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3-D Modeling of Fluid Flow, Compaction, Pore Pressure and Thermal Evolution of the Paris Basin, France, Over its 250 My History.

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Introduction

The Paris basin is a 600 Km wide and less than 3 Km deep sedimentary basin with small dips oriented toward the depocenter (Figure 1). The stratigraphic succession records a geological history, which started at the beginning of the Triassic and lasted for 250 My up to the present.

During the last decades, this basin has attracted strong economic interest which is still continuing, although weakening somewhat. The basin has been intensively explored for its hydrocarbon potential, especially in the period between the 1950's and the 1990's. A few oil fields are still exploited today but as Burrus (1997) has pointed out in a previous study, this exploration has revealed few prospects for the basin as a petroleum province.

From a hydrogeologic standpoint, this basin is a multi-layered aquifer-aquitard system associated with a southeast to northwest topographically-driven flow with recharge zones at the highest outcrops and discharge zones in the rivers or in the Channel. Some of these aquifers are exploited, e.g. the Albian sand formations, a deep protected aquifer, is used for water supply, the Dogger ooids carbonate formation for low enthalpy geothermal energy.

In the last decade a new potential interest has arisen from research concerning the fate of nuclear waste from nuclear electric power plants. This research program concerns the feasability of building a deep reversible geological repository. The geological formations currently investigated in France as possible repositories are shales and granite. One of the shaly aquitards of the Paris basin, the Callovo-Oxfordian formation, has been identified as potentially offering enough confining power to warrant further investigations. In this context, a best knowledge of the hydrodynamic properties of the basin at a regional scale and over long time scales is particularly important.

First 1-D, then 2-D basin models, coupling compaction-driven flow, thermal evolution and oil maturation were developed in the 1970's as quantitative tools in petroleum engineering to estimate oil migration, pore pressure and thermal evolution as well as the hydrodynamics at geological time scales and basin scale; such studies were carried out on the Paris basin or elsewhere (e.g. Bethke, 1985; Burrus, 1997; Pearson, 1998). For the last 5 years, 3-D basin models have been developed to account for the three-dimensional component of the processes involved in basin evolution. With these 3-D codes, it is possible to simulate the basin history and the influence of geological processes such as compaction, erosion, faults as pressure seals or drains, on pressure, temperature and possibly on permeability fields at the regional scale.

The reason for using such codes is their potential contribution to the understanding and knowledge in three dimensions of the hydrodynamic properties of the basin multi-layered system. The basin model should be able to give an acceptable idea of the initial hydrodynamic conditions within the aquifers and of the regional-scale permeability distribution. The simulation of the 250 My geological history of the Paris basin was carried out with the code NEWBAS developed at the Centre d'Informatique Géologique of the Ecole des Mines de Paris (Belmouhoub, 1996).

3D model of the Paris basin

Data input and calibration

The fine network of wells drilled for the petroleum exploration has provided a large amount of data recorded in well-logs. The database available on the basin includes its geometry. About 1100 well-logs have been collected by Guillocheau et al. (2000) allowing stratigraphic correlations at the basin scale. These correlations using sequence stratigraphy methods lead to 3D geometric constraints on the basin. In addition to the geometrical information these well-logs allow a precise description of the lithologic distribution mostly in the center of the basin.

Moreover hydrodynamic well tests carried out during drilling and exploration provide values of permeability, pressure, temperature and porosity for different reservoirs in the basin. These data have been collected and represent the main components of a hydrodynamic database used to calibrate and validate the 3-D model. Previous studies on aquifers and aquitards in the Paris basin, like those on the Albian and Dogger aquifers, are also included in this database (Wei H.F. 1990; Raoult Y. 1999). Other economic activities related to the basin have also provided some data especially for aquitards : the French institute for management of nuclear waste ANDRA and GDF, a natural gas utility concerned by gas storage in aquifers in the basin.

The few pressures recorded in the aquitards like the Kimmeridgian marls, the Toarcian and Callovo-Oxfordian shales and the lower Liassic sandy shale revealed weak overpressures (Figure 3). We can try to explain these pressures by the evolution of the basin and especially by the possible disequilibrium created by compaction. Moreover, the data set on permeability has been upscaled to calculate equivalent permeabilities at the scale of the meshes used in the model. Few values on aquitard permeabilities are available but, when upscaled, they provide some constraints on the values simulated by the code.

