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3D Fault Model of the Bouillante Geothermal Province Interpreted from Onshore and Offshore Structural Knowledge (French West Indies)

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ABSTRACT

The Bouillante area is known for its high-temperature geothermal field which produce electricity in a 15 MWe installed power plant (Guadeloupe Island, French West Indies). This zone is a complex geodynamic area. It stands at the convergence of the major tectonic and volcanic structures of the inner arc of the Lesser Antilles. The two main regional fault systems joining at the Bouillante geothermal field are the NW–SE Montserrat–Bouillante (MB) fault system, and the ESE–WNW to E–W Bouillante–Capesterre (BC) fault system.

Two other factors make rather difficult the interpretation of the geological structuration. Firstly, Bouillante is located on the West coast of the Guadeloupe Island. It means that data and observations both from the Island and from the sea are needed. Secondly, a wet tropical climate prevails in that region. That is why exposures suitable for direct structural measurements are almost only found on the seaside where coastal erosion has stripped away the soil.

The available data show that, on one hand, faults observed on the field mainly elongate along the E-W direction. On the other hand, offshore structures interpreted from marine seismic lines show a larger range of directions. In order to achieve a coherent interpretation of the Bouillante geothermal area, a 3D fault model is completed from onshore and offshore structural knowledge. A 15 km x 16 km zone crossing the island coastline is investigated down to 2 km depth.

The fault network constructed reveals a hierarchy in the family of structures and highlights the prevalence of the NNW-SSE direction, associated with secondary NE-SW-trending structures, and the E-W direction. On a geographical point of view, the modelled faults are gathered in 3 clusters along the coast. The 3D model facilitates a coherent interpretation of the faults in the Bouillante province but this model can also be a cradle for hydro dynamic simulation.

1. INTRODUCTION

The Bouillante geothermal province area is located in the French West Indies, on the West of the Guadeloupe Basse-Terre Island (Fig. 1). That zone is known for its high-temperature geothermal field (e.g. Bouchot et al., 2010) which produce electricity at the 15 MWe installed power plant in Bouillante (Fig. 1b). Our study aims at better understand the fault structuration of the Bouillante geothermal province. This is a prerequisite for a better knowledge of the Bouillante geothermal field understanding. At the scale of the geothermal province, onshore and offshore data are required to interpret in a coherent way the faults in the area because of its location both inland and at sea. Previous works aimed at describing the structural geology on land (e.g. Mathieu, 2010) and at sea (e.g. Thinon et al., 2010). We propose to merge data and knowledge from field work and from marine exploration to produce a model in 3 dimensions representing the faults down to 2 km depth at the scale of the 250 km² Bouillante geothermal province.

