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Hydrological behavior of a deep sub-vertical fault in crystalline basement and relationships with surrounding reservoirs

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SUMMARY

Crystalline-rock aquifers generally yield limited groundwater resources. However, some highly productive aquifers may be encountered, typically near tectonic discontinuities. In this study, we used a multidisciplinary experimental field approach to investigate the hydrogeological behavior of a sub-vertical permeable fault zone identified by lineament mapping. We particularly focused our investigations on the hydrogeological interactions with neighboring reservoirs.

The geometry of the permeable domains was identified from geological information and hydraulic test interpretations. The system was characterized under natural conditions and during a 9-week large-scale pumping test. We used a combination of piezometric analysis, flow logs, groundwater dating and tracer tests to describe the interactions between permeable domains and the general hydrodynamical behaviors.

A clear vertical compartmentalization and a strong spatial heterogeneity of permeability are highlighted. Under ambient conditions, the vertical permeable fault zone allows discharge of deep groundwater flows within the superficial permeable domain. The estimated flow across the total length of the fault zone ranged from 170 to 200 m^3/day. Under pumping conditions, hydrological data and groundwater dating clearly indicated a flow inversion. The fault zone appears to be highly dependent on the surrounding reservoirs which mainly ensure its recharge. Groundwater fluxes were estimated from tracer tests interpretation. This study demonstrates the hydrogeological capacities of a sub-vertical fault aquifer in a crystalline context. By describing the hydrological behavior of a fault zone, this study provides important constrain about groundwater management and protection of such resources.

1. Introduction

Crystalline rocks cover large areas throughout the world of about 35% of the continental surface (Amiotte Suchet et al., 2003; Blatt and Jones, 1975) and may constitute a crucial water resource for vast population. The porosity and permeability of primary crystalline rocks are extremely low, but their hydraulic properties can be greatly modified as a result of secondary physical processes (unloading, tectonic activities, etc.) and/or geochemical processes such as weathering and fluid circulation (Bahat, 1999; Caine et al., 1996; Evans et al., 1997; Henriksen and Braathen, 2005; Taylor and Howard, 2002, 1999). Various conceptual models of hydrogeological compartmentalization in crystalline rock aquifers have been proposed (Chilton and Foster, 1995; Dewandel et al., 2006; Maréchal and Wyns, 2004; Taylor and Howard, 1999; Wyns et al., 2004). They usually consist of two main reservoirs: (1) a layer of alterites (<15 m bgs), identified as a specific reservoir with a relatively high porosity and storage, highly sensitive to rainfall recharge; (2) a superficial fractured zone, of various thickness and which may be characterized by relatively dense sub-horizontal and sub-vertical fracturing. This fractured reservoir has in general a higher permeability although well yields are typically limited to less than 10 m^3/h.

However, highly productive zones have been locally highlighted in regions exposed to past or current tectonic activity, such as Brittany. In practice, although controversial (Gleeson and Novakowski, 2009), hydrogeologists often use fracture outcropping analysis or "lineaments" mapping to determine drilling localization, especially when such lineaments result from extensive tectonic activity (Gleeson and Novakowski, 2009; Henriksen and Braathen, 2005; Sander, 2006; Singhal and Gupta, 2010). Many factors must be

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considered to ensure the viability of the resource such as rock lithology affected by tectonic activity, stress fields and intensity of deformation. Such factors and fluid flow processes determine fault zone permeability (Caine et al., 1996; Evans et al., 1997; Gleeson and Novakowski, 2009; Goddard and Evans, 1995). Few hydrogeological studies examined relationships between lineaments structures, hydrogeological flow organization and productivity wells (Fernandes and Rudolph, 2001; Henriksen and Braathen, 2005; Holland and Witthüser, 2011; Richard et al., 2002; Sander, 2006). Fault zones may act as conduits, barriers, or as combined conduit-barrier systems that enhance or impede fluid flow (Bense and Person, 2006; Caine et al., 1996) but can also significantly influence groundwater flow, spring discharge, and water-table elevations (Apaydin, 2010; Gleeson and Novakowski, 2009; Melchiorre et al., 1999).

In some cases, aquifers near highly conductive fault zones and with relatively high production rates for crystalline rocks (from 20 to 100 m^3/h) have been described: Ploemeur aquifer, Brittany (Le Borgne et al., 2006a; Leray et al., 2013; Ruelleu et al., 2010), the New Hampshire Bedrock Aquifer (Richard et al., 2002), Crystalline Rock Aquifers in New England (Harte et al., 2008) and in the Limpopo Province of South Africa (Holland and Witthüser, 2011).

