3D geological & geophysical modelling of Plateau de Sault (Eastern Pyrenees) for good water management

Cécile Allanic, Lucile Martel, Bernard Monod, Thomas Jacob, Gabriel Courrioux, Vincent Bailly-Comte, Jean-Christophe Maréchal

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SUMMARY (200 words max)

Better constrain the geological geometries in 3 dimensions aids to improve subsequent hydrological modeling and simulations. The project "Plateau de Sault" (Eastern Pyrenees) aims to provide a better estimate and management of water resources of the region. The water flow occurs mostly underground via significant karst networks in a complex tectonic framework. Thus, a 3D geological model was built, as a prerequisite for hydrological studies, with the 3D GeoModeller software (©BRGM-Intrepid Geophysics) which is unique in interpolating complex geology using a potential field method. The construction of this 3D geological model has 3 main objectives: improve regional geology’s knowledge, propose geometries for limestone urgonian bars and define hypothetical connections between different aquifers. Structures at depth have been constrained by direct calculation and gravimetric inversion of the geological model thanks to newly acquired gravimetric data (around 250 stations) and densities of formations established in laboratory from 52 rocks sampled in the field. This study demonstrates the importance of integrative tools as 3D geological modeling for good water management.

Introduction

The establishment of a 3D geological model is a fundamental step to address groundwater problems. It will be the basis for: understanding the circulation systems, evaluation of resources, modeling the distribution of physical parameters (porosity permeability) and the numerical simulation of transfers. Flow is often largely controlled by faults, fracturing associated with folding, and solution features within limestone formations (ie. karst). It means that hydrogeological exploration in orogenic zones is always a challenging task because of the structural complexity and oversimplification of the initial geological model can lead to serious predictive errors. The aquifer system of the Pays de Sault (Eastern Pyrenees) is located on two different watersheds: Adour-Garonne and Rhône-Méditerranée. It occupies a strategic first-level position for the supply of water to the Aude and Ariège populations, hence the interest of a trans-basin approach. Although the Sault Plateau karst has been exploiting groundwater resources for several decades, it has never been resolved and has not been the subject of an operational investigation program until today. In order to acquire new knowledge about the functioning, structure and location of groundwater reserves of karstic systems in a geologically complex area such as the Sault Plateau, it is necessary to conduct a thorough structural geology study in three dimensions. This study makes it possible to constrain the geometry of the carbonate formations, basic data to identify the possible paths of the karstic flows and the position of the reservoirs and generate drill targets.

Regional geological setting

The Pays de Sault is located on the northern slopes of the Pyrenees (Figure 1), immediately south of the sub-Pyrenean zone (ZSSP). It covers three of the major structural zones of the chain from north to south: the northern Pyrenean zone (ZNP), the metamorphic internal zone (MIZ) and the axial zone (ZA).

