Typology of potential Hot Fractured Rock resources in Europe

Genter A., Guillou-Frottier L., Feybesse J.L., Nicol N., Dezayes C., Schwartz S.

BRGM, 3 avenue Claude Guillemin, BP6009, 45060 Orléans Cedex 2, France

Abstract

As a part of an European project about Hot Fractured Rock (HFR) hold at Soultz-sous-Forêts within the Rhine graben (France), a preliminary analysis of HFR resources in Europe was carried out in terms of geodynamical context. By considering the Soultz site as a referential HFR site, the major HFR criteria (temperature, fracture system, in situ stress) are presented. Based on the temperature distribution estimated at 5 km, 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 structures, corresponds geologically to Tertiary grabens (Rhine graben, Eger graben, Catalonia) and peri alpine foreland (Molassic basin). The second main type of interesting HFR zones is located inside the Alpine belt and corresponds to complex back arc basins (Pannonian basin, Tuscany area). A synthetic litho-tectonic map of Europe at the scale of 1:4,000,000 that takes into account this typology is presented.

Keywords

Hot Fractured Rocks, Geothermal Resources, Soultz-sous-Forêts, Europe

Introduction

This study is a part of the European Geothermal project which has been carried out at Soultz-sous-Forêts (France) from April 2001 to March 2004. The basic idea is to find other interesting areas in Europe where Hot Fractured Rock (HFR) technology could be applied from a geoscientific point of view. In that framework, we started a study dedicated to the typology and the mapping of deep continental HDR/HFR systems in Europe. Based on available or published scientific data, geothermal atlas and different maps, we have to demonstrate or not the reproducibility of the Soultz geothermal concept to other deep fractured areas in Europe. Therefore, the main objectives of this study could be summarised as follow: (1) define the main Hot Fractured Rock criteria based on the Soultz site characteristics, (2) classify and delineate the hottest HFR zones at a maximum of 5 km depth, and (3) evaluate the deep seated geology of these hottest zones in terms of geodynamical settings (lithology, recent volcanism, fracture system, in situ stress).

The basic HFR characteristic of the Soultz site

The Soultz project is located within the French part of the Upper Rhine valley which is a Cenozoic graben. In connection with the graben creation, this area is characterised by a system of normal faults that penetrated deeper within the hercynian crystalline basement. In the Soultz area, the post-Palaeozoic granite is overlain by Mesozoic and Cenozoic sediments of 1.4 km thick. The major criteria that support the HFR assessment are the sufficient temperature conditions at depth, the stress field conditions, the fracture system geometry, and the occurrence of crystalline rocks.

Temperature. The *Hot* criterion would correspond to a minimum temperature of 200°C at a maximum of 5km depth which is the optimal value for producing electricity. The choice of 5 km depth correspond to the actual depth reached at Soultz were 200°C were 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 and below 1000 m depth, the geothermal gradient decreases. A temperature log was carried out on July 2000 (Figure 1a) which shows the bottom temperature of 202ºC with the gradient of about 30ºC/km between 4000-5000 m depth [1].

Stress field and the 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 done in the deep wells show the vertical stress (σV) is maximum [2]. They also show that the minimum horizontal stress (σh) and the maximum horizontal stress (σH) magnitudes are very different that 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 developed within the granite shows small-scale fractures and large-scale normal faults associated with intense hydrothermal alteration [3]. The fracture orientation is nearly N-S and characterized by high dip values (Figure 1b).

Crystalline rock. The *Rock* criterion is due to the occurrence below the sediments of a huge granitic batholith of variscan age which was penetrated by the different Soultz wells. From 1.4 to 5 km depth, the deep seated geology deduced from borehole logging [3] 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 mineral 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 100g/l.

Based on more than 10 years of various on-site investigations in the deep wells, we consider that this experimental site has some relevant characteristics (temperature, fracture, in-situ stress, brines) that we have to find in other areas of Europe. In that way, we define Soultz as a referential HFR geothermal site.

