PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT

GEOTHERMICS

Geothermics 32 (2003) 701–710

www.elsevier.com/locate/geothermics

Typology of potential Hot Fractured Rock resources in Europe

Albert Genter*, Laurent Guillou-Frottier, Jean-Louis Feybesse, Nadège Nicol, Chrystel Dezayes, Stéphane Schwartz

Bureau de Recherches Géologiques et Minières, 3 avenue Claude Guillemin, BP6009, 45060 Orléans Cedex 2, France

Received 5 June 2003; accepted 10 June 2003

Abstract

As part of a European project on Hot Fractured Rock (HFR) held at Soultz-sous-Forêts within the Rhine graben (France), a preliminary analysis was made of HFR resources in Europe, in terms of geodynamical context. The major HFR criteria (temperature, fracture system, in situ stress) are presented, with the Soultz site as a reference HFR site. Based on the temperature distribution estimated at 5 km, the available geological data and geothermal inventories, the most favourable zones in Europe were delineated. The major HFR continental resources in Europe are related to the evolution of the Alpine system. The peri-Alpine rift system, which represents the first type of interesting HFR structure, corresponds geologically to Tertiary grabens (Rhine graben, Eger graben, Catalonia) and the peri-Alpine foreland (Molassic basin). The second main type of interesting HFR zone is located inside the Alpine belt and corresponds to complex back-arc basins (Pannonian basin, Tuscany area). A synthetic litho-tectonic map of Europe that takes into account this typology is presented here (1:4,000,000 scale).

Keywords: Hot fractured rocks; HDR; Geothermal resources; Soultz-sous-Forêts; France; Europe

1. Introduction

This study forms part of the European Geothermal Project carried out at Soultz-sous-Forêts (France) from April 2001 to March 2004. The basic idea was to find

* Corresponding author. Tel.: +33-2-3864-3938; fax: +33-2-3864-3334.
E-mail address: a.genter@brgm.fr (A. Genter).

0375-6505/$22.00 © 2003 CNR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/S0375-6505(03)00065-8

other interesting areas in Europe where Hot Fractured Rock (HFR) technology could be applied from a geoscientific point of view. Within that framework, we started a study on the typology and mapping of deep continental HDR/HFR systems in Europe. Based on available or published scientific data, geothermal atlases and a number of maps, we have attempted to demonstrate the reproducibility of the Soultz geothermal concept in other deep fractured areas of Europe. The main objectives of this study could therefore be summarised as follows: (1) to define the main Hot Fractured Rock criteria on the basis of the Soultz site characteristics; (2) to identify and classify the hottest HFR zones at a maximum of 5 km depth, and (3) to evaluate the deep-seated geology of these hottest zones in terms of geodynamical settings (lithology, recent volcanism, fracture system, in situ stress).

2. The basic HFR characteristics of the Soultz site

The Soultz project is located within the French part of the Upper Rhine valley, which is a Cenozoic graben. This area is characterised by a system of normal faults connected to the development of the graben, which have penetrated deep within the Hercynian crystalline basement. In the Soultz area, the post-Paleozoic granite is overlain by Mesozoic and Cenozoic sediments of 1.4 km thickness. The major criteria in support of an HFR assessment are the presence of sufficiently high temperatures at depth, the stress field conditions, the fracture system geometry, and the occurrence of crystalline rocks.

2.1. Temperature

The *hot* criterion corresponds to a minimum temperature of 200 °C at a maximum of 5 km depth, which is the optimal value for producing electricity. The choice of 5 km depth corresponds to the actual depth reached at Soultz where 200 °C was measured in the well GPK2. The thermal profile is not linear with depth but shows a high geothermal gradient in the sedimentary cover between 0 and 1000 m; below 1000 m depth the geothermal gradient decreases. A temperature log carried out in July 2000 is reported in Fig. 1a, showing the bottom temperature of 202 °C with a gradient of about 30 °C/km between 4000 and 5000 m depth (Weidler et al., 2002).

