Convective heat transfer at the Soultz-sous-Forêts Geothermal Site: implications for oil potential

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Introduction
Time, temperature and pressure are key parameters in oil maturation. One of the most difficult problems in oil exploration is the prediction of the temperature field as a function of both depth and time. Conductive models have been classically used for more than 30 years. However, it has been shown during the last decade that temperature can be highly affected by thermo-convective heat and mass transfers, phenomena which are still poorly understood. This paper investigates a numerical method for modelling the heat and mass transfers in anisotropic and heterogeneous porous media. The contribution of convective heat transfer is then evaluated using, as a case study, the Pechelbronn oil fields situated in the Rhine Graben (France).

Geological setting
The Rhine Graben is a classical area for both oil and geothermal exploration. It is a continental rift segment which extends for 300 km from Basle (Switzerland) in the south to Frankfurt (Germany) in the north and with a lateral extension ranging from 30 to 40 km. The thickness of the sedimentary cover ranges from a maximum of 6000 m at Saar-Nahe-Trog in the northwestern part, to an average value between 2000 and 4000 m (Edel 1975) in the south. The southern part of the Rhine Graben is characterized by a symmetric sedimentary cover, whilst the northwestern sedimentary cover is asymmetric (1400 m compared to 3500 m on the eastern part). Correspondingly, the surface heat flow pattern reported in several studies (e.g. Royer and Danis 1988) follows this asymmetry being constant across the graben south of Strasbourg, having an average value of 80 mWm⁻², whilst north of Strasbourg, the surface heat flow value decreases across the graben, from a maximum of 150 mWm⁻² in the west (at Soultz-sous-Forêts or at Landau) to a minimum of 70 mWm⁻² in the east (see Fig. 2). It is a favourable pattern for fluid circulation in the sedimentary cover as suggested by Gerard et al. (1984) and Flores and Royer (1993).

Soultz-sous-Forêts has been selected by the European Hot Dry Rock (HDR) geothermal project as a pilot zone for exploiting low enthalpy geothermal resources. It is situated east of the Merkwiller-Pechelbronn oil field, along the western limit of the Upper Rhine Graben in northern Alsace (France). The region is characterized by its high temperature at depth which represents a potential energy source (Gerard and Kappelmayer 1989; Kappelmayer and Gerard 1989; Kappelmayer et al. 1991).
Fig. 2. Surface heat flow. A maximum of 150 mW m$^{-2}$, i.e. twice the normal value, can be observed near Soultz.

However, little work has been done on the origin of such a heat flow pattern. Similar studies carried out on sediment filled grabens (Bachu 1985; Royer and Danis 1988; Clauser and Villinger 1990) have shown that water circulation can perturb the heat transfer.

**Oil production setting**

The Rhine Graben is a moderately productive oil basin that has been exploited for the last hundred and fifty years. The total production from the most important field, Pechelbronn, is about 3 million tonnes. Most of the productive zones are found in the Oligocene Pechelbronn Formation, at a depth between 500 and 1000 m (Tissot and Welte 1984). These productive zones are situated near normal faults, implying that fractures play a major role in oil migration and entrapment. Two potential source rocks exist in the Rhine Graben: the Lower Jurassic Toarcian Shale (Type I kerogen) and the Oligocene Pechelbronn Formation (Type III kerogen).

**Evidence of fluid circulation in the Rhine Graben**

Geophysical and geochemical studies carried out in the Rhine Graben have revealed several strands of evidence for water circulation within the Buntsandstein, Keuper, Muschelkalk and altered granitic rocks. First, the sedimentary cover is asymmetric having a depth of 1400 m along the west margin of the graben compared with 3500 m on the eastern flank resulting in a general circulation pattern from east to west and associated with a higher surface heat flow on the west (up to 150 m Wm$^{-2}$ compared to 70-80 m Wm$^{-2}$ on the east; see Fig. 2). Secondly, the vertical heat flow decreases from a mean constant value of 150 m Wm$^{-2}$ in the sedimentary cover to a lower value of 70 and 30 m Wm$^{-2}$ at 1700-2000 m depth, in the basement boreholes GPK1 and EPS1, respectively. Finally, fluid circulation is observed presently in the granitic fractured basement (Genter et al. 1992, Ledésert et al. 1993). Regional geochemical studies by Pauwels et al. (1991) and Fouillac and Genter (1991) suggest that these fluids result from a mixing of low salinity surface water from the west with higher salinity deep formational water from the east. The decrease of the geothermal heat flow at depth is likely attributed to fluid circulation through the sedimentary cover.