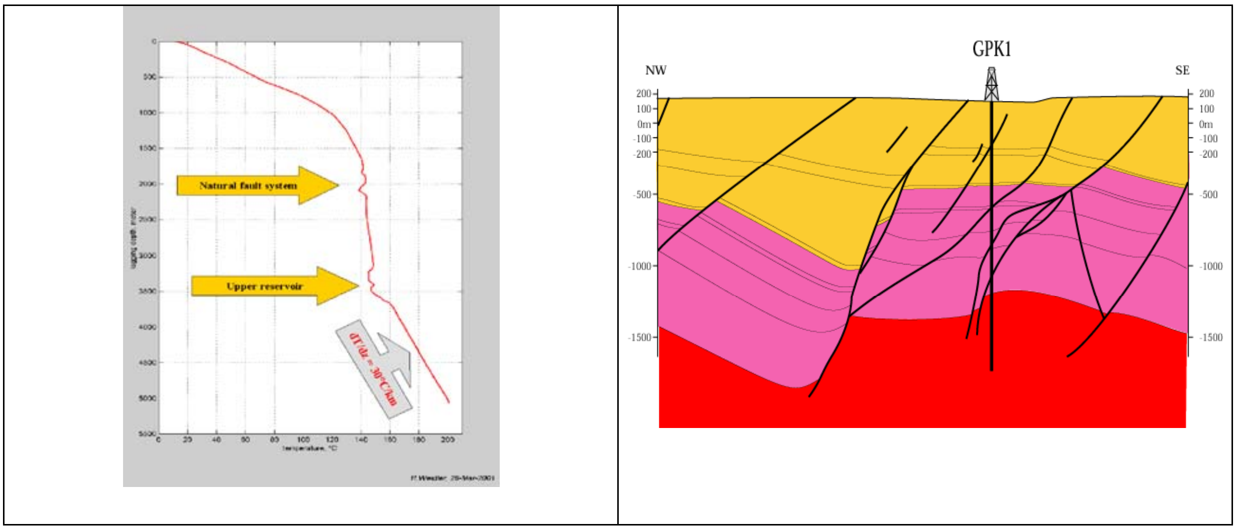

Figure 1: The HFR criteria based on the Soultz site. a - temperature profile in the GPK-2 well with 200°C at 5 km depth from [1], b - Geological cross-section of the Soultz site showing the deep seated fractured granite.

Analysis of the temperature map at 5 km depth in Europe

As a basic document, a map of temperature extrapolated at 5 km depth done by [4] and modified in 2000 by the *Economic Interest European Group* (E.I.E.G. Heat Mining, www.soultz.net) operating at Soultz, is used for delineating the main interesting zones at European scale (Figure 2). Due to the variable quality of the temperature data, the different corrections 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 [4]. The downward extrapolation of the 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. Based on this map, the different thermal zones were classified. For the highest temperature zones (>160°C), the whole analysis of the thermal map at 5km depth outlines several areas (Figure 2):

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

- Some very warm areas (**from 200 to 240°C and higher**), the French Massif Central, the Rhine graben, the Pannonian basin (Hungary, Austria, Slovakia, Romania, Slovenia, Croatia, 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 Czech Republic).

In order to validate or not the extrapolated temperature map at 5 km depth, a critical analysis of this map has been carried out for assessing the anomalous characteristics of the suggested areas. Based on an available database from the International Heat Flow Commission and from available data and literature, several areas have been checked. About 2500 well data have been used knowing that actual oil borehole data are not always accessible due to confidentiality. As only 5% of the wells are below 3500 m, the extrapolated map is then in some areas a pure linear extrapolation of the geothermal gradient measured at shallow depth. Then, the resulting map of the thermal conditions at depth has to be considered with care. The checking of the extrapolated temperature map at 5 km depth is illustrated on Figure 3.

