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The Concept of Exhumed Analogue for Characterization of High-Energy Geothermal Reservoir: an Example from Les Saintes Island (Guadeloupe Archipelago, Lesser Antilles) and Consequences for Exploration

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ABSTRACT

The recognition of a fossil equivalent of the active geothermal system of the Basse-Terre Island in Guadeloupe archipelago (Lesser Antilles arc) in Terre-de-Haut Island (Les Saintes archipelago) allow us to better constrain the structure, the mineralogy and the petrological characters of the deep parts of an active geothermal reservoir. First, we demonstrate the occurrence, in Terre-de–Haut Island, of an exhumed analogue of the deeper parts Bouillante geothermal field. In this exhumed paleo-geothermal reservoir we characterize the nature and the P-T evolutions of the hydrothermal mineral associations in relation with fluids transfers. Moreover, high-temperature hydrothermal activity is coeval with the development of ductile tectonic structures, particularly schistose corridors, and is dated at 2.59 ± 0.12 Ma on white micas, involving maximum activity of 600 ky. These data provide a conceptual model, including brittle-ductile transition located at a depth between 2.5 and 4 km. In this way, brittle and ductile tectonic structures are efficient drains to connected vertical and lateral fluids and heat transfers. This may provide new guides for exploration of geothermal resources in volcanic arcs.

1. INTRODUCTION

GEOTREF is a multidisciplinary platform for innovation and demonstration activities for exploration and development of high geothermal energy in fractured reservoirs in the Lesser Antilles arc.

Nowadays, in this volcanic arc, the only geothermal exploitation is located at Bouillante, within the active volcanic arc of the Basse-Terre Island (Guadeloupe archipelago). A significant number of geological, structural, geochemical and geophysical data are available on the geothermal Bouillante system (Iundt & Ouzounian, 1984; Abou-Akar et al., 1992; Sanjuan & Brach, 1997; Guillou-Frottier, 2003; Mas et al., 2006; Lachassagne et al., 2009; Thinon et al., 2010; Calcagno et al., 2012; Gailler et al., 2013). They allowed to characterize the superficial part of the reservoir. Based on these data a conceptual model was proposed for this geothermal field (Bouchot et al., 2010). However, the structure, the mineralogic and petrological characters of the deep parts of this geothermal reservoir are still poorly constrained.

Deciphering the geological properties of the lowermost part of geothermal reservoirs is therefore still challenging, probably because of the high economic cost of exploratory drillings. As frequently implemented in the study of mineral and/or oil resources, an efficient alternative to address this type of issue is the study of exhumed analogues (de Launay, 1934; Beck & Lehner, 1974). Older hydrothermal systems are highlighted by the mineralogical characterization of their volcanic rocks and their hydrothermal alterations. Distribution and nature of minerals resulting from hydrothermal transformation can be used to define the volume where the activity was concentrated (Chenevoy & Piboule, 2007), and to identify stages of old hydrothermal activity as possible indicators of the current systems (Gadalia et al., 2015).

In the Lesser Antilles arc, recent studies identified a presumed exhumed paleo-system on Terre-de-Haut island of Les Saintes archipelago (Verati et al., 2016; Navelot et al., 2018). Therefore, we investigate the structural, mineralogical and chronological evolutions of this exhumed analogue of the current Bouillante geothermal reservoir in order to better define the geometry of fluid flow pathways at depth, to estimate the lifetime of the high-temperature hydrothermal activity (i.e. timescales for efficient fluids and heat transfers) and therefore to propose specific criteria for improving exploration strategy for high-enthalpy geothermal systems.

2. GEOLOGICAL CONTEXT

The 850 km-long curve Lesser Antilles volcanic arc is located at the convergent boundary between the Caribbean and the American plates (Hawkesworth & Powell, 1980; Bouysse & Westercamp, 1988), at the velocity about 2 cm/yr (DeMets et al., 2000; López et al., 2006). The present-day geothermal gradient of the Lesser Antilles arc is well established (Manga et al., 2012), and was measured within the Guadeloupe archipelago in a range between 69.3 ± 1.5 and 98.2 ± 8.8 °C/km (*Figure 1-A*).

