
National Hydrological Research Programme (PNRH 99/35-01/44): Fluid Transfer Modelling of the Paris Basin

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ABSTRACT: A 3D basin model of the Paris basin is presented in order to simulate through geological times fluid, heat and solute fluxes. This study emphasizes: i) the contribution of basin models to the quantitative hydrodynamic understanding of behaviour of the basin over geological times and ii) the additional use of AGCM to provide palaeo-climatic boundaries for a coupled flow and mass transfer modelling, constrained by geochemical and isotopic tracers. We show the importance of topography at the beginning of Tertiary to explain high salinities in the Keuper reservoirs and the role of the Bray fault for the Dogger salinity evolution. An extended stratigraphic data base is used to test the possibility of reproducing the hydrogeologic heterogeneity for only three layers (Dogger/Callovo-Oxfordian/Lusitanian). This allows us to propose a satisfactory representation of the permeability field heterogeneity at the regional scale. As a perspective we present climate simulations for the present, the Last Glacial Maximum (21ka) and the middle Pliocene (3 Ma). The results indicate that a significant variation in climate variables occurred and hence illustrate the evolution of hydrogeological boundary conditions. These results will be used as input in a 3D groundwater model of the Paris basin.

1 INTRODUCTION

A 3D basin model of the Paris basin is presented here in order to simulate through geological times fluid, heat and solute fluxes. This study emphasizes: i) the contribution of basin models to the quantitative hydrodynamic understanding of behaviour of the basin over geological times, and ii) the additional use of Atmospheric General Circulation model (AGCM) to provide palaeo-climatic boundaries for a coupled flow and mass transfer modelling, constrained by geochemical and isotopic tracers.

Firstly, in a genetic way, basin model is used to reproduce geological, physical and chemical processes occurring in the course of the 248 My evolution of the Paris basin that ought to

explain the present-day hydraulic properties at the regional scale. As basin codes try to reproduce some of these phenomena, they should be able to give a plausible idea of the regional-scale permeability distribution of the multi-layered system, of the pre-industrial hydrodynamic conditions within the aquifers and of the diagenesis timing and type of hydrodynamic processes involved.

Secondly, climate records archived in the Paris basin groundwater suggest that climate and morphological features have an impact on the hydrogeological processes, particularly during the last 5 My. An Atmospheric General Circulation model (AGCM) is used with a refined spatial resolution centred on the Paris basin to reproduce the climate for the present, the Last Glacial Maximum (21 ky) and the middle Pliocene (3 My). These climates will be prescribed, through forcing functions to the hydrological code with the main objective of understanding the way aquifers and aquitards react under different climate conditions, the period and the duration of these effects.

Finally, the Paris basin has been studied for a number of years by different scientific communities (geologists, palynologists, rock and water geochemists, rock mechanists, hydrogeologists, climatologists, modellers and industrial companies (Gas Storage, Petroleum and Water resources exploitation), thus a large amount of data has been collected. By integrating all these actors in a same research programme (PNRH.99/35-01/44: 'Paris basin modelling') we were able to draw a more comprehensive view of the Paris basin evolution.

This work is still in progress, the basin model results will be first emphasized in this short paper, and while the hydro-climatologic modelling will be presented as a perspective for our future work.

2 BUILDING THE MODEL

2.1 Numerical code

The NEWBAS code developed by Belmouhoub (1996) reproduces processes such as sedimentation, erosion, fluid flow, heat and solute transport. It is a finite volume code taking into account evolution of the geometry along time. For the last two processes, we implemented the effect of density variations on the flow. We tested the accuracy of: i) a facies-model instead of a discrete litho-facies distribution for three layers of the system (Dogger, Lusitanian, Callovo-Oxfordian) and ii) a compaction and petrophysical law valid for carbonates (Lucia, 1995). In future work, this has to be generalised for the entire layers of the system (see below).

Fluid flow through the main faults was simplified. Most of the time, during the simulations, faults play a barrier role when a layer is geometrically disconnected from one bloc to another. But according to the geological evolution (direction of the main constraint) one of them, the Bray fault, plays a role as a drain during the last 50 My. We allowed vertical fluid flow at this time for those meshes representing the Bray fault.

