Origin and age of deep waters of the Paris Basin

Origine et âge des eaux profondes du bassin de Paris par l'utilisation des traceurs chimiques et isotopiques

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ABSTRACT – The origin and age of deep waters of the Paris Basin are considered on the basis of chemical and isotopic analyses carried out on almost 150 water samples collected from geothermal wells, oil wells, and Middle Jurassic and Late Triassic aquifers. The studies reveal that currently only Cl, Br, ^{2}H and ^{18}O species are present in the three aquifers, although one of the original waters was previously enriched in oxygen-18 probably due to a temperature effect. The combination of Cl/Br ratios and stable isotopes reveals the complex origin of these aqueous solutions that result from the mixing of two distinct secondary brines formed by the dissolution of Triassic salt by meteoric water. The first brine was derived from an ancient meteoric water that had undergone oxygen-18 enrichment. The second brine has the same origin as the first, but its isotopic composition has remained constant since infiltration. The evolution of these waters within the framework of the geological history of the Paris Basin suggests that the first generation of brine is sequential to exposure of the reservoir rocks in the east at the beginning of the Cenozoic, and that it is older than the general cooling of the basin at the end of the Oligocene. Vertical fluid transfer along faults also took place during this period which also explains the presence of hydrocarbons and late carbonate cements in the Dogger aquifer. The maximum outcropping in the east initiated the formation of the second brine which mixed with the already existing brine, traces of which can only be detected in the deepest parts of the Triassic aquifers. The addition of meteoric water, unaffected by salt dissolution, is responsible for the present salinity distribution in the three aquifers.

Keywords: Paris Basin, deep aquifers, Triassic, Rhaetian, Middle Jurassic, hydrochemistry, isotope geochemistry, sedimentary brines, residence time, paleocirculations.

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RÉSUMÉ – L'origine et l'âge des eaux profondes du bassin de Paris est discutée à partir d'analyses chimiques et isotopiques effectuées sur près de 150 échantillons d'eau produits par les puits géothermiques, pétroliers et d'eau souterraine du Jurassique moyen (Dogger, Fig. 1) et du Trias supérieur (Keuper et Rhétien, Fig. 2).

Les études effectuées montrent que seules les espèces Cl, Br, ^{2}H et ^{18}O sont actuellement conservées dans les trois aquifères étudiés bien que l'oxygène-18 ait connu dans le passé un enrichissement dans l'une des eaux originelles sous l'effet probable de la température (Fig. 3 et 4). Ces espèces sont donc des traceurs d'origine et peuvent aider à reconstruire l'évolution de ces eaux. Les isotopes stables révèlent que toutes les eaux étudiées sont le résultat du mélange d'eaux d'origine météorique plus ou moins enrichies en isotopes lourds alors que les rapports Cl/Br montrent une salinité acquise par dissolution d'évaporites marines contenant des inclusions de solutions-mères du sel (Fig. 5).

Ce résultat implique nécessairement l'existence de transferts verticaux entre les aquifère du Trias et celui du Dogger. Les rapports isotopiques du chlore des eaux du Dogger sont dans la moyenne de ceux du Trias (Fig. 6) et prouvent que ces transferts se sont effectués sans fractionnement isotopique au travers des 450 m d'argiles qui séparent les réservoirs. Un transport advectif rapide des saumures triasiques vers l'aquifère du Dogger peut seul expliquer l'absence de fractionnement et suggère donc le transfert des fluides à la faveur de failles. Un schéma hydrologique général est ainsi proposé pour expliquer l'origine des eaux profondes du bassin de Paris (Fig. 7).

Les rapports Cl/Br couplés aux isotopes stables montrent l'origine complexe de ces solutions aqueuses qui seraient le résultat du mélange de deux saumures secondaires distinctes formées par la dissolution de sel triasique avec des eaux météoriques. La première saumure serait issue d'une ancienne eau météorique ayant subi un enrichissement en oxygène-18 dans le passé. La seconde saumure aurait une origine identique à la précédente mais avec une composition isotopique inchangée depuis l'infiltration.

Corrélée à l'histoire géologique du bassin de Paris, cette évolution des eaux suggère que la première génération de saumure est consécutive à l'affleurement des réservoirs à l'est dès le début du Cénozoïque et est antérieure au refroidissement général du bassin à la fin de l'Oligocène. C'est également au cours de cette période étendue que se seraient effectués les transferts verticaux de fluides par faille et qui seraient à l'origine de la présence d'hydrocarbures et de ciments carbonatés tardifs dans le Dogger.

Le surélèvement maximal des affleurements à l'est, aurait initié la formation de la seconde saumure qui se mélangerait avec celle déjà en place et dont la trace n'est plus visible que dans la partie la plus profonde des aquifères tria-

siques. Des apports météoriques non affectés par la dissolution de sel, c'est-à-dire par le sud pour le Trias, expliquent la distribution actuelle des salinités dans les trois aquifères.