The northern part of the magmatic arc, including the Guadeloupe archipelago, is divided into two sub-parallel ridges (Westercamp, 1979). The eastern and ancient one is formed by late Oligocene to Pleistocene carbonate platforms (Grande-Terre) while the western arc is composed of a recent chain of volcanic islands (Basse-Terre and Les Saintes) active since 5 Ma (Bouysse & Westercamp, 1990). Basse-Terre island consists of a cluster of volcanic complexes (*Figure 1-B*), with from north to south (Samper et al., 2007; Ricci et al., 2017, 2018): the oldest Basal Complex characterized by 4.28 to 2.67 Ma aged volcanism (Favier et al., submitted), the Septentrional Chain between 1.81 to 1.16 Ma, the Axial Chain active during 1.02 to 0.41 Ma, the Grande Découverte – Trois Rivières Complex (< 0.2 Ma) including the present-day active La Soufrière volcano (Boudon et al., 1987, 2008), and the Monts Caraïbes Chain built at around 0.55 - 0.47 Ma (Blanc, 1983; Ricci et al., 2017). Southeast of Basse-Terre island, Les Saintes archipelago are composed of two islands: Terre-de-Haut with 3.63 to 2.00 Ma aged volcanism and Terre-de-Bas lesser than 1 Ma (Jacques et al., 1984; Jacques & Maury, 1988; Zami et al., 2014).

