# Interactions entre altération météorique et discontinuités (filons, failles, contacts lithologiques…). Quelles propriétés hydrogéologiques? Interactions between weathering and geological discontinuities (veins, dykes, geological contacts…). Which hydrogeological properties? The example of quartz reef in granitic terrain from south India

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## I. INTRODUCTION

Groundwater resources in hard rock aquifers are generally low in terms of available discharge per well (a few tens of $m^3/h$), compared to those from porous, karstic and volcanic aquifers. Their groundwater resources largely contribute to the economical development, especially for those regions exposed to arid and semiarid climatic conditions where the surface water resource is limited as in Africa and in India (Uhl and Sharma, 1978; Houston and Lewis, 1998). However, the knowledge of such aquifers, e.g., their geometry, their hydraulic properties, etc., is currently meagre and needs to be improved.
Significant advances have recently emerged for the geological and hydrogeological characterization of such complex aquifers (Lachassagne et al., 2001; Chilton and Foster, 1995; Taylor and Howard, 2000; Wyns et al., 2004, Maréchal et al., 2004; Dewandel et al., 2006; Lachassagne et al., 2011, 2015; Wyns et al., 2015). These studies show that the geometry and the hydrodynamical properties of hard rock aquifers mainly result from deep weathering processes of the parent rock (Taylor and Howard, 2000; Dewandel et al., 2006).
In granite type rocks (e.g. granites, gneisses), a typical weathering profile (Fig. 1; Wyns et al., 1999 and 2004) comprises two main stratiform layers sub-parallel to the paleo-surface contemporaneous of the weathering process. These layers constitute a composite aquifer with, from top to bottom:
- the saprolite layer, a sandy-clayey to clayey-sandy material derived from prolonged in situ weathering of the parent rock. The hydraulic conductivity of this layer ranges from $10^{-7}$ to $3 \times 10^{-5}$ m/s ($2 \times 10^{-6}$ m/s in average) and closely depends on the content in clay-rich materials.
This layer is usually assimilated to a porous medium. Where this layer is saturated, it mainly constitutes the capacitive reservoir of the composite aquifer.
- The fissured layer. This layer is usually characterized by a dense horizontal fissuring within the first few metres and a depth-decreasing sub-horizontal and sub-vertical set of fissures (Houston and Lewis, 1998; Howard et al., 1992; Maréchal et al., 2004, 2015; Wyns et al., 2004; Dewandel et al., 2006; Guihéneuf et al., 2014). The hydraulic conductivity of the fissured layer is highly variable and ranges between $10^{-9}$ m/s for the blocks up to more than $10^{-3}$ m/s for the conductive fissures network which drain the blocks (Maréchal et al., 2004). The presence of the two main sub-horizontal and sub-vertical fissure sets ensures a good connectivity of the fissures network and induces an anisotropy in hydraulic conductivity (Khoriz/Kvert~10, Maréchal et al., 2004). The effective porosity of the fissured layer is relatively low, between $10^{-3}$ and $10^{-2}$. This layer usually assumes the transmissive function of the composite aquifer.
- The underlying unfissured and fresh basement is permeable only locally and is related to tectonic fractures whose hydrodynamic properties are highly variable (Blomqvist, 1990).

