20th Technical Days of the International Association of Hydrogeologists, French Chapter

11 ▸ 13 June 2015 - La ROCHE-SUR-YON

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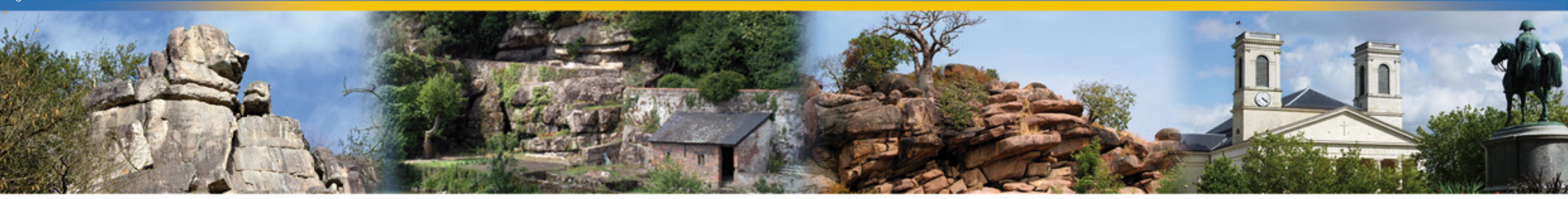
FIELD TRIP GUIDEBOOK

Hard-Rock Aquifers:

the up to date concepts and the practical applications



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Hard-Rock Aquifers: The Up-to-date Concepts and The Practical Applications

20th Technical Days of the International Association of Hydrogeologists, French Chapter

Field Trip Guidebook
June 13, 2015

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June 13, 2015 Field Trip Guidebook

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I. INTRODUCTION

This one-day field trip will lead us, in the morning, on outcrops showing fissured horizon characterized by planar jointing in 2-micas Mortagne granite (outcrops of Manis and Mallièvre). These outcrops will introduce discussions about fissuring mechanism related to lateritic weathering.

The Mont des Alouettes panorama will show us the morphostructural context of planation surfaces bearing lateritic profiles of different ages (ante-liassic, Early Cretaceous and Eocene), reactivated since late Miocene (Alpine compression).

The afternoon will be devoted to lukewarm springs of Avrillé granite (South of La Roche sur Yon). The site of "Moulin Neau" in Moutiers les Mauxfaits will show us one of the thermal springs of this granitic area, and will be the occasion to discuss of the different possible explanations. The Avrillé granite will be studied on an outcrop in Poiroux village, showing transition between upper fissured layer and laminated layer.

II. GEOLOGICAL AND GEOMORPHOLOGICAL REGIONAL SETTING

Vendée belongs to the internal zone of variscan belt and constitutes the southern part of the Armorican Massif. It includes metamorphic rocks organized in allochtonous units, and granitic plutons emplaced during Ordovician, Devonian and Carboniferous.

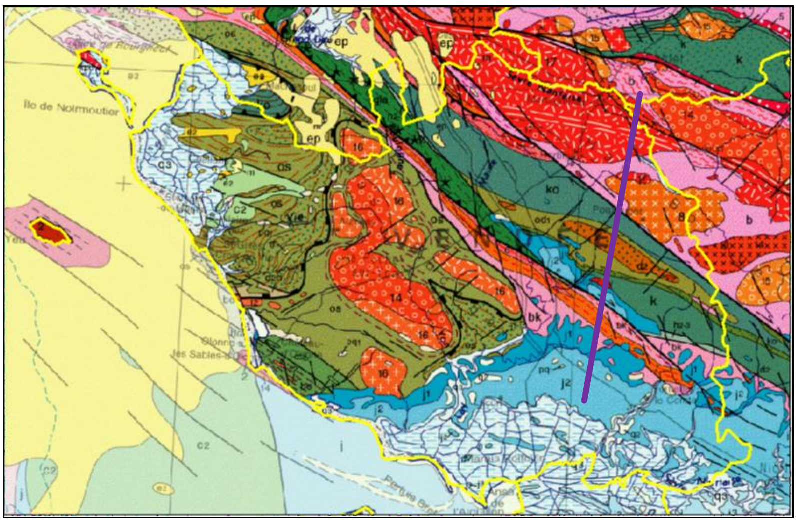


Figure 1 – Geological map of Vendée (from 1:1,000,000 geological map of France). Yellow line: department boundary. Violin: line of the cross-section of Figure 3

From a geomorphological point of view, the top of variscan basement, which has been peneplaned before Liassic transgression, is gently dipping southwards, towards Aquitaine margin.

The southern part of Vendée department (Luçon plain) is covered with Jurassic sedimentary layers, from Lias up to Dogger, the total thickness being about 100 m. The northern part of the department is made up of a plateau culminating between 200 and 290 m a.s.l. (granites of Mortagne and Pouzauges, *Figure 2*): this plateau forms a continental planation surface sealed (*Figure 3*) by Cenomanian deposits (Chambroutet, geological map of Bressuire).

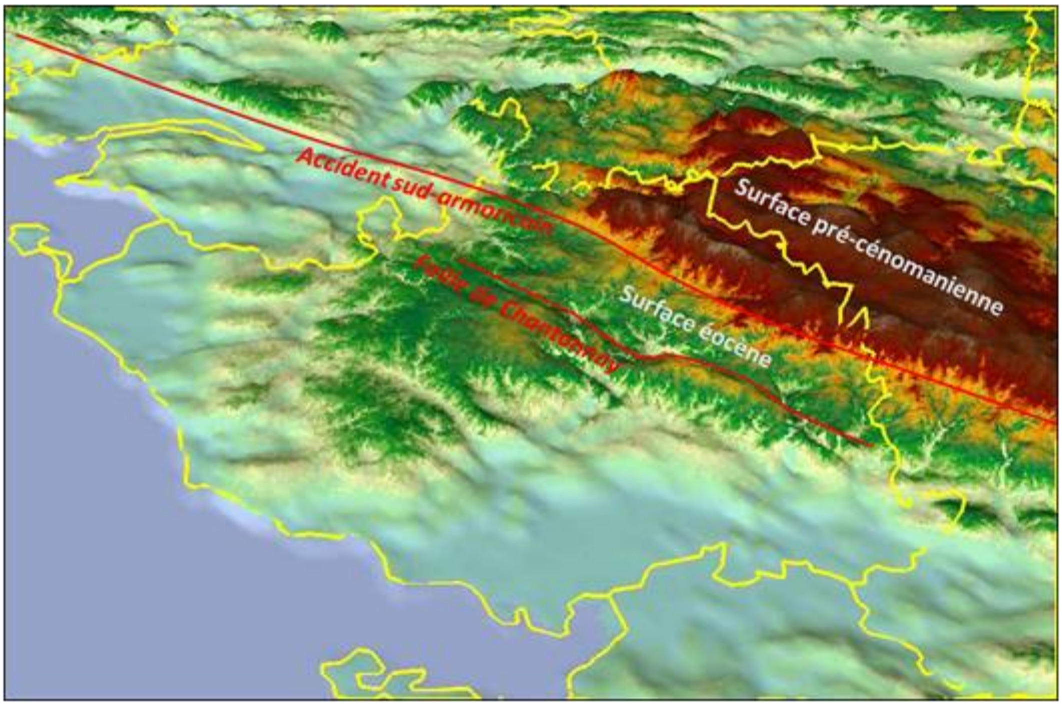


Figure 2 – Geomorphological sketch of Vendée

On the southern edge of these granitic massifs, a fault scarp of 100 to 200 m lowers the topographic surface: this fault scarp belongs to the southern branch of the South Armorican Shear Zone, which is a dextral transcurrent fault of Carboniferous age. Its present morphology results from a normal faulting along this deep accident, probably during Early Cretaceous (rifting of the Bay of Biscay). A more recent replay of the fault is possible (Tertiary), considering the freshness of relief, but has not been demonstrated to date.

At the foot of the fault scarp, a near horizontal planation surface, Eocene in age, spreads southwards up to the Chantonnay fault at an elevation of 100-130 m a.s.l. That normal fault, looking northwards, coincides with the carboniferous coal furrow of Vendée. A Jurassic sedimentary strip, dipping southwards, is preserved on the downthrow side of the fault. The Eocene planation surface is preserved on the upthrow side of the fault (Les Essarts horst), the offset of this surface being around 15 m along the fault plane. South of Les Essarts horst, the basement-Lias interface (pre-Liassic palaeosurface) gently dips southward. The Jurassic cover of south Vendée is truncated by a planation surface probably Early Cretaceous in age, which is sealed by Cenomanian sediments. In western Vendée, the Cenomanian deposits rest on Jurassic limestones (Les Sables d'Olonne), and on the basement to the north (Palluau): the pre-cenomanian palaeosurface partly coincides with the Eocene palaeosurface.

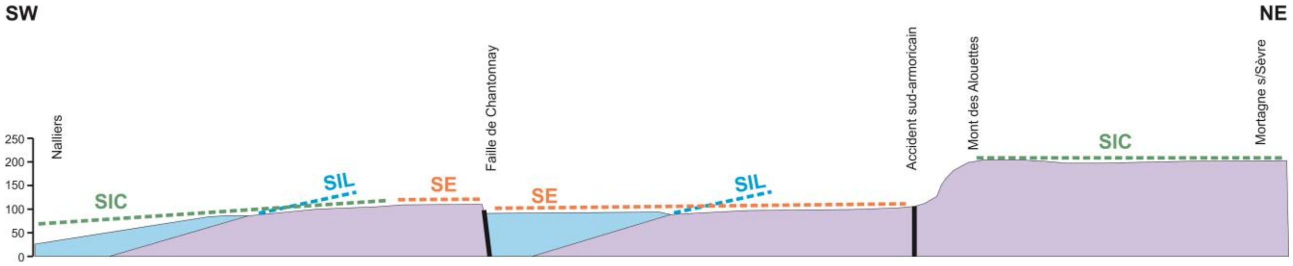


Figure 3 – Geomorphological cross-section sketch from Mortagne-sur-Sèvre to Nalliers, showing the relations between the planation palaeosurfaces. SIL = Infra-Liassic surface; SIC = Infra-Cenomanian surface; SE = Eocene surface; in violin = hercynian basement; in blue = Jurassic sedimentary cover.

The above described planation surfaces (pre-Liassic, pre-Cenomanian and Eocene) are all bearing lateritic weathering profiles. On Jurassic series, the subtractive weathering has led to complete decarbonatation of sedimentary deposits: at Saint-Martin-des-Fontaines, the Lias and Dogger together have a thickness of 8 m for an initial thickness of 80 m, and all fossils are silicified. On basement rocks, the subtractive weathering expresses differently regarding the initial lithology: biotite-rich rocks (granites and gneisses) weathering creates a fissured layer which constitutes a stratiform aquifer, while epimetamorphic schists, rhyolites and amphibolites, little weatherable due to absence of inflating minerals, are not or poor aquifers.

III. THE FISSURED LAYER OF LATERITIC PROFILES: A STRATIFORM AQUIFER

III. 1 Geodynamic control of weathering

The fissured layer develops in the deep part of subtractive weathering profiles on metamorphic or plutonic rocks (lateritic profiles). At a continental scale, weathering is controlled by drainage conditions, therefore by large scale deformations of continental lithospheres (*Figure 4*).

The main mechanism of subtractive weathering is hydrolysis of primary minerals due to water-rock interaction, leaching of the more soluble cations and anions, and their evacuation downstream. The resting, less soluble chemical elements, form new mineralogical phases (mainly clays, oxides and hydroxides). Primary minerals hydrolysis is possible only if water is permanently under saturated regarding rock minerals: that implies than water can flow, therefore one should be upstream at regional scale. Consequently, subtractive weathering develops on uplifted parts of continental lithospheres (rift shoulders, lithospheric buckling, hot spot beneath a continental plate), after a planation phase leading to a minimal mean slope necessary to allow water infiltration. The characteristic functioning life of a lateritic profile is several tens of Ma, and numerous of them are polyphased. Researches in progress show than lateritic profiles with very thick fissured layers exist in numerous mountain belts (Pyrénées for example).

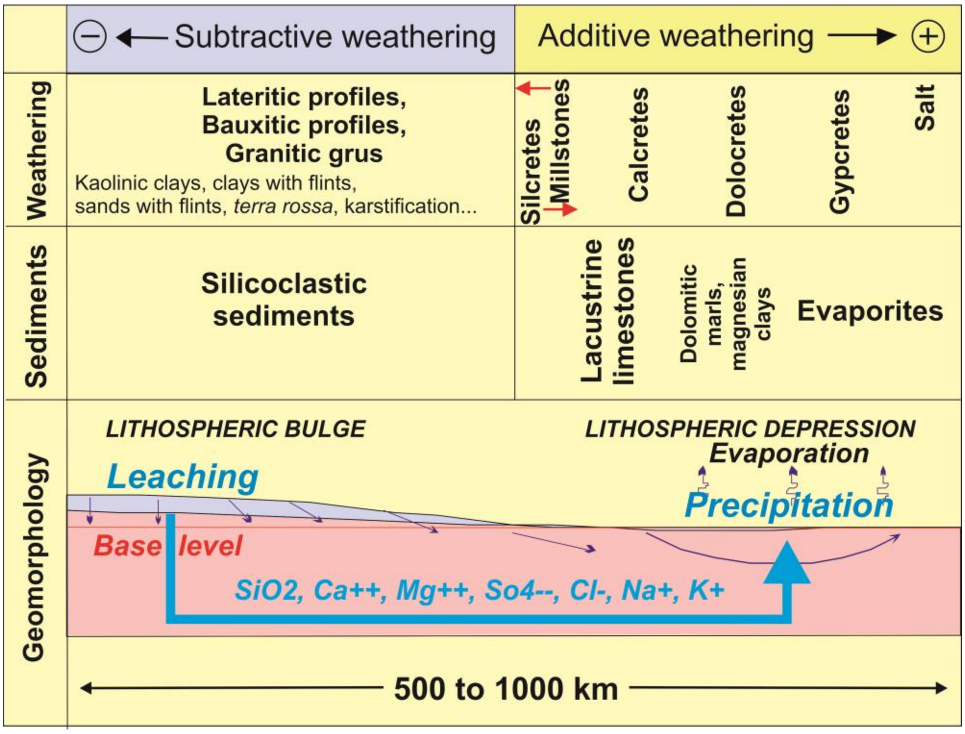


Figure 4 - Classification of supergene weathering (modified from Wyns 2002)

III. 2 Structure of a lateritic weathering profile

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 fissured layer at depth.

A lateritic profile usually shows, from top to bottom (*Figure 5*):

- A ferrallitic *duricrust*, 1 to 10 m thick, resulting from recrystallization of goethite (iron hydroxide) to hematite (iron oxide) due to seasonal dessication of the top of the profile. Goethite, results from oxidation of iron from ferro-magnesian minerals and sulphides in water-saturated medium. The duricrust can disappear from top of the profile, either by erosion or by rehydration when the profile gets clogged due to a lithospheric subsidence: it is generally the case for old weathering profiles that has been overlain below sedimentary covers.
- Loose alterites (*saprolite*), made up of a mixing of clays, hydroxides, oxides and residual minerals (quartz). Generally we can distinguish at the bottom *isalterites*, where initial rock structure is preserved (the leached material is replace by porosity), and at the upper part *alloterites*, where initial rocke structure is destroyed. 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 saprolite shows a characteristic laminated texture (*"laminated layer"*), due to high density of tension microcracks (millimetric spacing).
- A *fissured layer*, characterized by a high density of cracks in a hard rock. 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 fresh rock, where existing fractures all result from tectonic history.

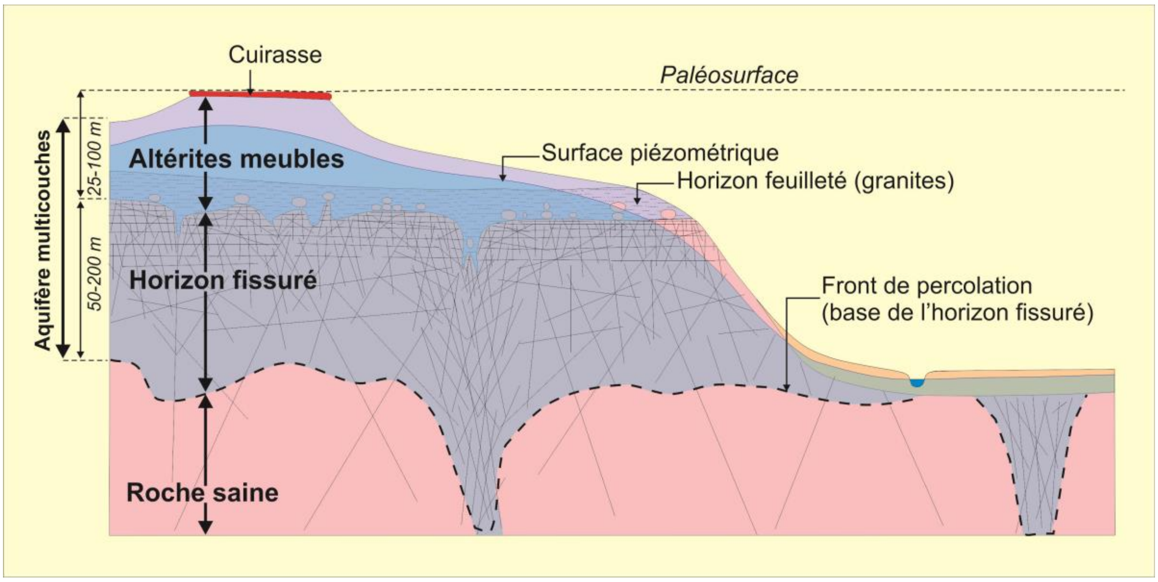


Figure 5 - Structure of a lateritic profile crosscut by present topography

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

III. 3 Fissuring mechanism

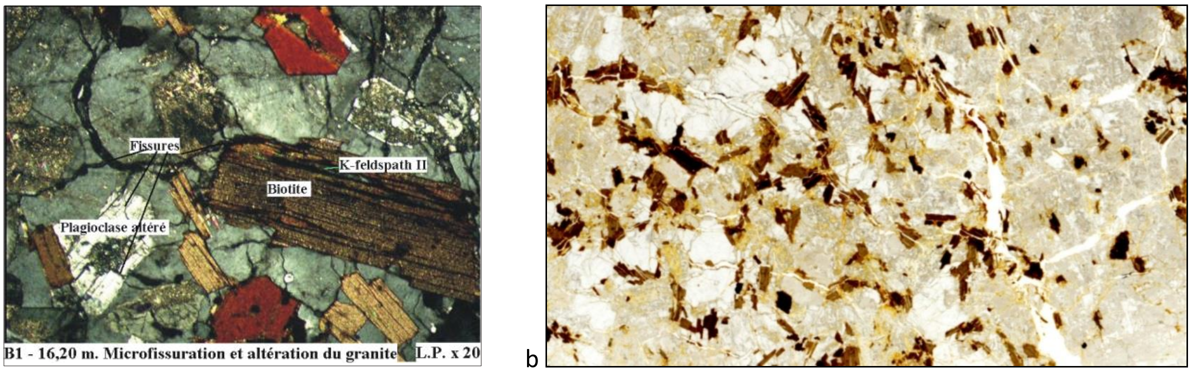
The existence of a fissured zone at the top of the bedrock below the saprolitic layer was known for a long time, but was interpreted either as resulting from erosional decompression (offloading), or resulting for thermal contraction during magmatic cooling.