The only way available to validate our model is on the present-day data set. So we have no control on what happens before and the model results are just a trend of what could have occurred according to the diagenetic data.

2.2 Geometry

According to the palaeo-geographic evolution of the Paris basin recorded in the literature (Dercourt et al., 2000), the present-day limit of the basin underestimates the real extent of the flooded surface area during certain periods over its 248 My geological history. Therefore, in order to prescribe meaningful boundary conditions at the proper location, the dimension of the resulting domain is 700,000 km². Due to the dimensionality and the variable nested squares meshing possibility of our code, the mesh is refined from the peripheral domains (20 km x 20 km_ mesh) where the knowledge is poor, towards the centre of the basin (2.5 km x 2.5 km_ mesh) following the main structural features where a more precise knowledge is available. The Z direction is accounted for by the time-varying thickness of the layers at each node. The precision of the study is at the regional scale, for the whole basin, except for a more accurate description at the centre of the basin where the number of data is larger. The time scale corresponds to geological events, ~1 My, but it is not precise enough for Quaternary period, for instance. This is the reason why a second model is in progress for the Quaternary, to test the hydrodynamic impact of palaeo-climatic and anthropogenic forcing effects.

2.3 Data set: input, constraints and validation

The present-day geometry and lithology (Fig. 1) is established using a stratigraphic data base of more than 1,100 petroleum well logs for the Paris basin *sensu stricto* (Guillocheau et al., 2000). For the German and the English areas, qualitative data were collected from the literature (Geyer and Gwinner, 1968; Sellwood et al., 1986; Baldschunh, 1996).

19 time surfaces inferred from a sequential stratigraphic approach were selected and, with the topographical (DEM) and basement surfaces, our model is described by 20 layers.

In a first approach, the lithology distribution over the simulation domain is described using a discrete litho-facies classification: the central points of 18 subdivided domains within two ternary plots which poles are shale, sand, carbonate (plot 1) or chalk (plot 2). A 19th lithology is added for evaporite deposits. In this first approach, the lithology proportions from the data base are interpolated by kriging on the mesh to give the discrete litho-facies distribution. In a second approach tested for two carbonate aquifers (Dogger and Lusitanian) and one aquitard (Callovo-Oxfordian) we have developed a facies model where the interpolated proportions, obtained by kriging with the pole lithologies, are then directly assigned to the cells.

For the compaction law, we used porosity-depth functions from the literature (Sclater and Christie, 1980; Burrus, 1997).

The palaeogeographical evolution is constrained by the mean topographical and water depth gradients deduced from recent work (Guillocheau et al., 2000). This work allows us to determine the timing of the main up-lifts and their amplitude.

The heat flux at the basement is considered as constant during the Paris basin geological evolution, but regionally variable due to the basement heterogeneity, as described by Lucazeau and Vasseur (1989) and Prijeac et al. (2000).

We need also data to constrain or validate our model. Those data concern hydrodynamic properties (porosity, hydraulic conductivity, water level, storage coefficient) and diagenetic observations (palaeo-temperature and palaeo-salinity deduced from fluid inclusions studies, Matray et al., 1989, Guilhaumou, 1993, Spötl et al., 1993, Demars et Pagel, 1994, present temperature profiles from petroleum monitoring, Demongodin et al., 1991, Gaulier and Burrus, 1998).

Unfortunately some useful data were missing: water levels of the main aquifers before anthropogenic exploitation; hydraulic conductivity values for the aquitards; more precise data about palaeo-topography, geometry and lithology at the outcrops. We will need data about

not only the geometry of the main faults of the basin but also the knowledge of their in-fillings and the timing of their evolution inferred from the tectonic constraints and the sedimentation rate from one block to another.

3 RESULTS

Regional scale fluid flow has currently been invoked in fluid inclusion studies to explain diagenetic cementation stages. These studies, which provide estimates of past temperatures and salinities, also provide some constraints for the model and in return, with the model, we can propose a timing calibration for the major cementation events (Tab. 1). Thus, the heat and salt transport reconstruction proposed in this work allows to determine the influence of hydrodynamics on diagenetic processes.