2.2. Stress field and fracture system

The *fracture* criterion is related to the present stress field conditions and the pre-existing fracture system geometry. At Soultz, in situ stress measurements in deep wells have shown that the vertical stress (σV) is a maximum (Hettkamp et al., 2002). They also showed that the minimum horizontal stress (σh) and the maximum horizontal stress (σH) magnitudes are very different, which induces a high horizontal stress anisotropy. The present stress field is therefore typical of a young graben system. The maximum horizontal stress (σH) orientation is N–S to NNW–SSE. The natural fracture system that developed within the granite shows small-scale fractures

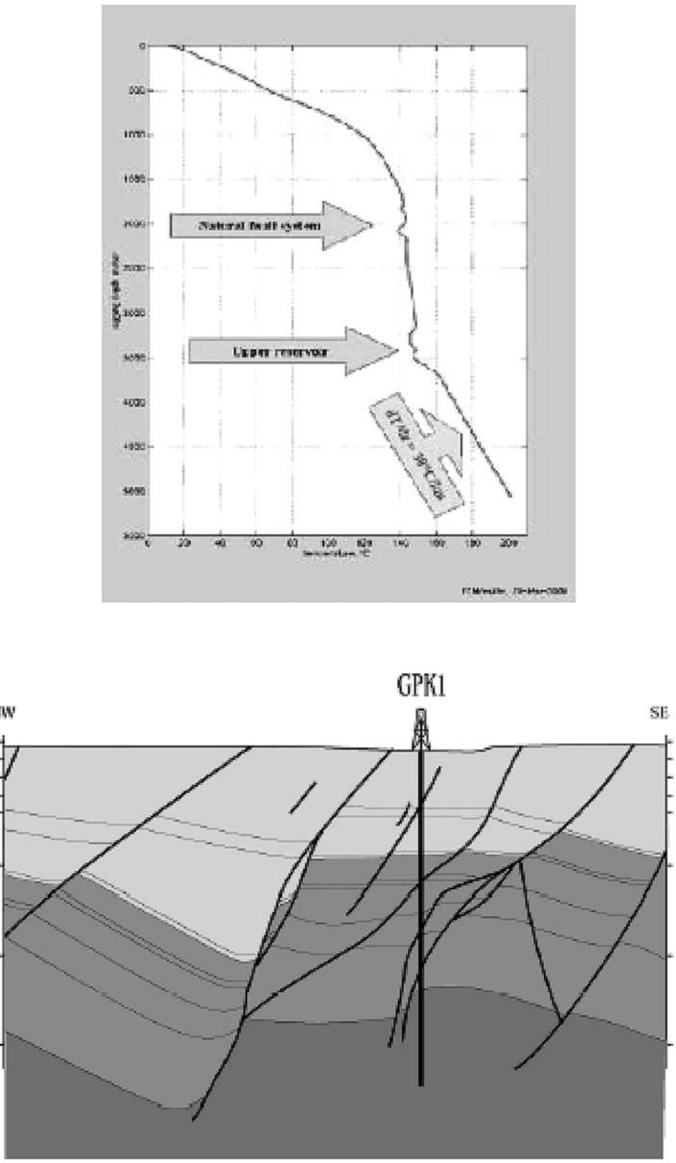

Fig. 1. HFR criteria on the basis of the characteristics of the Soultz site. Above: temperature profile in GPK-2 well, with 200 °C at 5 km depth (Weidler et al., 2002). Below: geological cross-section of the Soultz site showing the deep-seated fractured granite and the first well drilled, GPK1, 3590 m deep.

and large-scale normal faults associated with intense hydrothermal alteration (Genter et al., 2000). The fracture orientation is nearly N–S and characterized by high dip values (Fig. 1b).

2.3. Crystalline rock

The *rock* criterion is due to the occurrence below the sediments of a huge granitic batholith of Variscan age that was penetrated by different Soultz wells. From 1.4 to 5 km depth, the deep-seated geology deduced from borehole logging (Genter et al., 2000) corresponds to several granitic intrusions (porphyritic granite, fine-grained two-mica granite). Within the fracture zones, the granite was strongly hydrothermalised, the primary minerals being strongly altered in clay minerals. Moreover, a lot of hydrothermal minerals precipitated in the fractures (quartz, carbonates, illite, sulphides, Fe-oxides). Some of these hydrothermally altered and fractured zones are naturally permeable and bear natural brines characterised by a salinity higher than 100 g/l.

