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Flow of Formation Water in the Jurassic of the Paris Basin and Its [and Discussion] Effects

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Flow of formation water in the Jurassic of the Paris Basin and its effects

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The Jurassic of the Paris Basin is a major target for oil and geothermal exploitation. Interpretation of data from numerous wells reveals that the spatial distribution of fluid and reservoir parameters is heterogeneous with correlated anomalies for temperature and geochemistry. The multidisciplinary approach used to describe these typical characteristics shows that hydrodynamics provides the key to explain observed deviations from the usual correlations with depth. As a consequence of the coupling between hydrodynamics and fluid properties, the analysis of induced effects is a calibration criterion which can be used to improve the numerical simulation of the regional flow path. Compared to the results of the constant density approach, the new computer flow scheme, both gravity and density driven, is more consistent with the thermal and chemical anomalies observed. The refined analysis, including density effects, confirms the existence of a confined area and a mixing zone around Paris, previously identified by geochemical investigations.

1. Introduction

Formation waters from deep aquifers in the Paris Basin are of practical interest because of their association with oil and their use as a low enthalpy geothermal resource. At present more than three thousand oil wells and a hundred geothermal wells have been drilled here.

The Dogger reservoir, in particular around the centre of the basin (near Paris) is the main target of geothermal exploitation. Since 1985, 45 doublets (production-injection well-pairs) are exploited for space heating of around 150000 dwellings. From a scientific point of view and because of the abundance of available data, the Dogger reservoir is an excellent site for resource characterisation and methodological investigation.

For both oil or geothermal exploitation three types of information are needed: (i) knowledge of local resource characteristics (temperature, salinity, pressure, ...), (ii) understanding of the basic phenomena associated with resource properties (e.g. age and origin of the moving fluid) and (iii) information concerning the exploitation feasibility related to reservoir permeability, the major parameter controlling the potential flowrate.

In deep geothermal aquifers of sedimentary basins, the most common way to estimate temperature, salinity and pressure distributions is to relate them to depth assuming that, (i) these parameters are for the most part independent and (ii) the hypothesis of near horizontal geological layers is valid. When the density of wells and the accuracy of measurements increase (in this case, 100 wells around Paris), a detailed multidisciplinary approach can be used to show that the reservoir is

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heterogeneous, the main characteristics can be coupled, and some typical anomalies are associated with far phenomena. For these reasons we extended the limited study area to basin scale and suspected the incidence of regional flow.

This paper discusses present-day flow in the Dogger reservoir of the Paris Basin. Regional flow at basin scale is obtained by numerical modelling using two main hypotheses: (i) homogeneous constant fluid density, and (ii) variable density associated with detailed reservoir topography. The validation of flow modelling results is analysed using the coherence with the induced effects (geochemical and thermal anomalies, existence of confined and mixing areas).

2. Characteristics of the Dogger reservoir

The Paris Basin is an intracratonic basin with a diameter of 600 km and a maximum sediment thickness of 3 km. It is a late Tertiary structural depression whose tectonic deformation has led to the exposure of Middle Jurassic outcrops along the east margins of the basin (Ardennes, Lorraine and Burgundy). It is bordered by Palaeozoic massifs (Vosges, Armorican, Central and Ardenno-rhénan massifs) and widely open toward the Channel in its north-western part.

The Dogger aquifer with a thickness of 300 m is predominantly a limestone assemblage confined between the Liassic and Upper Callovian marls. The productive intervals for geothermal purposes are located in the Bathonian facies with, from the base to the top, a stratigraphic succession subdivided into three main units: 'Série des alternances' (external shelf sediments), white Oolit (reef deposits) and Comblanchian (internal shelf sediments, lagoon facies). For a given well, at least 60% of the total fluid production comes from white Oolit. These very permeable facies are present all over the basin.

The Dogger carbonate body is limited on the east (Lorraine) and southwest (Burgundy) by the outcrops which are the main area of ground water recharge with a maximum altitude around 400 m. The north and the southwest are limited by an impervious boundary. The southwest limit, with a main direction of N150, is a marly belt about 30 km wide, dividing the basin in two. The south-western part is not considered here.

(a) *Distribution of reservoir and fluid parameters*

The detailed study of the Dogger reservoir started in 1983, a few years after the second oil crisis, with two principal objectives: (i) improved knowledge of potential geothermal resources and (ii) analysis of optimum development conditions. A methodological investigation has been carried out by a multidisciplinary team working on three major themes: geology-sedimentology, geochemistry and hydrodynamism-transfers.

