

A TRACER TEST AT THE SOULTZ-SOUS-FORÊTS HOT DRY ROCK GEOTHERMAL SITE

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ABSTRACT

Soultz-sous-Forêts is the French site of the European Hot Dry Rock (HDR) project of which the objective is the creation of a heat exchanger at depth in the granite that constitutes the basement of the Rhine Graben. Geochemical studies permitted the characterization of the fluid circulation, which occur naturally in the Rhine Graben and are man-induced at the Soultz site. After the development of the heat exchanger, long-term circulation and tracer tests during the summer of 1997 have allowed for an improved characterization of the reservoir.

INTRODUCTION

Since 1987, Soultz-sous-Forêts has been the location of the European HDR project. The objective of this project is to create a heat exchanger at a depth of 4 km in the granitic basement. Two wells (GPK-1 and EPS-1) were drilled in 1987 and 1990 to depths of 2200 m. During this first phase, several geochemical tasks were carried out to characterize the chemistry of the fluids sampled in the granite (Pauwels et al., 1992, 1993). The project then began a second phase wherein the GPK-1 bore hole was first deepened to 3600 m and a third well (GPK-2) was drilled to a depth of 3800 m (Aquilina & Brach, 1995; Aquilina et al., 1997). During 1995, a circulation test was carried out to initiate the heat exchanger and, during 1997, a long-term circulation test was successfully completed.

RESULTS AND DISCUSSION

Deepening of the GPK-1 borehole to 3600 m has shown that fluid circulation can take place at least down to 3500 m. Fluids sampled at this depth have the same compositional range as those previously sampled in the upper part of the granite and the

sedimentary cover, which indicates that all these fluids have a common origin. However, it is also clear that they evolved differently.

Comparison of these deep fluids with shallower fluids sampled at Soultz and at other locations in the Rhine Graben gave information on the reactions occurring during the interaction of the fluids with both Triassic sandstone and granite within the Rhine Graben. Two clear trends can be observed between the fluids sampled in the granite and those collected in the Buntsandstein (see Fig. 1). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vs. the Rb/Sr ratios of fluids and minerals indicate that mica dissolution occurs in the Buntsandstein. In the granite, the fluid composition is related to the dissolution of plagioclase and probably the illitic phase in the fractures. Thus, although the two fluids have a common origin, they have experienced separate evolutionary processes after their separation.

Several differences appear between the fluids at 3500 m and those sampled at 1800-2000 m. This is true not only for the organic-matter and metal-trace content, but especially for the SiO_2 and $\delta^{18}\text{O}$ (SO₂). These differences indicate that, although they have a common origin, the fluids in the deeper part took a distinct evolutionary pathway once they invaded the granite. The geothermometers at 3500 m all give values close to 230°C. This gives a clear demonstration of the existence of a hot (about 230°C) reservoir in the Rhine Graben (Aquilina et al., 1997). The discrepancy between the geothermometer calculations at 2000 and 3500 m implies that the fracture zone at 3500 m is closely connected to the reservoir. This is assumed to be due to intra-granite fluid circulation, extending from 2 to 5 km depth in the granite as stated by Benderitter and Elsass (1995).

FLUID CIRCULATION MODEL

The first phase of the Hot Dry Rock project, before completion of a heat exchanger, has led to intensive research that improved the understanding of natural fluid circulation in the Rhine Graben and at the Soultz site. Chemical and isotopic analyses of fluids collected in the graben and from surface springs indicate the following phases of evolution: (1) Dilution of Triassic primary-brines by meteoric waters and migration throughout the whole Buntsandstein aquifer during the Eocene continental period. (2) Burial of the Triassic reservoir during graben formation (Oligocene) and sealing of the formations by Tertiary deposits. (3) Water-rock interaction in the sedimentary aquifer and equilibration with temperature. (4) Circulation of the brines from Buntsandstein into the granite.