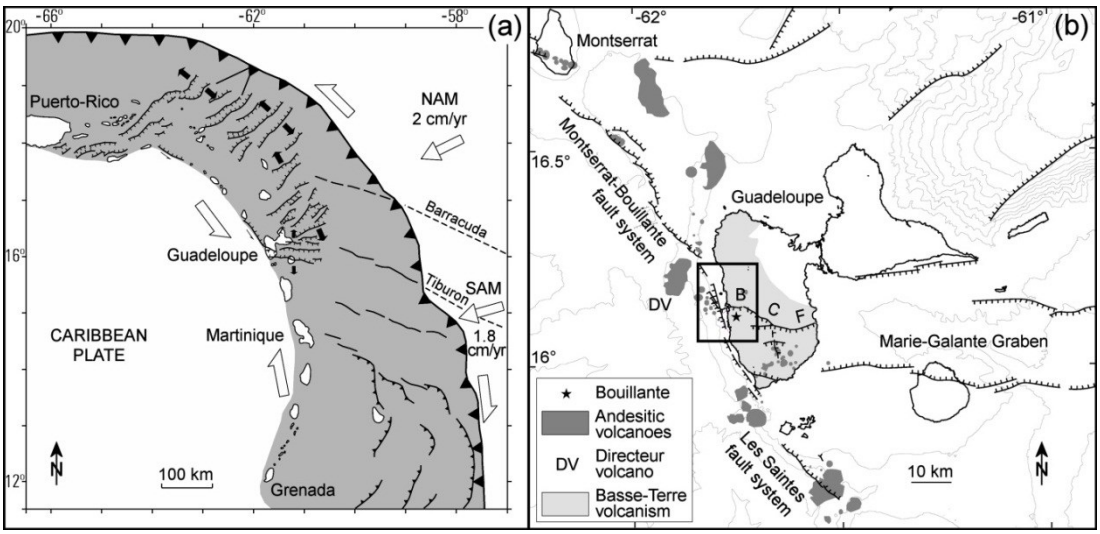


Figure 1: (a) Geodynamic context of the West Indies (modified from Feuillet et al., 2002). NAM: North American plate. SAM: South American plate. (b) Regional structural setting of the Guadeloupe Island (modified from Thinon et al., 2010). Thick square: location of the 3D fault model. BCF: Bouillante-Capesterre fault system.

A detailed version of this work can be found in Calcagno et al. (2012).

2. STRUCTURAL SETTING

The geodynamic context of the West Indies shows that the fore arc is developed on ~250 km wide in E-W between the subduction zone and the western edge of the volcanic arc of the Lesser Antilles (grey area on Fig. 1a). From North to South, the motion ranges from sinistral extensional shear to dextral oblique thrusting (Fig. 1a).

The Bouillante geothermal province is a regional key geodynamic area where the major tectonic and volcanic structures of the inner arc of the Lesser Antilles join. The Bouillante geothermal field is located at the junction of two regional fault systems (Fig. 1b). The first one, located at sea, is the NW-SE Montserrat – Bouillante (MB) fault system. The second one, interpreted on the Island, is the ESE-WNW to E-W Bouillante – Capesterre (BC) fault system. The trajectory of this hypothetical fault is extracted from the geological, morphological and structural map of southern Basse-Terre realized by Feuillet et al., 2002.

A third fault system, described by Thinon et al. (2010), is a N160°E-trending escarpment which limits the shelf of the Bouillante sector. This escarpment is interpreted as a major sinistral strike-slip system, playing the role of transfer zone between the MB and Les Saintes (LS) fault systems. This discontinuity belongs to the western limit of a zone of sinistral extensional shear, developed on 250 km wide in E-W between the subduction zone and the western edge of the volcanic arc of the Lesser Antilles (Fig. 1a).

2.1 Onshore structural knowledge

The studied area is located on the West side of the volcanic Basse-Terre Island where the prevailing climate is wet tropical. This specific geographic location constrains the acquisition of structural data. Exposures suitable for structural measurements are mainly found only on the seaside where coastal erosion has stripped away the soil (Fig. 2).

