Combining Onshore and Offshore Geological Knowledge: The Bouillante 3D Structural Model (French West Indies)

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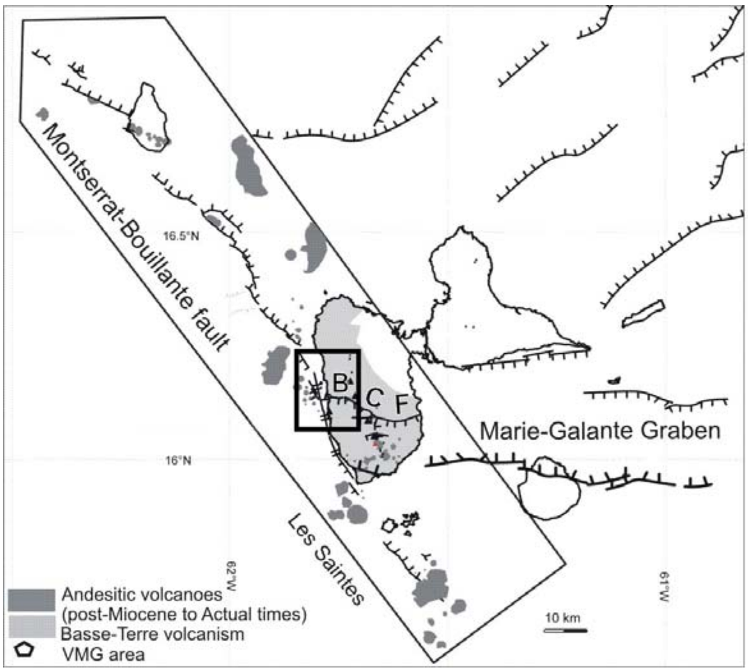
Summary

The Bouillante zone (Guadeloupe Island, French West Indies) hosts geothermal resources located in a complex structural area. 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 shows a larger range of directions. A coherent 3D interpretation is built through a structural model combining onshore and offshore knowledge. Connections between land and sea structures are established at some places. Offshore interpretation highlights possible places to be investigated onshore. The structural model will be filled by formations deposits before meshing the whole geological 3D model for simulation process.

Regional Geology

The Bouillante area is located on the West of the Guadeloupe Island (French West Indies). That area is known for its geothermal anomalies. The Bouillante sector is a key geodynamic area where the major tectonic and volcanic structures of the inner arc of the Lesser Antilles join (e.g. Bouysse et al. 1988; Feuillet et al., 2002). As far as can be determined from our present state of knowledge, the area is located at the junction of two regional fault systems: i) a major submarine N160°E strike-slip fault located in the prolongation of the normal-sinistral Montserrat-Bouillante system, only detected offshore (Thinon et al., 2010), and ii) the western end of the interpretative ESE-WNW Bouillante-Capesterre normal fault which is a major fault of the E-W Marie-Galante graben system (Figure 1).



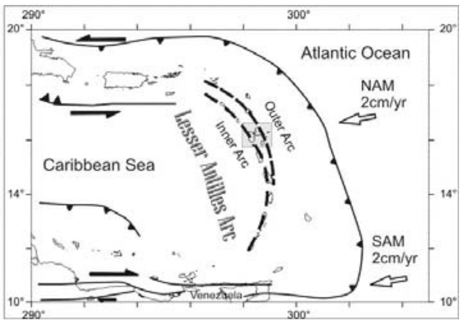


Figure 1
Regional structural setting (modified from Thinon et al., 2010).
VMG: Montserrat-Guadeloupe Volcanic area. BCF: Bouillante-Capesterre fault. Thick square: location of the 3D model including the Bouillante field.
Box: Guadeloupe Island location in the West Indies. NAM: North American plate. SAM: South American plate.

Onshore Geological Knowledge

The Bouillante geothermal field is located on the west side of the volcanic Basse-Terre Island in Guadeloupe 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 coast where coastal erosion has stripped away the soil. Since the 1970s when geothermal exploration began around Bouillante, several field missions have succeeded in acquiring sets of structural data. It would appear that almost all the measured faults have a trend E-W to ESE-WNW, are very steeply dipping and have a dominant normal throw (Bouchot et al., 2010). However, a very discreet second family consisting of only two faults visible onshore trends NE-SW with a strike-slip component and appear to continue offshore (Figure 2).
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 morphologies reflect erosion do provide indirect information on fault traces. Similarly abnormal geophysical signatures (e.g. contact between different ground resistivities) also provide indirect data likely to indicate the presence of a fault at depth.
In substance, the combination of direct and indirect structural data has enabled an interpretative onshore structural pattern to be considered, albeit poorly constrained at depth given the small amount of information available (borehole logs, electrical surveys, extrapolation of observed dips). The geothermal field being located partly onshore and partly offshore, the offshore data will provide essential information for our structural understanding.