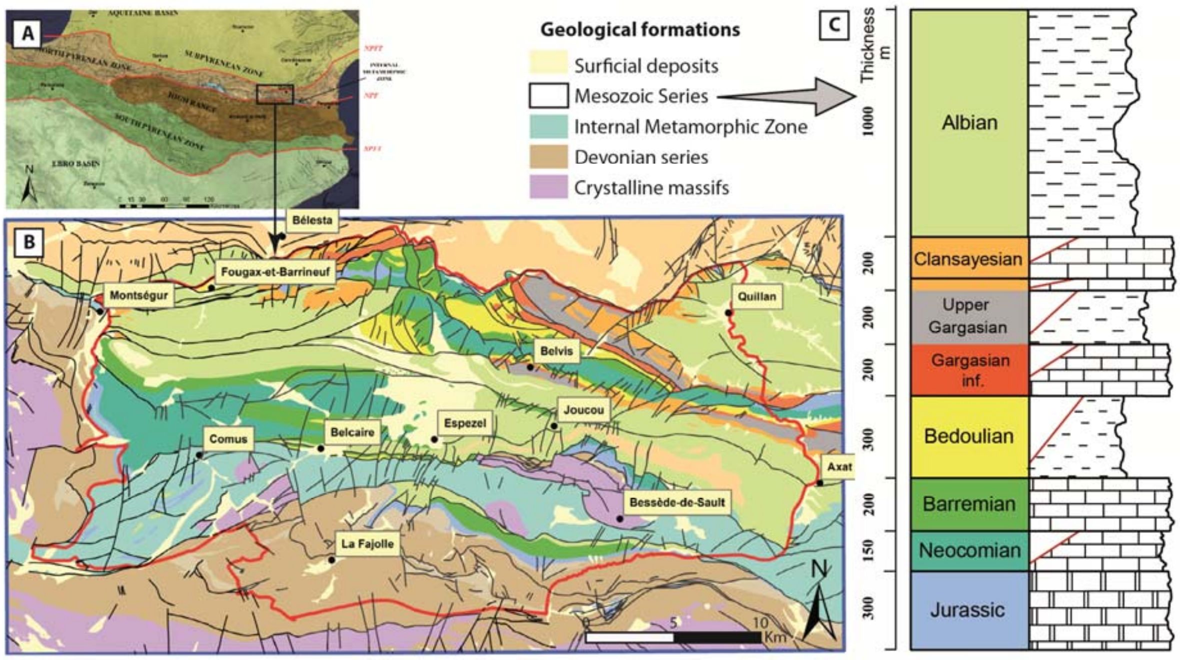

Figure 1 *(A) Location of the study area in the general structural framework of the Pyrenees; (B) Simplified geological map of the study area (Monod, 2015). In red: the study area. In blue: the zone of the 3D geological model; (C) Geological pile of the modeled formations.*

From south to north, the geological units of the modeled area are:

- the axial zone, consisting mostly of paleozoic and basements,
- the northern Pyrenean zone, composed of Mesozoic rocks from the Triassic to the Upper Cretaceous.
- To the south, the metamorphic inner zone (MIZ), consisting essentially of metamorphic terrains (marbles) from the Jurassic to the Lower Cretaceous
- the Pyrenean zone, consisting of Mesozoic to Cenozoic rocks from the upper Cretaceous to the Paleogene.

These 4 zones are delimited by major structural accidents such as the North Pyrenean fault (NPF), the north Pyrenean frontal thrust (CFNP) or the fault bordering the North of the MIZ (Figure 1). The formations present throughout the region essentially alternate between banks of massive limestones and marls (Figure 1C) (Bilotte, et al., 1988). As stated in the introduction, the main targets of this study are the limestone formations of the Barremian, Gargasian and Clansayesian facies. Indeed, their lithologies are favorable to the development of important karstic networks. The complexity of the zone is due to the fact that he thickness of some formations varies considerably within the zone, even to the disappearance of certain formations in places (Figure 1C, slash in red) (Peybernes, 1979) (Bilotte, et al., 1988). Thus, the calcareous formations of the Clansayesian and the Gargasian can see their thicknesses decrease so significantly that it becomes difficult to determine a stratigraphic contact between them and the neighboring formations. They are then grouped together in the form of a calcaro-marneuse unit (Bilotte, et al., 1988).

Preliminary implicit 3D geological modelling essentially from field data

As part of the hydrogeological study of the Sault Plateau, the building of a geological model for a three-dimensional representation of the geological system was required. The aim of the model was to improve the geological and structural knowledge of the system and the understanding of its geometry in order to better evaluate the transfer of fluids in the basin.
Primarily, the 3D modelling requires the consistency of all available data; it also allows to integrate the data in a common geometrical referential, and thus to merge them into a geological model that supports the 3D structural interpretation. The 3D preliminary model of the study area has been achieved using the geological map, including lithological boundaries, and field structural data.