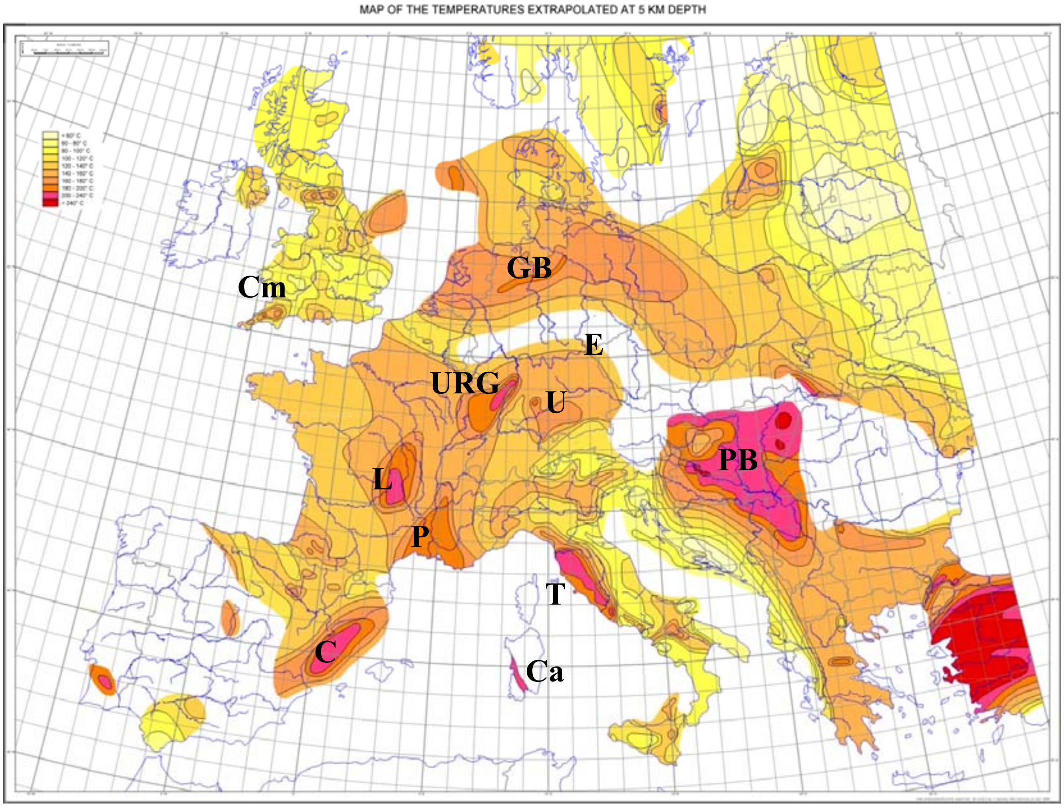

Figure 2. Map of temperature extrapolated at 5 km depth. From [4] modified by GEIE. URG: Upper Rhine Graben; U: Urach; L: Limagne-French Massif Central; P: Provence ; C: Catalonia; Ca: Campidano graben; Cm: Camborn granite; GB: German basin; T: Tuscany; PB: Pannonian Basin; E: Eger graben.

The comparison between the extrapolated temperature map at 5 km and the available thermal information can be summarised as follow : (1) a lot of areas are in agreement with the extrapolated temperature forecasted by 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 UK, and a large part of the North German basin, (2) some areas (Eastern Europe mainly) which were not documented within the basic map have been checked and suggested as favourable areas, (3) some areas are not in agreement with the extrapolated map (SW France) the temperature being at least 20°C below the extrapolated values, (4) some areas are partly 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 interesting even if the basic map shows a high extrapolated temperature at 5km depth (South Portugal).