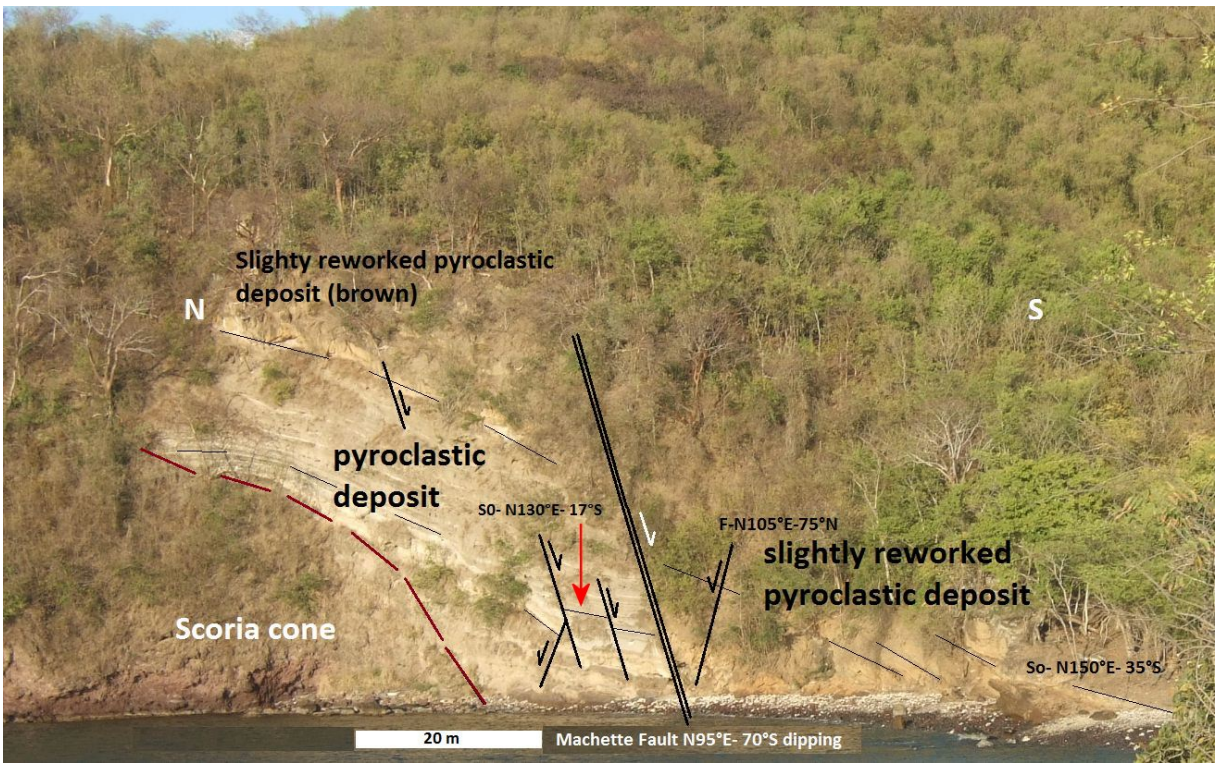


Figure 2: Outcrops are quite rare and minly located on the seaside. Here is a picture of the N95°E-striking, dipping 70°S normal Machette - Pointe à Sel fault located in the Anse Machette area.

As soon as one moves away from the coast, the volcanic island is covered by dense tropical forest on very steep relief. Given a rainfall that is 10 times higher than at the coast, this forest zone is the site of intense supergene alteration that impedes ground observation, except where ravines generated by torrents have been cut into the weathering profile. Nevertheless, the hilly areas where topographic regular structures are sharp can provide indirect information on fault traces (Feuillet et al., 2002).

From a recent synthesis of existing structural interpretation (Bouchot et al., 2008) and acquisition of new structural measurements by the authors (Fig. 2), it appears that most of the measured faults have a trend E-W to ESE-WNW, with a dominant normal throw showed by the evidence of normal offset of volcanic layer on each side of the fault surface with striae and drag fold in some places. Moreover, a very limited second family, consisting of only two faults visible onshore, trends NE-SW with a strong dextral strike-slip component, according to tectoglyphs such as striae and tension gashes.

2.2 Offshore structural knowledge

Three main surveys were conducted in the Bouillante Bay area in 1998 and 2003 by BRGM ((Bathybou98 and Geoberyx03 cruises; Guennoc et al., 2001; Thinon et al., 2010). Firstly, the bathymetry was investigated with a shallow water multibeam echosounder (MBES). The depth of the seabed is a reference data for the 3D model, as much as the topography. It reveals the shape of the bay and highlights major directions such as the the E-W-trending Marsolle escarpment in the northern part of the Bouillante Bay.

Secondly, a very high resolution (VHR) reflection seismic was acquired. A dense network, about 180 km long, shows the tectonic relations between the sedimentary cover and the volcanic basement (Fig. 3). The acoustic basement is interpreted as being the volcanic basement of Basse-Terre Island. Vertical throws of faults appears to be a few meters to tens of meters at least but the horizontal displacement is not interpretable and the faults within the acoustic basement are not visible.

