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Impact of the landscape evolution on the hydraulic boundary conditions of the Callovo–Oxfordian formation

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Abstract

The Callovo–Oxfordian formation in the Eastern part of France was recognized as a potential nuclear waste repository layer. The Andra (National Agency for Nuclear Waste Management) has launched a few years ago a research program that aims to define the mechanisms of importance in the impact of the surface environment evolution on the site hydrogeology.

Based on mapping and dating results, Andra has quantified the geomorphological evolution of the Meuse/Haute-Marne site in the past and has estimated the future evolution over 1 million years. The Callovo–Oxfordian boundary conditions depend on the hydraulic heads in the two surrounding aquifers, the Oxfordian limestone above, and the Dogger one, below. Both aquifer outcrops are modified over the next million years.

For the present study, the geomorphologic evolution is considered independently of other processes and translated in the hydrogeological model in terms of changes in the hydraulic boundary conditions at the surface. The hydrodynamic simulations have been performed with the code Cast3M (implemented by CEA (Atomic Energy Commissariat)) using a mixed hybrid finite-element formulation. For these groundwater flow simulations, three modelled stages are presented: the Present, 500,000 years (500 Ky) and 10^6 years (1 Ma) in the future. The landscape evolution is merely considered through the use of three different topographies on which the boundary conditions are applied. According to Andra predictions, at the Meuse/Haute-Marne site, the valley incisions on the Bure plateau will locally reach the Oxfordian limestone. Thus, the Oxfordian aquifer exhibits more changes due to topographic evolution than the Dogger aquifer.

Hydrodynamic simulations show a significant impact of the valley incisions on the groundwater flow by the creation of local outlets to the Oxfordian limestone aquifer in the North of the area for the 1 My topography. It induces local perturbations of the saturation level. The global erosion of the topography also pulls down the hydraulic heads on a regional basis. Changes induced by the geomorphologic evolution in the Dogger aquifer are located around 30 km East from the Underground Laboratory site, at the outcropping areas. Thus, at the Laboratory location, the piezometric surface does not show, for the future, significant modifications compared to the present state. The 20-m general lowering of the hydraulic heads in the Dogger is also globally less important than for the Oxfordian aquifer.

The consequence on the Callovo–Oxfordian boundary conditions for the future is an increase of the internal upward vertical hydraulic gradient which, at present state, is well developed only immediately to the North of the Laboratory.

Keywords: Geomorphology; Hydrogeology; Valley incision; Nuclear waste repository

1. Introduction

The Callovo–Oxfordian formation in the Eastern part of France (Fig. 1) was recognized as a potential deep nuclear waste repository layer. Potential geological host formations

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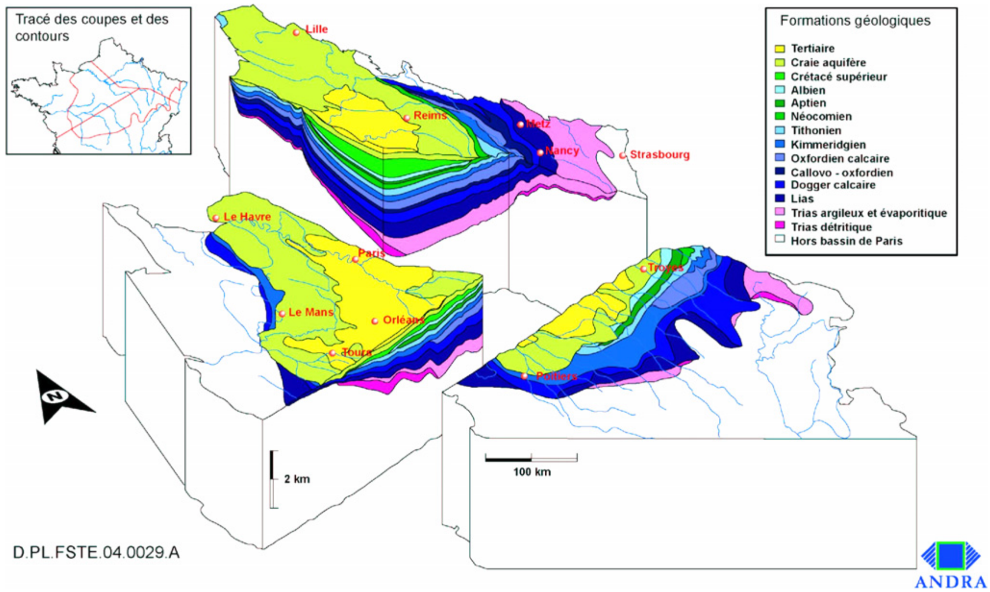

Fig. 1. Geological map and cross section of the sedimentary Parisian Basin.

