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Characterization of Reservoir Properties of Andesitic Rocks on Basse Terre de Guadeloupe (French West Indies) in the Framework of GEOTREF Geothermal Program

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ABSTRACT

Active volcanic areas are prone to the development of geothermal energy. Guadeloupe (French West Indies) already produces electricity thanks to Bouillante geothermal power plant. Geotref program, funded by the French Agency for Environment and Energy Management (ADEME), aims to locate a new geothermal resource south of Bouillante, close to the La Soufriere volcano. This zone is covered by an abundance of recent deposits, vegetation, buildings, and some geothermal evidence (found at the surface). A natural analogous system representing a 2.8 Ma, deep environment has been studied in the north of Basse Terre (Tillet Creek) in order to characterize fluid pathways. At Tillet Creek, andesitic rocks are strongly foliated and crosscut by fractures, thus showing a both vertical and horizontal network for fluid flow. This feature is measured from the metric to the millimetric scales. A scan line performed on the outcrop (30m long, along Tillet Creek) provides fracture data that was analyzed by classical means (orientation, density, spacing, …) and fractal analysis. The regional-scale fracture orientations are found on the outcrop. Similar clay minerals are found in both vertical and horizontal structures. They are clearly injected from vertical fractures into the horizontal schistosity, this means that fluid flow in such environments occurs due to vertical fractures as described at Bouillante and with a horizontal component from discontinuities such as schistosity and lava flow boundaries. They occur from millimetric to metric scale (and even more) in the 3 dimensions of space.

1. INTRODUCTION

Fractured rocks might constitute adequate drinking or geothermal water reservoirs, provided that the fractures act as drains to increase the permeability of the rocks and allow the link between drillholes. For geothermal purposes, at least 2 boreholes have to be drilled for production and reinjection. Each of them needs to be highly permeable, though not along their whole length, in specific zones located in the geothermal reservoir, where both water and high enough temperatures are to be found. Active volcanic areas are prone to geothermal development programs because of their temperature potential and tectonic setting, this leads to the creation of fracture networks and various kinds of discontinuities. Among these areas, Guadeloupe (French West Indies, Fig. 1) has already proven to be adequate for electricity production from geothermal origin as Bouillante geothermal power plant produces electricity since 1987. According to the French Ministry for Environment La Soufrière volcano receives a mean annual pluviometry of 10m close to its summit and the whole Basse Terre receives 3 Gm^3 of rain water each year. This provides a great water potential for geothermal systems on Basse Terre and in particular along the volcano flanks.

In the frame of energetic autonomy for islands, reduction of greenhouse gas emissions, and fossil energy consumption in Guadeloupe, the French Agency for Environment and Energy Management (ADEME) has financed a research program for the identification of a new geothermal resource, called Geotref. Geotref program has obtained an Exclusive Research Permit (ERP) in Vieux Habitants area, a few kilometers south of Bouillante geothermal power plant (Fig. 1). This zone is located close to La Soufrière volcano and is partly urbanized, covered by dense vegetation, or covered by recent volcanoclastic flows, depending on the considered area. As a consequence, very few surface information can be found about geothermal resource. No drillings have been performed yet. It is then important to find information about the underground geothermal reservoir using a surface analogous system in order to predict reservoir properties and location of drillholes according to discontinuity networks and present-day stress field. The geothermal reservoir in the considered ERP, is suspected to lie 2km below the surface. Because of erosion rates in this area (Verati et al., 2018 and references therein) rocks aged around 2-3 Ma have probably been exhumed from a depth of about 2km. As a consequence, in the north of Basse Terre island, rocks dated to be ~2.8 Ma might be considered as analogous to those being presently buried at 2km depth in Vieux Habitants area (Fig. 1). Tillet Creek (Fig. 1) allows a good view of 2.8 Ma rocks. Their ancient burial is indicated by the development of low-grade metamorphism (Verati et al., 2018) and schistosity. This study aims to characterize in detail the fracture/discontinuity network using different method at various scales; from the kilometric field scale to the microscopic scale observed in the lab.

2. MATERIAL AND METHODS

The outcrop at Tillet Creek is shown in Figure 2. Field work provided a scan line (30m-long along Tillet Creek), photographs of outcrop and rock samples. Scanlines were made using a graduated decameter fixed on the outcrop, along which each fracture was recorded with its location, dip-direction, dip, width, and mineral filling. To the west, on the other side of the beach, out of the scanline zone, andesite shows prismation (Fig. 3A) which disappears in the study zone. The study zone shows strong schistosity (Fig. 3B) and fractures (Fig. 3C), frequently showing red, yellow or white clay filling (Fig. 3D).