The Buntsandstein formation almost acts as a confined aquifer within which the fluids are trapped. At present, fluid circulation in the graben is thought to occur through three different systems: (1) On each side of the graben, mixing of the basin fluids with surface water infiltrating from the Vosges and the Black Forest. (2) Strong migration from the lower part of the graben to the upper part of the granitic basement. This migration may occur through several convection cells. (3) The possibility of a third level of circulation within the granite due to the difference between fluids at 1800-2000 m and those at 3500 m. In particular, the geothermometry indicates the proximity of a hot reservoir and suggests that circulation may take place in the shape of convection cells that function below the 3-km depth in the granite (Benderitter et al, 1995).

CIRCULATION TESTING

The borehole GPK-2 was drilled at the end of 1994 to a depth of 3880 m. It is located in the outer part of the seismic cloud recorded during the 1993 injections in GPK-I. At depth, the two wells are located about 450 m apart, which is a very large distance when compared to other HDR systems where this distance is generally less than 150 m. During the summer of 1995 two circulation tests of 18 and 20 days respectively were carried out and geochemically monitored to establish the communication between the two wells. A short pulse of 10 kg of fluorescein was injected into GPK-2 but was never detected in GPK-I. This result indicated that no short circuit was present and that the reservoir was larger than 100,000 m³. An evolution of the chemistry of the brines produced was noticed during the test, which indicated that the connection was changing during the test.

During the summer of 1997, a long-term circulation test was carried out, this time with injection into GPK-1 and production via GPK-2. The aim of this test was (1) to characterize the deep reservoir, especially through tracer experiments, and (2) to test the hydraulic connections and the capability of circulating during a 4-month period.

Circulation was initiated in the middle of July and continued until the middle of November with essentially no interruptions. Injection and production flow rates varied slightly between 22 and 24 l/s. No losses were observed during the production and no surface fluids were added to the loop. Although some degassing was observed, no corrosion was noticed. The temperature of the produced fluids increased continuously during the test and reached the value of 142°C at the end of the test.

Hydraulic stimulation of the wells GPK-1 and GPK-2 previous to circulation test resulted in the creation of several sets of fractures as determined by spinner-log flow testing (Baumgärtner et al., 1996, 1998). The most significant set of fractures in GPK-1 occurred just below the casing shoe between 2850 m and 2960 m. The fractures in this section received about 60% of the fluid entering the reservoir. Two additional sets of fractures at 3230 m and 3490 m received about 22% and 15% of the fluid, respectively. In GPK-2, there is a nearly continuous set of fractures between about 3200 and 3330 m and an additional set between 3460 and 3560 m.

A sharp decrease of the injection pressure at a constant injection flow rate was observed after about 60 days into the test. This change was related, as observed on flow logs carried out just before and after this event, to a change in the distribution of the flow in GPK-1. The fraction of brine flowing into the reservoir via a large set of fractures between 2850 and 2960 m remained unchanged with about 60% of the total flow. However, the flow into one large fracture at 2860 m (approximately 10 m below the casing shoe) increased from about 24% to about 44% of the total flow into the reservoir. The relationship between the changes in the spinner-log data and the pressure drop in GPK-1 is not evident.

THE TRACER TESTS

Three tracer tests were carried out during the circulation test, which are summarized in Table 1. In the first test, fluorescein and benzoic acid were mixed with 6 m³ of water in a tank. The contents of the tank were then injected into well GPK-I at a rate of 78 l/min. Deuterium was injected downhole using a dump bailer just above the large fracture zone at 3500

m. During the two remaining tests, amino G and rhodamine WT were mixed with 2 to 2.5 m³ of water and were injected in the same manner as fluorescein and benzoic acid.

Table 1 -Main Aspects of the Tracer Tests

Tracer	Mass (kg)	Date	1st detection
Deuterium	8.6	07/30	44
Fluorescein	150	08/01	70-75
Benzoic acid	292	08/01	72
Rhodamine WT	22	10/09	84
Amino G	29	10/25	120

* Due to detection limit effects, fist detection time differs from the first arrival time which can be deduced from the curves and does not show major differences between the tracers which travel time is close to 72 +/- 10 hrs.

