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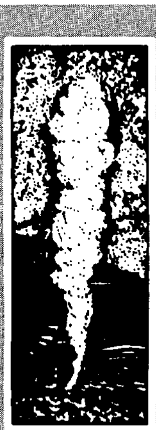

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DEVELOPMENT AND EXPLOITATION OF LOW ENTHALPY GEOTHERMAL SYSTEMS: EXAMPLE OF "THE DOGGER" IN THE PARIS BASIN, FRANCE

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ABSTRACT

A feature of French geothermal engineering is the development of industrial projects in normal gradient, non-convective areas. The economic feasibility of exploiting wells producing between 150 and 350 m^3/h at temperatures from 55° to 85° from depths of 1,500 to 2,000 meters, in sedimentary basins with normal gradient, for direct heat production has been proved by 50 plants providing heating for over 500,000 people during the last few years. This opens new possibilities for geothermal energy development the world over, in particular for areas where heat consumption is higher than 2,500 Tons oil equivalent (Toe)/year over several square kilometers.

The recent and rapid development of geothermal projects in France, in particular in the Paris Basin has provided much more information on the characteristics of the Jurassic Dogger, which is the unit tapped by geothermal doublets (one production and one injection well).

Detailed study of the Dogger reservoir in the Paris Basin is one of the main objectives of the IMRG research and development program drawn up in 1983. The preliminary results presented here are oriented towards (1) improved knowledge of the potential geothermal resources, and (2) analysis of optimum development conditions.

INTRODUCTION

The sedimentary beds of the Paris Basin host numerous aquifers. The main ones are shown in figure 1. Several of these deep aquifers offer good geothermal energy possibilities, but the main interest was concentrated on the Dogger limestone. This limestone is better known because it was the subject of intensive drilling for petroleum exploration. Thanks to this drilling and also geothermal energy research this formation was found to be a very large aquifer. At present it constitutes the no. 1 geothermal energy objective in France and alone provides 90% of the geothermal energy resources in the country. The reserves in place are estimated at 6 x 10^8 calories, i.e. the equivalent of 600 millions Toe.

1 - CHARACTERISTICS OF THE RESERVOIR

1.1 - Methodology

The sedimentological analysis aimed to:

(1) Characterize the sedimentary environments and their distinguishing criteria and study the relations between the various facies and the different productive layers.
(2) Draw up vertical well sections including all these components in order to establish correlations between wells as a base on which to reconstitute the paleogeography of the reservoir.

The work was carried out in successive stages comprising:

(1) Detailed sedimentological analysis of a cored drill hole so as to define the facies, (depositional) environments, petrology and diagenetic phenomena affecting the reservoir.
(2) Well logging characterization of facies cut by this drillhole enabling facies in other boreholes to be identified by morphological study of curves (electrofacies).

At the same time as the logs were gone through, cuttings from some boreholes were examined section by section so as to:

Check a logging hypothesis.
Try to characterize the porosity from cuttings impregnated with coloured resin and mounted on thin sections.

1.2 - Lithostratigraphy

The Dogger of the Paris Basin corresponds to a predominantly limestone litho stratigraphic assemblage located between the marl at the top of the Lias and the lower Callovian marl.

During the Bathonian, a large carbonate platform was built up and its formation accelerated with subsidence of the basin.

Oolitic reef bars formed on the basin borders and progressed towards the centre leaving behind them a protected internal shelf zone. This zone, in which lagoon-type facies (*Comblanchian*) were deposited came progressively to occupy the center of the basin at the end of the Bathonian (Fig. 2). This northwest-striking carbonate body is bounded on the west by a marly belt which in its turn limits the oolitic reef flat installed on the Armorican margin.

All the geothermal wells are located east of the marl belt. The rocks encountered in the wells comprise the lower part of the Callovian and a great thickness belonging to the Bathonian. These Bathonian facies come within the regressive changes known to occur at this time in the Paris Basin.

This change is characterized by the successive deposition, from the base to the top, of external shelf sediments (Alternances) of reef deposits (White oolite) and internal shelf sediments (Comblanchian).

As an example, the description of the type stratigraphic succession encountered in one of the geothermal wells is given below and in figure 3. From the bottom to the top:

At the base, the first unit, belonging to the "Alternances", comprises more-or-less clayey, gravelly-bioclastic limestone of external facies, or more granular facies (grainstone to packstone) of the fore reef. In some wells the first productive layers are found in these fore reef facies.

The second unit belonging to the "White oolite" comprises granular reef facies of grainstone type. The main productive horizons are located in these facies.

The third unit corresponds to Comblanchian lagoon facies with beige micrite and grainstone-type oolitic passages. The productive layers occurring in this unit generally correspond to the oolitic facies.