Le schéma d'écoulement actuel du Dogger (Fig. 8) permet d'estimer à environ 1 Ma le temps de transfert dans l'aquifère en dehors de la zone centrale perturbée pour laquelle un temps de résidence plus long est probable. Ce résultat montre que les méthodes de datation directes par les radio-isotopes ^{3}H et ^{14}C se révèlent inadaptées dans le cas des eaux profondes du bassin de Paris et ne sont applicables qu'aux fluides de bordure.

Mots clés : bassin de Paris, aquifères profonds, Trias, Rhétien, Jurassique moyen, hydrochimie, géochimie isotopique, dépôts salés, temps de résidence, paléocirculations.

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INTRODUCTION

In order to reconstruct the history of deep waters in a sedimentary basin, it is necessary to study the mixing poles that make up the present fluid. Generally, this involves the search for preserved chemical and isotopic species, i.e. species whose concentration has only been modified by the mixing itself.

Formation waters of the deep aquifers in the Paris Basin have been extensively studied due to their association with hydrocarbons, their use as a low-enthalpy geothermal resource, and their potential for subsurface storage of gas. Three deep aquifers have been studied in particular: the Dogger comprising Middle Jurassic marine carbonates, and the Keuper and Rhaetian Late Triassic fluviatile sandstones.

This paper is a synthesis of all studies relative to the origin of the water from these three aquifers. It discusses the application of geochemical tracers and shows to what extent these can be used to constrain the origin, paths and modes of transfer, and the residence time of waters in deep aquifers of a sedimentary basin.

THE AQUIFERS

The Paris Basin is an intracratonic basin 600 km in diameter, containing a sediment pile almost 3 km thick. It is a structural depression formed at the end of the Oligocene, the tectonic deformation of which led to the exposure of rocks of Middle Jurassic (Dogger) age in the east and south, and of Late Triassic (Keuper and Rhaetian) age in the east. However, the first uplift of outcrops is estimated to have taken place in the east at the very beginning of the Cenozoic.
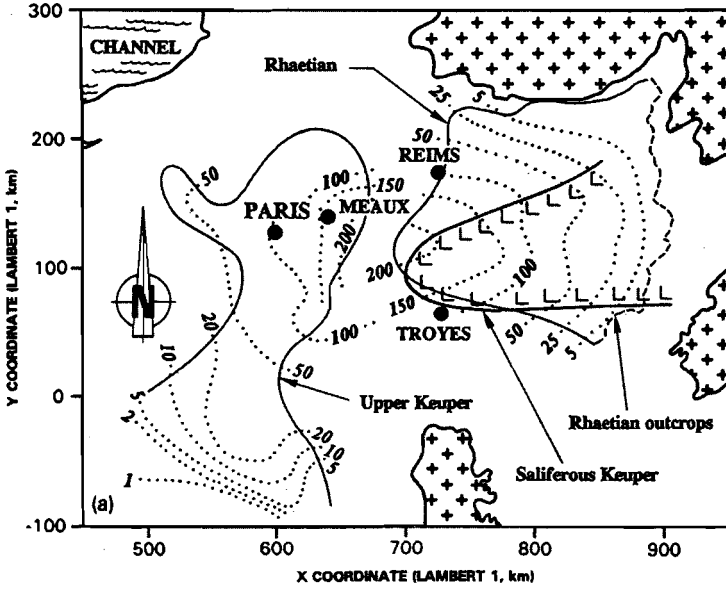
FIGURE 1.

Extension of the Late Triassic aquifers with isosalinity curves (dotted lines).

Extension des aquifères du Trias supérieur avec courbes d'isosalinité (traits pointillés).
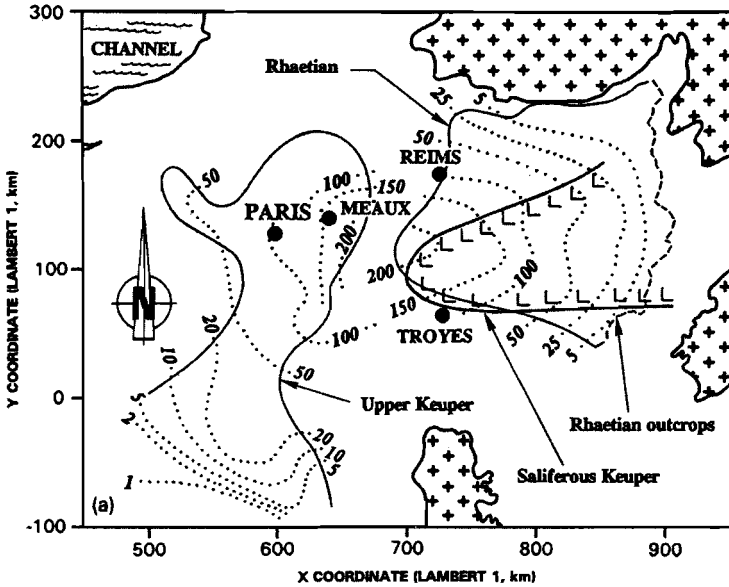

FIGURE 2.