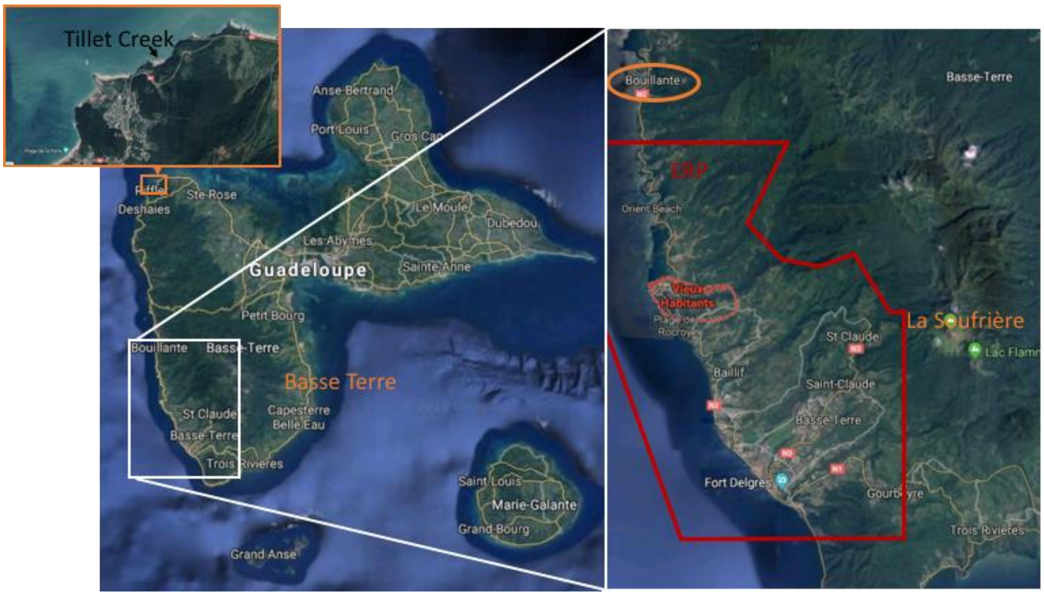

Figure 1:Map of Guadeloupe with location of Bouillante, Tillet Creek and Exclusive Research Permit around Vieux Habitants.

Figure 2: Photograph showing the outcrop at Tillet Creek. The red rectangle indicates the zone in which the 30m-long scanline was performed.

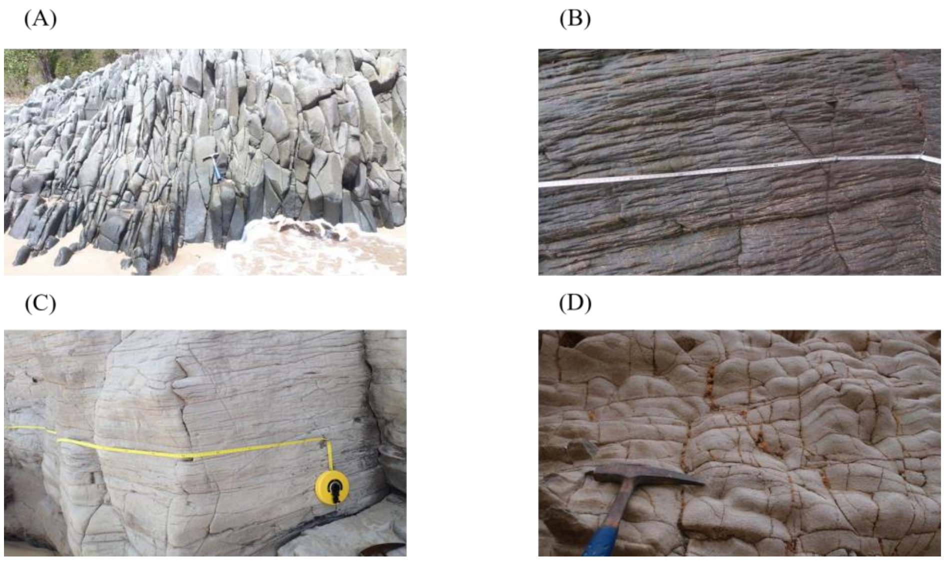

Figure 3: Photographs showing the outcrop at Tillet Creek. A- Prismatic structure, B and C- Horizontal foliation with a few vertical fractures, D- vertical fractures with red clay filling.

Three kinds of fractures were recorded: minor ones occur only between two contiguous schistosity planes, intermediate ones crosscut a few of those planes, major fractures crosscut the outcrop on a metric scale (Figure 4).