Tension cracking by decompression requires a rapid fall of the vertical stress component. It is the case for example during mine gallery digging. In natural conditions, the fall of vertical stress component due to erosion is too slow to enable tension cracking, because stresses can reorganize at the scale of grain joints. The existence of a fissured layer in 2-micas Mortagne granite (*Figure 6*) and its absence in Thouars microgranite 50 km away, whereas both sites have undergone the same erosional history, illustrates than offloading cannot explain planar jointing.

Furthermore, planar jointing in granites cannot result from thermic contraction during magmatic cooling, because it also exists in deformed granites and in orthogneisses.

The mechanism of planar jointing in granites has been understood by petrographic study of two core drills carried out in lateritic profiles in Brittany. At depth, more than 50 m beneath the base of grus, biotites generally are fresh. Then they become more and more weathered (chloritized or vermiculitized) upward, and the cleavages are deformed, due to inflating of interleaves from 10 Ǻ to 14 Ǻ (*Figure 7 a*). Within the laminated layer, all biotites have been weathered (*Figure 7 b*) and we can observe a dense network of microcracks.

Figure 6 - Left: the fissured layer in 2-micas granite at Mallièvre. Right: absence of planar jointing in Thouars microgranite, 50 km away from Mallièvre. Both massifs underwent the same erosional history: the lack of planar jointing in Thouars microgranite shows than erosional decompression cannot explain planar jointing.



a b

Figure 7 - a: biotite crystal in way of weathering in fissured layer (Langonnet granite, Morbihan, France). Note the deformation of cleavages on each side of chlorite bands and apparition of microcracks. b: base of saprolite (laminated layer). All biotites have been weathered (brown spots due to goethite). Note the dense microcracks network.

Thus the chloritization of a biotite crystal induces a potential swelling of crystal of 40 %. This transformation occurs in hard rock, within the fissured layer. In these conditions, the swelling is not possible (except along preexisting diaclases), due to the rock hardness. It results on increasing horizontal stress. In vertical plane, the swelling will be possible after the vertical lithostatic stress will be offset by vertical swelling stress.

In a granite, after compensation of lithostatic stress, the vertical stress no more increases and can be replaced by dilatation, while horizontal stress continue to increase. The maximal stress components (σ_1 and σ_2) become horizontal, whilst minimal one (σ_3) becomes vertical. Tension cracking occurs when the difference between minimal and maximal stress components reaches the elastic limit of the rock. The tension cracks will be orthogonal to minimal stress component, i.e. horizontal.

In isotropic rocks as granites or in vertically foliated rocks, the tension cracks will be horizontal (*Figure 8 a*). In folded rocks (schists and micaschists), tension cracks geometry will be random (*Figure 8 b*). When foliation is horizontal, there is no increase of horizontal stress, and the rock swells vertically and acquires a laminated structure.

In silico-aluminous rocks (granites and metamorphic rocks), the mineral that is able to swell during weathering is primarily biotite: this mineral is very reactive in presence of water, because the interleaves bonds are weak. In white micas, the swelling occurs later due to a more high activation energy to break interleaves bonds: their swelling occurs after rock has been saprolitized by biotite weathering. Plagioclases are highly weatherable, but it not appears than they swell during weathering.

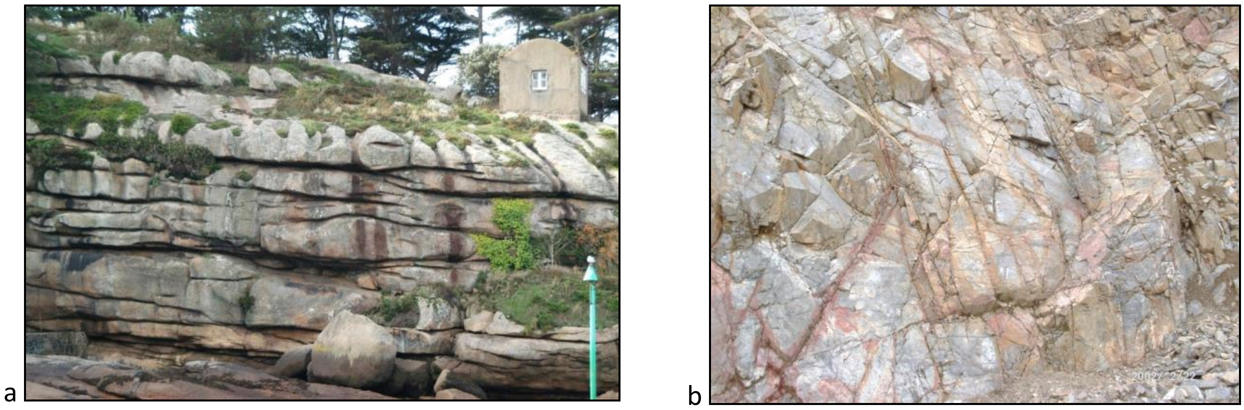


Figure 8 - a: planar jointing in Ploumanac'h granite (Brittany, France); b: the fissured layer in gritty, folded schists (North of Massif Central, France)

In basic and ultrabasic rocks (dolerites, basalts, gabbros, peridotites), the existence of a fissured layer is conditioned by the presence in the rock of pyroxenes and/or olivine, that seem the only minerals to swell during weathering. Amphiboles do not show swelling ability and amphibolites do not have a developed fissured layer. Amphibolitized dolerites and basalts generally are slightly weathered and are poor aquifers. Gabbros undergo the same cracking mechanisms than granites, and can bear a well-developed fissured horizon, especially if they contain biotite, pyroxene and olivine. Peridotites can crack with planar or irregular jointing, then evolve toward a karstic functioning below the saprolite cover.

Figure 9 – Quartz veins fissured by stress generated by weathering of surrounding granite (India)

The poorly weatherable rocks as quartz or rhyolitic veins can be fissured due to stress resulting from the weathering of surrounding rocks (*Figure 9*). These veins where fractures stay open allow a more rapid sinking of weathering horizons, and can be interesting, highly permeable drains favourable for drill hole siting. The width of unweatherable rock veins that can be fissured by weathering can exceed 200 m.

III. 4 Layout of fractures within the fissured layer in a granite, and role of tension cracks in water-rock interaction

In granitoids, the usual layout of tension cracks is planar, parallel to the topographic surface contemporaneous with the weathering.

In the case of tectonic movement following the weathering phase, the planar joints can be tilted, as we can observe along edges of Massif Central grabens (*Figure 10*).

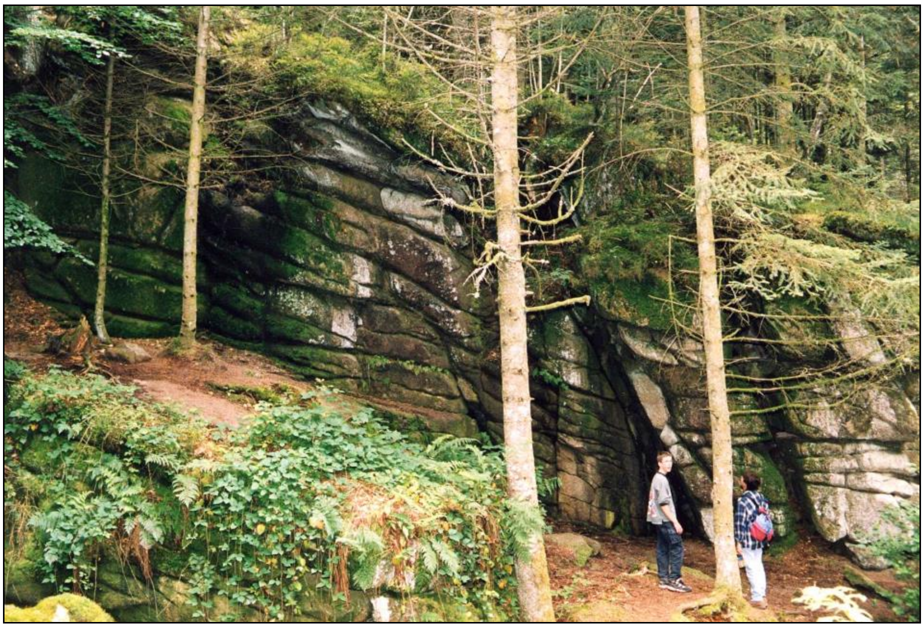


Figure 10 – A tilted fissured layer at the edge of Limagne graben (South of Thiers, Puy de Dôme, France)

Fissure spacing is minimal at the top of the fissured layer, and increases downward. The basal boundary of the fissured layer can be defined as the surface beyond which the spacing tends to infinity.

Water-rock interaction preferentially occurs along the two walls of fissures where water can circulate, so we can calculate the reactive areas by rock volume depending of the joint spacing (*Figure 11*): surfaces available for water-rock interaction increase as twice the inverse ratio of joint spacing.

Field observations together with drilling statistics (Courtois et al., 2010) and geophysical data (MRS, electric tomography) allow to divide fissured layer in an upper, more productive part (upper fissured layer = "usefull" part of the aquifer), and a lower, less productive part (lower fissured layer). The upper part is commonly 15 to 50 m thick, depending of the profile thickness and the lithology, and the joint spacing varies between 5 and 50 cm. The transition between upper and lower fissured layer can be underlined by a seismic discontinuity (doubling of wave velocity) (Wyns at al., 2005).

The laminated layer forms a transition zone, generally 10 to 20 m thick, between saprolite and upper fissured layer. The joint spacing is millimetric (1 to 5 mm, *Figure 12*). With such a spacing, all the minerals are in contact with water, and the rock becomes crumbly.

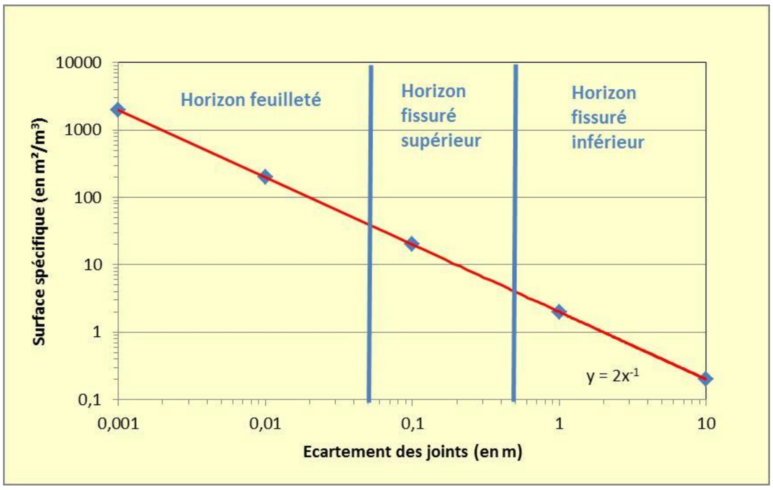


Figure 11 – Reactive surfaces available for water-rock interaction versus joint spacing in granite, and spacing range of joints for laminated, upper fissured and lower fissured layers.

Figure 12 – The laminated layer in a granite (India)

Water-rock interaction consequently does not develop by a front sinking downward, but by numerous fronts linked to joints whose spatial density rises during time.

III. 5 Mineralogical, textural and structural control of fissuring

Mineralogy, texture and structure are the main factors that control the fissured layer development.

Mineralogy

Only three mineral families have been identified as able to swell during weathering, and therefore to generate a fissured layer: biotite, pyroxenes and olivine. Plagioclases are highly weatherable, but it not appears than they swell during weathering. Muscovite and K-feldspar weather later, when rock is already completely saprolitized by biotite weathering, so that they play no real role in fissuring. Amphibolites and chlorite schists weather with difficulty and do develop a large fissured layer: tey are poor aquifers. Epimetamorphic schists, with sericite/chlorite, are poorly documented.

Texture

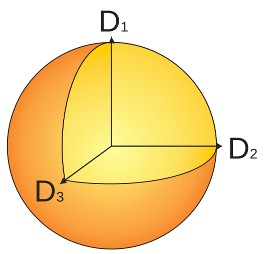
The first textural criterion is the crystal size: coarse-grained rocks weather more easily than small-grained ones, and more the swelling mineral size is coarse, more the fissured layer will easily develop. There fore, for the same mineralogical composition, a plutonic rock will fissure more easily than volcanic or hypovolcanic one.

In lepidoblastic rocks (gneisses, micaschists, schists), micas are oriented and generally there is a composition layering, with alternating beds rich in phyllites and rich in quartz. It follows anisotropy of preferential fissuring planes: the joints generated by mineral swelling will be drived by the weakness planes of the rock.

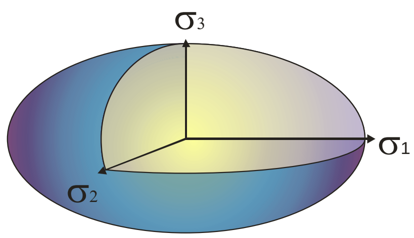
Structure

In a rock where swelling minerals are randomly oriented (case of isotropic plutonic rocks), the swelling potential is isotropic. The medium canning be considered as infinite in horizontal dimension, the horizontal stress components accumulate, whilst vertical stress stay invariant after lithostatic stress offset: we obtain horizontal tension joints (*Figure 13*).

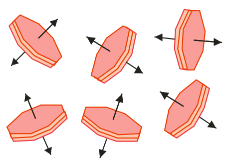
For foliated but unfolded rocks (gneiss, orthogneiss), the foliation dip plays an important role on joints aperture: when foliation is vertical, all the dilatation potential is horizontal and is converted into horizontal stress, and we can observe horizontal joints wide open (*Figure 14*). On the contrary, when the foliation is horizontal, the rock swells vertically and there are only horizontal microcracks giving a laminated texture to the rock (*Figure 15*).