Building the model

A study of the paleogeographic evolution of the European plate from the Triassic to the present shows that the present-day limits of the Paris basin must be widely extended (Dercourt, 2000). A Triassic to Jurassic connection to the German domain as well as a nearly continuous connection with the London basin justify this extension. In order to prescribe boundary conditions with geological significance, a reasonable limit has been selected. This limit corresponds to low subsidence areas, paleogeographic extensions, high and threshold zones as close as possible to present-day limits. The simulated domain is represented in Figure 2 with its Digital Elevation Model (DEM). This domain is then discretized in the XY plane using a nested square mesh, which is refined at the center of the present-day basin following the main structural setting. This 5400-node mesh is used for each of the 20 layers of the model. The Z direction is taken into account by the varying thickness of the geological layers. The sequence stratigraphic analysis on the well logs resulted in the definition of 19 time surfaces for the simulation. These time surfaces associated with present-day topography given by the DEM and with the basement surface limits the 20 layers of the model.

The first model inputs are the present-day geometry and the distribution of lithologies. Then, hydrodynamic, thermal and mechanical properties are attributed to the material of each layer. Finally, a geological history including paleogeography, paleobathymetry, uplifts and erosion events constitutes the last input for the simulation.

The present-day geometry of the basin is described by means of the stratigraphic database for the Paris basin itself and data from the literature for the English and German parts of the domain (Sellwood, 1986; Baldschuhn, 1996). The thicknesses derived from this database are interpolated by kriging in the domain in agreement with the paleogeography recorded in the literature. This interpolation also provides data for erosions.

Lithologies are described in the model as domains of a ternary plot whose poles are “pure” lithologies defined as clay, sand and carbonates; each layer is thus represented as a vertical stratigraphic succession of these elementary terms, in variable proportions. For each material, mechanical compaction rules as well as hydrodynamic and thermal properties evolution as a function of compaction are derived from previous work (Sclater, 1980; Burrus , 1997).

The geological history input describes the paleogeographic evolution of the domain derived from the interpolations of sediment thickness associated with a mean paleobathymetry for each stage. In addition, two erosion stages have been identified :

- the first one at the end of the Lower Cretaceous, related to the opening of the Atlantic ocean
- the second one is a general uplift and erosion event during the Tertiary related first to the N-S Pyrenean compressive stage and then to the S-E to N-W Alpine compressive stage

This last episode results in the present-day geometry of the basin and leads to the present-day topographically-driven flow context.

Simulation Outputs

The model provides calculated permeabilities which are less than one order of magnitude away from the upscaled measured permeabilities for the aquifers, and in good agreement with the few values available for the Kimmeridgian, Callovo-Oxfordian, Toarcian and Lower Lias aquitards. The calculated head distribution in steady-state for the present-day in the aquifers is also in good agreement with the general understanding of the flow in the basin, with a SE to NW natural head gradient and the associated topographically-driven flow. With the calculated permeabilities, weak overpressures are found in the aquitards during the compaction history of the basin (Figure 5). Combined with the sedimentation rates, they produce values of overpressures only up to 1.5 MPa. Then, during the Tertiary, when the system tends toward equilibrium with the topographically-driven flow, pressures in the aquitards reach values close to those measured today (Figure 4).