1.3 - Facies - physical characteristics relations

Study of the porosity in the limestones showed that their physical characteristics depend on:

- The depositional environments and their hydrodynamic energy.
- Diagenetic changes which can affect them.

The porosity is clearly of two types:

(1) Macroporosity, intergranular (pore radius > 7.5 microns) *typical of oolitic grainstone* of reef facies (Fig. 4).
(2) Microporosity, inter or intragranular (pore radius < 7.5 microns) typical of gravelly-bioclastic facies of the external shelf (Fig. 5).

The permeability = f (total porosity) relation is not clear but a good correlation is obtained when applied to the macroporosity.

(1) Thus high permeability values are shown by samples with high macroporosity. These values are obtained in reef facies and more particularly in the "White oolite".
(2) Normal decrease in the permeability is shown by facies further away from the oolitic reef domain. In the external facies microporosity is prevalent.

The values obtained by interpretation of porosity logs do not convey the degree of productivity of the rock. In fact, at equal porosity values, the limestone from the series of "Alternances" does not have the same productivity as the "White oolite" (Fig. 3). The origin of this difference is probably due to different diagenetic evolution in these ancient reservoirs: thus rocks belonging to the "Alternances" sequence are blocked with a deposit of cement reducing the intergranular space, while at the same time, the micropore network is increased by reduction of the macropores and by microsolution of the matrix. On the other hand, the limestone belonging to the "White oolite" facies and the Comblanchian, have kept their original porosity and in places it is even increased by fracturing-solution.

2 - GEOCHEMISTRY OF DOGGER AQUIFER FLUIDS

We present here the preliminary results concerning isotopic and chemical studies. The gas chemistry is described in another paper (Criaud, et al., this volume).

2.1 - Analytical procedures

The major element chemistry for 55 drillholes is available (Criaud, et al., 1986). Most of them were sampled (by the BRGM) under steady state flow conditions (during production) but a few analyses were taken from drill reports. Nonetheless these analytical data do not induce *significant* error and prove useful for understanding the general chemistry of the aquifer.

The general methods for field and laboratory operations are described.

The geothermal fluids are sampled as close as possible to the well head. Temperature and pH are measured on site. Total alkalinity was determined on site because of abundant dissolved hydrogen sulfide. *Total* H_2S *is measured by potentiometry* in the same conditions.

The waters were filtered on line through

0.45 micron membranes and immediately acidified with concentrated HCl for cations determination. Cadmium acetate is added in excess to precipitate sulfide, and the surnageant is analyzed for sulfate and corrected for dilution.

Cations were determined by ICP and flame atomic absorption spectrophotometry. Boron was determined with spectrophotometric method for the earlier results and by ICP since 1983.

Standard ion chromatography (Dionex) with conductivity detector was used to measure Cl, SO_4 and F. Non-suppressed ion chromatography with a UV detector was used for bromide determination.

2.2 - Discussion

The chemical analyses are widely disparate in composition and total salinity (from 6.4 to 35 g/l) and a number of phenomena may account for these differences. Assuming an initial fluid close to sea water, evaporation, diagenesis, mixing with dilute or saline water, and dissolution of evaporites, may occur separately or have a general effect in the sedimentary environment.

First, attempts were made to explain these variations by a simple mixing model involving two components - this was sustained by the correlation between Cl and Br (Bastide, 1985). The Cl/Br molal ratios comparable to the composition of present-day seawater, and is explained by the diagenetic evolution of initial seawater concentrated by evaporation. Then this ratio would remain constant through simple mixing with a low TDS component.

The oxygen 18 and deuterium isotope studies indicate present-day recharge of the aquifer, as shown by isotope composition of the most southern samples. The regression line δD-$\delta^{18}O$ does not intersect the SMOW $\delta^{18}O$ value and the highest mineralized fluids do not correspond to the highest isotope enrichment. Complex processes including membrane filtration effect, exchange with host rocks and mixings have been proposed (Fouillac, et al., 1986) but obviously the aforementioned mixing model must be discarded.

The variations in boron or sulfate contents in relation to chloride enable several groups to be distinguished among the fluids according to the different Cl/B and Cl/SO_4 ratios. A general enrichment in boron relative to seawater is observed, and both elements are considered as conservative due to mixing processes.

(1) The water from the Seine-St-Denis area is recognized as the oldest component, B is quite constant, but not Cl; the high sulfide content and the sulfate isotope study (Fouillac, et al., 1986) show that bacterial reduction has proceeded in a uniform way. Cl/SO_4 ratio is best explained by diagenetic changes in seawater.
(2) The samples from south of Paris are characterized by a unique molal ratio Cl/B = 265 (seawater = 1330) and a fair correlation between Cl and SO_4. The sulfide concentrations are low. A mixing model involving a high salinity and temperature fluid distinct from the water which lead to the group (1) above, and a low mineralized water satisfactorily explains the homogeneity of this area (Criaud, et al., 1986).
(3) The southernmost samples of low TDS are marked by low Cl/SO_4 and Cl/B ratios. In this group a young and dilute component is detected (Criaud, et al., 1986).
(4) The fluids from the borders (east and west) of the study area are distinct and do not belong to any of these groups.