Extension of the Middle Jurassic aquifer with isosalinity curves (dotted lines).

Extension de l'aquifère du Jurassique moyen avec courbes d'isosalinité (traits pointillés).

Keuper deposits form the central and southern parts of the basin and are essentially composed of fluviatile sandstone, clay and dolomite, with an average thickness of 100 m. Their lateral equivalent is a bedded halitic complex which is the only saliferous complex in the basin, apart from another smaller, older complex. The Rhaetian sandy and clayey reservoir overlies this saliferous interval.

The Dogger is a 300 m thick carbonate unit, sealed above and below by Callovian and Liassic clays which are 450 m thick in the centre of the basin.

Liassic clays are the source rocks for the hydrocarbons in the three aquifers studied.

Aqueous solutions associated with these aquifers are highly concentrated. Their salinity ranges from a few hundred mg.l^{-1} along the edge of the aquifers to 175 g.l^{-1} for the Keuper, 220 g.l^{-1} for the Rhaetian, and 35 g.l^{-1} for the Dogger. Maximum values are found in the deepest parts of the aquifers.

SAMPLING AND ANALYSIS

Specific samples for chemical and isotopic analysis of water and gas were collected in 120 wells for the Dogger, 20 for the Keuper, and 12 for the Rhaetian. The sampling and analysis procedures are described by Rojas *et al.* (1989) for geothermal fluids and by Matray *et al.* (1993), Fontes and Matray (1993a) and Worden *et al.* (1994) for petroleum fluids. Most chemical and isotopic analyses were carried out according to conventional methods. Representative samples of the three reservoirs were analysed in more detail; for example, stable isotope analysis of chlorine at the University of Utrecht using the Kaufmann (1984) method.

THE SEARCH FOR PRESERVED SPECIES

A preserved chemical or isotopic species is one whose concentration has not been modified by thermodynamic exchange reactions, kinetics, or bio-physico-chemical processes related to transportation, radioactive decay, bacterial activity, etc. Only a mixing of fluids can change their concentration. Such species can thus be used to estimate the number of poles in the final mixture and to define the origins of the fluid.

Geochemical studies of deep fluids reveal that waters of the Middle Jurassic and Late Triassic have chemical components that are generally either constrained by equilibrium with mineral or gaseous phases, or under the influence of bacterial metabolism (Michard and Bastide, 1988; Fouillac *et al.*, 1990; Matray *et al.*, 1993; Worden *et al.*, 1994). Although disagreement exists regarding the phases that constrain the geochemical system, it is accepted that Cl and Br are the only truly preserved species. Their relationship can therefore be used as a mixing tracer and to reveal the sources of chlorides. In this manner,

at least four sources of chlorides have been identified for the Dogger aquifer, three for the Rhaetian and six for the Keuper. This clearly demonstrates the complexity of the deep fluids and the difficulties involved in understanding their origin.

Of all isotopic species, stable water isotopes are probably the only ones that show a certain degree of preservation. In many basins, however, the isotopic composition of fluids is modified by isotopic exchanges with minerals or other fluids (gas, hydrocarbons). This is especially true for isotopic exchanges between oxygen isotopes and sedimentary rocks because the minerals that make up these rocks represent an important supply of oxygen atoms. These exchanges take place under the combined effects of temperature, a long residence time and a low water/rock ratio. For the deep aquifers of the Paris Basin, the ^{18}O contents of the least-concentrated solutions of the Middle Jurassic and the Late Triassic do not correlate with reservoir temperatures (Fig. 3). This indicates that the ^{18}O content of these solutions is not influenced by exchanges with minerals.
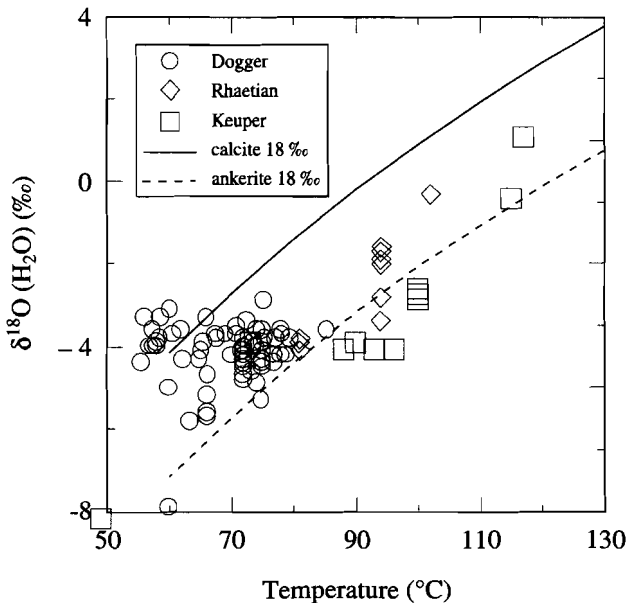

FIGURE 3.