We show the importance of topography to explain high salinities in the Keuper reservoirs and the role of the Bray fault for the Dogger salinity evolution. The major uplift of the basin at the beginning of the Tertiary causes a topographically-driven flow which replaces the compaction-driven regime, thus allowing brine migration from the Eastern salt formation towards the Western Keuper reservoirs. The recharge at the outcrops affecting the aquifers leads to sufficient pressures to allow an upward motion of brines from the Keuper to the Dogger by considering enhanced permeabilities for the liassic aquitards. Although dominated by its conductive component, heat flow is also influenced by hydrodynamics with a possible convective cooling effect related to the main uplift and the recharge at the beginning of the Tertiary. This effect is likely to explain part of the highest temperatures inferred from fluid inclusions and probably coeval with the end of the Chalk deposition. From our calculations, the major diagenetic events recorded by fluid inclusions are related to the Tertiary uplift for thermal reasons (maximum burial and convective cooling) and chemical reasons (topographical event favourable to brine migration in both the Keuper and Dogger reservoirs).

Concerning the use of the basin code as a qualitative tool to estimate regional scale permeabilities, our approach presents similarities with both the genetic and the geostatistical approaches. The sedimentation and the compaction are simulated using a 3D basin model that takes as a major input a heterogeneous facies model generated by geostatistical methods. An extended stratigraphic data base is used to test the possibility of reproducing the hydrogeologic heterogeneity for only three layers (two carbonates: Dogger and Lusitanian and one argillaceous: Callovo-Oxfordian). This allows us to propose a satisfactory representation of the permeability field heterogeneity at the regional scale (Fig. 2). This method should now be applied to the entire stratigraphic model and the permeability fields could be used in a more classical hydrogeologic model as the starting point for a fluid flow calculation to be calibrated on hydraulic head data. This approach should be compared also to other kind of methods currently used in hydrogeology (inversion, stochastic...).

The main difficulty is to validate our model. Our sensitivity study shows that from an hydrodynamic point of view, our modelled system is fixed. Because, for the last 8 My, the hydrodynamic boundary conditions prescribed on surface are unchanged and, our model has reached a steady state. This is a non-negligible simplification which sensitivity will be tested through the hydro-climatologic modelling. The validation can be done on present-day data set. For the past evolution, we had to use diagenetic data. For the validation of our hydrodynamic results, the main difficulties were: i) the difference in scale between our results (more than 2.5 km in space) and the data acquired (around 100 m in x, y space, less for vertical resolution); ii) the unequal knowledge on the different layers and the heterogeneous distribution of the data. To compensate those problems, we used an upscaling method based on the work of Renard et al. (2000) to compare upscaled permeabilities calculated from the data set to those calculated by the simulations.

4 CONCLUSIONS AND PERSPECTIVES

The model is able to reproduce palaeo-fluids flow and their diagenetic implications based on reasonable permeability field and hydrodynamic boundary conditions. During the geological evolution of the basin, we show that no overpressure due to compaction effects existed for a time (less than 100,000 years). Other potential effects to explain the observed overpressures in some of the aquitards can be invoked, such as osmotic effects, changes in hydrodynamic and tectonic boundary conditions. For those two last effects our work is still in progress.

The present-day geometry and hydrodynamic features are now used for another modelling looking for small time scale (last 5 My) and testing the climatic and anthropogenic effects on present-day hydrodynamic.

The originality of our work lies in the way it has been performed, i.e.: the quality of the data set we used (the most complete ones), the number of scientists involved in this work (pluri-disciplinary cooperation), the time and space scales we used, the efforts of considering all the relevant processes in the evolution with time of the sediment properties.

During this program, our goal was to provide data to our models but we did not neglect to use the Paris basin case study to develop more theoretical work on more focused aspects (Bruel et Violette, 2002; Cosenza et al., 2002; Luo et Vasseur, 2002; Jost et al., 2003; Gonçalvès et al., submitted, cited for examples).

