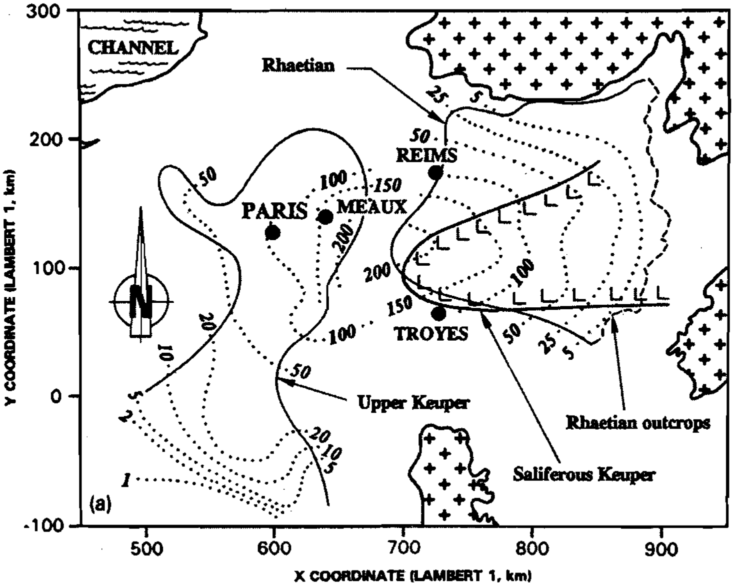

FIGURE 1.

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

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

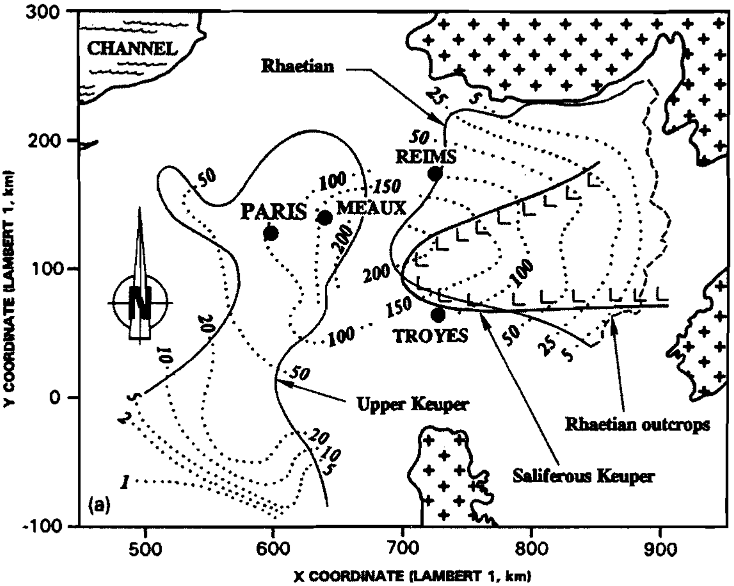

FIGURE 2.

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

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

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.

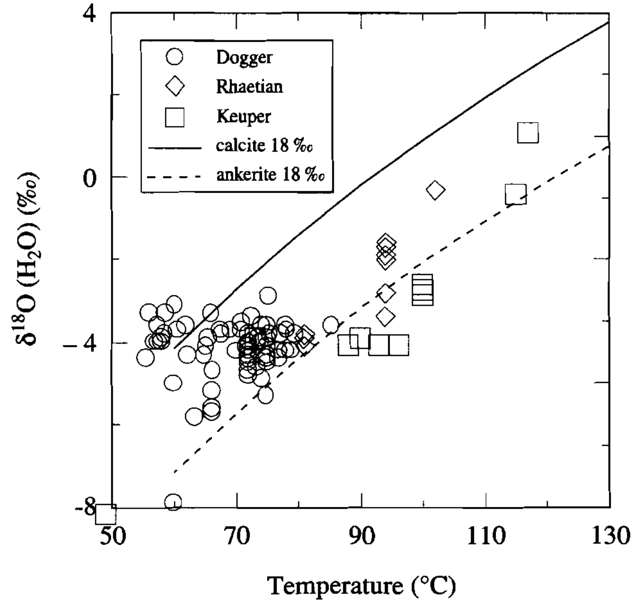

FIGURE 3.

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 étudiés.

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.

