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The role of fault-zones on groundwater flow in crystalline basement
Influence des zones de faille sur les écoulements souterrains en milieu de socle cristallin

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I. Introduction

Crystalline rock aquifers are commonly described as restricted in the sub-surface part of the basement (< 50m bgs) where jointing and weathering occurred. These sub-surface aquifers are generally well represented at the watershed scale and constitute the main reservoir for groundwater supply in many crystalline regions (especially in semi-arid regions such as India and Africa). But, the average hydraulic properties of sub-surface crystalline rocks are low - permeability ranging from 10^{-15} to 10^{-17} m^2 at regional scale (Ranjram et al., 2015) - and wells often present limited yield of few cubic meters per hour (Dewandel et al., 2011).

Fault-zones have always triggered the attention of hydrogeologists seeking for high productive structures. It is known that fault-zones can influence flow paths at various depths (Bense et al., 2013) and can locally constitute conductive structures for groundwater flow (Leray et al., 2013). The role of fault-zones on the hydrological cycle and their potential to constitute a sustainable water resource remains poorly understood in crystalline regions. Our study aims to describe the hydrological functioning of a permeable fault-zone identified near a major lineament in the Armorican Massif, France (Carn-Dheilly and Thomas, 2008). We mainly concentrate our investigations toward two objectives: i) describe the influence of the fault zone on natural groundwater flows and ii) understand the hydraulic behavior of this deep structure under pumping condition.

II. Experimental Site and Methodology

The experimental site is located in Brittany, NW of France (municipality of Saint-Brice en Coglès, Figure 1). It is implemented into Brioverian hornfels schist formation, in the epimetamorphism zone of a large Cadomian pluton. Its direct vicinity is characterized by series of parallel N-S normal faults that form extensional basins. During a first drilling campaign, one well (F3 in Figure 1) revealed high yields (100 m^3/h), essentially related to a single permeable fault-zone identified at 110 m depth.

The additional well setups were designed in order to capture the different compartments involved in the system. Three deep boreholes - 80 to 250 meters deep - were drilled at relatively short distances (30-40 meters), orthogonally to the fault direction. The deeper well (FC4) has been cored for detailed geological information. Shallower boreholes were also drilled (7 to 20 m deep) to characterize the upper fractured and weathered compartment.