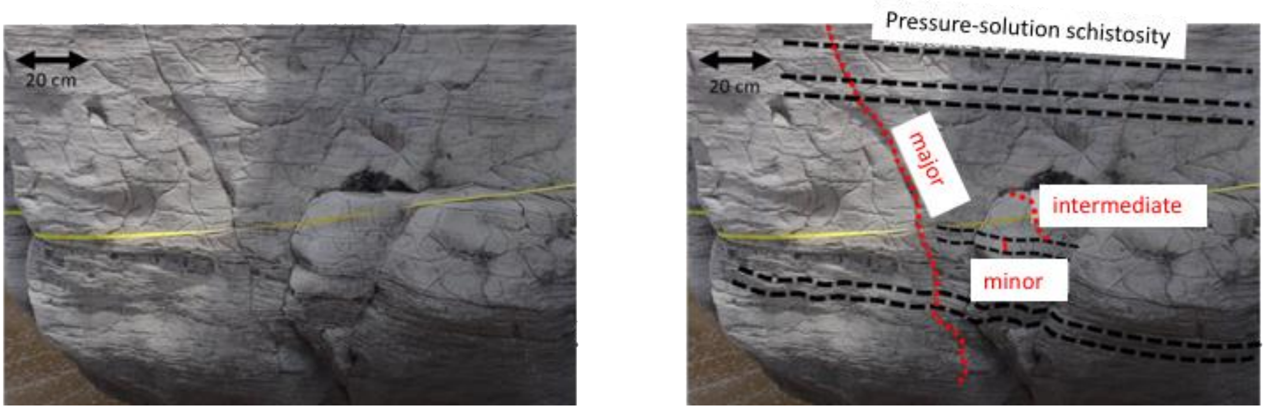

Figure 4: Photographs showing the outcrop at Tillet Creek. Left : the outcrop, right : interpretation in terms of fracture type (major, intermediate, minor; red dashed lines) and schistosity (black dashed lines).

Discontinuity networks were binarized on photographs of the outcrop as seen in Figure 5 along the scanline. Each picture belongs to a fracture plane that dissects the andesite and gives the outcrop its particular geometry.

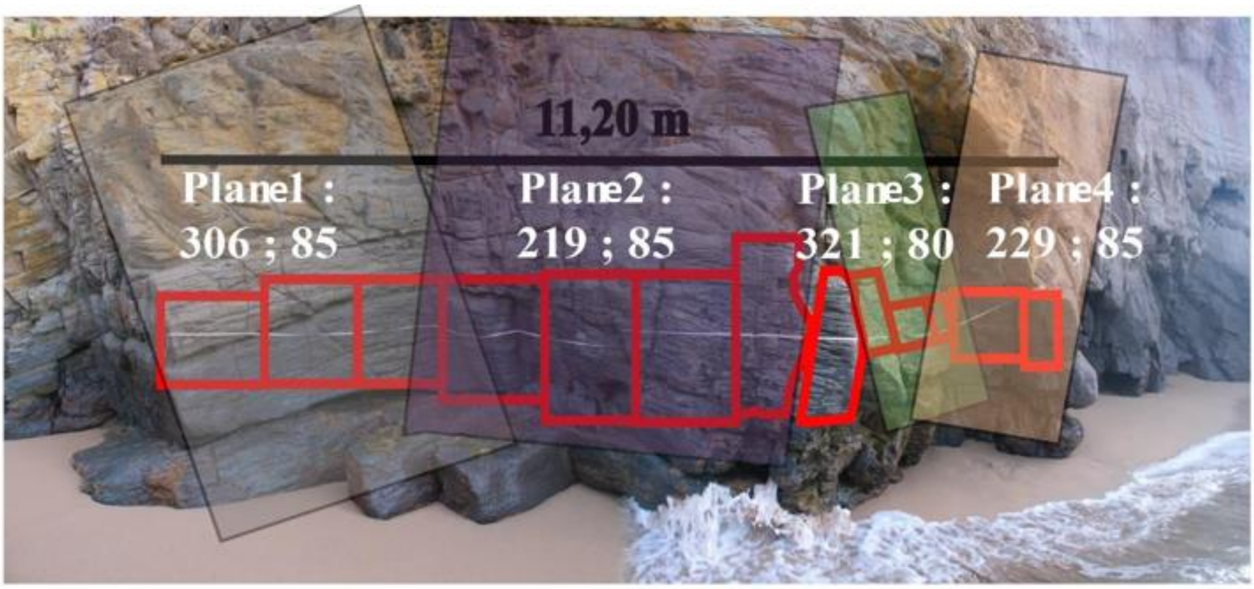

Figure 5: Photograph of the outcrop at Tillet Creek along the first 11.2m of the scanline. Each red shape represents a picture in which fractures were digitized. They belong to fracture planes (plane 1 to 4) which orientation, expressed as "dip direction; dip" (e.g. 306; 85 for plane 1), gives the outcrop its particular geometry.

