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How can an integrated multi-method geophysical approach optimise the groundwater management in the Chalk aquifer? Case study of the Seine fault system (France, Normandy).

Comment une approche géophysique multiméthode intégrée peut-elle optimiser la gestion des eaux souterraines dans l'aquifère de la craie ? Etude de cas du système de failles de la Seine (France, Normandie)

Angélie Portal^{1,*}, Baptiste Meire², Erwan Idée³ and Pierre-Yann David³

¹ BRGM, F-45060 Orléans, France

² BRGM, F-59810 Lesquin, France

³ BRGM, F-76130 Mont Saint-Aignan, France

Abstract. The Cretaceous chalk aquifer is a strategic water resource in the north of France, especially in Normandy where it faces increasing pressure in terms of its quality and availability. The effective and sustainable manage of this resource relies on a deep understanding of its complex geological and hydrogeological nature. However, modelling this hydrosystem has its limitations due to the spatial and qualitative heterogeneity of the data available. The integration of geophysical data using various methods and scales has improved the geological knowledge by identifying the different chalk formation and highlighting the geometry of the Seine fault system near Rouen. Geophysical analysis has revealed highly complex fault geometries in this area and clarified their impact on the chalk formations. Additionally, it has provided detailed information about the vertical heterogeneity of the chalk, both geologically and hydrogeologically. This new knowledge feeds into the existing 3-D regional geological model, especially in areas with limited data. Supporting hydrogeological modelling, this updated model has already enabled to drill new boreholes. In the future, it will contribute to a better understanding and management of groundwater resources in this region.

* Corresponding author: a.portal@brgm.fr

Résumé. L'aquifère de la craie du Crétacé constitue une ressource en eau stratégique du grand nord de la France, et notamment en Normandie, où des pressions croissantes pèsent fortement sur sa qualité et sur sa disponibilité. Aujourd'hui, la gestion efficace et durable de cette ressource requiert une compréhension approfondie de sa nature géologique et hydrogéologique complexe. Mais la modélisation de cet hydrosystème présente des limites à cause de l'hétérogénéité spatiale et qualitative des nombreuses données disponibles. L'intégration de données géophysiques utilisant des méthodes variées et opérant à différentes échelles a permis d'améliorer significativement les modèles géologiques et structuraux de la zone du système faillé de la Seine près de Rouen. La géophysique a révélé des géométries de failles très complexes dans ces zones et préciser leur impact sur la géométrie des formations crayeuses. Elle a permis d'observer avec un niveau de détail inédit l'hétérogénéité verticale de la craie, tant d'un point de vue géologique qu'hydrogéologique. Ces connaissances nouvelles alimentent aujourd'hui un modèle géologique 3-D régional, notamment dans les secteurs pauvres en données. Support de la modélisation hydrogéologique, ce modèle mis à jour a déjà permis l'implantation de nouveau forage. A l'avenir, il contribuera à une meilleure compréhension et gestion de la ressource en eau souterraine dans cette région.

1 Introduction

The Cretaceous chalk is the main aquifer in the Paris basin and in eastern Normandy. This strategic water resource, only fed by precipitation, is characterised by a high porosity (~40% in matrix and fissure, locally fractured and/or karstified) which favours its supply but makes it particularly vulnerable to pollution. In a context of pressure on its availability and quality, the management of this resource is therefore a major challenge.

Effective management of this resource requires a thorough understanding of the complex nature of the subsoil. Numerous studies have shown that the chalk is highly heterogeneous in terms of the nature of its formations [1–5] (Figure 1). Each lithological unit (formation) defined by the authors (nature of the facies) has its own petrophysical characteristics which affect the hydrogeological properties (permeability, porosity and type of fracturing in particular) [6]. The chalk aquifer is therefore vertically compartmentalised. Understanding this hydrogeological stratification is therefore a key issue in geoscience.