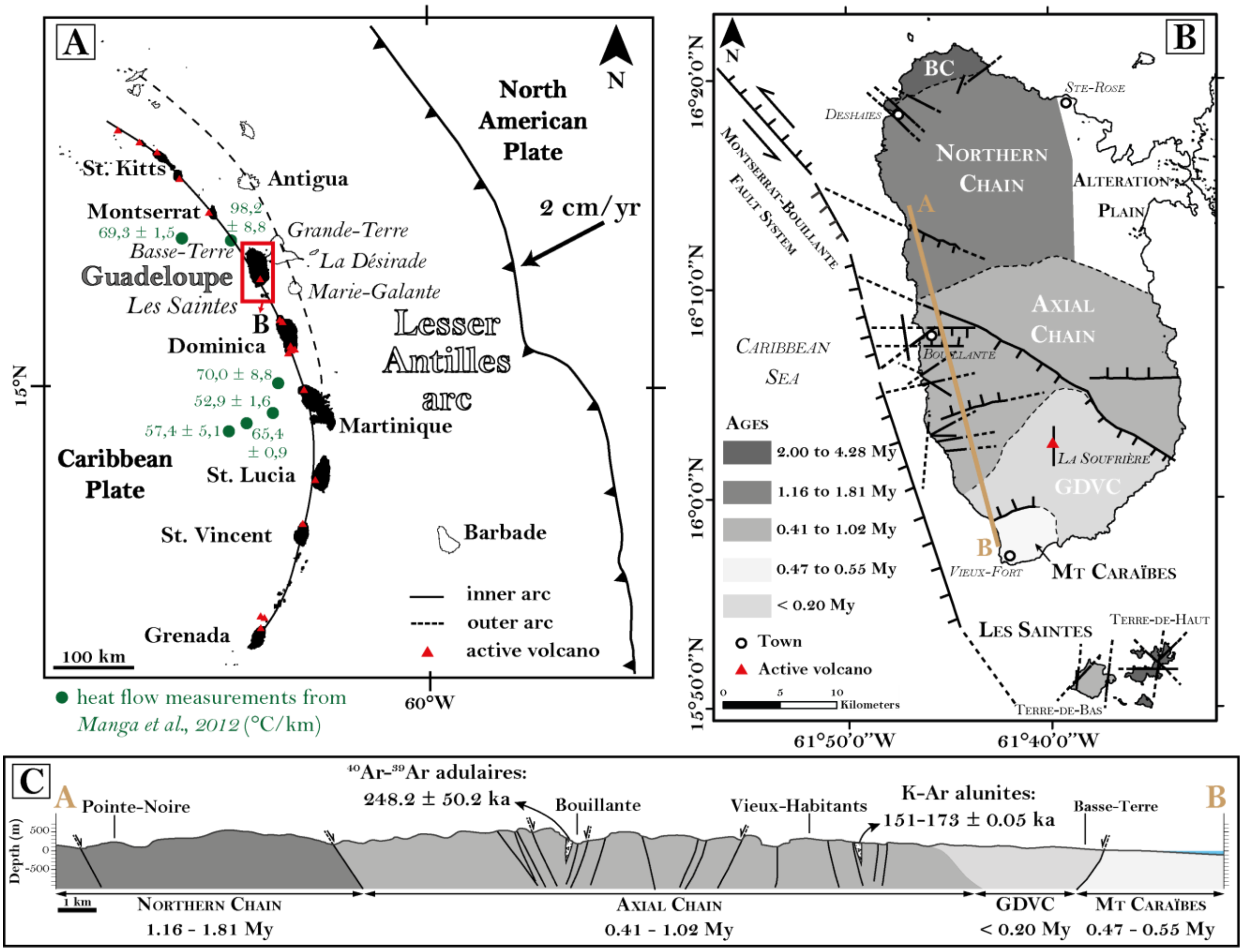

Figure 1: A) Geodynamic setting of the Lesser Antilles arc (after Feuillet et al., 2001), B) Map of the active volcanic arc in Guadeloupe archipelago (i.e. Basse-Terre and Les Saintes) displaying the different volcanic complexes and the main tectonic structures modified after Verati et al. (2018) (BC= Basal Complex, GDVC= Grande Decouverte Volcanic Complex), C) Cross-section NNW-SSE from Basse-Terre island (location in fig 1-B) displaying the spatio-temporal distribution of brittle structures, volcanic complexes and hydrothermal breccias (Ar-Ar dating from Verati et al., 2014 and K-Ar from this study).

Terre de Haut Island, the oldest volcanic complex from Les Saintes islands, is characterized by the occurrence of a highly hydrothermalized area in its central part (*Figure 2*), within which the initial magmatic structures and mineralogy have been completely erased (Jacques & Maury, 1988; Verati et al., 2016). Concidering the age of volcanic activity combined with the fact that Guadeloupe archipelago is subjected to intense weathering and erosion processes with mechanical and chemical erosion rates of around 1-2 mm/yr (Sak et al., 2010; Lloret et al., 2011; Rad et al., 2013; Dessert et al., 2015; Ricci et al., 2015a, b), the central part of this island was possibly overburden by more or less three kilometers of volcanic materials.

Regionally, in the Guadeloupe archipelago, four major directions of brittle faults have been identified: N50-N70, N90-N110, N120-N140 and N160-N10 (Feuillet et al., 2001, 2002; Thinon et al., 2010; Mathieu et al., 2011; Calcagno et al., 2012; De Min et al., 2015). These faults are generally compatible with normal faulting frequently associated to strike-slip movements, and consistent with the actual regional transtensive tectonic regime recognized in Guadeloupe. Many studies (Bouysse, 1979; Bouysse & Westercamp, 1990; Feuillet et al., 2002, 2004; Corsini et al., 2011; Lardeaux et al., 2013; De Min, 2014; Legendre, 2018; Verati et al., 2018; Favier et al., submitted) have emphasized the importance of the structural heritage, thus tectonic reactivation, on the present-day active finite deformation pattern.

