3D GeoModelling for a Democratic Geothermal Interpretation

Philippe Calcagno

Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

3D GeoModelling for a Democratic Geothermal Interpretation

Philippe Calcagno

BRGM, 3 avenue C. Guillemin, BP 36009, 45060 Orléans cedex 2, France

p.calcagno@brgm.fr

Keywords: 3D Geomodelling, geothermal exploration, interdisciplinary interpretation, data integration, consensual interpretation, geology, gravimetry, magnetotellurics, geochemistry, conceptual model.

ABSTRACT

Geothermal exploration aims at locating favourable areas for exploitation. To reach this goal, various disciplines are implemented. Among the most common ones are geology, geophysics and geochemistry. Data are generally acquired in the field, such as geological observations, gravimetric surveys or thermal sources sampling. These data are interpreted to characterize the geometry, and the properties of the studied zone. They provide separate but complementary information to understand the area explored. However, combining geological, geophysical and geochemical interpretations is not an easy task.

In such a context, one of the main difficulties lies in how to mix all the information to infer a coherent geothermal conceptual model. Merging them in the same space can help their combination to lead to a consistent understanding. First of all, this methodology allows to check the location of separate figures and to ensure their coherence. Moreover, it makes possible to build an overall interpretation based on various information. GeoModelling in 3-dimensions is an interesting candidate for this job because it allows to input materials from various origins to achieve an interpretation of the geothermal area.

GeoModelling provides a common platform for interpretation during the exploration phase of a geothermal project. The final model can be completed through successive stages bringing new information at each step. For instance, a preliminary 3D geomodel can be based on very rough data from bibliography, even before any field work dedicated to the exploration. In a second time, geological data can be observed on the ground and incorporated in the model to refine the interpretation. The process can be continued using a gravimetric survey to improve the model at depth. Then, magnetotelluric resistivity can be injected in the model to infer possible fluid occurrence. Finally, location and properties of geothermal springs can be displayed in the 3D model to complete the interpretation. This kind of interdisciplinary workflow leads to a coherent geomodel filled by geology, geophysics and geochemistry.

Making a 3D geomodel by associating complementary interpretations is an interesting perspective but giving the experts of each discipline the opportunity to interact in a democratic process is even more powerful. Indeed, geological, geophysical, and geochemical interpretations are not disconnected. Even if a preliminary work has to be carried out separately by each discipline, the interpretation coming from one can be fed by the others instead of putting them one after the other in a sequential workflow. To do so, the methodology has to be object oriented, where the central object is the 3D geomodel. In this light, the 3D model benefits from a common interpretation implemented jointly by geologists, geophysicists and geochemists. In other words, they can compare, connect, discuss, and adapt their own approaches for a mutual result in a GeoModelling environment. At the end, the conceptual model is not a conglomerate of distinct interpretations but a consensus shared by the contributors.

The methodology described above is illustrated with two examples. These case-studies show how 3D GeoModelling is helpful to infer a democratic interpretation during the exploration phase. Beyond the interpretation for exploration, the geomodel can be enhanced during the next phases, when new data are acquired, to provide an up-to-date image of the investigated region. Such a 3D model can also be used to mesh the geometry of the zone and to compute dynamic simulations.

1. INTRODUCTION

The main objective of geothermal exploration is to target favourable zones for successful drilling in the scope of future resource exploitation. Drilling is the only way to access directly the subsurface structure and parameters, at least along the borehole (lithology, temperature, permeability, etc.) However, considering the high investment needed for a drilling campaign, various techniques are used to investigate the subsurface prior to any drilling (Flovenz et al., 2012). The major ones for interpreting geological structures of the underground are geological field observation, exhumed analogues and seismic or gravimetric measurements. Parameters such as temperature or permeability can be inferred from hydrogeology, geochemistry or geophysical electric methods investigations.