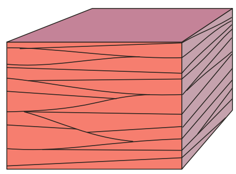
Potential deformation ellipsoid: D1=D2=D3



Stress ellipsoid: σ_1 and σ_2 horizontal, σ_3 vertical, with $\sigma_1 \geq \sigma_2 >> \sigma_3$



Randomly oriented swelling minerals



Horizontal joints

Figure 13 – Deformation, stress and fissuring characteristics for an isotropic rock (granitoids)

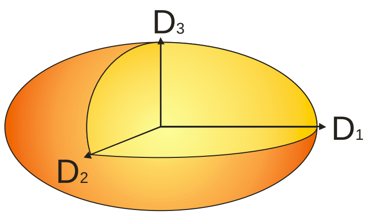
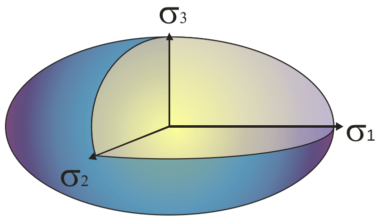
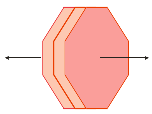
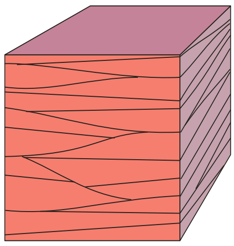
 Potential deformation ellipsoid: D1>>D2=D3	 Stress ellipsoid: σ_1 and σ_2 horizontal, σ_3 vertical, with $\sigma_1 >> \sigma_2 \approx \sigma_3$
 Vertical swelling minerals, horizontal dilatation	 Wide open horizontal joints

Figure 14 - Deformation, stress and fissuring characteristics for a vertically foliated rock

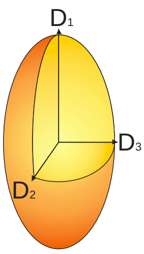
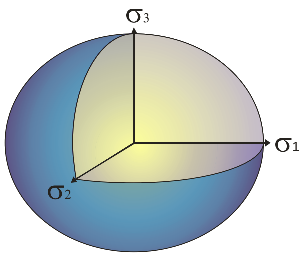
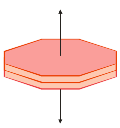
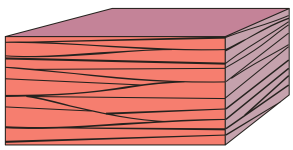
 Potential deformation ellipsoid: D1>>D2=D3	 Stress ellipsoid: σ_1 and σ_2 horizontal, σ_3 vertical, with $\sigma_1 \approx \sigma_2 \approx \sigma_3$
 Horizontal swelling minerals, vertical dilatation	 Lamination, no open horizontal joints

Figure 15 - Deformation, stress and fissuring characteristics for a horizontally foliated rock

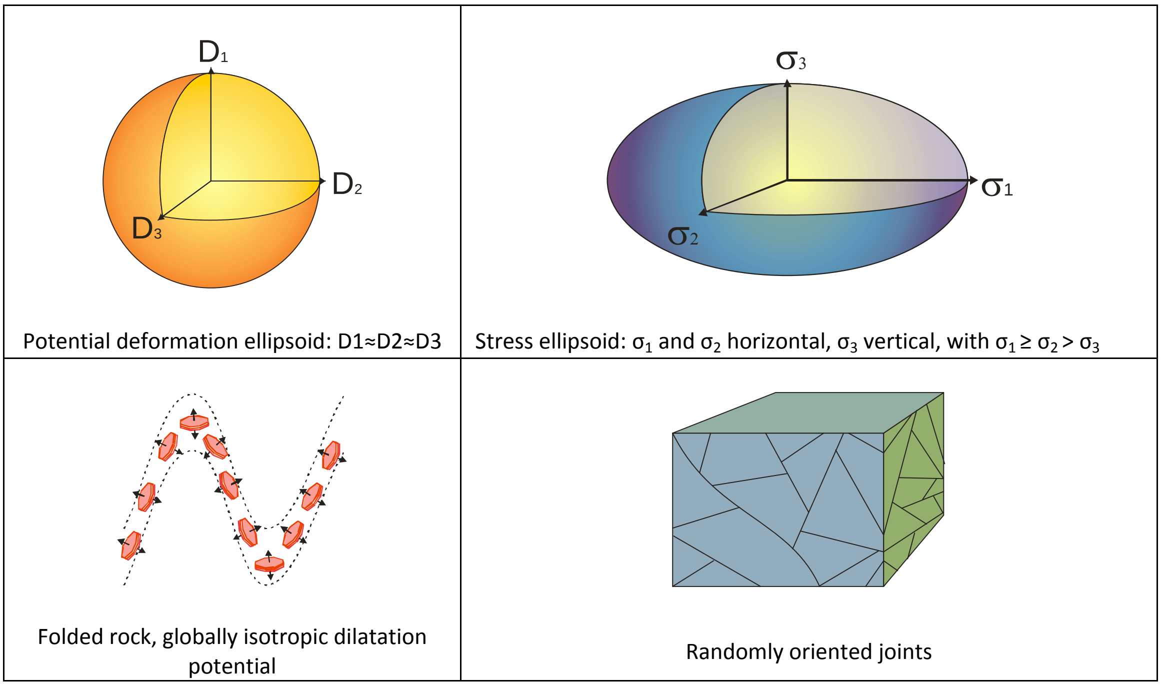


Figure 16 - Deformation, stress and fissuring characteristics for a folded rock (schist, micaschist)

In a folded rock (micaschist, schist), the presence of metric to hectometric scaled folds modifies laterally the attitude of stress tensor, but also the weakness planes orientation, so that a folded rock generally shows a randomly oriented jointing (*Figure 16*).

III. 6 Conclusions

From field observations and petrographic studies above mentioned, we can establish a hierarchy of rocks regarding their ability to develop a fissuring layer during weathering.

Extremely favourable rocks: coarse grained rocks rich in swelling minerals: biotite granites, diorites, quarz-diorites, gabbros, peridotites.

Very favourable rocks: 2-micas granites, gneisses, biotite micaschists, mica-rich migmatites.

Favourable rocks: leucocratic gneisses, micaschists, basalts, dolerites, andesites.

Poorly favourable rocks: amphibolites, muscovite leucogranites, fine-grained granites, metabasalts, sericitoschists.

Defavourable rocks: acidic hypovolcanic or volcanic rocks, microgranites, quartzites, leptynites, rocks without micas.

IV. THE THERMAL EFFECT OF LATERITIC WEATHERING

Lateritic weathering is dominated by oxidation and hydration reactions that are highly exothermic: the total weathering of 1 m^3 of granite releases approximately 400 MJ of energy as heat. If the permeability of the medium is enough, heat can be evacuated in real time by thermic convection. Depending of time constant values for convection or reaction kinetics, heat can be dissipated or not.

Therefore, in the vicinity of the percolation front (base of fissured layer), the very low permeability (< 10^{-10} m/s) does not allow water circulation, and a large amount of water is used for hydration reactions. In that zone, heat is thus mainly dissipated by conduction. In crystalline rocks, thermal conductivity tends to decrease when temperature rises. The rock will heat if the thermal diffusivity does not allow a rapid cooling (*Figure 17*).

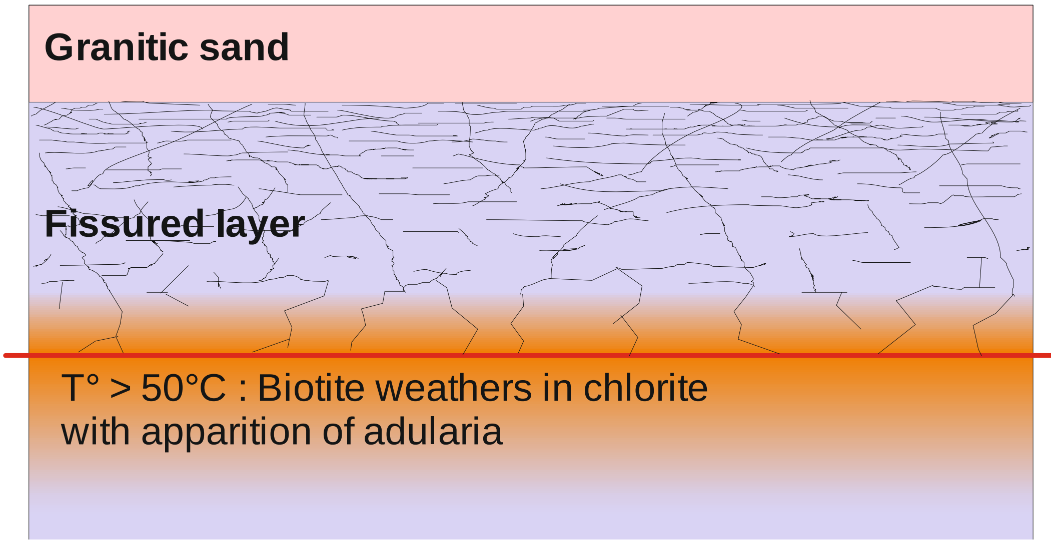


Figure 17 - Position of heating zone (in orange) at the percolation front (base of fissured layer) in a granite

The modelling of heating at the percolation front in a granite (Wyns at al., 2015) shows than a temperature of 100 °C can be reached after 10 Ma of weathering. These theoretical results should still be validated on the field, for example by an experimental drill hole.

V. ABSTRACTION OF DRINKING WATER: THE FIRST BOREHOLE IN VENDEE REGION IN HRA, THE "TAIL" IN POUZAUGES

V.1. Drinking water abstraction in Vendée

Drinking water abstraction in groundwater in Vendée is less than 10% of total distributed volumes in the department. The other source is dam reservoirs. Dogger aquifer is used by Fontenay-le-Comte city (Gros Noyer catchment) and water company which manages water services in Thouarsais-Bouildroux. The Lower Lias aquifer is used in Luçon (Sainte-Germaine catchment), in Saint-Martin-des-Fontaines and in Benet.

Two boreholes and one well use waters in hard rock aquifers in Pouzauges, la Pommeraie-sur-Sèvre, Saint-Michel-Mont-Mercure, Saint-Mars-la-Réorthe and Fondebert, La Tardière city (*Figure 18*). In the Northwestern part of the department, two drinking water abstractions use groundwater in sedimentary rocks, Eocene limestones in Challans, and a multilayer aquifer (Senonian sandstones, Cenomanien limestones,..) in Commequiers (Villeneuve catchment).

V.2. Why a drinking water abstraction in HRA at Pouzauges?

The Tail catchment in Pouzauges provides drinking water to Pouzauges and La Meilleraie-Tillay villages since 1957. His declaration of Public Utility allows an instantaneous flow of 12 liter/s with a maximum of 1000 m3 per day. This drinking water abstraction wellfield, draws water from a fissured hard rock aquifer which is developed at contact between the Pouzauges granite and the surrounding hornfels. Numerous faults crosscut this contact, and the wellfield is sited along a strong fracturing corridor striking NW-SE.

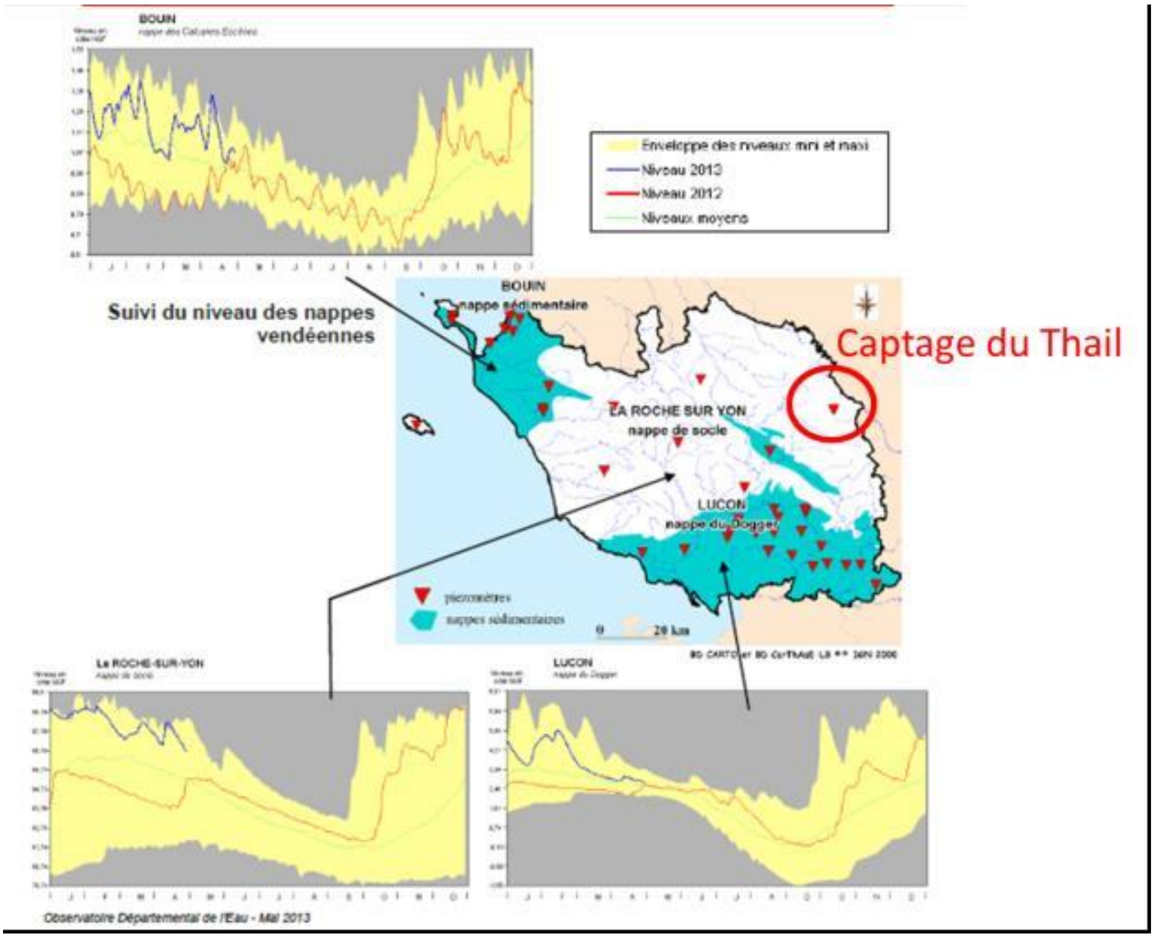


Figure 18 – Map showing drinking water abstractions in groundwater in Vendée

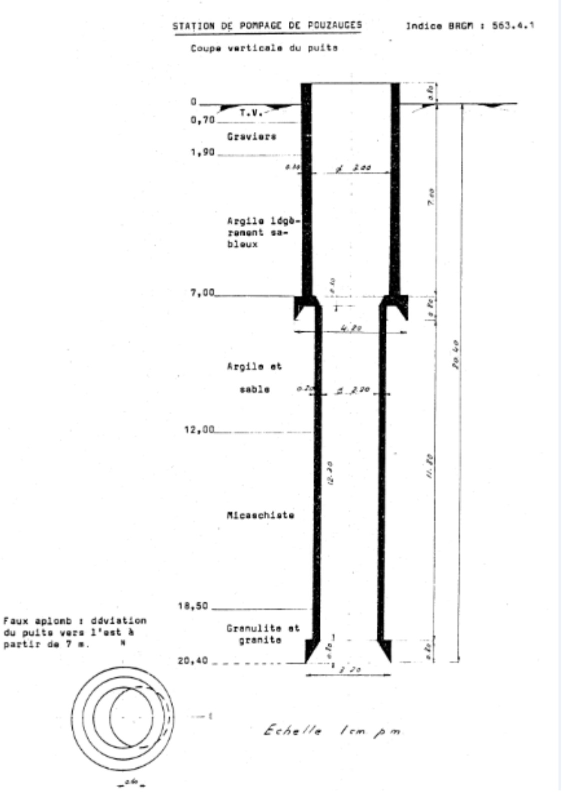
The Tail catchment is the first borehole in Vendée in hard rock aquifers drilled with down to the hole hammer technology in 1976, just after the exceptional drought, under the leadership of Gilles Bresson. It's also the first drinking water protected area setting up just after the French Water Law of 1992, preliminary studies have been carried on in 1995. In this new impulse, this site was integrated in the monitoring network on quality and quantity, in which the department of Vendée was involved, under the leadership of Claude Roy.

V. 3. History of the Tail catchment

- In 1953, two test drilling and boring work with a depth of 15 meters near a watershed area : a five meters diameter well was drilled with a total depth of 20,40 m in the fissured zone, with a confined aquifer, isolated by argillaceous alluvium layers (Thickness : 12 meters). Well code: 05634X0001/P (called "PUITS AEP") (*Figure 19*).
- In 1976 a campaign of geophysical prospection, VLF, was involved with the drilling of 5 piezometers and the drilling of a 54 m deep main production research borehole (F1 borehole), with a fissured productive area to a depth of 52 m. A pumping test with an average flow of 65 m3/h during 33 hours, with a final drawdown of 30,6 m and with hydrodynamical parameters: transmissivity: 8,8 10^{-4} m²/s and storage coefficient: 3 10^{-3}.
- In 1980, near F1 borehole, a new borehole was drilled, deeper of 10m than F1; new borehole F2 code: 05634X0012/F2

Figure 16) to place the pump below the productive fracture to allow more important drawdowns during periods of law water level (Equipment: perforated casing PVC in Ø 250 mm), with 3 new tests boring.

- In 1990s, the water production of the site reached 200 - 250 000 m³/year with 50 % with the original well of 1953 and 50 % with the borehole F2; borehole F1 is used as a piezometer to ensure the water level monitoring.



05634X0001/P

Log géologique numérisé

Nombre de niveaux : 9

Profondeur	Lithologie	Stratigraphie
De 0 à 1.4 m	ARGILE TOURBEUSE	QUATERNAIRE
De 1.4 à 1.6 m	GRAVIERS	QUATERNAIRE
De 1.6 à 7.5 m	ARGILE SABLEUSE	QUATERNAIRE
De 7.5 à 9.2 m	ARGILE PLUS GLAISEUSE	QUATERNAIRE
De 9.2 à 9.5 m	ARGILE SABLEUSE	QUATERNAIRE
De 9.5 à 13.75 m	LIMON ARGILO-SABLEUX	QUATERNAIRE
De 13.75 à 17.05 m	SCHISTE MICACE POURRI	PRIMAIRE
De 17.05 à 20 m	SCHISTE MICACE PLUS MASSIF	PRIMAIRE
De 20 à 20.4 m	GRANITE NON ALTÉRÉ (A BIOTITE)	PRIMAIRE

Figure 19 – First well (code BSS 05634X0001/P): drilling and geological log

- In 1998, a third borehole (F3) 05634X0019/FORAGE (*Figure 20* and *Figure 21*) was drilled until 160 m, in 20 m upstream to the drillings F1 and F2. A cementation was made in head to isolate granitic sands, already withdrawn by the two other boreholes. The borehole intersected F3 numerous lenses of corneal and granite and three groundwater inlets respectively at 54, 65, and 118 m depth. The flow de lentilles de granite et de cornéennes et 3 principales arrivées d'eau à 54, 65 et 118 m de profondeur. Blower flow rate was about 30 m³/h. A pumping test of 22 days with an average flow rate about 24 m³/h induced a drawdown of 48,44 m in the borehole F3 () and an additional drawdown in the two other boreholes of 4 to 8 m in the well and between 12 to 13 m in the borehole F2. The borehole F3 can be exploited with a flow rate of 25 to 30 m³/h and the borehole F2 with a flow rate of 20 m³/h.

