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FLUID-ROCK INTERACTIONS IN HOT DRY ROCK RESERVOIRS. A REVIEW OF THE HDR SITES AND DETAILED INVESTIGATIONS OF THE SOULTZ-SOUS-FORETS SYSTEM.

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ABSTRACT

The European Hot Dry Rock programme is located in the Rhine Graben at Soultz-sous-Forêts. Two deep boreholes (GPK1and GPK2) were drilled in fractured granite to depths of 3590 and 3876 m, respectively, reaching temperatures between 150 and 170°C. Separated from each other by a horizontal distance of 450 m, the two wells were tested in 1997. A four-month circulation test with a permanent flowrate up to 25 kg/s provided thermal, hydraulic and geochemical data from the Soultz system. Since this test, one of the wells (GPK2) was deepened to 5,000m.

In order to model water-rock interactions, the following processes have to be defined, measured or analysed: minerals assemblages in contact with water, fluid composition, temperature evolution, pressure and flow rate in the different interaction zones, such as the porous matrix, small and large fractures.

Another goal of this work is to develop a geochemical model that will handle highly saline solutions (brines up to 100 g/l) at temperatures up to 200°C, and to include reactions. A new geochemical code is under development, based on CHEMTOUGH.

To acquire a better understanding of the geochemical processes taking place between the fluids and the fractured hot rocks, geochemical data from six different Hot Dry Rock reservoirs are reviewed. Saturation indexes are computed with the code PHREEQC. Using data from the Soultz reservoir, a thermodynamic model is developed based on a simplified Pitzer approach. The goal of the work is to use realistic assumptions to better constrain the model and to mitigate the lack of Pitzer parameters for the Soultz brine. Later, kinetic laws will be included in the model in order to couple reactions with transport.

1. INTRODUCTION

This study is carried out in the frame of the European research programme Joule 4, called European concerted action for the support of Hot Dry Rock geothermal energy R&D activities 1998-2001. This programme takes place in Soultz-sous-Forêts, northern Alsace, France, on the western edge of the Rhine Graben, about 50 km north of Strasbourg. This programme started in 1987 with the aim to extract energy from a hydraulically fractured, hot, granitic reservoir. No fresh water was injected after stimulation experiments and only the highly saline formation fluid was circulated. A 4-month flow test was carried out in 1997 to allow fluid circulation between GPK1 and GPK2 boreholes at a depth of 3200 to 3600 m. At their total depths, the two vertical wells are separated by 450 m. The flow rate was maintained at a rate of up to 25 l/s and the rock temperature ranged between 150 and 170°C. Wellhead temperature reached 142°C and all the fluid was cooled to about 65°C without degassing before reinjection at depth. Since this test, one of the former production well (GPK2) was deepened to 5,000m where the rock temperature reaches 200°C (Gérard et al., 1999)

As part of the Swiss contribution to the Soultz programme, the project on which this paper is based is aimed toward the coupling of geochemical fluid-rock interactions to thermal, hydraulic, and mechanical processes. As the final goal of the Soultz programme is to build and to test a geothermal pilot power plant, it is mandatory to forecast the probable behaviour of the reservoir during exploitation. Prevision can be realised by numerical modelling as well as by laboratory experiments. In addition to temperature changes and thermo-mechanical contractions, a full model should also include geochemical fluid-rock interactions. This would allow an evaluation of both scaling and corrosion risks and the permeability decrease or increase within the fractured reservoir resulting from mineral deposition or dissolution.

Our goal is to set up a kinetic geochemical model of the geochemical fluid-rock interactions for the Soultz reservoir and then to couple some geochemical modules to the thermo-hydraulic simulator FRACTure in collaboration with the team of the Geophysical Institute of ETH-Zurich (Kohl & Hopkirk, 1995). To take advantage of the previous experience acquired from different HDR sites and projects, we have compiled selected published geochemical data from reservoir development and circulation experiments in various HDR reservoirs, including Bad Urach (Germany), Fenton Hill (USA), Hijiori and Ogachi (Japan), Rosemanowes (UK) as well as of course Soultz-sous-Forêts (France). This compilation forms the first part of this paper and is followed by the specific geochemical modelling of the fluids in Soultz. In this study, existing codes such as PHREEQC (Parkhust, 1995), PHRQPITZ (Plummer et al., 1988), EQ3/6 (Wolery, 1992) and TEQUIL (Duan et al., 1996) are used and a new geochemical code is under development, based on CHEMTOUGH (White, 1995).