Taking advantage of the 110 geothermal wells drilled during the past 15 years, the study first focused on a restricted and well-documented zone of 10000 km^2 (90 km × 100 km around Paris) and hereafter called the 'geothermal area'. Using precise measurements from geothermal tests, a comprehensive and homogeneous set of data was analysed to (i) build a well database, (ii) determine the regional distribution of the main parameters (regionalised database) and (iii) develop a synthetic and conceptual model of the reservoir, suitable for further computer-oriented approaches.

In a second step, the area studied was enlarged to include the whole basin, up to the eastern outcrops and included the results of previous inventories (Maget 1983) and oil-fields data in order to gather the required information for the analysis of flow and its effects. Five groups of parameters were selected as primary informations to build the well-database: geometry to situate measurements, geology with facies markers, temperature (dynamic and static profiles), chemical parameters and hydrodynamical parameters from production tests and flow meter logs. The raw data were then processed using geostatistical methods to obtain estimated values at the nodes of a regular grid, for parameter mapping and input into numerical models. The main result of this detailed characterization is the identification of significant lateral and vertical heterogeneities the origin of which is to be related to both present processes and past history.

The systematic use of flow meter logs during production tests demonstrates that the production profile of the Dogger is very stratified with numerous (from 5 to 20) thin layers spread out vertically over around 50 m. The cumulated productive thickness (net pay), a major parameter for geothermal exploitation with doublets, is around 15–25 m, representing 10–15% of the total thickness of Dogger limestones. Perhaps the most important feature for flow analysis is that the average intrinsic permeability of layers (2–3 Darcies) obtained from tests is 10 times greater than the equivalent value determined on core samples in the laboratory. This high value which is representative of reservoir conditions takes into account not only the matrix, but also fractures and numerous dissolution channels.

The second characteristic of the Dogger reservoir is the great lateral variability (Rojas *et al.* 1989) in the geothermal area for temperature and salinity as illustrated in figures 1 and 2. Three other major parameters are presented in §§5 and 6: intrinsic transmissivity (figure 3), fluid density (figure 4) and average production depth (figure 5).

(*b*) *Correlations and identification of local anomalies*

When the distribution of the five parameters mentioned above are analysed it is seen that the general trends are in agreement with the global structure of the basin. In more detail, and in particular inside the geothermal area, a few typical anomalies can be identified. Two abnormal zones, one hot (anomaly of +10 °C) and one cold (anomaly of −8 °C), south and north of Paris respectively, are observed both at a same depth of 1700 m. The two spatial anomalies coincide spatially with two equivalent anomalies for total salinity (figures 1 and 2). According to the topographic distribution, these perturbations might be induced by two kinds of local phenomena: near horizontal regional flow and/or abnormal geothermal flux. The maximum values of transmissivity, which may induce high velocities, are found in the deepest area, coinciding with a hot and salty zone which, according to independent geochemical investigations (Fouillac 1990) was expected to be confined.

The detailed analysis of the various maps has finally brought to light the existence of a coupling of the principal parameters, including hydrodynamism: hydraulic head and pressure are conditioned by the relative transmissivity, which depends on fluid viscosity and therefore on temperature and salinity. Temperature and salinity distributions are controlled by regional flow, which, in turn, is determined by hydraulic head and pressure. This leads to the following major consequences for basin range modelling:

(i) Gravity driven flow (hydrogeological approach) may be locally perturbed by density driven flow.

