Fluid origin and circulation in the heat exchanger of Soultz-sous-Forêts (France) estimated using geochemical and tracer test data.

Bernard Sanjuan, Romain Millot, Chrystel Dezayes, Michel Brach

EC Contract SES6-CT-2003-502706

PARTICIPANT ORGANISATION NAME: BRGM

Related with Work Package 2

Related with Working Group 6

FLUID ORIGIN AND CIRCULATION IN THE HEAT EXCHANGER OF SOULTZ-SOUS-FORÊTS (FRANCE) ESTIMATED USING GEOCHEMICAL AND TRACER TEST DATA

SANJUAN Bernard, MILLOT Romain, DEZAYES Chystel and BRACH Michel
BRGM - 3, Av. Claude Guillemin - 45065 ORLEANS Cedex 02, France
e-mail: b.sanjuan@brgm.fr

EXTENDED ABSTRACT

In the framework of the European Hot Dry Rock Energy (HDR) Program, three deep wells (5000 m) have been drilled into a fractured granite basement at Soultz-sous-Forêts, located within the Rhine Graben, in order to develop a deep heat exchanger (GPK-3 as injector and GPK-2/GPK-4 as producers) and produce electricity after the creation of an EGS reservoir. Despite very few representative analyses of deep geothermal fluids, often contaminated by drilling fluids or injected waters, the geochemical data provide interesting information on the nature, origin, circulation and deep temperature of these fluids (Sanjuan *et al.*, 2006a and c). They indicate similar chemical and isotopic compositions (NaCl fluids) and high salinity values (TDS about 100 g/l) which suggest a common sedimentary origin and identical water-rock interaction processes. This sedimentary origin is confirmed by the presence of organic matter in highly fractured and altered granite cores (Ledésert *et al.*, 1996) and of dissolved organic carbon in fluid samples. The chemical and gas geothermometers suggest that the native geothermal brine and associated gases are equilibrated with a mineralogical assemblage at temperatures close to 220-240°C (> 200°C measured a t the bottom-hole; Sanjuan *et al.*, 2006a and c). According to the Na/Li geothermometer and the δ^7Li values, these equilibrium reactions would occur in a sedimentary rather than granite reservoir (Fig. 1). Given the location of the Soultz site and these constraints, this reservoir would be situated more eastern, towards the Graben centre where the sedimentary formations (Trias) are the deepest and hottest (Fig. 2). From tracer tests carried out after 2000, the natural flux of the native geothermal brine was estimated at 1-1.2 m^3/h, which is identical to that calculated for the fluid flux parallel to the Graben strike, based on a convection model and numerical 3D modeling (Bächler, 2003; Sanjuan *et al.*, 2006b and c). During all the production and circulation tests, the tracer tests and geochemical data showed the omnipresence of the native geothermal brine in the discharged fluids even after injection of large amounts of external water into the wells. The existence of at least three fluid flow pathways between the wells GPK-2 and GPK-3 with different effective fluid velocities, which contrasts with a poor hydraulic connection between GPK-3 and GPK-4 (Fig. 3), was highlighted during the fluid circulation loop and the associated tracer test using fluorescein, carried out between July and December 2005 (Sanjuan *et al.*, 2006b and c).