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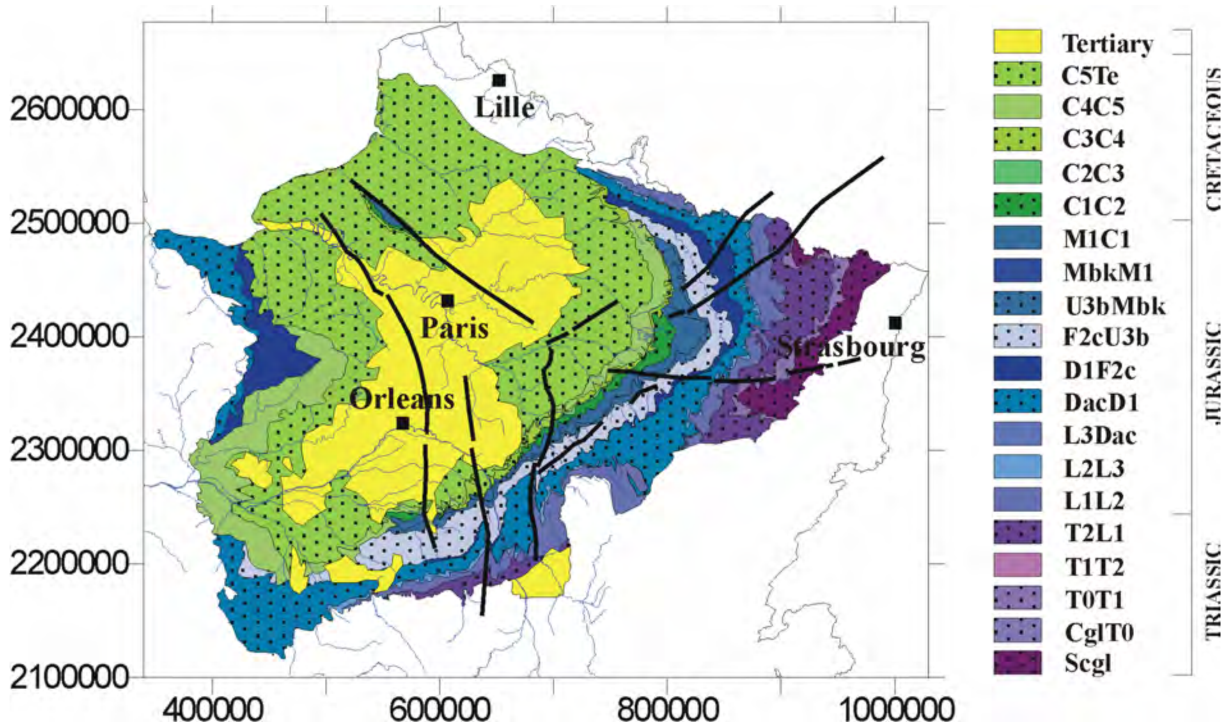

Figure 1 : Geological map of the Paris basin strictly speaking, using time surfaces from sequence stratigraphic analysis (dotted surfaces for the main aquifers)