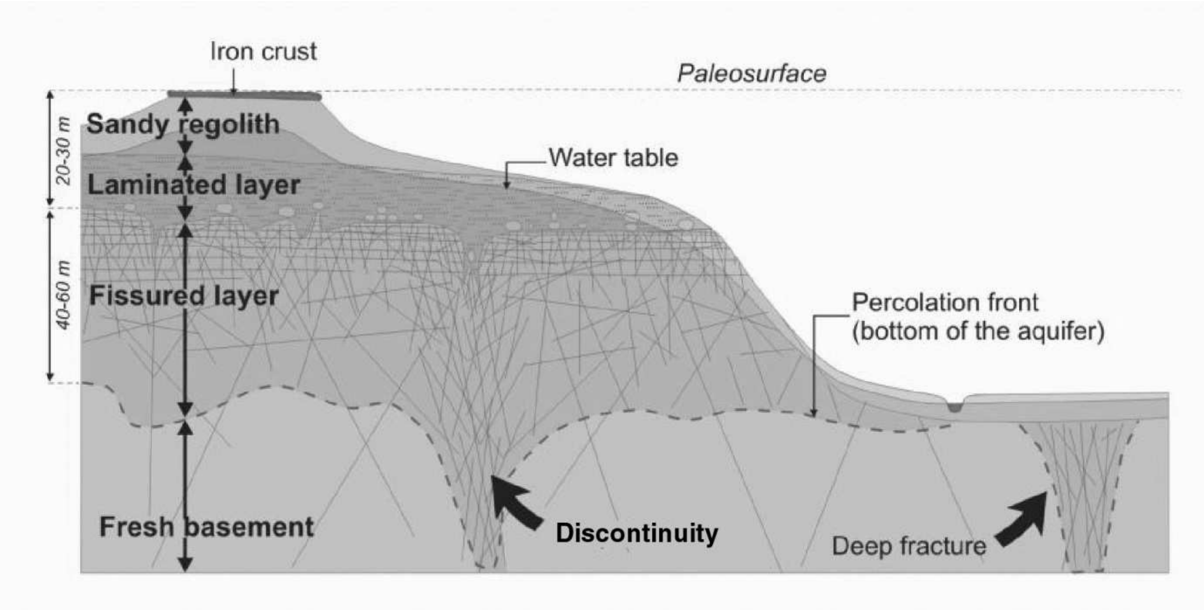


*Figure 1 – Idealized single phase weathering paleoprofile in hard-rocks, crosscut by the current topography (Wyns et al., 1999 and 2004).*

Therefore where the formation is not affected by geological discontinuities, e.g., fault, vein or dyke, together the saprolite and the fissured layers make up a superficial (from 30 to 100 m thick) composite aquifer that can be considered as a multilayer system. However, where the granite is intruded (quartz, pegmatite veins, dolerite dyke, younger granite), or affected by tectonic faulting, the layers geometry and hydrodynamic properties may substantially be affected and may thus differ from the above-presented conceptual model.
The objective of the present paper is to study the aquifers associated with such geological discontinuities (Dewandel et al., 2011). This study has been carried out on two sites in South India along 20-40 metre-thick quartz reef intruding a granitic body that have been exposed to deep weathering processes (Fig. 2, Maheshwaram area, Ranga Reddy District, Andhra Pradesh, India). The sites, IFP1 and Kothur sites, have been equipped with 20 borewells.

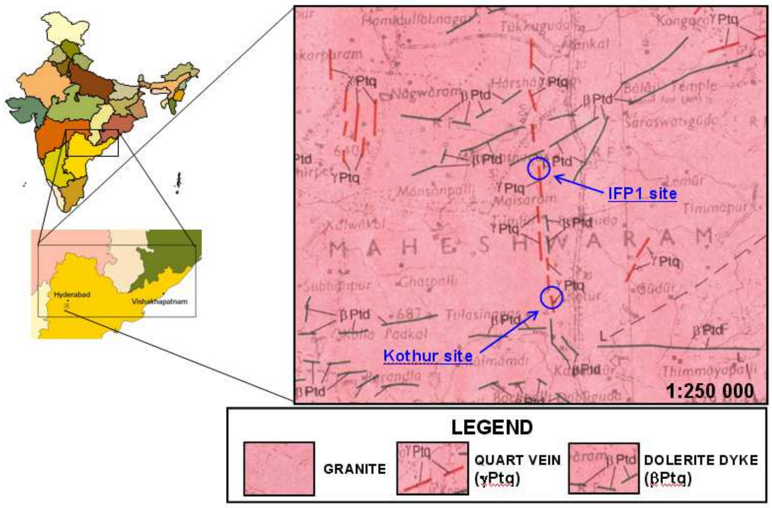


*Figure 2- Geological map of the studied area (G.S.I., 2002). The circles depict the location of the hydrogeological investigations.*