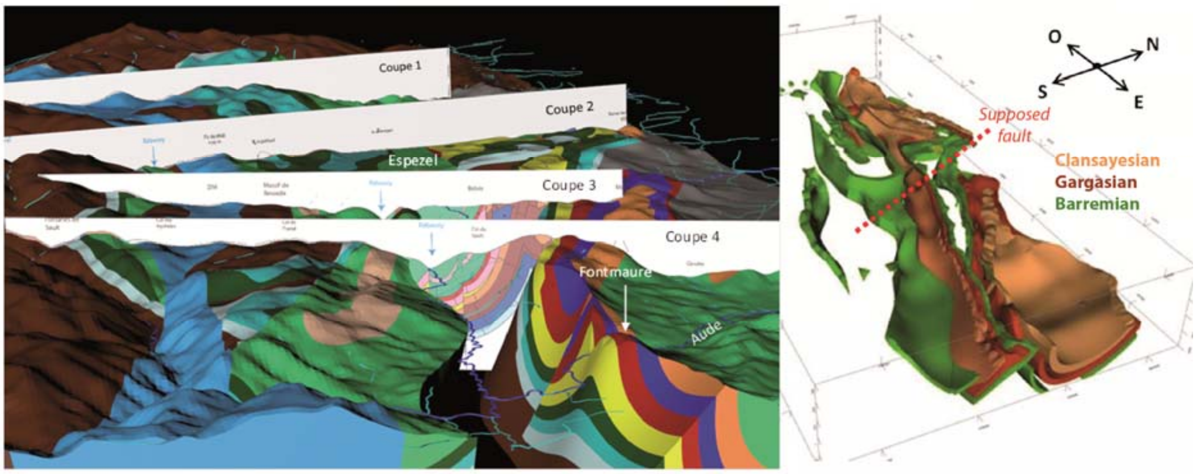

Figure 2 *View toward the west of the preliminary implicit 3D geological model of Plateau de Sault and details (to the right) of the geometries of the three Urgonian facies formations.*

For this purpose, we used the ''3D Geomodeller'' software (© BRGM - Intrepid Geophysics; http://www.geomodeller.com) (Aug 2004, Guillen et al. 2004, Martelet et al. 2004), which reproduces

3D geological geometries based on interpolation of a scalar field in space (Chilès et al. 2006, Lajaunie et al. 1997), where a lithological contact corresponds to an isovalue of this field and the dipping of the structures corresponds to the gradient of this field. The topological relationships between the different lithological units and the geometrical relationships, like superposition, intrusion or cross-cutting relations, are taken into account through a ‘‘lithological pile’’, in order to reproduce complex geological systems as realistically as possible. A 40*20*2 km 3D model of the regional geology was thus interpolated (Figure 2). This model is preliminary since no constraints have been introduced yet concerning the depth of geological bodies. At this stage, the geometry derives from a geostatistical extrapolation of surface geological observations of contacts and dips.

Gravimetric acquisition

The geological and geometrical coherence of the 3D geological model has been reached but an important phase is missing: the question of the validity of the model. The construction phase of the model made it possible to highlight the lack of depth constraint. This is why 258 gravimetric stations have been implanted and measured in gravimetry and differential GPS on the study area. A Scintrex CG-5 field gravimeter (CG5 # 028) was used to perform gravimetric measurements. The calibration coefficient of the gravimeter is 0.999872. It was established between two absolute bases IGN during the mission: Camurac I and Bouriege A, for a difference of 205,493 mGal. This coefficient was taken into account when the data were reduced.