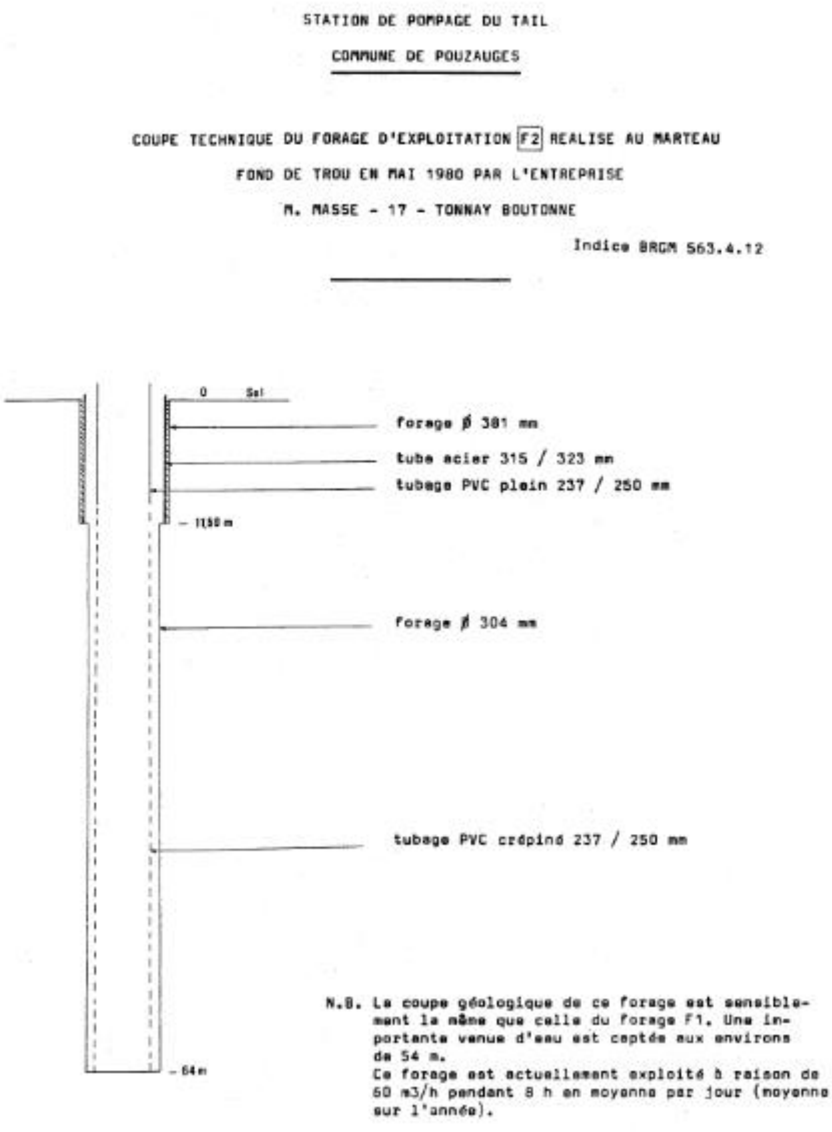


Figure 20 – Drilling log, borehole F2 (05634X0012/F2)

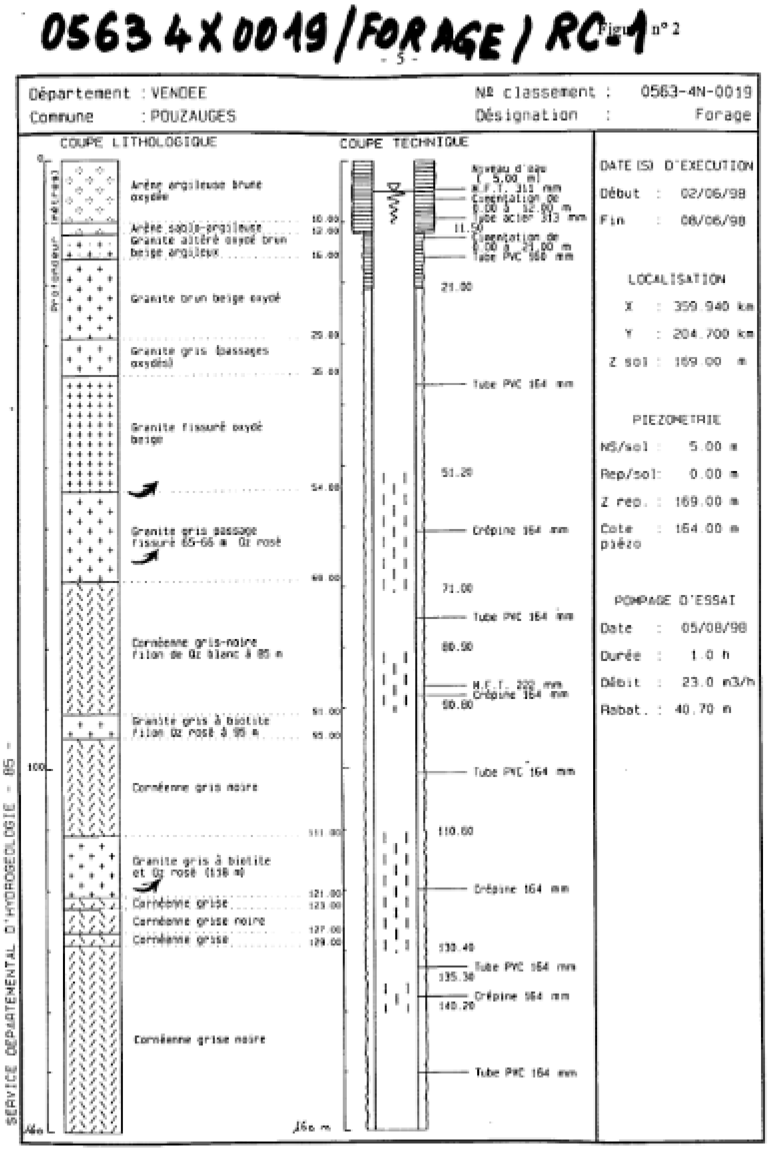


Figure 21 – Drilling log, borehole F3 (05634X0019/FORAGE)

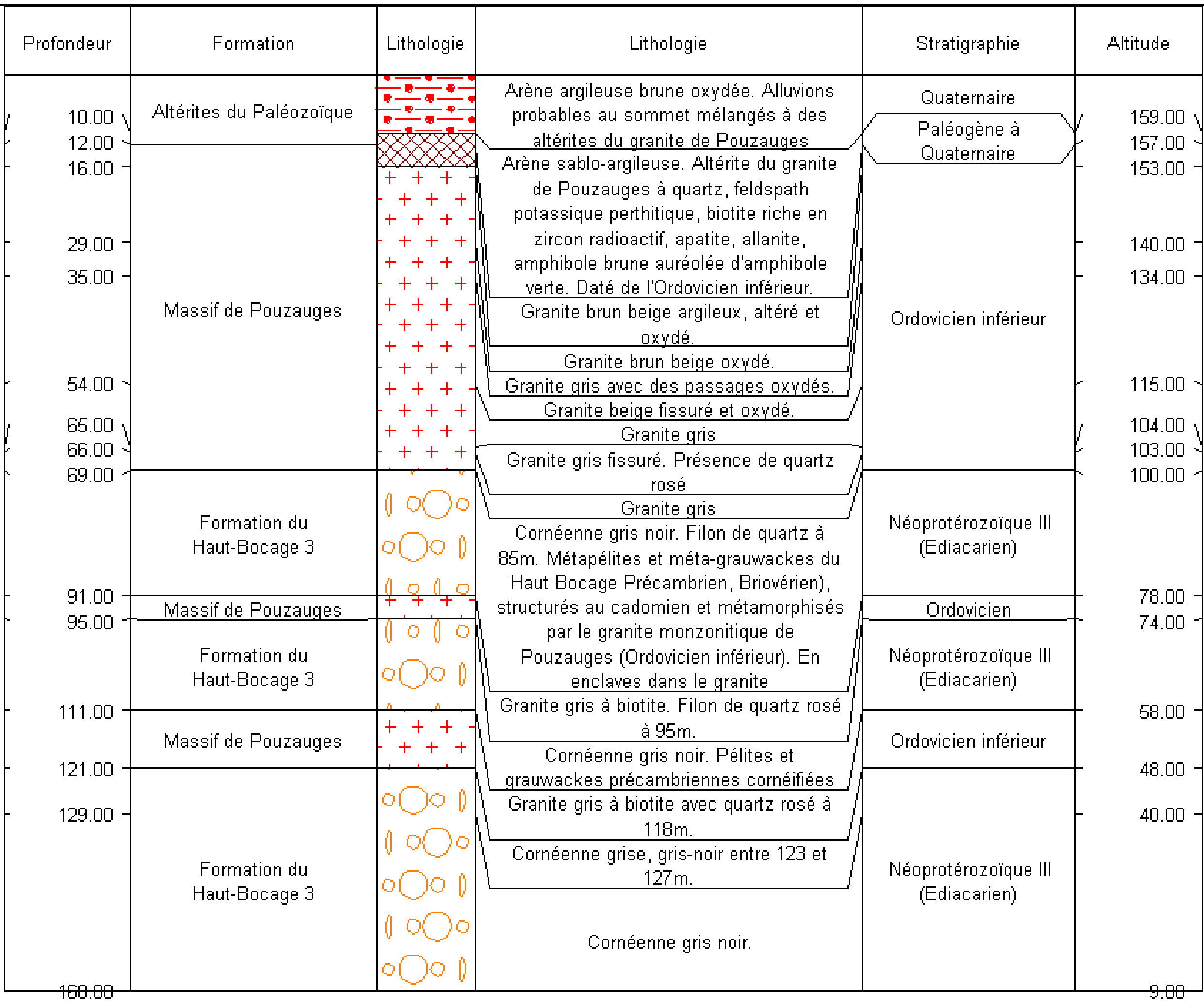


Figure 22 – Validated geological log, borehole F3 (05634X0019/FORAGE)

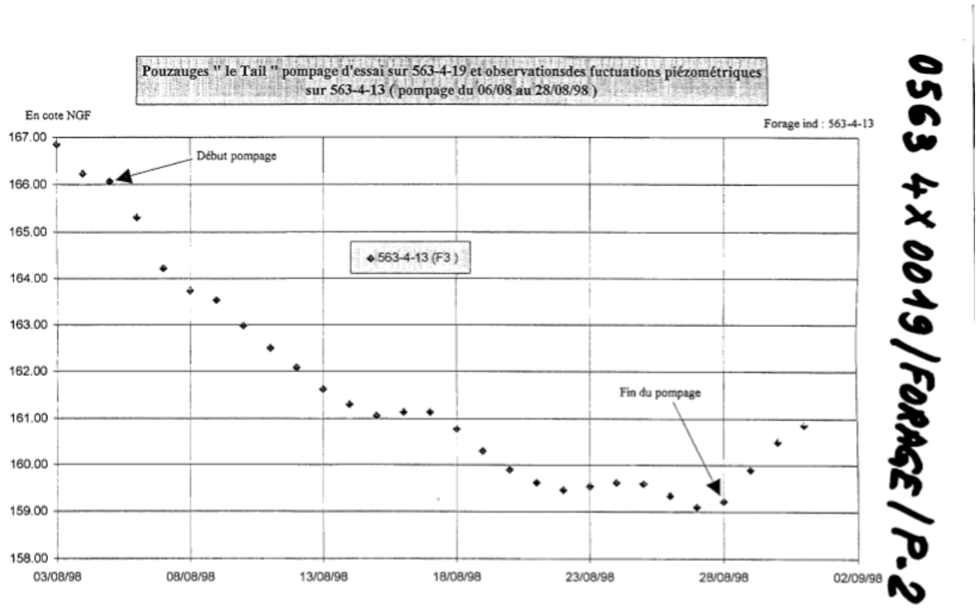
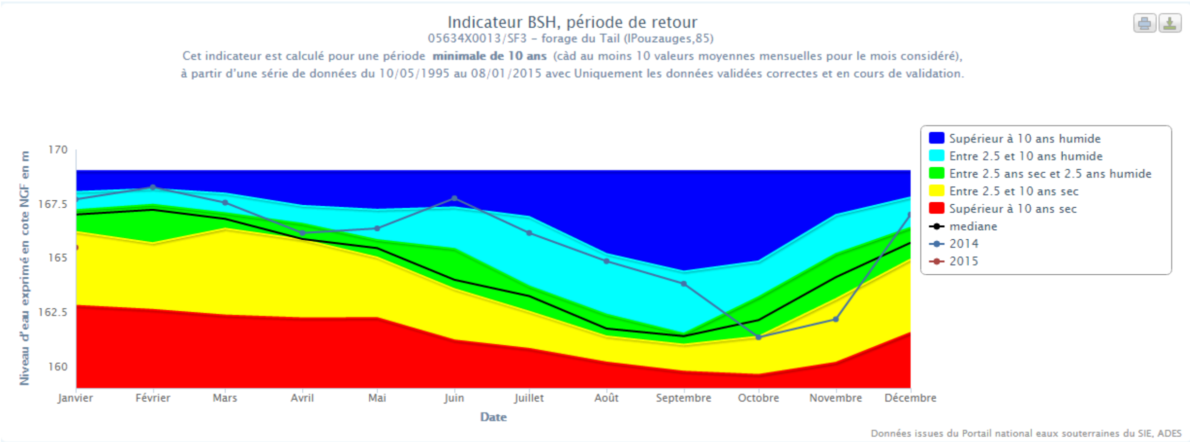


Figure 23 – Pumping test, borehole F3 (05634X0019/FORAGE)

Today 3 water catchment work in the water drinking supply of Pouzauges city *(Figure 24 and Figure 25)*:
- The first well, national code 05634X0001/P
- The borehole F2 drilled in 1980, national code 05634X0012/F2
- The new borehole drilled in 1998 F3, national code 05634X0019/FORAGE

The declaration of Public Utility (22/10/2013) is engaged with exploitation limit of 1000 m3/j. Borehole F1 is used as a piezometer for the water level monitoring.



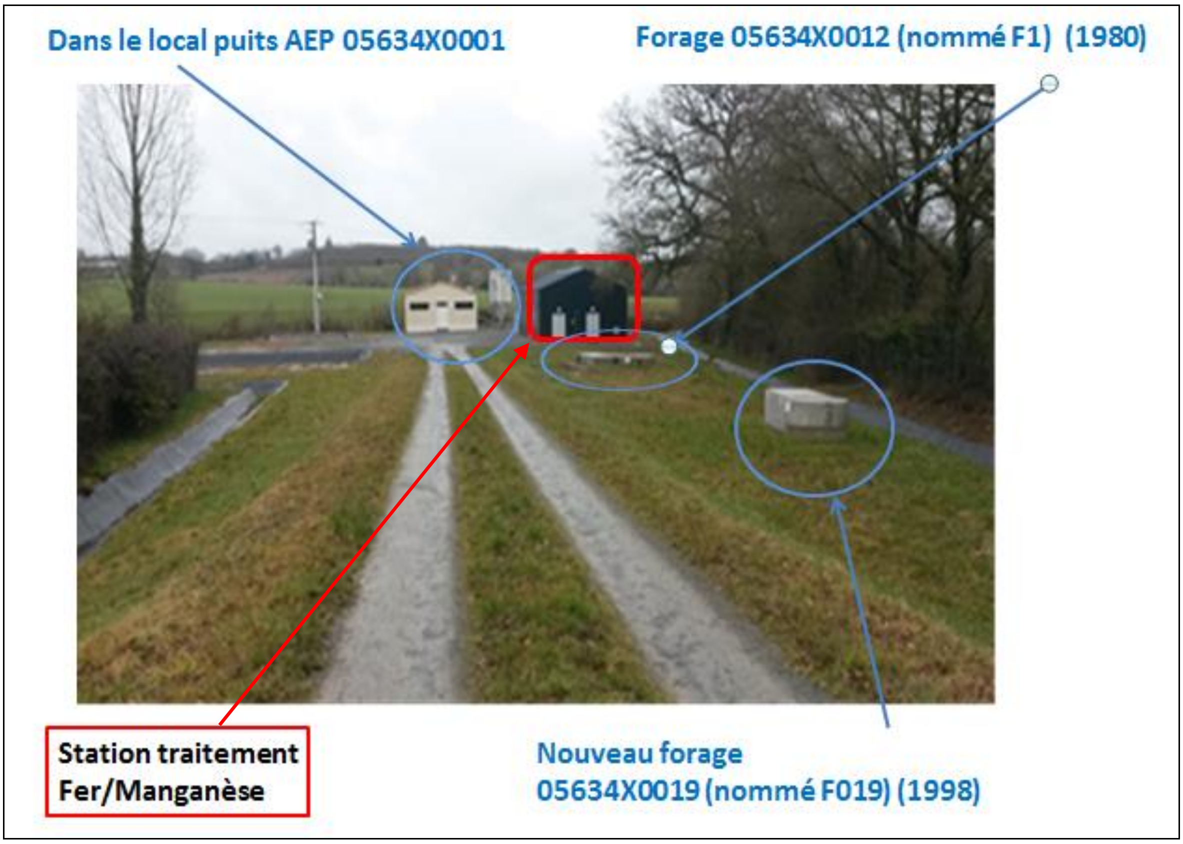


Figure 24 – View of the installation of drinking water supply, The Tail, Pouzauges

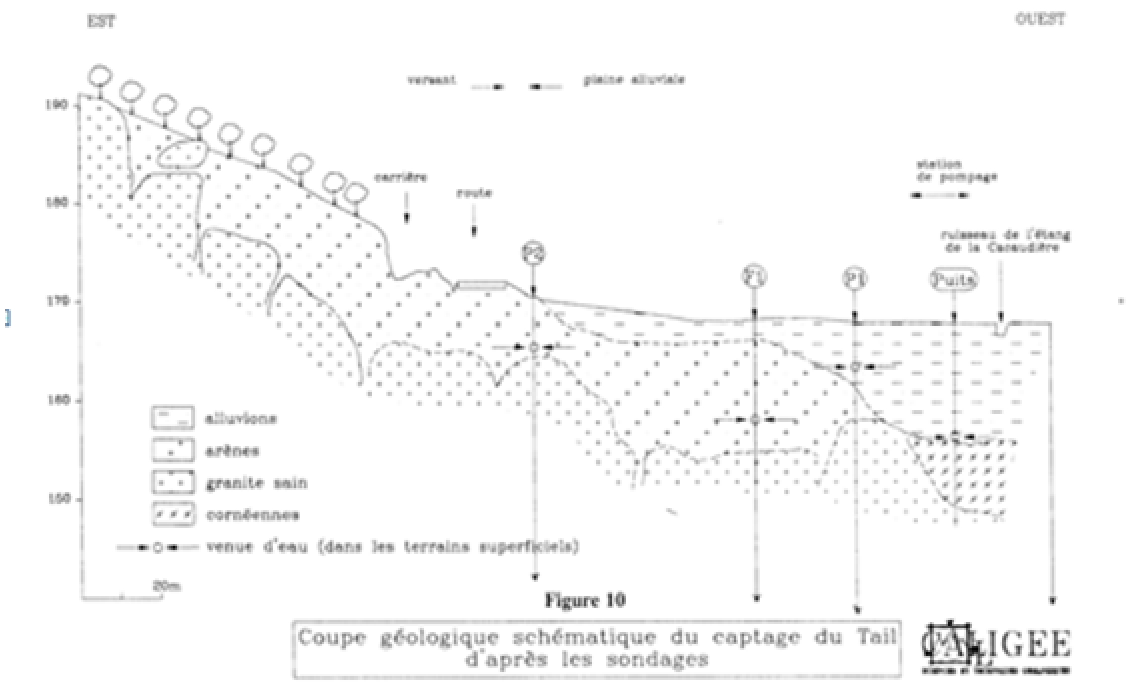


Figure 25 – Geological cross section

V.4. Quality and water treatment

Originally, a treatment with lime to correct the naturally acid pH occured into the well and the borehole F2 and also disinfection before distributing water.