**Theoretical background for convection in porous media**

The governing equations used to study free convection for incompressible fluids in a porous domain are: the heat transfer equation, the Darcy equation (motion equation), the conservative equation and the variation of the fluid characteristics with temperature. The convection equation is simplified here into a set of two coupled equations using a specific dimensionless formulation (Royer and Flores 1994) involving both temperature and stream function ($T, \psi$). The system is then numerically solved by a finite-difference scheme, using a double iterative approach that allows mutual coupling of the dimensionless form of the heat and Darcy equations. This flip-flop procedure is iteratively applied until the solution converges. This model takes into
account several parameters such as the heterogeneity of the medium, the conductive structure of the basement, the anisotropy of the physical properties, the thermodependence of physical parameters and the geometry of the geological layers (Traineau et al. 1991).

Resolution of conduction–convection heat transfer equations using a 2D Finite difference scheme along a E–W vertical cross-section

The conduction–convection heat transfer equations have been solved numerically using a 2D Finite difference scheme along an E–W cross-section (see Fig. 1). In order to evaluate oil maturation and migration, it is necessary to investigate the temperature and pressure conditions through time during the evolution of the graben. Two stages corresponding to different geological architectures of the basin have been investigated. The first one is the present-time geometrical model built from various seismic, geological and structural studies which was modelled using GOCAD software. The second one corresponds to the situation 20 Ma. It has been deduced from the present-time geological model by estimating the sedimentation and erosion rate from previous studies (Person and Garven 1992). Each geological domain is then represented as a regular grid of 74 × 6 km, with 149 × 31 nodes.

The physical parameters used in the model (thermal conductivity, permeability, heat production) were estimated from geophysical investigations (Rummel 1991; Flores 1992) made on different geological units shown in Fig. 3 and Table 1. An important assumption is the anisotropy of the physical properties and the high permeability of the altered granitic layers and the sedimentary layers. This strongly influences the fluid circulation in all the formations.

Fig. 3. Geological cross-sections showing the different lithological units used in the numerical model (a) present time; (b) 20 Ma.
Table 1. Permeability, thermal conductivity and heat production of the main lithology units used to compute the temperature field and filtration velocity at the Soultz-sous-Forêts geothermal site, at the present time

<table>
<thead>
<tr>
<th>Code</th>
<th>Lithology</th>
<th>Hydrostratigraphy</th>
<th>Permeability k (m²)</th>
<th>Porosity (%)</th>
<th>Thermal conductivity W/m°C</th>
<th>Heat production A (µW m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Granite, gneiss</td>
<td>unaltered granite</td>
<td>1.10⁻²⁰</td>
<td>1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>L2</td>
<td>Granite, gneiss</td>
<td>moderately permeable granite</td>
<td>1.10⁻¹⁴</td>
<td>9</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>L3</td>
<td>Buntsandstein, Muschelkalk, Keuper Triassic</td>
<td>Permeable dolomite, limestone and sandstone</td>
<td>4.10⁻¹⁴</td>
<td>17</td>
<td>2.9</td>
<td>0.8</td>
</tr>
<tr>
<td>L4</td>
<td>Lias, Toarcian, Dogger, (Jurassic) red series (Eocene)</td>
<td>moderately permeable layers</td>
<td>1.10⁻¹⁶</td>
<td>19</td>
<td>2.8</td>
<td>1.2</td>
</tr>
<tr>
<td>L5</td>
<td>Tertiary, Pechelbronn (Oligocene)</td>
<td>low permeability clays and marls</td>
<td>5.10⁻¹⁸</td>
<td>17</td>
<td>3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>L6</td>
<td>Miocene, Pliocene Quaternary</td>
<td>clay sediments</td>
<td>1.10⁻¹⁸</td>
<td>10</td>
<td>2.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The boundary conditions are as follows:

