GEOTREF: a multidisciplinary innovation and demonstration platform for the exploration and development of high geothermal energy in fractured reservoirs

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General Overview

GEOTREF is a project aimed at improving the understanding of fractured geothermal reservoirs functioning. "Geological risk" will to be reduced, on the one hand, by optimizing exploration costs, by providing a geological reservoir model; on the other hand a sustainable exploitation of the reservoir must be guaranteed during the production phase, by providing a dynamic exchanger model. GEOTREF is an innovative and complete tool, committed to excellence, and fostering industrial development; it therefore is supported by the French state through the "Investments for the Future" financing program.

The project was split into two phases: 1. Research & Development, 2. Experimentation & Demonstration. It brings together three French private companies (Teranov, Kidova and Magnitude) and nine French world-renowned laboratories which are either research organizations or universities (Mines Paristech, ENS Paris, GeoAzur, GeoRessources, IMFT, IPGS, LHyGes, UA, and GEC).

GEOTREF's ambition is to take up a series of technical challenges:

- Devise innovative methods and tools for the study, modelling and integration of all type of available data relating to fractured reservoirs on an unique software platform
- Develop skills and synergies on all methodologic aspects of reservoir modelling, by improving or complementing in-use tools and methods for petroleum exploration/exploitation, adapting them to the geothermal context.
- Apply these methods and tools on the Vieux-Habitants site, in Guadeloupe (French Lesser Antilles, Caribbean) which is potentially conducive to geothermal exploitation.

Among the direct expected results:

- IT tools dedicated to geothermal reservoirs study, from the exploration to the exploitation phase
- technologic leadership in a strategic activity area, promising for future development
- Identification and characterization of geothermal resource in Guadeloupe on the most promising sites in terms of electrical production (Vieux-Habitants).

Geothermal power generation market is currently a booming sector: according to an ADEME recent study, the world market of high-temperature geothermal energy is estimated at 3 to 4 b€/year for the next 10 years. In this context, all the innovation brought by the GEOTREF project will act as a beacon in the development of the French geothermal branch. They will attest of the French know-how and technologic leadership with a worldwide outreach or more specifically in the Caribbean and Latin America - some very attractive markets which are close to the project.

In order to achieve the project's goal of excellence in research, several doctoral & post-doctoral positions have been opened, in various fields. These include geology, petrography, geophysics, geochemistry, reservoir modelling…

Study zone and geological context

Basse-Terre Island is the western part of the Guadeloupe archipelago in the Lesser Antilles.

The GEOTREF study zone is centered on the Vieux-Habitants town on the western coast of Basse-Terre. It begins 5 km in the south of Bouillante town where a high-temperature (260°C) geothermal field has been identified in the 1970's (Bouchot et al. 2010). This geothermal field is exploited since 1985 for electricity generation. Now, the geothermal plant covers approximately 7% of the electrical needs of La Guadeloupe.

The Lesser Antilles arc is an 850 km long volcanic arc convex to the east between the Atlantic Ocean and the Caribbean Sea (Figure 1). The Guadeloupe archipelago is more precisely

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located on the northeastern edge of the Caribbean plate where the Atlantic plate subducts under the Caribbean plate at a rate of around 20 mm/yr (DeMets et al., 2000).

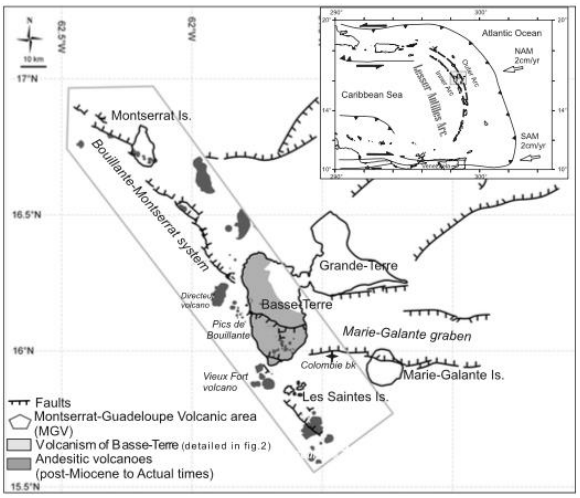


Figure 1: Regional framework of the Guadeloupe archipelago [Thinon et al., 2010].