## II. GEOLOGICAL SETTINGS OF THE AREA

The area is composed of Archean biotite granite with porphyritic K-feldspar that is locally intruded by smaller bodies of leucocratic granite. Some younger kilometric scale geological features locally intrude these granites: decametre-wide quartz veins (Archean in age) and meter-wide doleritic dykes of several geological ages (2.5 to 1.6 Ga; G.S.I. 2002; Fig. 2).
Previous works showed that these granites are affected by deep in-situ weathering processes similar to those described in the introduction of the present paper. Here, the weathering profile results from multiphase weathering processes (Dewandel et al., 2006) and in the absence of geological discontinuity, it shows, from top to bottom:

- a 1-3 m thick layer of sandy regolith, which is locally capped by a lateritic crust (< 50 cm in thickness),
- a 10-15 m thick layer of laminated saprolite. This layer is characterized by an unusual network of preserved mainly sub-horizontal and some sub-vertical fissures partially filled up by clayey minerals,
- the fissured granite occupies the next 15-20 m, where weathered granite and a few clayey minerals commonly partially fill up the fissures,
- the unfissured granite (bedrock) is usually reached at a depth ranging from 30 to 45 m.

All layers interfaces more or less follow the current topography.

In order to explore the impact of discontinuities on such a weathering profile's structure and hydrodynamic properties, investigations were carried on two sites, 'IFP 1' and 'Kothur' (Figs. 2, 3 and 5). These two sites, distant of 7 km, are located on the same sub-vertical north-south decametre-wide quartz reef.

### II. 1 Geological setting of IFP1 site

IFP1 site is located in a pinch out zone of the quartz reef in (Fig. 3). The surrounding granite is the one commonly found in the area (biotite granite). However, the granite is highly deformed and chloritized within the first tens of meters from the quartz reef. Moreover, a sub-vertical and meter-thick dolerite dyke, sub-parallel to the quartz reef, outcrops at a few metres East of the quartz reef.

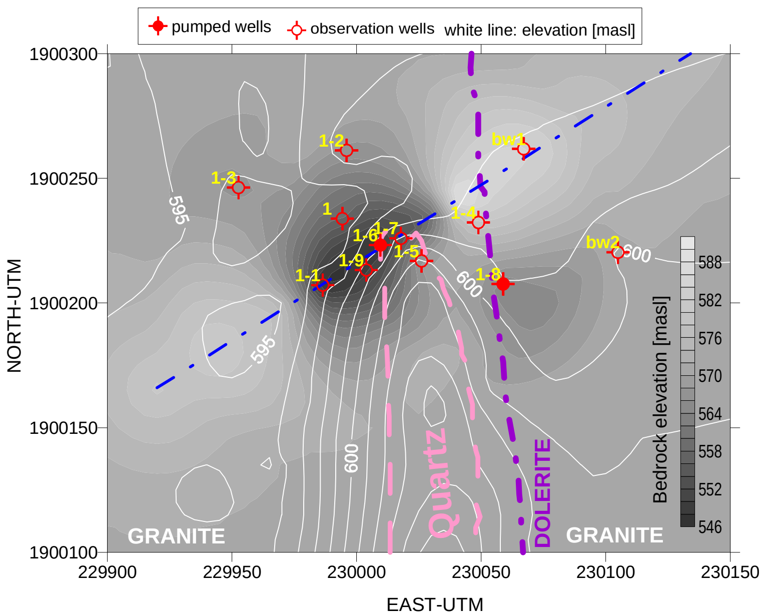


*Figure 3 - Geological map and borewells location at IFP1 site. The grey scale depicts the elevation of the top of the unfissured granite (based on geological log and ERT profile). The blue dotted line materialises the location of the electrical resistivity profile. White curves represent the soil elevation (masl), contour interval 5 m. BW: farmer's wells.*

