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Groundwater sources and geochemical processes in a crystalline fault aquifer

Clément Roques [a,*,1], Luc Aquilina [a], Olivier Bour [a], Jean-Christophe Maréchal [b], Benoît Dewandel [b], Hélène Pauwels [c], Thierry Labasque [a], Virginie Vergnaud-Ayraud [a], Rebecca Hochreutener [a]

[a] OSUR Research Federation – Géosciences, University of Rennes 1, CNRS, Av. Du Général Leclerc, 35 042 Rennes, France
[b] BRGM, Water Dept., New Water Resource & Economy Unit, 1039 rue de Pinville, 34 000 Montpellier, France
[c] BRGM, Water Dept., 3 Av. Guillemin, BP 36009, 45060 Orléans Cedex 2, France

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SUMMARY

The origin of water flowing in faults and fractures at great depth is poorly known in crystalline media. This paper describes a field study designed to characterize the geochemical compartmentalization of a deep aquifer system constituted by a graben structure where a permeable fault zone was identified. Analyses of the major chemical elements, trace elements, dissolved gases and stable water isotopes reveal the origin of dissolved components for each permeable domain and provide information on various water sources involved during different seasonal regimes. The geochemical response induced by performing a pumping test in the fault-zone is examined, in order to quantify mixing processes and contribution of different permeable domains to the flow. Reactive processes enhanced by the pumped fluxes are also identified and discussed.

The fault zone presents different geochemical responses related to changes in hydraulic regime. They are interpreted as different water sources related to various permeable structures within the aquifer. During the low water regime, results suggest mixing of recent water with a clear contribution of older water of inter-glacial origin (recharge temperature around 7 °C), suggesting the involvement of water trapped in a local low-permeability matrix domain or the contribution of large scale circulation loops. During the high water level period, due to inversion of the hydraulic gradient between the major permeable fault zone and its surrounding domains, modern water predominantly flows down to the deep bedrock and ensures recharge at a local scale within the graben.

Pumping in a permeable fault zone induces hydraulic connections with storage-reservoirs. The overlaid regolith domain ensures part of the flow rate for long term pumping (around 20% in the present case). During late-time pumping, orthogonal fluxes coming from the fractured domains surrounding the major fault zone are dominant. Storage in the connected fracture network within the graben structure mainly ensures the main part of the flow rate (80% in the present case). Reactive processes are induced by mixing of water from different sources and transfer conditions. A specific approach is applied to quantify the reaction rate involved along the pumping time. Autotrophic denitrification coupled with iron minerals oxidation is highlighted and water rock interaction is clearly enhanced by the flux changes induced by pumping.

1. Introduction

Groundwater resources in igneous and metamorphic crystalline rocks are often restricted within weathered subsurface fractured bedrock and saprolite that typically extends up to 50 m depth (Dewandel et al., 2006; Guihéneuf et al., 2014; Hencher et al., 2011; Maréchal et al., 2004; Wright, 1992). In deeper part of the bedrock, groundwater flows is mainly controlled by the presence of *fractures* in an impervious *matrix* (Banks et al., 2002, 1996; Clauser, 1992; Singhal and Gupta, 2010). The rock *matrix*, which refers to the porous structure of the fresh bedrock mass, is characterized by low permeable pores at grain scale and microcracks. The rock matrix controls groundwater storage and solute transport, even at great depth (Bucher and Stober, 2010; Ingebritsen and

* Corresponding author at: OSUR Research Federation – Géosciences, UMR 6118, University of Rennes 1, CNRS, Av. Du Général Leclercq, 35 042 Rennes, France.
E-mail address: roquesclem@gmail.com (C. Roques).
[1] Present address: Oregon State University, Department of Biological & Ecological Engineering, 116 Gilmore Hall, Corvallis, OR 97331, USA.

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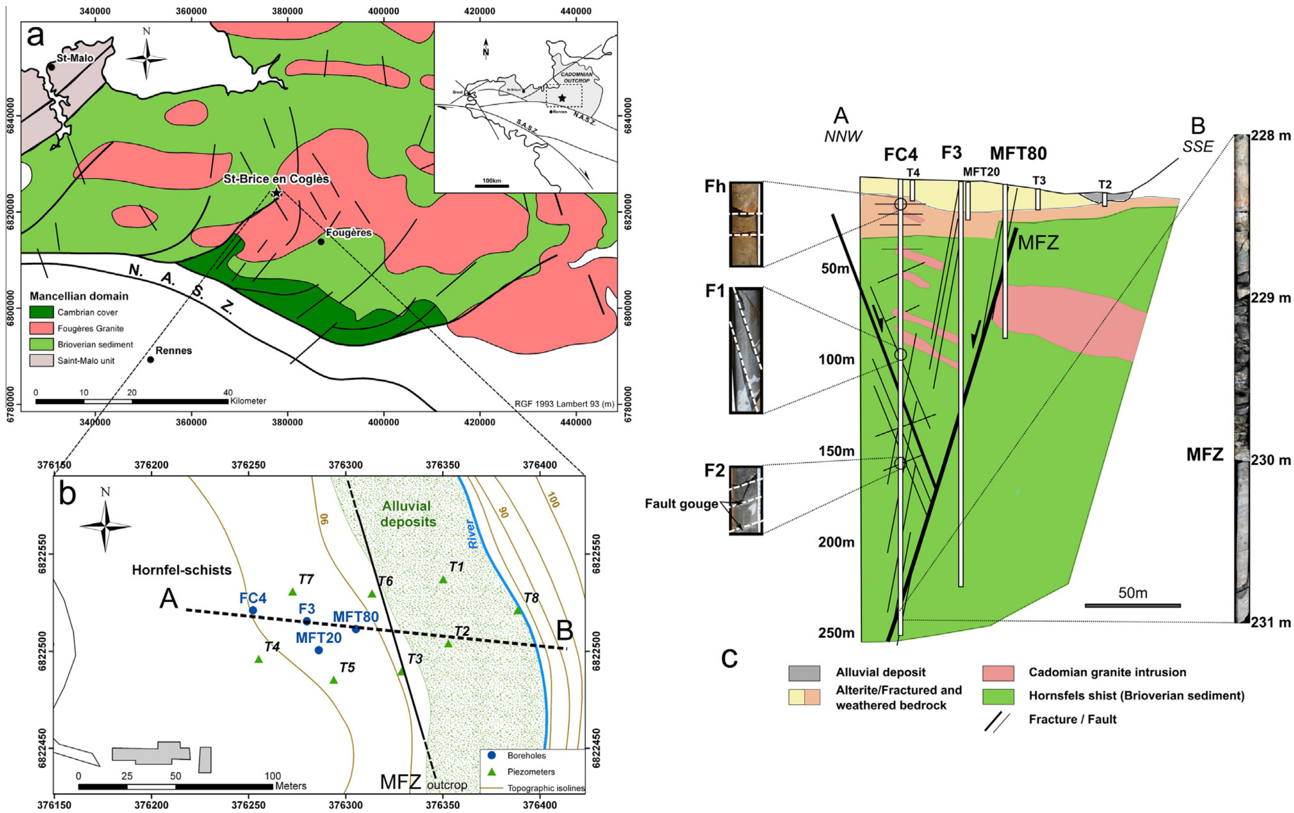