Each of the methods described above gives a piece of knowledge. Gathering these pieces is a key for a comprehensive interpretation (Noorollahi et al., 2008; Shako and Mutua, 2011; Witter and Phillips, 2012; Higuchi et al., 2013; Calcagno et al., 2014). That is why, as much as possible, data coming from various disciplines are combined to enhance the understanding of a geothermal area. But often the more available are the sources of data; the more complex is the interpretation. In this paper we propose a collaborative way to combine multi-sources data to achieve an interpretation shared by the specialists of each discipline. The principle is illustrated by two case-studies.

2. DEMOCRATIC INTERPRETATION

The word "democratic" is used in this paper for synthetizing two major ideas. On one hand, the geothermal interpretation benefits from the input of multiple scientific fields. On the other hand, these disciplines collaborate for a cooperative and cohesive interpretation of the geothermal area. Such a shared interpretation will be easier to produce if the experts have a common platform to help them for exchanging.

2.1 3D GeoModelling

3D geological modelling is dedicated to the representation of the solid Earth using surface and underground data in a computer aided process (Houlding 1994; Mallet 2002; Wu et al. 2005). Numerous packages implement several methodologies to achieve 3D geological models. Indeed, 3D geomodelling is based on integrating and combining data and aims at representing 3-dimensional structures. In that sense, 3D geomodelling is a good candidate to help geothermal explorers.

We focus here on building 3D static models that represent a georeferenced interpretation of the subsurface structure. Data such as geological measurements on the field, gravimetric and seismic surveys can be combined to infer the geological formations and their shapes. The resulting structural framework can be the cradle for locating and associating results from electric methods and geochemistry to enhance the interpretation and design a conceptual model of the geothermal area.

2.2 Principle for a democratic interpretation

As stated above, 3D geomodelling enable multi-disciplinary data combination. In the meantime, we look for a way helping the experts to collaborate and – even more important – to interact. Building a 3D geomodel allows to shape and to visualize a current knowledge and to update it when new data or interpretation are available. The classical protocol followed to aggregate data is the workflow procedure (Maxelon et al., 2009; Moretti et al., 2010). Let's take an example where four scientific fields contribute in the exploration phase: geology, gravimetry, magnetotellurics, and geochemistry. Typically, in a workflow, the contributions from each of the scientific fields are added one after the other in a sequential process to complete the final model (Fig. 1).

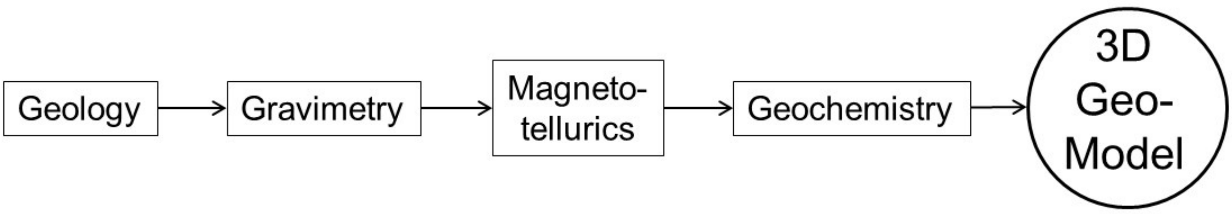

Figure 1: Workflow is the classical way for combining data. The 3D geomodel is the final result of sequential interpretations.

Associating data in a workflow methodology satisfies the forecasted objective to combine multi-discipline contributions. However, scientific fields are used chronologically and independently; making difficult common reasonings. Moreover, the closer to the final model a scientific field is, the bigger impact it may have, i.e. "the one who is right is the last one who spoke".

Merging the contributions from the fields instead of simply aggregating them is a step forward. The interpretation of a given discipline may benefit from the interpretation of another discipline, with no chronological preference. For instance, the geological interpretation could benefit from the magnetotellurics interpretation or vice versa. In that case, the geomodel is no more only the final result of the integration process but the geomodel is the main and central object of the interpretation process (Fig. 2).