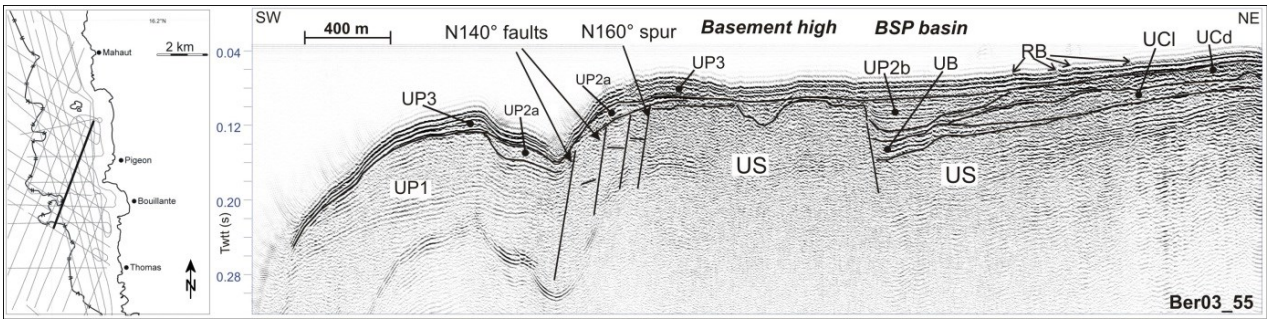


Figure 3: A Geoberyx03 VHR seismic profile (Thinon et al., 2010) showing the sedimentary cover (UP, UC, RB, UB), the acoustic basement (US), and the major faults. RB: surficial formation. Various seismic units are noted (names starting by U). Location of the marine seismic section on the left hand side (West Guadeloupe offshore).

Thirdly, a high resolution (HR) magnetic survey was performed and processed (e.g. Truffert et al., 2004). The conbination of the geophysical data provides a good image of the geometry of the structures. However, no geological data are available to constrain the age neither the type of formations, nor the dips of the faults.

The interpretation of these three surveys shows that the main structures elongate along NNW-SSE and E-W directions but some NW-SE and NE-SW features also occur (Thinon et al., 2010). For instance, the main N160°E-trending escarpment is interpreted as a major sinistral strike-slip system, playing the role of transfer zone between the NW-SE MB and LS fault systems. Furthermore, E-W major structures are observed crossing the NNW-SSE- and NW-SE-striking faults.

3. 3D FAULT MODEL

A 15 km x 16 km zone (see Fig. 1b for location) is modelled down to 2 km below sea level in the local "Guadeloupe, St. Anne – UTM20 – IGN", WGS84 projection system. In that zone, faults are interpreted by taking into account both offshore and onshore geological knowledge.

3.1 Data

Onshore, data consist in strike and dip measurements of fault measured during field work. Due to outcrops accessibility, these data are located on the coast. Inland, some structures are interpreted from previous works (e.g. Feuillet et al, 2002). Offshore, location and dip of the faults are derived from the interpretation of 52 Geoberyx03 seismic profiles (Thinon et al., 2010). The magnetic lineaments, interpreted as markers such as faults or dykes are clues for the existing orientations of structures on the shelf (Henkel and Guzman, 1977). The information on the age and nature of geological formations are derived from geological surveys at land.

The top of the 3D model is bounded by a Digital Elevation Model (DEM). This DEM combines information from the land and from the sea. The IGN data (Institut Géographique National, France) were used on the Island. Regarding bathymetry, two sets of data were taken into account: the deep water multibeam echosounder of the AGUADOMAR cruise (1998-1999, IPG, Deplus et al., 2001) and the shallow water multibeam echosounder of the Bathybou98 cruise (1998, BRGM, Guennoc et al., 2001). Then, a coherent 50 m resolution DEM covering the whole modelled area was interpolated with the GDM[(1)] geostatistics software (Bourgine et al., 2008)

3.2 Methodology

It was shown in the previous section that the pre-existing knowledge describes structures interpreted separately onshore and offshore. The present study doesn't consist in trying to connect these features but in interpreting them in a coherent way over our sea and land area. To build a consistent structural 3D interpretation, the geometry of a fault is computed using a set of data merging marine and inland locations of this fault (e.g. the Bouillante fault on Fig. 4). Faults are interpolated using the potential field interpolation and geological rules methods developed in BRGM (Lajaunie et al., 1997; Calcagno et al, 2008) and implemented in the 3D GeoModeller[(2)] software.

