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Review article

The fracture permeability of Hard Rock Aquifers is due neither to tectonics, nor to unloading, but to weathering processes

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ABSTRACT

The hydrogeology of superficial (~0–100 m b.g.l.) Hard Rock Aquifers (HRA; i.e. plutonic and metamorphic rocks) has so far been dominated by a few concepts considered to be relevant by a large majority of the HRA community. One of the most fundamental of these concepts is that their (secondary, fissure/fracture) permeability is either of tectonic origin or related to unloading processes. We will show that these genetic concepts are erroneous. We will demonstrate how the hydraulic conductivity of HRAs is a consequence of the (palaeo) weathering processes, with a stratiform fissured layer located immediately below the unconsolidated saprolite and, to a lesser extent, a verticalized fissured layer at the periphery of (or within) pre-existing discontinuities (veins, joints, ancient faults, lithological contacts, etc.). This result opens up large perspectives in terms of applied hydrogeology and applied geology. A specifically dedicated methodological toolkit well adapted to the operational survey, management and protection of HRAs is briefly presented.

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Introduction

Hard Rocks (HR) (Michel and Fairbridge, 1992) are plutonic and metamorphic rocks, from which we exclude marbles, as they can be karstified, and obviously limestones and non-metamorphosed volcanic rocks. HR make up the basement of the continents and, as such, outcrop over large areas throughout the world (namely a large part of Africa, South and North America, India, Australia, etc.) mostly in tectonically stable regions such as ancient cratons. The groundwater resource of the associated aquifers (Hard Rock Aquifers; HRA) is rather low in terms of sustainable discharge per productive well (from several 100 L h^{-1} to a few tens of m^3 h^{-1}; Courtois *et al*., 2009) as compared to that from porous, karstic and volcanic aquifers (see for instance Wright, 1992; Dewandel *et al*., 2006), 'dry' wells being also very common (Courtois *et al*., 2009). However, HRA are well suited for water supply to scattered populations and small-to-medium-size cities, or the suburbs of the larger cities. Their groundwater resource contributes to the well-being of the population and to the economic development, especially in areas exposed to arid and semi-arid climatic conditions where the surface water resource is limited. For instance, in India, HRA water resource largely contributed to the 'green revolution' that allowed the food self-sufficiency of the country (Swaminathan, 2007; Mukherji, 2008), nevertheless not without drawbacks such as over-exploitation and groundwater quality degradation (Maréchal and Ahmed, 2003).

Even if a few authors describe their structure (and particularly the geometry of fracture sets) without proposing any genetic explanation (see references in Genetics of the fissured layer by unloading), the hydrogeology of HRA has so far been dominated by a few genetic concepts considered as relevant by a large majority of the HRA's hydrogeologists community. The most fundamental of these concepts is that their (secondary, fissure/fracture) permeability is either of tectonic origin or related to unloading processes (see references in Genetics of the fissured layer by unloading).

In this article, we will show that, even though the basic geological structure of HRA has been appropriately described by geologists and hydrogeologists, and more particularly the decrease of their hydraulic conductivity with depth (see for instance Davis and Turk, 1964), the two proposed genetic concepts, namely tectonic fracturing and unloading, are erroneous. We will demonstrate that the hydraulic conductivity of HRA is a consequence of (palaeo) weathering. On this basis, we will propose a complete toolkit well adapted to the real structure and properties of such aquifers, thus well adapted to their operational survey, management and protection.

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Discussion of some 'established' concepts in HR hydrogeology

The fissure/fracture permeability of HRA: a secondary origin

HR intrinsically present a very low (below 10^{-8} m s^{-1}) matrix hydraulic conductivity (see for instance Uhl and Sharma, 1978). That explains, among other arguments, why these rock masses are good candidates for nuclear waste storage at least in depth (see for instance Gustafson *et al*., 2009). Their hydraulic conductivity exclusively relies on secondary fissure/fracture permeability (see for instance Boutt *et al*., 2010). Then, a well providing a significant yield in HR (a few m^3 h^{-1}; Maréchal *et al*., 2004;

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Dewandel *et al.*, 2006) crosscuts the low permeability non-productive rock matrix alternating with a few centimetres to decimetre thick permeable layers ('water strikes', 'fissures', 'fractures') that provide the pumped water. Thus, a pumping well must imperatively tap this secondary 'fracture' permeability.

The fissures located at the bottom of the unconsolidated saprolite and the subhorizontal jointing of granites: the same geological object, the fissured layer

The groundwater resource of HR was mainly discovered in the sixties in tropical countries (mostly Africa) by practitioner hydrogeologists (Plote, 1968). The development of a new drilling method (the down-to-the-hole hammer; Plote, 1985) largely revealed their permeability, their exploitability by small diameter (a few decimetres) deep wells (a few tens of metres) and thus made it possible to describe their geological structure (Moussu, 1981; Guiraud *et al.*, 1990). Before the development of that drilling technique, only their superficial (metre to decametre thick) unconsolidated (weathered) fringe was prospected and exploited (where saturated and permeable enough) by large diameter wells (Guérin-Villeaubreil, 1962; Biscaldi, 1968; Lelong and Lemoine, 1968; Faillat, 1986). Since that period, millions of 'deep' wells have been drilled in HR throughout the world, particularly in the sahelian countries of Africa, with the main aim of providing water, and in some cases safer water, to the population (Lenck, 1977; Guiraud *et al.*, 1990; Wright and Burgess, 1992) and, in India, mostly for irrigation (Swaminathan, 2007).

These drillings revealed the presence of the permeable fissured/fractured zone located in the first few tens of metres of the 'unweathered' HR (both crystalline and metamorphic) underlying the unconsolidated weathered layers (regolith or saprolite) (Biscaldi, 1968; Acworth, 1987; Guiraud *et al.*, 1990; Wright, 1992; Taylor and Howard, 1999, 2000). The above-lying unconsolidated weathering profile was described in details by several authors (see for instance Acworth, 1987 – Fig. 1), mainly those working in tropical countries. And yet neither hydrogeologists (see the same references as above) nor the specialists of soils and weathering processes (Duchaufour, 1984; Nahon, 1991; Mac Farlane, 1992; Tardy and Roquin, 1998; Bétard, 2010) have ever attributed the underlying fissured/fractured zone to the weathering profile; they have never described this layer since the main object of palaeogeography (Betard) or soil (Duchaufour) and palaeoclimate (Tardy) specialists does not consist in explaining the genesis of deep underground structure. Tectonics and unloading processes (see references in Genetics of the fissured layer by unloading) are the most common genetic hypotheses formulated to explain the development of such fissures/fractures. Nevertheless, several authors also stress the fact that preexisting tectonic fracturing might favour weathering (Biscaldi, 1968; Chilton and Smith-Carington, 1984; Acworth, 1987; Wright, 1992). It is noteworthy that the descriptions of this fissured/fractured layer are mostly provided by hydrogeologists, surely as a consequence of its remarkable hydrodynamic properties (cf. all the previous references – to the exclusion of soil and weathering process specialists – and also Hsieh and Shapiro, 1996; Day-Lewis *et al.*, 2000).