Ten borewells (Fig. 3) from 35 to 74 m in depth were drilled using the down-to-the-hole hammer technique: 3 on the quartz reef (3 borewells), however they reached the granite after only a few tens of metres, and 7 in the granite. Detailed geological logs were prepared from cuttings collected every meter. Borewells IFP 1-4 & 1-8 cross cut the dolerite dyke.
In addition to the ten drilled wells, 2 pre-existing farmer's borewells (bw1 and bw2) drilled within the granite are also present, however their exact depth (>40 m) and geological logs are unknown.
Within the first ten metres from the surface, the quartz reef is highly weathered and highly fissured from centimetre to decametre scale, which gives a gravel aspect to the drilled cuttings. Deeper, the quartz is fresh and moderately fissured. Fissures are mostly sub-vertical and essentially organized in two sub-orthogonal sets, one sub parallel to the quartz vein (N000 90°) and, the other sub orthogonal to it (N100 90°).
The dolerite dyke is highly weathered within the first 5 to 7 m from the surface (clayey material), poorly fissured from 5-7 to 15 m and then hard and compact.

An Electrical Resistivity Tomography profile (470 m in length) was carried out to complete the geological investigation (Fig. 4). Resistivity data were collected using a Wenner–Schlumberger array configuration with inter-electrode spacing of 10 m.

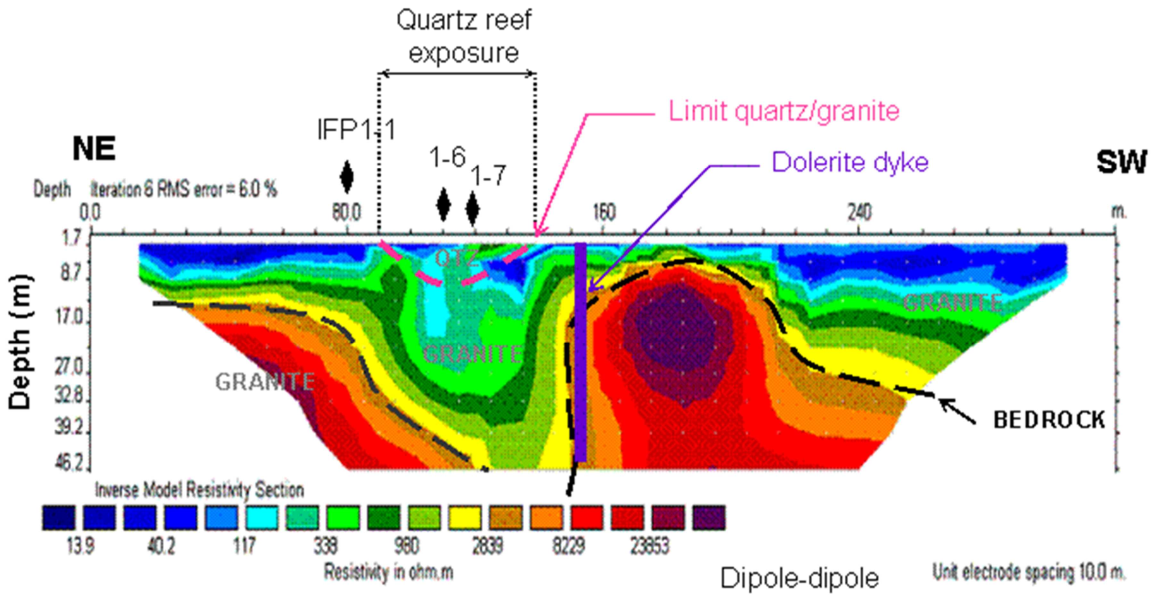


*Figure 4 - Electrical resistivity tomography profile at IFP 1 (location on Fig. 3).*

From the geological and geophysical data the base of the fissured layer, and thus the base of the weathering profile, was mapped for characterizing the 3-D geological structure of the weathering profile (Fig. 3). Near to the contact between the granite and the quartz reef the fissured zone and thus the weathering profile is significantly deepened in the granite and is characterized by an U-shape geometry. On the opposite, near the dolerite dyke this deepening is abruptly stopped as if the dyke acted as a barrier to the weathering (Fig. 4).