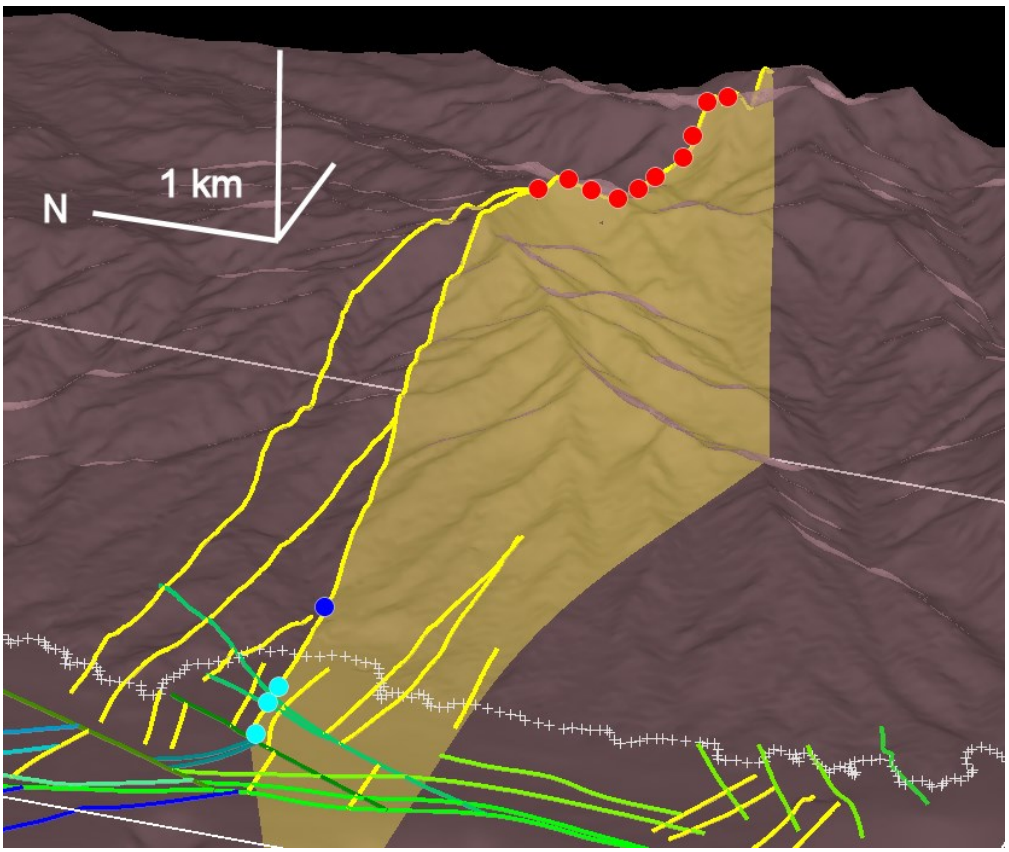


Figure 4: Example of onshore and offshore knowledge combination: The Bouillante fault (yellow surface) is constructed from onshore field observation (dark blue point), onshore interpretation (red points) and offshore seismic profiles interpretation (light blue points). View from WSW. The coastline (white crosses) separates onshore and offshore domains. See Fig. 1b for modelled area location.