Local linear trends in the correlations between chloride and, calcium or magnesium again show that the water/rock interactions occurred in different ways depending on the area and the processes involved (Criaud, et al., 1986). Bastide (1985) demonstrated that the concentration of Ca and Mg remained under the control of the solubility of calcite and dolomite during evolution.

All the fluids are close to equilibrium with chalcedony, albite, microcline, kaolinite and fluorite. Na/K and silica geothermometers provide good estimations of the downhole temperatures of the fluids.

3 - CHARACTERISTICS OF PRODUCTIVE LAYERS

Detailed analysis of the parameters of the productive layers is particularly important for several practical reasons:

(1) Characterization of the reservoir (temperature of the resource, productivity, mapping, etc.).
(2) Location of the two boreholes of a geothermal doublet (distance between wells, thermal breakthrough, lifetime, production pressures, etc.).
(3) The management of the resource (distance between doublets, respective orientation, hydraulic and thermal interference, invasion of the reservoir by reinjected cold water, etc.).

3.1 - Methodology

The principal hydraulic and thermal parameters are determined by three types of measurements in the reservoir (open hole):

(1) The diameter-flowmeter profile in production.
(2) The temperature (absolute and differential) profile in production.

(3) Recording of the pressure and temperature at the casing shoe during a production test followed by a build up (about 24 h).

The various geometrical, physical and chemical data from each geothermal well (111 boreholes at present) are archived in two forms:

(1) A data bank containing raw information, for consultation.
(2) A data base where data from different interpretations are filed. This information is subsequently exploited so as to estimate the regional distribution of parameters and modelling of the reservoir.

The detailed information on the producing units are, in principal, not essential in the case of normal exploitation, function basically concerned with the general transmissivity of the reservoir. However this information is of great interest for knowledge of the reservoir, optimization of future projects and particularly if possible operational anomalies arise during production: deposits, dissolution or clogging of productive layers, drift of injection pressures and drawdown over a period of time.

3.2 - Vertical structure of the reservoir

The systematic use of flowmeter profiles and thermometry showed that there are six to eighteen units, with an effective thickness only up to as much as a meter, participating in productivity or injection (Fig. 6). The various productive layers show a high average permeability range that is very variable: from 200 mD per measure on the cores, up to 20 Darcy locally, from the production tests. Secondary permeability related to local fracturing and to dissolution is generally added to the matrix permeability of these layers.

These secondary characteristics, often very local and unpredictable, make standard correlation between individual layers difficult and uncertain, however spatial correlation by groups of layers from the same assemblage is possible, i.e. according to facies classification. Generally, for the wells under consideration, the main productive layers (i.e; between 50% and 80% of the total flow rate of a well) are located in the middle oolite facies. The rest of the production is assured by small layers, distributed in part in the Comblanchian facies. Only some of the layers from the "Alternances" facies, at the base of the reservoir, participate somewhat uncertainly in the total production.

The first study area, about 26 km by 17 km (domain 1, Fig. 7) northeast of Paris was selected to be analyzed in detail according to the facies classification under consideration. Vertical limits of the facies enabling classification of layers are deduced from examination of logs, cuttings, estimation of permeability, and a reference borehole cored on the whole reservoir. Figure 8 shows the respective contributions of three facies: Comblanchian, Oolite, and Alternances, with the total production for the 26 wells located in this domain. Note that for approximately all the wells (88%) more than 50% of the production is assured by the oolite facies, i.e. an average flow rate of 100 m^3/h for a cumulated productive thickness of about 10 m.

A similar facies analysis is in progress in a second domain about 26 km by 28 km, with a high well density, south of Paris (domain 2, Fig. 7). Taking into account the nearness of the southwest impermeability limit (marl belt) examination of the detailed characteristics of the productive layers enabled the lateral limits of each of the facies to be fixed locally by noting their presence or absence in each well.

The main conclusion from the analysis of the characteristics of the various productive layers for each well is the identification of the vertical heterogeneity of the reservoir:

- Multiple productive layers.
- Stratified structure.
- High variability in permeability and productivity for each layer.
- Low (about 16 to 30 m) total productive thickness in comparison to the thickness of the Dogger formation (100-300 m).

This particular fine structure was identified by the systematic establishment of flowmeter profiles in production associated with thermometry measurements.

3.3 - Regional distribution of parameters

After identifying the structure and vertical heterogeneity of the reservoir in a limited number of places (wells) the second stage was to estimate the lateral continuity of the productive layers and the regional distribution of their parameters from this spot information.