## II. 2 Geological setting of Kothur site

The Kothur site is located 7 km south from IFP1 on the same quartz reef (Figs. 2 and 5). A series of 11 borewells from 48 to 91 m in depth were drilled in the central area, in the pinch out zone (northern part) of the reef and in the surrounding granite. Detailed lithologs were also prepared.

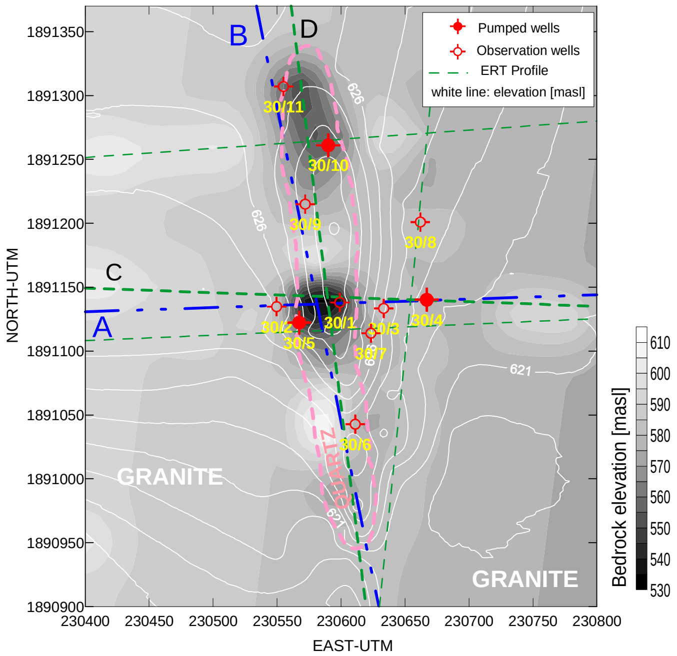


*Figure 5 - Geological map and borewells location at Kothur site. The colour scale depicts the elevation of the top of the unfissured granite (based on geological and ERT profiles). The green dotted lines materialise the location of the five electrical resistivity profiles. White curves represent the soil elevation (masl), contour interval 5 m.*

Similarly to IFP1 site, the biotite granite is also highly deformed and chloritized in the vicinity of the quartz reef. The quartz reef is highly fissured and orientation of major fissures are mainly sub-vertical and organized in two main sub orthogonal sets, one sub parallel to the quartz vein (N005 90°) and, the other sub orthogonal to it (N100 90°).

Five ERT profiles, three perpendicular to the quartz reef and two along it were carried out (Fig. 6; each ERT length is about 470 m with 10 m electrode-spacing).