3.3 Results

The 3D interpretation of the faults displays coherent structures gathering onshore and offshore knowledge (Fig. 5). Most of the faults belong to one of the two main families: The Montserrat – Bouillante – Les Saintes (MBLS) fault system, and the E-W- to ESE-WNW-striking fault system. In more detail, the main set of the offshore faults is striking ESE-WNW, and mainly dipping SSW. Two others sets are striking NNW-SSE and NE-SW with opposite dipping. In contrast, the main set of the onshore faults is striking from E-W to ESE-WNW and dipping north or south as a horst and graben pattern. Taking into account the whole set of onshore and offshore faults, it appears that at the model scale, faults are mainly striking from ESE-WNW to NNW-SSW and mainly dipping SSW to WSW.

3.3.1 The MBLS fault system: the case of the NNW-SSE-trending section around Bouillante

The MBLS fault system is considered as a sinistral strike slip fault zone recognized over 300 km long between St Kitts and Les Saintes north to south (Fig. 1b). We combine the NW-SE MB fault system between Montserrat and Directeur Volcano seamount (Duperret, 1991), and the NNW-SSE MB fault system between Malendure and Coreil and the NW-SE LS fault system (Deplus et al., 2001) to model the MBLS fault system. This fault system is generally oriented NW-SE, but forms a NNW-SSE-trending virgation along the Northern part of Basse-Terre volcanic island (Fig. 5). This virgation is characterised by a sub-continuous 30 km long fault zone which strikes N160°E and dips west. In contrast, on both end of the virgation, the NW-SE-striking corridors consist of east-dipping ESE-WNW-striking oblique fault. This “en echelon” oblique normal faults network is interpreted as an indicator of a sinistral transtension (Fig. 1) and the NNW-SSE section of the MBLS fault zone as a N160°E sinistral strike slip fault (Thinon et al., 2010).

In addition, a network of several parallel faults, well developed offshore, striking NE-SW, and 3 km long is linked to the offshore N160°E-striking faults. The onshore expression of these faults is very limited (Fig. 5). Identified only twice on the coast (Bouillante and Malendure outcrops), the NE-SW-striking faults show a dextral movement with a weak normal component. We interpret these short faults as a dextral conjugate network, grafted onto the main N160°E-striking sinistral fault, as a pinnate pattern. In the 3D fault model, some NW-SE-striking faults were also modelled mainly on the insular slope (2 dark blue faults) and on the external shelf (2 blue faults). They are located offshore the Bouillante Bay (Fig. 5). They are limited and sometimes shifted by the E-W and NE-SW faults. The NW-SE faults are also present at North of Malendure, near Pointe Noire town (see Malendure cluster below).