Verification of the hydraulic continuity of the reservoir and the possible limits is especially important in the case of development of the resource by well doublets with reinjection. Firstly, it's because of reinjection and the continuity of the reservoir that their productivity can be maintained; thanks to hydraulic interference between the two doublet wells the exploitation pressure can be maintained fairly constant over a period of time. However, in the case of scarce and thin productive layers there is a risk of quick recyclage of reinjected cold water towards the production well.

Exact knowledge of the geometrical characteristics enables the distance between the wells and the production flow rate to be planned in correspondance with the desired life time of the system.

3.4 - Methodology

An interference test (or loop) is realized on site after carrying out production tests on the two doublet wells. For practical and economic reasons, this short period test (about 12 h) only checks whether interference does or does not occur. It is generally not long enough to reliably identify the average transmissivity of the reservoir between the two wells which are about 1000 m apart.

The regional distribution of the parameters and the continuity of the reservoir are estimated by geostatistical methods, by digital processing of spot information filed in the data base.

Geostatistics is a method of estimating based on the theory of regionalized variables (Chiles, 1977). Its implementation comprises two main stages:

(1) Determination of a variogram which defines the structure of the experimental values: continuity, uncertainty factor, notion of overall regional drift, notion of range, i.e. the distance from the interior of which a correlation exists between the values of the variable under consideration.
(2) Estimation of the value of the variable at every one of the intersections of a regular grid by exploiting the aforementioned variogram model.

This method, well adapted to the problem under consideration enables an efficient and reliable relation to be established between, the analysis of spot data on the wells, and the simulation of reservoir behaviour by heterogeneous models requiring a large quantity of data. The method offers three main advantages:

Automatic mapping of the estimated parameters.
Mapping the precision of the estimations (standard deviation).
Automatic generation of data files at the geometric grid intersections identical to that required by the simulation models.

3.5 - Parameters studied

The main parameters studied are those required by the modelling and the estimation of the geothermal energy resource:

(1) Geometric, barycentric depth of levels ZB and depth of top of reservoir ZT in meters in comparison to sea level.
(2) Hydraulics, transmissivity Kh (Dm), permeability K (D), cumulated production thickness h (m), reservoir pressure PG (bars).
(3) Thermal, temperature measured at the top of the reservoir in production, TP.
(4) Chemistry, total salinity of the fluid TDS (g/l).

The analysis is first realized for all the productive layers, then selectively for each of the 3 facies under consideration. Table 1 summarizes the principal statistical results of samples analyzed subsequently (all the layers).

Table 1
Statistical results on boreholes analyzed in domain 3

Variables	KH(Dm)	TP(°C)	TDS(g/l)
Number of points	66	66	31
Mean	38.9	69.9	20.5
Standard deviation	25.3	6.4	5.3
Minimum	6.7	56.6	10.2
Maximum	113.8	79.7	30.5

3.6 - Study domain

The area studied is represented by a square of side 50 km, approximately centered on the Parisian agglomeration (domain 3, Fig. 7). This domain comprises 79 boreholes of which 66 only were used in this study taking into account data collection in progress or being processed. The 32 boreholes located outside domain 3, and too far away, are not included in this analysis because they provide little information concerning geostatistical estimation.

The domain is bounded to the southwest by an impermeable zone (marl belt) which constitutes the limit of lateral extension of the various productive facies.

3.7 - Production temperature at bottom hole, TP

The production temperature measured at the casing shoe, i.e. the mean temperature of the reservoir, is a continuous physical variable (Fig. 9) characterized by a low variance of estimation. The regional east-west drift is very marked, this drift is in good correlation with the depth of the top of the aquifer, and the maximum temperatures measured to the east and outside the domain (85 °C at a depth of 1,950 m).

This distribution of temperatures characterizes the geothermal energy resource in the central part of the Dogger reservoir where a fairly constant normal geothermal gradient is between 3 and 3.5 °C/100 m.

3.8 - Mean transmissivity of reservoir Kh

The mean transmissivity of the reservoir is a more heterogeneous parameter which also shows a fair northeast regional drift. On a larger scale, the characteristic southeast strike and the regional drift identified are consistent with the occurrence of the impermeable marl belt to the west and the various regression stages of the paleogeographic model (Fig. 10).

3.9 - Mean salinity of reservoir TDS

This reservoir fluid mean variable is similar to the temperature variable, and is very continuous with an overall regional drift in a northeast-southeast direction (Fig. 11). Interpretation of the distribution of this parameter is complex and calls for specific studies. The different causes, still poorly known concern: the origin of the salinity (see 2), the regional flow path responsible for mass transfer, the age of the water in relation with the fluid velocity and supply to the reservoir.