Relationship between $\delta\,^{18}O_{H_2O}$ and reservoir temperature for all the fluids studied, with carbonate/water equilibrium curves for the late diagenetic species of the aquifers.

Relation entre $\delta^{18}O_{H_2O}$ et la température des réservoirs pour l'ensemble des fluides étudiés avec courbes d'équilibre carbonates/eau pour les espèces diagénétiques tardives des aquifères.

Furthermore, the low gas/water ratios recorded in these fluids exclude any enrichment by exchange with dissolved gases (Matray *et al.*, 1993, Worden *et al.*, 1994). As water is the main reservoir of hydrogen atoms, it is likely that exchanges between hydrogen isotopes and minerals (or other fluids) are even more limited than for oxygen.

In conclusion, stable water isotopes are the species preserved throughout the Dogger, as well as in the part of the Keuper where concentrations are the weakest, i.e. less than 90 g.l^{-1} total salinity. For higher salinities, ^{18}O enrichment is observed that is as much as 4‰ in the Keuper and Rhaetian aquifers, unlike deuterium, which remains relatively constant around $- 25$‰ $\pm$ 5. For the most-concentrated solutions of the Keuper and Rhaetian aquifers, the ^{18}O contents fall in the field of the Paleogene (65-25 Ma) late diagenetic carbonates observed in the three reservoirs (Worden *et al.*, 1994). The similarity between the oxygen-18 contents and salinities (in equivalent NaCl) of the mother solutions of these carbonates and of the most-concentrated current brines, leads to the assumption that the latter are residual solutions of the precipitations (Spötl *et al.*, 1993; Worden *et al.*, 1994). However, the deposits formed at temperatures 20 to 30°C higher than present temperatures, indicating a former oxygen-18 enrichment under a higher temperature effect. Thus, the relationship observed between ^{18}O and temperature for the brines is one of mixing rather than current exchange.

ORIGIN OF THE WATER

Determination of a water's isotopic composition is the most important factor for identifying its origin (Kharaka and Carothers, 1986).

The isotopic contents of the Dogger aquifer show identical behaviours, attributed to the preservation of these tracers. Two zones are distinguished by plotting isotopic content against chlorides (Fig. 4):

1) 0 to 5 g.l^{-1}: The isotopic contents correlate with chlorinity, indicating mixing between one pole with a concentration of 5 g.l^{-1} and up to several other diluting poles, the most impoverished of which is identical to the current meteoric pole (Dever *et al.*, 1990).

2) 5 to 20 g.l^{-1}: The isotopic contents show no correlation with chlorides. Two processes can explain such behaviour. The first is dilution of a concentrated pole by meteoric water of the same isotopic composition. The second suggests that this concentrated pole is sufficiently diluted so that its isotopic composition is no longer perceptible in the mixture. In both cases, the diluting solution is one devoid of dissolved salts and corresponds to a palaeo-meteoric water with a composition of about $- 4$‰ oxygen-18 and $- 33$‰ deuterium. For the concentrated solution, the generally accepted hypothesis in the past was that of seawater preservation. This explained,

in particular, the remarkable concordance between salinities in the central part of the aquifer and the seawater. However, isotopic data show that this hypothesis is not plausible because the Dogger waters have isotopic contents much lower than the variation range generally accepted for the isotopic composition of seawater during the Phanerozoic (Sheppard, 1986). In addition, the Dogger solutions show an enrichment in Br compared to seawater.