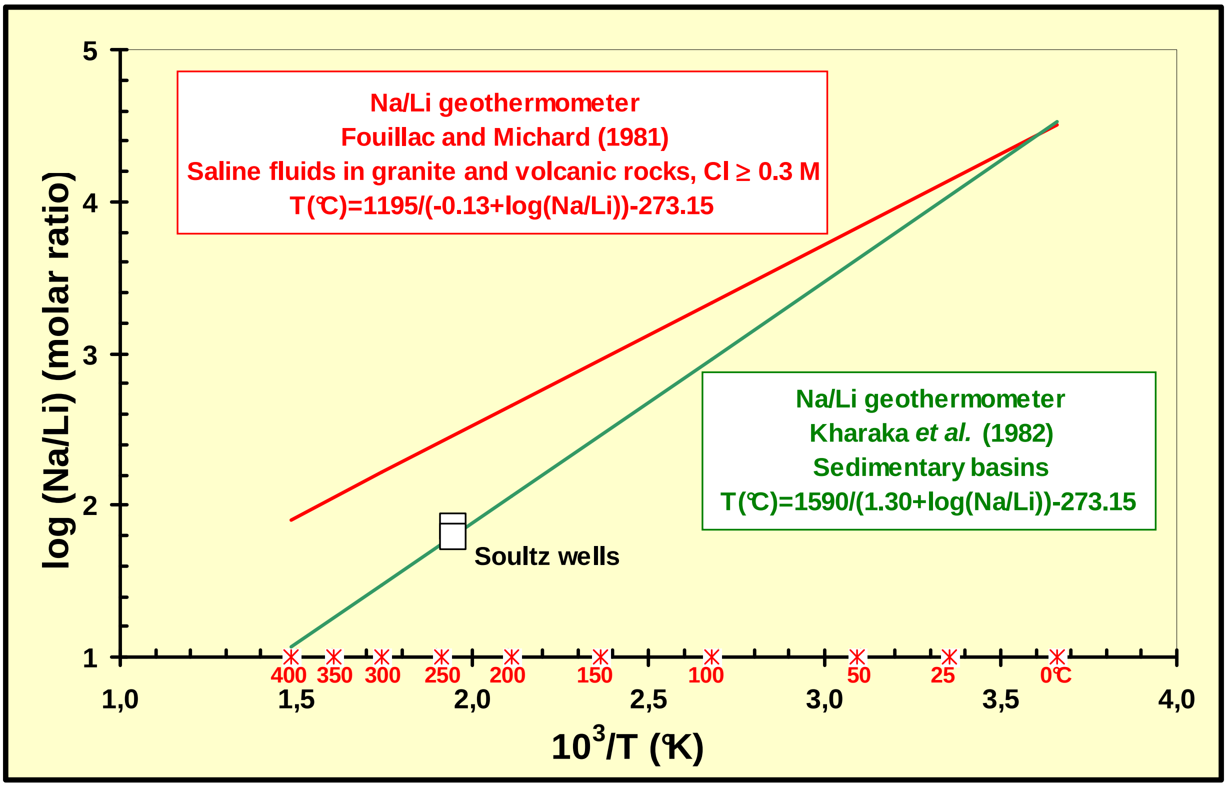

Figure 1 - Na/Li geothermometric relationships existing in the literature for sedimentary and granite or volcanic reservoirs. The analytical results suggest that the Soultz native geothermal brine is equilibrated with sedimentary rather than granite rocks at 230±20℃. This estimated temperature is concordant with the other estimations performed using other chemical geothermometers such as Na/K, Na/K/Ca, K/Mg, or Mg/Li (which is another geothermometer determined in sedimentary basins; Sanjuan et al., 2006a and c; Kharaka and Mariner, 1989). It is slightly higher than the temperature measured at the bottom-hole into the wells GPK-2, GPK-3 and GPK-4 (close to 200℃ at a depth of 5000 m). According to the experimental and literature data obtained for the Li isotopic fractionation at 230℃ (Chan et al., 1994; James et al., 1999; Millot et al., 2009), the δ^7Li value for the rock in equilibrium with the native geothermal brine (analyzed δ^7Li ≈ -0.1‰) would be lower than -6‰. This value is not characteristic of granites (δ^7Li ≈ 0-10‰) but would rather correspond to that of carbonated sediments (Coplen et al., 2002).