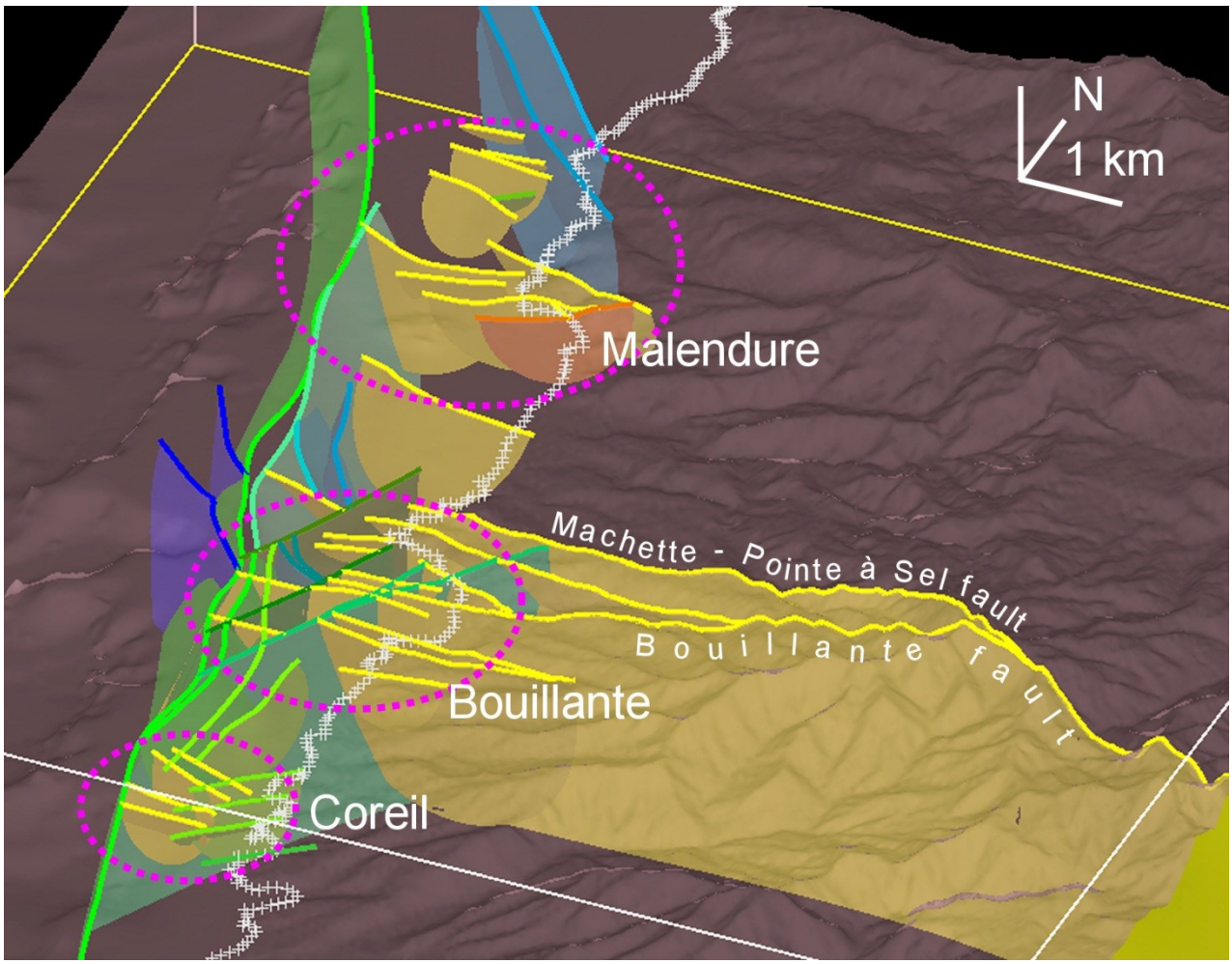


Figure 5: The whole 3D fault interpretation combines onshore and offshore knowledge. The coastline (white crosses) separates onshore and offshore domains. Two main families of faults are modelled: the MBLS fault system (green and blue faults); the E-W to ESE-WNW-striking fault system (yellow faults). Three clusters are identified (purple dashed ellipses). See Fig. 1b for modelled area location. View from SE.

3.3.2 The E-W- to ESE-WNW-striking fault system

Onshore and on the shelf, the main fracturing strikes E-W to ESE-WNW. These structures can be gathered into 3 clusters of faults from North to South: Malendure, Bouillante, and Coreil (purple dashed ellipses on Fig. 5).

The Malendure cluster is located at the junction between the NW-SE section and the NNW-SSE section of the MB fault system, in the Malendure area (Fig. 1b and Fig. 5). On the shelf, the vertical offsets of two NW-SE-striking faults are low. Onshore, these faults are correlated to discrete fracture zones, controlling reddish hydrothermal alteration. The E-W- to ESE-WNW-striking normal faults do not seem connected to a regional E-W fault but they are well developed between the NW-SE and the NNW-SSE sections of the MBLS fault system. At north of the Malendure cluster, the NW-SE faults observed on coast have been correlated to the faults observed on the seismic profiles. The low density of marine data prevents from specifying the tectonic network and the relationships between the NW-SE Pointe-Noire faults and the EW faults of Malendure.