4 - CONCLUSIONS

At present the main subject of geothermal energy research in France, the Dogger reservoir limestone of the Paris Basin, is one of the most developped low-enthalpy fields in the world. At the end of 1986, 55 geothermal doublets, i.e. 110 wells were realized. These various wells, realized and analyzed first with petroleum technology methods, then more specifically with geothermal methods have progressively provided a large quantity of information for analysis and the detailed knowledge of the reservoir.

Firstly, the development of the resource is distinguished from that of wells for water and petroleum on two main points: (1) an average temperature of 70 °C and (2) a high production of about 150 to 250 m^3/h per well.

The characteristics of the initial oversimplified concept of an homogeneous reservoir progressively changed towards a more complex representation of a stratified structure, with a large number of thin producing levels, more-or-less continuous, with high permeability.

Study of the fluid geochemistry shows a wide geographic variability of chemical parameters over the whole basin. Depending on the area considered, phenomena such as evaporation of seawater, chemical interaction with the surrounding rocks, confinement and complex mixings are recognized, so salinities cannot be explained by a single process.

The geometrical characteristics and the understanding of numerous heterogeneities, both vertical and horizontal, still comprise a certain number of unknowns related notably to the paleogeography and the fluid history of the reservoir.

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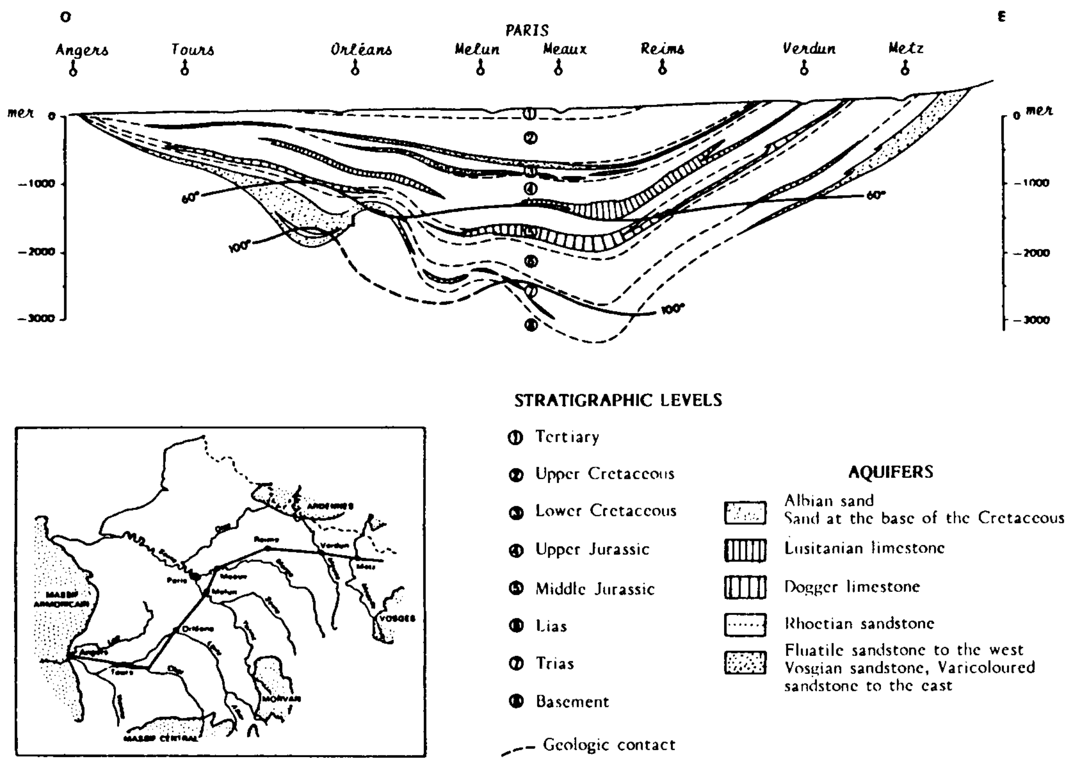