(and their surroundings) are chosen in particular for their long-term stability, their ability to accommodate the waste disposal facility, and to attenuate potential release of radioactivity. To estimate potential transfers from the host formation to the biosphere, it is important to understand the evolution through time of the hydraulic boundary conditions of the clay layer as well as the evolution of the whole hydrological system. The Andra (National Agency for Nuclear Waste Management) has launched in 1994 a research program on the geoprospective of the Meuse/Haute-Marne site, where the underground research laboratory is being constructed. This program aims to define what could be, for the next million years, the possible evolution of the climate, the surface environment (geomorphology, hydrology and permafrost dynamics), and to assess their potential effects on the surface and subsurface hydrodynamics in the Bure area. In order to assess evolution through time of this system and to support a coupled phenomenological approach, Andra develops a generic modelling. It aims to define the main mechanisms in the surface environment evolution that impact the site groundwater dynamics. Here, generic means simpler and easier to handle. This generic model will serve as a basis for the future integrated models.

Over 1 million year, natural system evolution mainly depends on internal geodynamical (tectonics) and external climate conditions. One may reasonably assume that, in the North-East of France, tectonics play a minor role in terms of site stability at a time scale of a few hundred thousands of years since it exhibits slow uplift and deformation kinetics (Brulhet, 2004). However, the regional uplift drives the long-term landscape evolution mainly through valley incision dynamics. Plateaus should not be much eroded over 1 million years (Brulhet, 2004; Cojan et al., 2006). On the contrary, climate cyclic variations may have important regional and local consequences at a shorter scale. The period of these cycles varies from 1000 up to a 100,000 years (Jousseaume, 1999). The two main climatic variables, temperature and precipitation, influence the surface and subsurface environmental conditions mainly through two types of processes: erosion (landscape evolution) and ground freezing (permafrost formation). Besides these natural forcings, one should bear in mind the anthropic forcings which importance is now recognized [greenhouse gas emission (Duplessy, 2001), deforestation, urbanization,...]. These anthropic impacts on long-term climate evolution has been investigated (BIOCLIM program, Texier et al., 2003).

The purpose of this work is to assess through numerical modelling the impact of the topography evolution through time on the hydrological system of the Bure site and on particular, on the boundary conditions of the Callovo–Oxfordian formation. The Callovo–Oxfordian boundary conditions depend on the hydraulic heads in the two surrounding aquifers, the Oxfordian limestone, on top, and the Dogger one, below. Both aquifer outcrops are modified over the next million years. Here, a natural evolution of the landscape is considered, it embeds both geodynamical and natural climate forcings. The modelled area and the data used for the numerical simulations are first described. Secondly, simulation results are presented for both aquifers surrounding the Callovo–Oxfordian formation. Lastly, the implications on the head gradient in the host formation is studied.

2. Geological and geomorphological context

The deep underground laboratory is located in the Callovo–Oxfordian formation in the Eastern part of the sedimentary Parisian basin (Fig. 1). This sedimentary basin has been active from the Triassic period up to the Tertiary.

In the Eastern part of the Basin, at the deep underground laboratory site, the most recent remaining layer was deposited during the Lower Cretaceous period. The site exhibits an extensive tabular structure dipping westward with a 1–2° slope (Fillion et al., 2000).

The geomorphologic evolution in the Eastern part of the Paris Basin has been important during the last two million years. The landscape evolution has been characterized mainly by outcrop retreat linked to valley incisions. The outcropping limestones have been affected by karst development. The hydrographical network has evolved through a stepped process due to river piracies. In the Meuse/Haute-Marne region, the Meuse River tributaries have been captured progressively by rivers of the Seine basin. The upstream part of the Meuse River network has been diverted towards the Rhine basin (Pissart et al., 1997; Harmand et al., 1998). Specifically, on the Bure area, the Saulx and Ornain Rivers became tributaries of the Marne River since circa 200 Ky B.P (Cojan and Voinchet, 2004).

Based on mapping and dating results, Andra has quantified the geomorphological evolution of the Meuse/Haute-Marne site for several hundred thousand years in the past and has estimated the future evolution over 1 million years.