MAP OF THE TEMPERATURES EXTRAPOLATED AT 5 KM DEPTH

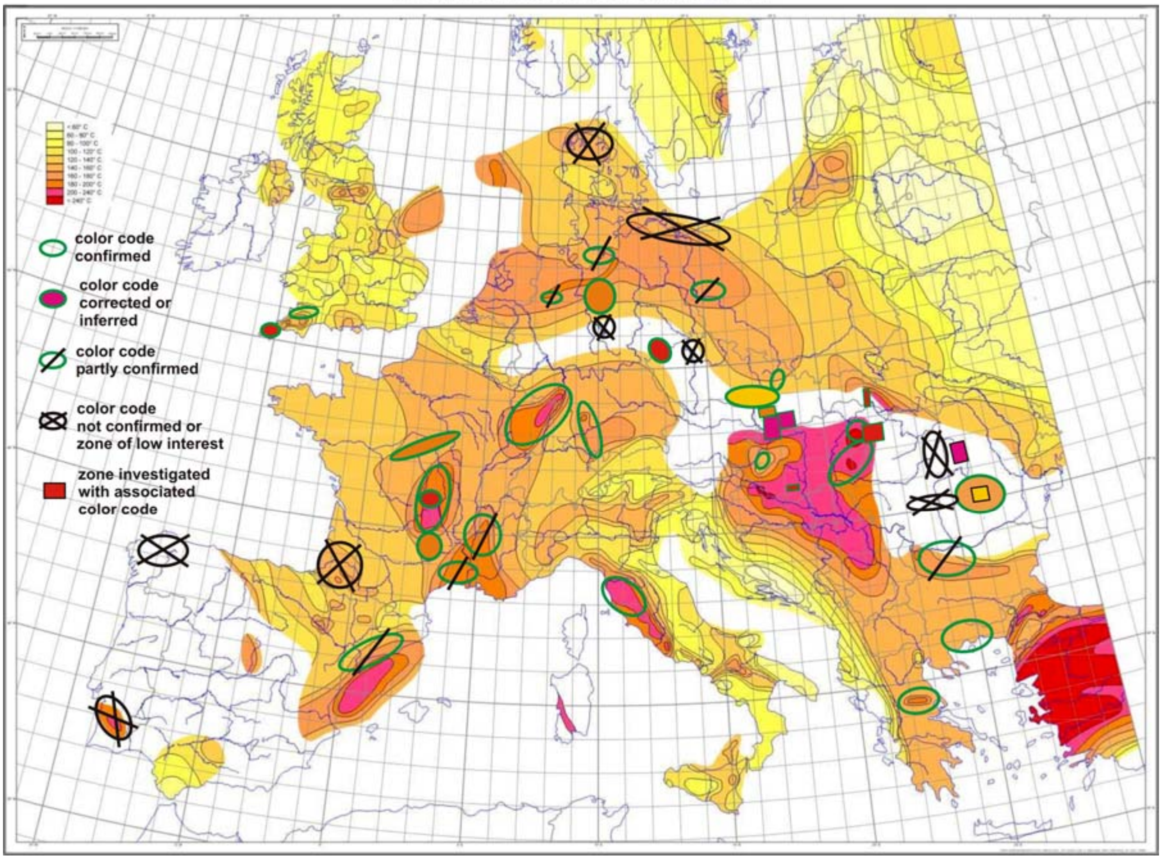

Figure 3. Validation of the temperature map at 5 km depth

Typology of HFR zones

For characterizing the main promising HFR zones, a large-scale geological map was built at 1:4,000,000-scale which takes into account the main litho-tectonic structures of Europe (Figure 4).

The first type of the most promising HFR zones are distributed around the alpine front in external position. From the Norway to the North, to the Mediterranean Sea to the South, a series of intra-continental graben cuts the western European platform called the west European rift system [5]. Those rift structures were created at the Oligocene due to the thinning of the continental crust. The main Tertiary grabens are the upper Rhine graben, the Limagne system, the Rhône valley, a part of the Provence, the Catalonia and the Eger graben. The Molassic basin as well as the Urach area located in Germany is characterised by Tertiary volcanism within the European platform are also geothermal HFR potential zones located externally according to the Alps belt. The Molassic basin could be also considered as an interesting zone located outer of the Alps front. The Lower Rhine Embayement graben, which is a 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 summarize hereafter the main characteristics of that rift system. Its length is about 300 km and its average width is 40 km limited by large-scale normal faults. In this graben, the post-Palaeozoic sediments of the western European platform overlain the Hercynian basement which is made of granite, granodiorite or other related basement rocks [6]. This area which is characterised by a thin continental crust, the Moho being located at 25 km depth, shows a Tertiary volcanism that occurred by means of isolated volcanoes of alcaline composition related to a mantellic magmatic activity [7]. In some other grabens (Limagne, Eger), the volcanic activity was also developed during the Quaternary. Most of these areas show a strong seismic activity with a high concentrations of deep seismic events. For the Rhine graben, their distribution is clearly localised in its southern part in connection with the Alpine front. A lot of thermal springs are located on the graben borders in connection with the large scale faults. Moreover, several areas show interesting geothermal anomaly within the graben such as Soultz, Landau or near Speyer.

