ireland (IGI), the Geological Survey of Ireland (GSI) and the Geological Survey of Northern Ireland (GSNI). In the same year, the 43<sup>rd</sup> Annual Congress of the International Association of Hydrogeologists (IAH) in Montpellier, France hosted a specific session on the hydrogeology of fractured hard rock aquifers. This Special Publication reflects contributions made as part of these two events to the field of modern groundwater studies in fractured bedrock environments.

Hard rock aquifers play a dominant role in groundwater supplies in Sub-Saharan Africa (*MacDonald and Davies, 2000*). In their contribution to this Special Publication, *Adekile and Carter* pay tribute to Robin Hazell who devoted most of his extensive professional career to the development of groundwater in the hard rock aquifer systems of Sub-Saharan Africa, in particular across Nigeria. Robin presented at the Belfast Geological Society Conference in 2016 and passed away in March

2017. In a further contribution to this publication, *Fouche et al.* explore the typology of groundwater encountered in a granitic aquifer system in Ivory Coast, investigating geochemical facies as indicators for connectivity across saprolite and saprock units. *MacDonald et al.* provide insights into the permeability distribution in Cretaceous Shales of West Africa affected by dolerite intrusions. Traditional hydraulic well testing in highly tectonised Mediterranean hard rocks is employed by *Baiocchi et al.* to evaluate sustainable well yields. *Newton* applies dye tracing field experiments to investigate the dependence of conduit flow on groundwater levels in the karstified Carboniferous Limestone of the Eastern Mendip Hills (UK). *Kennel and Parker* investigate the use of acoustic borehole televiewer amplitude data to derive bulk porosity values for a dolostone aquifer and benchmark these against porosity values derived from traditional gamma-gamma and neutron log data. The effects of weathering processes on hard rock aquifers are investigated by *Belle et al.* and *Vasseur and Lachassagne*. *Belle et al.* employ Electrical Resistivity Tomography (ERT) to characterise the weathering profile while *Vasseur and Lachassagne* explore the thermal processes associated with the physico-chemical weathering of hard rocks. ERT together with Magnetic Resonance Sounding (MRS) is employed by *Comte et al.* to derive flow and storage properties for a metamorphic aquifer in northwest Ireland at relevant scales for the integration into numerical groundwater flow models. MRS-derived transmissivity data alongside more traditional hydrological monitoring data are used by *Dickson et al.* in developing basin-scale numerical groundwater flow multi-model analyses for metamorphic basement units in Benin. Model evaluations in this study aim to improve the conceptualisation of the weathered zone within these low productivity units and to assess their role for rural water supplies.

Contaminant transport through fractured hard rock aquifers presents complex challenges due to the combined processes of fracture flow and matrix diffusion. The transport of non-aqueous phase liquids (NAPLs) in this context poses additional challenges in terms of density-dependent flow components. Across two contributions, *Parker et al.* provide insights into the fracture network connectivity in a DNAPL-contaminated shale bedrock system using multiple lines of field evidence and present the results of a long-term investigation of DNAPL migration and high-resolution source zone characterisation in a fractured dolostone aquifer.

The competing demands for the exploration of subsurface energy resources versus the protection of water resources provides ongoing scientific and societal challenges. The rise of unconventional hydrocarbon exploration over recent years and observed environmental impacts from these activities adds to these challenges. However, at the same time, facing these challenges provides an opportunity for new proposed exploration projects to establish suitable monitoring programmes ahead of the start of exploration activities in order to minimise impacts on water resources. In this context, *Stroebel et al.* present an approach to comprehensive groundwater baseline monitoring across the Eastern Karoo Basin in the context of proposed Shale Gas extraction in the region.

Increasing our understanding of the behaviour of fractured bedrock environments continues to be a research challenge demanding multi-disciplinary approaches, in particular in the context of the competing demands for the use of the subsurface for engineered interventions and exploration activities on the one side and the need for protecting groundwater resources on the other. This Special Publication aims to make a contribution towards meeting this challenge.

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### Figure Captions

**Figure 1:** Typical hydrogeological contexts of fractured bedrock environments

**Figure 2:** a)-d) Two-yearly publication numbers for the period 1990-2017 as recorded by the Web of Science Index (*Clarivate, 2018*) for various combinations of topical search terms.

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