Figure 1

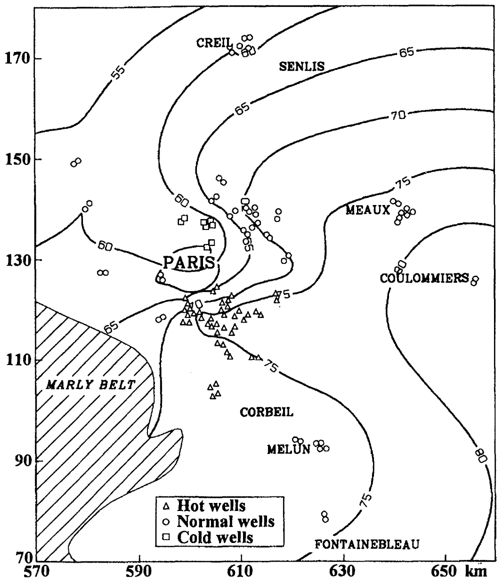

Figure 2

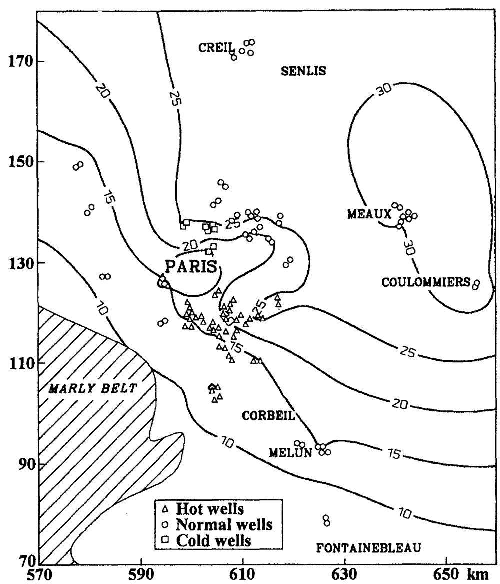

Figure 1. Map of average reservoir temperature (°C) in the geothermal area (Dogger, Paris Basin).
Figure 2. Map of average fluid salinity (g l^{-1}) in the geothermal area (Dogger, Paris Basin).

(ii) In this sedimentary basin, the spatial distribution of a given parameter is not independent, but related to the structure of the other coupled variables. This introduces the concept of coherence between the various distributions; a method to integrate multidisciplinary results and an additional fitting criterion to improve reservoir characterization.

(iii) The detailed knowledge of hydrodynamics is essential for the understanding of the thermodynamic state of the reservoir.

3. Formulation of the flow problem

In a deep porous reservoir, the filtration velocity V is defined by the generalized Darcy's law,

$$V = -(K/\mu)[\nabla P + \rho g \nabla Z], \tag{1}$$

where K is the intrinsic permeability, μ is the fluid viscosity, ∇P is the pressure gradient, ρ is the fluid density, g is the acceleration of gravity and Z is the elevation (referenced to sea level) of any point along the aquifer.

The conventional approach for basin hydrogeology assumes a constant density value ρ_0 and the velocity field is thus derived from a unique scalar potential (hydraulic head H). When measured in a well, this is equivalent to the height of fresh water equilibrating the downhole reservoir pressure. When both variations in fluid density and reservoir altitude are included, equation (1) written for pressure can be modified to include two driving forces, according to the same concept of hydraulic head (Frind 1982):

$$V = -\frac{K\rho_0 g}{\mu}\left[\nabla H + \frac{\rho - \rho_0}{\rho_0}\nabla Z\right] \tag{2}$$

with
$$H = Z + P/\rho_0 g. \tag{3}$$

The global driving force of fluid motion (terms in brackets) is thus the vectorial sum of two components: the classical gradient of hydraulic head ∇H (constant density hypothesis) and a correction term related to the local fluid density variation and the dip angle of the productive layers. Since a reservoir is generally not horizontal, fluid density varies with local temperature, salinity and pressure. In practice, this correction term which takes density effects into account introduces a few typical or new features into specific areas of the reservoir:

(i) Density effects which are superposed on the usual gravity driven flow will show their maximum amplitude when a slanted portion of aquifer is combined with a lateral variation in fluid density as, for instance, around the deepest area of a sedimentary basin.

(ii) When the correction term is locally significant, the rotational of the velocity vector is not zero and consequently the streamlines are not orthogonal to the hydraulic potential contours. Flow interpretation is thus more complex and several maps are needed for its analysis (potential, density, depth).

(iii) Generally, the density and gravity components of flow are independent. In some places, the competition between the two forces and the composition of the two velocity vectors are able to reduce or amplify the global velocity. This buoyancy effect may cause local thermosyphon flows (closed or open-loop) in the absence of topographic drive (constant hydraulic head H) or may increase some existing topographic drive.

Finally, to complete the formulation of the flow problem with density effects, the classical hydraulic balance based on volumes is revised to account for mass conservation.