3. Hydrological simulations

3.1. Modelled area

The modelled area has an extension of 60 km by 40 km. It is centered on the underground laboratory site (Fig. 2). Six geological layers have been modelled in 5 numerical layers (Fig. 3). At the surface, the Tithonian limestones of Barrois and Cretaceous sands are modelled by a single top layer. The other layers represent respectively, from top to bottom, the Kimmeridgian marls, the Oxfordian limestones, the Callovo–Oxfordian clays (the host formation), and the Dogger limestones. The maximum total thickness represented by these five layers reaches 800 m. Two horizontal resolutions have been considered: 500 m

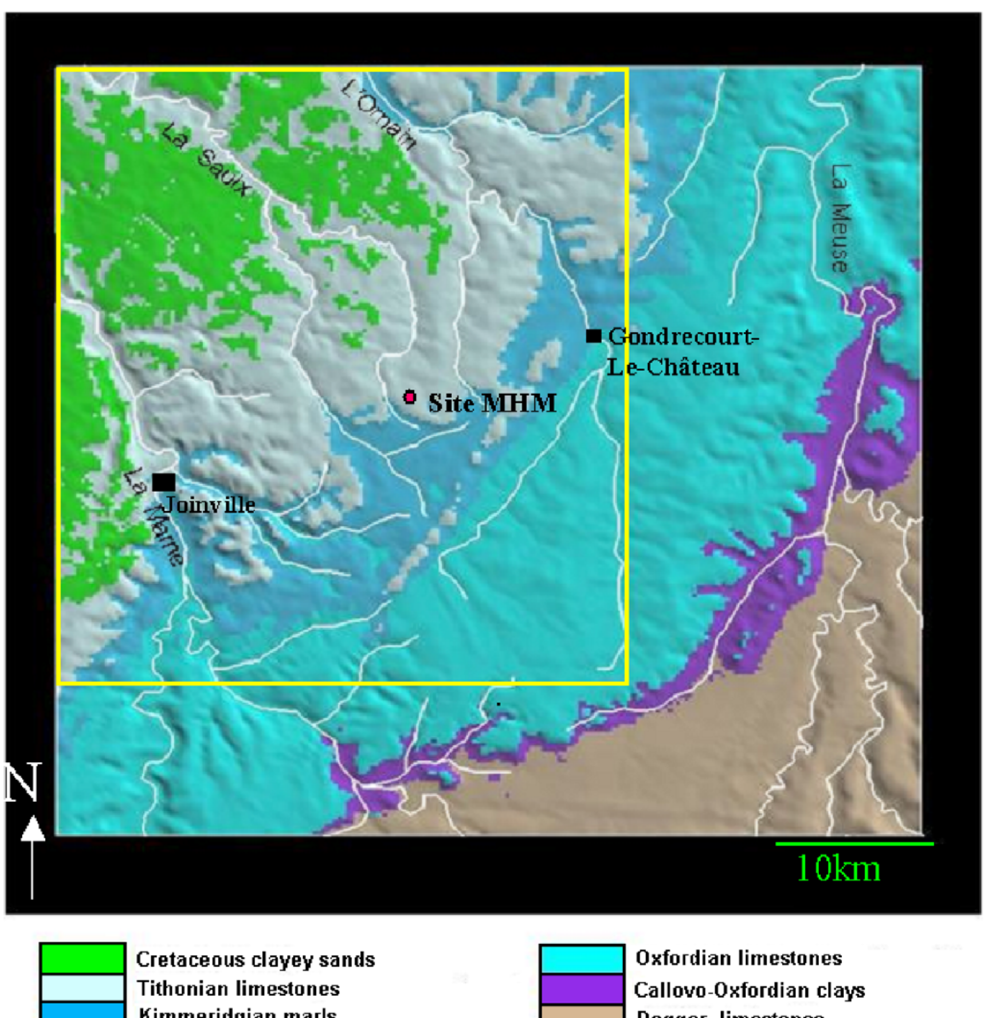

Fig. 2. Geological map of the modelled area.