The second main types of HFR promising zones in Europe is also related to the Alpine front but it correspond to complex back-arc basins (Pannonian basin, Tuscany-Latium) located inside the Alpine belt. The hottest HFR zone at shallow depth is represented by the Tuscany area. The Pannonian basin, which is an intra-montane rift is characterised by extension and the coeval occurrence of compression and subduction in the surrounding Carpathian and Dinaric chains [8]. 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 synrift to postrift stage. Other interesting areas inside the Alpine belt correspond to post collisional grabens in Greece and Bulgaria.
The well-exposed granites of Cornwall (UK) as well as the deep German basin represent HFR zones which are not directly related to the Alpine system.

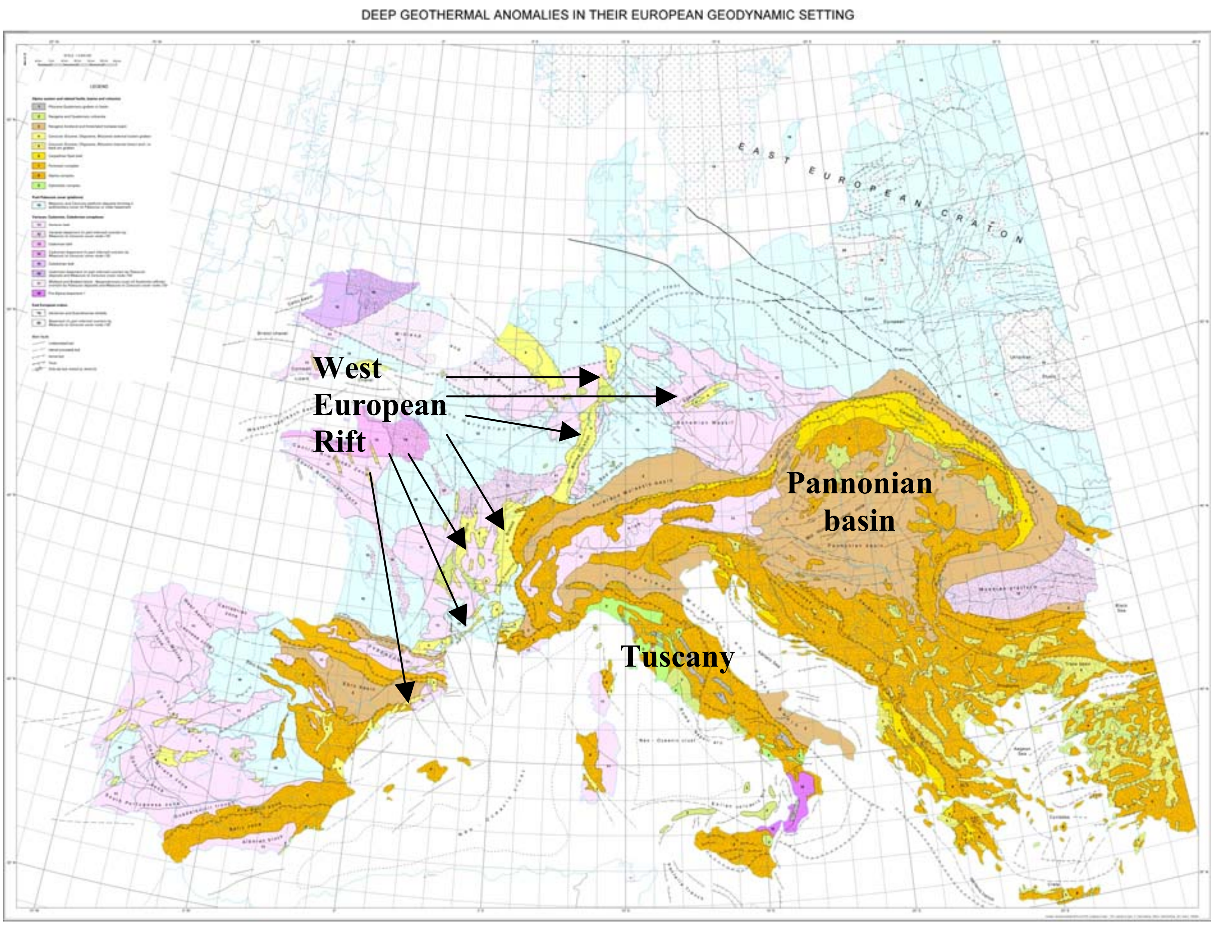

Figure 4. Large-scale map of Europe illustrating the typology of HFR zones in Europe. The structures belonging to the west European Rift (WER) are distributed around the Alps belt.

Focus on a promising HFR area

In order to better characterize the HFR potential of the hottest zones**,** some promising zones such as the Upper Rhine graben, the Eger graben, the Tuscany or the Pannonian basin were investigated in more detailed but in this paper, only the Pannonian basin is presented. This is an area with high thermal conditions due to a high terrestrial heat flow. The thermal system is evidenced by a lot of thermal springs and the occurrence of geothermal reservoirs well known even at shallow depth [9]. The volcanic activity was also intense from Tertiary. Within the Pannonian basin, there is a series of internal sedimentary sub-basins of several kilometres thick as it is illustrated in Figure 5. The superimposition of the extrapolated temperature data at 5 km and the thickness of the sedimentary sub-basins within the Pannonian basin shows that some faulted sub-basins have favourable thermal conditions at depth (Figure 5). Among the main promising sub-areas, there are the Drava through, the Békés basin, a part of the Little Hungarian plain and a part of the Great Hungarian plain. In these hottest areas, the deep lithology is very variable, but the best zones should be represented by fractured hard rocks even though they are not crystalline rocks.