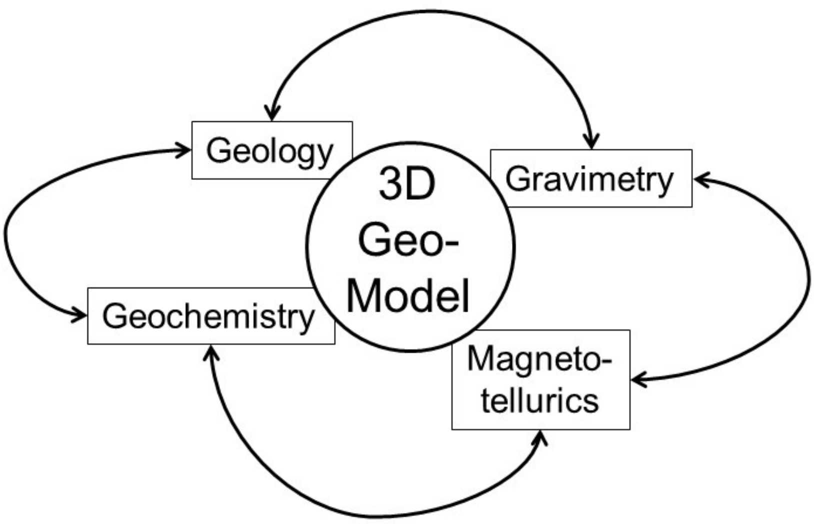

Figure 2: The 3D geomodel is the central part of the democratic interpretation. Scientific fields cooperate and interact to enhance the interpretation.

The democratic interpretation (Fig. 2) is an iterative and interactive practice where making the geomodel is the way for cross-interpretation of the scientific disciplines. It requires an interactive geomodel generation platform to achieve such a cooperation in real time.

This principle is illustrated in the two following case-studies.

3. CASE-STUDIES

These case-studies regard the geothermal exploration phase. A multidisciplinary approach is used to complete a consensual geothermal interpretation. In both cases, 3D geomodels are used to make easier the interaction between the disciplines involved in the geothermal exploration.

3.1 Interpretation combining knowledge from geological field and seismic marine: The 3D fault model of the Bouillante geothermal province

The Bouillante area is located on the West side of the Guadeloupe Island (French West Indies); a region well known for geothermal resources. This sector is a key geodynamic area (e.g. Bouysse et al. 1988; Feuillet et al., 2002) at the junction of two regional fault systems: i) a major submarine N160°E strike-slip fault belonging to the normal-sinistral Montserrat-Bouillante-Les Saintes system, only detected offshore (Thinon et al., 2010), and ii) the western end of the interpretative ESE-WNW Bouillante-Capesterre normal fault which is probably a major fault of the E-W Marie-Galante graben system (Fig. 3a). At the junction, faults observed on the field mainly elongate along the E-W direction (Bouchot et al., 2010) whereas offshore structures interpreted from marine seismic lines shows a larger range of directions (Thinon et al., 2010).

Onshore, data consist in faults observed and measured during field work (Fig. 3a). Due to outcrops poor accessibility, these data are mainly located on the coast where sea erosion is intense. Inland, some structures are interpreted from previous works mainly based on topography (e.g. Feuillet et al, 2002). Offshore, location and dip of the faults are derived from the acoustic basement offset interpreted in 52 seismic profiles representing about 180 km long in total (Fig. 3b).