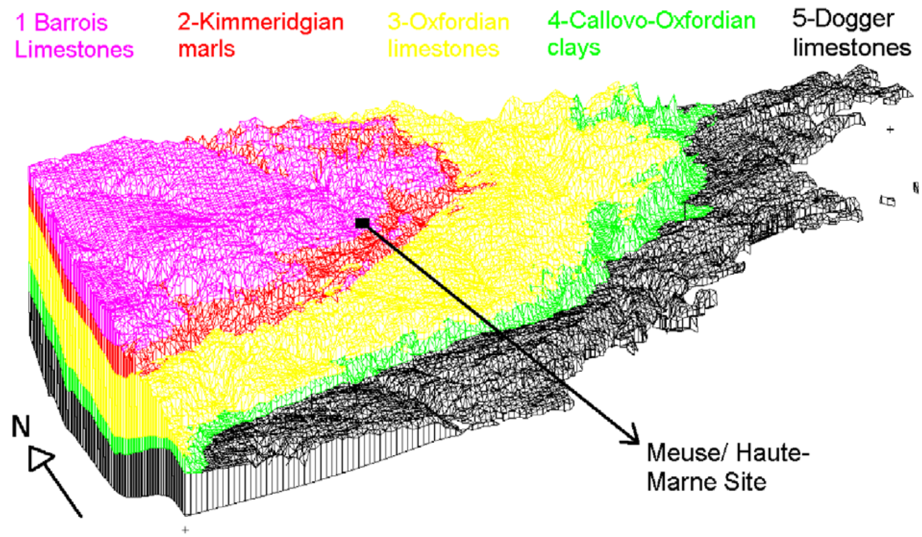

Fig. 3. 3D view of the model mesh representing 5 top geological layers at the local scale (70 × 80 km) (94,575 mesh elements).

and 250 m. The latter was directly given by the geologic software GOCAD, embedding all the geological geometries of the area. Results do not depend on the resolution at which the simulation are run. The same results are observed for the two resolution scales. Each layer has been meshed automatically with triangle-based prisms. Triangles allow a good description of the layer surfaces, and vertically, there is one mesh element per layer.

3.2. Hydrogeological data

The hydrodynamic simulations have been performed with the code Cast3M (Verpeaux et al., 1988; Le Fichoux, 1998) implemented by CEA (Atomic Energy Commissariat), using a mixed hybrid finite-element formulation to solve Darcy equations (Chavent and Roberts, 1991; Dabbene and Martin, 1994). This formulation has been proved to be adequate for sedimentary basin such as the Paris Basin (Mouche and Treille, 1997; Bernard-Michel et al., 2004).

Since this site has been under investigation by Andra since 1994, numerous data have been collected through mapping, core drilling, well logging 2D seismic transects, and hydrogeologic studies (hydraulic pulse, piezometric monitoring). Data used for the present work comes from this collection of data (Andra, 1999). Table 1 presents the hydraulic conductivities considered here, and consistent with previous hydrogeological models (ANTEA, 2001). The cinematic porosity is assumed in the aquifers to be equal to 10%.

Table 1
Modelled layers and their hydrological parameters

Layers	Hydrological behaviour	Hydraulic conductivity, m/s
Cretaceous sands Barrois limestones	Aquifer	3×10^{-5}
Kimmeridgian marls	Impervious layer	10^{-12}
Oxfordian limestones	Aquifer	3×10^{-9}
Callovo–Oxfordian clays	Potential Host formation, impervious	10^{-13}
Dogger limestones	Aquifer	3×10^{-9}

3.3. Geomorphological evolution

Based on regional mapping and dating results, Andra has quantified erosion rates depending on lithology (carbonates vs. claystones) and location (rivers vs. plateaus). The map of extrapolated erosion rates is represented in Fig. 4. On plateaus, erosion rates depend on lithology, with larger values for claystones (20 m per 500,000 years) than

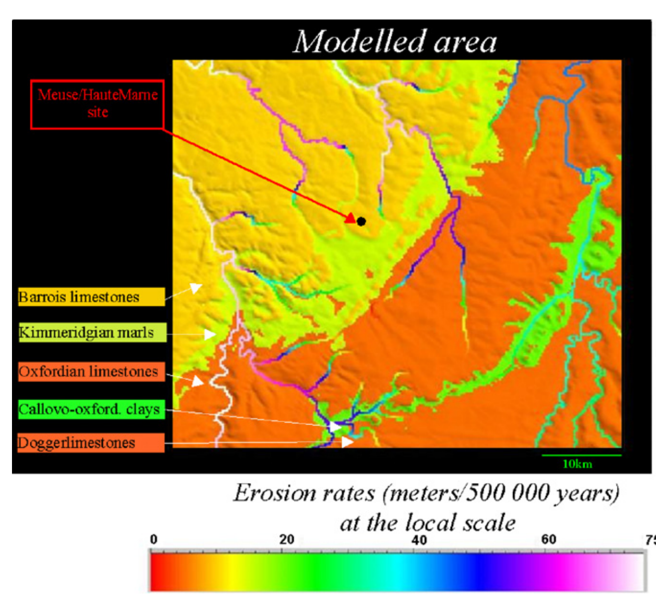

Fig. 4. Map of erosion rates over 500,000 years.

for limestones (between 5 and 10 m per 500,000 years). Furthermore, erosion rates are weaker on the plateaus than in the valleys where the river incision rate may reach a value of 60 m per 500,000 years for the largest rivers of the area. This is a very schematic view, and it should be considered as a maximum erosion scenario (Brulhet, 2004). According to these Andra predictions, over the next million years at the Meuse/Haute-Marne site (Fig. 5), the valley incisions on the Bure plateau could reach the Oxfordian limestones in the Ornain River valley in the northern part of the studied area. In the Marne and Saulx River valleys, the valley incision would extend the Oxfordian outcrops. Besides, a general erosion of the cretaceous layer and general retrograding outcrops are expected, as well as erosion of the Barrois limestones at the underground laboratory location. Although, three stages (Andra, 2003) were computed: the Present period, 500,000 years (500 Ky) and 10^6 years (1 My) in the future, only the first and last one are presented and illustrated here.