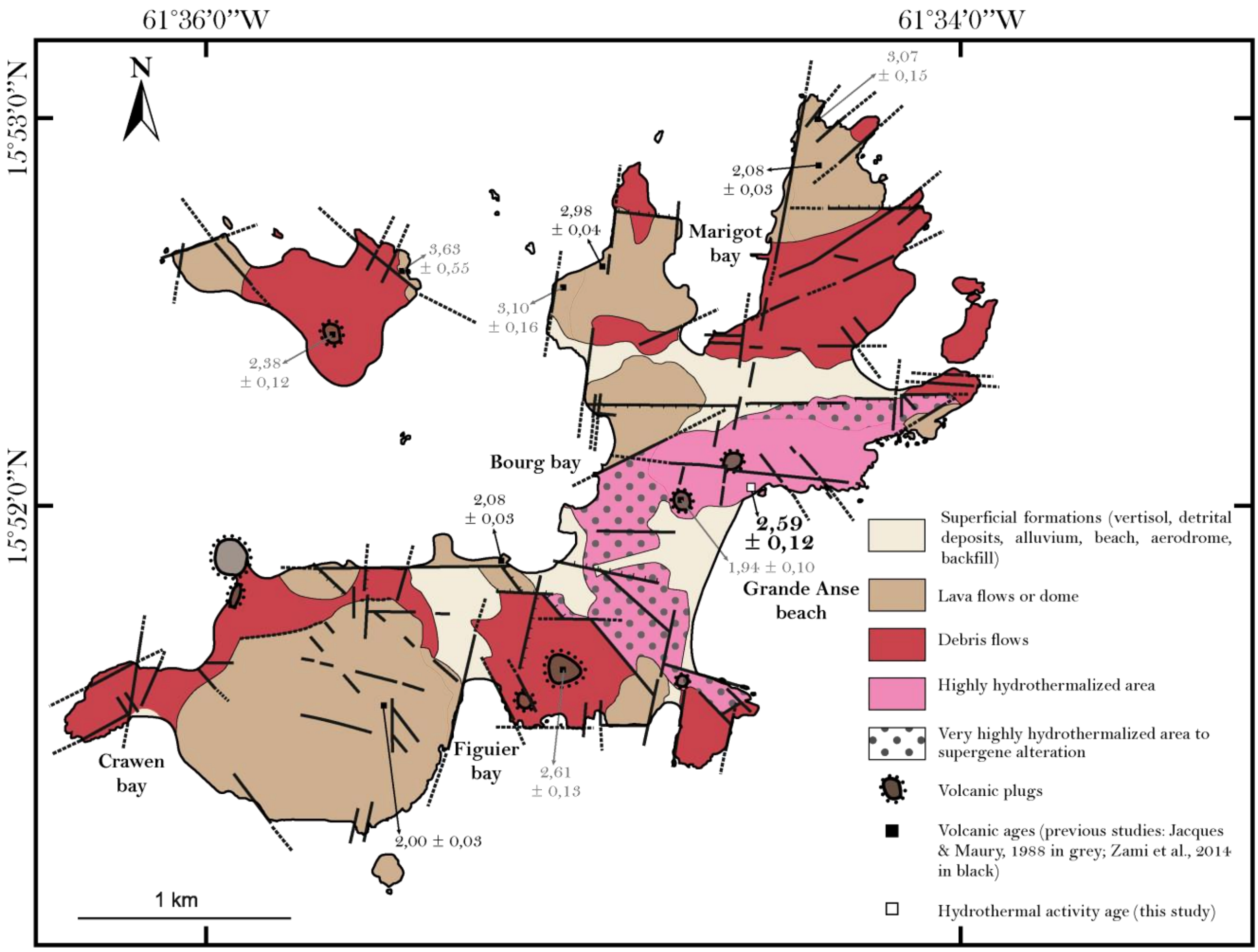

Figure 2: Simplified geological map of Terre-de-Haut island where the main faults observed are reported (after Jacques et al., 1984, Jacques & Maury, 1988, Verati et al., 2016 and Navelot et al., 2018).

3. GEOTHERMAL FRAMEWORK IN BASSE-TERRE ISLAND: STATE OF THE ART AND INPUT OF NEW CHRONOLOGICAL DATA

A geothermal field is identified since the 1970s in Bouillante bay (Cormy et al., 1970; Demians d'Archimbaud & Munier-Jolain, 1976; Demians d'Archimbaud & Surcin, 1976) and defined as a high-energy geothermal system favorable for electricity production.

Surficial indicators of recent to present geothermal activity are present around Bouillante by the occurrence of hydrothermal breccia. Petrographic investigations have described high-temperature mineral associations (>200°C, Patrier et al., 2013). More specifically K-rich minerals, particularly adularia, were identified and dated by $^{40}Ar/^{39}Ar$ geochronology at 248.2 ± 50.2 ka (2σ, Verati et al., 2014). Interestingly, the active Bouillante geothermal field is located at an intersection between three main tectonic structures of the Bouillante chain (Calcagno et al., 2015). Furthermore, the age of the geothermal mineralogy is consistent with the age of the active Grande-Découverte–Soufrière volcanic system and not with the age of the Bouillante volcanic chain (included in the Axial chain, Figures 1-B and C).

Recently, near Vieux-Habitants, we identified new hydrothermal breccias composed of K-rich minerals, in this case mainly alunites. Here also, hydrothermal breccias are located at faults intersections (*Figures 1-B and C*). We studied alunites using K-Ar geochronology and we obtained ages, for hydrothermal activity between 151 and 173 ± 0.05 ka (2σ). Once again these results are in agreement with the volcanic activity of the active Grande-Découverte–Soufrière system (circa 200 ka to present day).

For volcanic geothermal systems, the nature of K-rich minerals recognized within hydrothermal breccias is characteristic of the sulfidation level of the epithermal system (Heald et al., 1987). In addition, the identification of these epithermal mineral deposits can be interpreted as the fossil equivalents of geothermal systems, and methods developed for mineral exploration methods can be applied to geothermal exploration (Bogie & Lawless, 2000). Alunites are typically developed in high-sulfidation acid-sulfate bearing epithermal systems. On the other hand, adularias are typical for low-sulfidation adularia-sericite bearing epithermal system consistent with a reduced environment. Altogether, these new data allow us to interpret the Basse-Terre active geothermal field as a distal epithermal system. If true, this interpretation implies fluids and heat lateral transfers and drastically change the exploration strategy in this area. It is therefore critical to evidence the physical pathways allowing lateral transfers. A key target to address this question is the potential exhumed paleo-geothermal reservoir exposed in the hydrothermal system of Terre-de-Haut (Les Saintes archipelago).