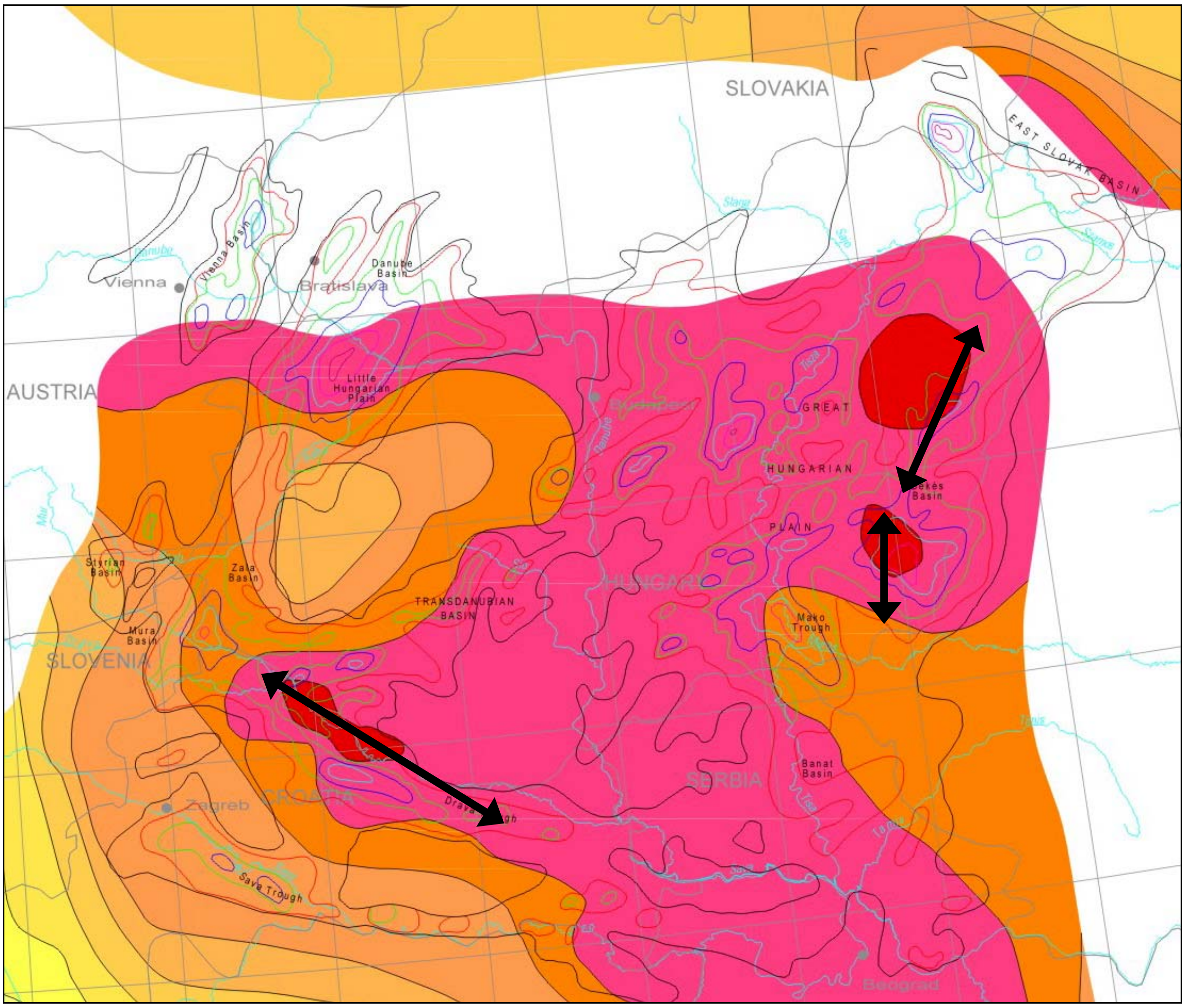

Figure 5. Extrapolated temperature map of the Pannonian basin at 5 km depth from [1]. This map is a focused map of the Figure 1. The arrows underline the superimposition between the Tertiary sub-basin locations and the highest temperature zones. Pink areas and red areas correspond to temperatures higher than 200°C and 240°C respectively.

Conclusions

By considering Soultz as a geothermal HFR pilot site, the major Hot Fractured Rock criteria were considered. HFR continental resources in 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 main interesting structures.

References

1. R. Weidler, A. Gerard, R. Baria, J. Baumgartner, R. Jung, *27th Workshop on Geothermal Reservoir Engineering*, Stanford, (2002)
2. T. Hettkamp, G. Klee, F. Rummel, *Geologisches Jahrbuch,* (1998)
3. A. Genter, H. Traineau, B. Bourgine, B. Ledesert, S. Gentier, *World Geothermal Congress*, (2000)
4. E. Hurtig, V. Cermak, R. Haenel, *V. Zui, Hermann Haack*, 1992, p. 156
5. P.A. Ziegler, *Blundell D J, Gibbs A. D. (Eds),* 1990, 36 p.
6. J.P. Edel, P. Fluck, *Tectonophysics*, **169**, 4, (1989).
7. Wenzel F. and co-workers, *Earth Planetary Sciences Letters*, **104**, 2-4, (1991).
8. R. Huismans, Y. Podladchikov, S. Cloetingh, *Tectonics,* **20**, 6, (2001)
9. P. Ottlik, J. Galfi, F. Horvath, K. Korim, L. Stegena, Geothermal Systems: Principles and Case histories, 1981

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