The digitized discontinuities on each plane are shown in Figure 6. They include schistosity and fracture planes.

Several classical geometrical parameters were calculated from these pictures: according to Dershowitz (1984), P10 quantifies the number of fractures per length unit (in f/m) and P21 represents the length of discontinuities per surface unit (in m/m^2). S quantifies the spacing between discontinuities (in m). Lm, is the mean length of discontinuities and is obtained from the cumulative length divided by the number of discontinuities (in m). When fractures were filled by secondary minerals, they show a width that can be recorded to calculate a surface occupied by ancient opening (now secondary minerals) over the whole analyzed surface of the photograph.

Fractal analysis was performed using Cantor's dust method as described in Velde et al. (1990) and Ledésert et al. (1993) on the fracture network only (Figure 7).

Optical microscopy was performed on thin sections to find evidence of fluid flow at the millimeter scale.

X-ray diffraction was performed on the clay deposits found in fractures and schistosity plane to identify the nature of clay minerals, then compare them according to their occurrence. It was done using a Bruker D2 diffractometer in the following conditions: Cu anti-cathode, 30kV, 10mA.

Centimetric rock samples showing schistosity planes and minor fractures were investigated by X-ray tomography in order to show possible fluid pathways in 3D at the same scale as thin sections.

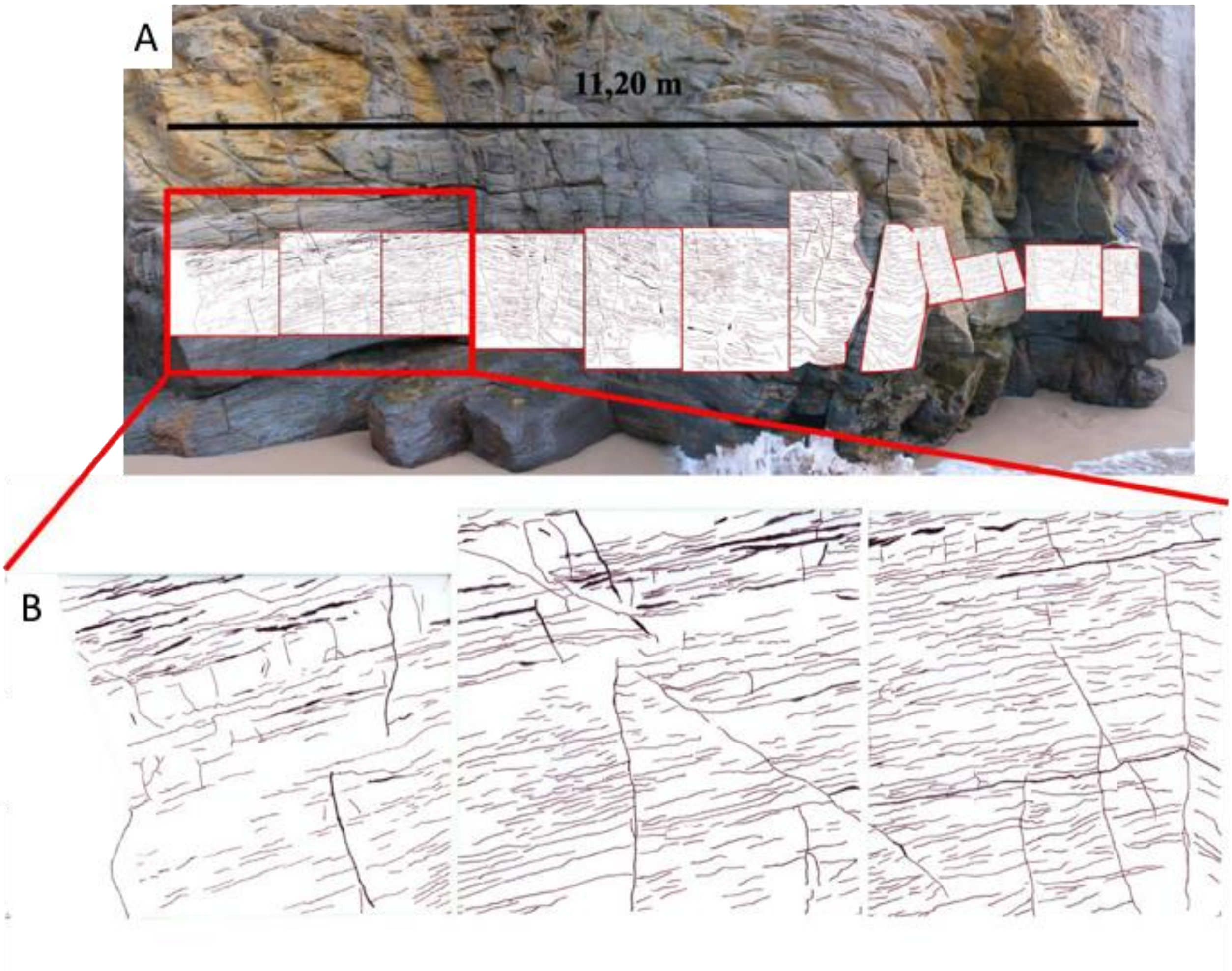

Figure 6: Digitized discontinuities including schistosity and fracture planes, along the first 11.20m length of the scanline. A- The outcrop showing the digitized discontinuities, B-Focus on 3 successive photographs.