Figure 1 - Generalized cross-section of deep aquifers in the Paris Basin

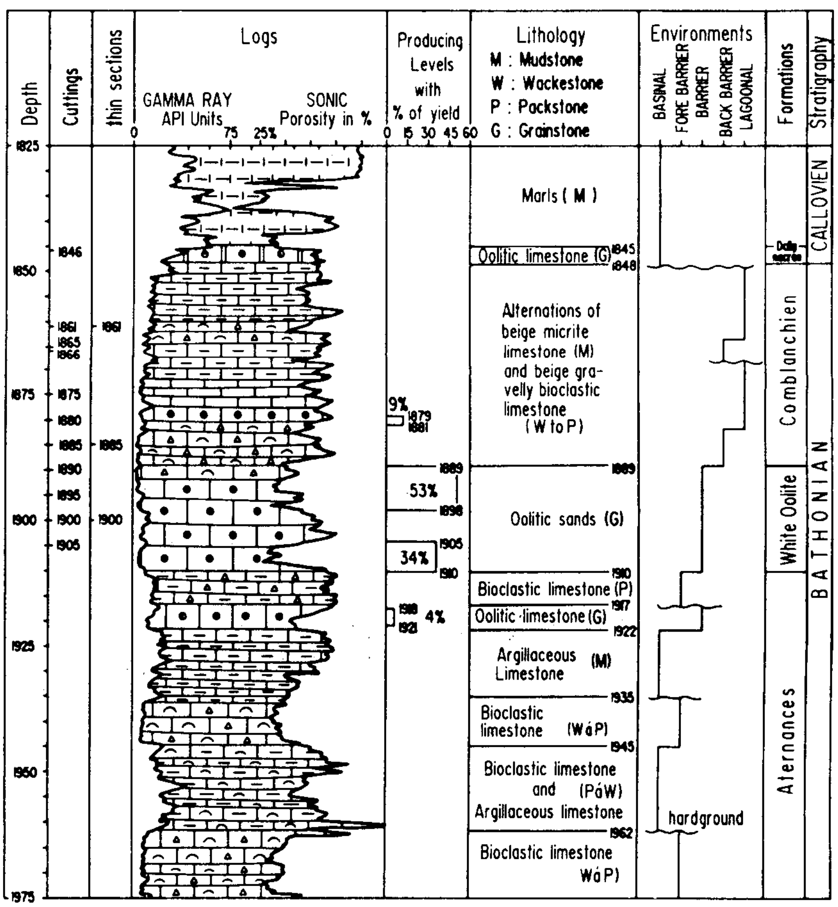


Figure 3

Typical sequence of Dogger in the Paris Basin

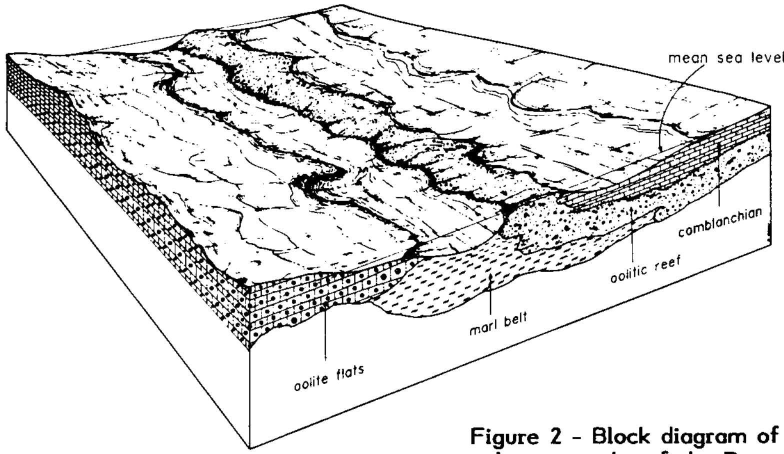


Figure 2 - Block diagram of paleogeography of the Dogger at the end of the Bathonian.