Figure 2
In foreground, the outcrop of Marsolle Point is localised on the coast line (Bouillante Bay). This outcrop is characterized by occurrence of two faults, ESE-WNW and NE-SW. In background, the volcanic island, marked by a very steep relief, is covered by dense tropical forest, limiting structural data acquisition.

Offshore Geological Knowledge

To improve our geological knowledge of the structural context of the island and to extend the structures identified onshore, high-resolution bathymetric, shallow and VHR reflection seismic (Figure 3) and magnetic surveys were conducted in 1998 and 2003 by the BRGM – the French Geological Survey – on the west Basse-Terre Island shelf, centred on the Bouillante Bay sector (Thinon et al., 2010).
The interpretation of these surveys has helped to highlight several major structural features:

i. The sedimentary cover is generally thin, except on the outer shelf where thick sedimentary unit deposition induced an important widening of the shelf. The bathymetry map doesn't reflect the morphology of the volcanic basement.
ii. The main directions of structures, observed on the shelf, are N160°, EW, NE-SW and NW-SE.
iii. The western edge of the shelf is a N160°W escarpment, may be a major sinistral strike-slip system, playing the role of transfer zone between the N140° Montserrat-Bouillante fault and the Les Saintes system. This structure limits also an asymmetric horst, faulted and sometimes shifted, where reefs or beach-rocks are located.
iv. The N140°-trending faults of the Montserrat-Bouillante system exist locally on the insular slope and on the external shelf off the Bouillante Bay.
v. A volcano edifice extends over the shelf on south of Bouillante Bay, according to an observed large magnetic anomaly.

vi. The Marsolle escarpment, located in the Bouillante area, could be the offshore prolongation of the EW-trending Bouillante-Capesterre fault, from the coast to the shelf-break crossing the N160° and N140° structures of the shelf.

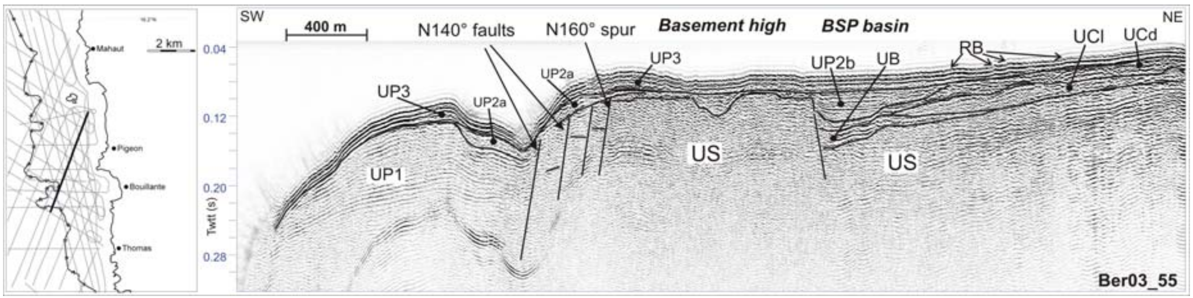


Figure 3
Example of the Geoberyx03 Very High Resolution (VHR) seismic profile through the NW shelf offshore Bouillante (Thinon et al., 2010). It shows the thickness of the sedimentary cover (UP, UC, RB, UB), the morphology of the acoustic basement (US), the apparent dip and the vertical throw of the major faults, the N160° basement high and the geometry of basins (BSP) on the internal shelf. RB: surficial formation visible on bathymetry. Various seismic units are defined and noted by the symbol U. Box: location of the marine seismic section (West Guadeloupe offshore).

3D Structural Modelling

Preliminary to the 3D model, a Digital Elevation Model (DEM) was created to combines onshore and offshore data in a coherent 50 m resolution 2D grid covering the whole modelled area. Onshore data are provided by the Institut Geographique National. Offshore, two bathymetric surveys are used: AGUADOMAR from 1998-1999 (Deplus et al., 2001) and the high-resolution acquisition from 1998 (e.g. Guennoc et al., 2001). The data were interpolated using a geostatistical method to combine them and to fill the remaining gaps. The resulting DEM limits the top of the structural model.
A 15 km x 16 km zone is modelled down to 10 km vertical extension to interpret regional and crustal structures (see Figure 1 for location). The model is set up to combine onshore and offshore data in a coherent structural 3D interpretation (Figure 4a). Data are interpolated using the potential field method developed in BRGM and implement in the 3D GeoModeller software (Calcagno et al, 2008).