Moreover, (sub) horizontal jointing (or sheeting fractures), with a depth-related increasing spacing, is described in granites (s.l.) mainly in areas currently exposed to a temperate climate (Fig. 2). Jahns (1943) put forward a comprehensive description of such joints from observations in several places in New England (New Hampshire, Massachusetts, USA) where this horizontal fissuring appears to be particularly well outcropping, notably in quarries. He clearly demonstrated

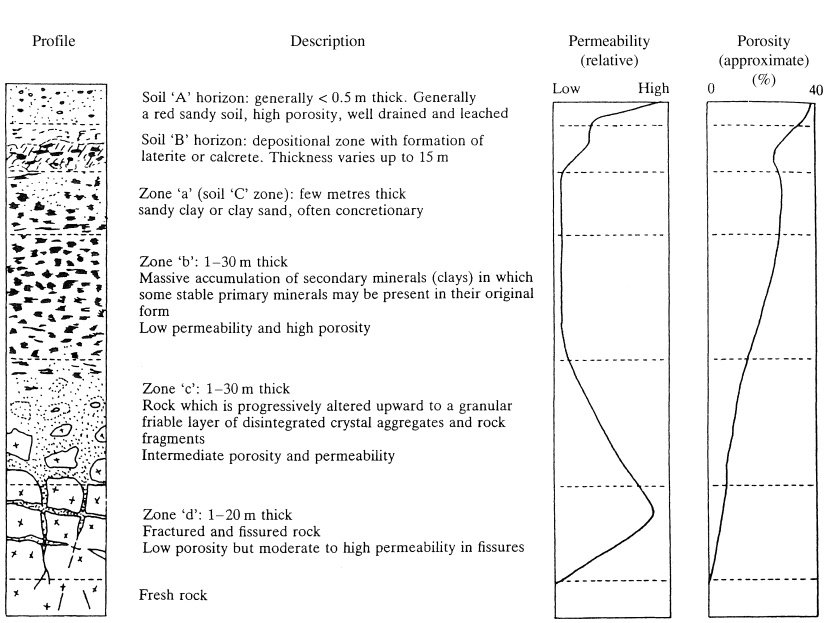

Fig. 1 Typical weathering profile developed upon crystalline hard rock (Acworth, 1987).

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Fig. 2 The fissured horizon in granites (Lozère, France) outcropping (left: near the village of Serverette; the ~5 m high phone pile gives the scale) and in a former quarry (right: near the village of Rieutort de Randon).

that these structures have no genetic relationships with the emplacement and cooling of the involved plutonic rocks. He invoked several hypotheses for joint genetics: unloading, insulation, hydration and weathering, the action of fire, cold and vegetation, but he did not propose any demonstration. Similar observations were reported always for granites (s.l.) in the USA (Mabee *et al*., 2002; Mandl, 2005), Sweden (Carlsson and Olsson, 1980/1981), Australia (Twidale, 1982; Ollier, 1988; Hill *et al*., 1995; Taylor and Eggleton, 2001), Africa (Wright, 1992; Chilton and Foster, 1995), Hong-Kong (Shaw, 1997) but also without any demonstration of their genetics. Nevertheless, a few authors have described that this jointing is located at the base of a weathering profile (Ollier, 1988; Hill *et al*., 1995; Shaw, 1997; Taylor and Eggleton, 2001 – see for instance Fig. 3), including Jahns (1943) who highlighted their relationships with grus remains.

Mabee *et al*. (2002), citing notably Hsieh and Shapiro (1996), Day-Lewis *et al*. (2000), clearly stated that 'horizontal…sheeting fractures can be a significant source of fresh water', 'can often dominate the flow system', and 'may account for the lack of correlation between well yields and lineaments in some studies'. A few other authors describe such subhorizontal fracturing, and particularly its hydrodynamic role (Paillet *et al*., 1987; Paillet and Duncanson, 1994; Le Borgne *et al*., 2006a,b, 2007; Boutt *et al*., 2010).

From their descriptions, it appears that the fissured zone and the subhorizontal jointing of granites must constitute the same geological object, located at the bottom of the unconsolidated weathering profile. We will later name it the 'fissured layer', sheeting fractures constituting a type of fissured layer specific to granite type rocks. Unloading and tectonics are the most common genetic hypotheses proposed to explain the development of the joints constituting the fissured layer.

Genetics of the fissured layer by unloading

The 'vertical unloading of a rock mass that formed in depth under high triaxial compression' (Holzhausen, 1989) or 'dilation following the unloading of Earth pressure' (Farmin, 1937) are processes proposed to explain the origin of subhorizontal joints also known as 'sheet structure' or 'large-scale exfoliation' (Holzhausen, 1989). That hypothesis is also often invoked by hydrogeologists (see for instance Twidale, 1982; Houston and Lewis, 1988; Guiraud *et al*., 1990; Wright, 1992; Chilton and Foster, 1995; Taylor and Howard, 1999, 2000; Mabee *et al*., 2002). None of them has ever demonstrated it or gone through the rock mechanics literature to look for its demonstration.

Rock mechanics specialists, such as Pollard and Aydin (1988), and Mandl (2005) proposed a comprehensive approach of joints (definition, mechanics, etc.). Among other results, they have confirmed the existence of a relative displacement perpendicular to the joint (opening), the absence of striation thus being no proof of an absence of movement. Pollard and Aydin (1988) and Mandl (2005) never invoked the process of 'unloading'. However, Pollard and Aydin (1988) stated that subsurface cavities or microcracks submitted to a high fluid pressure might create joints. In an isotropic rock this may even generate joints perpendicular to the least compressive strain (σ_3'), namely subhorizontal joints. Nevertheless, they did not propose any genetic mechanism likely to reach such a high fluid pressure. Mandl (2005) demonstrated that sheeting fracturing subparallel to the topographical surface can only form at shallow depths (a few tens of metres – for low σ_3') but also requires a strong compression (σ_1) parallel to the surface. He did not propose any physical mechanism allowing such a compression. In the literature, the only proposed mechanisms are:

1 'artificial' unloading to explain the superficial ruptures observed at deep wells or mine gallery walls that are due to the lithostatic stress. Chang and Haimson (2007) showed that such fractures appear for $\sigma_1 > 290$ MPa (for a rhyolite and when the rock is saturated) and when a high stress differential ($\sigma_3 \ll \sigma_1$) is applied; for other conditions (and particularly smaller stress differential) much higher σ_1 values are required;
2 the load induced by the rocks making up the top of a cliff (in

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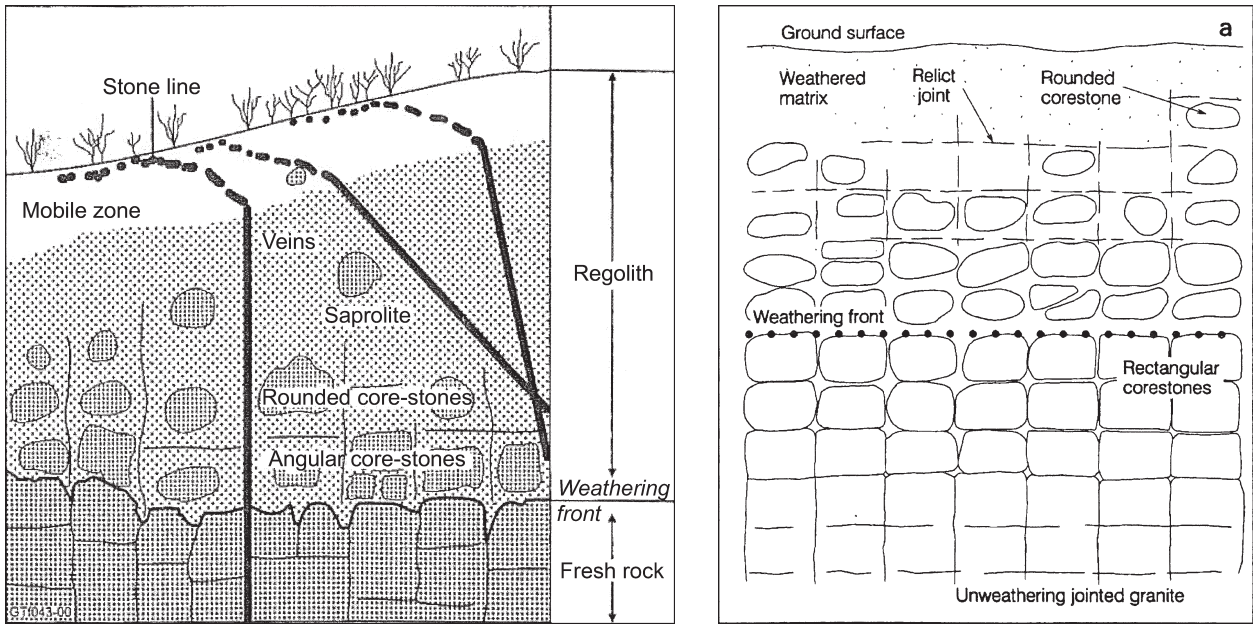

Fig. 3 Schematic representations of granites jointing at the base of a weathering profile (left: Taylor and Eggleton, 2001; right: Shaw, 1997).

the case of cliff vertical exfoliation joints) inducing successive buckling and splitting processes (Bahat *et al.*, 1999);

3 the powerful vertical forces accompanying upward flow. Cobbold and Rodrigues (2007) demonstrated that without any rock anisotropy or strong horizontal stress such flow can cause the principal effective stresses to become tensile and can generate such horizontal fractures. Their development is applicable in sedimentary basins where high fluid pressure can form at great depths. However, this process is merely applicable to the hydrogeological conditions prevailing in shallow HR.