- for the Fourier equation: the mean temperature is constrained at the surface to a value ranging from 5 to 20°C depending on elevation, lithology and environment; a constant heat flow is imposed at bottom at a mean value ranging from 80 to 90 mW m⁻² depending on various hypotheses; the horizontal heat flow is assumed to be zero on the lateral boundaries, corresponding to vertical conductive heat transfer;
- for the Darcyequation, the boundary conditions are expressed using the stream function (ψ): at surface, a water flow rate is constrained to a value deduced from hydrological studies; at the bottom and on the lateral borders, the potential ψ is assumed to be zero, corresponding to no water exchange with the exterior.

Results

The numerical model of the coupled conduction–convection heat transfer at the present time shows three hydrothermal circulation systems (Fig. 4). The first one is expressed at the surface near to Baden-Baden. The second has a complex path, consisting of six convective cells extending from the Rhine axis to Pechelbronn. The third and smallest one consists of two cells, which originate in the western part of the graben and continue to Hochwald. The maximum filtration velocity observed is about 1 m yr⁻¹.

The thermal regime of 20 Ma is more complex and shows six hydrothermal circulation systems (Fig. 5). The first one is around Baden-Baden. The second and largest one is centred around the Rhine axis. The third one is located east of Soultz. Two smaller cells are situated around Soultz and Pechelbronn, respectively, and a final one is formed near Hochwald. The maximum filtration velocity observed is about 0.3 m yr⁻¹.

These results show clearly that the thermal regime is strongly influenced by fluid circulations. These movements can explain the existing distribution of temperature within the Rhine Graben (Flores 1992).

Validation of the numerical models

In order to verify these results, several cross-checks were carried out, among them the comparison of the observed temperature profiles in the exploration boreholes with the profiles obtained from the model, the vertical surface heat flow interpolated from observations with that obtained from the model and finally the filtration velocities observed in the boreholes with those of the model. The model temperature profiles are in good agreement with the temperatures observed by Schellschmidt and Schultz (1991) in boreholes GPK1, 4616, 4550 and 4601, with an error of less than 5% (Fig. 6). The computed vertical heat flow is also in good agreement (±15%) with the vertical heat flow observed at the surface (Flores 1992).

The present filtration velocities obtained from the model range between 0.3 and 1 m yr⁻¹. They are of the same order of magnitude as those found by preliminary 1D models and fit the pumping test (Jung 1991; Rummel and Baumgartner 1991) in the GPK1 borehole.

The study of ⁸⁶Sr/⁸⁷Sr isotopic composition of water at Helions showed that the Triassic ground water at Helions is likely to be in equilibrium with the Triassic sandstone unit and/or the granitic basement but not with the upper Keuper and Muschelkalk formations (Flores and Royer 1993).

The chemical composition of three formation-water samples collected at different depths (Flores and Royer, 1993) shows similar geochemical patterns for the water from the granite at GPK1 and for the Buntsandstein sandstone formation-water at 4616, respectively (Pau-
wells et al. 1993). These results are in agreement with the fluid pattern derived from numerical modelling and show that water exchange between the Triassic and the fractured granite layers has taken place.

The formation-waters are in equilibrium with their respective lithology. For instance, the temperatures calculated by different geothermometers (Truesdell 1984) are in good agreement with the measured temperatures (Table 2). This last observation is strong circumstantial evidence to support the hypothesis of water circulation between the Triassic rocks and the fractured granite.

Fluid incision studies were made in the EPS1 borehole, at a depth of 2175 m, in an open fracture, where there is active water circulation. They show two phase primary inclusions (liquid and vapour), with a salinity of 3.6% wt eq NaCl and a homogenization temperature of 147±2°C, which should be compared to the 148°C temperature, measured directly in that borehole at that depth. Measured and computed temperatures are thus in good agreement.