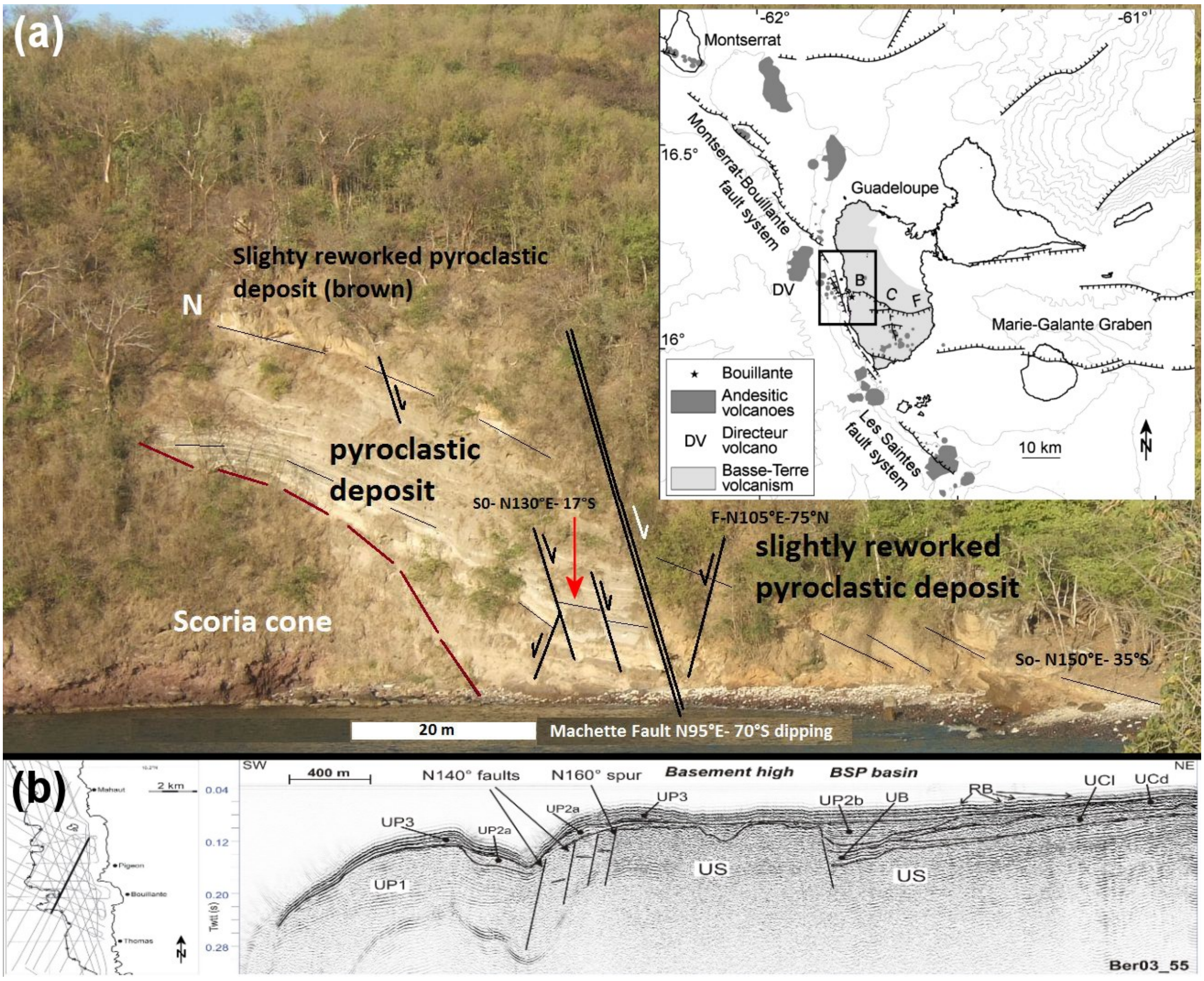

Figure 3: Example of the onshore and offshore knowledge in the Bouillante geothermal province.
a. Picture of the Anse Machette inland outcrop at the north end of the Bouillante bay (Bouchot et al., 2010); view from W, see box in b. for location. Box: Regional structural setting of the Guadeloupe Island (modified from Thinon et al., 2010). Thick square: location of the 3D fault model. BCF: Bouillante-Capesterre fault system.
b. A Geoberyx03 very high resolution marine seismic profile opposite to the Bouillante bay; see box on the left hand side (Thinon et al., 2010).

The challenge is to mix knowledge from the sea and from the Island to infer a coherent structural model of the faults at the scale of the Bouillante geothermal province that includes both inland and sea domains. To achieve this goal, marine and ground geologists worked conjointly, applying the following methodology:

- E-W structures observed onshore were as much as possible a guide to interpret and to connect E-W structures offshore.
- Faults crossing the coastline are identified both offshore and onshore to gather a unique set of data to model geometry (e.g. the Bouillante fault on Fig. 4a)

Finally, a coherent fault interpretation of the zone combining data and observations from the sea and from the ground is built through a 15 km x 16 km 3D model down to 2 km vertical extension (Fig. 4b). The Bouillante geomodel is achieved 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(1) software.