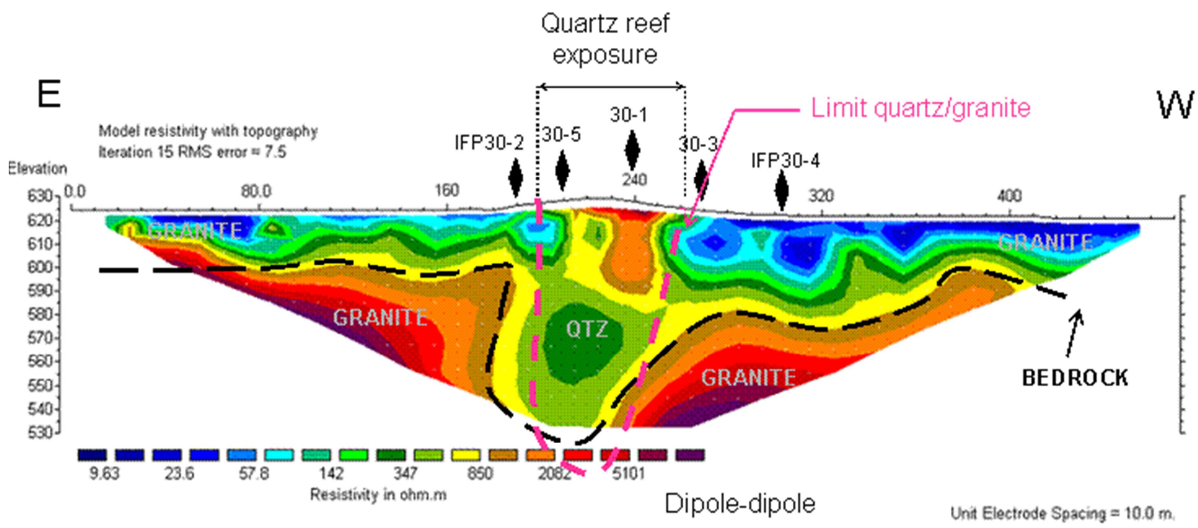


*Figure 6 - Example of electrical resistivity tomography profile at Kothur (location on Fig. 5). Profile "A" perpendicular to the quartz reef.*

Similarly to IFP1 site, an important deepening of the granite weathering profile is observed in the immediate neighbourhood of the quartz reef and also in its pinch out zone (northern part; Fig. 5). Near the

quartz reef the weathering in the granite (saprolite + fissured layer) reaches more than 70 m in depth (Fig. 6) whereas farther from the quartz reef the weathering profile stops at about 40-45 metres depth.
These investigations also provide information on the 3-D structure of the weathering profile within the quartz reef, which was not accessible at the IFP1 site due to its location at the extremity of a pinch out zone. In the central part of the quartz reef, the quartz is highly weathered and highly fissured within the first ten metres from the surface whereas along the borders, and particularly along its western contact and in the pinch out zone, the quartz is highly weathered and fissured up to 70 m in depth. Thus, both in the quartz reef and in the surrounding granite, weathering is more pronounced near the contact.

Previous studies (Maréchal et al., 2004; Dewandel et al., 2006) showed the relative homogeneity of the hydrodynamic properties of the weathered-fissured hard rock aquifers where they are not influenced by such discontinuities. The question is now: what are the hydrodynamic properties of such a weathered-fissured quartz reef and the surrounding weathered granite and how are they different or similar from the ones of the classical weathering profile? To give an answer, 21 slug tests and 5 interference pumping tests were performed on both sites.

## III. RESULTS AND DISCUSSION

### III. 1 Structure of the weathering profile at the quartz reef

Geological and geophysical investigations performed in IFP1 and Kothur sites show that in the vicinity of the quartz reef the weathering fronts within the granite (bottom of saprolite and of the fissured layer) are noticeably deepened. Figure 7 presents the conceptual hydrodynamic model of the aquifer associated to the quartz reef (Dewandel et al., 2011).

The bottom of the fissured layer reaches a depth of about 100 metres near the contact whereas the stratiform layer only reaches a depth ranging between 40 and 50 m in the same granite far from the reef (Dewandel et al., 2006). In an average, the thickness of the saprolite increases by a factor 1.5 to 3 and the one of the fissured layer by a factor 3 to 5. Near the contact, the geometry of the weathering profile in the granite is, as for the classical stratiform weathering profile (Fig. 1), characterized by two sub-parallel layers: the saprolite and the fissured layers. Nevertheless they are not sub-parallel to the paleo-surface contemporaneous with the weathering phase but sub-parallel to the discontinuity borders. As a consequence the weathering profile exhibits a 'U' shape composed of parallel layers.

The quartz reef itself is characterized by mainly sub-vertical fissures sub-parallel and sub-orthogonal to the reef axis. The top layer is highly fissured and weathered whereas the fissure density rapidly decreases with depth. In addition, the density in fissuring and the grade of weathering vary in space and are more important near the contact with the granite, on the sides of the quartz reef and near the pinch out zones, than at the heart of the vein.