4. Data set and hypotheses for flow modelling

When estimating flow at basin scale using a numerical approach, a large set of data is required to develop a synthetic reservoir model. A regionalized database was built using geological maps, geothermal and petroleum syntheses and by applying geostatistical methods (Menjoz & Lambert 1991). These are convenient tools for the standardization of several sets of homogeneous data of various origin. The geometrical and kriging meshes are identical in order to be able to superpose the maps of the experimental data and the results of modelling. The simulated area is represented by one thousand (9 km × 9 km) square cells. To account for the lateral heterogeneity observed, each cell of the reservoir model is characterized by a set of different parameters. The vertical heterogeneity is simplified by cumulating the thickness of the individual productive layers to obtain the equivalent of a single-layer model. The typical feature of this synthetic model is therefore the use of a low representative thickness which varies between a maximum value of 40 m in the centre of the basin and a minimum value around 10 m near the outcrops.

The flow problem is solved using a finite element model and integrating the density effects formulated in the previous chapter. The computed variables are hydraulic head, pressure and the Darcy velocity field used to estimate the streamline pattern. Using numerical models, the major problem is the validation of the estimated flow (direction and amplitude). This has been achieved by using other calibration parameters representative of the phenomena induced by the fluid flow. For this purpose two sets of parameters have been selected (^{18}O and ^{2}H of water). These

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components are assumed to be conservative and considered here as perfect tracers, they are convected and dispersed by the velocity field without any interaction with minerals (Matray *et al.* 1993).

5. Regional flow model using constant density hypothesis

The normal approach used at basin scale for regional flow estimation uses the hypothesis of a constant fluid density (equal to one) and serves as a reference base for coherence analysis with the other reservoir parameters.

(*a*) *Modelling results*

Figure 3 is a map of intrinsic transmissivity of the aquifer in Darcy·metres (dashed contours). The experimental distribution of this major parameter is in agreement with the global structure of the basin. The largest values, higher than 50 D·m, are measured in the centre of the basin and in the deepest area. With this approach, the flow is conditioned only by the topographic drive (elevation of outcrops in the south east). Transmissivity is therefore the main constraint when analysing the flow path characteristics.

The flow scheme at basin scale is represented by a selected number of streamlines (full lines). These lines, parallel to the velocity vector, represent the path of water particles issued from the outcrops and converging north west towards the low pressure area.

The computed flow path is homogeneous for both amplitude and azimuth with an average Darcy velocity on the order of 0.05 m a^{-1}.

(*b*) *Coherence analysis and weakness of the constant density hypothesis*

For the overall view of the basin, this standard approach can reproduce the major and known characteristics of the regional flow (average direction and amplitude): the reservoir is now invaded by meteoric waters from outcrops and in a near hydrostatic state with a very low regional velocity.

Beyond this global coherence, when studied in more detail, this approach is not consistent with numerous observations in the central area of the basin in several aspects:

(i) The computed pressure field does not agree with the measured distribution, in particular with the area of low hydraulic gradient, just north of Paris.

(ii) Looking at the other parameters correlated to flow, the computed, rather homogeneous, velocity field is not able to produce (convection-dispersion process) the observed distortions of the temperature and salinity contours lines, especially in the north and south of Paris area.

(iii) The high velocity found in the deepest zone, north-east of Paris, is contrary to the anticipated low value suggested by the fact that (i) it is inside an area of maximum salinity values and (ii) geochemical analyses show it to be a confined area with bacterial reduction of sulphates and sulphur enrichments (Fouillac *et al.* 1990; Matray *et al.* 1993).

(iv) The velocity computed for the area to the south of Paris cannot show the observed mixing with young waters.

These discrepancies in the computed results were the main reasons for doubting the validity of the constant density approach and showed the need for a more refined description of the flow path, especially in the central area of the basin. Density