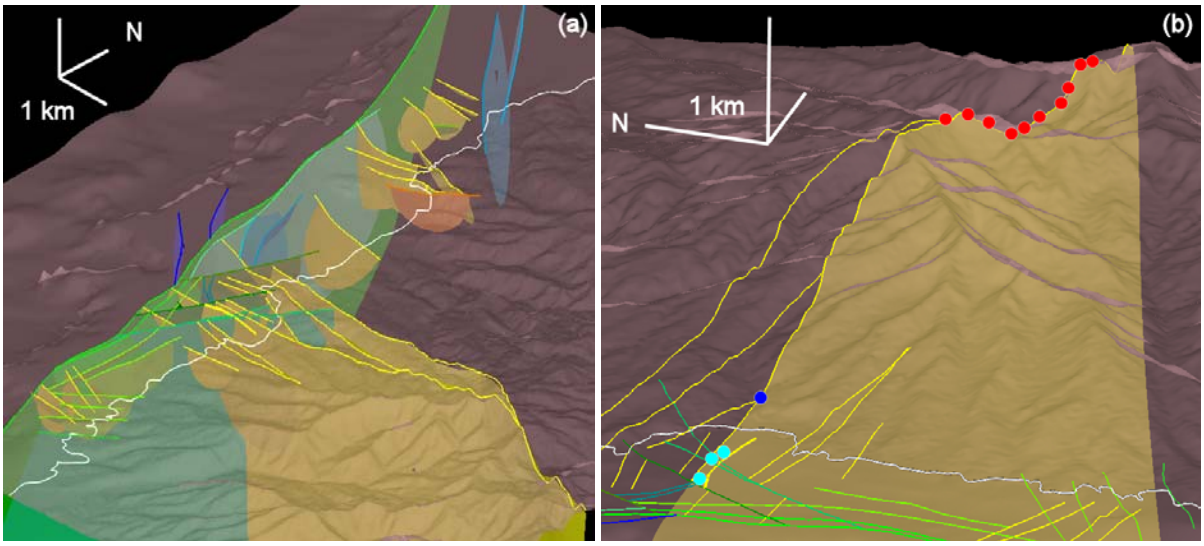


Figure 4
3D structural model. The DEM (shaded pink surface) is constructed from inland terrain model and offshore bathymetry. The coast line (white curve) separates onshore and offshore domains. See Figure 1 for modelled area location.
(a) The whole 3D structural interpretation combines onshore and offshore knowledge. View from SE.
(b) Example of onshore and offshore knowledge combination: The Bouillante-Capesterre 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.

Onshore, data consist in faults contact location and associated dips measurement observed 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 acoustic basement offset interpreted in the 52 seismic profiles that have been used. To construct a coherent interpretation, E-W structures observed onshore were as much as possible a guide to interpret and to connect E-W structures offshore (e.g. the Bouillante-Capesterre fault on Figure 4b).
The final 3D interpretation highlights coherent structures onshore and offshore. Faults mainly oriented E-W are set in 3 clusters: (i) on the Southern part of the zone, (ii) on the Bouillante field where fracturation is intense, and (iii) on the Northern part of the zone. This distribution may be interpreted as westward E-W fault corridors, consistent with a major fault located on Bouillante city. Offshore data highlight a NE-SW direction that is not observed onshore, except at the Pointe Marsolle outcrop. NE-SW oriented faults stop on the border of NNW-SSE fault on the West; they vanish eastward. Probably combining normal and strike slip movements, these faults could limit E-W fractured blocks as interpreted offshore Bouillante city. NW-SE oriented faults are limited on the Montserrat-Bouillante-Les Saintes fault zone; such a direction is not observed onshore.

Perspectives

Our 3D structural model provides indications for future field work. It was not possible to connect some E-W structures interpreted offshore to observation onshore. 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. Here again, the 3D model is a tool to point out probable areas where to explore for such structures onshore.
The next step is to fill the structural model with geological formations observed in the field and in the Bouillante boreholes for the upper part of the model. Deeper formations will be interpreted from deep penetration seismic profiles. Finally the geometry of the model will be meshed to simulate flow and temperature distribution.

Acknowledgement

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Footnote

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

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