Fig. 1. (A) Regional geological map, (B) boreholes location at the field site and (C) Geological cross section and identification of fracture families. NASZ = North-Armorican Shear Zone; RGF = French Geographic Reference and MFZ = major fault zone.

Manning, 1999; Mazurek, 2000; Stober and Bucher, 2000. 1999; Waber and Smellie, 2008). The *fractures*, which consists in cracks, joints and faults may provide fluid pathways at depth when fracture permeability is large enough (Berkowitz, 2002; Singhal and Gupta, 2010; Stober and Bucher, 2006). Groundwater flow at depth depends on rock porosity, fracture aperture distribution and connectivity of the fracture network. Specifically, fault zones can affect a large area of a massif and can greatly influence fluid flow at the regional scale (Bense and Person, 2006; Bense et al., 2013; Evans et al., 1997; Forster and Evans, 1991; Gleeson and Novakowski, 2009; Rojstaczer et al., 1995). Fault zones are characterized by an internal structural complexity (Bense et al., 2013; Caine et al., 1996) which control their capacity to drain or to act as barrier to groundwater flow. High permeable fault zones have been described at relatively great depth (>200 m) in the Armorican Massif (Dewandel et al., 2014; Le Borgne et al., 2006; Leray et al., 2013; Roques, 2013; Roques et al., 2014) and in other crystalline basements (Holland and Witthüser, 2011; Mabee, 1999; Masset and Loew, 2010; Neves and Morales, 2006; Seebeck et al., 2014).

This structural heterogeneity implies that the nature of flow behaviour is highly complex and often challenging to constrain. Consequently, the origin and chemical composition of groundwater can vary considerably. Such variations may depend, not only on permeability properties and flux conditions, but also on rock mineralogy and residence-time, as well as the reactive processes involved along flow paths (Bucher et al., 2008; Fritz, 1997; Gascoyne and Kamineni, 1994; Gascoyne, 2004; Smellie et al., 1995; Waber and Smellie, 2008). Some studies have described a weakly mineralized groundwater composition with fast transfer conditions, while others have identified a highly mineralized composition, even salt water or brine, resulting from paleo-recharge and circulation processes (Armandine Les Landes et al., 2014; Bucher and Stober, 2010; Cook et al., 2005; Fritz, 1997; Stober and Bucher, 1999).

In the water abstraction context, it is commonly stated that to ensure a long-term pumping rate, the local transmissive structure should be connected to a widespread fractured network (Stober and Bucher, 2005). The low storativity of the local fractured bedrock can be also compensated either by matrix water stored in adjacent rock (Moench, 1984; Warren and Root, 1963) or by storage in connected reservoirs (Dewandel et al., 2011; Leray et al., 2013; Neves and Morales, 2006; Roques et al., 2014; Stober and Bucher, 2006). In the case of fault, models of transient hydrodynamic behaviour during pumping are now well established (Anderson, 2006; Dewandel et al., 2014, 2011; Rafini and Larocque, 2012; Roques et al., 2014). It involves two main phases: (i) an early stage where water is mainly coming from storage in the fault and (ii) due to the limited storativity of this structure, a second stage during which adjacent reservoirs contribute to the flow by leakage (Escobar and Hernández, 2010; Gringarten, 1996; Moench, 1984; Rafini and Larocque, 2009; Roques et al., 2014; Tiab, 2005). These transient hydrodynamic specificities imply some temporal exchange and mixing between reservoirs during pumping that may be associated with geochemical changes. Identification of water sources under natural conditions and quantification of transient mixing rates under pumping constitute major challenges when characterizing the groundwater resource in a crystalline rock context. Mixing of different water types may lead to an increased chemical reactivity and modified geochemical signature (Banwart et al., 1994; Elliot and Younger, 2007; Mazor, 1985; Stober and Bucher, 2005). Chemical evolution investigations during groundwater pumping are of great importance in terms of resource availability and sustainability. Studies have mainly focused on pollutant migration, such as nitrate, induced by