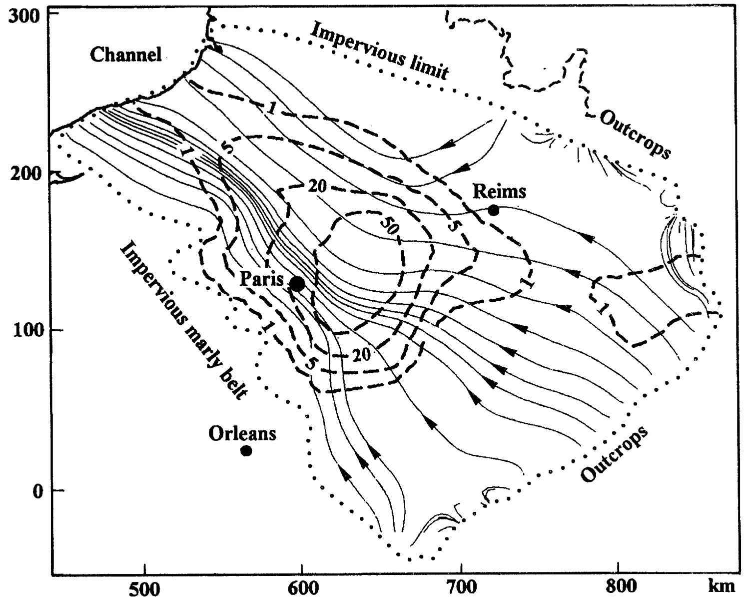

Figure 3. Regional flow using the constant density hypothesis in the Dogger reservoir. Computed streamlines superposed on the map of intrinsic transmissivity (D·m, dashed lines).

effects, neglected in the first approach, may be the main origin for the observed and missing anomalies.

6. Regional flow model taking into account density effects

This refined approach to reservoir behaviour modelling uses the same set of data (geometric mesh and heterogeneous distributions of the main parameters produced by geostatistics) to enable a comparison with the previous analysis. To include density effects two new types of data are added: the topography of the average aquifer depth around which the total net pay of the individual productive layers is cumulated; the spatial distribution of fluid density as a function of local temperature, salinity and pressure.

At this stage of the analysis, the fluid density data are fixed. The simulation process integrates the coupling between hydrodynamism and thermo-chemical phenomena in order to produce a flow scheme consistent with the given reservoir description representative of present state. The feedback of fluid motion on density (transient state) is not included in this approach. In a first step, the object of the simulations described here is to improve a global coherence between the various coupled phenomena.

The results of flow modelling taking into account density effects are summarized on two maps (figures 4 and 5). As mentioned in the chapter on flow formulation, the typical events induced by buoyancy effects imply that keeping in mind the characteristics of altitude and density gradients may be of help in the interpretation of simulated flow.

Figure 4 shows fluid density contours in the Dogger reservoir (imposed data, dashed lines) and the streamline pattern (modelling results, full lines). To facilitate flow analysis, the starting location of water particles along outcrops, used to draw streamlines, are the same as in the previous approach with constant density.

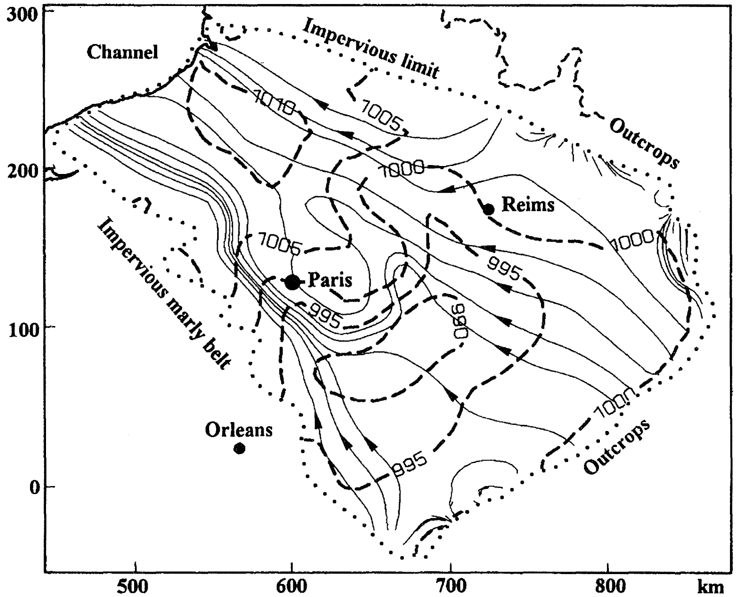

Figure 4. Regional flow with density effects in the Dogger reservoir. Computed streamlines superposed on the fluid density contours (dashed lines).

Figure 5 shows the same computed flow path superposed on the average productive depth (referenced to sea level) and the main faults. The map of reservoir altitude (dashed lines) also shows the global structure of the various aquifers, including Dogger, in the Paris Basin. This large-scale view of the basin shows that the deepest area for the Dogger reservoir (around 2 km) is located right in the centre of the basin. It is characterized by the highest temperature (85 °C, under normal geothermal gradient) and the highest salinity (35 g l^{-1}). Curiously, as a consequence of the opposite effects of temperature and salinity, the fluid density value is, for this particular place, the same as that of fresh water.