Oxygen and hydrogen isotopes show a different behaviour for the Late Triassic aquifers. Deuterium contents are relatively constant and only slightly higher than those for the Jurassic. In contrast, oxygen-18 contents have an excellent positive correlation with chlorides, attributed to specific mixing of each aquifer due to the current preservation of isotopic ratios. This result implies the presence of two groups of Triassic brine as well as diluting solutions. The most-concentrated brine was formed during a period favourable to isotopic enrichment under a high-temperature effect implying an initial fluid with an isotopic composition of about -23‰ deuterium and -3.5‰ oxygen-18. The second brine did not undergo isotopic enrichment and its isotopic composition is identical to the palaeo-meteoric water found in the most-concentrated Dogger solutions. This palaeo-meteoric water could be partially responsible for the general dilution observed in these aquifers.
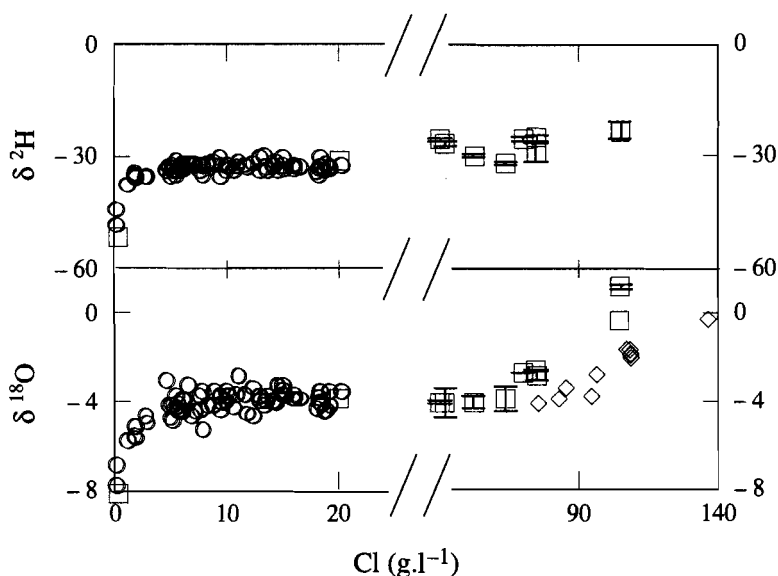

FIGURE 4.

Relationship between heavy isotope contents and chlorinity for deep waters of the Dogger (circles), Rhaetian (rhombi) and Keuper (squares) aquifers.

Relations entre les teneurs en isotopes lourds et la chlorinité pour les eaux profondes des aquifères du Dogger (cercles), Rhétien (losanges) et Keuper (carrés).

ORIGIN OF THE CHLORINITY

As the chlorine in these aqueous solutions could not have been derived from seawater, three possible hypotheses remain: the concentration of solutes on a clayish membrane by filtration, the contribution of an evaporite mother brine, and the dissolution of evaporites. Representative points of the three aquifers studied are shown on the Cl/Br *vs.* Cl diagram (Fig. 5).

The Cl/Br weight ratios of the Rhaetian aquifer are highly impoverished in bromine compared to seawater, which is characteristic of brines formed by halite dissolution. This is not surprising, considering the position of the reservoir in relation to the Late Keuper halite.

The problem is more delicate for the Dogger and Keuper fluids. The fact that the Dogger and Keuper aquifers have identical Cl/Br ratios excludes the hypothesis of saline filtration which is known to enrich the residual solution
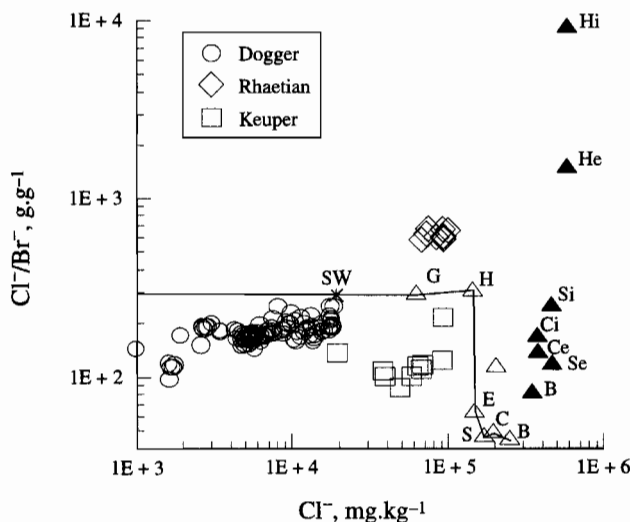

FIGURE 5.

Distribution of Cl and Br contents in aqueous solutions from the Dogger (circles), Rhaetian (rhombi) and Keuper (squares) aquifers with recognized domains of primary chlorinated evaporites (solid triangles: H halite, S sylvite, C carnallite and B bischofite) at the beginning (i) and the end (e) of precipitation, and the dilution/evaporation curve of seawater (SW) at the beginning of salt precipitation (empty triangles: H halite, E epsomite, S sylvite; C carnallite and B bischofite).

Distribution des teneurs en Cl et Br dans les solutions aqueuses du Dogger (cercles), Rhétien (losanges) et Keuper (carrés) avec domaines reconnus des évaporites primaires chlorurées (triangles pleins avec H halite, S sylvite, C carnallite et B bischofite) en début (i) et fin (e) de précipitation et courbe de dilution/évaporation de l'eau de mer (SW) au début de la précipitation des sels (triangles évidés avec H halite, E epsomite, S sylvite, C carnallite et B bischofite).

in Br (Kharaka and Berry, 1973). Dilution of a primary marine brine (evaporated seawater) is also improbable because this does not explain the high Br contents and Cl/Na molar ratios between 1.2 and 1.3 observed for the Dogger and Keuper fluids.