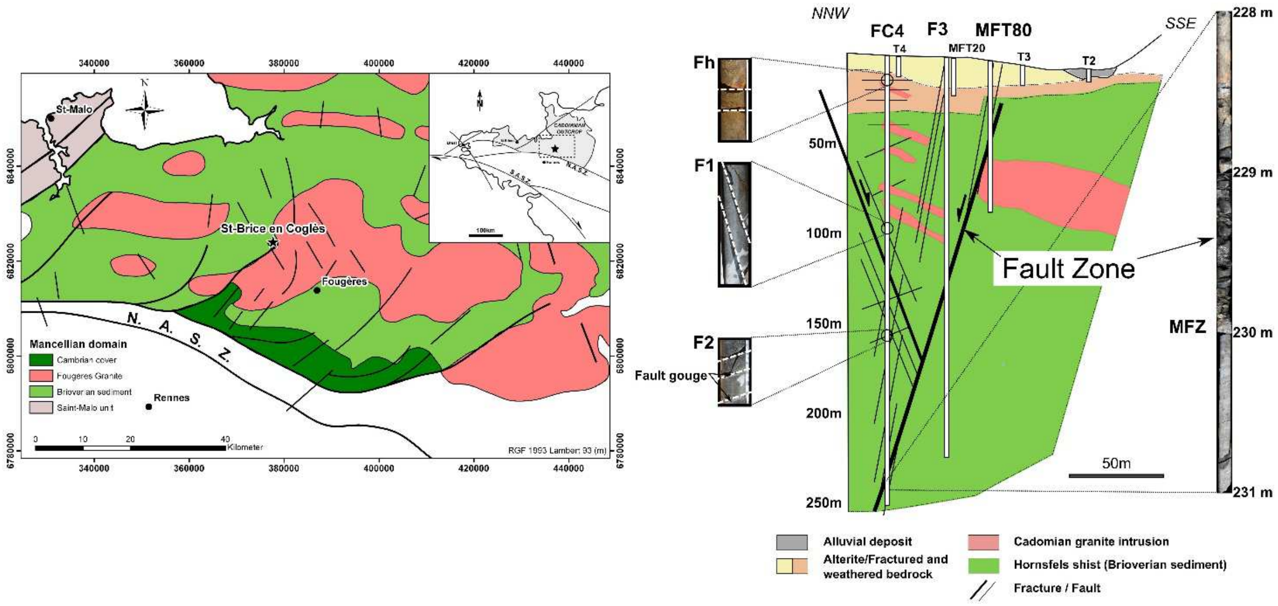

Figure 1 - On the left is presented the regional geological map with the location of the Saint-Brice en Coglès experimental site. On the right are displayed the geological cross section of the site and different fracture families (pictures of the FC4 core samples). NASZ = North-Armorican Shear Zone; RGF = French Geographic Reference and MFZ = Major Fault Zone.

The system has been characterized both in natural conditions and during a 9-week large scale pumping test carried out at a pumping rate of 45 m^3/h. We applied a multidisciplinary approach including: (a) geology, geophysics and aquifer testing to describe the compartmentalization of the system, (b) high-resolution flow loggings to identify fracture connection and flow partitioning, (c) tracer tests to estimate transfer times and groundwater fluxes between main compartments and (d) geochemistry and groundwater dating (CFC's, SF6 and noble gases) to identify water origin and mixing processes between the different reservoirs. Sampling campaigns for geochemical analysis were performed along the hydrological cycle during the 2 years of the project (5 campaigns) and also during the pumping test (7 additional campaigns).

III. Results and discussion

Aquifer compartmentalization controlled by the main tectonic structure

The system is developed within an extensional N150E basins collapse, where series of normal fault-zones border a graben structure. One major permeable fault-zone, sub-parallel to the basin, has been intersected by the three deep boreholes at different depths (FC4, F3 and MFT80 – MFZ in the Figure 1 and 2). The dip of the fault zone is about 70-80 toward the west. With an average of $7.10^{-4}\ m^2.s^{-1}$ estimated from high resolution flow meter testing, the Major Fault Zone transmissivity appears to be relatively constant with depth (maximum values measured at 250m depth – FC4). The MFZ is embedded within a lower permeable compartment but still affected by series of faults and fractures. Sub-vertical N150E fractures prevail in this compartment (F1 in the Figure 1 and 2) and can contribute significantly to borehole flow (10-20%).

In the sub-surface, horizontal fractures (Fh in the Figure 1 and 2) are observed until 50 m depth, overlaid by alterite (regolith) material in the first 10 m depth. As commonly observed, the density of these horizontal fractures present a depth decreasing relationship according to core samples (FC4). Geophysical profiles suggest that this compartment appears to be mainly developed within the depressed block of the graben, along the MFZ. This sub-surface compartment displays lower hydraulic properties with an estimated transmissivity of $< 10^{-5}\ m^2.s^{-1}$ for the fractures and $< 10^{-6}\ m^2.s^{-1}$ for the regolith.