The return curves for the tracers injected during the first tracer test (benzoic acid, fluorescein, and deuterium) are presented in Figure 2. The fluorescein curve is issued from several analytical sets which have been carried out in order to remove strong matrix effects. The confirmation of the values is under process. Fluorescein and benzoic acid show a relatively similar pattern with peak maxima occurring between about 6 and 10 days. Both return curves have the long flat tails that are characteristic of tracer flow in hydrothermal systems. Rhodamine and amino G, although the restitution is short, show different curves with a less defined peak at the begining of the restitution, amino G even showing a secondary peak clearly higher than the first increase.

The return curve for deuterium shows a completely different pattern, due partly to the fact that this tracer was injected only at depth. The curve shows two distinct increases. First, the curve rises simultaneously with fluorescein and benzoic acid to form a subtle peak. It can be concluded that a common pathway is present for the tracers injected from the surface and the one injected at depth. A second peak, much more significant than the previous one, is observed about 18 days after injection, whereas no increase is noticed in the other tracers at this time. It is assumed that this peak is related to the flow of fluids into the fractured zone at 3500 m into which deuterium was injected. However, the lack of increase for benzoic acid and fluorescein correlated to the deuterium increase and the deuterium-curve evolution are still not clearly understood.

A convenient method of plotting and comparing these returns is through the residence-time distribution function, E(t) (Danckwerts, 1953):

$$E(t) = \frac{Q \cdot F(t)}{mp}$$

where Q is the fluid mass flow rate, F(t) is the tracer mass fraction (concentration) as a function of time and mp is the mass of the tracer pulse. What makes the E(t) function particularly useful is that it allows for the normalization of each tracer relative to the amount injected. Thus, for conservative tracers that neither adsorb nor decay, plots of E(t) should coincide as long as no changes have occurred within the reservoir to create different flow patterns. However, the fact that injection conditions (dilution of tracer in a different volume [6≠2-2.5 m³]) differed from the first as regards the two other tests has to be taken into account.

Figure 3 shows plots of E(t) vs. time for benzoic acid, fluorescein for the first test and rhodamine WT and amino G for the subsequent two tests. The time scales for the rhodamine WT and amino G traces have been shifted in order to create common injection times with fluorescein and benzoic acid.

It is evident from the reduced relative return that rhodamine WT adsorbed strongly onto the reservoir rock. Whereas rhodamine WT is known to adsorb in ground-water tracing applications, it has been successfully used without adsorbing in a hydrothermal system at Steamboat Hills, Nevada, just 20°C warmer than the reservoir fluids at Soultz (Rose and Adams, 1994). It is possible that differences in the mineral composition between the formations at Steamboat Hills and at Soultz have accounted for this enhanced adsorption of rhodamine WT in the Soultz reservoir.

The initial part of the fluorescein return curve is preserved by the small initial amino G curve. A large amino G peak then follows that overshoots the comparable portion of the fluorescein return curve. However, due to the different injection duration time, one could expect higher normalized curves for rhodamine and amino G than for benzoic acid and fluorescein. It can be concluded from this results and from the shape of the curves in Figure 2 that the first test shows a different tracer-behavior. This difference can be either attributed to (1) a strong adsorption effect for both rhodamine and amino G, or (2) to the changes in the formation which have occurred between the two tracer tests, the most significant of changes being a redistribution of flow just below the

casing shoe in GPK-1 at 2860 m, as revealed by the spinner logs.

Integration of $E(t)$ allows for a determination of $R(t)$, the fractional recovery of each tracer at a given time:

$$R(t) = \int_0^t E(t) dt$$

Application of equation 2 over the period of time that each tracer was produced results in recoveries of 35%, 21%, 8%, and 2% for benzoic acid, fluorescein, amino G, and rhodamine WT, respectively. However recycling of the tracers has not been taken into account in this preliminary computation.