The new flow scheme obtained is more heterogeneous and very different, especially in the middle part of the basin. Starting from the eastern part of outcrops, the main parallel stream tubes still follow the steepest slope of the aquifer (as in the previous approach under gravity drive), but in this case do not cross the central area and diverge in two parts around the central area with the highest salinity. This zone is very rich in typical features induced by the local competition between the gravity and density driven flows.

7. Discussion and conclusion

Comparison of the two flow schemes confirms that it is the density and altitude variation (or gradient) rather than their absolute values which conditions density effects. This fact, in agreement with theory, can be seen all around basin borders where density effects have a very limited incidence on the azimuth of the velocity vector. Along the outcrops where the flow is mainly gravity driven, the velocity vector is still orthogonal to the lines of constant hydraulic head (or density). This standard feature is completely modified all over the central area of the basin. The local streamlines can be either orthogonal or parallel to the fluid density contours.

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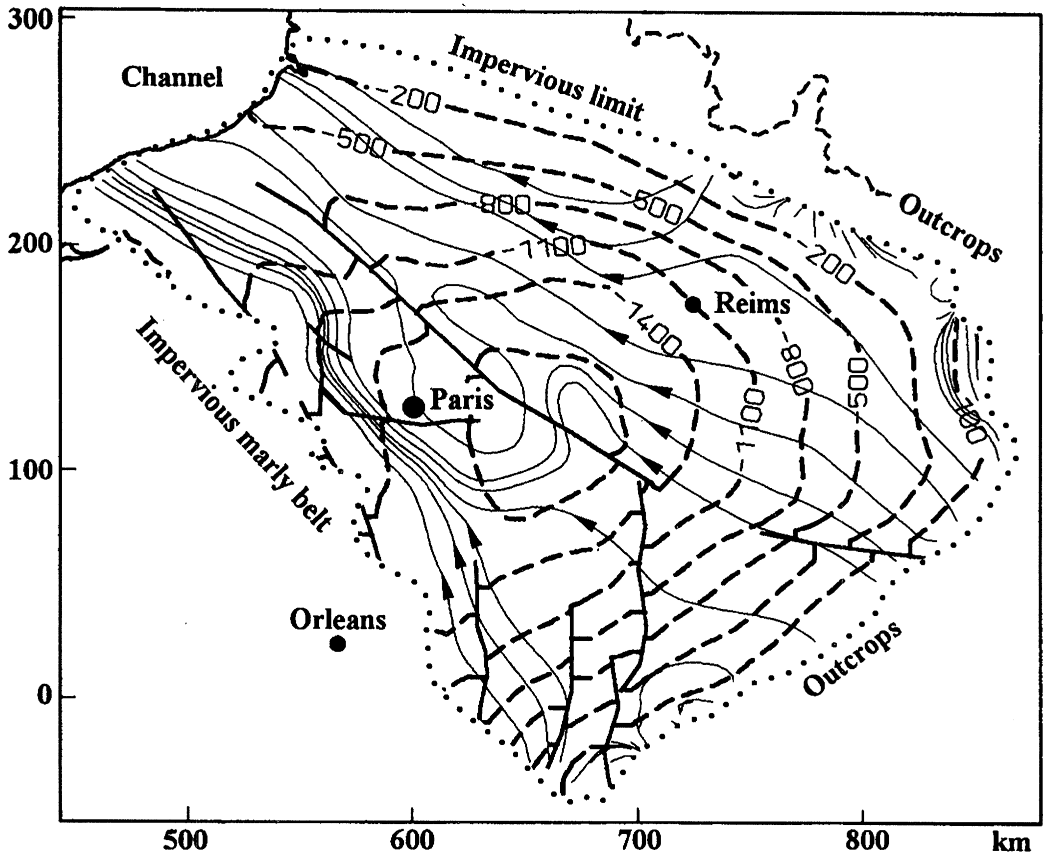

Figure 5. Regional flow with density effects in the Dogger reservoir. Computed streamlines superposed on the distribution of the average production depth (dashed lines) and main faults.

The understanding of flow azimuth is rather complex because it is related to the vectorial characteristics of the three gradients involved: hydraulic head, fluid density and reservoir altitude.