The third hypothesis is that of the dissolution of highly recrystallized evaporites which releases bromine into the solutions (Land and Prezbindowski, 1981). Brines trapped in the Keuper salt have been sampled and analysed (Fontes and Matray, 1993b). They have an average Br/Cl activity ratio equal to the majority of the Dogger and Keuper solutions, i.e. of the order of 4.453 10^{-3} (log $a_{Br-}/a_{Cl-} = -2.35$). According to Stoessel and Carpenter (1986), the Br content of salt at thermodynamic equilibrium with these trapped brines should be approximately 70 ppm. For the Keuper salt, this value is 130 ppm on average (Geisler, 1979). The difference reflects the state of non-thermodynamic equilibrium of the Br content of salt compared to that of the trapped brines, despite evidence of recrystallization, hence, recrystallization can only be partially responsible for the high Br contents in the waters. The only remaining hypothesis is that of a mixing between a dissolution brine (secondary brine) and an evaporated seawater (primary brine). By studying the trapped brines in the Keuper salt, the evaporation stage reached by this primary brine was estimated to be an evaporated seawater that precipitated potassic and magnesian salts (Fontes and Matray, 1993b). However, such salts are currently absent, implying important leaching of the halitic deposits. Using mass balance, it is estimated that approximately 99 % of the Cl was derived from the secondary brine and only 1 % from the primary brine. Consequently, vertical transfer of Triassic brines must have occurred in the Dogger.

EVIDENCE OF VERTICAL TRANSFER

Much evidence of vertical transfer exists. The most obvious is the presence of diagenetic carbonate minerals in the Dogger, whose mother solutions, trapped in fluid inclusions, have salinities (in equivalent NaCl) of the order of those measured in the most-concentrated current brines of the Triassic (Worden et al., 1994).

Stable chlorine isotopes provide further evidence of vertical fluid transfer (Fig. 6).

In sedimentary domains, chlorine isotopes essentially fractionate during transport processes, such as diffusion and ultrafiltration. Advective transport does not modify the ratio (Kaufmann et al., 1988). The $\delta^{37}Cl$ values measured in Dogger waters are abnormally negative for a marine chlorine, but correspond to those observed in the Keuper and Rhaetian waters. This reveals that the origin of the chlorine in the Dogger waters is Triassic, and suggests advec-
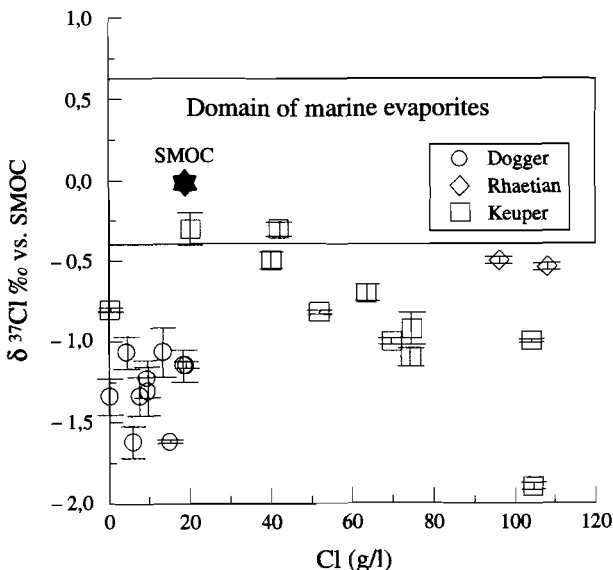
FIGURE 6.

Relationship between $\delta^{37}Cl$ values and chloride content for aqueous solutions of the Dogger (circles), Rhaetian (rhombi) and Keuper (squares) aquifers.

Relations entre les valeurs de $\delta^{37}Cl$ et la teneur en chlorures pour les solutions aqueuses du Dogger (cercles), Rhétien (losanges) et Keuper (carrés).

tive transfer via fractures. The fact that no relationship is observed for chloride content between the Dogger fluids supports the hypothesis of multiple transfer in various places.

Other evidences of vertical advective movement exist among which the presence of oil in the Dogger which can be also explained by the transfer of hydrocarbons from Triassic reservoirs via faults (Poulet and Espitalié, 1987).

The excess of helium-3 compared to in-situ production in the Dogger aquifer has been attributed to the addition of helium of crustal origin, and thus to vertical fluid transfer from the basement (Marty *et al.*, 1993).

A schematic hydrologic model may be proposed to account for the origin of deep formation waters in the Paris Basin (Fig. 7).