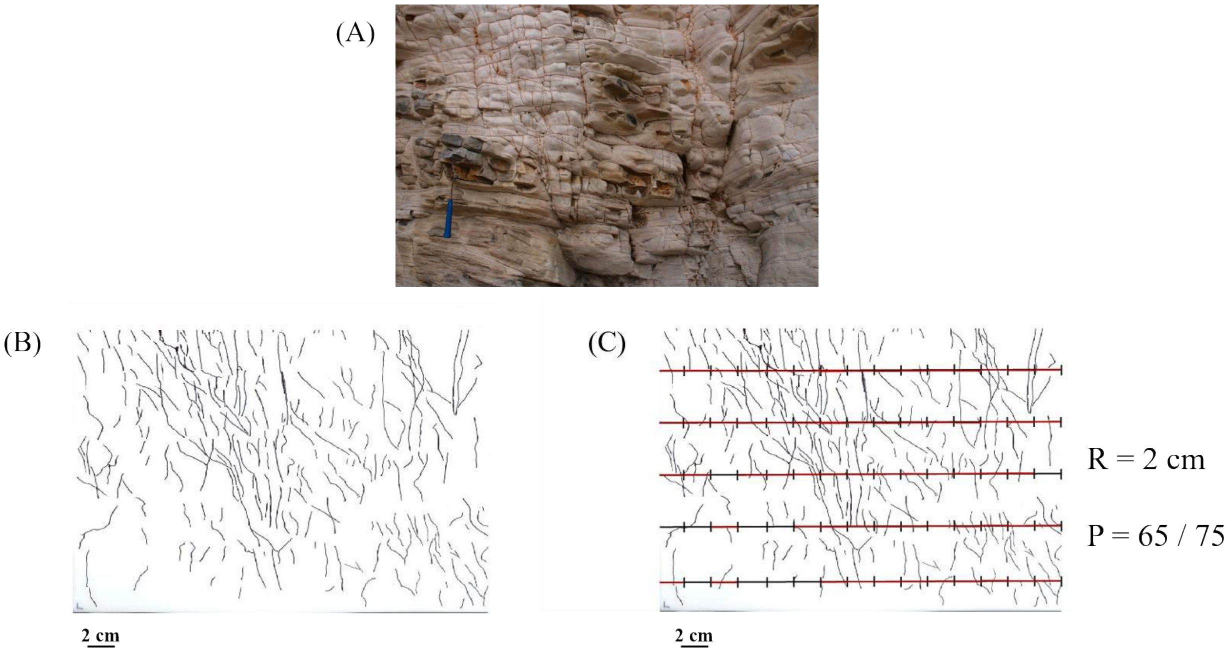

Figure 7: Cantor's dust method applied to digitized fractures for their fractal analysis. A- the outcrop, B-the digitized fracture network (the schistosity was not reported on purpose as it is nearly parallel to the analysis grid), C-the analysis grid with a spacing R of 2cm. Here 65 segments out of 75 intersect fractures. Only 10 segments (in black) intersect no fracture.

3. RESULTS

3.1 Analysis of Fractures

The 30m-long scanline crosscuts 273 fractures (Figure 8), among which 68 major, 109 intermediate and 96 minor fractures.

3.1.1 Orientation

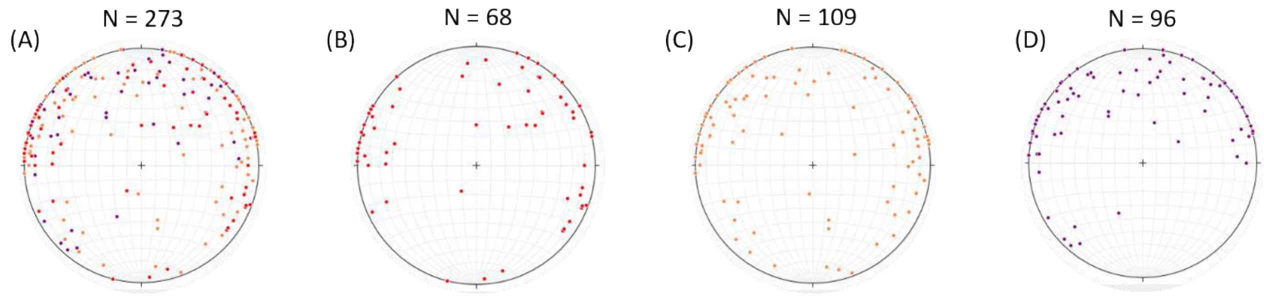

Figure 8: Stereograms (Schmidt, lower hemisphere) showing the dip-direction and dip of (A) the whole fracture network, (B) major fractures, (C) intermediate and (D) minor fractures.