Based on more than 10 years of different on-site investigations in the deep wells, we consider that this experimental site has some relevant characteristics (temperature, fracture, in situ stress, brines) that should be sought in other areas of Europe. We can thus define Soultz as a reference HFR geothermal site.

3. Analysis of the temperature map of Europe at 5 km depth

The temperature map extrapolated at 5 km depth [Hurtig et al., 1992; modified in 2000 by the Economic Interest European Group (E.I.E.G. Heat Mining, www.soultz.net) operating at Soultz], has been used as a basis for defining the main zones of interest on a European scale (Fig. 2). Due to the variable quality of the temperature data, the different corrections used and the inhomogeneous distribution of the data, the temperature isolines of the map extrapolated at 5 km depth correspond to an approximation to the real geothermal field (Hurtig et al., 1992). The downward extrapolation of temperature should not exceed 50% of the actual borehole depth. The map of the temperature extrapolated at 5 km depth shows temperature variations between 60 and 240 °C. The different thermal zones were classified on the basis of this map. For the highest temperature zones (>160 °C), the overall analysis of the thermal map at 5 km depth evidences several areas (Fig. 2).

(1) Some relatively warm areas (from 160 to 200 °C) in France, such as the Limagne basin, characterised by a Neogene and Quaternary volcanism that developed in the Massif Central, the Rhine graben borders, the Rhone valley and Provence, the North German basin, a part of the Molassic basin (Germany, Switzerland), a part of the European platform (Urach) and some well-exposed Paleozoic granites of Cornwall in the UK. In Catalonia (Eastern Spain), there is a narrow zone coastal range parallel to the Mediterranean Sea that corresponds to a Tertiary rift associated with intra-plate volcanism. In the northern part of Bulgaria there is also a relatively hot zone;

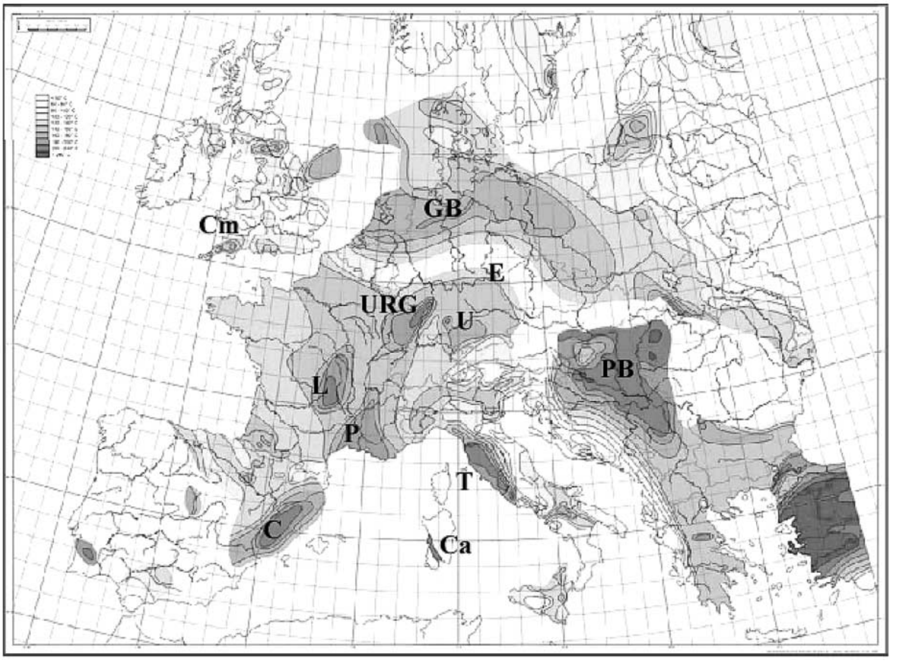

Fig. 2. Map of temperature extrapolated at 5 km depth. From Hurtig et al. (1992), modified by GEIE. URG: Upper Rhine Graben; U: Urach; L: Limagne-French Massif Central; P: Provence ; C: Catalonia; Ca: Campidano graben; Cm: Camborne granite; GB: German basin; T: Tuscany; PB: Pannonian Basin; E: Eger graben.