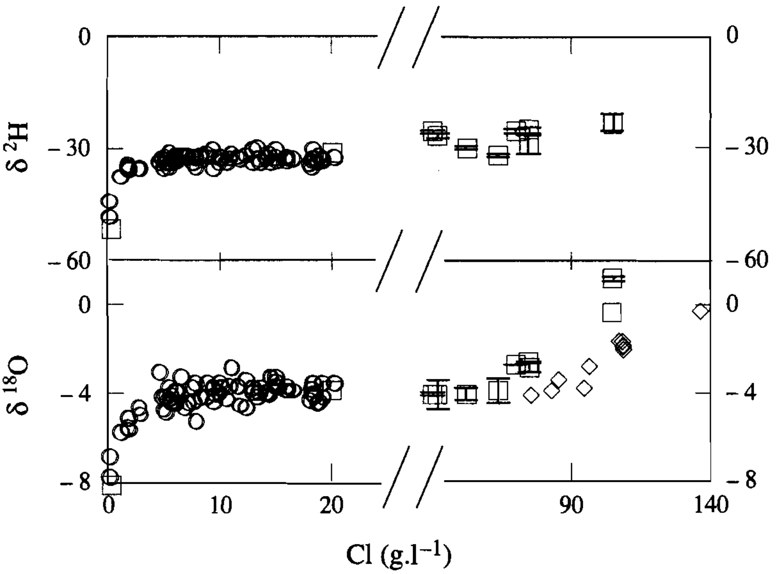

FIGURE 4.

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

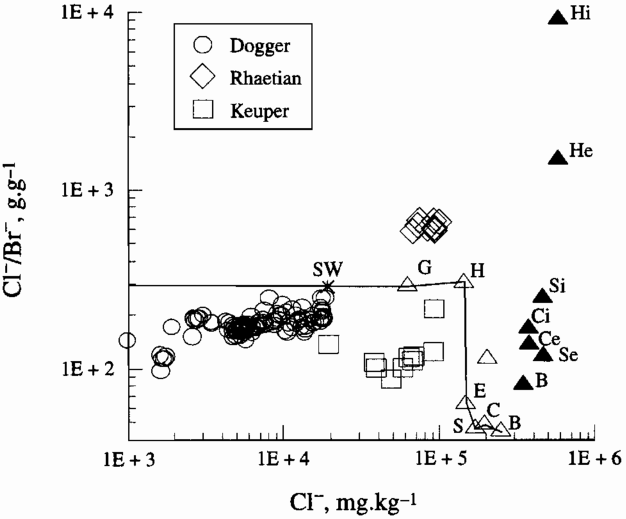

FIGURE 5.

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).

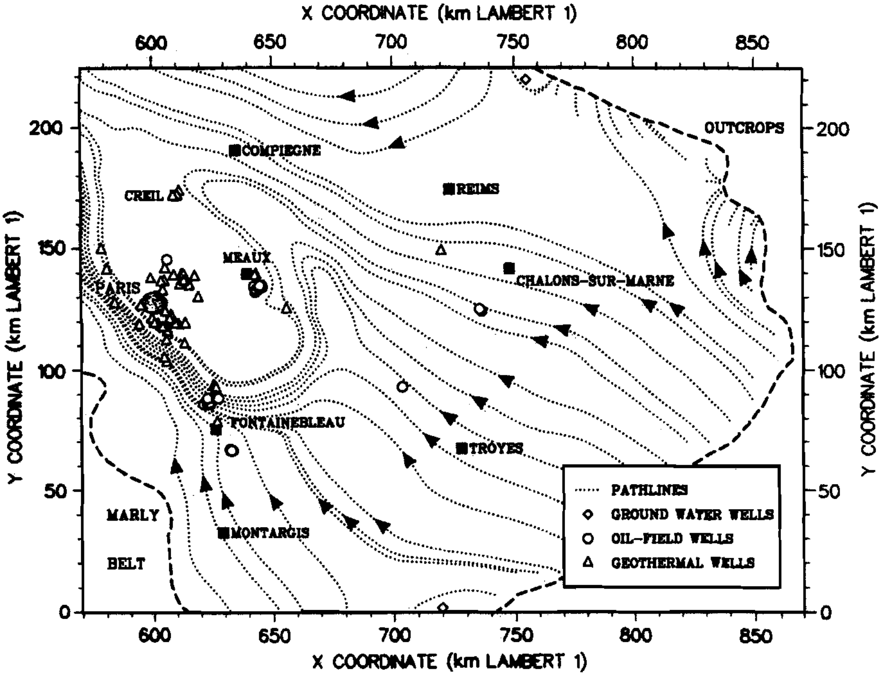

FIGURE 8.

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.

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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