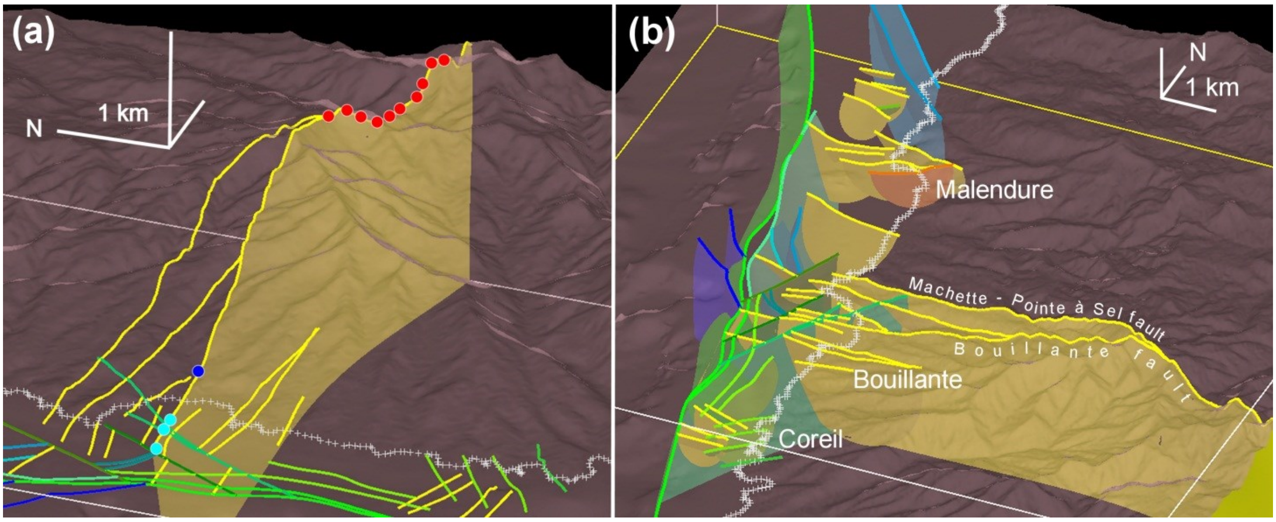

Figure 4: Two views of the fault model achieved for the Bouillante geothermal province (see Fig. 3a for location). The coastline (white crosses) separates onshore and offshore domains.
a. The Bouillante fault (yellow surface) is constructed from onshore field observation (dark blue point), onshore interpretation (red points) and offshore seismic profiles interpretation (light blue points). View from WSW.
b. The final 3D interpretation reveals three main families of faults (yellow, green, and blue). View from SSE.

The 3D fault model of the Bouillante geothermal province presented here (Fig. 4b) is the final state of numerous iterations. Preliminary models were constructed to test various hypotheses for interpreting faults. These intermediary models were modified, rejected or refined conjointly by the experts but they are not shown here. Such an iterative process lead to the final model presented above. Even if the methodology is deterministic - i.e. a single model is presented - the evolution of the interpretation is intrinsic to the final model.

This work is fully detailed in Calcagno et al. (2012) where the 3D interpretation of the faults is presented and discussed as well as the implication for exploring the Bouillante geothermal province.

3.2 Inter-disciplinary mutualisation: geology, gravimetry, magnetotellurics, and geochemistry

Note: This case-study refers to a confidential exploration project; let's call it the x-area. No mention of location or values of the parameters are displayed in the text and figures of this section. The main geological body in the x-area is a granitic formation. This case-study is used to illustrate a methodology that can be reproduced elsewhere.

The exploration of the x-area starts by a bibliographic compilation. Since the very beginning, a preliminary 3D geomodel is built to gather information on geological structures (Fig. 5a). This step allows to display the existing information in the same framework where the bibliographic data are checked and turned into a coherent interpretation. This preliminary 3D geomodel is used to prepare the fieldworks stage by helping to target interesting places for investigation.