3.4. Numerical simulations

For the hydrological modelling, the geomorphological evolution is considered independently of other processes. For each period, one numerical steady-state simulation is run. The landscape evolution is merely considered through the use of different topographies. At the surface, the hydraulic boundary conditions are constant heads equal to elevation. At the lateral boundaries of the two undercover aquifers, constant heads are prescribed from a large interpolation of the heads measured in wells in the area. These lateral head values are not modified between simulations. This assumption is not valid per se in the long-term. However, as the aim of these simulations was to study the modifications induced by the changes in topography alone through time, it was assumed that, between stages, changes affect only the topography and the associated constant heads at the top surface.

Transport is modelled with a hundred particle trajectories computed in both surrounding aquifers (Oxfordian and Dogger limestones). In order to simulate leaks from the host formation, particles are launched at the bottom of the Oxfordian layer and at the roof of the Dogger layer. Horizontal coordinates of particle starting points are drawn at random in a 3-km radius area centered on the laboratory. This area is assumed to cover the Laboratory area and the potential lateral spreading distance by diffusion in the Callovo–Oxfordian Formation before a potential pollution reaches the aquifers. These pathlines represent only advection, with no dispersion nor diffusion. Particles were launched at the beginning of each simulations, which were run for 1 million years at steady-state.

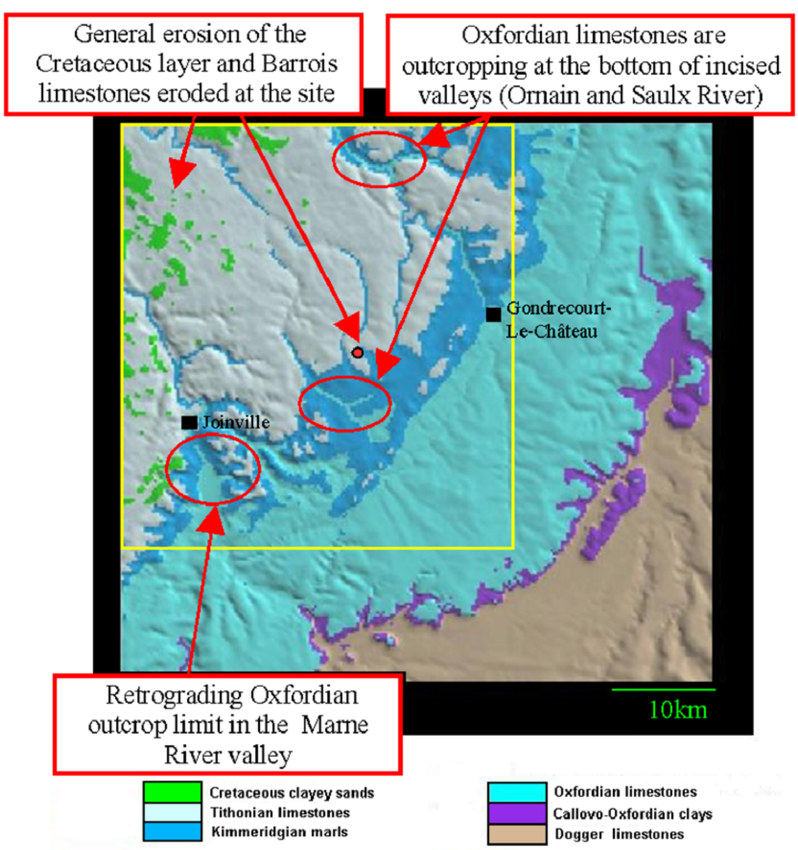

Fig. 5. Geological map estimated at 1 million year in the future. Main modifications are highlighted.