Thus, the fissured layer cannot be explained by natural unloading processes. With the exception of some specific conditions (artificial unloading – deep wells, mine galleries – cliffs, deep sedimentary basins), no natural phenomenon able to induce a strong compression parallel to the surface appears to exist. In addition, gravity structures can only be invoked in very specific contexts such as high reliefs, for instance in Alpine valleys (Maréchal, 1999).

Genetics of the fissured layer by tectonic fracturing

Several authors have described and characterized the structure of HRA and particularly the geometry of fracture sets and their scaling without proposing any genetic explanation for the origin of the fractures (see for instance Acworth, 1987; Ollier, 1988; Hill *et al.*, 1995; Shaw, 1997; Taylor and Eggleton, 2001; Le Borgne *et al.*, 2006a,b). Bonnet *et al.* (2001) have proposed a large review of fracture system scaling but specifically for tectonically active sets of faults. Neuman (2005) proceeded with an in-depth review of the hydrodynamics of fractured HR without analysing their geological structure. In fact, his approach of fractured rocks does not only deal with HR, but also with other types of fractured rocks, particularly volcanic rocks, and is focused on the hydrodynamics of low permeability fractured rocks and not on HR fracture genetics.

Several other authors have described and/or characterized the assumed structure of HRA and stated that their fracturing is of tectonic origin (see for instance Guiraud *et al.*, 1990; Key, 1992; Wright, 1992; Faillat *et al.*, 1999; Lasm and Razack, 2001; Razack and Lasm, 2006; Neves and Morales, 2007; Bamory *et al.*, 2008; Batte *et al.*, 2008; Kouamé *et al.*, 2010). And yet they did not demonstrate that hypothesis. Pollard and Aydin (1988) and Mandl (2005), despite exhaustive bibliography reviewing did not cite any tectonic process able to generate the above described mechanical conditions required for the formation of sheeting fractures, and consequently for the genesis of the fissured layer. The only invoked mechanisms are thermal (but only for volcanic rocks) and dessication cracking (for clayey sediments).

Tectonic fracturing and hydraulic conductivity in tectonically active areas

The genetic relationship between tectonic fracturing and the permeability of rocks (not only HR) is well documented in tectonically active areas (TAA): mostly plate boundaries, i.e. actively spreading ridges and transform faults, rifts, subduction zones and convergent or collisional plate boundaries. These areas only occupy a few percent, even less (NASA, 2003), of the earth's emerged surface. Their restricted areal extent and concentration of strain by definition make them anomalous in regard to the average

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properties of the crust (Ingebritsen and Manning, 2010).

To the best of our knowledge, the structure of the fissured layer of HRA has never been described in such contexts. Nevertheless, tectonics must be regarded as having an influence on the hydraulic conductivity of rocks, and in some cases on the hydraulic conductivity of HR. The relationships between tectonics, in fact the response to large earthquakes (Rojstaczer *et al*., 1995), and the hydraulic conductivity of rocks can be summarized as follows.

Permeability of seismogenic faults. At the crust scale, deep fault-zone permeabilities are substantially higher, at least two orders of magnitude higher (Ingebritsen and Manning, 2010), than the surrounding crust. For instance the permeability of the 'shallow' crust (< 5 km) of the Black Forest (Germany) tectonically active rifting environment is much higher than that of a normal crust (Ingebritsen and Manning, 2010). Kitagawa *et al*. (2002) have shown that large earthquakes can temporarily increase the hydraulic conductivity of the active fault. In fact, they did not show the increase of the hydraulic conductivity of the fault at the root of the earthquake (the M7.2 Hyogoken-Nanbu earthquake – Japan) but, from injection tests (540 → 790 m) in two deep wells drilled in granite, they quantified the temporal decrease of a permeable zone of the Nojima branch fault due to healing processes. Incidentally, they show that the healing processes are very fast at the geological time-scale: during the 1997–2000 period after the 1995 earthquake, the hydraulic conductivity decreased by a factor of about 2.

Permeability enhancement in the vicinity of seismogenic faults. Increased discharges of streams and/or shallow springs occurring just after a large earthquake in the vicinity of the seismogenic fault have been known for more than 2000 years (Muir-Wood and King, 1993). After being attributed to the expulsion of water from the upper or middle crust due to elastic compression (Muir-Wood and King, 1993), most of these great hydrological changes were correlated with significant piezometric drops in shallow aquifers (see for instance Rojstaczer *et al*., 1995; Tokunaga, 1999; Wang *et al*., 2010), and were consequently attributed to permeability enhancement in these shallow aquifers (Rojstaczer and Wolf, 1992; Tokunaga, 1999; Brodsky *et al*., 2003).

Tokunaga (1999) described an increase of the discharge of shallow springs in the vicinity (a few kilometres) of the Nojima branch fault just after the Hyogoken-Nanbu earthquake. Such increased discharge is correlated to an important drop (up to 70 m) of the water table in superficial unconfined weathered granite aquifers. From these data, he inferred a five times increase of their permeability during the earthquake. Similar hydrological observations were performed by Muir-Wood and King (1993) particularly for two major (M7.3 and 7.0) normal fault earthquakes in the US, by Wang *et al*. (2010) in Taiwan after the M7.5 Chi-Chi earthquake and by Rojstaczer *et al*. (1995) after the M7.1 Loma Prieta earthquake in California (on average one order of magnitude of permeability increase at basin scale).

In shales, Rojstaczer *et al*. (1995) suggested that the permeability enhancement is due to existing fractures enhancement. Wang *et al*. (2010) showed that during the quake the vertical permeability of the groundwater system is enhanced by the fracturing (or by fracture enhancement) of a shale aquitard overlying the sandstone aquifer which is discharging to the river. Such observed permeability enhancement in the vicinity of active faults after a large earthquake will occur at distances reaching several tens of kilometres: more than 15 km for the M7.1 Loma Prieta earthquake (Rojstaczer *et al*., 1995), 20–30 km for the M7.5 Chi-Chi earthquake (Wang *et al*., 2010), 50 km for the M7.3 Hegben Lake and M7.0 Bora Peak earthquakes (Muir-Wood and King, 1993).