Then, the acquisition on the field allows to enhance the previous geological interpretation. These new field data imply changes in the whole 3D model. Even if they are measured on the ground, they also impact the interpretation at depth. On the x-area, the location and dip of faults are revised, a contact aureole is observed around the granite body, springs are located, and an altered zone is identified and interpreted in the underground (Fig. 5b).

In the next step, a gravimetric survey is completed on the zone to obtain a Bouguer anomaly map of the x-area. Densities are associated to the geological formations of the geomodel. Then, the Bouguer anomaly is combined with the geological bodies of the geomodel in an inversion process based on the Monte Carlo algorithm (Guillen et al., 2008). The result of the inversion contributes to refine the 3D interpretation in a common work done by geologists and geophysicists, while keeping coherence with the observations of the previous stage (Fig. 5c).

A last survey is performed on the x-area to measure the magnetotelluric signal. Afterwards, data are turned into a 3D resistivity interpretation and input in the geomodel. Here, the cooperative interpretation derived from geology and gravimetry is upgraded with the resistivity contribution. On top of that, information from springs' fluid analysis helps the final interpretation. All the material is shared by geologists, geophysicists and geochemists. A conceptual model forecasting the hydrothermal behaviour of the x-area is collectively achieved by the experts (Fig. 5d).

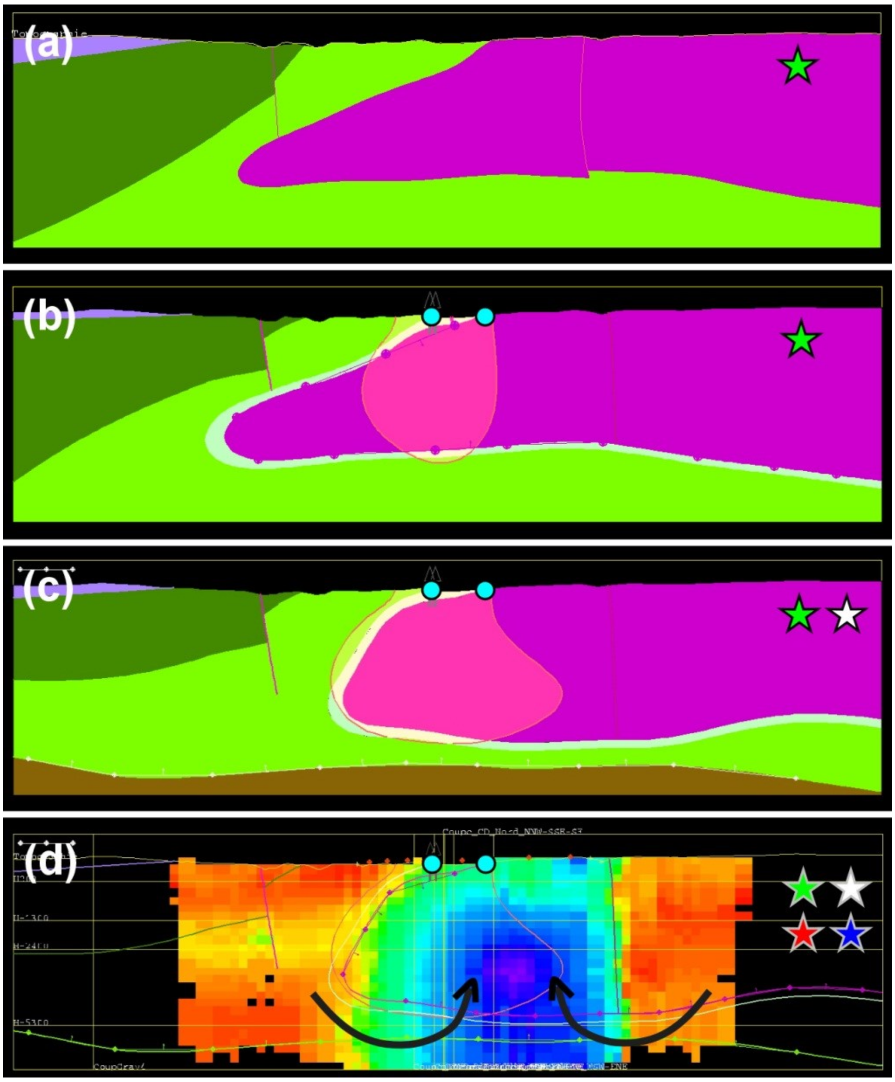

Figure 5: The x-area is modelled in 3-dimensions. The progress in the interpretation is illustrated here in the same vertical cross-section. The main geological feature is a granitic body (purple). Light blue dots locate the springs observed in the field. Stars show the mutual involvement of experts and data: geology (green), gravimetry (white), magnetotellurics (red), geochemistry (blue).
a. The preliminary 3D geomodel is built from bibliography knowledge.
b. The geological data acquired in the field are used to refine the interpretation. Fault dips are changed, an altered area is interpreted in the middle of the section (red border and lighter colours), and springs are located.
c. The gravimetric survey inversion leads to shorten the "nose" of the granite, and to interpret a new basement (brown).
d. Resistivity computed from a magnetotelluric 3D survey is superimposed to the geological/gravimetric interpretation (coloured curves) to infer a conceptual model of the x-area, shared by all the experts.

The interpretations and hypothesis made by the experts in their own fields were gathered, pooled, and confronted to lead to a consensual interpretation. The successive 3D geomodels of the x-area (Fig. 5) were completed using the potential field interpolation, the geological rules, and the gravity data inversion methodologies developed in BRGM (Lajaunie et al., 1997; Calcagno et al, 2008; Guillen et al., 2008). They are implemented in the 3D GeoModeller[(1)] software.

4. CONCLUSION AND PERSPECTIVES