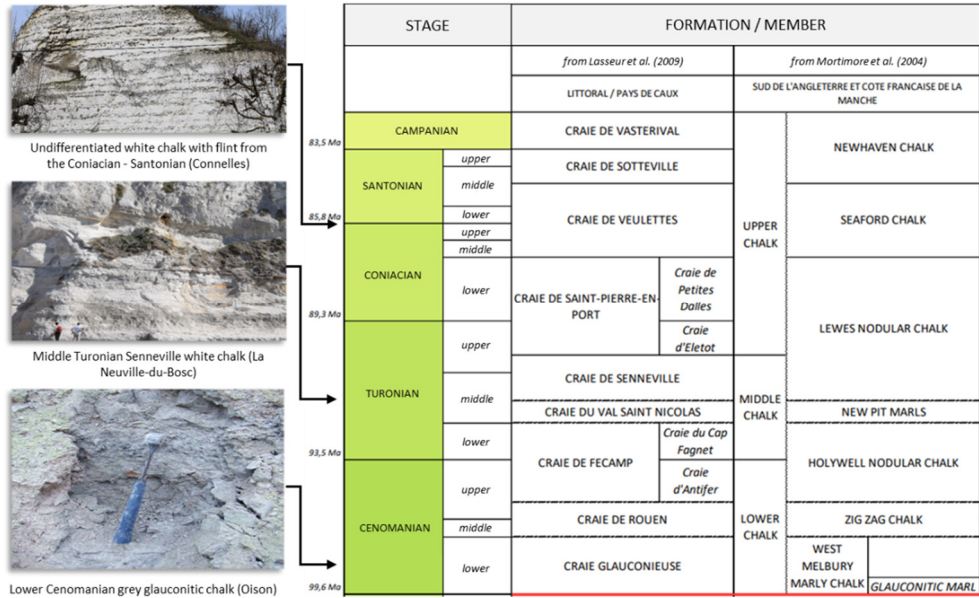


Fig. 1. Litho-stratigraphic synthesis of the chalk in the Rouen region by Meire et al. (2019) [7].

We present here an innovative integrated multi-method geophysical imaging approach. Applied to several sites in Normandy, this strategy allowed us to identify the different formations, to avoid uncertainties associated with the geometry and properties of the chalk aquifer and to constrain the main structures affecting them. In these areas, this approach has proved to be an indispensable asset in updating the geological models needed to understand the Chalk hydrosystem [7–10].

2 Methodology

We have designed a three-stage multi-method geophysical approach to achieve the previously described objectives (Figure 2):

1. At the scale of the entire study area, gravimetry was performed in order to finely map the major faults affecting the chalk and to identify the different tectonics blocks linked with the basement. (scale: several km²; regular mesh: 200-300 m);
2. High-resolution seismic reflection was deployed on the steepest gravimetric gradients in order to investigate, at depth, the geometry of the structures at the origin of these gradients (scale: 0-500 m; receivers and shot spacing: 5 and 10 m);
3. Based on the seismic sections, we carried out electrical imaging profiles (Electrical Resistivity Tomography - ERT) to provide a detailed characterisation of the geometry and heterogeneity of the lithologies for geological and hydrogeological interpretation (scale: 0-150 m; spacing: 10 m).

This strategy offers the advantage of exploring geological targets at different and complementary scales and resolutions.