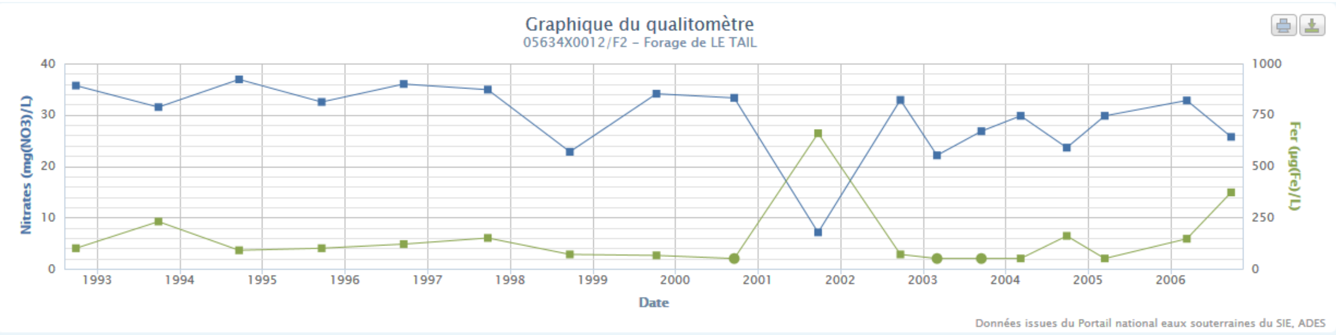
Borehole F3 05634X0019/FORAGE with water from deeper aquifer presents water with iron and manganese. Recently, a new drinking water treatment facility was built for iron and manganese removal.

Nitrate concentrations remained below 30 mg/l in 1980s. Since 1990s, the levels for nitrates involve above 35 to 40 mg/l.

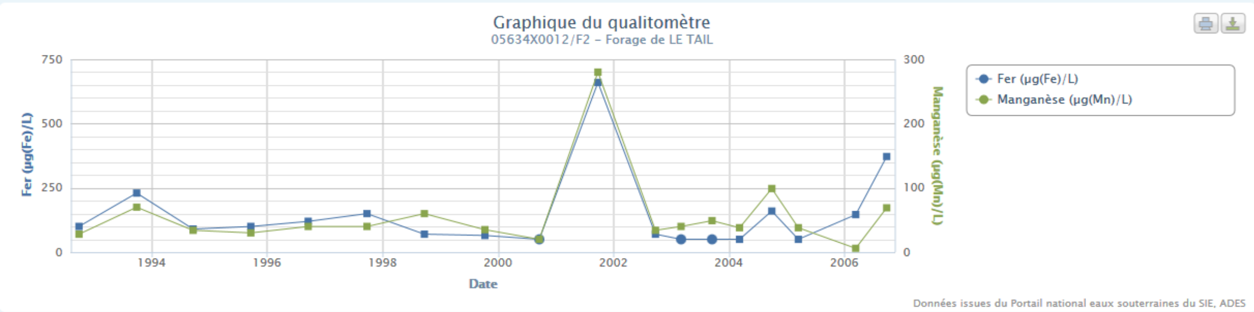
Borehole F2 05634X0012/F2 belongs to the monitoring quality network of the Department of Vendée.

The quality monitoring of waters of this borehole presents the following evolutions:

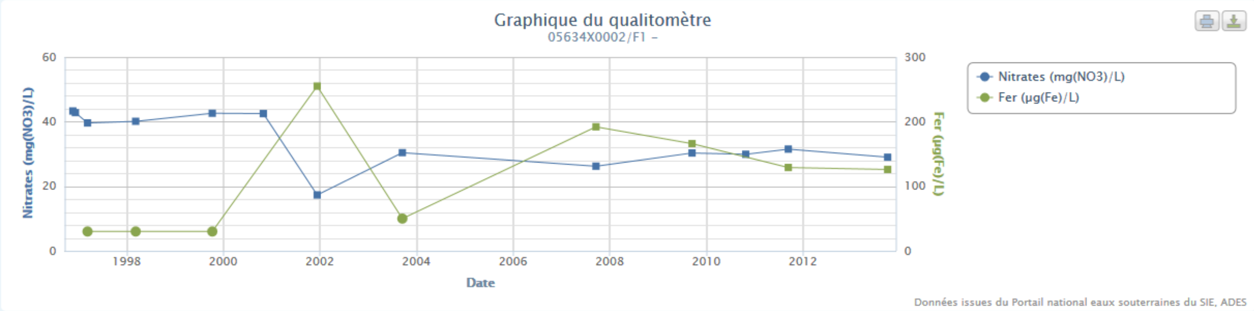
- Stability of nitrates contents between 1993 and 2006, 25 to 38 mg/l, which show activities of mixed farming and breeding in the basin catchment. A decrease can be observed since 2006, to be confirmed (influence of protected area?)



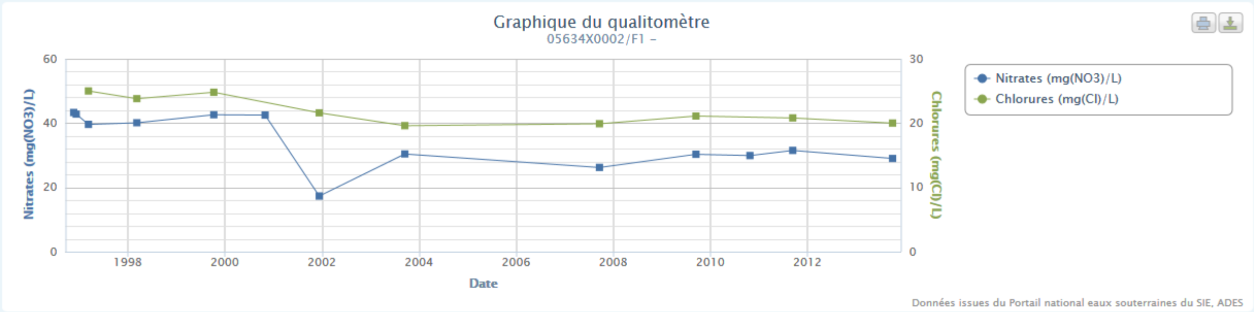
- Iron and manganese contents correlated with contents above threeshold values for drinking water supply, respectively 200 µg/l and 50 µg/l.



Borehole 05634X0002/F1 is sampling and monitoring by the health control for drinking water supply.

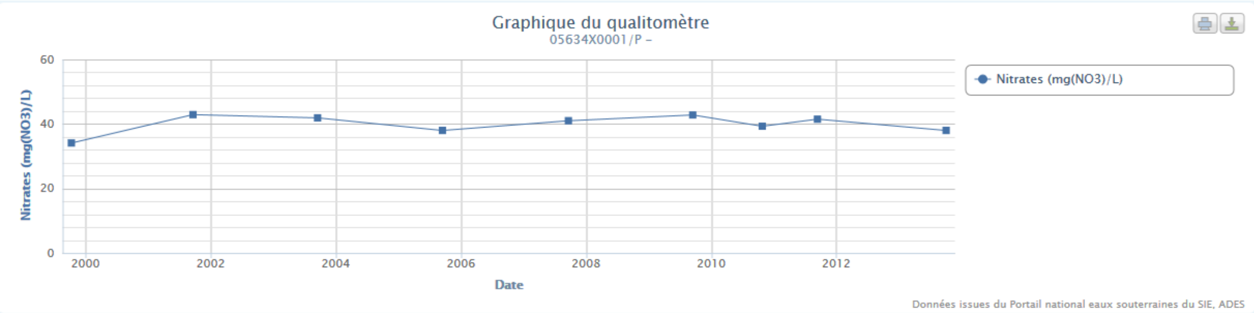


Nitrates contents are well correlated with chloride contents and confirm an agricultural origin.



The well 05634X0001/P is also monitoring by the health control for the drinking water supply.

Nitrate contents in this well are stable and about 40 mg/l. A small decrease since 2012?



V.5. Protected area

Protected area were determined in 1996 after complete preliminary studies with detailed geological mapping, pedological studies, and analysis of land use, associated with a detailed survey with the farmers.

Ces investigations ont porté sur le bassin versant topographique du captage d'une superficie de 6,5 km², dont les altitudes varient entre 281 m et 168 m.
These investigations concerned topographic watershed a 6,5 km2 surface, with altitudes ranging from 281 m to 168 m.

Geological and hydrogeological in situ measurements (*Figure 26*) conducted to define a groundwater recharge area restricted to 4,2 km² (*Figure 27*) following:
- The upstream part of the watershed does not contribute to the recharge of the drinking water supply of the Tail, because this part is drained by numerous springs which give birth to small streams. These springs sustain hill reservoirs. In spite of their high topographic position and thus the low surfaces susceptible to feed them by gravity, these springs do not seem to dry up in low-water according to the farmers in the catchment area.
- A little area was added to the catchment downstream to take into account the extension of the fractured corridor within which is implanted the drinking water supply.

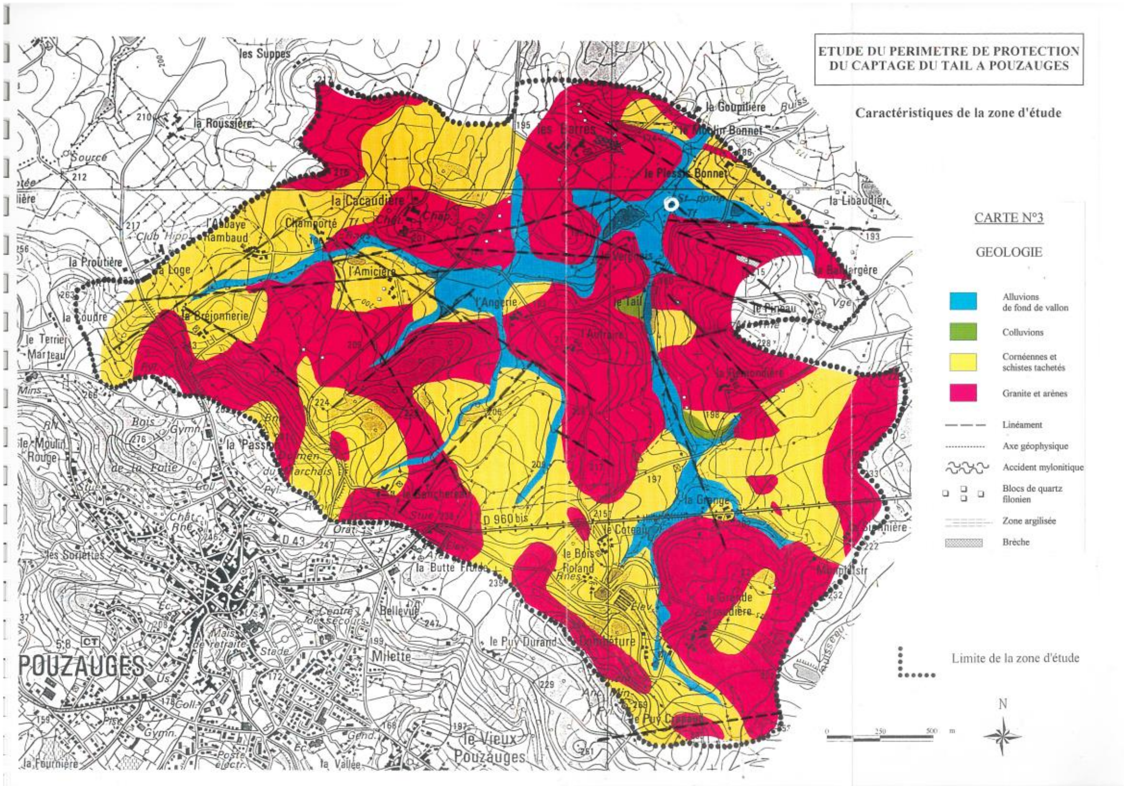


Figure 26 – Geological map on the protected area

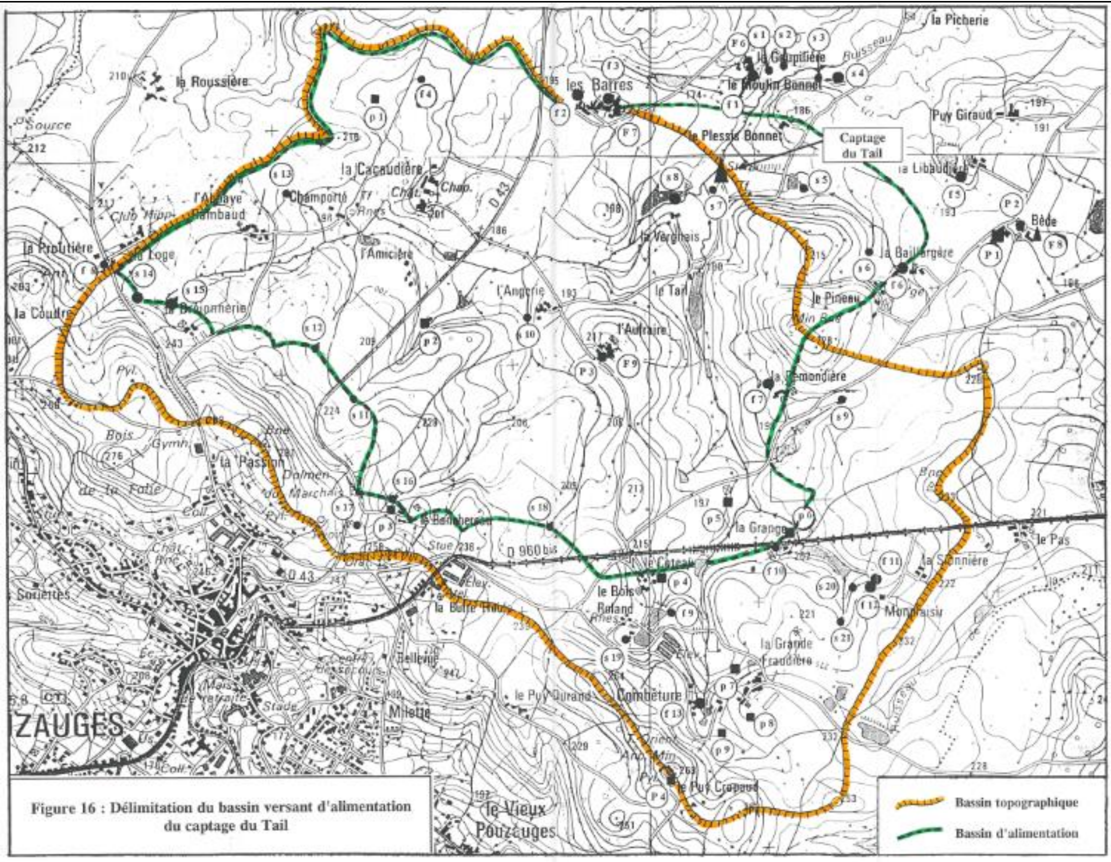


Figure 27 – Catchment area of drinking water supply

VI. THE THERMOMINERAL WATERS OF THE AVRILLÉ GRANITE

VI.1. History of the site and of the intended uses of the groundwater

The Vendée region and its Hercynian substratum are not really known for their groundwater richness, and even less for their geothermal activity. However, in Moutiers-Les-Mauxfaits, a spring stirs several concerns.

The history begins during the early sixties with Lucien Poiroux, a young farmer who settles at the « Moulin Neau » (the "new water mill" in the local language) place to cultivate watercress. "At that time, the spring was abandoned. In the past, this spring was used to feed a water reservoir which itself, with a valve system, was used to run the wheel of a water mill. But for a long time it wasn't functioning". The permanent presence of water allowed him to grow watercress, and he is the only producer in the Vendée Departement (the local authority).

When being the owner of the site, in 1967, Lucien Poiroux noticed with a great astonishment that the water was warm… "A discovery made by chance; it was in the mid of the summer: we were working nearby the spring, I wanted to refresh there some beer. Undrinkable, the temperature of the beer was … 23°C!"

From this time, the spring allowed him to speed the growth of its watercress and to maintain it out of freezing within his greenhouses. During his whole activity, that was the use of this spring which is exceptional regarding both its quality and discharge.

However, curious and dynamic, Lucien Poiroux is ambitioning another future pour this unique spring from Vendée. That's why the following successive exploitation solutions were studied: a tropical botanical garden, a spa for the "Chaîne Thermale du Soleil", a sea water therapy or wellness center associated with ecotouristic activities, a fish, a crocodile, an exotic fish farm, … and then a place to produce energy from deep geothermy. Several things that keep the mystery … on this spring!