Since the variation of reservoir depth is gradual, the flow perturbation induced by density effects increases towards the centre of the basin where the major typical events are encountered. In the deepest area, and in particular on the downstream side, the sign of the dip angle changes and the fluid density increases. Even with the additional contribution of pressure gradient, the net buoyant flow initially takes a direction opposite to the regional one and then vanishes. There is a specific zone therefore where the velocity falls to zero.

The most important result of flow modelling at basin scale with density effects is the demonstration of a central area with a zero velocity (and a maximum transmissivity value). This zone located north-east of Paris is in fact hydrodynamically confined and characterized by the existence of a closed-loop thermosyphon scheme. The localization of this confinement phenomenon is in full agreement with experimental results from fluids geochemistry (bacterial reduction of sulphates and ^{34}S enrichment (Fouillac *et al.* 1990; Matray *et al.* 1993)). The computed results are also consistent with the observed piezometry characterized by a very low hydraulic head gradient in the area where the closed-loop thermosyphon scheme (which is not pressure driven) is thought to be. The estimated low velocity is also in agreement with the normal geothermal gradient (33 °C km^{-1}) measured in deep wells. Surprisingly, the two modelling approaches lead to opposite results in this zone (maximum velocity for the constant density hypothesis and zero velocity when density effects are included).

On the other hand, since the conservative hydraulic flux must pass round the central zone and is also forced into a restricted path by the transmissivity field. The flow is split into two preferential paths on either side, with an important amplification of velocity. Then, downstream beyond this area, where density effects are significant, the two separate flows converge again in a unique direction, parallel to the maximum hydraulic gradient. The second important result of this simulation is therefore the identification of a zone of higher velocity in the south of Paris which is also an area of mixing with young waters from the east and the south-east. This event is confirmed by the results of fluids geochemistry (Matray *et al*. 1993), and also by the existence of a large positive thermal anomaly on the order of +10 °C.

Looking back to figure 4, one can note that the two preferential paths mentioned above are very consistent with the two main distortions observed on the fluid density contours (north-east and south of Paris).

The results obtained with the simulation of this case study show that the deepest zones in the aquifers of sedimentary basins may seriously perturb the expected regional flow. A detailed reservoir characterization is thus important to avoid estimation errors on fluid thermodynamics, origin and ages of waters, and mixing processes. In the central area, where buoyancy effects are maximum, large differences have been identified between the two hydraulic approaches. The error can reach the value of 180° on the azimuth of the velocity vector and a ratio of 5 to 7 on the amplitude of flow (Menjoz *et al*. 1991). The use of a refined flow formulation, including density effects, is a way to connect more closely the flow characteristics and the numerous geochemical informations on the moving fluids.

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Discussion

L. M. Walter. What are the effects of salinities up to 6 molal on modelling hydrodynamics in such basins?

A. Menjoz. Salinity is the main contribution to fluid density variations, in competition with temperature. The effects are limited, for any salinity, if the spatial distribution is constant all over the basin. But the effects are significant as soon as a lateral variation of salinity exists and is locally combined with a variation of reservoir depth. This typical situation is found in the deepest areas of basins or as the result of a brine invasion (salt spot) in a reservoir filled with near-fresh water. In these cases, the effect of buoyancy is the generation of closed-loop patterns, superposed to the usual gravity driven flow. The heterogeneity and amplification of the local velocity, roughly proportional to the maximum salinity, induce mixing processes between fluids of different salinities and a global smoothing of salinity distribution.

D. Emery. What causes the differences in density? Is it a mineral? Why is the water saltier?

A. Menjoz. The origin of the salinity in the Dogger is still an open question: we have evidence that it is not old seawater although salinity is around $35\,g\,l^{-1}$. One hypothesis is migration from the Triassic through faults into the basin centre and then washed out over several million years with a decrease in salinity. Numerical modelling shows that present-day salinity might be induced by such past scenarios.

M. L. Coleman. Variations in Cl isotopes allow mapping of the Cl/water travel path. Keuper salts dissolve and salinity increases: the water then flows through faults into the Keuper. In the basin centre, the Keuper and Dogger have similar Cl isotopes but the Dogger fluids are more dilute. This is evidence for vertical, cross-formational flow between the Keuper sands and salt and the Keuper and the Dogger.