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6 REFERENCES

- [1] BALDSCHUHN R., FRISCH U. & KOCKEL F. (1996). Geotektonischer Atlas Von NW Deutschland. BGR, Hannover;
- [2] BELMOUHOU B. (1996). Modélisation tridimensionnelle hydro-thermo-mécanique d'un bassin sédimentaire au cours de son histoire géologique. *PhD Thesis*, Ecole Nationale des Mines de Paris, 256p.;
- [3] BRUEL, D. and VIOLETTE S. (2002). Coupling diagenetic effects in a basin model for mass transfer predictions at the regional scale. *AAPG, Houston*;
- [4] BURRUS J. (1997). Contribution à l'étude du fonctionnement des systèmes pétroliers : apport d'une modélisation bi-dimensionnelle. *PhD Thesis*, Ecole des Mines de Paris, 500 pp.;
- [5] DEMARS C., and PAGEL M. (1994). Paléotempératures et paléosalinités dans les grès du Keuper du bassin de Paris : inclusions fluides dans les minéraux authigènes. *Compte Rendus de l'Academie des Sciences de Paris*, **319**, 427-434;
- [6] DEMONGODIN L., PINOTEAU B., VASSEUR G., AND GABLE R. (1991). Thermal conductivity and well logs: a case study in the Paris Basin. *Geophysical Journal International*, **105**, 675-691;
- [7] DERCOURT J., GAETANI M., VRIELYNCH B., BARRIER E., BIJU-DUVAL B., BRUNET M.F., CADET J.P., CRASQUIN S., SANDULESCU M. (2000). Atlas Peri-Tethys. Paris, Commission for the geologic maps of the world;

- [8] GAULIER J.M., and BURRUS J., 1998, Modeling present and past thermal regimes in the Paris basin : petroleum implications, *in* A. Mascle, ed., Hydrocarbon and geology of France: Berlin, Springer-Verlag, 61-74;
- [9] GEYER O. & GWINNER M. (1968). Einführung in die geologie von Baden Wurtemberg. *In*: N. U. Obermiller (Ed). E. Scheizerbart, E. Scheizerbart, 228 pp.;
- [10] GONÇALVÈS J. (2002). Modélisation 3D de l'évolution géologique du bassin de Paris : implications hydrogéologiques et diagénétiques. *PhD Thesis*, Université Pierre et Marie et Curie, 301 pp.;
- [11] GONÇALVÈS J., MARSILY G. de, VIOLETTE S., WENDLING J., (*submitted*). Analytical and numerical solutions for overpressuring processes: Application to the Callovo-Oxfordian in the Paris basin, France. *Journal of Geophysical Research*;
- [12] GUILHAUMOU N. (1993). Paleotemperatures inferred from fluid inclusions in diagenetic cements: implications for the thermal history of the Paris basin. *European Journal of Mineralogy*, **5**, 1217-1226;
- [13] GUILLOCHEAU F., ROBIN C., ALLEMAND P., BOURQUIN S., BRAULT S., DROMART G., FRIEDENBERG R., GARCIA J.P., GAULIER J.M., GAUMET F., GROSDOY B., HANOT F., LE STRAT P., METTRAUX M., NALPAS T., PRIJAC C., RIGOLLET C., SERRANO O. & GRANDJEAN G. (2000). Meso-Cenozoic geodynamic evolution of the Paris basin : 3D stratigraphic constraints. *Geodynamica Acta*, **13**, 189-246;
- [14] JOST A, KAGEYAMA M.; RAMSTEIN G.; VIOLETTE S.; de MARSILY G. (2003). The Last Glacial Maximum climate over Europe: high resolution simulations. 'EGS - AGU - EUG Joint Assembly' *Proceedings*;
- [15] LUCIA F. (1995). Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG Bulletin*, **79**(9), 1275-1300;
- [16] LUO X. and VASSEUR G. (2002). Natural hydraulic cracking: numerical model and sensitivity study. *Earth and Planetary Science Letters*, **201**, 431-446;
- [17] MATRAY J.M., MEUNIER A., THOMAS M., and FONTES J.C., 1989, Les eaux de formation du Trias et du Dogger du bassin parisien : histoire et effets diagénétiques sur les réservoirs. *Bulletin des centres recherche exploration production Elf-Aquitaine*, **13**, 483-504;
- [18] PRIJAC C., DOIN M. P., GAULIER J. M. & GUILLOCHEAU F. (2000). Subsidence of the Paris basin and its bearing on the late Variscan lithosphere evolution: a comparison between Plate and Chablis models. *Tectonophysics*, **323**, 1-38;
- [19] RENARD P., LE LOC'H G., LEDOUX E., DE MARSILY G. AND MACKAY R. (2000). A fast algorithm for the estimation of the equivalent hydraulic conductivity of heterogeneous media. *Water Resources Research*, **36**(12), 3567-3580;
- [20] SCLATER J. G. & CHRISTIE P. (1980). Continental stretching : an explanation of the post-mid-cretaceous subsidence in the central north sea basin. *Journal of Geophysical Research*, **85**, 3711-3739;
- [21] SELLWOOD B. W., SCOTT J. & LUNN G. (1986). Mesozoic basin evolution in southern England. *Proceedings of the geologists' association*, **97**, 259-289;
- [22] SPÖTL C., MATTER A., and BRÉVART O. (1993). Diagenesis and pore water evolution in the keuper reservoir, Paris basin (France): *Journal of Sedimentary Petrology*, **63**, 909-928.