(2) Some very warm areas (from 200 to 240 °C and higher) in the French Massif Central, the Rhine graben, the Pannonian basin (Hungary, Austria, Slovakia, Romania, Slovenia, Croatia, and Serbia), the Campidano graben in Sardinia, the Tuscany-Latium area in Italy, a narrow graben in central Greece and the western part of Turkey. Some areas are not well documented, such as Spain and eastern Europe (Romania, parts of the Czech Republic).

In order to confirm the validity of the extrapolated temperature map at 5 km depth, a critical analysis was made of the map to assess the anomalous characteristics of the suggested areas. Based on a database available from the International Heat Flow Commission and from available data and literature, several areas have been checked. About 2500 well data have been used, bearing in mind that actual oil bore data are not always accessible due to confidentiality. As only 5% of the wells are below 3500 m, the extrapolated map in some areas is thus a purely linear extrapolation of the geothermal gradient measured at shallow depth.

The resulting map of the thermal conditions at depth has therefore to be used with some caution. The checks done on the extrapolated temperature map at 5 km depth are illustrated in Fig. 3.

The comparison between the extrapolated temperature map at 5 km and the available thermal information can be summarised as follows : (1) the data for a lot

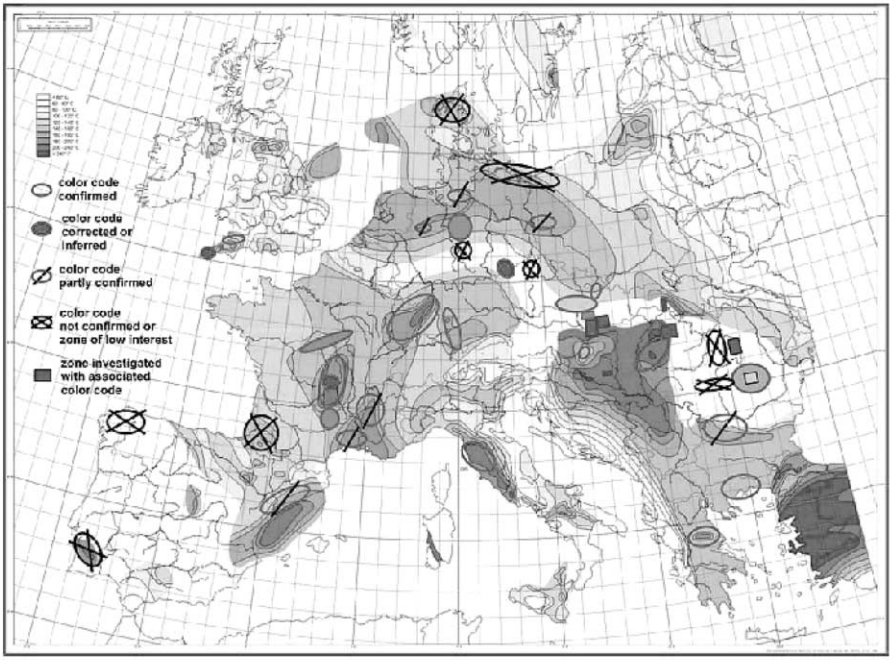

Fig. 3. Validation of the temperature map at 5 km depth.

of areas are in agreement with the extrapolated temperatures estimated in the map, such as the Rhine graben, the Massif Central-Limagne, the Molasse basin in Switzerland and South Germany, the Urach area in the Swabian Alb, a large part of the Pannonian basin, several grabens in Greece, Tuscany-Latium area, Cornwall in the UK, and a large part of the North German basin; (2) some areas (mainly Eastern Europe), which were not documented in the basic map, have been checked and proposed as favourable areas; (3) the data for some areas are not in agreement with the extrapolated map (SW France), the temperature values being at least 20 °C below the extrapolated values; (4) the extrapolated data for some areas have in part been confirmed, suggesting that the favourable thermal conditions are not ubiquitous but are localised in some more restricted sub-areas (French Massif central-Limagne, Provence, North German basin); (5) some areas are not of interest, despite the fact that the basic map shows a high extrapolated temperature at 5 km depth (South Portugal).