Several disciplines are involved in the exploration phase of a geothermal project. The more they can interact, the better is the final interpretation and the better constrained is the conceptual model of the geothermal area. It was shown here that achieving a 3D geomodel is a good way to gather and share most of the information in a common platform. Moreover, starting this geomodel since the very beginning of the exploration allows to use it as a framework for planning field work and updating the interpretation of the area.

Beyond the multi-disciplinary integration, it has been demonstrated the added-value of experts working together to revise their own interpretation depending on the ones of the others. Instead of a sequential workflow process where the scientific fields are quite disconnected, it has been introduced the democratic interpretation concept where disciplines interact. The democratic interpretation leads to a cooperative interpretation validated by all the experts. Two examples – the Bouillante geothermal province and the so called x-area – have been used to illustrate how the mutual work on a shared 3D geomodel enhances the interpretation in the exploration phase.

In this light, the experts and their interaction are even more important than the data themselves. The extra time spent on the collaborative effort is awarded by a conceptual model shared and validated by the community. On a tool point of view, the approach requires a flexible and interactive platform to enhance in real-time the geomodel during common work sessions.

Other disciplines than the ones cited above can be integrated in the process; hydrogeology for instance. Even if some do not directly contribute to the design of the 3D geomodel, they can use it as knowledge support. In addition, a current model can be enhanced and turned into an up-to-date interpretation if new data are available after the exploration phase. Another perspective is to use such static 3D geomodel describing the inter-disciplinary interpretation for dynamic simulation purpose.

ACKNOWLEDGEMENTS

This work is supported by IMAGE (http://www.image-fp7.eu). This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No: 608553.

The work regarding the Bouillante geothermal province was supported by ADEME (French Agency for Energy and Environment): contract 0805C0044 (GHEMOD) and contract 0805C0039 (GEO3BOU).

FOOTNOTE

(1) 3D GeoModeller is a commercial software developed by BRGM and Intrepid Geophysics. For further information visit: http://www.geomodeller.com.

REFERENCES

Bouchot, V., Sanjuan, B., Traineau, H., Guillou-Frottier, L., Thinon, I., Baltassat, J.M., Fabriol, H., Bourgeois, B., Lasne, E, 2010, Assessment of the Bouillante geothermal field (Guadeloupe, French West Indies): toward a conceptual model of the high temperature geothermal system, in WGC-2010 - World Geothermal Congress - Bali - Indonesia - 25-30/04/2010

Bouysse, P., Mascle, A., Mauffret, A., Mercier De Lepinay, B., Jany, I., Leclere-Vanhoeve, A., Montjaret, M. C., 1988, Reconnaissance des structures tectoniques et volcaniques sous-marines de l'arc récent des Petites Antilles, Marine Geology, 81, 261-287.