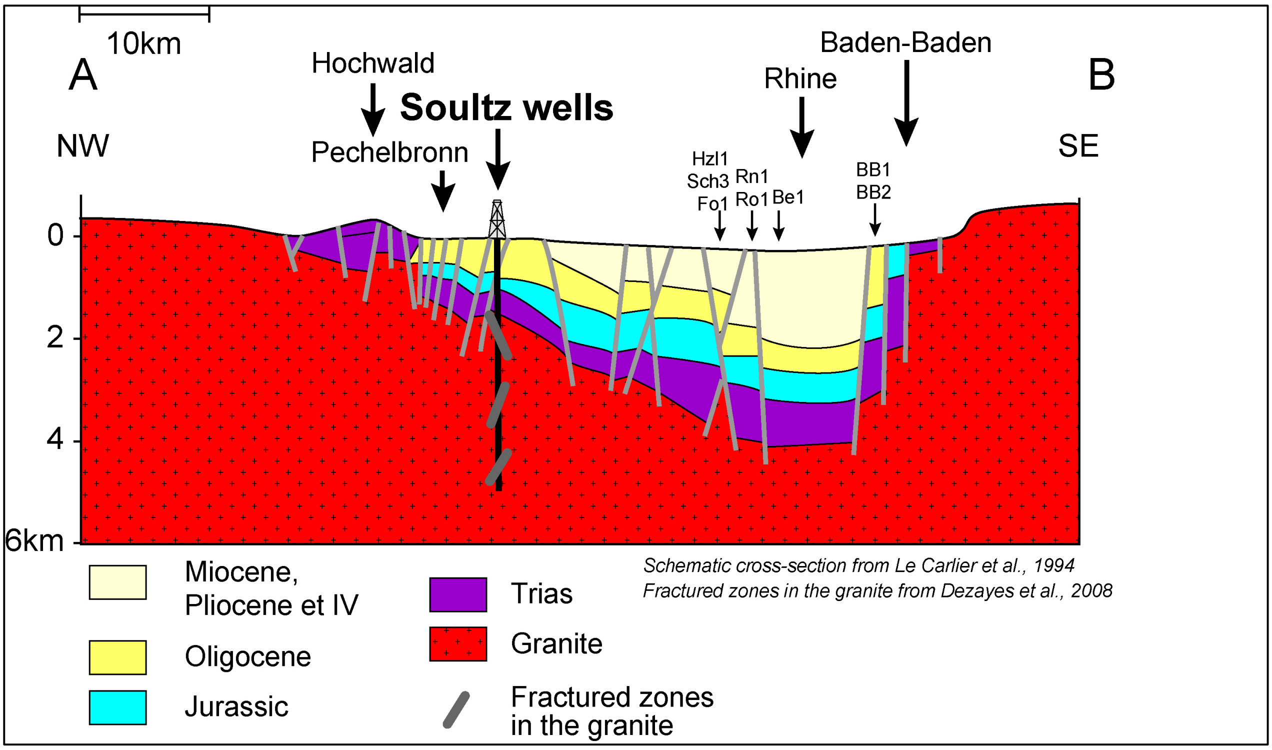

Figure 2 - Schematic NW-SE cross section (from Le Carlier et al., 1994) and location of the three fractured zone clusters in the Soultz wells represented with an average orientation (Dezayes et al., 2008). In the Graben centre, are reported eight deep wells (HZL1, SCH3, FO1, RN1, RO1, BE1, BB1 and BB2; up to a depth of about 2500 m) where thermal gradient values ranging from 50 to 60℃/km were measured (Vernoux a nd Lambert, 1993). According to these values, the Triassic formation can reach temperatures close to 200-240℃ in the Graben centre (corresponding to a depth of about 4 km). Consequently, this sedimentary formation can be considered as the most probable reservoir in which the Soultz native geothermal brine is originated and is equilibrated with sedimentary rocks at 230℃. After, this brine would move from the Graben centre to its external borders (Soultz) through a complex system of faults still badly defined.