4. STRUCTURAL AND MINERALOGICAL ANALYSIS IN TERRE-DE-HAUT EXHUMED ANALOGUE

Detailed structural, geochemical and petrological analysis (bulk-rock geochemistry, mineralogical analyses, thermodynamic modeling) were carried out on the hydrothermalized area of Terre-de-Haut. Among the main results obtained:

4.1 Brittle Structures

Recent studies have clearly established the main characteristics of the finite brittle field on Terre de Haut Island (Verati et al., 2016; Navelot et al., 2018). The faults are usually strongly dipping, and mostly compatible with normal fault developments frequently associated to strike-slip movements. Four main statistical structural directions of fault networks orientations have been identified (*Figure 2*): N000-N020, N050-N070, N090-N110 and N130-N140 trending fault systems (Verati et al., 2016).

4.2 Ductile Finite Strain Pattern

However, for the first time in this island, we discovered also the occurrence of ductile tectonic structures, particularly schistose zones. At both local and map scales, the schistosity planes are heterogeneously distributed and concentrated in plurimetric schistose corridors. The schistosity planes display variable dips (from 90 to 10°), but are more likely slightly dipping.

Four directions of schistose corridors have been observed and measured in the field: (1) N030-N060, (2) N120-N150, (3) N080-N110, and (4) N160-N020, from the oldest to the youngest ones. This relative chronology is based on geometrical criteria (intersections, superimposed structures …) visible at the map scale (*Figure 3-A*).

At the outcrop-scale, the geometry of the schistosity planes corresponds to spaced disjunctive cleavages (Powell, 1979; Beach, 1982; Passchier & Trouw, 2005; *Figure 3-B*). In thin-section, the processes of schistosity formation correspond to pressure-solution mechanisms (Rutter, 1976; Beach, 1979), and these planes are clearly underlined by high-temperature hydrothermal mineral associations.

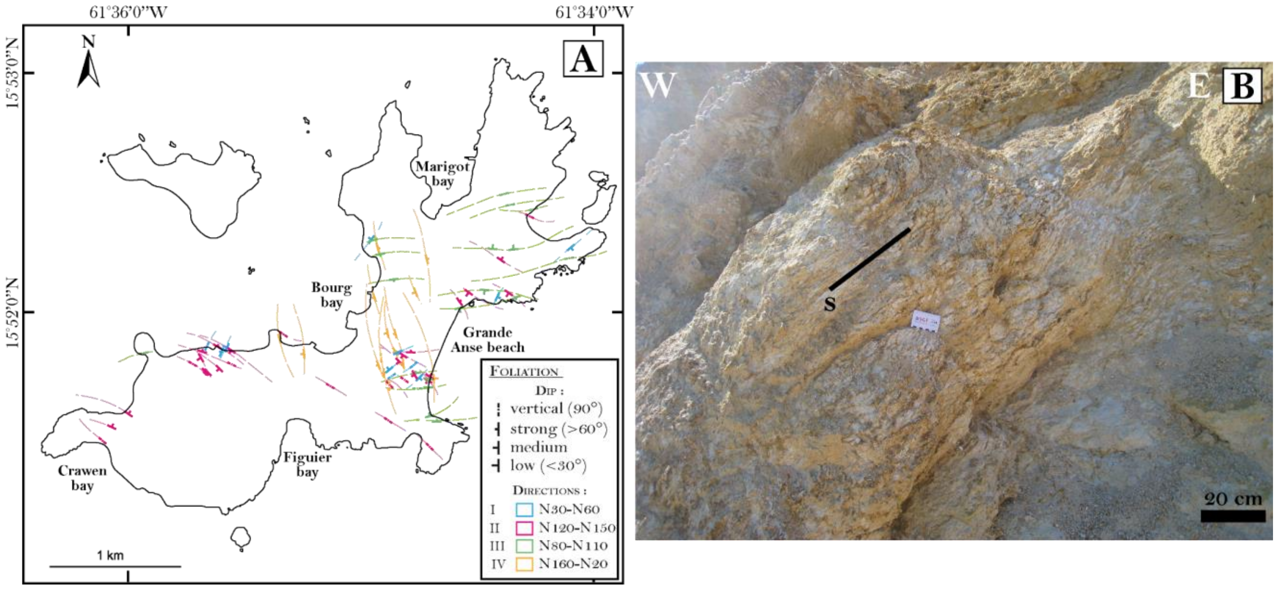

Figure 3: A) Map of schistosity trajectories on the Terre-de-Haut island, B) Meta-rhyodacite lava flow, present in the North of Grande-Anse beach belonging to the highly hydrothermalized area, deformed with schistosity plane (s).