4. Typology of HFR zones

In order to characterize the main promising HFR zones, a large-scale geological map was constructed on a 1:4,000,000 scale, taking into account the main litho-tectonic structures of Europe (Fig. 4).

The first type of most promising HFR zones are distributed around the Alpine front in an external position. From Norway in the north to the Mediterranean Sea

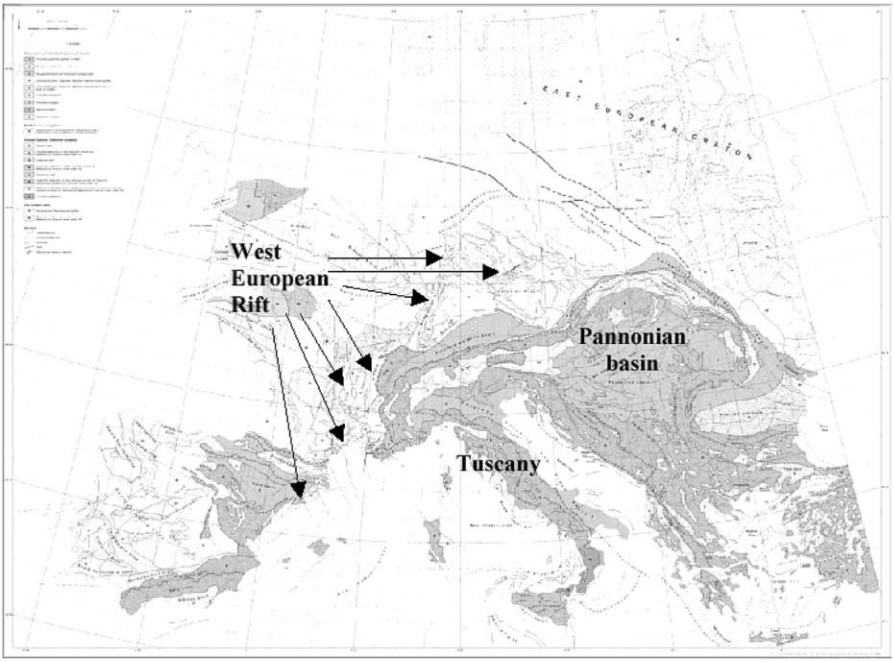

Fig. 4. Large-scale map of Europe illustrating the typology of HFR zones in Europe. The structures belonging to the West European Rift (WER) are distributed around the Alpine belt.

in the south, a series of intra-continental grabens cuts the western European platform, called the west European rift system (Ziegler, 1990). These rift structures were created in the Oligocene as a result of the thinning of the continental crust. The main Tertiary grabens are the upper Rhine graben, the Limagne system, the Rhône valley, a part of Provence, the Catalonia and the Eger grabens. The Molassic basin, as well as Urach area in Germany, are characterised by Tertiary volcanism within the European platform; these are also potential HFR geothermal zones located externally to the Alpine belt. The Molassic basin could also be considered an interesting zone located outside of the Alpine front. The Lower Rhine Embayement graben, which forms part of the western European rift, does not correspond to a hot zone at depth because it is probably too far from the Alpine front.