The whole fracture set and the three sub-sets show a rather wide dispersion in terms of dip-direction and dip (Figure 8). However, when one considers the strike of fractures, 4 directions are highlighted: N0-N30 (29% of the whole fracture set), N30-N50 (19%), N120-N150 (21%; close to the N140 strike of the Montserrat-Bouillante regional fault) and N160-N170 (9%). N0-N30, N30-N50 and N120-N150 fracture systems affecting the Tillet Creek outcrop are compatible with the global tectonic framework of the entire Guadeloupe archipelago (Verati et al., 2016 and references therein).

3.1.2 Length, width and spacing of fractures

The length of fractures was not measured along the scanline, but on binarized photographs. It could be measured only for minor and intermediate fractures, major ones are longer than the frame of the pictures.

The 96 minor fractures show a length between 0.5 and 3.45cm. They begin at a schistosity plane and end at the next one. They have a width in the range 0-0.5mm. The 109 intermediate fractures have a length between 6.3 and 83.3cm. They begin and end at a schistosity plane and crosscut others, thus interconnecting the schistosity planes as minor fractures do, but on a greater distance. The width of intermediate fractures is comprised between 0 and 3mm. There is no relationship between length and width, for neither minor nor intermediate fractures. Major fractures, extracted from the data set because of their length larger than that of the pictures, represent 25% of the whole data set.

The surface occupied by fracture filling (and thus ancient opening) was calculated and compared along the scan line. The scan line can be divided into 3 thirds according to the values obtained. The surface area occupied by secondary minerals goes from 5% to 17%. The first third of the scanline (0 to 10m) is characterized by a surface area of 5 to 12,5%. The second third of the scanline shows values up to 15.5%, whereas in the third part the discontinuities occupy more than 16% of the studied surface. The average surface occupied by opening of discontinuities is 10.5% of the whole surface. Figure 9 shows an example on which the surface occupied by discontinuities is 7.6% and the intensity of discontinuities (P21) is 0.24cm/cm^2.

Figure 9: Example of surface occupied by filling or aperture of discontinuities (7.6%) and intensity of these discontinuities (P21=0.24cm/cm^2).

Spacings between fractures are in the range 0.06m-0.35m. Numerous fractures show a small spacing: only 2 fractures are spaced 0.3m apart while 18 fractures show a 0.07m spacing. The average spacing between 2 contiguous fractures is 0.12m. Power law is the law that describes best the spacing between fractures. As a consequence, a fractal analysis was performed on the fracture set.

3.1.3 Fractal analysis

The fractal analysis of the fracture network indicates that fractures are indeed characterized by a power-law distribution. For the whole fracture set, it gives a fractal dimension (D) of 0.42 indicating that fractures are grouped in clusters separated by unfractured zones. When the fractures are separated into the 3 classes, the values are as follows: minor fractures, D=0.41; intermediate fractures, D=0.47; major fractures, D=0.38, indicating that this latter shows the most irregular distribution. These 3 classes are characterized by close values of D, rather similar to that of the whole fracture set, showing that there is no to little difference in the organization of fractures according to their length.

3.1.4 Discussion about fracture analysis

The dispersion in orientation of fractures together with their intensity and the dense schistosity, create a very interconnected network favorable to fluid flow (Figures 3, 4 and 6). The fracture network studied here occurs as highly fractured zones separated by less to not fractured areas. The aperture of discontinuities, filled by clay minerals, occupies approximately 10% of the outcrop, indicating a potential 10% of volume of the rock occupied by fluids. Petrography and mineralogy described in the following section (section 2.2) will focus on the relationship between fractures and schistosity.

3.2 Petrography and Mineralogy

Petrography and mineralogy data allow to show evidences of ancient fluid flow. In some cases, newly-formed minerals that precipitated in the discontinuities can be easily dissolved for enhancement of permeability in enhanced geothermal systems. It is thus very important to locate and identify them for geothermal purpose. Figure 10 gives an example of such fillings.