4.3 Mineralogical and Petrographical Investigations

Volcanic rocks are partially to totally transformed and primary ferromagnesian volcanic phases are mainly pseudomorphosed by secondary minerals (*Figures 4-A and -B*) like chlorite, muscovite, illite, biotite, epidote, quartz, actinolite, titanite, calcite (*Figures 4-C and -D*) . Moreover, the observed mineral associations as well as the microstructures of the reaction sites (i.e. progressive and/or complete replacement of pyroxenes by new mineral phases) are similar to the ones described in hydrothermal rocks from the Bouillante wells (Mas et al., 2006). These types of reactions and microstructures also characterize the mineralogy observed in epi- to mesothermal systems, which are frequently compared to geothermal systems (Henley & Ellis, 1983; Rancon, 1983; Reyes, 1990; White & Hedenquist, 1995; Bouchot & Genter, 2009; Lagat, 2009, 2014).

4.4 P-T Conditions for Hydrothermalism

Chlorite is stable over a wide temperature range in geothermal systems (< 100°C to > 350°C, Henley & Ellis, 1983; Reyes, 1990; White & Hedenquist, 1995; Lagat, 2009, 2014). We have identified several stages for chlorite crystallization, and we investigated their temperature of formation with various chlorite thermometers (Cathelineau, 1988; Lanari et al., 2014; Bourdelle & Cathelineau, 2015). Grey automorphous chlorites, associated with muscovite, and developed at the expense of magmatic pyroxenes (*Figure 4-D*) yielded temperatures between 290 and 380°C. With the green-grey to yellow fibrous chlorite grains (*Figure 4-C*) in equilibrium with quartz, epidote, muscovite and illite we obtained temperatures between 110 and 250°C.

On the sample containing high-temperature chlorites, we performed a thermodynamic modelling with a free energy minimization program Theriak-Domino. For this specific single bulk-rock composition and with H_2O considered in excess (to be consistent with the conditions of a fluid-saturated hydrothermal system), we calculate a phase diagram revealing the various stability fields of the different equilibrium mineral assemblages. This enabled us to define a domain where our mineralogical assemblage (albite + chlorite + muscovite + biotite + clinozoisite + epidote s.s. + quartz) is stable, in this case between 360-380°C and 0.9-1.4 kbar. This result is in excellent agreement with chlorite geothermometry.