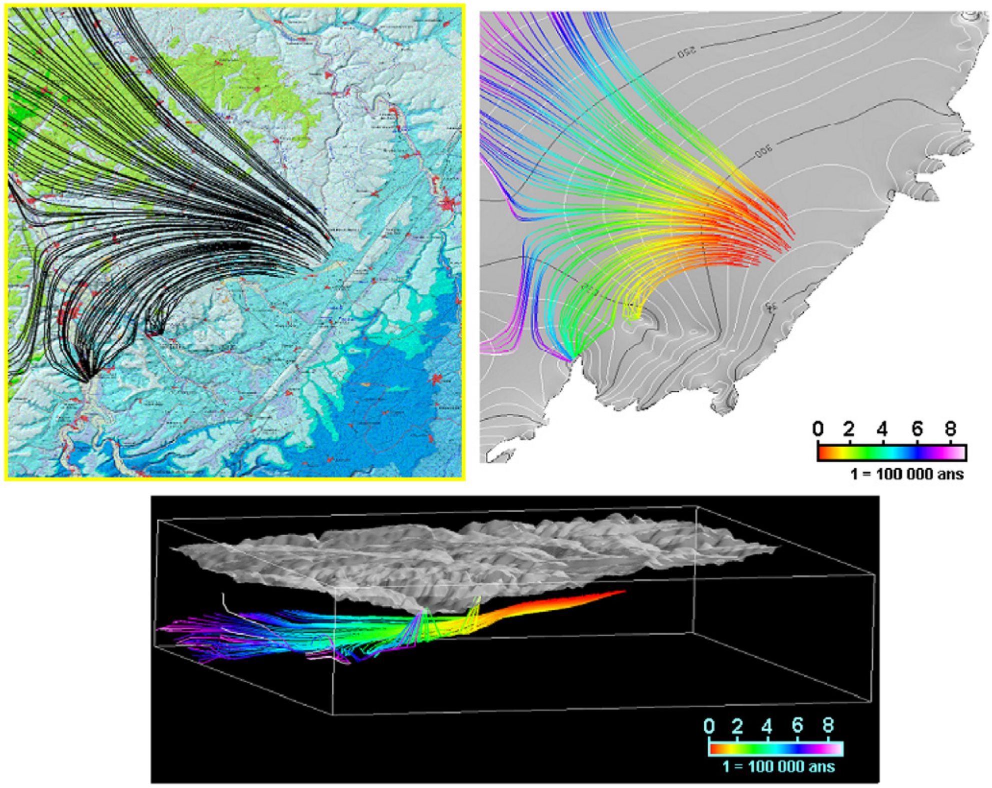

Fig. 6. Simulation results for the Present. Top, maps of particle trajectories with head map on the right side. Bottom, 3D view of particle trajectories and topography in grey.