As the Soultz site is located within the Rhine graben, we have summarized the main characteristics of its rift system. It is about 300 km long, with an average width of 40 km, limited by large-scale normal faults. In this graben, the post-Paleozoic sediments of the western European platform have overlain the Hercynian basement, which is made of granite, granodiorite or other related basement rocks (Edel and Fluck, 1989). This area, which is characterised by a thin continental crust and a Moho at 25 km depth, shows a Tertiary volcanism that occurred in the form of isolated volcanoes of alkaline composition related to a mantle magmatic activity (Wenzel et al., 1991). In other grabens (Limagne, Eger), the volcanic activity also developed during the Quaternary. Most of these areas show a strong seismic activity with high concentrations of deep seismic events. In the case of the Rhine graben, their distribution is clearly localised in its southern part, in connection with the Alpine front. Many thermal springs are located on the graben borders, and are related to the large-scale faults. Several areas show interesting geothermal anomalies within the graben, such as Soultz, Landau or near Speyer.

The second main type of promising HFR zone in Europe is also related to the Alpine front but corresponds to complex back-arc basins (Pannonian basin, Tuscany-Latium) located inside the Alpine belt. The hottest HFR zone at shallow depth is represented by Tuscany region in Italy. The Pannonian basin, an intra-montane rift, is characterised by extension and the coeval occurrence of compression and subduction in the surrounding Carpathian and Dinaric chains (Hiusmans et al., 2001). This is a back-arc basin with oceanic and reduced continental crust. The main features are the strong differential thinning of the lithosphere beneath the Pannonian basin, its active post-rift evolution and the succession of volcanics in the syn-rift to post-rift stage. Other interesting areas inside the Alpine belt correspond to post-collisional grabens in Greece and Bulgaria.

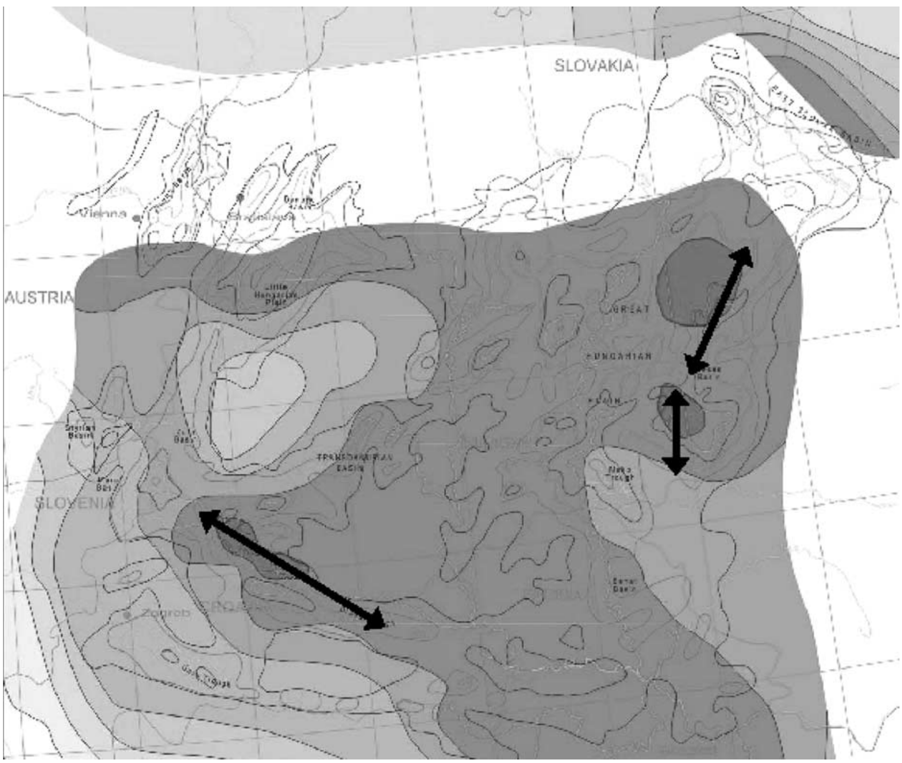

Fig. 5. Extrapolated temperature map of the Pannonian basin at 5 km depth (Hurtig et al., 1992). This map is a close-up of part of Fig. 2. The arrows indicate the coincidence of Tertiary sub-basin locations and the highest temperature zones. The darker areas beneath the arrows correspond to temperatures of more than 240 °C, while the widespread lighter area around these darker "islets" correspond to temperatures of more than 200 °C.