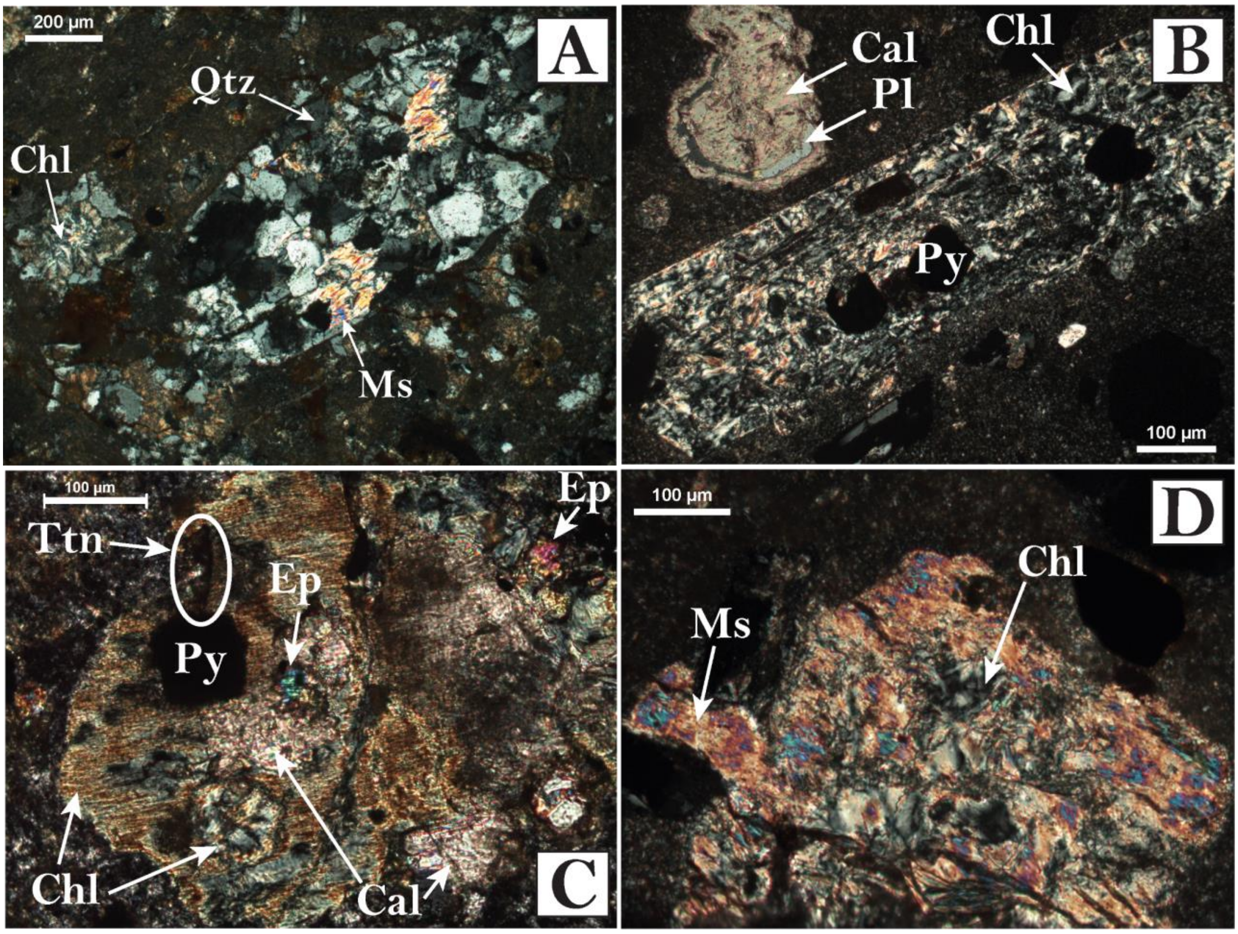

Figure 4: High-temperature hydrothermal transformations (Cal = calcite, Chl = chlortite, Ep = epidote, Ms = muscovite, Pl = plagioclase, Py = pyrite, Qtz = quartz, Ttn = titanite)

4.5 $^{40}Ar/^{39}Ar$ Dating High-Temperature Hydrothermalism

We have been successful in separating a high-temperature K-rich neoformed phase with white micas in pseudomorphosed volcanic pyroxenes. Our $^{40}Ar/^{39}Ar$ investigations yield an age for high-temperature hydrothermal activity at 2.59 ± 0.12 Ma (2σ). By comparing this result with the volcanic activity previously dated at Terre-de-Haut (Figure 2), we constrained the duration of the high-temperature hydrothermal activity at a maximum of 600 ky. Previously the activity was estimated at a maximal timescale of about 400 ky by Verati et al. (2016). Considering the few geochronological investigations available on active geothermal fields, the proposed timescales range from less than a million to only a few thousand years ago (Faure, 1986; Deloule & Turcotte, 1989; Nakai et al., 1993; review in Barnes, 1997). This new assessment is still consistent with previous studies, for example in the Taupo volcanic zone with a duration of at least 200 ky (review in Rowland & Sibson, 2004) or the timing of the geothermal activity proposed for the Bouillante geothermal field (Verati et al., 2014).

5. A CONCEPTUEL MODEL FOR LOWERMOST PART OF THE GEOTHERMAL RESERVOIR AND CONSEQUENCES FOR EXPLORATION

The structural heritage is a key factor in the fluid flows, both from a tectonic (ductile to brittle deformation) and volcanic (magmatic fluidality and lithological interfaces; Navelot et al., 2018) perspective. In addition to herited volcanic structures (magmatic fluidality and lithological interfaces; Navelot et al., 2018) and superposed brittle faults, the observed ductile finite structural pattern is particularly favourable to both vertical and lateral fluid transfers. Because schistose corridors are clearly geometrically connected, these tectonic structures constitute efficient vertical and lateral drains for hydrothermal fluid circulation.

In the Guadeloupe archipelago, the regional standard conductive geothermal gradient has been calculated between 69.3 ± 1.5 and 98.2 ± 8.8 °C/km (Manga et al., 2012). Recent study has demonstrated the same order of paleo-conductive gradient in the Basal Complex (Verati et al., 2018; Favier et al., submitted). In the Bouillante geothermal field, temperatures in the range of 230- 255°C are measured at depths between 475 m and 1,2 km (Guillou-Frottier, 2003; Bouchot et al., 2010). In the highly-hydrothermalized zone from Terre de Haut island, we discovered the occurrence of high-temperature hydrothermal mineral parageneses stable under a temperature range between 360 and 380°C and very low-pressure conditions, thus consistent with a paleo-gradient in range of 90 and 140°C/km. This result represents a significant deviation with respect to the value of the regional standard conductive geothermal gradient but is compatible with ranges of temperature measured in drillings in different geothermal fields around the world (Browne, 1978; Del Moro et al., 1982; Battaglia et al., 1991; Mas et al., 2006; Bogie et al., 2008).