Constraints resulting from the development of the weathering profile in the granite induce the fissuring of the quartz reef. This weathering induced-fissuring enhances water circulation and in return favours a local deepening of the weathering fronts in the granite near the contact with the quartz reef. The lower strain appears thus to be deviated in the direction of the discontinuity which favours the development of a verticalized fissured layers in the granite at the contact. Thus, during the weathering of granitic formations such a breakable discontinuity favours a local deepening of the weathering fronts in the host rock and thus favours a thickening of the transmissive part of the aquifer. In addition, the quartz vein is also subject to weathering that induces small scale fissures and weathered materials that enhance its hydraulic conductivity. This weathering amplifies the above-described process.

Veins which weathering products are of low to very low permeability, such as those of dolerite dykes, do not allow nor favour water circulation neither within them nor at their vicinity. The stratiform weathering profile of the neighbour granite remains thus undisturbed. Moreover such dykes act as low permeability barriers that compartment the stratiform granite aquifer.

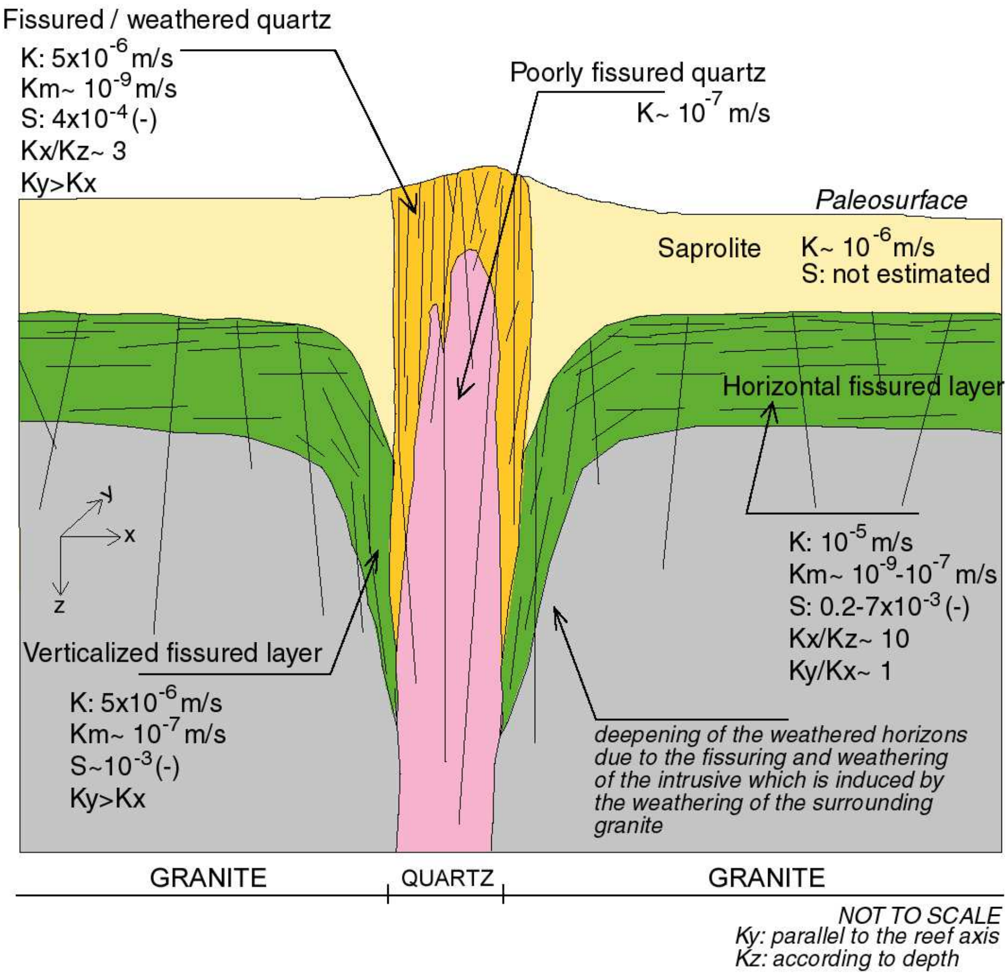


*Figure 8 - Idealized conceptual hydrodynamic model of the aquifer associated to the quartz reef from Dewandel et al., 2011. Data from the horizontal stratiform fissured layer are from Maréchal et al. (2004) and Dewandel et al. (2006).*