Parallel, in the eighties, the Departement's hydrogeological Bureau launches a series of studies and surveys to deepen the hydrogeological knowledge about this site.

VI.2. History of the surveys

Contrary to all classical hydrogeological researches that go from the general to the local scale, the case of the « Moulin Neau » private site on the Moutiers-les-Mauxfaits commune used an inverse approach.

The specificities of the spring (water temperature and electrical conductivity, artesian discharge) are unique as regards all the groundwater of the Vendée basement. Consequently, the studies first focused on this site, and extended later towards a better knowledge of the granite batholith and its surrounding rocks.

From 1988 to 2014, the chronology of the main studies performed under the umbrella of the Department was the following:

June 1988	FORALO	Drilling of a 101 m deep borehole in the immediate vicinity of the spring in the talweg.
October 1994	GEOTHERMA	Study of the Moutiers-les-Mauxfaits thermal spring (inventory, step tests, well logs).
December 1994	FRONTY	Preliminary architectural landscape sketch for the development of the spring.
January 1995	ATOS	Definition of the morphological and tectonic context to identify warm springs.
August 1995	FORALO	Long duration pumping test.
September 1995	University (Bordeaux II)	Complete chemical analyses.
November 1995	GEOTHERMA	Feasibility study for the use of the Moutiers-les-Mauxfaits thermal waters.
July 1996	University	Water action on rats diuresis.
	Bordeaux II	Study of the human transcutanate transfer of water elements (in vitro study).
October 2007	Electricité de Strasbourg	First elements for the survey of deep geothermal ressources in the Vendée Department.
January 2009	BRGM	Potential geothermal resources in the Avrillé granite.
April 2010	CNRS/EOST	Magnetotelluric measurements in the Avrillé granite
March 2015	IUEM Brest-Iroise	Seismological observations in Vendée (3 years).

The use of the site was first focused on the feasibility to valorize the thermal waters from the Moutiers-les-Mauxfaits borewell. Indeed, the resource characteristics and the nearby shoreline were auguring well for an exceptional site for a therapeutic use of the water [1].
The main characteristics of the tapped water are the following:

- a 22°C constant temperature, 10°C, over the mean groundwater temperature in Vendée;
- a well with an approximately 20 m^3/h steady natural artesian discharge;
- a remarquable pumped discharge for a granite aquifer, with a 100 m^3/h exploitation discharge;
- a specific chemical composition of the water with chloride (1200 mg/l), sodic (500 mg/l) and calcic (260 mg/l) waters that can only be explained by a deep and slow flow in the granite; moreover, some elements such as strontium or lithium are interesting for osteo-articular pathologies.

However, the project progressively appeared incompatible with the legitimate French Health Administration requirements regarding the vulnerability of this site as regards the pollution risks; the context of the spring wasn't allowing to avoid parasite superficial waters from the granite saprolite to contaminate the spring.

The surveys were then targeted towards the geothermal resources of the Avrillé granite. Whereas the Vendée geological context is not a priori favorable to geothermy, mid energy as well as low energy, the clue of a temperature over the average at several springs around the granite massif was incentive for new surveys. It was then necessary to evaluate the potentialities, the origin of the thermo-mineral water, the size and geometry of the reservoir [2].

VI.3. Hydrogeological context

The Moutiers-les-Mauxfaits granite is a deca-kilometric batholith located near the contact with the first Jurassic sediments from the Aquitaine basin. It shows NW-SE geological structures which are characteristic of the Armorican massif. It is bounded by metamorphic rocks. It comprises several hydrothermal springs which are unique in the region (Figure 27).

A magnetotelluric survey provided a sketch map of the electrical conductivity of the subsoil, with 800 to 2000 m thick superficial conductive layer. However, the numerous uncertainties of this method didn't allow understanding the origin of the hydrothermal anomaly [3].

Parallel, the hypothesis that the natural seismological activity of the region may be at the origin of a high density of deep fractures was the subject of an expertise.

A temporary 10 stations seismological network was installed to characterize a potential micro-seismicity in the granite massif related to the flow of geothermal fluids [5]. After one and a half year of monitoring, no particular micro-sismic activity was monitored in this area. This method was not appropriate to localizing the geothermal reservoir.

On the other hand, this network allowed identifying 3 seismic zones at the scale of the Vendée Departement. Consequently, the network was re-sited to better characterize these zones. The monitoring is ongoing. The first results confirm a seismicity near the shoreline, with recurrent quite high magnitude earthquakes (up to 5), and also a diffuse seismicity related to active faults that will have to be better localized. For instance, in 2013, about 15 earthquakes were detected with magnitudes from 1.4 to 2.5.

The presence of thermal springs (17 to 28°C) allowed the BRGM to propose a technical program comprising water geochemistry and soil gas analyses [4].

VI.4. Hydrochemical study

Water chemistry shows that the thermo-mineral waters result from the mixing of deep and superficial meteoric waters, recent and ancient.

Figure 28 shows geological context and sampling springs location for chemical and isotopic analysis.

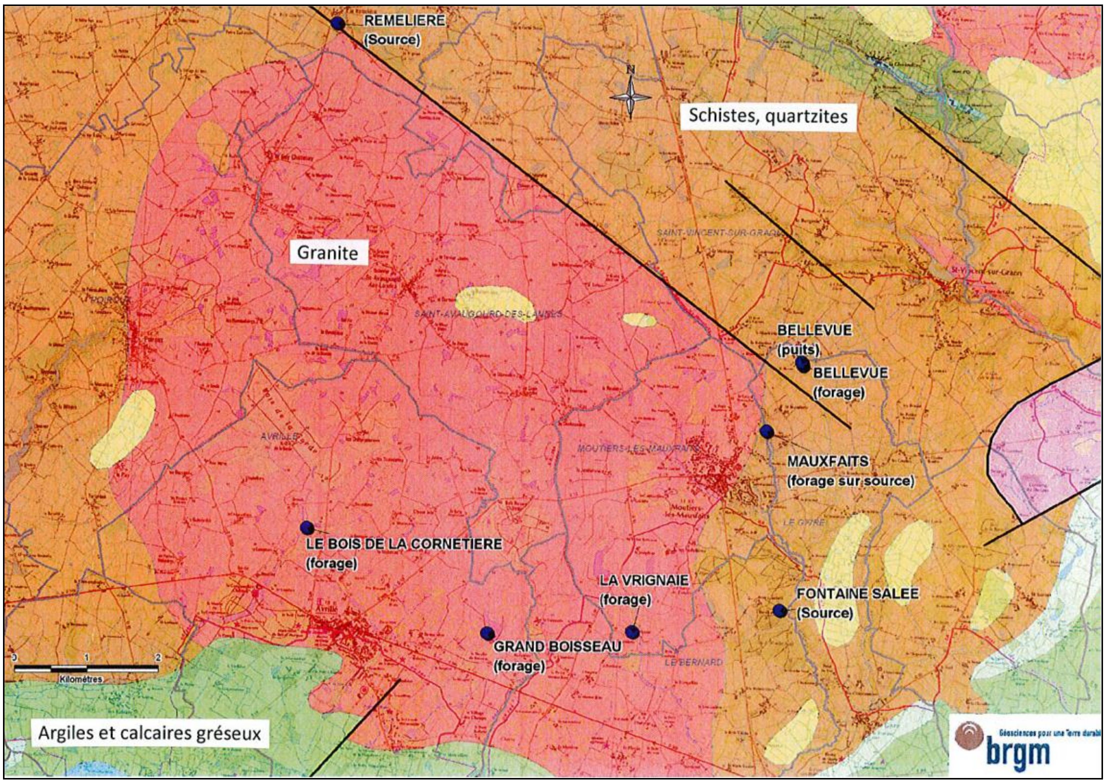


Figure 28 – Geological context and location of the geothermal springs (BRGM [1]).

Hydrochemical facies and in situ parameters

The Piper diagram (*Figure 29*) shows the water composition, with a marqued chloride-sodic type of some springs: Fontaine Salée, Moutiers les Mauxfaits, Bellevue. The Grand Boisseau spring keeps a calcium bicarbonate facies, classical in hard rock aquifers. pH between 5.9 and 7.5 show the acid type of these waters.

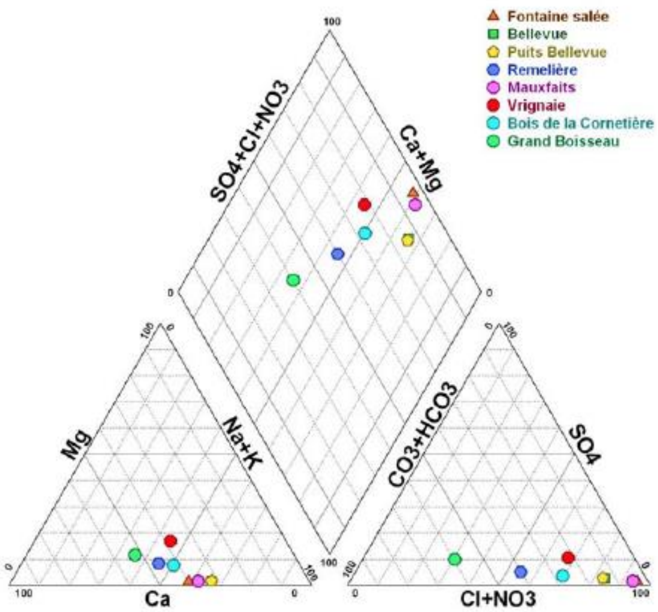


Figure 29 - Piper Diagram of the surveyed springs

The water electrical conductivity shows variable salinities, from 520 µS/cm to 10 mS/cm, and no correlation with temperature: the Fontaine salée spring is the saltiest but not the warmest. The waters from the Vrignaie and Grand Boisseau borewells are the less mineralized.

In a first interpretation, one can identify (*Figure 30*):

- low mineralization waters: Vrignaie and Grand Boisseau with bicarbonate-calcic facies, a slight trend towards a chloride-sodic facies, and low temperature;
- more mineralized waters (Fontaine Salée, Moutiers les Mauxfaits) with a chloride-sodic facies and higher temperatures;
- the Bellevue Borehole provides the highest temperature but with a low mineral content.

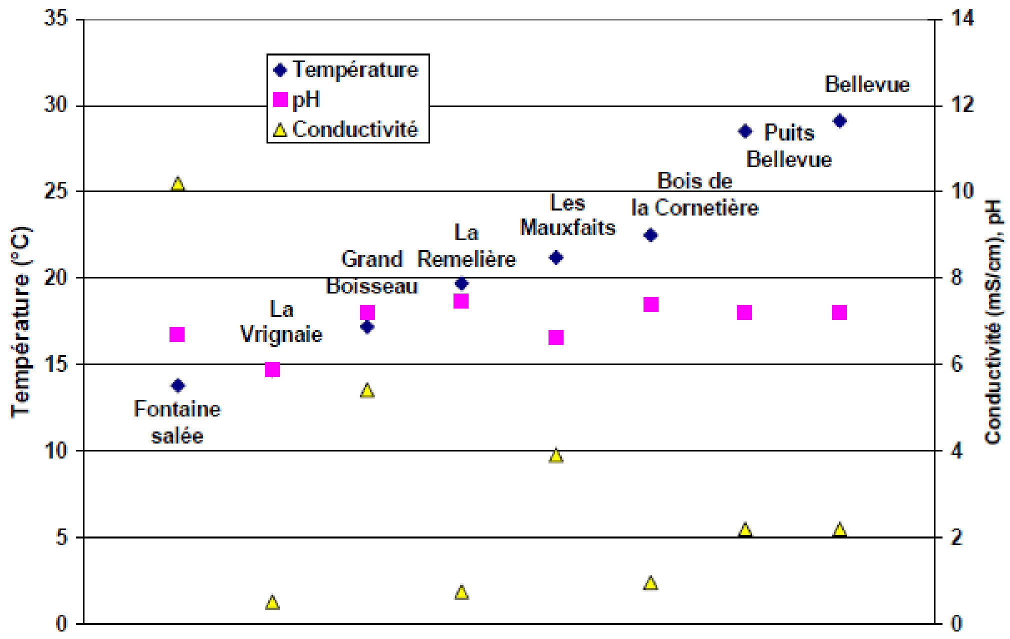


Figure 30 - In situ parameters (pH, electrical conductivity, temperature)

Soil Gases

About 20 soil gases (CO2, radon, helium) profiles were located to cross the two main faults at the contact between the granite and the surrounding schists. These profiles show CO_2 anomalies where they cross the faults. Numerous radon anomalies are also observed at these faults (*Figure 31*).
Carbone 13 isotopic ratios (-24.6 °/₀₀) demonstrate that the CO_2 is mostly of superficial origin (biological activity in the soil).
Gases reach the soil surface from open fractures. The radon anomalies result from the 238 uranium and 232 thorium disintegration chain, these elements being abundant into granites. The anomalies in the schists (near the Fontaine Salée) are associated to the underlying granite. The Helium anomalies originate from the granite. The high « Les Mauxfaits » anomalies are intermittent.

The gas surveys provided new information on the fractures orientation as well as the relationships between some fractures in the schists and the underlying granite. The northern fault is confirmed. The eastern border of the granite massif comprises NNE-SSW faults cut by WNW ESE faults (*Figure 32*).

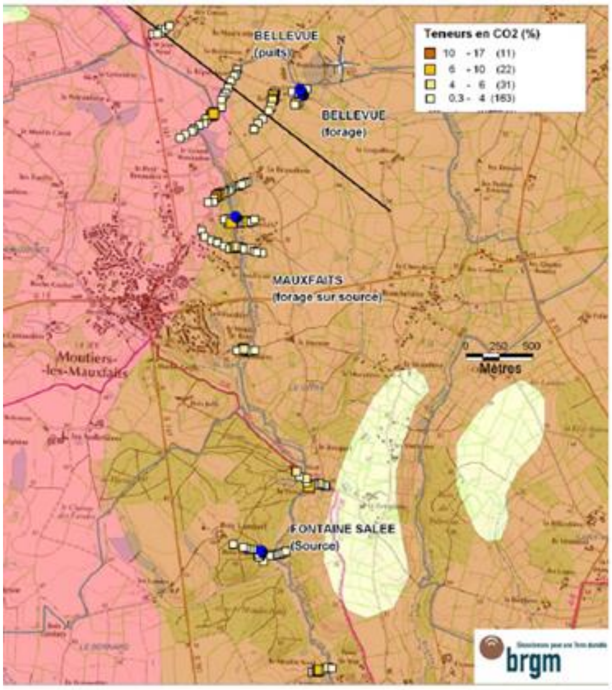


Figure 31 - Soil CO2 (September 2008 survey)

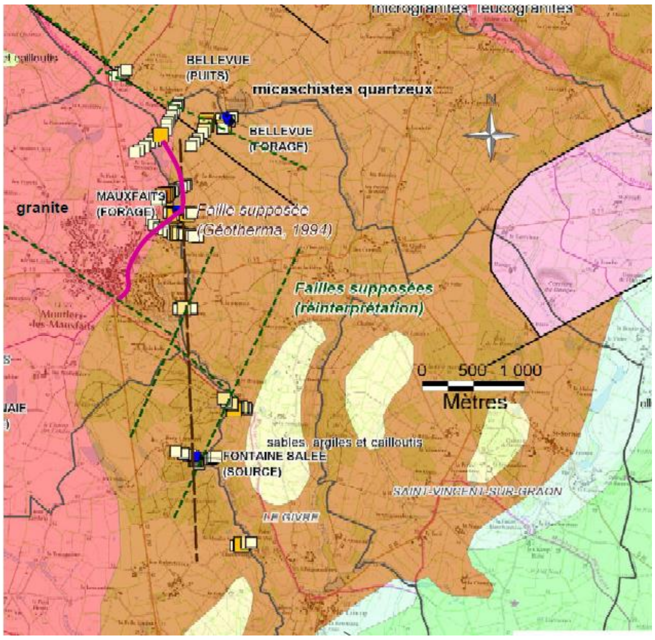


Figure 32 – Réinterpretation of the Avrillé granite - schists contact and of the fracturation from new geological and soil gas profiles surveys (Bechennec, 2008)

These inputs are important as regards understanding the geological structure, notably regarding groundwater arrivals near the surface. The thermo-mineral springs seem to be related to fractures with a link with depth. However only a superficial origin of the gases was demonstrated. A partly deep origin is probable but wasn't demonstrated.

Geochemistry and isotopes to identify the origin of waters

The comparison of the chemical compositions (table 1) allowed identifying the origin of the sampled waters. From the Giggenbach (1988) diagram, that correlates the anions (Cl, SO4, and HCO3), 3 samples have a deep origin: Fontaine Salée, Mauxfaits, Bellevue (*Figure 33*). These more mineralized waters as well as those from the Bois de la Cornetière borewell and from Remelière follow a straight line from the most mineralized pole (Fontaine Salée) towards the less mineralized pole (Remelière). The Grand Boisseau and Vrignaie samples are outside this straight line.