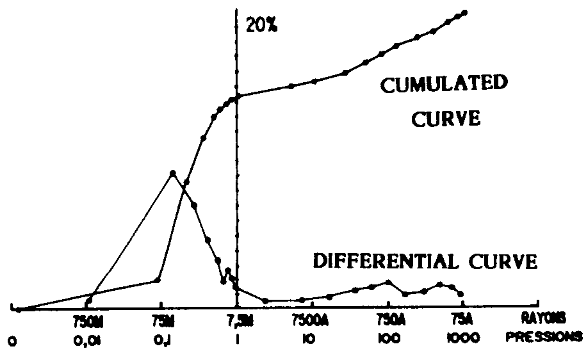


Figure 4

Oolitic limestone from the reef 1 730,5 m

Permeability : 200 mdy

Macroporosity : 14.16 %

Microporosity : 5.51 %

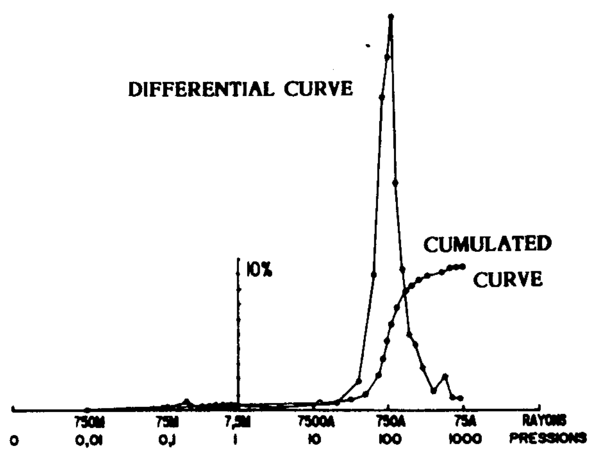


Figure 5

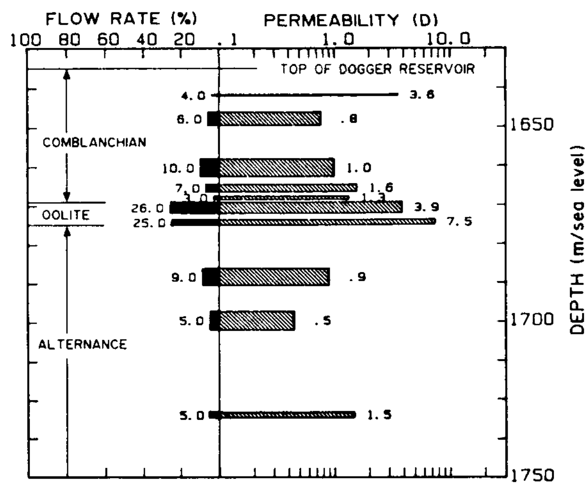
Compact micrite

External shelf 1 782,50 m

Permeability : 0,007 mdy

Macroporosity : 0.32 %

Microporosity : 9.42 %



WELL:AULNAY-SOUS-BOIS-I

MEAN PARAM.	FACIES COMBL.	FACIES OOLITE	FACIES ALTER.	ALL FACIES
H m	11.5	4.5	11.0	27.0
KH Dm	13.5	22.9	8.5	44.8
K D	1.2	5.1	.8	1.7
Q %	30.0	51.0	19.0	100.0
ZB NGF	1657.3	1672.3	1700.6	1673.2

Figure 6 - Detailed vertical structure of productive layers calculated from flowmeter and temperature logs.

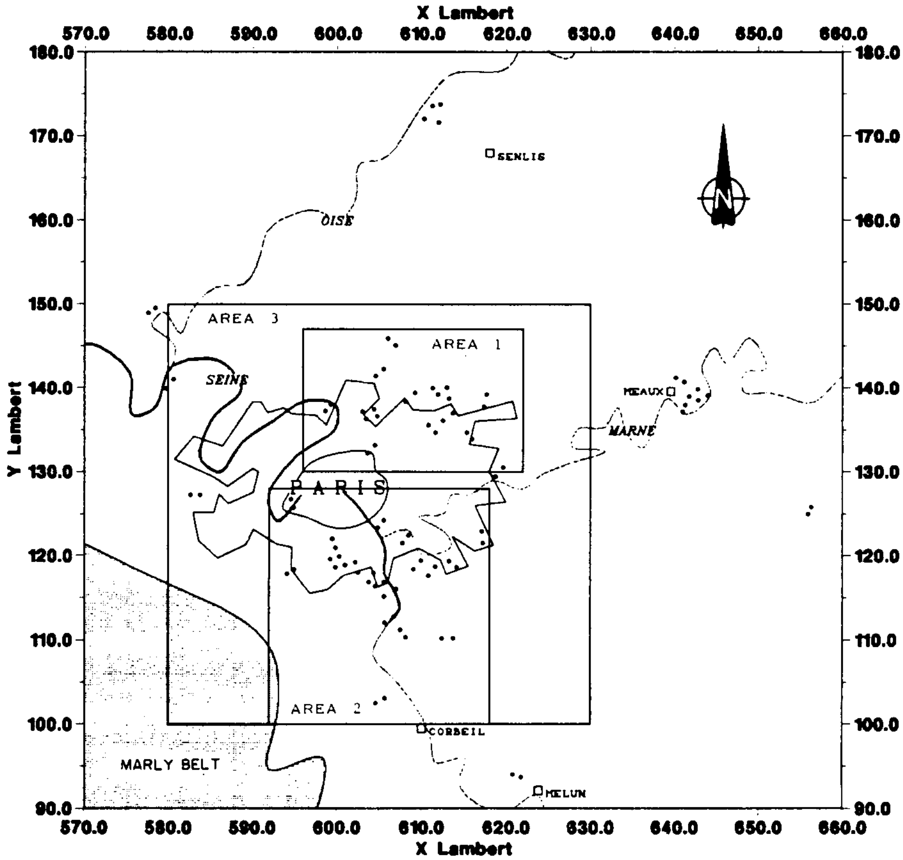


Figure 7 - Location of the geothermal wells in the Dogger reservoir (all wells not represented)