In the Bouillante cluster, the roughly EW-striking, steeply dipping, normal faults network forms a horst and graben pattern. However, on the shelf, i.e. approaching the main N160°E-striking fault system, the E-W faults are discontinuous and stopped on the NE-SW-striking faults (Fig. 5). Evidence of intense deformation, focused on the Bouillante cluster, is a strong argument to defend the existence of the major fault zone of BC fault system (Feuillet et al. 2002). The steeply south dipping E-W-striking Bouillante fault appears as a main member of the regional E-W fault, on which are associated the other E-W-striking normal faults whose dips are opposed (Fig. 5). The fracturing cluster of Bouillante is interpreted as the junction zone between the major E-W fault zone through Bouillante town, and the major sinistral-(normal) N160°E strike-slip faults on which were grafted dextral-(normal) NE-SW strike slip fault (Fig. 5).

The Coreil cluster highlights two sets of offshore faults: a NE-SW-striking faults set and an ESE-WNW-striking faults set (Fig. 5) and few indicators of deformation exist onshore. The set of 4 short NE-SW-striking faults (Fig. 5) are interpreted as a conjugate strike slip network, grafted onto the main N160°E-striking sinistral fault. Between the Coreil and Bouillante clusters, the 3D model highlights an area without observed faults, which coincides with a strong sub-circular magnetic anomaly and a convex morphology of the shelf. These observations could mark the occurrence of young volcanic magnetic product - hiding the faults - as suggested by youngest K/Ar age obtained around Bouillante, on the Muscade volcanic rock (479 ± 16 ky; Sanjuan et al., 2008).

4. CONCLUSION AND PERSPECTIVES

Merging onshore and offshore data improves the geological interpretation of the MBLS fault system. The resulting 3D fault model helps to better understand the regional structural geology of the Bouillante geothermal province. Data from the sea and data from the land are used simultaneously to build a coherent interpretation across the coast (e.g. Fig. 4 for the Bouillante fault). In addition, the geological knowledge from the land benefits to the comprehension of the structures at sea and reciprocally. This methodology is significantly more powerful than trying to connect two separate interpretations, one onshore and the other offshore.

The interpretation presented in previous works (e.g. Thinon et al., 2010) is refined. In particular, our methodology highlights NE-SW structures linked to the MBLS fault system. Such structures define, limit and shift compartments where the E-W to ESE-WNW faults elongate. The marine seismic interpretation combined to the field observation is a guide to define the faults hierarchy by showing that the NE-SW-striking faults cut the E-W to ESE-WNW ones. This example demonstrates how the methodology allows to build a fault network giving clues for geometry and kinematics pattern.

The 3D fault model provides indications for future field work. It was not possible to connect some E-W structures interpreted offshore to observation onshore and vice versa. However places were these modelled E-W faults cross the coast will be interesting spots to investigate. Some NE-SW structures modelled offshore would affect inland terrains if prolonged. In that way this 3D fault model is a tool to point out probable areas where to explore for such structures onshore. In particular, the clusters of faults identified from the fault model could be a guide for exploration. They emphasize areas where permeability is a priori favourable, making them potential geothermal fields. In addition, the geometry of the fault model will be used to constrain hydrothermal simulations. Such simulations will help to understand how fluids circulate within these promising permeable areas.

Another step is to fill the fault model with relevant geological formations at the regional scale. Outcrops correlated to the seismic units would help to set the geometry of the geological formations. Furthermore, integrating deep refraction seismic data would help to extend the 3D model at depth in order to describe deeper geological structures. Then, geophysical data, e.g. gravity and magnetics, would be additional information to validate and refine the model by combining its geometry to geophysical data in a forward or an inversion process.

ACKNOWLEDGEMENTS

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FOOTNOTES

(1) GDM is a commercial software developed by BRGM. For further information visit: http://gdm.brgm.fr/?lang=en.

(2) 3D GeoModeller is a commercial software developed by BRGM and Intrepid Geophysics. For further information visit: http://www.geomodeller.com.

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