In HR the genetics of such permeability increase is not specifically documented [for instance Tokunaga (1999) proposes no explanation]. Elkhoury *et al*. (2006) showed that seismic waves can explain such permeability enhancements but they do not propose any genetic explanation at the scale of the fracture. Their case study in South California deals with a rather deep granodiorite (two wells open from 61 m down to their bottom, respectively, 137 and 211 m deep) with a quite low hydraulic conductivity ($\sim 10^{-8}$ m s^{-1}). The process is only observed for earthquakes inducing great shakes in the well-zone (vertical peak ground velocity > 0.2 cm s^{-1}), i.e. for high magnitudes/epicentre distance ratios (respectively, 4.8/10 km and 7.3/200 km in this case study). The dynamic rather than static stress is the likely cause of the increased permeability: a linear relationship is observed between the increase in permeability (reaching 2–3) and the ground shaking (a proxy for the dynamic stress field). These authors have also shown that, after an earthquake, it will take 1–2 years for the hydraulic conductivity to be back to its initial value: an order of magnitude similar to those observed by Claesson *et al*. (2007) in Iceland (basalts) and Kitagawa *et al*. (2002) in Japan (granite). Such fast healing processes (10^1 to $< 10^2$ years) observed in various kinds of rocks after the earthquake (see for instance the review proposed by Ingebritsen and Manning, 2010) can indirectly provide clues about the processes at the origin of the enhanced permeability, as feedback between permeability enhancement and decay is largely invoked (see for instance Kitagawa *et al*., 2002; Elkhoury *et al*., 2006; Ingebritsen and Manning, 2010). Healing due to mineral precipitation and hydrothermal alteration under conditions of strong chemical or thermal disequilibrium (Ingebritsen and Manning, 2010) can be balanced by the crushing of such minerals or by the de-clogging of soft mineral phases precipitated in the fractures. The thermoelastic stresses due to cooling (Ingebritsen and Manning, 2010) can be balanced by opposite thermoelastic stresses due to heating (higher temperature water inflow). Wang and Manga (2010) invoke that dynamic stress can 'dislodge blockage from fractures' or 'blockage from fluid passageways' and 'break up flocs of small particles' and that 'time varying fluid flow can change permeability by dislodging particles or breaking up aggregates of colloidal pore-blocking particles' or can change 'particle redistribution within fractures'; they also state that 'seismic waves may dislodge

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minute clogs from fractures to enhance permeability and redistribute pore pressure'. Brodsky *et al.* (2003) propose a similar explanation: 'a temporary barrier deposited by groundwater flow is…removed by the more rapid flow induced by the seismic waves'. Thus, various processes occurring in existing fractures are described.

Fracturing and hydraulic fracturing induced by rock failure are also invoked (Rojstaczer *et al.*, 2008). Fracturing induced by high pressure fluids injected into deep boreholes (Dorbath *et al.*, 2010) and also reservoir-induced seismicity (El Hariri *et al.*, 2010) and seasonal variations in seismicity due to natural piezometric (Christiansen *et al.*, 2005) or to snow cover changes (Panza *et al.*, 2011) are proven to be sufficient to fracture critically stressed rocks either through pore-pressure diffusion (from the surface in the last cases) or through crustal loading/unloading. In fact, in TAA, many fractures appear to be in a state of incipient failure (Rojstaczer *et al.*, 2008). Thus, faulting due to large earthquakes may also activate or re-activate faults other than the fault at the origin of the earthquake in its vicinity.

This leads us to the partial conclusion that, in TAA, tectonics can undoubtedly be at the origin of the permeability of HRA, not only along the seismological faults but also over larger zones as far as several tens of kilometres from the earthquake epicentre. Nevertheless, healing processes appear to be more efficient than fracturing or permeability enhancement; then the return period of permeability-efficient earthquakes must be high enough to counterbalance healing. Moreover, at shallow depths like those of the fissured layer of HRA (several tens to one hundred metres), it appears difficult to invoke the hypothesis of the creation of new fractures outside the main active faults that are identified by ruptures at the surface. As a matter of fact on the one hand such shallow foci have never been observed at the subsurface (Thouvenot *et al.*, 2009) and on the other hand reservoir-induced or natural piezometric changes-induced seismicity, all being surface-induced phenomena, have never been the subject of any shallow observation. For instance 'shallow' reservoir-induced earthquakes in a Precambrian basement were only observed at depths between 1.5 and 3 km (El Hariri *et al.*, 2010). Thus, even in TAA it seems difficult to invoke seismically induced fracturing of HRA outside the active fault itself. Seismically induced declogging of existing fractures most surely explains the observed temporary permeability enhancements.

Such processes can only be invoked in TAA, a few percent of the earth's emerged surface, and clearly not in stable cratonic area to which most HR belong in the world. We will nevertheless discuss below the hypothesis of tectonic fracturing outside this very specific context of TAA.

Tectonic fracturing of HR outside TAA

The theory of tectonic fracturing to explain the origin of the secondary fissures/fractures of HR outside TAA requires at least the two main following conditions:

1. The existence of tectonic processes able to create a fracture and/or reactivate an existing one. It also requires that such a fracture be permeable.
2. The repetition of these processes sufficiently frequent (on the geological time-scale) to avoid the sealing of the fracture.

We will dispute and develop these points hereafter. Most of the cited examples are taken from the French 'Massif Armoricain' (French Brittany), a HR area presently considered as almost inactive (Moreau *et al.*, 2006) (from a tectonic standpoint it is often considered as a median between TAA and really stable areas) but comprising, like most HR areas in the world, several thousands of water wells (Mougin *et al.*, 2005).

Tectonic fracturing does not systematically create permeable structures. Tectonic faults/fractures are often considered only as permeable structures (see for instance Razack and Lasm, 2006; Bamory *et al.*, 2008; Kouamé *et al.*, 2010). However, faults are complex geological objects, with various facies (Caine *et al.*, 1996) and thus exhibit a wide range of hydraulic conductivities from permeable to highly impermeable. Sander (1997) has confirmed this point for HR: the heart of the fractures is often made up of an argillaceous low permeability gouge to be dodged by drilling wells far enough from it. Even a single fracture is not homogeneous and its hydrodynamic properties can be described only through 'channelling' concepts (Tsang *et al.*, 1991; Abelin *et al.*, 1994; Tsang and Doughty, 2003). For instance in the 2–4 km deep Soultz granite, hydrothermal products seal 99% of the surface of natural fractures, only 1% showing evidence of permeability and residual aperture (Genter and Traineau, 1996; Ledésert *et al.*, 2010). At the scale of a local fault network, the various fractures can play different roles (Bruel *et al.*, 1999), namely as a drain, even as a hydraulic barrier, and also a multi-purpose role (barrier against the flow in a perpendicular joint network and without effect for a different set of small faults). At a regional or aquifer scale, numerous faults act as hydraulic barriers (Mayer *et al.*, 2008). Mines and quarries in HR areas also constitute sound integrative examples due to their large vertical and spatial extent, as they often crosscut several faults. Their generally quite low dewatering discharge testifies to the fact that most faults exhibit a low hydraulic conductivity.

Only the strongest earthquakes can generate fractures at shallow depths. The energy dissipated during a seismic event depends on the surface area of the fault plane on which the displacement occurs (Wells and Coppersmith, 1994). Most of the hypocenters being located in depths ranging from several kilometres to several hundred kilometres (Thouvenot *et al.*, 2009), only the shallow earthquakes or those generating a move over a very large fault plane are likely to propagate to the surface. Seismologists consider that 'shallow' earthquakes are those occurring in the first 40 km (Thouvenot *et al.*, 2009) and a literature thorough search performed by these authors does not provide any evidence for foci shallower than 1–2 km. As a first approach, only earthquakes with a magnitude over 5.5 may generate ruptures on the surface (Wells and Coppersmith, 1994). For instance, a surface throw >1 m requires at least a $M > 6.5$ event (Baize *et al.*, 2007).

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The 'Massif Armoricain' is currently considered as a low to moderate seismic area with quite shallow (a few tens of kilometres) earthquakes. Seismologists consider that M > 5 earthquakes can hardly occur in this area. In other words, the magnitude of the most energetic earthquakes that may nowadays occur in French Brittany is not high enough to generate or reactivate fractures up to a shallow depth (that of a water well, i.e. a few tens of metres below ground surface). Thus, in the 'Massif Armoricain' to surely attribute a tectonic permeability to HRA at shallow depths would require considering that such magnitudes or higher ones were reached in the past, during a more active geological period and that these fractures were not sealed.