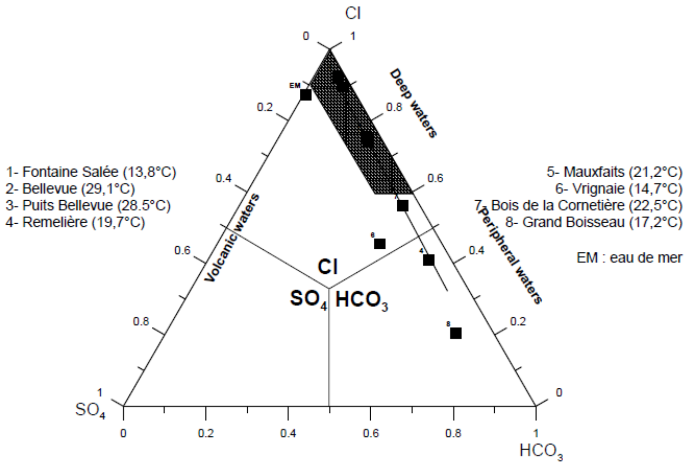


Figure 33 – Giggenbach diagram. Relative contents in Cl, SO4 and HCO3

	Elément		Al (Aluminium)	As (Arsenic)	B (Bore)	Ba (Baryum)	Br- (Bromures)	CID (Carbone Inorganique Dissous)	COD (C. org. dissous)	Ca (Calcium)	Cl (Chlorures)	Co (Cobalt)	Cr (Chrome)	Cs (Césium)
	Limite de quantification (LQ)		2	0,05	10	2	0,1	0,5	0,5	0,5	0,5	0,2	1	5
N°	Point d'eau	Date prélèvement	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	µg/l	µg/l
1	Fontaine salée	09/09/2008	< LQ	3,78	772	177	12,9	50,6	0,9	876	3647	3,5	16	129
2	Bellevue	09/09/2008	< LQ	0,56	164	219	2	11,7	< LQ	133	633	< LQ	23	52
3	Puits Bellevue	09/09/2008	< LQ	1,02	174	209	4,9	12,8	0,7	131	609	< LQ	18	56
4	La Remelière	09/09/2008	< LQ	2,09	53	254	7,7	13,3	< LQ	72,5	150	< LQ	28	13
5	Mauxfaits	10/09/2008	< LQ	0,96	322	208	17,1	9,7	< LQ	282	1315	< LQ	16	31
6	La Vrignaie	22/09/2008	29	0,28	28	136	0,31	15,8	1	37,9	78,7	1,8	< LQ	< LQ
7	Bois de la Cornetière	23/09/2008	23	1,6	62	194	0,87	31	1	77,3	215,4	< LQ	< LQ	6,4
8	Grand Boisseau	10/09/2008	2	8,32	18,1	177	0,24	36,5	1,7	53,5	55,7	0,9	<0,2	2,4

	Elément		Cu (Cuivre)	F (Fluorures)	Fe (Fer)	Ge (Germanium)	K (Potassium)	Li (Lithium)	Mg (Magnésium)	Mn (Manganèse)	NH4 (Ammonium exprimé en NH4)	NO2 (Nitrites exprimés en NO2)	NO3 (Nitrates exprimés en NO3)	Na (Sodium)
	Limite de quantification (LQ)		0,3	0,1	0,02	5	0,5	2	0,5	5	0,1	0,01	0,5	0,5
N°	Point d'eau	Date prélèvement	µg/l	mg/l	mg/l	µg/l	mg/l	µg/l	mg/l	µg/l	mg/l	mg/l	mg/l	mg/l
1	Fontaine salée	09/09/2008	< LQ	1,8	0,52	< LQ	36	1971	20,6	1723	0,2	< LQ	< LQ	1458
2	Bellevue	09/09/2008	0,3	2,3	0,05	< LQ	11,1	411	3,9	< LQ	< LQ	< LQ	5,3	303,1
3	Puits Bellevue	09/09/2008	0,3	2,4	< LQ	< LQ	11,6	411	3,9	24	< LQ	< LQ	4,9	299,4
4	La Remelière	09/09/2008	6,8	2,5	< LQ	< LQ	3,7	73	8,1	11	< LQ	0,02	7,7	79,5
5	Mauxfaits	10/09/2008	0,5	1	< LQ	< LQ	14,2	712	7,7	< LQ	< LQ	< LQ	17,1	534,9
6	La Vrignaie	22/09/2008	2,8	0,6	< LQ	< LQ	2,5	57	10,2	842	< LQ	< LQ	76,2	49,6
7	Bois de la Cornetière	23/09/2008	1,6	2	< LQ	< LQ	3,1	128	8,6	< LQ	< LQ	< LQ	20,5	105,6
8	Grand Boisseau	10/09/2008	3	2,2	0,1	< 0,2	1,6	30,6	7,2	422	< LQ	< LQ	0,9	40,8

	Elément		Nd (Néodyme)	Ni (Nickel)	PO4 (Ortho-Phosphates en PO4)	Pb (Plomb)	Rb (Rubidium)	SO4 (Sulfates)	SiO2 (Silice)	Sr (Strontium)	Th (Thorium)	U (Uranium)	V (Vanadium)	Zn (Zinc)
	Limite de quantification (LQ)		0,1	0,5	0,1	0,1	5	0,5	0,5	2	0,5	0,1	0,4	2
N°	Point d'eau	Date prélèvement	µg/l	µg/l	mg/l	µg/l	µg/l	mg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l
1	Fontaine salée	09/09/2008	< LQ	6,5	< LQ	6,3	290	78	18,5	20337	< LQ	2	< LQ	42
2	Bellevue	09/09/2008	< LQ	< LQ	< LQ	< LQ	108	27,8	27,4	2736	< LQ	3	< LQ	< LQ
3	Puits Bellevue	09/09/2008	< LQ	< LQ	< LQ	< LQ	116	28,5	27	2775	< LQ	3,5	0,6	< LQ
4	La Remelière	09/09/2008	< LQ	< LQ	< LQ	5,5	25	20,1	23,7	554	< LQ	13	< LQ	805
5	Mauxfaits	10/09/2008	< LQ	< LQ	< LQ	< LQ	118	30,5	33,9	6221	< LQ	4	0,5	19
6	La Vrignaie	22/09/2008		3,6	0,1	0,7	8	26	35	134	< 5	2	< LQ	8
7	Bois de la Cornetière	23/09/2008		< LQ	< LQ	0,1	17	15,7	34,5	958	< 5	13	0,5	3
8	Grand Boisseau	10/09/2008		1,9	<0,1	31	7,1	24,8	20,8	147	< 0,1	4,7	<0,2	364

	Localisation	Date	δD	δ18O	δ13C	14C	δ13C	87Sr/86Sr	δ18O SO4
N°	Point d'eau prélevé		‰ vs SMOW	‰ vs SMOW	‰ vs PDB	Activité (%)	fiole 14C		‰ vs SMOW
1	Fontaine Salée	09/09/2008	-32,5	-5,6	-15,0	69,5	-14,8	0,71433	12,4
2	Bellevue	09/09/2008	-34,8	-5,8	-17,0	56,1	-19,3	0,714373	8,4
3	Puits Bellevue	09/09/2008	-34,1	-5,8	-16,9				8,5
4	La Remelière	09/09/2008	-34,1	-5,8	-15,9			0,714022	7,8
5	Les Mauxfaits	10/09/2008	-34,1	-5,8	-17,3			0,714381	12,7
6	La Vrignaie	22/09/2008	-33	-5,6	-17,3			0,712155	4,9
7	Le Bois de la Cornetière	23/09/2008	-34,3	-5,8					8,2
8	Grand Boisseau	10/09/2008	-20,4	-3,0				0,71251	7,1

Table 1 - Chemical and isotopic analyses

These trends are also observed in the Piper diagram (*cf.* fig. 26) but also in a δ^2H-Chloride diagram (*Figure 34*). The waters originate from a mixing between a salty pole (Fontaine Salée, deeper, without nitrate and a low content in dissolved oxygen) and a meteoric freshwater with a more depleted signature (more depleted than the one of the present rain; Dax, Southern France rainfall station) (*Figure 35*). The water from the la Vrignaie well is similar to the present rainfall.

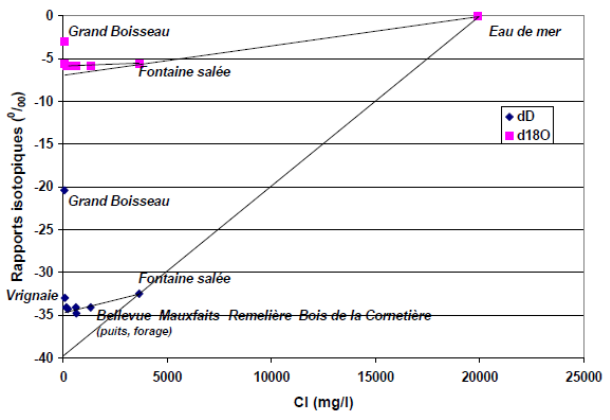


Figure 34 – Comparaison between the isotopic compositions and chloride contents

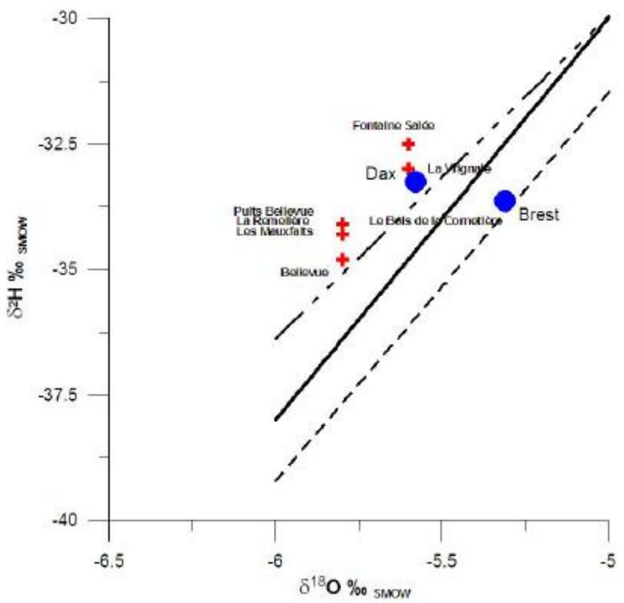


Figure 35 - Relationship δ2H versus δ18O and comparison with the world meteoric lines (Craig and Dax)

The offset of some points (Bellevue, Remelière, Mauxfaits) may testimony from a more ancient recharge. Fontaine Salée shows a different recharge origin.
The presence of near surface waters is confirmed (Bellevue, Grand Boisseau). The discharge of these artesian wells increases during heavy rainfall events. The Grand Boisseau different signature is not explained.

The sampled waters do not show any high temperature isotopic exchange with rock silicates (enrichment in 18oxygene which induces a shift towards the right on the δ^2H versus δ^{18}O graph). The graph rather shows a shift of the points towards the left (18-oxygene depletion) due to a possible interaction with soil CO_2.

The water from Fontaine Salée seems to be constituted from a marine contribution (about 20%) and freshwater from an ancient recharge, and with a Cl/Br ratio near the one of sea water. This marine contribution may be related to the marine immersion episodes which are well known in the area geological history (Pliocene marine red sands superficial deposits and Lias red-haired clayey limestones on the Avrillé granite).

Surface waters show nitrates (76 mg/l NO3 in the le Vrignaie borewell) and a high Mg/Cl ratio which is also a clue of surface waters.

Water dating

The Mauxfaits (Moulin de Neau) water has no tritium (Géotherma, 1994). A 14C analysis shows a mean age between 1000 and 5000 years. A similar age is obtained for the Fontaine Salée borewell. The age of the the Bellevue borewell water is between 4000 and 7000 years. However as these waters result from mixings, it is difficult to identify the age of the poles constituting the blend.
The water age is confirmed by they chemical content. The most mineralized waters are enriched in Ca, Sr, HCO3, SIO2, Fe, F, and depleted in Na, K, Mg, SO4. This implies water rock interaction (alumino silicates dissolution, such as plagioclase, and magnesium and sulfate phases precipitation).
Equilibrium computations show an equilibrium with calcite and fluorite, a sursaturation with quartz and chalcedony, and an undersaturation with dolomite and gypsum.

Geothermometers

The Giggenbach diagram (*Figure 36*), based on the reactions at the thermodynamic equilibrium at a given temperature allows to fast estimate the degree of water-rock interaction and the maximum temperature reached by the water.

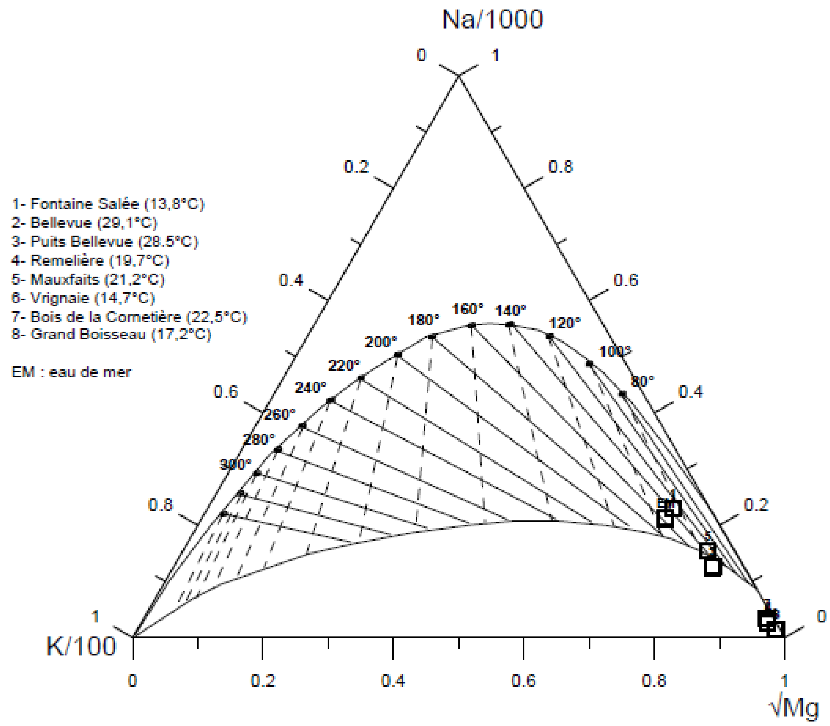


Figure 36 - Giggenbach Diagram. Interpretation of the water temperature at depth from Na, K, Mg

This diagram shows that the waters from Fontaine Salée, Maufaits, and Bellevue have the highest water-rock interactions. The temperatures are between 80 and 120°C (with a slight overestimation). The other points are nearer the Mg pole and are characterized my more superficial waters.

The application of various geothermometers, chemical and isotopic (table 2) shows that the water was submitted to a maximum 70-90°C temperature. This temperature is consistent for the various thermos-mineral waters, and coherent with the chemical content interpretations.

VI.5. Conclusions and perspectives

The history of the hydrogeological survey of the Moutiers-les-Mauxfaits massif is long and certainly unfinished. The physic-chemical and thermal characteristics of the springs demonstrate a hydrogeological anomaly as regards the context of the Vendée hard rock aquifers. What is the origin of these geothermal waters emerging from the granites as well from the schists, but always near the fractured contact of the batholith? What is the extent of the reservoir at depth? So much questions which will require complementary investigations.

Unsuitable for drinking water or irrigation uses, the Moutiers-les-Mauxfaits resource is still unused unless its interest for health as well as for low enthalpy geothermy. The local conditions were not appropriate for a valorization and a development of this resource.

Point de prélèvement	Date	$T_{émerg.}$ °C	T_{Qz} °C	$T_{Calcéd.}$ °C	$T_{Na/K}$ °C	$T_{Na/K/Ca\ (\beta=4/3)}$ °C	$T_{Ca/K}$ °C
1- Fontaine salée	09/09/2008	13,8	61	40	85	87	120
2- Bellevue	09/09/2008	29,1	76	55	111	73	109
3- Puits Bellevue	09/09/2008	28,5	75	54	114	74	112
4- La Remelière	09/09/2008	19,7	70	49	128	40	78
5- Mauxfaits	10/09/2008	21,2	85	63	89	71	104
6- La Vrignaie	22/09/2008	14,7	86	64	134	37	75
7- Bois de la Cornetière	23/09/2008	22,5	85	64	96	37	70
8- Grand Boisseau	10/09/2008	17,2	65	44	115	20	54

Point de prélèvement	Date	$T_{K/Mg}$ °C	$T_{Na/Li}$ °C	$T_{Mg/Li}$ °C	$T_{K/Sr}$ °C	$T_{Na/Rb}$ °C	$T_{Na/Cs}$ °C	T_{FK} °C	$T_{Fe/K}$ °C	$T_{Mn/K}$ °C	$T_{\delta_{18}OH2O-SO4}$ °C	$T_{estimée}$ °C
1- Fontaine salée	09/09/2008	88	93	104	83	91	85	139	111	40	88	**60-90**
2- Bellevue	09/09/2008	80	93	84	76	109	99	109	110	*n.d.*	124	**70-90**
3- Puits Bellevue	09/09/2008	81	94	84	77	112	101	112	*n.d.*	72	122	**70-90**
4- La Remelière	09/09/2008	47	72	38	63	106	98	82	*n.d.*	48	130	**60-90**
5- Mauxfaits	10/09/2008	77	92	90	68	94	76	93	*n.d.*	*n.d.*	84	**70-90**
6- La Vrignaie	22/09/2008	37	84	32	76	85	*n.d.*	41	*n.d.*	-16	171	**?**
7- Bois de la Cornetière	23/09/2008	43	87	49	46	85	77	72	*n.d.*	*n.d.*	126	**70-90**
8- Grand Boisseau	10/09/2008	32	62	24	57	87	76	59	19	-18	177	**?**

n.d. : non déterminé
T_{Qz} : Fournier and Rowe (1966) ; $T_{Calcéd.}$: Helgeson et al. (1978) ; $T_{Na/K}$: Michard (1979).
$T_{Na/K/Ca}$: Fournier and Truesdell (1973). $T_{K/Mg}$: Giggenbach (1988).
$T_{Ca/K}$, $T_{K/Sr}$, $T_{Na/Rb}$, $T_{Na/Cs}$, T_{FK}, $T_{Fe/K}$ and $T_{Mn/K}$: Michard (1990).
$T_{Na/Li}$: Fouillac et Michard (1981). $T_{d18OH20-SO4}$: Mizutani and Rafter (1969).