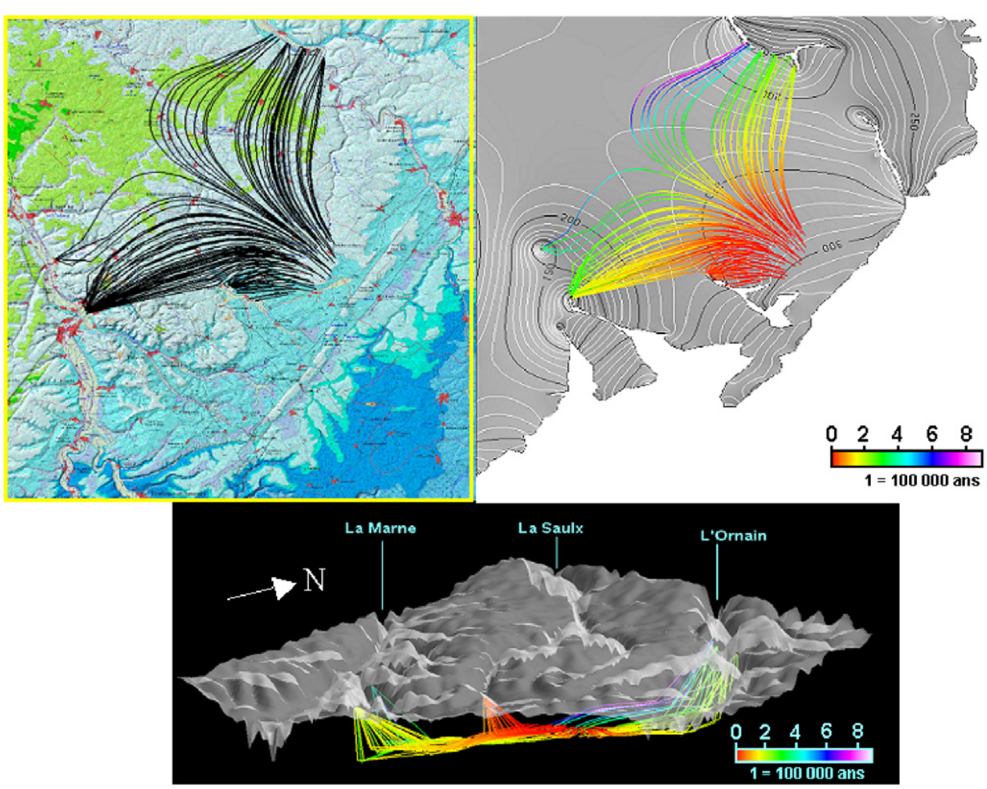

Fig. 7. Simulation results with 1 million years. Top, maps of particle trajectories with head map on the right side. Bottom, 3D view of particle trajectories and topography in grey.

4. Simulation results

4.1. Top boundary layer evolution

Results of simulations in the Oxfordian limestones are presented in Figs. 6 and 7, for the Present and the 1 My situation respectively. On these figures, particle pathlines are shown on geological background and on the head field map. A 3D view shows also the particle trajectories and the surface topography. For the ‘Present period’ simulation, in the Oxfordian layer, most of the pathlines follow the regional flow oriented towards NW. The particles are staying within the Oxfordian limestone aquifer. These results are consistent with observations in local wells and other studies (ANTEA, 2001; Fillion et al., 2000). Over time, as erosion incises the Kimmeridgian impervious