Basse-Terre is a late Tertiary to Quaternary still active volcanic island that belongs to the Inner Arc of the Lesser Antilles. It consists in six major eruptive complexes that are successively emplaced from north to south according to a NNW-SSE direction (Figure 2):

- The Basal Complex (3-2 My)
- The Northern Volcanic Chain (1.8-1.1 My)
- The Axial Chain (1.25-0.45 My)
- The Bouillante Chain (850-250 ky)
- The Monts Caraïbes Complex (500-400 ky)
- The Trois Rivières-Madeleine eruptive field (<100 ky)
- The Grande Découverte-Soufrière system (250 ky-present)

Due to the oblique convergence between the Caribbean and the North American plates, the Guadeloupe archipelago is an area of trench-parallel extension (Feuillet et al., 2002). Three major fault directions (N130°E ± 10°, N40°E ± 10° and N90°E ± 10°) have been identified and are still active.

The Bouillante geothermal field is located at the junction between the NNW-SSE trending Montserrat-Bouillante sinistral transtensional fault system and the E-W to NW-SE network of steeply dipping normal faults belonging to the western part of the Marie-Galante graben (Verati et al., 2013).

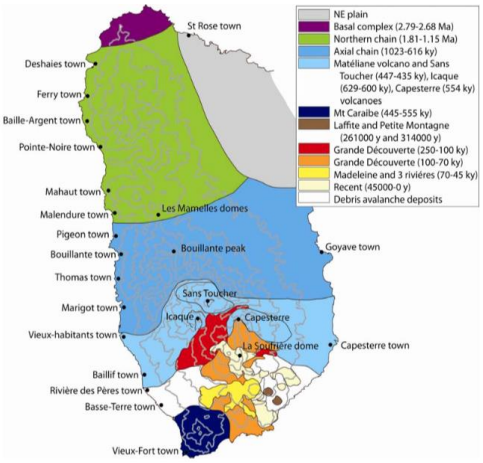
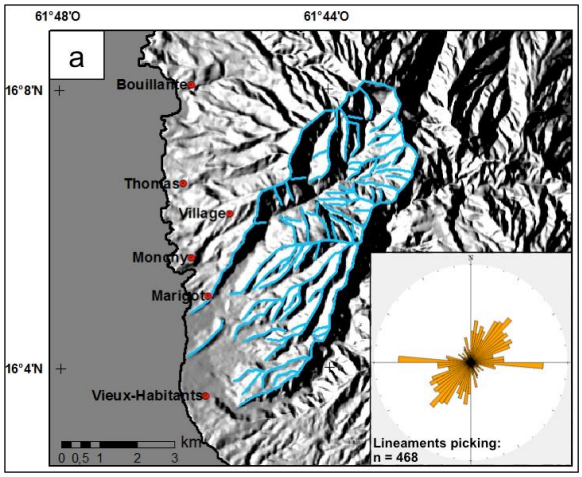


Figure 2: Major eruptive complexes of Basse-Terre island (Mathieu, 2010), ages after Samper et al., 2007)

Geological study

The objectives of the geological study can be separated into four main challenges:

- Understand the large-scale structural context of the Basse-Terre Island using morphological and tectonics analysis to better constrain the formation and location of the geothermal reservoir.



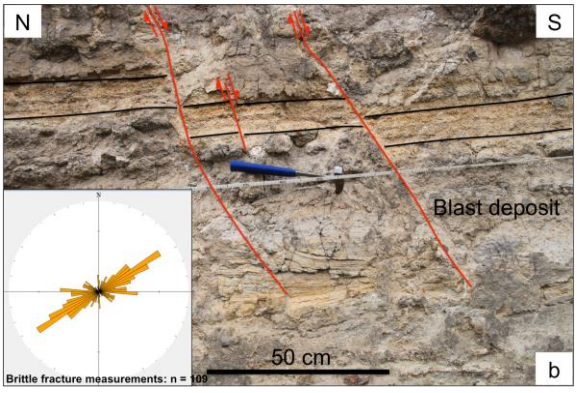


Figure 3: a) Lineaments picking in the Vieux-Habitants system and corresponding density distribution. b) Fractures measurements on an outcrop consisting of blast deposit in Monchy.

Picking of lineaments on aerial photography and digital elevation model permitted to isolate major structural directions N90°E ± 10°, N50°E ± 10° and N00 ± 10° which were confirmed by several scanlines (Figure 3). With the exception of the absence of the N130°E ± 10° family, these directions fall in the same groups previously identified on offshore seismic acquisition (Thinon et al, 2010) or on field (Feuillet et al., 2002).