Active faults and HR water wells do not display the same spatial pattern. In HR areas, productive water wells are quite evenly spatially distributed (see for instance Fig. 4; Maréchal *et al*., 2004; Mougin *et al*., 2005; Courtois *et al*., 2009), their emplacement being often suited to the location of the water need (village, farm, plot, etc.). However, the spatial distribution of active faults is not so even. The recent fault pattern of the 'Massif Armoricain' is quite well-known due mainly to the work of Guillocheau (personal communication; Bonnet *et al*., 2000) and his students (Bonnet, 1998; Thinon, 1999; Thomas, 1999; Brault, 2002):

1 The present-day strain regime (Grellet *et al*., 1993) began during the Tortonian stage (11.2–7.12 Ma). It accounts for the present-day moderate relief. The preceding period was quite calm from a tectonic standpoint.
2 Since the Tortonian paroxims, over the last 5 Ma, deformation has almost exclusively been concentrated along a few main faults (Fig. 5) which delimit a few structural blocks (Bonnet *et al*., 2000). The faulted areas are less than a few kilometres across and are evidenced by rare dated faults (Thomas, 1999), locally thicker sedimentation (Chevalier and Delanoe, 1989; Chevalier *et al*., 1989a,b; Thinon, 1999), and river drainage anomalies (Bonnet *et al*., 1998, 2000; Chaplot *et al*., 1999).
3 During the Tortonion paraxism, faulting probably occurred within each of these few blocks, but also along pre-existing and cartographically known (NW–SE, NE–SW) faults that individualize a few smaller undeformed structural blocks within the previously described larger blocks.

It appears that the present-day faulting (if any near the surface, see Only the strongest earthquakes can generate fractures at shallow depths) is only concentrated on the boundaries of a few structural blocks. The resulting picture (Fig. 5) is very different from that of the spatial distribution of the HR productive water wells (Fig. 4). Thus, it is very difficult to attribute to tectonic faulting all the permeable structures tapped by water wells in HR areas.

Temporal frequency of faulting. Lineaments (Sander, 2007) are frequently used in HRA to locate 'fractures', and then to site water wells, often without checking whether a deterministic relationship exists between such objects and real fractures (see for instance Gombert, 1997, 1999; Lasm and Razack, 2001; Razack and Lasm, 2006; Prasad *et al*., 2008). So, even if most water wells of the 'Massif Armoricain' were sited without any previous hydrogeological study, one may state that they are all located on such a lineament. From geomorphological (DEM), aerial magnetic and spectrometric surveys, Mougin *et al*. (2005) have identified more than 50 000 km of lineaments at the scale of the 'Massif Armoricain' as a whole. This order of magnitude, 1–2 km of

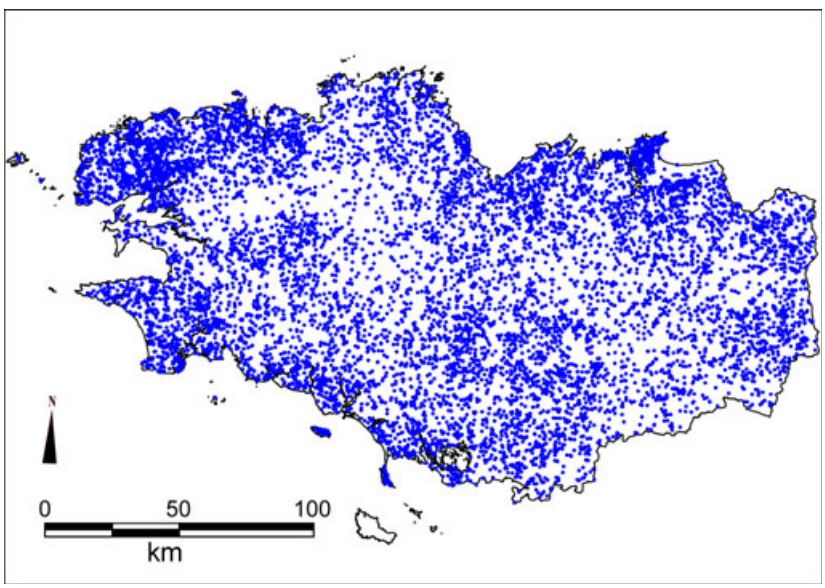

Fig. 4 Location of the hard rock borewells from the Massif Armoricain with a discharge > 1 m^3 h^{-1} (data from the Underground French National DataBase; from Mougin *et al*., 2008).

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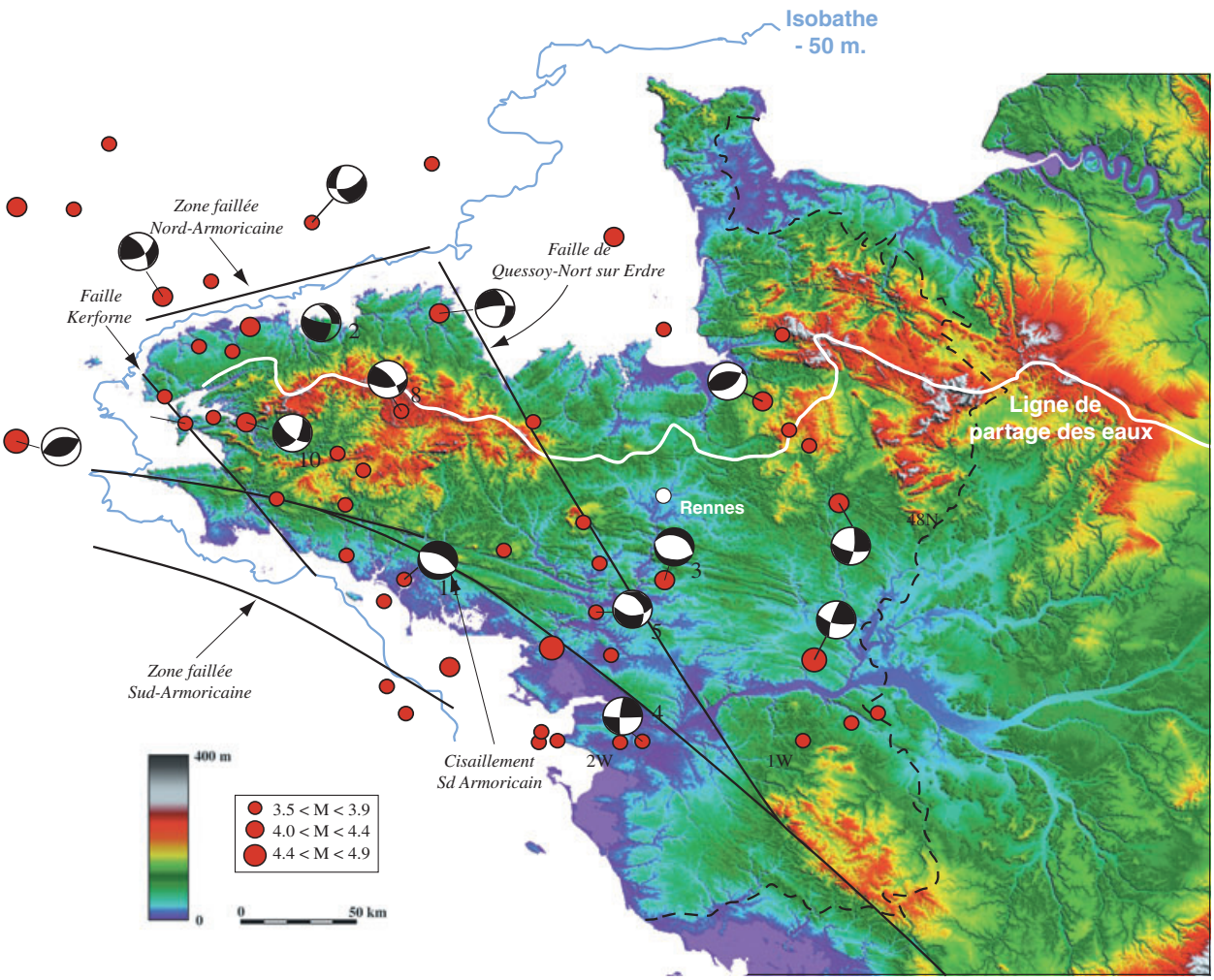