REGIONAL FLOW AND AGE OF THE FLUIDS

Triassic aquifers

Due to the lack of reliable hydraulic test data and the confidentiality of oil exploration results for the Triassic aquifers, only indirect estimations of brine transit times could be attempted. The meteoric origin of these brines neces-
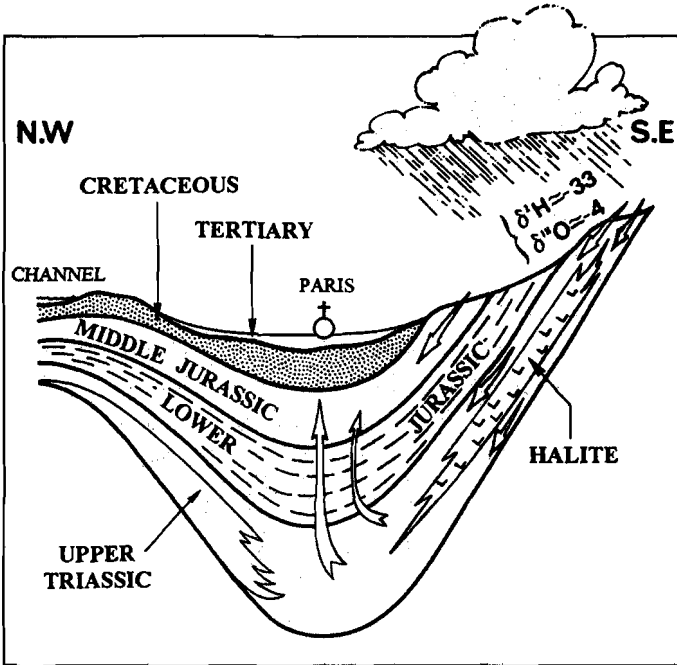
FIGURE 7.

Schematic diagram showing the hydrologic model proposed by Matray *et al.* (1994)
to explain the origin of the deep formation waters from the Paris Basin.

Diagramme schématique montrant le modèle hydrologique général proposé par Matray
et al. (1994) pour expliquer l'origine des eaux profondes du bassin de Paris.

sarily implies formation consecutive to the first uplift of exposed rocks 65 Ma
ago. Furthermore, the study of stable water isotopes has revealed at least two
series of brines.

The first, formed during a period of high geothermal gradient, is respon-
sible for the main late diagenetic mineralizations observed in the deep reser-
voirs (Worden *et al.*, 1994). This period inevitably ended with maximum uplift
of the outcrops at the end of the Oligocene (25 Ma).

The formation of a second series of brines followed, reaching a maximum
in the Miocene, and possibly still continuing. The strong dilutions observed
along the rim of the Triassic aquifers reflect a supply of meteoric water (without
evaporite dissolution) via outcrops for the Rhaetian and probably via the over-
lying aquifers for the Keuper. These diluted, tritium-free fluids should be
analysed using the carbon-14 method; such analysis is superfluous for brines
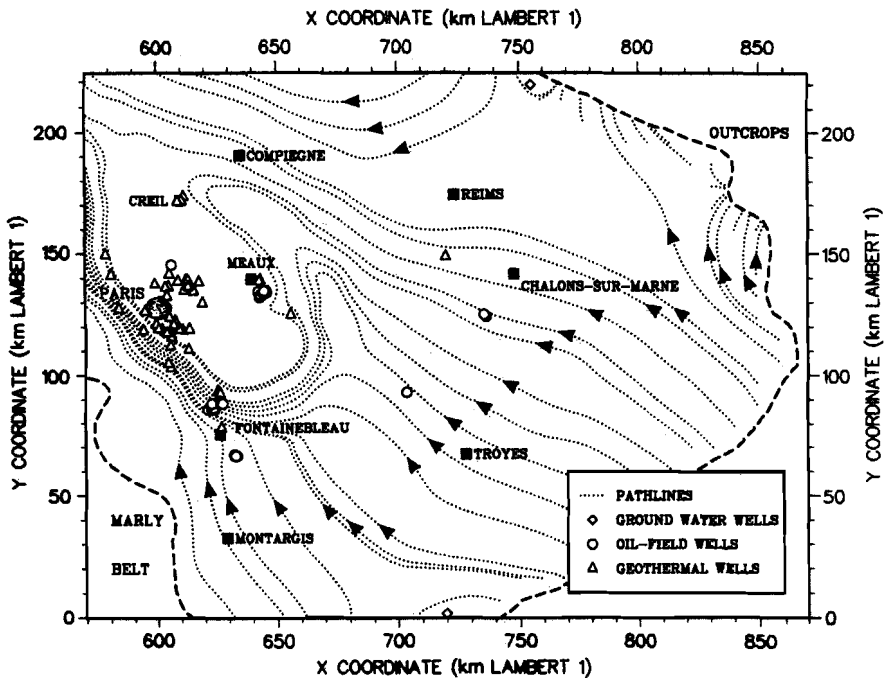with a residence time of more than a million years.

FIGURE 8.

Flow pattern with current lines calculated using the density approach for the Dogger aquifer (after Menjoz et al., 1993, in Matray et al., 1994).

Schéma d'écoulement avec lignes de courant issues de l'approche densitaire dans l'aquifère du Dogger (d'après Menjoz et al., 1993 in Matray et al., 1994).