- Establish a new geological map of the study zone to replace the obsolete one. Study the relation between every facies and improve the geological model doing an evaluation of the lateral and vertical extensions of facies thanks to analogs.

- Quantify petrophysical properties (thermal conductivity, P and S-wave velocity, porosity, permeability and resistivity) of all facies composing field analogs on outcrops and in laboratory to determine which facies is a good reservoir or a cap rock and which one is a pathway for fluids. This data will be provided to modelers to build the flow model and useful to do a comparison with borehole data.

Petrophysical properties of volcanic rocks in Guadeloupe are poorly known. The textures of facies are very heterogeneous with lahar deposit, debris flow, lava flow, pyroclastites, scoria cone projections, ash and pumice, (Figure 4) even if the composition of rocks is relatively similar to an andesitic composition. In addition to an anisotropy of properties due to the deposit condition (explosive volcanism), it can exist several orders of magnitude in permeability between the different facies.

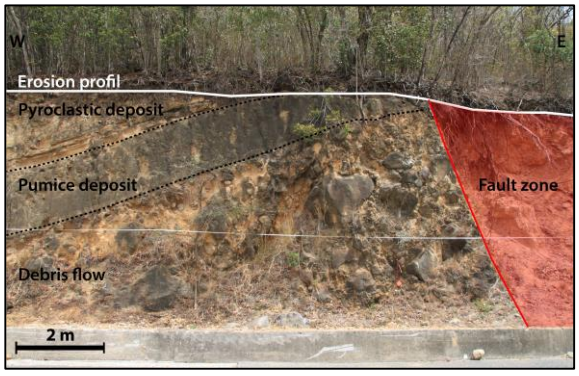


Figure 4: Example of the textural heterogeneity between the different volcano sedimentary deposits at the Malendure Pointe.

- Build a geological model that gathers all information of the previous objectives.

Geophysical study

Beside the outcrop analysis, geophysical data interpretations are used to determine the internal structure of the interest zone and of the reservoir at many different scales.

Various type of data are to be acquired and processed for GEOTREF but our working group is mainly specialized in non-seismic geophysics.

During the recent field work (June 2015), we acquired on-site preliminary magnetic data, in order to better understand the sources of magnetic anomalies in Basse-Terre. This was done using a compact mono-sensor system developed in-house. It is composed of a small electronics housing, a three-component Bartington fluxgate magnetometer, and a basic GNSS system (5 m accuracy). The magnetometer was attached to a wooden pole to make the acquisition easier. Obviously, the quality of the measurements highly depends on the acquisition context: magnetic noise is mostly due to the proximity of human activity (electrical installations, roads). However, using a calibration method adapted to the acquisition system (Munschy et al., 2007) we are able to achieve a mean 25 nT accuracy in Basse-Terre's noisy contexts.

Meter-scaled profiles were acquired over characteristic lithological contacts in the different geological systems of Basse-Terre, in order to measure their magnetic response. This type of measurement can be done in many different contexts (vertical, horizontal, roof acquisition) depending on the geometry of the geological outcrops.

The strongest magnetic variations we observed occurred when andesitic rocks and volcano-sedimentary rocks such as pyroclastites, tuffs or debris flow meet. The amplitude of these anomalies can go up to 500 nT. Andesites are indeed strongly magnetized rocks whereas volcano-sedimentary rocks show little magnetization.

Andesites transformed by hydrothermal activity also seem to have a decreased magnetization because we get a significant contrast of 50 to 200 nT between them and massive andesites, depending on the size of the altered veins (Anse à la Perle results).

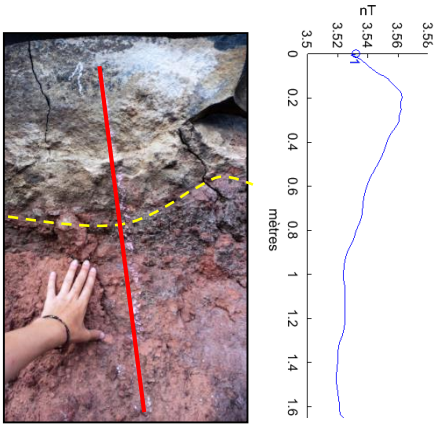


Figure 5: Left: photography of a contact between a massive andesite (gray rock on top) and a pyroclastic flow (redish rock on the bottom), in Anse à Thomas. The acquired profile is indicated by a red line whereas the dotted yellow line roughly outlines the contact. Right: resulting magnetic profile in nT/m.

