ORIGIN OF FRACTURING IN HARD-ROCK AQUIFERS: WHAT ARE THE FACTORS CONTROLLING THE PROPERTIES OF THE FRACTURED LAYER?

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The discovery, during the last 1990s, of a thick fractured layer below the saprolite in lateritic profiles developed on crystalline rocks has resulted in a redefinition of hardrock aquifers. During the first 2000s, numerous researches were conducted in different continents in order to validate this new concept of stratiform hardrock aquifer linked to weathering processes. Commonly, the term of "lateritic profile" is used for subtractive weathering profiles developed on metamorphic, plutonic or volcanic rocks. They are the only rocks that are able to develop a fractured layer at depth.

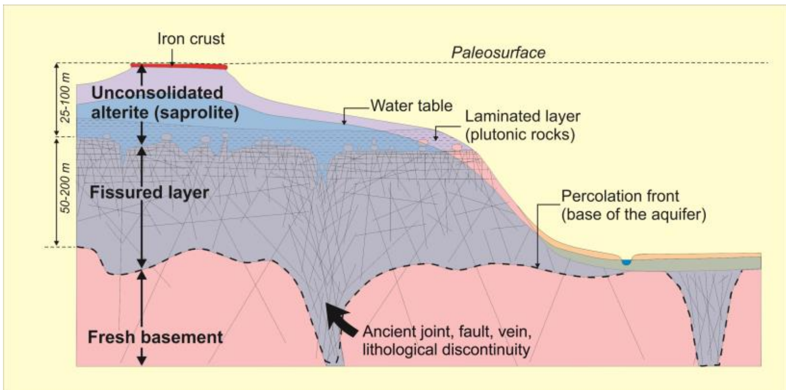

Figure 1 – Structure of a lateritic profile partially eroded by the present topography

A lateritic profile usually shows, from top to bottom (*Figure 1*):

- A ferralitic *duricrust*, 1 to 10 m thick, resulting from recrystallization of goethite (iron hydroxide) to hematite (iron oxide) due to seasonal desiccation of the top of the profile. Where preserved from later erosion and recharged by heavy rainfall this duricrust can give rise to seasonal perched aquifers, particularly in tropical humid areas.
- Loose alterites (*saprolite*), made up of a mixing of clays, hydroxides, oxides and residual minerals (quartz). At the top of saprolite, *mottled clay* (meter-thick) is a transition horizon to iron crust. In granular rocks (granitoids, gabbros), the lower part of the saprolite shows a characteristic laminated texture (*"laminated layer"*), due to high density of tension microcracks (millimetric spacing). The saprolite is of rather low hydraulic conductivity, about 10^{-6} m/s in granites, lower in their laminated layer and at the top (more clayey) of the

saprolite (10^{-7} - 10^{-8} m/s). This plays the capacitive role of the hard rock aquifer.

- A *fractured layer*, characterized by a high density of cracks in the hard rock that plays the permeable role of the hard rock aquifer. The density and connectivity of cracks are maximal at the top and decrease downwards. The primary rock stay hard and little weathered, except along fractures and capillaries. In isotropic granular rocks, fractures take the form of open, planar joints. The hydraulic conductivity of this layer can reach up to 10^{-4} m/s.
- The *fresh rock* is of very low hydraulic conductivity. Pre-existing heterogeneities such as veins, dykes, ancient faults or joints, contacts between different geological units may locally favor the weathering process and can create local hydraulic conductivity.

The thickness of the saprolite reaches commonly several tens of m, and can exceed 100 m. The fractured layer is generally twice as thick as the saprolite.

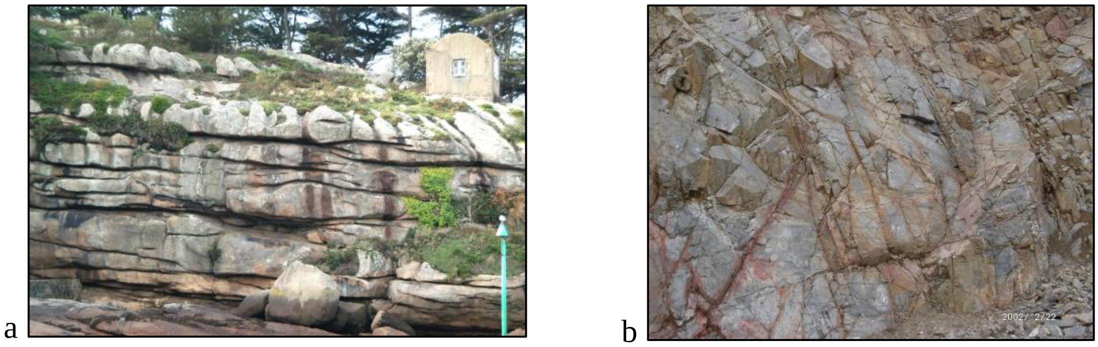

Figure 2 - a: planar jointing in Ploumanach granite (Brittany, France); b: the fractured layer in gritty, folded schists (North of Massif Central, France)

The mechanism of fracturing has been understood by field observations and petrographic study on two core drills in granites. The weathering of biotite is clearly an early process, occurring when the rock is still indurated. The potential increase in volume of biotite crystals during the weathering process is 40%, due to inflating of interleaves from 10 Å to 14 Å. As they cannot inflate ‘freely’ due to rigidity of the rock, a stress tensor is created. In granular rocks like granites with a quasi-random orientation of swelling minerals, the potential expansion tensor is isotropic. At the beginning, the stress increase is also isotropic. Consequently, the horizontal stress component accumulates during the weathering. In the vertical axis however, the stress increases until the lithostatic component is offset, then lets place to vertical expansion, while horizontal stress continues to increase. Consequently, the resulting stress tensor is characterized by a minor vertical component (σ_3), and two major ones (σ_1 and σ_2) that are horizontal. When the stress deviator reaches the elastic limit of the rock, tension cracks appear. For granitic rocks, in accordance with rocks mechanics, the resulting fractures are perpendicular to the minor stress (subvertical) and consequently are subhorizontal, parallel to the gentle topography contemporaneous with the weathering, and leads to the formation of the subhorizontal jointing of granites (Figure 2a). In foliated and folded rocks, the variability of 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 (Figure 2b).
Only three minerals are known for inflating during early stages of weathering: biotite, olivine and pyroxenes.
Weathering of plagioclase does not give way to inflating, nor amphiboles. Weathering of K-feldspar and white micas occurs at a later stage of weathering, when the rock is transformed into loose saprolite. Potentially, all rocks containing one of these three minerals can develop a

significant permeable fractured layer, if they have been emerged during a long time (ten millions years or more).