**Implication for oil potential**

These geothermal results can be used to track the thermal history of potential source rocks over time (Fig. 7). The convective heat transfer causes significant distortion of the isothermal lines, which implies significant variations in their thermal history. Lower Jurassic Toarcian shales (unit 4; Fig. 3) situated at the centre of the graben probably achieved thermal maturity during the Middle Miocene. The maturation lasted until the late Miocene when the oil window moved upward due to convective heat transfer effects and subsidence. At the present time, the oil window is situated

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>$T_{\text{calc}}$ (°C)</th>
<th>$T_{\text{mes}}$ (°C)</th>
<th>$T_{\text{quartz}}$ (°C)</th>
<th>$T_{K,Mg}$ (°C)</th>
<th>$T_{KCaNa,KMg}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1815</td>
<td>135</td>
<td>140</td>
<td>136</td>
<td>212</td>
<td>232</td>
</tr>
<tr>
<td>4616</td>
<td>1114</td>
<td>102</td>
<td>105</td>
<td>143</td>
<td>168</td>
</tr>
</tbody>
</table>

Table 2. Temperatures calculated using different geothermometers. Temperatures calculated by $T_{\text{quartz}}$ are in good agreement with the measured temperatures, while $T_{K,Mg}$ and $T_{KCaNa,KMg}$ overestimate the real temperature.
Fig. 5. Temperature field and stream function computed for 20 Ma. (a) Temperature field is highly influenced by fluid circulation. (b) The stream function shows three hydrothermal systems: the first one under Baden-Baden, the second the Rhine axis to the Pechelbronn; the third located in the western part near Hochwald. Arrows indicate direction of the fluid movement. The maximum filtration velocity is about 0.3 m yr⁻¹.

Fig. 6. Calculated temperatures (-----) are comparable with the temperatures observed (——) in the boreholes GPK1 (1), 4550 (b), 4616 (c) and 4801 (d).
on the western part of the basin (unit 4 and 5; Fig. 3) indicating that the Pechelbronn source rocks (Oligocene) are still immature. This is in good agreement with other studies (Person and Garven 1992).

A model for oil migration could be: primary expulsion of oil from source rock (Toarcian shales), followed by migration of oil driven by force of buoyancy and pressure. Based on the filtration velocity calculated from our model, the time duration for oil migration can be estimated to within several hundred thousand years. The oil would probably follow the same path as circulating formation-water, until entrapment occurs in favourable structures such as the Pechelbronn faults. The two cells around Pechelbronn and Soultz, and also the larger cell east of Soultz, probably concentrated the oil near the Pechelbronn faults, because these faults are associated with the circulation of fluids passing through the potential source zones (as indicated by arrows in Fig. 7b).

**Conclusion**

The value of a hydrothermal model in studying fluid circulations in a sedimentary basin, and especially in the Rhine Graben, has been demonstrated. Water circulation in the Muschelkalk, Keuper, Buntsandstein and the fractured granite basement produce a redistribution of the heat flow from the axis to the sides of the graben (Soultz, Pechelbronn and Baden-Baden). These movements can explain the current thermal regime in the Rhine Graben, and more precisely, the thermal anomaly near Soultz. The results obtained are in good agreement with both measured temperature and flux and also with geochemical studies.

The results show the major effects of convective heat transfer on petroleum generation in sedimentary basins. First, because it causes significant distortions in the temperature field, and thus on location of potential mature source zones, and secondly, because the circulating water can influence the migration of oil.

The predominant factor in convective heat and mass transfer is the permeability of the rocks. The most critical problem is to evaluate its variation in both space and time in order to obtain accurate results. Another problem is to take into account local fluid circulation which can cause important local variations (Flores 1992). Careful investigations and interpretations of measured data are essential to obtain reliable information.

**Fig. 7.** Location of potential source rock. (a) Present time; (b) 20 Ma. Toarcian shales probably reached maturity whilst the Pechelbronn Formation was still immature.
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References
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