Fig. 5 Main faults in the Massif Armoricain where post-tortonian deformation are localized (F. Guillocheau, personal communication) (main earthquakes focal mechanisms; colours: elevations in m a.m.s.l.; faille = fault; zone faillée = faulted zone; ligne de partage des eaux = main surface water divide).

lineaments per square km, is classical in HR areas (Kouamé *et al.*, 2010). Even if most of these lineaments do not coincide with the known main faults (Fig. 5), a few empirical estimations of the minimum duration required for the creation or reactivation of such a lineament network have been made on the basis of a few hypotheses: all these lineaments result from faulting; only M > 5.5 earthquakes can generate a fault at shallow depths; only M5.5, 6 and 7 earthquakes occurred; the relation between earthquake magnitude and the length of surface ruptures established by Wells and Coppersmith (1994): M5.5 → 2 km, M6 → 6 km, M7 → 45 km; Gutenberg–Richter's law (Corral, 2007) to link the magnitude of the earthquakes with their frequency. This rough analysis shows that:

1 in the present-day tectonic context, with an hypothesis of a 10-ka return period for M6 earthquakes, a 25-Ma duration is necessary to create or rejuvenate such a lineament network. In other words, each lineament would have a mean 25-Ma period without any tectonic activity;
2 during the Tortonian paroxysm, while the return period was supposedly increased by a factor of 10, the duration was reduced to 2.5 Ma.

Instead of only considering lineaments, if one considers the above described (Active faults and HR water wells do not display the same spatial pattern) conceptual scheme of faults delimitating stable structural blocks, this analysis suggests that:

3 the Tortonian paroxysm may have reactivated all of the faults that were active at that time (main blocks and smaller ones). These faults must have been reactivated several times (up to 10 times) during that event, if it lasted a few million years;
4 during the last calmer 5 Ma, if one considers that only the 1000 km of faults limiting the main blocks were active, they were only rejuvenated every 0.5 Ma;
5 if the lineaments/faults located within the smaller blocks do really

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exist they may have been (re)activated once during the Tortonian stage. If not, as stated above, their activity period is reasonably higher than 25 Ma.

In such a HR area, the temporal frequency of activity of each fault segment appears to be comprised between 0.5 and 25 Ma. It is then necessary, at least if such faults or lineaments really exist and if the faulting propagated to the surface, to check that such quite long periods of rest did not lead to their sealing.

Sealing of faults. Geological observations show that most permeable fractures were later sealed/filled by mineral precipitation, the most important ones being at the origin of ore deposits. Thus, mining geology and mineral deposit studies provide information on this subject as well as on the rate/speed of the creation of such ore bodies, and as a result on the rate of sealing of these fractures.

In a hydrothermal context, several scales correlated in space and time are hierarchized (Jaques *et al*., 2002) as listed below: the geodynamic event, lasting from 20 to 200 Ma, the building-up of a volcanic edifice, comprising several successive intrusions with a time-scale up to a few million years, the intrusion and cooling of a single magmatic intrusion with a duration from 10 to 200 ka (Cathles *et al*., 1997), and the fracture giving birth to a mineral vein, the active lifespan of which must be less than or at least equal to the one described above, especially when one takes into account the fact that such veins have a polyphased functioning and a smaller spatial scale. If one considers that one intrusion is at the origin of ten successive mineralization episodes (which must be a default estimate), and that the process of fracturing and sealing is cyclic, then the lifespan of a permeable fracture would be from 20 to 1 ka. As described above, observations performed in TAA show much shorter durations (Tectonic fracturing and hydraulic conductivity in tectonically active areas): 10^1–10^2 years. This last order of magnitude is similar to the ones obtained from lab experiments at high temperature/pressure conditions (#1000 °C; Tenthorey *et al*., 2003) as well as in epithermal conditions (120 °C; Hiramatsu *et al*., 2005; Kay *et al*., 2006). Incidentally, Claesson *et al*. (2007) have shown from their observations in Iceland that the aquifer was submitted to such a tectonic fracturing say from 10 to 100 times during the last 10 ka. This suggests that this fault was permeable only during 20–200 years, i.e. only during 0.2–2% of that period of time, if one only considers tectonic fracturing.

Similar results are obtained at a lower temperature in fluorite, barite, lead and zinc deposits that can constitute more accurate analogues of the processes occurring at shallow depths in stable HR areas (Lavery and Barnes, 1971; Rowan and Goldhaber, 1995) and in polyphased fluorite-barite-quartz ore deposits (Jaillard, 1985; Marcoux *et al*., 1990). So it appears that the speed for fracture sealing is excessively fast at the geological time scale.

Synthesis

We are led to the conclusion that unloading and tectonic fracturing cannot be invoked as genetic concepts to explain the origin of the secondary fissures/fractures in HR, and as a way of consequence their hydraulic conductivity. Unloading would require a very high horizontal stress or stress differential. Such a process does not exist in the shallow subsurface. Moreover, such a process, if real, would also be observed for types of rocks other than HR.

As a matter of fact, tectonic fracturing faces several inconsistencies. In tectonically stable areas such as most HR areas in the world it requires:

1 a tectonic process to create the fracture. It is clear that, the occurrence of such fractures is very rare both in time and space;
2 that the resulting fracture be permeable. It is obvious that a tectonic fracture is a complex structure that is far from being systematically permeable;
3 that the resulting tectonic fracture reaches the subsurface (i.e. the depth of a HR water well), whereas tectonic fractures do not reach the last kilometres below ground surface;
4 that a permeable fracture be not fast sealed (at the geological time-scale), when in fact rejuvenation is overbalanced by sealing. In fact tectonic fractures are old and thus sealed;
5 the ubiquity of such fractures. We have shown that tectonic fractures are spatially unevenly distributed and thus cannot account for the thousands of evenly distributed productive water wells in HR areas.

In addition to that, other arguments can be put forward: the absence of thermal springs in such tectonically stable areas whereas the main active faults quite systematically exhibit several of these thermal springs (see for instance Chenevoy and Piboule, 2007; Renac *et al*., 2009); the fact that most tectonic fractures have a strong dipping and should thus hardly ever be tapped by standard vertical wells as opposed to the subhorizontal jointing of granitoids and the variously dipping fractures of the other HR stratiform fissured layer (SFL) which are systematically cut by vertical wells.

The fracture permeability of HRA is due to weathering

This first discussion leads us to discard the concepts of unloading or tectonic fracturing. An alternative conceptual model has been built during the last 10 years from observations performed all over the world: France (Lachassagne *et al*., 2001b; Wyns *et al*., 2004), South Korea (Cho *et al*., 2003), Burkina Faso (Courtois *et al*., 2009), and India (Dewandel *et al*., 2006) and also from several other observations performed by the authors in various regions of France (Brittany, Massif Central, Vosges, Corsica), other African countries, French Guiana, etc. (mostly BRGM reports, see http://www.brgm.fr).