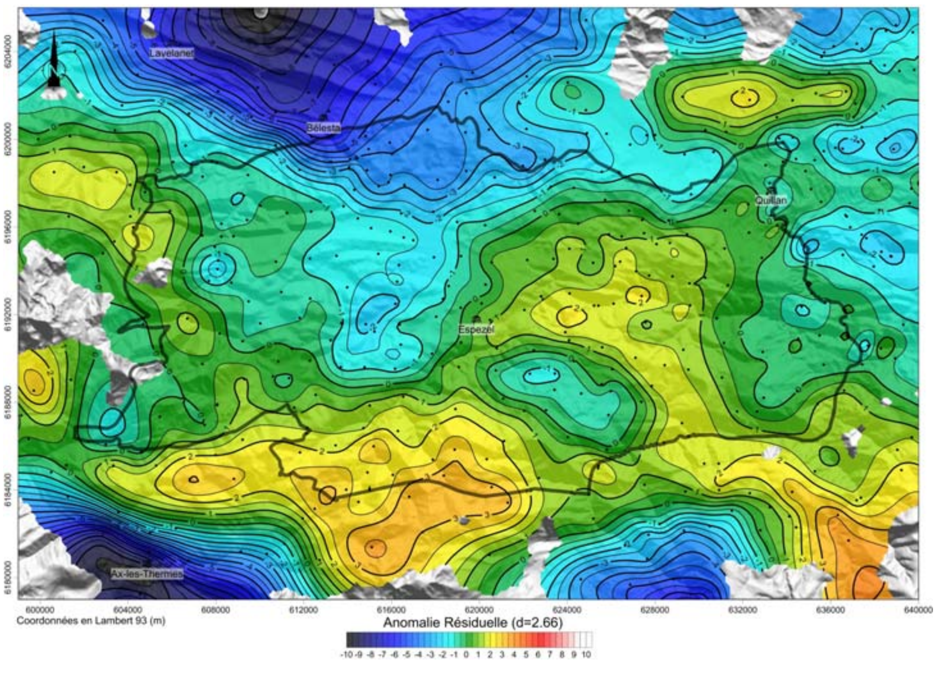

Figure 3 *Residual gravimetric anomaly of the studied area, used for subsequent gravimetric inversion of the 3D geological model.*

The residual anomaly, in figure 3, is obtained by subtracting the regional anomaly from the Bouguer anomaly and shows the variations in gravity in relation to the variations in density between the surface and a depth at least equal to 2000 m. The residual anomaly varies from -10 mgal to 4 mGal.

Direct calculation and gravimetric inversion of the preliminary 3D geological model

In a third step, inverse modelling of the Bouguer gravity anomaly was performed in order to refine the preliminary 3D geology, especially in depth. In order to improve the geometrical models realized above, a 3D gravity inversion has been carried out. We used a statistical formulation of the inverse problem (Bosch et al. 2001, Guillen et al. 2008, Guillen, et al. 2004). This inversion scheme is particularly adapted to refine existing models since a realistic and topologically consistent starting model is needed in order to achieve a meaningful convergence of the inversion process. Being part of 3D Geomodeller software, the inversion algorithm is designed to investigate the space of possible density models following a Monte–Carlo algorithm (Guillen et al., 2006). The inversion process is briefly explained here and we refer to Guillen et al. (2008, Guillen, et al. 2004) for a thorough description of the method. In order to compute the gravity effect of the 3D model, the starting geometrical model is discretized into 3D elementary voxels. Densities of the different modeled units of the study area were determined in laboratory from rocks sampled in the field.

Conclusions

Even with no seismic data, quasi exclusively with field structural measurements, it has been possible to propose 3-D coherent geometries for Sault hydrogeological reservoirs. This model is currently the most up-to-date support. It integrates most of the data collected in history in the region. Additionally, it brings new clues on the deep structure from geophysics. This integrated approach has highlighted the dichotomy between the east and west of the Sault plateau, present on the geological map and on the residual gravimetric anomaly. A central negative anomaly, of orientation N040 °, hitherto unmapped, delimits the west and east parts of the plateau. This limit has been modeled as a blind fault present in the base. On the eastern part, the basement appears to be relatively close to the surface (little or no Triasic evaporites), indicating a predominant tectonic base, while on the western part the basement seems deeper and /or with the presence of more important Triasic evaporites. Well-defined negative anomalies are noted at the MIZ level. These were interpreted as local thicker marble. A major discontinuity of direction N120 ° is observed in the northwest of the study area, limiting a parallelepipedic basin of flyschs.

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