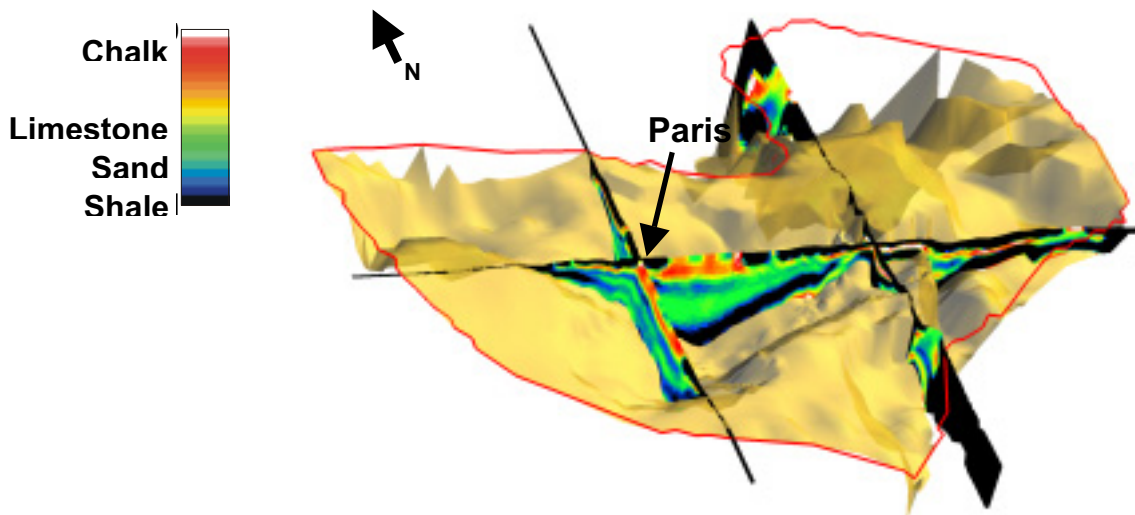


Figure 1: 3D geometry and discret-model lithologies distribution of Paris basin over three cross sections at present time.

	KEUPER	DOGGER
Temperature: processus quantification	Blanketing + erosion a 20°C Surface temperature a 10°C Convective effect a 5 à 10°C	Surface temperature
Salinity: processus	gravity flow motion when topography exists	Convective movement along Bray fault but calculated salinity lower and very local
Chronology	Qz/Fd : 85 My Dolomite : 65 My ↔ 80 à 40 My by dating	Calcite up to 50 My

Table 1 : Synthesis of the diagenetic impact of different processes for two reservoirs in the Paris basin.

Figure 2: Correlation between upscaled permeabilities calculated from measurements and simulated permeabilities, Dogger: (a) discrete facies and (b) precise facies.