The basic concept of this model is that the SFL belongs to the weathering profile as well as the above-lying unconsolidated layers (saprolite). The building-up of a lateritic weathering profile thick enough to be efficient from a hydrogeological standpoint is first of all a matter of time: millions to tens of millions years (Wyns, 2002; Wyns *et al*., 2003). In addition, such a building-up requires, of course, not only the emersion of the affected area, but also water (hot or cold deserts are thus not favourable to weathering)

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(Acworth, 1987; Wyns *et al.*, 2003). The weathering profiles are of lateritic type, characterized by leaching, with the evacuation of dissolved chemical elements extracted from the rock. These conditions need a favourable geodynamical context: regional uplift linked to a long wavelength lithospheric deformation which leads to the formation of peneplanes (Wyns, 2002; Wyns *et al.*, 2003; Guillou-Frottier *et al.*, 2007) with gentle slopes, more precisely a topographical surface verging on the equilibrium with the erosion rate not exceeding the weathering one (Wyns *et al.*, 2003), and thus allowing the weathering profile to thicken. The temperature (climate) is a secondary order factor acting only on the kinetics of the weathering process, with only a factor of about 1.7 between a tropical (28 °C) and a temperate climate (15 °C) (Oliva *et al.*, 2003). Moreover, the characteristic period of the climate (10^2–10^3 years) cannot explain the functioning of the weathering profiles which is much longer (Nahon, 2003; Wyns *et al.*, 2003). When the geodynamical context changes, the weathering profile may be (partially) eroded; conditions again favourable to the accumulation of a new weathering profile lead to polyphased structures (Dewandel *et al.*, 2006). Thus, most HR areas of the world exhibit relicts of one or several generations of weathering profiles (see for instance Jahns, 1943; Chilton and Smith-Carington, 1984; Theveniaut and Freyssinet, 1999, 2002; Thiry *et al.*, 2005; Dewandel *et al.*, 2006). In Europe, since the end of the Primary era (during which at least Carboniferous, infra Permian and infra Triassic weathering profiles are also known), the Early Cretaceous, and the Early and Middle Eocene, having lasted, respectively, 45 and 25 Ma, have constituted the most recent periods during which such processes lasted long enough to build thick (a 50–70 m thick fissured layer underlying a 20–30 m layer of unconsolidated saprolite) weathering profiles (Wyns *et al.*, 2003).

The result of the weathering process is a SFL parallel to the palaeotopography contemporaneous with the weathering (Fig. 6). Its fractures are caused by the stress induced by the swelling of some minerals (particularly biotite being progressively hydrated and turning into hydro-biotite, then vermiculite, then mixed clay layers, etc.: Mac Farlane, 1992; Hill, 1996; Wyns *et al.*, 2003), the weathering of biotite being clearly an early process particularly in granites and granodiorites (Tieh *et al.*, 1980). The increase in volume of the mineral can reach 30% (Banfield and Eggleton, 1990) and that of the total rock 50% (Folk and Patton, 1982). In granular rocks like granites with a random orientation of swelling minerals, the potential expansion tensor is isotropic, but expansion is impossible in the horizontal plane, as the medium is infinite in this direction. Thus the horizontal stress components are increasing during the weathering. In the vertical axis, stress increases until the lithostatic component is offset, providing vertical expansion, while horizontal stress continues to increase. In the resulting stress tensor the minor component (σ_3) is vertical, and the major ones (σ_1 and σ_2) are horizontal. When the stress deviator reaches the elastic limit of the rock, tension cracks appear (Wyns *et al.*, 2004). For granitic rocks, in accordance with rocks mechanics (Pollard and Aydin, 1988; Mandl, 2005), the resulting fractures are perpendicular to the minor stress (subvertical) and consequently are subhorizontal (parallel to the gentle topography contemporaneous with the weathering) and lead to the formation of the subhorizontal jointing of granites (see The fissures located at the bottom of the unconsolidated saprolite and the subhorizontal jointing of granites: the same geological object, the fissured layer). In foliated and schistose rocks, the variability of

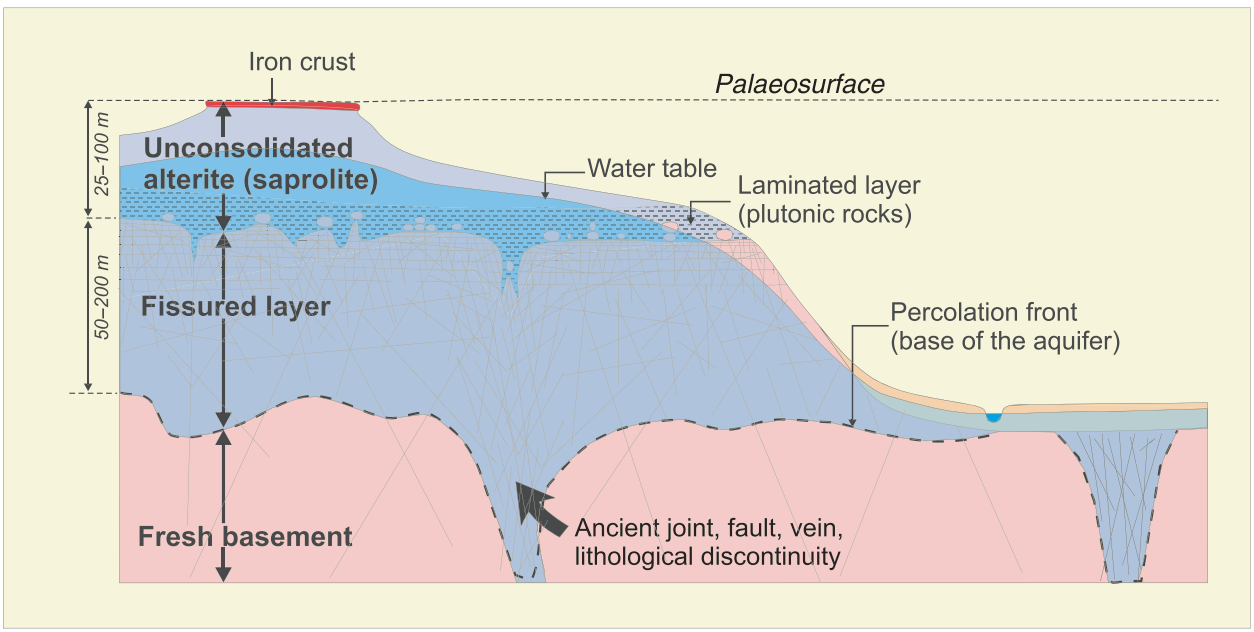

Fig. 6 Conceptual model of a partly eroded palaeo-weathering profile on hard rock (modified from Wyns *et al.*, 2002 and Dewandel *et al.*, 2006).

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the orientation of the minerals able to swell as well as the ones of the weaker surfaces of the rock (foliation, schistosity) induce an anarchic fracturing (without any preferential orientation). The fracturing is often parallel to the foliation (Boutt *et al.*, 2010). It is clearly the early stage of biotite weathering that provokes the fracturing. In fact, the later stages produce clay which exhibits a tendency to fill newly formed pores round about the fractured and weathered minerals (Bisdom *et al.*, 1982). Nevertheless, even if the early weathering of biotites leads to a local clogging of the biotite mineral and its surroundings at a millimetre scale, the density of biotites in the parent rocks is not high enough so as to clog the permeability of all the fractures of the fissured layer at a metre to decametre scale.

The thickness of the fissured layer is approximately two to three times that of the saprolite (Dewandel *et al.*, 2006). The density of the fractures decreases with depth towards the base of the weathering profile; thus the decrease of the hydraulic conductivity of HRA is not a consequence of a lower permeability of the fractures or their 'closure' but a consequence of their disappearance in depth (Maréchal *et al.*, 2004; Dewandel *et al.*, 2006). Within a vertical profile, the geological observations make it possible to identify several tens of such fractures; however, due to various processes (further healing of the fracture, its weathering, channelling within the fracture plane, etc.), only 0 up to a maximum of 4–5 of these fractures are permeable enough to be detected as 'water strikes' in a water well which explains the often large variability of the discharge of nearby wells, and even a 'dry' well in the immediate vicinity of a productive one (Maréchal *et al.*, 2004; Dewandel *et al.*, 2006; Boutt *et al.*, 2010). On top of that, ancient palaeoprofiles may have been completely sealed particularly as the result of diagenesis due to their burying below marine sediments. In granitoids, the diameter of each subhorizontal fracture constituting the SFL is a few tens of metres (Maréchal *et al.*, 2004). Such horizontal permeable fracture set is on average 10 times more permeable and more numerous than the subvertical joint set. The hydraulic conductivity of these permeable fractures does not show a large variability (Maréchal *et al.*, 2004; Dewandel *et al.*, 2006), which constitutes another argument for a unique origin (weathering).