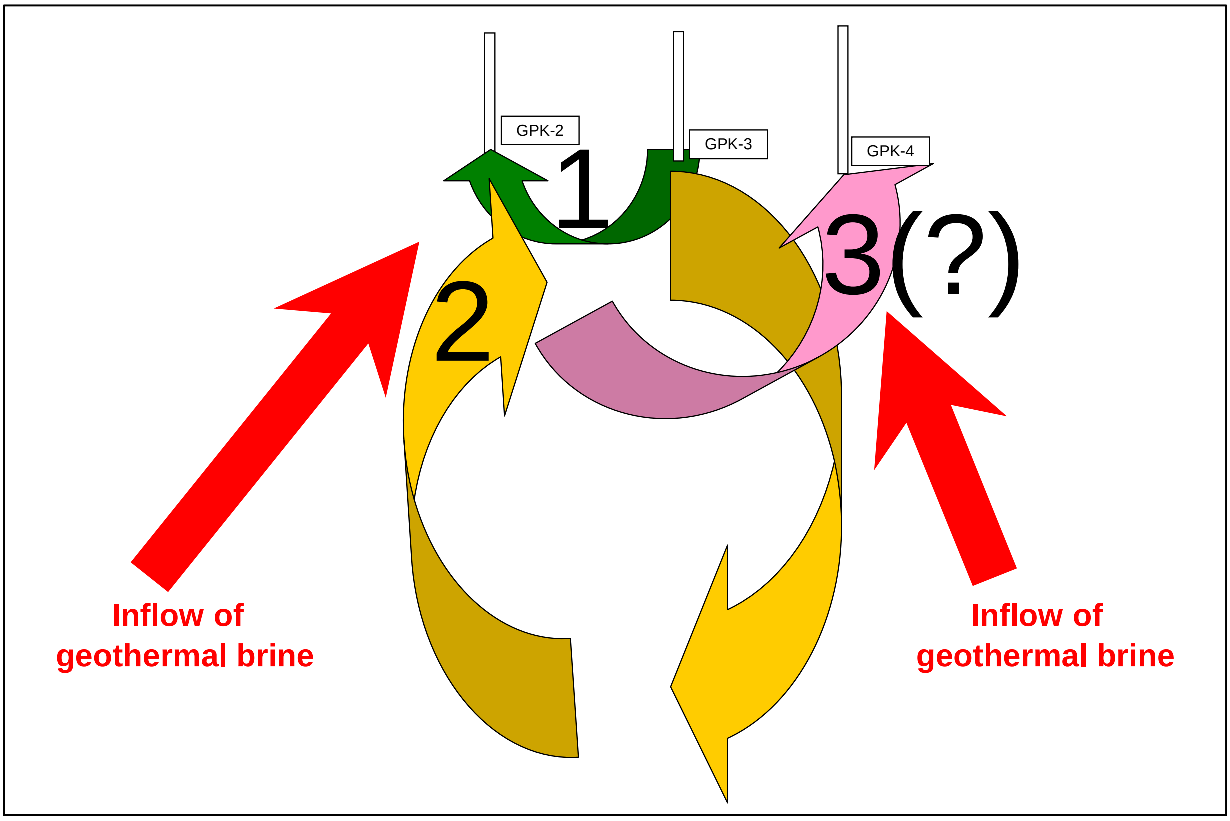

Figure 3 - Conceptual model of fluid circulation in the Soultz geothermal heat exchanger established after the 5 month-circulation test carried out in 2005 (injection rate into GPK-3 close to 15 l/s, with 11.9 l/s coming from GPK-2 and 3.1 l/s from GPK-4) and the associated tracer test using fluorescein (after Sanjuan et al., 2006b). 1) Short-scale loop between GPK-3 and GPK-2 (fluorescein recovery rate of 15.6%; mean linear fluid velocity of 1.1 m/h). 2) Large-scale loop between GPK-3 and GPK-2 (fluorescein recovery rate of 7.9%; mean linear fluid velocity of 0.3 m/h). 3) Hydraulic connection between the large-scale loop and GPK-4 (fluorescein recovery rate of 1.8%; mean linear fluid velocity of 1.1 m/h).The existence of another quasi-infinite loop, which would connect both GPK-2 and GPK-4 to GPK-3, is highly probable. The presence of such a loop could explain the low fluorescein recovery rate estimated at the end of the tracer test (15.6 + 7.9 + 1.8 = 25.3%). The omnipresence of the native geothermal brine (with a natural flux estimated at 1-1.2 m^3/h) was observed in the three deep wells during all the production and circulation tests carried out after 2000. Similar (or slightly lower) mean linear fluid velocities (0.25-0.45 m/h) and tracer recovery rate (26%) were obtained between GPK-1 and GPK-2 at 3500-3900 m depth during the 4 month 1997 circulation test when 21 to 25 l/s injection rates were used (Vaute, 1998; Aquilina et al., 2004).

REFERENCES

Aquilina, L., De Dreuzy, J.-R., Bour, O., and Davy, Ph. (2004) - Porosity and fluid velocities in the upper continental crust (2 to 4 km) inferred from injection tests at the Soultz-Sous-Forêts geothermal site. *Geochim. et Cosmochim. Acta*, 68, 11, 2405-2415.

Bächler, D. (2003) - Coupled thermal-hydraulic-chemical modelling at the Soultz-sous-Forêts HDR reservoir (France). *Thesis Doctor of Natural Sciences, Swiss Federal Institute of Technology, Zurich,* 151 p.