We also acquired longer profiles (40 to 50 meters) along visible geological structures such as the Malendure's fault. In this case we get a noticeable magnetic contrast of about 500 nT between pumices and volcanic ash as well as between pumices and the debris flow layer.

This preliminary study allows us to better apprehend the sources of anomalies during the study of larger scale magnetic maps. Such maps can be created thanks to data coming from different sources. In 2013, the SkyTEM company, under the auspices of BRGM, carried out an airborne geophysical survey over Guadeloupe islands, including TEM measurements and magnetism (GuadEM survey) [Deparis et al., 2013].

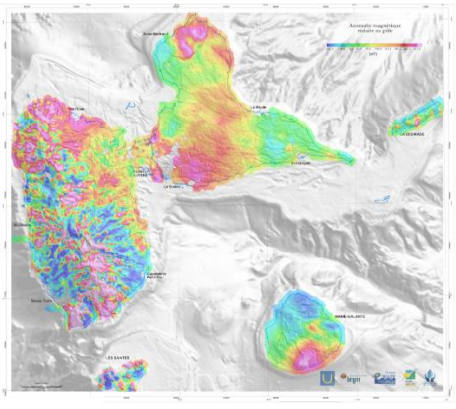


Figure 6: Reduced to pole magnetic anomaly map of the GuadEM survey. Figure from (Deparis et al., 2013).

Offshore, the University of Antilles within the Geotref project conducted a marine geophysical survey of Basse-Terre's coasts. It included high resolution seismics, as well as bathymetric and magnetic measurements. Marine maps will be completed by NGDC and Ifremer data in order to also study magnetic signals at the scale of the Caribbean.

References

Bouchot, V., Sanjuan, B., Traineau, H., Guillou-Frottier, L., Thinon, I., Baltassat, J.-M., Fabriol, H., Bourgeois, B., and Lasne, E., Assessment of the Bouillante Geothermal Field (Guadeloupe, French West Indies): Toward a Conceptual Model of the High Temperature Geothermal System, *in* Proceedings World Geothermal Congress 2010, Bali, 2010.

DeMets C., Jansma P. E., Mattioli G. S., Dixon T. H., Farina F., Bilham R., Calais E., and Mann P., GPS geodetic constraints on Caribbean-North America plate motion, Geophysical Research Letters, **27**, no. 3, pp. 437-440, 2000.

Deparis J., Reninger P. A., Perrin J., Marthelet G., Monpelat J.-M., and Legendre Y., Heliborne electromagnetic and magnetic measurement campaign (GUADEM), BRGM, RP-62704-FR, 2014.

Feuillet N., Manighetti I., Taponnier P., and Jacques E., Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles, Journal of Geophysical Research, **107**, 2331, 2002

Mathieu L., The structure of Guadeloupe, Malderas and Mt Cameroon volcanoes and the impact of strike-slip movements, PhD Thesis, Université Blaise Pascal Clermond Ferrand II, Trinity College Dublin, pp. 9-59, 2010

Munschy M., Boulanger D., Ulrich P., and Bouiflane M., Magnetic mapping for the detection and characterization of UXO: Use of multi-sensor fluxgate 3-axis magnetometers and methods of interpretation, Journal Applied Geophysics, **61**, no. 3–4, pp. 168–183, 2007.

Thinon I., Guennoc P., Bitri A., and Truffert C., Study of the Bouillante Bay (West Basse-Terre Island shelf): contribution of geophysical surveys to the understanding of the structural context of Guadeloupe (French West Indies - Lesser Antilles), Bulletin de la Société Géologique de France, **181**, no. 1, pp. 51–65, 2010.

Samper A., Quidelleur X., Lahitte P., and Mollex D., Timing of effusive volcanism and collapse events within an oceanic arc island: Basse-Terre, Guadeloupe Archipelago (Lesser Antilles arc), Earth and Planetary Science Letters, **258**, pp. 175-191, 2007.

Thinon I., Guennoc P., Bitri A., and Truffert C., Study of the Bouillante Bay (West Basse-Terre Island shelf): contribution of geophysical surveys to the understanding of the structural context of Guadeloupe (French West Indies - Lesser Antilles), Bulletin de la Société Géologique de France, **181**, no. 1, pp. 51-65, 2010.

Verati C., Patrier-Mas P., Lardeaux J. M., and Bouchot V., Timing of geothermal activity in an active island-arc volcanic setting: First $^{40}Ar/^{39}Ar$ dating from Bouillante geothermal field (Guadeloupe, French West Indies), The Geological Society of London, **378**, pp. 285-295, 2013.