RESERVOIR-FLUID VOLUME

There exist two fundamental approaches for defining the fluid volume of a hydrothermal system based upon tracer-return data. The modal volume is the volume of the hydraulically connected fractures. The overall fluid volume is usually much larger and consists of not only the volume of the hydraulically connected fractures but also the volume of the relatively stagnant regions (dead-end fractures, vugs, and pores) that are accessed primarily by diffusion.

The overall reservoir-fluid volume can be determined from an analysis of the long tailing portion of the return curve. After a conservative tracer has been produced and reinjected over a long period of time in a closed reservoir, the tail of the return curve attains a constant value (Ito and coworkers, 1977). The volume is estimated through the expression:

$$M_f = m_i \cdot F_i$$

where M_f is the overall fluid mass, m_i is the mass of tracer injected and F_i is the tracer mass fraction measured after a sufficiently long time for the tracer to be evenly mixed throughout the reservoir and for the return curve to attain a constant value.

Rose and coworkers showed that equation 3 can also be used to estimate the overall fluid mass for an open reservoir (Rose et al., 1995; Rose & Apperson, 1997). In such reservoirs, there is aquifer cross-flow and the long tailing portion of the return curve attains a constantly sloping profile after a sufficiently long time. An extrapolation of the linear portion of the return curve to its interception with the y axis yields a value for F_i . Application of equation 3 then results in a value for M_f , which can be converted to an equivalent fluid volume.

Figure 2 shows that the benzoic acid and fluorescein return curve attained a rather constantly sloping profile after about 80 days. Extrapolation of this straight portion of the curve allows to define an intercept of the y axis and thus a concentration. Solution of equation 3 results, at the present state of the tracer processing, in a range of the reservoir-fluid volume of several millions of m^3 . This computation does not take into account the tracer recycling and a possible extrapolation of the curves for an increased restitution time. It constitutes thus a minimum value.

CONCLUSIONS

production fluid temperature increased gradually, reaching a maximum value of 142°C at the end of the test. An abrupt drop in the injection-fluid pressure

Three tracer tests were conducted during the circulation test, with breakthrough measured for five tracers including benzoic acid, fluorescein, amino G, rhodamine WT and deuterium. An analysis of the return-curve data indicated that rhodamine WT adsorbed strongly onto the reservoir rock, whereas the remaining four tracers behaved more conservatively. Deuterium was injected downhole in order to trace the flow processes of brine through a set of fractures intersected by the injection well at the 3500-m depth.

A comparison of the return curve for amino G, which was injected late in the circulation test, with that of benzoic acid and fluorescein, which were injected early, seems to show that formation changes occurred during the test, resulted in a modified interwell flow pattern but it can also be interpreted as an impact of the mass of tracer injected on the apparent adsorption coefficient. An analysis of the long tailing portion of the fluorescein return curve indicated an overall reservoir-fluid volume in the range of several millions of m^3 .

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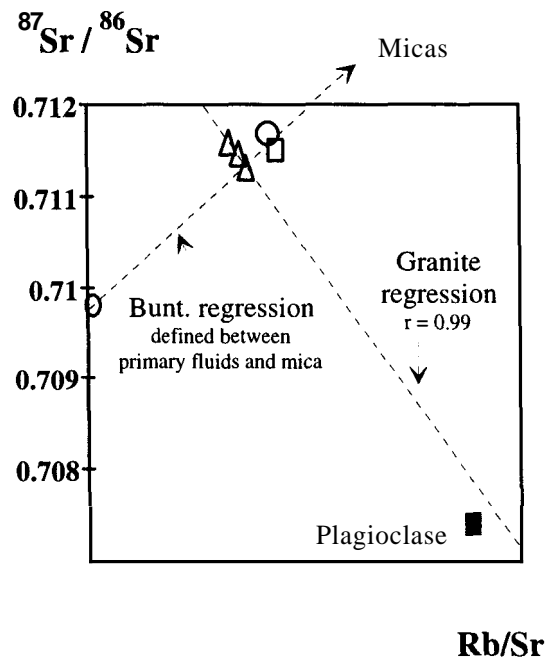