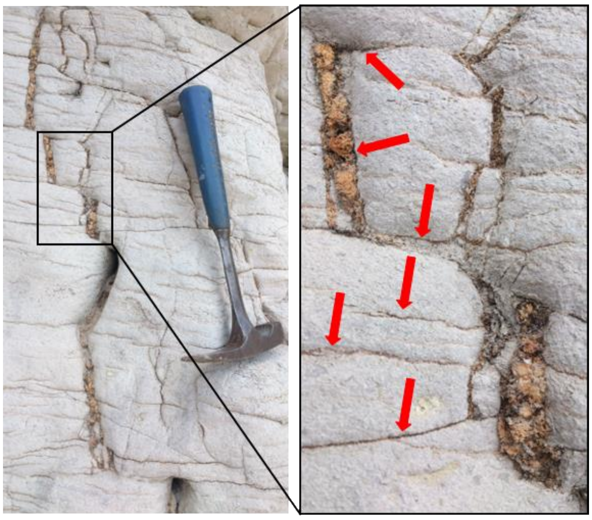

Figure 10: Illustration of the interconnexion of fractures and schistosity planes: the same red to yellow clay filling is encountered in those two kinds of discontinuities. Red arrows indicate clay deposits in schistosity planes (near-horizontal) and fractures (near-vertical).

3.2.1 Petrography by optical and SEM microscopy

Thin sections observed by optical and scanning electron microscopy, confirm the interconnection of fractures and schistosity as they contain the same clay filling (Figure 11A). In addition, schistosity also contains euhedral quartz crystals (Figure 11B) indicating that fluid flow indeed occurred in those near-horizontal planes. Both these features show that ancient fluid flow occurred both vertically and horizontally and in three dimensions of space. This allows to complete Bouchot et al. (2006) simplified scheme of fluid flow in Bouillante geothermal reservoir which indicates that propagation of fluids occurs thanks to “high-angle E-W faults”. Thanks to the outcrop studied at Tillet, we can infer from the observations that fluid flow occurs not only vertically, but also near-horizontally in a dense network of schistosity planes, from meter- to micrometer-scale.

3.2.2 X-ray tomography

X-ray tomography performed on cm-scale samples displays the features visible in Figure 12: parallel schistosity planes are linked by an open fracture, both of them crosscutting the andesite light grey matrix including altered pyroxene crystals (dark small rectangles). The focus on a pyroxene shows (in green) the unconnected porosity, very abundant in the mineral studied. When seen in 3D, the same sample shows connected porosity, unconnected porosity and clay filling in the schistosity (Figure 13).

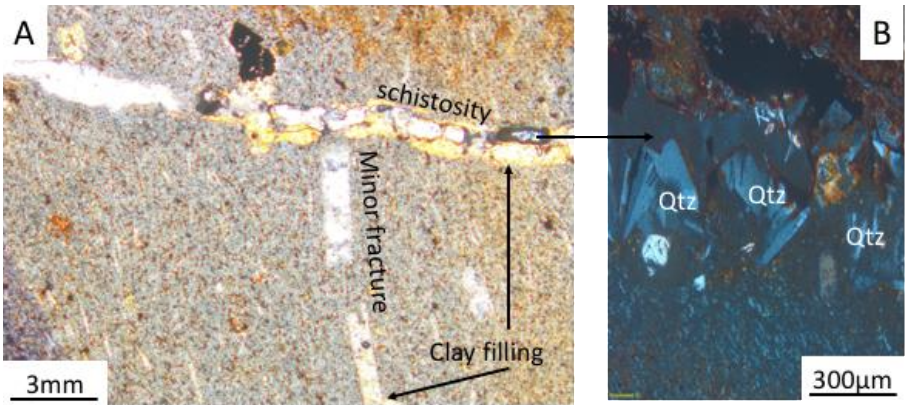

Figure 11: Relationship between schistosity and minor fracture at Tillet Creek, optical microscopy. The clay filling in both types of discontinuities is the same, as highlighted by XRD (smectite+chlorite) showing that they are interconnected. In addition, schistosity plane contains euhedral quartz (qtz; as evidenced by SEM-EDS) indicating also the circulation of hydrothermal fluids.