Calcagno, P., Baujard, C., Guillou-Frottier, L., Dagallier, A., Genter, A., 2014. Estimation of the deep geothermal potential within the Tertiary Limagne basin (French Massif Central): An integrated 3D geological and thermal approach. Geothermics, Volume 51, 496–508.

Calcagno, P., Bouchot, V., Thinon, I., Bourgine, B., 2012, A New 3D Fault Model of the Bouillante Geothermal Province Combining Onshore and Offshore Structural Knowledge (French West Indies). Tectonophysics, 526–529 (2012), 185–195.

Calcagno, P., Chilès, J.P., Courrioux, G., Guillen, A., 2008, Geological modelling from field data and geological knowledge, Part I – Modelling method coupling 3D potential-field interpolation and geological rules. Physics of the Earth and Planetary Interiors, 171, 147–157.

Feuillet, N., Manighetti, I., Tapponier, P., Jacques, E., 2002, Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles, J. Geophys. Res., 107(B12), 2331.

Flóvenz, Ó.G., Hersir, G.P., Sæmundsson, K., Ármannsson, H., Friðriksson, Þ., 2012, 7.03 - Geothermal Energy Exploration Techniques, In Comprehensive Renewable Energy, edited by Ali Sayigh, Elsevier, Oxford, 51-95, ISBN 9780080878737.

Guillen, A., Calcagno, P., Courrioux, G., Joly, A., Ledru, P., 2008, Geological modelling from field data and geological knowledge, Part II, Modelling validation using gravity and magnetic data inversion, Physics of the Earth and Planetary Interiors, 171, 158–169.

Higuchi, S., Nishijima, J., Fujimitsu, Y., 2013, Integration of Geothermal Exploration Data and Numerical Simulation Data using GIS in a Hot Spring Area. Procedia Earth and Planetary Science, Volume 6, Pages 177-186.

Houlding, S.W., 1994, 3D Geoscience Modeling; Computer Techniques for Geological Characterization. Springer-Verlag, Berlin, Germany.

Lajaunie, C., Courrioux, G., Manuel, L., 1997, Foliation fields and 3D cartography in geology; principles of a method based on potential interpolation. Mathematical Geology 29, 571–584.

Mallet, J.L., 2002. Geomodeling. Oxford University Press, Oxford, New York.

Maxelon, M., Renard, P., Courrioux, C., Brändlid, M., Mancktelow, N., 2009, A workflow to facilitate three-dimensional geometrical modelling of complex poly-deformed geological units. Computers & Geosciences 35, 644-658.

Moretti, I., Charry, G.R., Morales, M.M., Mondragon, J.C., 2010, Integrated exploration workflow in the south Middle Magdalena Valley (Colombia). Journal of South American Earth Sciences, 29, 187-197.

Noorollahi, Y., Itoi, R., Fujii, H., Tanaka, T., 2008, GIS integration model for geothermal exploration and well siting. Geothermics, Volume 37, Issue 2, 107-131.

Shako, L., Mutua, J., 2011, Geo-Scientific Data Integration to Evaluate Geothermal Potential using GIS. Kenya Geothermal Conference, Nairobi, November 21-22, 2011.

Thinon, I., Guennoc, P., Bitri, A., Truffert, C., 2010, Study of the Bouillante Bay (West Basse-Terre Island shelf): contribution of geophysical surveys to understanding of the structural context of Guadeloupe (French West Indies − Lesser Antilles). Bull. Soc. géol. Fr., t. 181, N°1, 51-65.

Witter, J. D., Phillips, N., 2012, Integrated 3D Geophysical Inversion and Geological Modelling for Improved Geothermal Exploration and Drillhole Targeting. GRC Transactions, vol. 36, 831-834.

Wu, Q., Xu, H., Zou, X., 2005. An effective method for 3D geological modeling with multi-source data integration. Computers & Geosciences 31, 35-43.