The hydrodynamic functioning of fault structures in various geological contexts has been investigated in several studies. In sedimentary media, Bense and Person (2006), Bense et al., (2003) showed the important effects of the geometry and anisotropy of a fault zone on its hydraulic properties. Numerical studies, such as those by Anderson and Bakker (2008), also highlighted the influence of a vertical fault on groundwater flow. In the crystalline context, some studies have described the permeability architecture and hydrogeological functioning of fault zones for groundwater resources (Boutt et al., 2010; Caine and Tomusiak, 2003; Evans et al., 1997; Ganerod et al., 2008; Stober and Bucher, 1999) or hydrocarbon entrapment (Aydin, 2000). However, very few studies have analyzed the hydrological functioning of faults in a water abstraction context. In this context, aquifer yields will mainly depend on the ability of interactions between the fault and the surrounding reservoirs to allow recharge and water availability. On the other hand, groundwater abstraction from a deep resource will undoubtedly modify the hydrodynamic gradients and lead to mixing between the different reservoirs. The hydrogeological influence of deep fault zones on overlaying reservoirs is poorly known and is apparently difficult to characterize by field studies (Banwart et al., 1994; Carucci et al., 2012; Folch and Mas-Pla, 2008; Gannon et al., 2011; Sophocleous, 2002). This question has been tackled out only through few numerical studies, which have reported the hydrological efficiency of fault zones to act as preferential flow zone that enhances recharge processes from surrounding reservoirs (Folch and Mas-Pla, 2008; Leray et al., 2013).

The first aim of this study is to characterize the hydrodynamic functioning of a sub-vertical permeable fault zone in crystalline basement from a large-scale field experiment. The main objectives are to (i) describe the architecture of the aquifer system, (ii) define the flow organization between the permeable zones and recharge processes towards the deep fault zone under natural and pumping conditions and (iii) characterize the origin of groundwater and mixing processes due to groundwater abstraction. The experiment is carried out on a specific field site in Brittany (Western France), identified by lineament observation (Carn-Dheilly and Thomas, 2008), where a permeable fault zone at more than 100 m depth is able to provide about 100 m^3/h according to air-lift flow measurements.

We first describe the characteristics of the groundwater system under ambient conditions to highlight the hydrologic functioning of deep structures at the catchment scale. We then describe a 9-week large-scale pumping test that was carried out to identify the hydraulic properties of the aquifer system. During this test, various complementary experiments and measurements were conducted to investigate flow interactions between the different reservoirs and to identify mixing processes. Finally, the combined analyses from this multidisciplinary experiment are used to develop a hydrogeological conceptual model of a sub-vertical fault zone in crystalline context.

2. Geological and hydrogeological setting

The experimental site of Saint-Brice en Coglès is located in the Mancellian Domain of the "*Massif Armoricain*", in Brittany (France), where it constitutes the north western French part of the Cadomian and Variscan orogenies (Fig. 1a). This formation outcrops from western to central Europe and is mainly composed of low to high grade (migmatite) metamorphic rocks, with regional-scale magmatic intrusions (Cadomian granodiorites). The Mancellian Domain is limited in the north by the English Channel, and to the south by the North Armorican Shear Zone (NASZ). The main lithologies encountered are Precambrian (Brioverian) sedimentary rocks (Fig. 1a), composed of alternating series of argillites/siltites and sandstones. These sedimentary rocks have been affected by low grade metamorphism which has formed a metamorphic aureole around the Cadomian granodiorites on a regional-scale (Ballèvre et al., 2009; Brun et al., 2001; Chantraine et al., 2001; Cogné and Wright, 1980). The most important deformation zone corresponds to a major ESE-WNW dextral strike-slip shear zone, the NASZ attributed to hercynian orogeny. Secondary SW–NE reverse faults are also found around this main shear zone. These terrains have been affected by Pyrenean and Alpine orogenies that have generated a diffuse deformation characterized by half-graben basins (Rennes basin, Landéan basin, etc.) and NW–SE sub-vertical faults (Grellet et al., 1993; Van Vliet-Lanoë et al., 1997).

The Saint-Brice en Coglès site is located in the epimetamorphism zone of a large Cadomian pluton (Fougère granite). The rocks consist of Brioverian sediments metamorphosed into hornfels schists. The vicinity of the site is characterized by parallel extensional N–S normal faults that form localized extensional basins (Geological map, BRGM (Dadet et al., 1984), Fig. 1b).

Local geological structures were imaged by carrying out a structural analysis including landscape, geological mapping and geophysical (electric and seismic tomographies) analysis. Sub-vertical faults and extensional graben structures were clearly identified (Fig. 2a). In addition, three deep boreholes (MFT20, MFT80 and, F3) were drilled using "Down Hole Air Hammer" drilling method. Another deep borehole (FC4, 250 m), which has been entirely cored, has been drilled along a profile perpendicular to the orientation of the main accident lineament (Fig. 2b). The borehole characteristics are detailed in Table 1. Several shallow boreholes (labeled T in Fig. 2b) were also drilled to characterize the shallow weathered compartment. The first 10 m contained highly weathered material with high clay and sand contents. Examination of the cores revealed that the Brioverian rocks were highly deformed and fractured, and intruded by metric aplites, pegmatites and quartz veins, oriented N 50° to N 70°. Particularly, in the vicinity of the fault outcropping, the Brioverian rocks are affected by horizontal fractures, characterized by a density decrease with depth, to an average of about 40–50 m. The main fault zone was identified in each borehole as a highly fractured and productive zone, ranging from a few meters thick (see core sampling in Fig. 2c) to 15 m in the outcropping part of the borehole (Tables 1 and 2). The fault typically dips by 70° to the NNW (Fig. 2c). Wells were completed with a slotted casing in the deep productive zones.