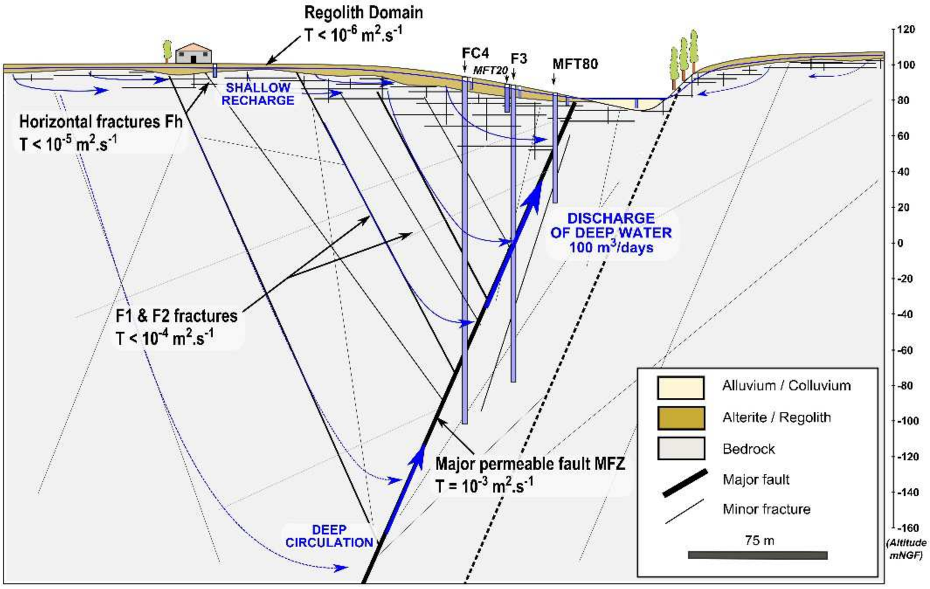

Figure 2 - Hydraulic compartmentalization of the Saint-Brice en Coglès aquifer and flow partitioning in natural condition (Roques et al., 2014a, 2014b).

Fault-zone recharge at depth involves transient regimes

Hydraulic head gradient within the fault-zone (measured on F3 and FC4 wells) allows deep water up-flows toward the superficial part of the aquifer and the stream at the watershed outlet (Figure 2). The discharge rate of deep water was estimated at around 100 - 200 $m^3.days^{-1}$ combining head data analysis, ambient flowmeter measurements and permeability values of the MFZ.

The origin of water flowing through the system appears to be strongly dependent on sampling depth and the permeability of the aquifer domain considered. It also varies according to the general hydrological regime (high and low water level periods). The regolith domain involves present-day apparent ages (CFCs and SF6 at the equilibrium with actual atmospheric concentrations) with a modern recharge temperature (Ne/Ar ratio), confirming rapid water transfer during recharge events. However, the MFZ drains deep circulation loops presenting two distinct water types along the hydrological cycle:

(1) During low water level periods, the upward flow is dominated by water with an apparent age higher than 60 years (CFCs and SF6 in trace) and a recharge temperature of 7°C deduced from Ne/Ar. These values indicate that a fraction of this water has been recharge during the last glacial or inter-glacial period (residence-time of thousand years scale also confirmed by a carbon-14 activity of 80%). These characteristics imply the remobilization of weakly mobile or immobile waters stored in matrix domains (fresh bedrock) and/or of water transferred through large-scale circulation loops at the regional scale.

(2) During low water level periods, the mean apparent age is still higher than 60 years but the recharge temperature is modern (12°C). The hydraulic head increases in the upper part of the aquifer due to recharge events leads to enhance fluxes down to the deeper part of the bedrock and the MFZ at the local scale.

These results highlight a complex and dynamic hydrological behavior of this fault-zone. It implies different timescales of groundwater recharge and transfer at depth, related to distinct circulations loops involved within the compartments and the watershed. Although of limited natural flow rate (100-200 $m^3.h^{-1}$), this behavior should be considered when estimating water fluxes, hydrologic budget and solute transport at the watershed scale in crystalline basements.

Pumping in the fault-zone appears highly dependent of connected reservoirs

Hydrodynamic and geochemical data measured during the 9-weeks pumping test allow us to quantify the temporal flow contribution from the different reservoirs. We derived a conceptual model (displayed in Figure 3) synthetizing structural features and hydraulic behavior for the sub-vertical fault-zone of Saint-Brice en Coglès.