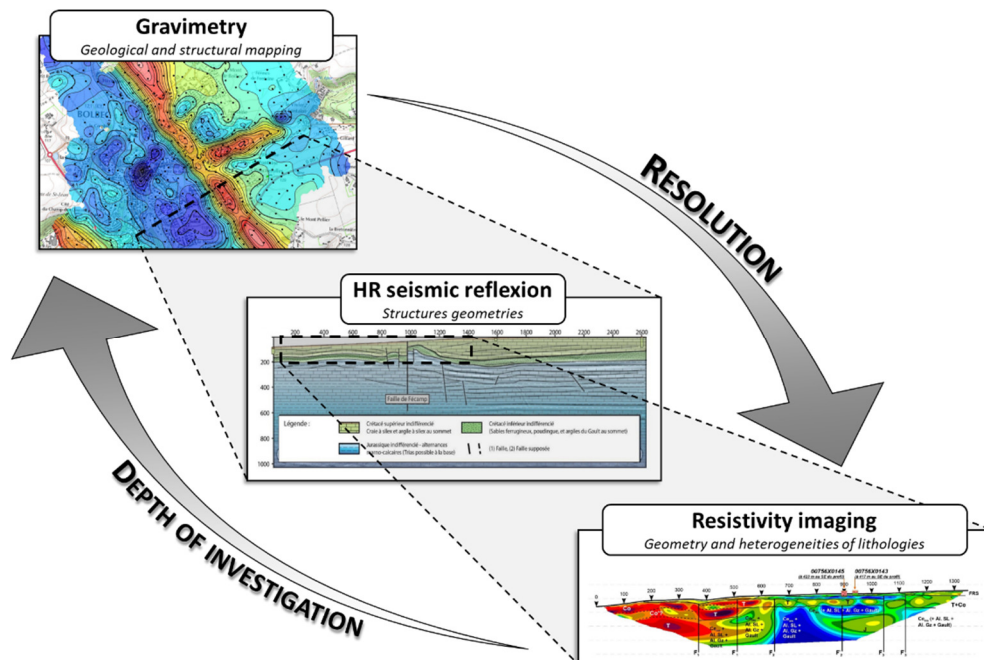


Fig. 2. Scheme of the focusing multi-scale and multi-method approach designed for the detailed characterization of the chalk aquifer.

3 Results

3.1 The Fécamp-Lillebonne fault (Bolbec area)

In the Bolbec area, the integration of geophysical results and geological available data has led to the proposal of a new structural scheme revealing previously unknown structures (Figure 3)[7]. The Fécamp-Lillebonne fault is a N150°-trending bundle structure that sometimes delimits tilted blocks. This complex structure evolves longitudinally to form spindle-shaped braided faults characteristic of shear zones. In addition, N45°- oriented narrow grabens intersected these bundles. All these structures isolate stair-stepped, tilted or pinched blocks. A faulted antiform structure at the northeast edge of the main fault leads to an uplift of the formations from the base of the Upper Cretaceous (Cenomanian chalk) and of the Lower Cretaceous.

In addition to controlling the geometry of Cretaceous aquifers, each of these structures can act as a drain for water flows, especially when they intersect carbonate formations in which dissolution will enlarge fractures and accentuate karstification [11]. As a result, these structures have played a major role in the development of a highly developed karstic system, using the Fécamp-Lillebonne faulted network as the main vector. Locally, the entire functioning of the hydrosystem of the Rivière du Commerce valley is influenced both by the geometry of the formations and by the existence of this network of faulted structures. The

groundwater level and the water supply to the river are thus influenced, and the development of a major karstic system modifies the water flows.

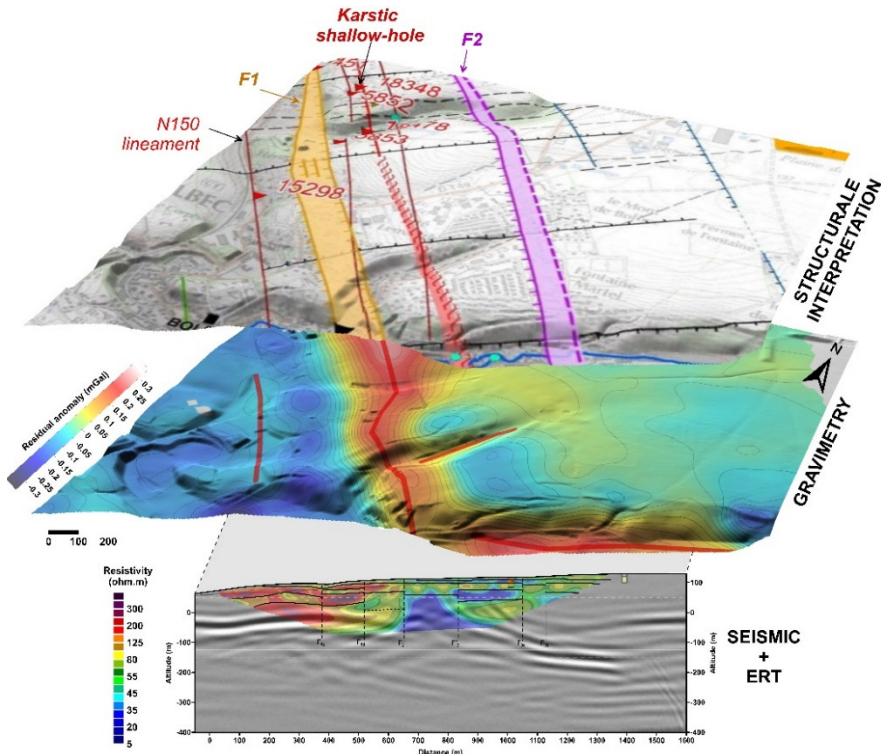


Fig. 3. Synthesis of the geophysical results and their structural interpretations along the Fécamp-Lillebonne fault in the Bolbec area.