As described by several authors (see for instance Biscaldi, 1968; Chilton and Smith-Carington, 1984; Acworth, 1987; Sander, 1997; Owen *et al.*, 2007), pre-existing heterogeneities within the HR such as veins (quartz veins, pegmatite, aplite, etc.), dykes, ancient fractures or joints, or even contacts between different geological units (see for instance Neves and Morales, 2007; Le Borgne *et al.*, 2004, 2006a,b; Durand *et al.*, 2006), locally favour the weathering process. There the weathering process turns out to be at the root of fissure development and of a related enhanced local hydraulic conductivity in the surrounding HR in the immediate periphery of these heterogeneities (Dewandel *et al.*, 2011) as well as in some thick discontinuities (quartz vein, pegmatite for instance) in the vein itself (Dewandel *et al.*, 2011). Near these discontinuities, the HR weathering profile (saprolite + fissured layer) is characterized by a

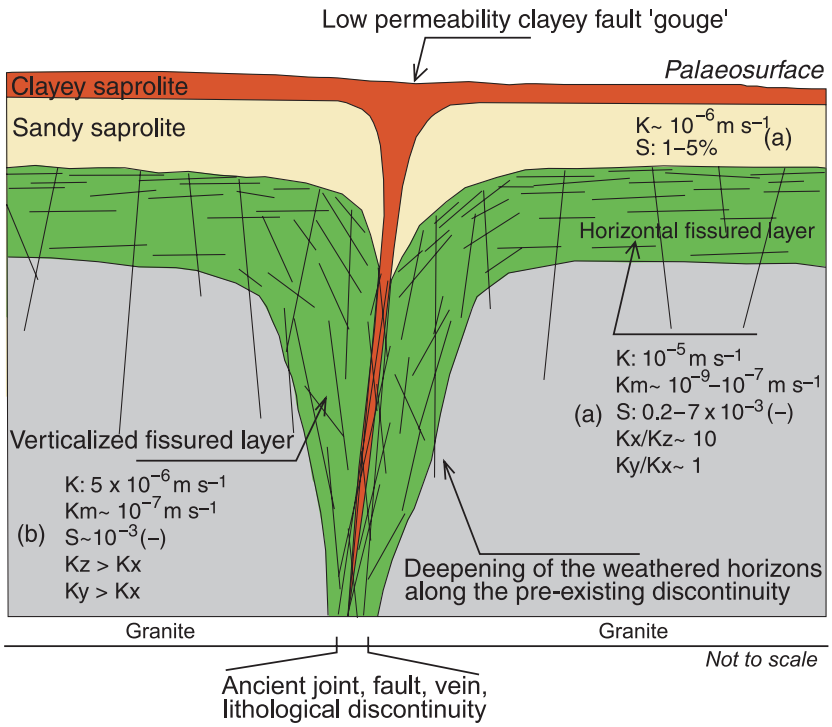

Fig. 7 Conceptual hydrodynamic model of a vertical discontinuity in hard rock [data from (a) Maréchal *et al.*, 2004; Dewandel *et al.*, 2006 and (b) Dewandel *et al.*, 2011.].

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sharp deepening of the weathering layers in the HR close to the contact with the vein (Fig. 7), the fissured layer being 'verticalized' parallel to the vein. As a consequence there the fissured layer reaches much greater depths than the classical previously described SFL (up to several hundred metres – see for instance Rhén *et al.*, 2007). Such geological structures are of high hydrogeological interest in areas where the SFL has been eroded (or is unsaturated, lying above the piezometric level); they constitute there the only available target for water well siting.

Practical applications from this conceptual model

This new genetic conceptual model of HRA leads us to revise the methodologies used for characterizing the structure and functioning of such aquifers, and thus boost their efficiency. Moreover, it enables us to propose a wise range of practical applications in hydrogeology as well as in other domains in applied geosciences. For instance, the strategy for siting a water well will be different in the general case (looking for the subhorizontal fractures of the SFL that will efficiently be tapped with vertical boreholes) or where the SFL has been completely removed by erosion (searching for a vertical fissured layer located along both walls of a subvertical discontinuity). In the former case, the survey will focus on the SFL preserved from erosion, not clogged by further weathering or diagenesis, and saturated with water (below the piezometric level). In the latter case, standard techniques for water well siting such as lineament analysis or radon surveys (Lachassagne and Pinault, 2001) will be applied. In that case inclined boreholes will be more efficient than vertical ones.

The main consequence of this new conceptual scheme is that HRA can now be considered as 'continuous aquifers'. As a way of consequence it is now possible to map (or model in three-dimensions) the geometry (elevation, thickness) and the physical properties of their various constituting layers: saprolite, with mostly capacitive hydrodynamic properties, SFL, with mostly transmissive but also capacitive properties (Lachassagne *et al.*, 2001a,b; Wyns *et al.*, 2004; Dewandel *et al.*, 2006). This mapping methodology is based on geomorphological, geological (outcrop observations, well logs), geophysical (both field and aerial; Carrier *et al.*, 2006), and hydrogeological approaches. Several hydrogeological applications have been derived from these concepts and methodologies.

1 Mapping hydrogeological potentialities at various scales ranging from a whole country (Courtois *et al.*, 2009) to the local area (water well siting) (Courtois *et al.*, 2003), without forgetting the intermediate regional scale (Lachassagne *et al.*, 2001b; Wyns *et al.*, 2004). It allows us, among other assets, to forecast the HRA productivity and useful thickness, and thus to define and size hydrogeological surveys and drilling campaigns.
2 For the first time, the quantitative management, and thus the modelling of HRA groundwater resource at the watershed scale (Lachassagne *et al.*, 2001b; Marechal *et al.*, 2006; Dewandel *et al.*, 2007, 2010).
3 Assessing HRA groundwater reserves from the watershed to the regional scale (Wyns *et al.*, 2002, 2004; Baltassat *et al.*, 2005; Vouillamoz *et al.*, 2005) and, on this basis, evaluating the durability of non-point source (nitrates for instance) pollutions.
4 Managing and protecting HRA groundwater resource (delineation of groundwater protection zones, optimization of piezometric networks; Zaidi *et al.*, 2007).
5 Computing the drainage discharge and the hydrogeological and hydrological impacts of tunnels (Lachassagne *et al.*, 2006, 2007, 2008).

Before being largely improved and developed for hydrogeological applications, these concepts were first used as markers of geodynamic evolutions (Wyns, 1991) with geological mapping objectives (see for instance Wyns *et al.*, 1998) and radioactive waste storage safety analysis (Wyns, 1991, 1997). Applications have also been developed in the field of soil and rock mechanics, notably for the forecast at cartographical scale of the near subsoil mechanical properties for applications such as the burying of (electrical, telephonic) networks (Wyns *et al.*, 1999, 2005), and also for quarrying in HR (Rocher *et al.*, 2003): evaluation of the thickness of the cover cap, determination of optimal geo-mechanic quality of the materials, etc. In the near future more applications are expected to crop up such as preliminary surveys for linear works (highways, railways).

Conclusion

It turns out that the hydraulic conductivity of HR is inherited from weathering profiles, within their SFL located immediately below the unconsolidated saprolite and, to a much lesser extent, within the vertical fissured layer at the periphery of or within pre-existing discontinuities. This result opens up large perspectives in terms of applied hydrogeology and geology.

This article shows that some concepts still considered as relevant by a majority of applied geologists should be revised. It reminds us that all the genetic concepts in geosciences must mandatorily be demonstrated before being taken for granted, including some concepts that may appear as obvious from a logical standpoint or that may have been considered as proven for quite a long time. With this objective the applied geoscientist must involve the specialists of other branches of geosciences (in the present case: geologists specialized in HR, in weathering processes, seismologists, etc.) before building-up or accepting a theory. He must also take advantage from his frequent position as a project manager to involve such specialists in his applied projects and then improve their efficiency and results.

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