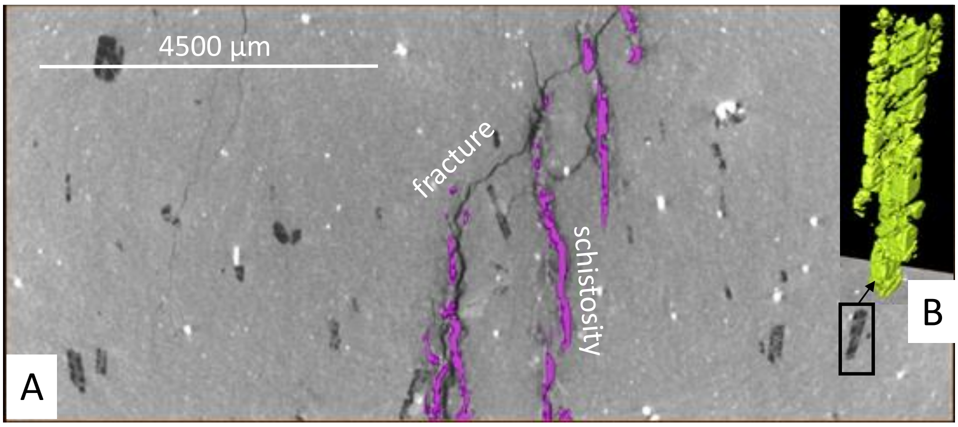

Figure 12: 2D image obtained by X-ray tomography (6µm resolution) showing schistosity planes filled with clay deposit (in prink) connected by a fracture, all of them crosscutting the light grey andesite matrix including dark grey pyroxene crystals (A). Pyroxenes are altered and more than half-dissolved: unconnected porosity appears in green (B) in a focus on a pyroxene crystal.

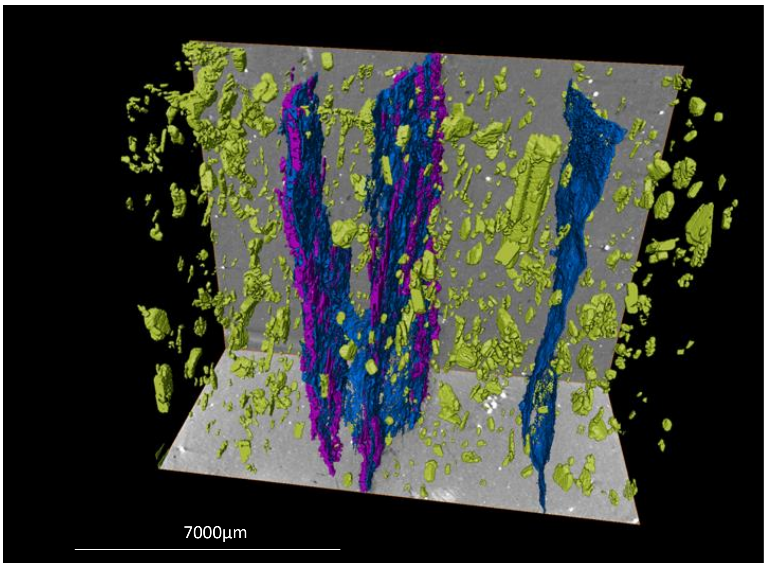

Figure 13: 3D image obtained by X-ray tomography (6µm resolution) showing connected porosity in schistosity planes (in blue), ancient connected porosity filled by clay deposit (in pink) connected by a fracture which is not visible in this view. Fracture and schistosity crosscut the matrix including altered pyroxene crystals which porosity is not connected (in green).

3.2.3 Discussion about petrography

Microscopical observations confirm the connectivity of fractures and schistosity, already observed at the outcrop scale. X-ray tomography brings a new insight at the sample scale: fractures and schistosity are clearly visible and, in addition, the unconnected porosity is highlighted and appears to be abundant.

4. CONCLUSION

Multi-scale analysis performed from the outcrop to hand-sample- and microscopic-levels shows several features: 1) the regional-scale fractures are recorded at the outcrop scale, 2) discontinuities that carried hydrothermal fluids are identified, 3) their characterization is possible (the fractal dimension of fracture network is 0.42; the surface occupied by fracture fillings is 10% of the total studied surface of outcrop), 4) fractures and schistosity show a similar partial filling with newly-formed hydrothermal minerals, 5) observations at various scales show a clear connectivity between near-vertical fractures and near-horizontal schistosity, 6) remaining porosity, both connected and unconnected, is highlighted by X-ray tomography, 7) the mineral filling shows vertical fluid transfer as already described for geothermal reservoirs in such environment (e.g. Bouillante; Bouchot et al., 2010) but also horizontal as shown by evidences of clay deposits in the schistosity planes from vertical fractures. All of the evidence indicates that fluid flow in such environments occurs (i) not only from vertical fractures as described at Bouillante, but also via horizontal discontinuities such as schistosity and likely lava flow boundaries and (ii) occur from millimetric to metric scale (and likely even more) in the 3 dimensions of space. Thus, the ground reservoir in Vieux Habitants area (ERP of the GEOTREF program), located on the western flank of La Soufrière volcano, probably drains hot rain-water thanks to both vertical and horizontal structures at a kilometric scale as it is considered as a deep analogous system of exhumed Tillet Creek.

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