3.2 North of the Seine valley (Rouen area)

In the North of Seine valley north near Rouen, the application of the multi-method focusing approach has considerably enhanced our understanding of the geometry of the Seine fault and the Grand-Tendos fault, and their impact on fracturing and alteration of the chalk [12]. These faults represent major complex tectonic structures, characterised by fault bundles several hundred metres wide, including a number of fractures with low vertical rejection. Within these faults, the chalk formations show greater fracturing and/or alteration. These geometries have structural similarities with the Fécamp-Lillebonne fault.

Analysis of the electrofacies in this region revealed that they reflect the lithostratigraphic division of the chalk formations proposed by Lasseur [2] rather than the classic biostratigraphic division. This lithostratigraphic division is of crucial importance for understanding the hydrosystem, as the hydrogeological behaviour of the chalk formations is closely linked to their lithologies rather than their age. . The study enabled to draw up an electrical "identity card" of the different chalk formations. Demonstrating the ability of electrical imaging to characterise this lithostratigraphic division represents a major advance in the study of these complex hydrosystems [8].

3.3 The "Boucle de Poses" area (Seine valley south of Rouen)

To the south of Rouen, this approach has enabled us to redraw the complex structural scheme of the "Boucle de Poses" sector. In particular, the geophysical results indicate that the Seine fault is a braided fault structure (Figure 4), similar to the Fécamp-Lillebonne fault. These faults define a faulted anticline structure on the eastern raised compartment. The raised blocks are characterised by the upwelling of early and pre-Cretaceous terrain.

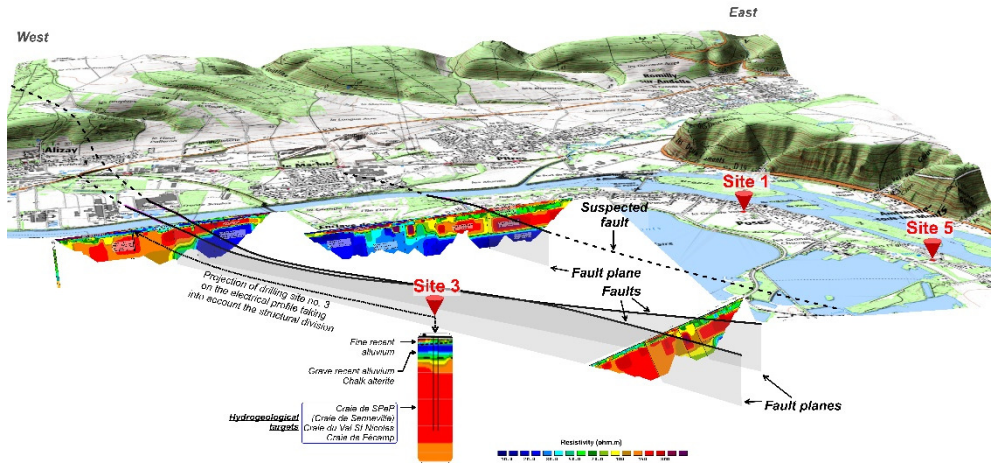


Fig. 4. Synthesis of the electrical results and their structural interpretations along the Seine fault in the boucle de Poses area (South of Rouen). Ancient terrain are visible in blue colors on the scheme (early-Cretaceous clay and sands).

This new structural scheme, together with all the available geophysical and geological data, has led to the production of a summary map of the sectors suitable for water resource exploration. In this sector, the role of tectonic structuring and weathering on the productivity of the chalk formations is questionable. Borehole investigations clearly indicate a positive effect on the transmissivity of formations located near the main faulted structures. On the other hand, the compartmentalisation into horsts and grabens could have a negative effect on the ability to mobilise water resources, despite the proximity of the Seine. This implies that some of these structures probably have a limiting role on flows.

4 Conclusion

The multi-method focusing approach presented here and applied to the Cretaceous formations of Normandy has proved its effectiveness in characterising the geometry of the chalk formations and the major fault systems that affected them. Thanks to a robust analysis method based on high-quality borehole geological data, resistivity imaging in particular has demonstrated its ability to offer a wealth of detailed information for characterizing the lithostratigraphic division of the chalk. This approach is now making it possible to spatialize information at different scales (local and large scale). All this new data has enabled BRGM teams to feed a 3D geological model of the Seine estuary, bringing together all the sites investigated.

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