The most relevant observation is that the sub-vertical fault-zone is clearly connected with the sub-surface reservoir. Due to the limited storage in the fault zone, water fluxes during pumping are mainly supported by the overlaying reservoir and adjacent domains. Pumping in the deep structure induces downward groundwater flow from the upper part of the aquifer domain. Based on the results obtained from tracer tests and geochemical mixing models, we could estimate that the superficial horizontal fractures (Fh) and the deeper fractures (F1 and F2) within the graben mainly sustains the pumped flow rate (70-80%). Due to high storage capacities, the regolith domain ensures almost 20% of the flow for long-term pumping times.

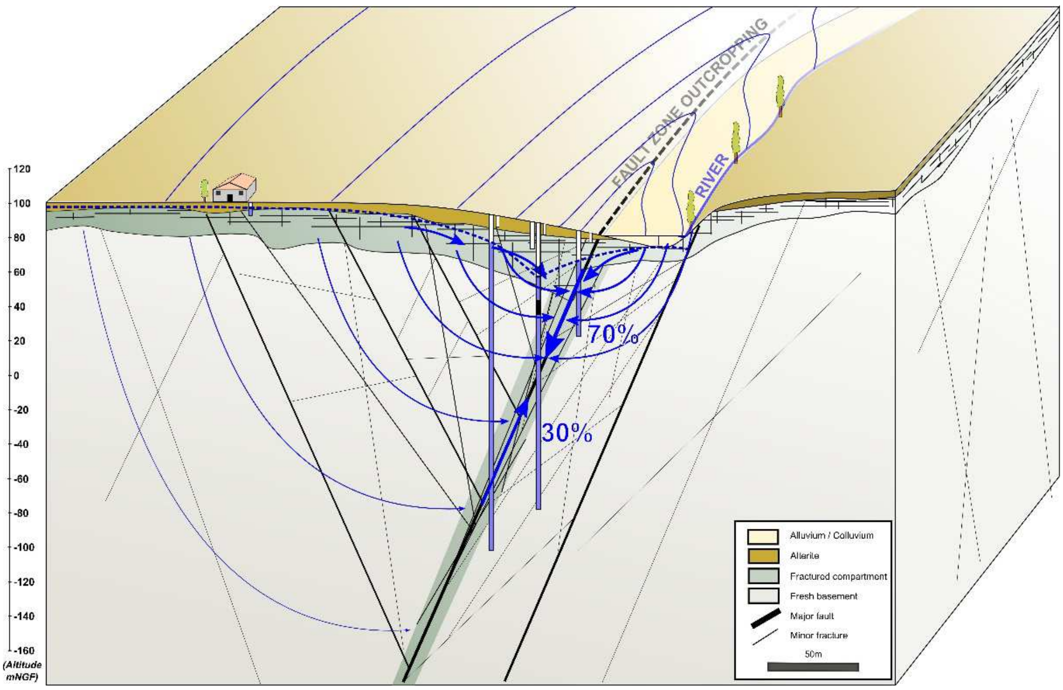

Figure 3 - Conceptual model of groundwater flow at the Saint-Brice en Coglès site under pumping conditions (Dewandel et al., 2014; Roques et al., 2014b)

These results demonstrate that fault-zones, when they are permeable, may allow pressure diffusion along the fault-zone plane that can act as a boundary condition to drain water from the surrounding reservoirs. Although they can display significant conductive properties, their ability to constitute a groundwater resource will be highly dependent on the presence of connected reservoirs with sufficient storage capacities. In the case of the Saint-Brice en Coglès aquifer system, our analysis suggest that the flow rate applied during the pumping test (45 $m^3.h^{-1}$) was too high to be sustainable. The major downward flow may also lead to the question of sensitivity of this deep structure to sub-surface contaminant transfer which may impact water quality (Roques et al., 2014a).

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