Dogger aquifer

Hydraulic test data from geothermal wells have allowed Menjoz and his co-authors to establish a flow model that is concordant with the distribution of chemical and thermal variables (Menjoz et al., 1993). Results of the simulation which are shown in Figure 8 take into account the effects of density in the flow formulation and reveal a major disturbance in the centre of the aquifer which is attributed to a marked lateral density variation and a varying dip of the layers.

In this disturbed zone, lines of equal hydraulic load are no longer systematically orthogonal to current lines where density effects become important. This is particularly the case along the northwest rim of the central depression to the north of Paris where the saline solution is denser and cannot ascend the slope, creating a zone where velocity is almost zero.

This rim is delimited by the high production of sulphides attributed to bacterial sulphate reduction in a confined environment (Fouillac *et al.*, 1990). Another consequence is that lines of initially parallel current have the tendency to deflect around the maximum salinity zone.

Outside the disturbed zone, isodensity and density hypotheses are equivalent and the average calculated Darcy velocity is of the order of 0.05 m.yr.$^{-1}$ (Menjoz *et al.*, 1993), which corresponds to a residence time in the aquifer of the order of 1 Ma for a water infiltrated at the eastern rim and an average porosity of 15 %. In the disturbed zone, the fluids must be older because they contain a large proportion of older Triassic brine.

About 15 geothermal Dogger waters have previously been analysed by standard ^{14}C methods (Rojas *et al.*, 1989). Recorded activities indicate contamination by atmospheric CO_2. After correction for this contamination, activity is almost 0 %, i.e. almost at the detection limit of the tool, which gives ages of more than 45,000 years, concordant with ages calculated by hydrodynamic modelling.

Twenty kilometres from the outcrops, ^{14}C analyses have provided maximum age estimations of Holocene, with high transfer velocities of the order of 2 m.yr.$^{-1}$ that reflect a high hydraulic gradient (J.-Ch. Fontes, pers. comm.).

The carbon-14 tool used for this type of carbonate aquifer does not allow a proper age evaluation. Dissolved inorganic carbon is subject to mixing-exchange processes with the matrix, without taking into account the possible mixing of water within the reservoir. Uncertainty regarding the age increases as the fluid path becomes more complex. Dating by chlorine-36 has also been attempted for some deep fluids from the centre of the basin. Measured ratios (with uncertainty levels between 18 and 60 %) are between 0 and 10×10^{-15}, and probably correspond to secular equilibrium ratios of Triassic chlorinated evaporites, which would confirm the salt analysis.

CONCLUSION

Taking into account geological and hydrodynamic studies, geochemical study of deep fluids of the Paris Basin allows several conclusions to be drawn concerning the origin and evolution of the fluids:

(1) Cl, Br, ^{18}O and ^{2}H are currently preserved in the aquifers and their contents can thus be used to reconstruct the evolution of the waters. These waters are the result of a mixing of waters that are different for each aquifer.

(2) The study of water isotopes reveals a meteoric origin for all components and the Cl/Br ratios reflect chlorine released from Triassic evaporites.

(3) The combination of chemical and isotopic tracers indicates that the aqueous solutions of these three aquifers are the result of mixing between two secon-

dary brines formed by the dissolution of Triassic evaporites by meteoric waters with meteoric waters unaffected by salt dissolution. The first brine is affected by the temperature effect on oxygen-18 which reveals a Paleogene origin (65 Ma – 25 Ma). Vertical transfer of this brine via faults explains the presence of saline solutions, hydrocarbons and carbonate cements in the younger aquifers. These flow transfers also explain the excess of helium of mantle origin, and the presence of dissolved chlorine impoverished in ^{37}Cl in the Dogger. The second brine, with an isotopic composition unaffected by temperature effects, is Neogene and may currently still be continuing. It mixed with the brine already present, traces of which are only found in the deepest parts of the aquifers. The general dilution of all the aquifers by meteoric waters unaffected by salt dissolution explains the current salinity distribution in the aquifers.

(4) The current flow pattern of the Dogger provides an estimation of approximately 1 Ma for the transfer time in the aquifer outside the central zone, which is hydrodynamically disturbed by the presence of dense fluids and the varying dip of the aquifer. As a result, velocity is almost zero in this sector, which has a tendency to reduce flow to the outlet in the northwest.

(5) Direct radio-isotope dating methods are unsuitable for deep fluids with ages of much more than 50,000 years. Nevertheless, they give an estimation of transfer velocities along the rim of the basin and provide data on the origin of dissolved chlorides and carbonates. In the vicinity of the exposures, these tools confirm the origin and velocity of the supply source.

(6) Combined use of chemical and isotopic tracers is essential for reconstructing circulation in deep sedimentary aquifers. However, such techniques can only provide partial information on the age and origin of fluids, and must, where possible, be coupled with hydrogeological studies.

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