## III. 2 Hydrodynamic properties of the granite aquifer near the contact with the discontinuity

The "classical" stratiform horizontal fissured layer of the granite (far from the quartz reef) is characterized by a dual-porosity behaviour (Kfissures: 4 x $10^{-6}$ m/s and S: 0.2 to 7.5 x $10^{-3}$; Kblocks: 8 x $10^{-9}$ m/s). These properties are similar to the ones of the granite commonly found in the area (K: 2-5 $10^{-5}$ m/s, S: 6 x $10^{-3}$ Maréchal et al., 2004; Dewandel et al., 2006).

The hydraulic conductivity of the granite fissured zone that is verticalized along the quartz reef is in an average 4.3x$10^{-6}$ m/s and the storage coefficient about $10^{-3}$. These hydrodynamic properties, especially the hydraulic conductivity, appear to be slightly lower than the ones from the 'classical' stratiform horizontal fissured layer in the same granite.

Moreover, this verticalized layer is characterized by an anisotropy in hydraulic conductivity onto the X, Y plane (ratio: 1.7), with a major axis sub-parallel to the direction of the quartz reef. This reflects the existence of the weathering induced dominant fissures set sub-parallel to the intrusion that controls the hydrodynamic parameters of the medium.

### III. 3 Hydrodynamic properties of the quartz aquifer

The fissured quartz is characterized by a dual-porosity behaviour (Kfissures: 4-6 x $10^{-6}$ m/s, S: 3-5 x $10^{-4}$ Kblocks: 2.4 x $10^{-9}$ m/s). Hydrodynamic properties are highly variable in space and closely depend on the grade of weathering-fissuring, e.g. hydraulic conductivity vary from 10-7 m/s at the heart of the intrusion where the quartz is poorly fissured and fresh to 1.6 x $10^{-5}$ m/s near the contact with the granite where the quartz is highly fissured and weathered.

Because of the well-organized fissuring resulting from the weathering of the surrounding granite, the quartz aquifer is characterized by a 3-D tensor in hydraulic conductivity (Kx/Ky=3 and Kx/Kz=3) with a major axis sub-parallel to the intrusion. The anisotropy in hydraulic conductivity on the horizontal plane is explained by a major set of sub-vertical fissures sub-parallel to the quartz reef that control the flow while the anisotropy on the vertical plane is the consequence of a depth-decreasing hydraulic conductivity due to a depth-decreasing density of fissures.

## IV. CONCLUSION

The obtained results complement the conceptual hydrogeological model developed for granite aquifers (Taylor and Howard, 2000; Maréchal et al., 2004; Dewandel et al., 2006; Lachassagne et al., 2011, 2015; Wyns et al., 2015) in places where the weathering profile is disturbed by such discontinuities.

At the discontinuity, a 'U' shape geometry characterizes the structure of the aquifer which appears to be controlled by the weathering processes themselves and at the origin of an enhanced local hydraulic conductivity both in the vein and in the surrounding granite. Therefore, such zones encompass more favourable hydrogeological targets as the aquifer transmissivity is increased and thus act as local drains.

Other geological discontinuities such as deep fissures, leucocratic dykes, pegmatites or contact between different geologies, may also constitute local drainable structures where the weathering can propagate in depth. As a result, the weathering front will form a 'U' shape geometry more or less well defined according to the verticality of the discontinuity. Such type of structure often searched and observed by hydrogeologists and geophysicists in the vicinity of discontinuities (see for instance Sander, 2007) was often attributed to "tectonic fracturing" ('fault gouges'). The novelty here is to demonstrate their weathering-related origin in term of geometrical structure and hydrodynamic properties. At the opposite, discontinuities that produce low permeable weathering material, such as dolerite dyke, does not locally enhance the thickness of granite's weathered layers or its hydraulic conductivity, making such structures unfavourable targets.

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