Figure Evolution of the strontium isotopic and the Rb/Sr ratios of the fluids in the Rhine graben and the Sultz site (Triangles : Sultz granite fluids, circles and square: Buntsandstein [Bunt.] fluids, black square granite mineral)

Benzoic acid and Deuterium (mg/l)

Fluoresceine ($\mu\text{g/l}$)

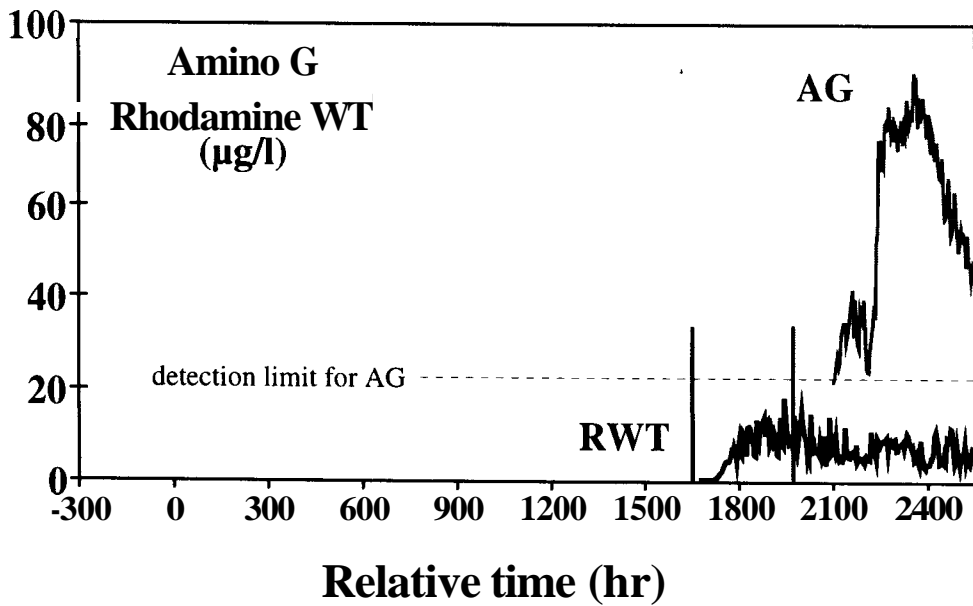
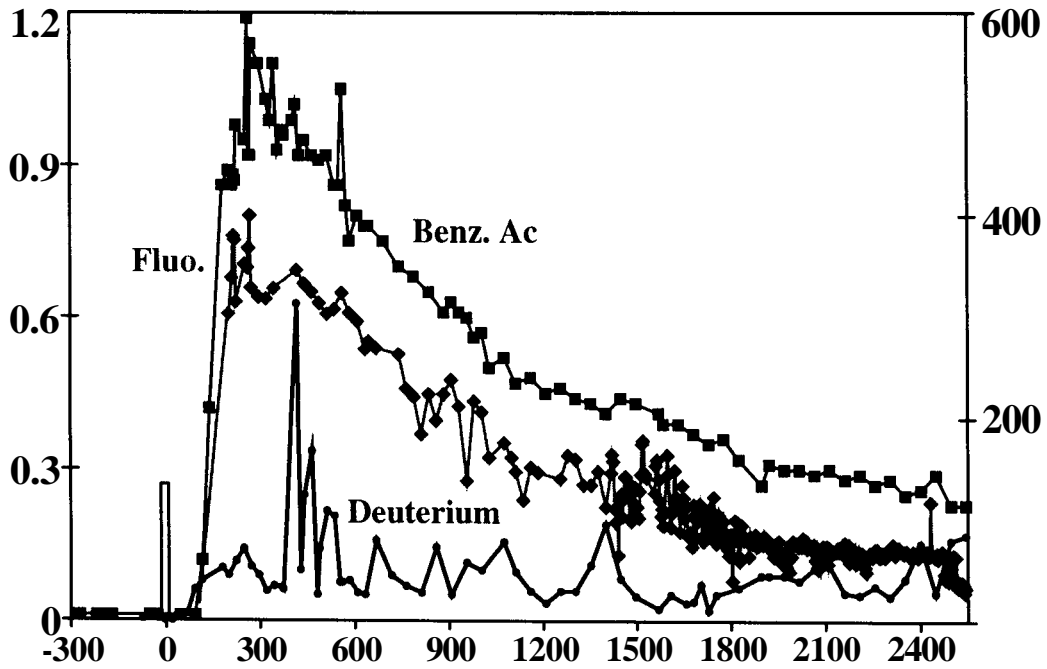