The occurrences of mineralogical records of high temperature fluids circulations, of abnormally high geothermal conditions and of connected lateral and vertical structural drains for fluids and heat transfers demonstrate that Terre de Haut hydrothermal domain constitutes an eroded, and thus exhumed, paleo-geothermal reservoir. The latter can be used as an analogue of the deepest parts of active geothermal systems in Basse-Terre Island and thus can be used to better constrain its operative modes.

The calculated P-T conditions for high-temperature hydrothermal mineral associations combined with ages of volcanic formations and regional erosion rates allow us to restore the depth of the lowermost part of the Terre-de-Haut paleo-reservoir at around 2.5km.

Close to the surface, and thus on the upper part of the reservoir, the volcanic structures (lithological interfaces, fluidality, prismation) and the variations in petrophysical rock properties are important components of the fluid flow process (see discussion in Navelot et al., 2018). Faults also contribute to fluid-flow through the recharge of supergene fluids (meteoric water and seawater, Millot et al., 2010) in the geothermal system, leading the development of convective cells in the range of 500m and 2.5km in the geothermal reservoir. At a depth of 2.5 or 3 km, corresponding to the lowermost domain of the reservoir, anastomosed schistose corridors become efficient drains for both vertical and lateral fluid circulations.

Altogether, these data can be combined to propose a conceptual model for the deep part of Basse-Terre island active system (*Figure 5*), with a brittle-ductile transition located at a depth between 2.5 and 4 km. In this model the structural ductile and brittle patterns offer efficient pathways for vertical and lateral fluids transfers and thus for convective cells development. In this perspective, the exploration for the regional geothermal resource in the Lesser Antilles arc must take into account both vertical and horizontal fluid and heat transfers in the framework of distal epithermal systems. This underlines also the interest of studying exhumed paleo-reservoirs, in order to better understand the structures and the thermodynamics of fluids-rocks interactions in geothermal fields.

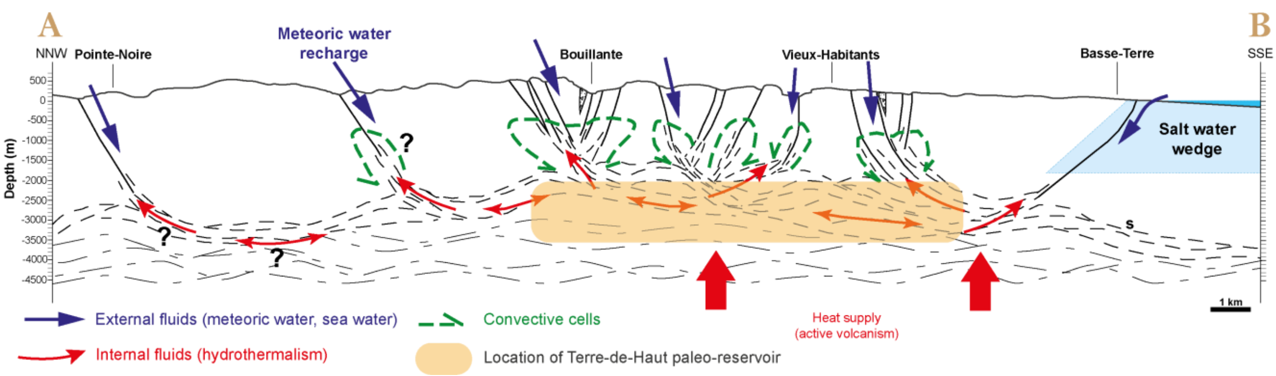

Figure 5: Conceptual model for the deeper part of the Basse-Terre island geothermal reservoir (s: schistosity). Cross-section is located in figure 1-B.

6. CONCLUSIONS

- Terre de Haut Island (Les Saintes archipelago) is a key target to identify an exhumed analogue of a paleo-geothermal reservoir,

- In such an analogue, we recognize structural drains for both vertical and lateral fluid and heat transfers,

- In the Lesser Antilles arc, the brittle-ductile transition is located at depths between 2.5 and 4 km and must be regarded as an efficient horizon for hot fluids circulation,

- With respect to information deduced from surface indices, the geothermal resource in Guadeloupe is potentially more important than previously suggested,

- In geothermal high-enthalpy systems, the occurrence of ductile schistose corridors must be taken into account as a new guide for resource exploration.

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