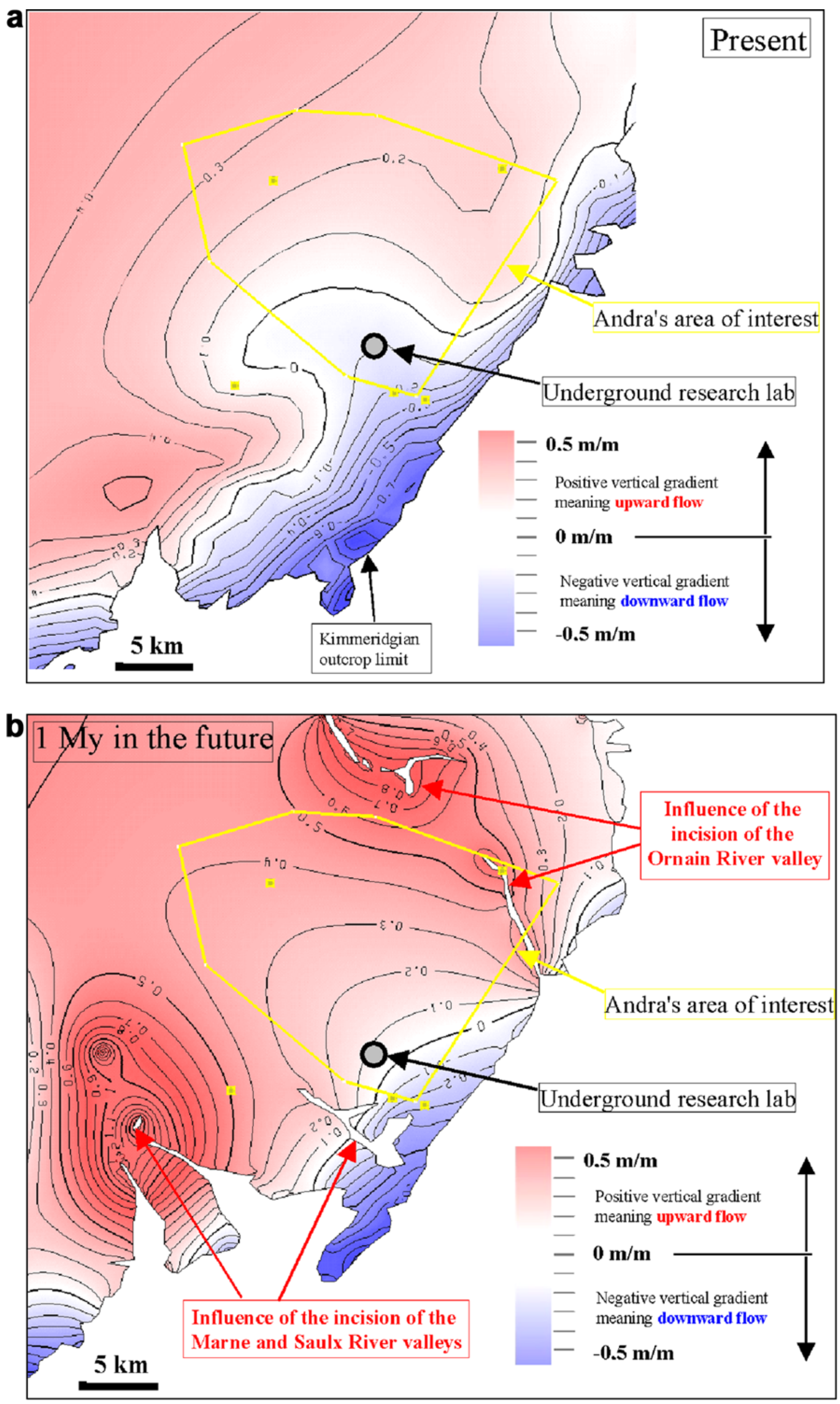

Fig. 8. Top, present vertical hydraulic gradient in the Callovo–Oxfordian clay layer. Bottom, vertical hydraulic gradient in the Callovo–Oxfordian clay layer reconstructed with the topography at 1 million years in the future.

layer, the river valleys reach the Oxfordian limestones. For the '1 My in the future' simulations, these valley incisions have created new local outlets for the Oxfordian limestone aquifer on the Ornain River, in the Northern part of the modelled area, and on the central part of the Marne River. These outlets act as pumping wells. They tend to capture the pollution pathlines. At 1 My in the future (Fig. 7), all the outlets of the laboratory area are local whereas they are following the regional flow for the present topography.

4.2. Bottom boundary layer evolution

In the Dogger aquifer, groundwater simulations with the present topography and with the one estimated for 1 million years in the future show a general decrease of the head field of 20 m, with no major changes in pattern. This is due to the fact that the modified outcropping area is 30 km away. The general pattern of simulated head field does not fit the actual piezometric measurements in wells. Thus, for the Present, we considered the head field fitted on actual well data, and shifted it down 20 m for the 1 million year state.

4.3. Hydraulic gradient in the Callovo–Oxfordian formation

The consequence on the Callovo–Oxfordian boundary conditions for the future is an increase of the internal upward vertical hydraulic gradient which, for the Present, is well developed only immediately to the North of the Laboratory. Fig. 8 shows the map of the vertical hydraulic gradient through the host layer. This gradient is the difference between the heads in the Dogger aquifer below and the ones in the Oxfordian aquifer on top. Thus, here, a positive vertical gradient means a potential upward flow whereas a negative gradient means a potential downward flow. One should note that, given the hydraulic conductivity of the Callovo–Oxfordian formation ($K_{co} = 10^{-13}$ m/s), the dominant transport process in the host layer is diffusion.

In Andra's area of interest, head fields in the surrounding aquifers (Oxfordian and Dogger limestones) result in an upward flow through the Callovo–Oxfordian clays with average values from 0.1 to 0.2 m/m. At 1 My in the future, valley incisions influence the vertical hydraulic gradient in the Callovo–Oxfordian formation. In this area, it induces a stronger upward flow through the host formation with average values of 0.3–0.4 m/m.

5. Conclusion

The hydrogeology of the potential nuclear waste site in the Meuse/Haute-Marne area has been modelled with a mixed hybrid finite-element model Cast3M. The main purpose was to study the impact of the landscape evolution on the hydraulic boundary conditions of Callovo–Oxfordian formation.

Hydrodynamic simulations show a significant impact of the valley incisions on the groundwater flow by the creation of local outlets to the Oxfordian limestone aquifer in the North of the area. It induces local perturbations of the saturation level. The global erosion of the topography also pulls down the water table on a regional basis. Changes induced by the geomorphologic evolution in the Dogger aquifer are located around 30 km East from the Underground Laboratory site, at the outcropping areas. Thus, around the Laboratory location, the piezometric surface does not show, for the future, significant modifications compared to the Present state, but only a general 20-m decrease. The Oxfordian aquifer exhibits more changes due to topographic evolution than the Dogger aquifer.

At 1 My in the future, both aquifers would exhibit a decrease in their head fields. This decrease results in an increase of both the vertical hydraulic gradient and the upward flow in the Callovo–Oxfordian clay layer.

These results are part of the Andra's generic modelling to assess the evolution of the system. They show the potential effects of the geomorphologic evolution through time on the hydrological system. Quantitatively, given the simplified system description, these results give orders of magnitude of the phenomena. Various aspects of these simulations can be improved and will be considered in the future. For example, topography and groundwater flow should evolve contemporaneously. However, as such, they are consistent both with average flow times from natural tracers (isotopes for example) and with the results of Andra's performance assessment. The general performance assessment exercise for the Underground Laboratory site was conducted on a more complex and detailed model of the geological system, including spatial heterogeneity of the aquifer layers (available on Andra's website).

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