Figure 2 : Return curves for benzoic acid, fluorescein, deuterium, the three tracers used in the initial tracer test ; and for rhodamine WT and amino G, the tracers used in the second and third test.

Restitution curve normalized to the injected mass

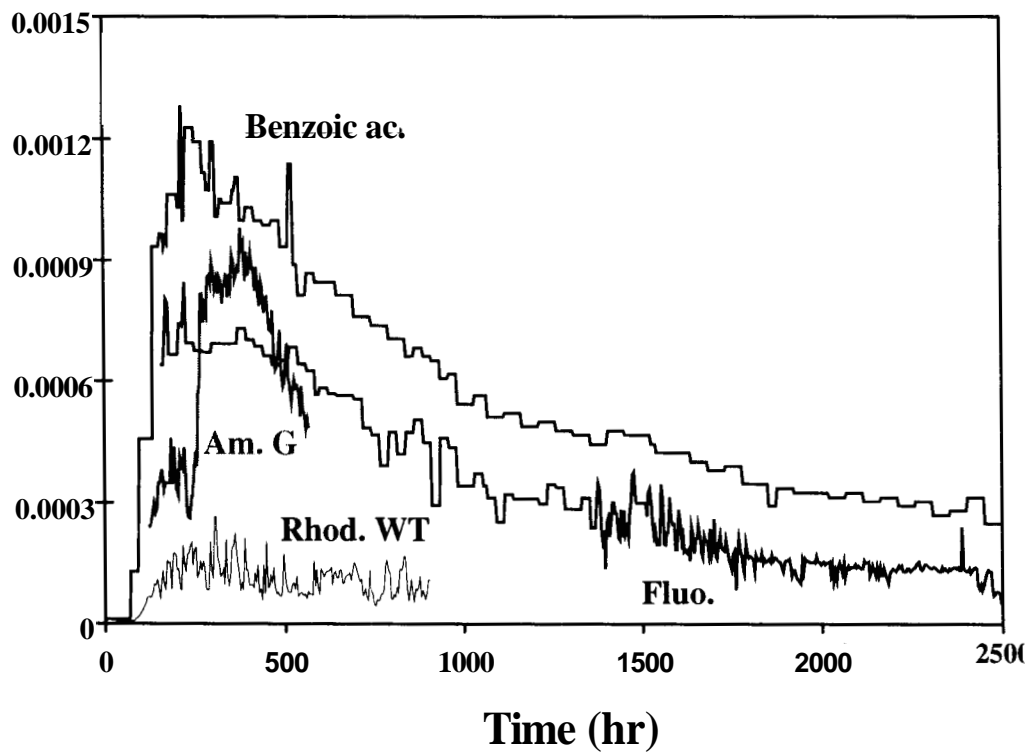


Figure 3 : Residence-time distribution functions for the tracers. Benzoic acid and fluorescein were injected during the first test, rhodamine and amino *G* were used in the two later tests.