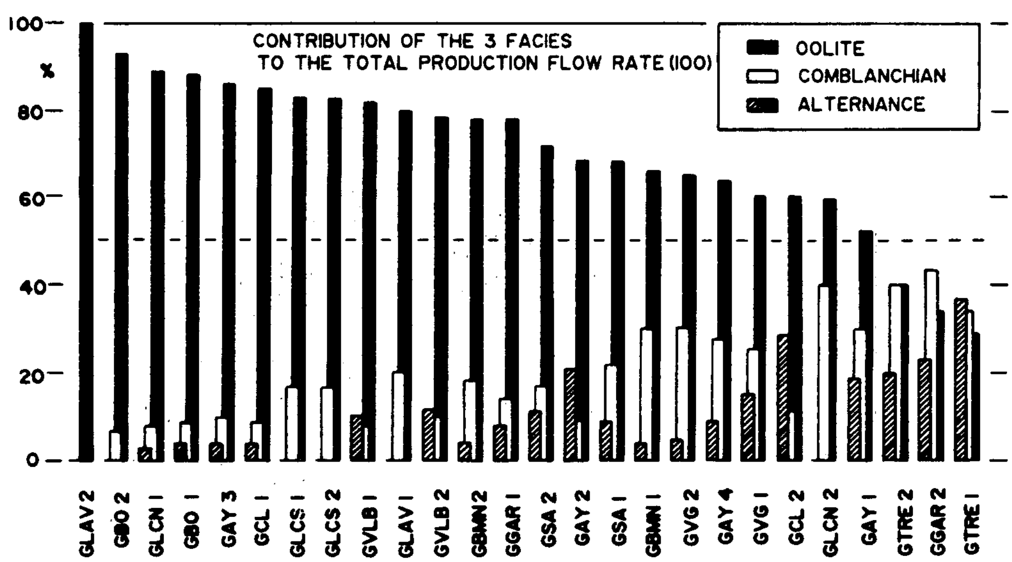


Figure 8 - Relative production of the 3 facies from 26 geothermal wells drilled in domain 1, classed according to the contribution of oolite facies.

FIGURE 9 - RESERVOIR TRANSMISSIVITY IN D.M (FROM PRODUCTION TESTS)

LEGEND :

ABOVE	*80.0*
	60.0 – 80.0
	40.0 – 60.0
	20.0 – 40.0
BELOW	*20.0*

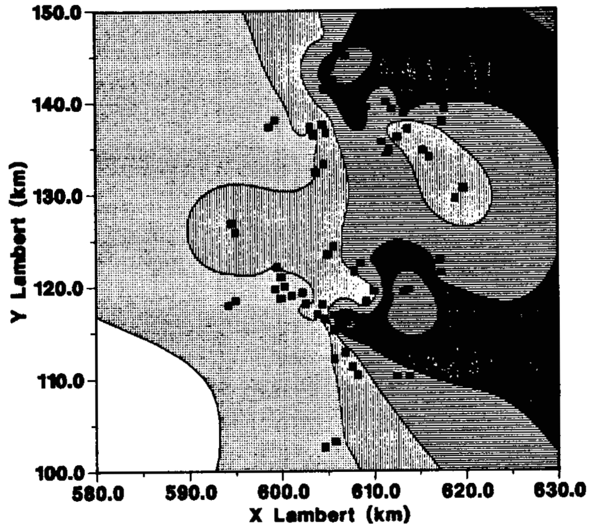


FIGURE 10 - TEMPERATURE OF RESERVOIR FLUID (MEASURED DOWN HOLE IN CELSIUS DEGRES)

LEGEND :

ABOVE	*80.0*
	75.0 – 80.0
	70.0 – 75.0
	65.0 – 70.0
	60.0 – 65.0
BELOW	*60.0*

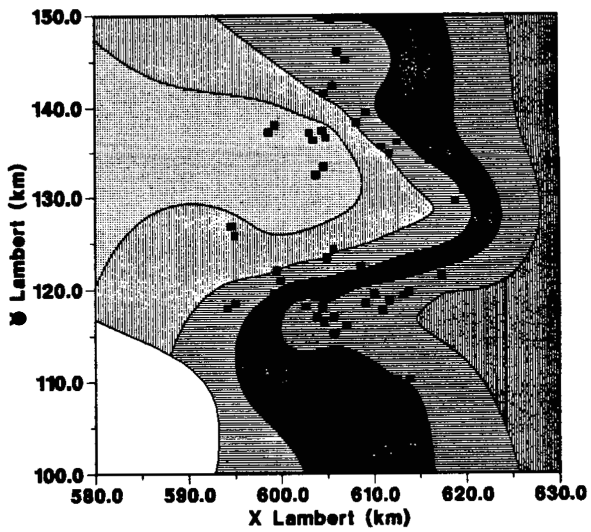


FIGURE 11 - FLUID TOTAL SALINITY (WELL HEAD MEASUREMENTS IN G/L)

LEGEND :

ABOVE	*30.0*
	25.0 – 30.0
	20.0 – 25.0
	15.0 – 20.0
	10.0 – 15.0
BELOW	*10.0*