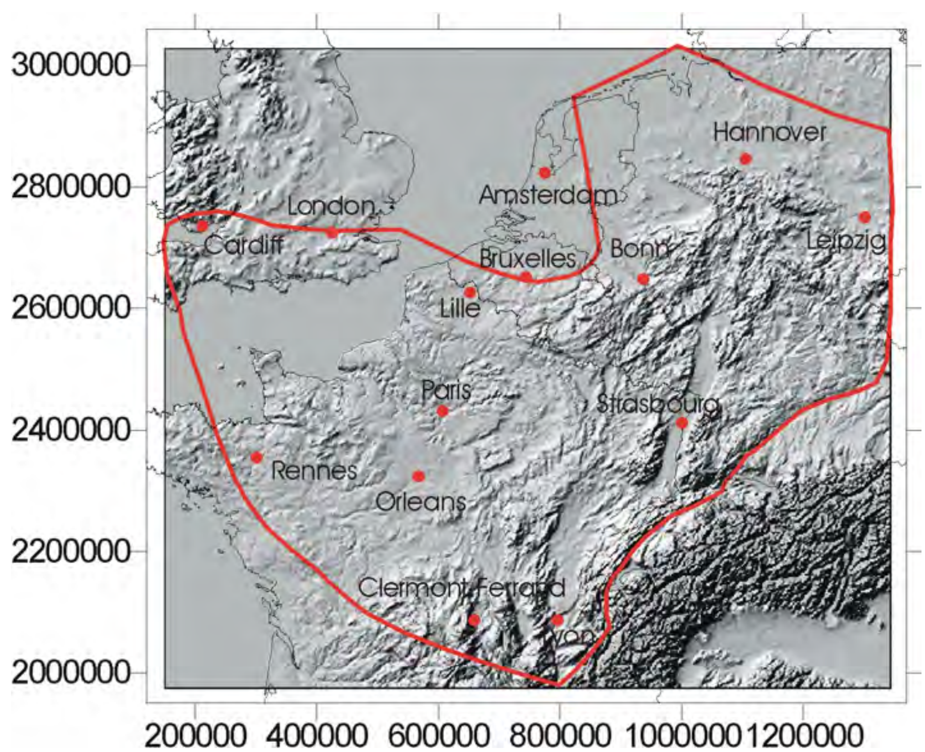

Figure 2 : Simulation domain with its Digital Elevation Model

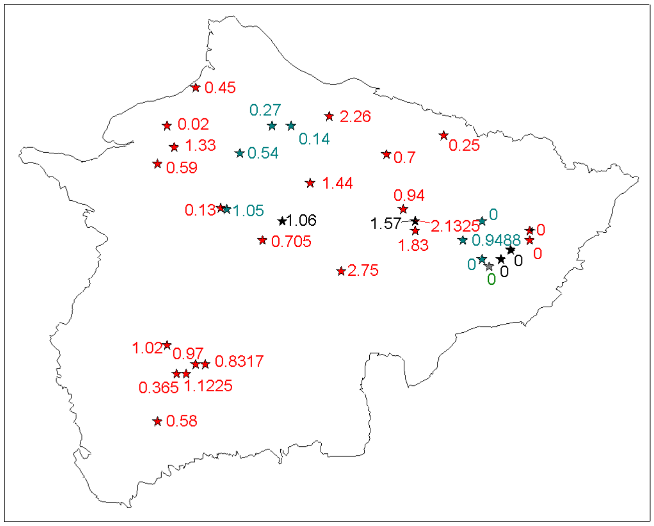

Figure 3 : Mean measured overpressures in the Lower Lias sandy shales (red), Toarcian (dark) and Callovo-Oxfordian shales (green) and Kimmeridgian marls (blue)

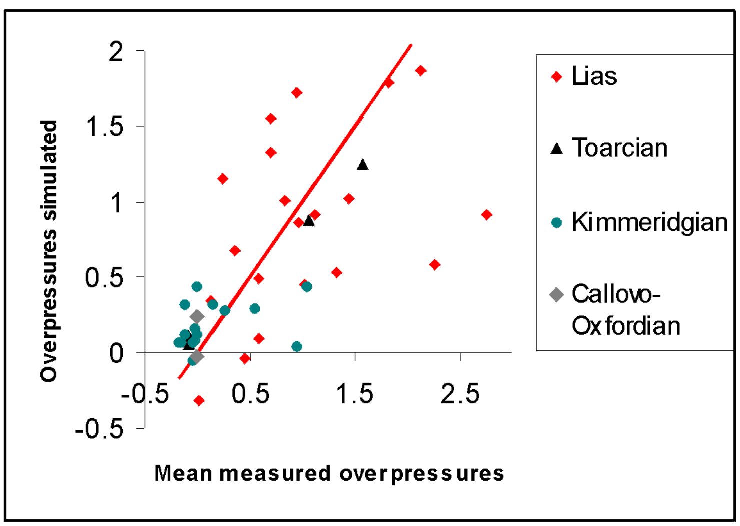

Figure 4 : Correlogram of the simulated versus mean measured overpressures

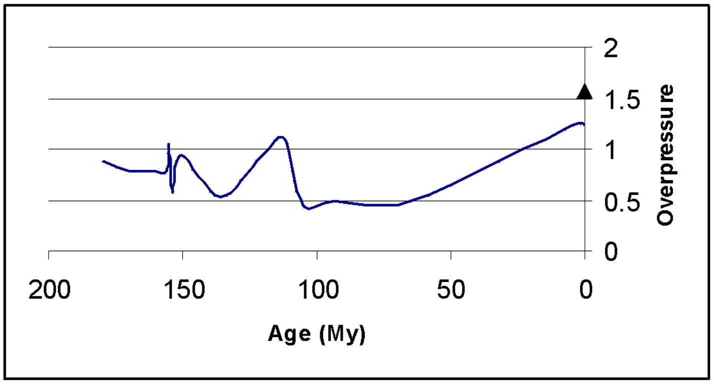

Figure 5 : History of the simulated overpressures for a Toarcian node in the center of the basin