The well-exposed granites of Cornwall (UK), as well as the deep German basins, are HFR zones that are not directly related to the Alpine system.

In order to better characterize the HFR potential of the hottest zones, some promising zones such as the Upper Rhine graben, the Eger graben, Tuscany or the Pannonian basin, were investigated in more detail, but only the Pannonian basin is presented in this paper. This is an area with high temperature conditions due to a high terrestrial heat flow. The thermal system is evidenced by a large number of thermal springs and the occurrence of geothermal reservoirs even at shallow depth (Ottlik et al., 1981). The volcanic activity was also intense from the Tertiary. Within the Pannonian basin there is a series of internal sedimentary sub-basins of several kilometres thickness, as shown in Fig. 5. The superimposition of the temperature data extrapolated at 5 km and the thickness of the sedimentary sub-basins within the Pannonian basin indicate that some faulted sub-basins have favourable thermal conditions at depth (Fig. 5). Among the most promising sub-areas are the Drava trough, the Békés basin, part of the Little Hungarian plain and part of the Great Hungarian plain. In the hottest areas, the deep lithology is highly variable, but the best zones should be represented by fractured hard rocks, although they are not crystalline rocks.

5. Conclusions

Soultz was taken as a pilot geothermal HFR site, and the main Hot Fractured Rock criteria were determined on this basis. HFR resources in continental Europe are mainly related to the evolution of the Alpine system. The peri-Alpine rift system, as well as the basins located in the inner part of the Alpine belt, represent the most interesting structures.

Acknowledgements

This work was funded by the European Union (contract n°ENK5-CT2000-00301). The authors are grateful to J.P. Quinquis for his helpful assistance.

References

Edel, J.B., Fluck, P., 1989. The upper Rhenish Shield basement (Vosges, Upper Rhinegraben and Schwarzwald): main structural features deduced from magnetic, gravimetric and geological data. Tectonophysics 169, 303–316.

Genter, A., Traineau, H., Ledesert, B., Bourgine, B., Gentier, S., 2000. Over 10 years of geological investigations within the HDR Soultz Project, France. World Geothermal Congress 2000, Japan 6, 3707–3712.

Hettkamp, T., Klee, G., Rummel, F., 2002. Stress regime and permeability at Soultz derived from laboratory and in situ tests. Geologisches Jahrbuch: Sondehefte: Reihe E: Geophysik; H. SE1. International Conference 4th Hot Dry Rock (HDR) Forum, Strasbourg, France, Sep 1998, pp.165–172.

Huismans, R.S., Podladchikov, Y., Cloetingh, S., 2001. Dynamic modeling of the transition from passive to active rifting, application to the Pannonian basin. Tectonics 20, 1021–1039.

Hurtig, E., Cermak, V., Haenel, R., Zui, V. (Eds.), 1992. Geothermal Atlas of Europe. Hermann Haack Verlagsgesellschaft mbH, Germany.

Ottlik, P., Galfi, J., Horvath, F., Korim, K., Stegena, L., 1981. The low enthalpy geothermal resource of the Pannonian Basin, Hungary. In: Rybach, L., Muffler, L.J.P. (Eds.), Geothermal Systems: Principles and Case Histories. Wiley & Sons, pp. 221–245.

Weidler, R., Gerard, A., Baria, R., Baumgartner, J., Jung, R., 2002. Proceedings Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, USA, pp. 95–100.

Wenzel, F., Brun, J.-P., 1991. ECORS-DEKORP working group, A deep reflection seismic line across the Northern Rhine Graben. Earth Planetary Sciences Letters 104, 140–150.

Ziegler, P.A., 1980. Tectonic and palaeogeographic development of the North Sea rift system. In: Blundell, D.J., Gibbs, A.D. (Eds.), Tectonic Evolution of the North Sea Rifts. Clarendon Press, Oxford, pp. 1–36.