Chan, L.H., Gieskes, J.M., You, C.F., and Edmond, J.M. (1994) - Lithium isotope geochemistry of sediments and hydrothermal fluids of the Guaymas Basin, Gulf of California. *Geochim. et Cosmochim. Acta,* 58, 4443-4454.

Coplen, T.B., Hopple, J.A., Böhlke, J.K., Peiser, H.S., Rieder, S.E., Krouse, H.R., Rosman, K.J.R., Ding, T., Vocke, R.D.Jr., Révész, K.M., Lamberty, A., Taylor, P., and De Bièvre, P. (2002) - Compilation of minimum and maximum isotope ratios of selected elements in naturally occurring terrestrial materials and reagents. *U.S. Geological Survey, Water Resources Investigations, Report 01-4222.*

Dezayes, Ch., and Genter, A. (2008) - Large-scale fracture zone network based on Soultz borehole data. *Proceedings EHDRA Scientific Conference, 24 and 25 September 2008, Soultz-sous-Forêts (France),* 12 p.

Fouillac, Ch., and Michard, G. (1981) - Sodium/lithium ratio in water applied to geochemistry of geothermal reservoir. *Geothermics*, 10, 55-70.

James, R.H., Rudnicki, M.D., and Palmer, M.R. (1999) - The alkali element and boron geochemistry of the Escanaba through sediment-hosted hydrothermal system. *Earth and Planetary Science Letters*, 171, 157-169.

Kharaka, Y.K., Lico, M.S. and Lax, L.M. (1982) - Chemical geothermometers applied to formation waters, Gulf of Mexico and California basins. *Am. Assoc. Petrol. Geol. Bull.*, 66, 588.

Kharaka, Y.K. and Mariner, R.H. (1989) - Chemical geothermometers and their application to formation waters from sedimentary basins. *In: Naeser, N.D. and McCulloch, T.H. Eds, Thermal history of sedimentary basins: methods and case histories*. *Springer-Verlad, New York,* 99-117.

Le Carlier, C., Royer, J.-J., and Flores, E.-L. (1994) - Convective heat transfer at Soultz-sous-Forêts geothermal site: implications for oil potential. *First Break,* 12, 11, 553-560.

Ledésert, B., Joffre, J., Amblès, A., Sardini, P., Genter, A. and Meunier, A. (1996) - Organic matter in the Soultz HDR granitic thermal exchanger (France): natural tracer of fluid circulations between the basement and its sedimentary cover. *J. Volcan. and Geotherm. Researc*h, 70, 235-253.

Millot, R., Scaillet, B., and Sanjuan, B. (2009) - Lithium isotopes in island arc geothermal systems: Guadeloupe, Martinique (French West Indies) and experimental approach. *Submitted to Geochim. and Cosmochim. Acta.*

Sanjuan, B., Pinault, J.-L., Rose, P., Gérard, A., Brach, M., Braibant, G., Crouzet, C., Foucher, J.-C., Gautier, A., Touzelet, S. (2006a) - Geochemical fluid characteristics and main achievements about tracer tests at Soultz-sous-Forêts (France). *Proceedings EHDRA Scientific Conference, 15 and 16 June 2006, Soultz-sous-Forêts (France),* 14 p.

Sanjuan, B., Pinault, J.-L., Rose, P., Gérard, A., Brach, M., Braibant, G., Crouzet, C., Foucher, J.-C., Gautier, A., Touzelet, S. (2006b) - Tracer testing of the geothermal heat exchanger at Soultz-sous-Forêts (France) between 2000 and 2005. *Geotherm*ics, 35, Special Issue, 622-653.

Sanjuan, B., Pinault, J.-L., Rose, P., Gérard, A., Brach, M., Braibant, G., Crouzet, C., Foucher, J.-C., Gautier, A., Touzelet, S. (2006c) - Geochemical fluid characteristics and main achievements about tracer tests at Soultz-sous-Forêts (France). *BRGM/RP-54776-FR final report,* 64 p.

Vaute, L. (1998) - Tests de traçage réalisés sur le site géothermique de Soultz-sous-Forêts (juillet-novembre 1997). *BRGM report n°40230* , 39 p.

Vernoux, J.-F., and Lambert, M. (1993) - Aquifères profonds d'Alsace. Constitution d'une base de données à usage géothermique. *SGN/IRG ARG 93 T37 final report*, 41 p.