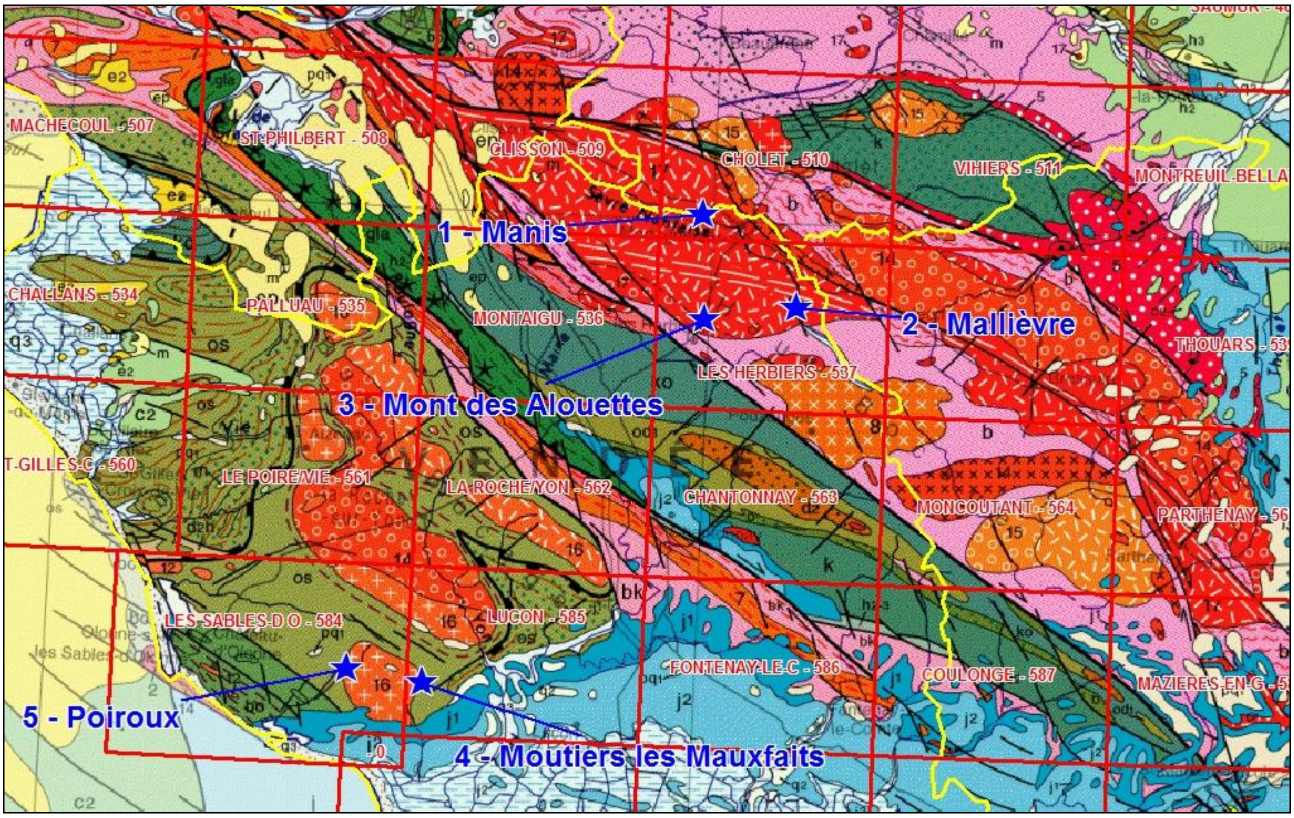
Table 2 – Estimation of deep reservoir temperature from chemical and isotopic geothermometers

However, the various studies allowed identifying the main characteristics of the geothermal potential. The thermal waters result from a mixing between deep waters (1000 to 2000 m, 90°C) and more superficial cool waters. A finer study of the massif fracturation with the siting of boreholes to explore geothermal gradients may surely help to reduce the present uncertainties.

References:

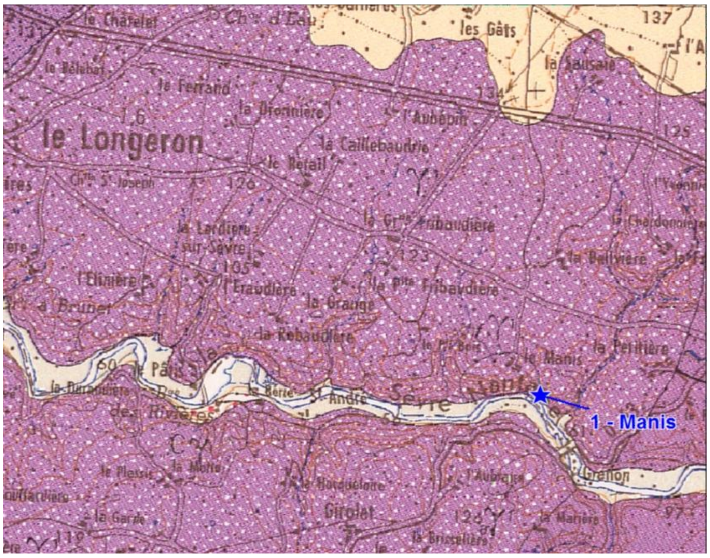
[1] Grière O. (1994) – Etude de la ressource thermale de Moutiers-les-Mauxfaits – Géotherma SA.
[2] Gérard A., Graff J.J. (2007) – Eléments vers une reconnaissance de possibles ressources géothermiques profondes exploitables dans le département de la Vendée – Electricité de Strasbourg.
[3] Wawrzyniak P., Sailhac P. (2009) – Campagne de mesures magnétotelluriques du massif granitique d'Avrillé – Equipe de Géophysique Expérimentale, IPG Strasbourg, UMR 7516.
[4] Le Guern C., Conil P., Négrel P. avec la collaboration de Sanjuan B., Jouin F., Brach M., Loislard M., Fléhoc C. et Béchennec F. (2009) – Reconnaissance de ressources géothermiques potentielles dans le secteur du massif granitique d'Avrillé (Vendée) – Phase 1 : Géochimie. Rapport BRGM/RP-57000-FR, 86 p.
[5] Perrot J., Geoffroy L. (2015) – Observation sismologique en Vendée – IUEM, UMR 6538, Technopôle Brest-Iroise, Plouzané.

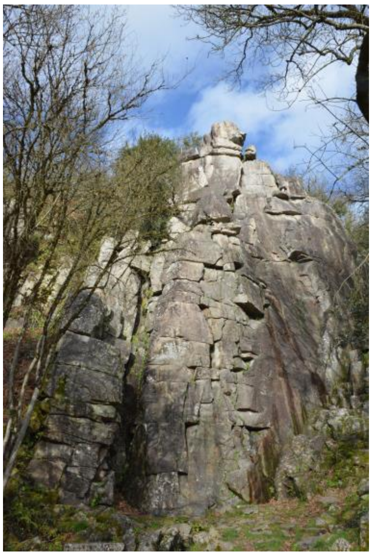
DESCRIPTION OF OUTCROPS



NOTES

STOP 1 : LE MANIS CLIMBING CLIFF





1:50,000 geological map: Cholet (510)

Granitic massif of Mortagne, sodic, two-micas bearing leucogranite

Fissured layer, middle part

The Manis cliff, on the right bank of the Sèvre Nantaise River, is a 30 m high climbing site.

Geology

The Le Longeron leucogranite forms a late intrusion within Mortagne granite, which has been dated at 313 ± 15 Ma. It is a medium-grained granite, made up of porphyroblasts of microcline, automorphic albite (5 to 7 mm), small crystals of oligoclase partly sericitized, globular quartz, large, tabular primary or secondary, poikilitic muscovites. Biotite is less abundant than muscovite. Accessory minerals include apatite and zircon.

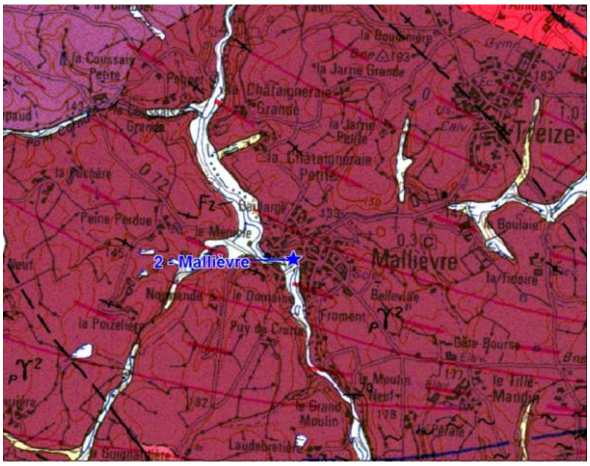
Weathering

The cliffs are crosscut by spectacular planar joints, resulting from stress generated by biotite weathering. Biotites commonly show chloritization evidences, with decoloration of peripheral part of the crystals, opening of leaves, and precipitation of ochre goethitic grains from iron exsolved from biotites.

The mean spacing of joints varies from 0.5 to 1.5 m. The base of grus (granitic sand) lies about at + 120 to + 130 m a.s.l., le foot of the cliff is around + 70 m: the outcrop is situated in the middle part of fissured layer, 40 to 50 m below the base of grus.

NOTES

STOP 2 : MALLIEVRE CLIFF



1:50,000 geological map: Les Herbiers (537)

Granitic massif of Mortagne, 2-micas bearing, porphyroid leucomonzogranite (313 ± 15 Ma)

Fissured layer, middle part

The Mallièvre cliff is located on the right bank of the Sèvre Nantaise River; a pedestrian track along the cliff allows close observation of granite and planar jointing.

Geology

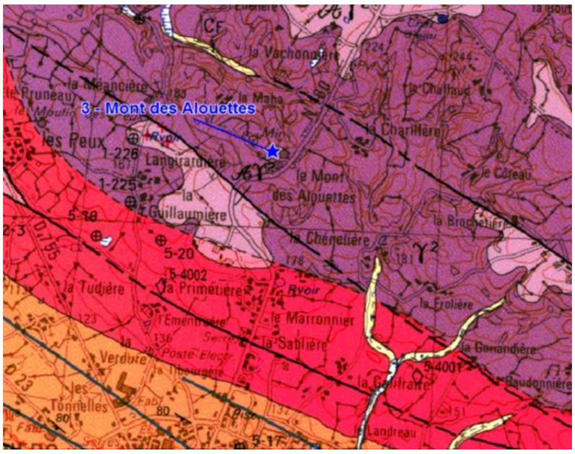
The granite shows a granular, porphyroid texture, with K-feldspar phenocrysts underlining the vertical magmatic foliation. Biotite is more abundant than muscovite.

Weathering

The cliff is crosscut by numerous planar joints with a spacing of 1 to 2 m. The base of grus lies between + 190 and + 200 m a.s.l., the outcrop around + 135 m: we are about 60 m below the base of grus, in the middle part of the fissured layer. The footpath allows a close observation of the outcrop: on each side of the large horizontal joints, the granite shows a laminated facies resulting from local multiplication of tension microcracks at the contact between water (circulating in macrojoints) and rock. The microcracks spacing is millimetric, they crosscut K-feldspar phenocrysts without any displacement.

NOTES

STOP 3 : MONT DES ALOUETTES



1:50,000 geological map: Les Herbiers (537)

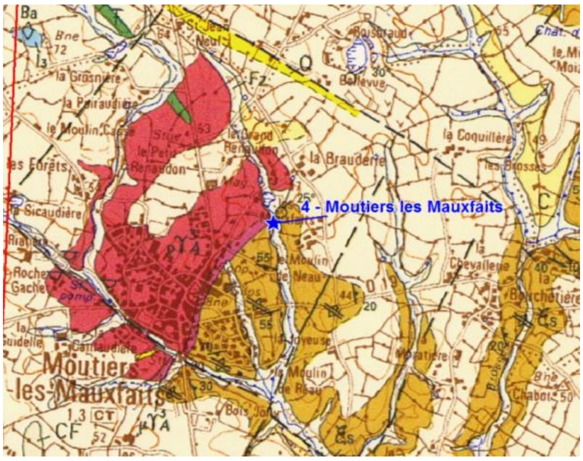
Granitic massif of Mortagne, 2-micas bearing, porphyroid leucomonzogranite (313 ± 15 Ma)

The « Mont des Alouettes » was a famous site during vendean war, at the end of 18th and beginning of 19th centuries: the millers used to give informations about republican army positions to royalist army by orientating the windmill wings in a particular way.

The site is at + 227 m a.s.l., on the southern edge of the large plateau corresponding to the remnants of pre-cenomanian planation surface. It permits a good, south-looking panorama over the Eocene planation surface, at the foot of the south armorican fault escarpment, wich lies around + 100 to + 110 m a.s.l. At the horizon, we can see the Chantonnay fault escarpment, which vertically shifts the Eocene surface of about 15 m.

NOTES

STOP 4 : MOUTIERS LES MAUXFAITS - THERMAL SPRING OF « MOULIN DE NEAU »



1:50,000 geological map: Luçon (585)

In the past, the spring of « Moulin de Neau » in Moutiers les Mauxfaits fed a water mill. During sixties, it has been worked for watercress. In 1988, a 101 m deep borehole has been carried out: it yields 20m^3/h of artesian water at a T° of 22°C, with a conductivity of 2960 µS/cm and a pH of 7.37. Water contains chlorides (1200 mg/l), sodium (500 mg/l) and calcium (260 mg/l).

A feasibility study has been carried out in order to create a water-cure establishment, but has concluded to a too big risk of contamination of surface waters.

The borehole has crossed a weathered, biotite-bearing granite, with numerous aquifer fissures, up to 71 m, then an alternation of medium-grained and fine-grained granite. The pumping tests give a transmissivity of 4 m²/h and a possible production yield of 100 m^3/h.

This spring is one of a tenth of thermomineral water occurrences spread on and around the Avrillé granite. These waters have temperatures between 17 and 31 °C, while normal T° of groundwater in this area is 12 °C. The chemical and isotopic geothermometers indicates a mixing of cold, surface water and deep, hot water, the latter having been heated around 90 °C. The mean age of the water, determined by ^{14}C method, is included between 1000 and 4000 to 7000 years.

Several assumptions are proposed for explaining these thermomineral waters:

1. Deep circulation

   For a normal geothermal gradient, (33 °C/km), the hot component of water (90 °C) should come from an approximate depth of 2.500 m. However, this interpretation encounters a difficulty in the fact that local hydraulic gradient is too low to initiate by advection a water circulation at such a depth: the difference of elevation between uplands and valleys is 15 to 20 m. Consequently, the hydraulic load is too weak to offset hydraulic head loss resulting from frictions along channel walls.

2. Volcanism

   There is no volcanic occurrence in the area which can explain a strong geothermal gradient.

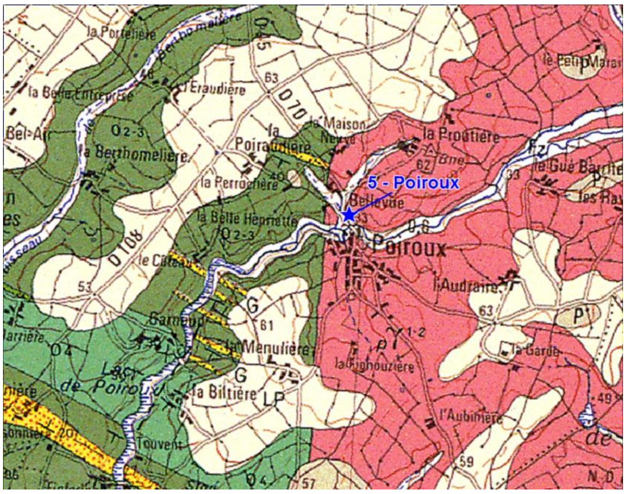
3. Exothermic weathering front at a shallow depth

   The petrographic studies carried out in order to understand the mechanism leading to the rock fissuring and formation of the fissured layer of the granites has shown that when biotite weather in chlorite, very thin crystals of adularia (low T° K-feldspar) often precipitates within biotite cleavages. The

$\delta^{18}O$ of adularia and chlorite indicates a probable crystallization at 70 to 80 °C (Wyns et al., 2015). A modelling of rock heating due to exothermic reactions (oxidation and hydration) in the vicinity of percolation front (where the permeability is too low to allow water circulation) has been done. The results shows than for a thermal power ≥ 10 mW/m^3, a temperature of 100 °C can be reached after 10 Ma of weathering. If this hypothesis is correct, the thermomineral waters of Avrillé granite could then indicate the existence of a functioning weathering front at a shallow depth (200 to 300 m).

NOTES

STOP 5 : POIROUX – AVRILLE GRANITE



1:50,000 geological map: Les Sables d'Olonne (584)

Avrillé biotite monzogranite (313 ± 3 Ma on monazite, 293 ± 3 Ma on zircon)

Transition between fissured layer and laminated layer

The outcrop is located on the road side, at the north exit of Poiroux village.

Geology

The Avrillé monzogranite shows a porphyroid texture with K-feldspar phenocrysts underlining the magmatic foliation. It is rich in large biotite crystals, and includes plagioclase and quartz.

Weathering

At the outcrop, the granite is strongly weathered. Biotites are chloritized and show an ochre halo of iron hydroxides (goethite). Relicts of planar joints are well preserved. The rock appears sometimes hard (fissured layer), sometimes soft and laminated (laminated layer) or loose (grus). We are in the transition zone between fissured layer and laminated layer.

The age of weathering is unknown. It is possible than the weathering profile was polyphased, with a first weathering phase during Early Cretaceous, followed by a second phase during Early Tertiary (Palaeocene-Eocene) and a third one beginning during Late Miocene. This polyphasing could explain the high thickness of laminated horizon (Dewandel et al., 2006 ; Lachassagne et al., 2011).

The high content of this monzogranite in large biotites explains his high weatherability, and could be relied with the occurrences of thermal waters.

Patrimoine géologique vendéen

HAVRE ET POINTE DU PAYRÉ

JARD-SUR-MER

Vue aérienne de l'estuaire du Payré depuis le sud-est. Les falaises de la Pointe du Payré sont visibles au premier plan, tandis que la forêt du Veillon apparaît en rive gauche de l'estuaire. L'intérêt du site ne réside pas seulement dans sa beauté, mais aussi dans sa richesse géologique exceptionnelle.