2. REVIEW OF GEOCHEMICAL DATA FROM HOT DRY ROCK RESERVOIRS

Selected data for Bad Urach represent a fluid analysis from a bottom hole sample collected at a depth of 3325 m several weeks after completion of the borehole (Althaus, 1982; Dietrich, 1982; Stenger, 1982). No quantitative analyses exist for chloride and sulphate and no analysis were performed for bicarbonate and fluoride. Fenton Hill data are taken from a 3.5-month flow test (Winchester, 1993). Hijiori data are coming from a 3-month flow test, but no analyses are

available for magnesium, fluoride and aluminium (Matsunaga et al. 1995). Ogachi data originate from a sample collected at the end of a circulation test of 22 days (Kiho and Mambo, 1995). Magnesium, iron and aluminium contents are not available. Rosemanowes data are taken from a sample collected at the depth of 2780 m, after a circulation test (Richards et al., 1992). Soultz-sous-Forêts data issue from a wellhead sample taken at the end of a 4-month circulation test (Jacquot, 2000). Bicarbonate concentration was computed in equilibrium with calcite for reservoir conditions.

All selected physical and geochemical data are synthesised in Table 1 and Table 2 . Fluid saturation indexes are computed with PHREEQC for the most frequently encountered minerals in this type of fractured reservoirs. The calculations were done at the fluid production temperature, except for Soultz for which the rock temperature was considered. For Fenton Hill, Hijiori and Ogachi sites, missing data such as chemical analyses, pH and redox potential allowed only a certain approximation of the fluid chemistry. For the case of Soultz, available data are sufficient but the formation fluid is a brine with a total dissolved solids of over 100 g/kg therefore, the theoretical validity of the PHREEQC model reaches its limit. The method used to estimate saturation indexes of Soultz fluid is discussed below. All the fluids being slightly oversaturated with quartz, the oversaturation increasing with the difference between production fluid and reservoir temperatures. The silica concentration in the production fluid is mostly governed by the maximum oversaturation possible with quartz. The heavy oversaturation in iron oxides and oxi-hydroxides for the Fenton Hill and Rosemanowes fluids indicates that the reservoir conditions are probably more acidic and reducing than those given by surface observations.

3. FLUID GEOCHEMICAL MODELLING OF THE BRINE IN THE SOULTZ-SOUS-FORETS RESERVOIR

Geochemical interactions in the Soultz-sous-Forêts fractured reservoir were described by Azaroual (1992) and Aquilina et al. (1997). It has been shown that the fluids originate from a brine in Triassic sediments at the border of the Rhine Graben, diluted by a mature meteoric water that dissolves micas and sulphates in the Triassic Buntsandstein and in the granitic basement. Then, the fluids percolate into fractured granites, dissolving plagioclases and precipitating secondary minerals in veins such as quartz, illite, montmorillonite, calcite, dolomite and pyrite. Fluid-rock interaction modelling in the fractured reservoir of Soultz has been studied by Jacquot (1998), who pointed out the importance of the knowledge of mineral assemblages in contact with the fluid during the circulation. Indeed, the fluid flowing into the fractures is not in contact with fresh granite but with altered granite and newly formed minerals, such as clay minerals, representing almost 40% of this assemblage volume.

The first problem arising in modelling the geochemical behaviour of the Soultz brine is the lack of chemical data. Samples of the 1997 circulation test were completely analysed only 1.5 years after sampling and can not inform about the original dissolved CO_2 and the distribution between sulphates and sulphides. Physico-chemical parameters such as redox potential and pH, even if measured on site, can significantly differ from real values at depth and moreover, aluminium analyses are not reliable in such fluids. Therefore, it is necessary to present realistic assumptions such as the thermodynamic equilibrium of the fluid with the mineral assemblage observed in the veins.

The second problem, already mentioned before, comes from the high salinity of the fluid (TDS >100 g/kg). Most of the models used to calculate geochemical equilibrium in solution consider the concept and the formula of Debye-Huckel to calculate activity coefficients of the aqueous species. The validity domain of Debye-Huckel formula extends to an ionic strength of 0.8, whereas the ionic strength of the Soultz brine goes beyond 1.5. For this type of fluid, a calculation method based on the Pitzer equations is more correct (Harvie et al. 1984).

A parallel modelling of the speciation in solution for the Soultz brine was carried out at different temperatures with the codes PHREEQC for the Debye-Huckel concept and TEQUIL for the concept of Pitzer. The results show that the difference of the saturation indexes foreseen by these models can be really significant as shown in figure 1. Unfortunately, the use of Pitzer equations brings new problems. Firstly, they increase the complexity of the code and decrease the performances of the model. Secondly, the equations parameters are unknown for aluminium, and for some species, they are not available at temperatures in the range of 165°C and above. For the present study, it has been considered that chloride and sodium are the most influencing species in the calculation of the activity coefficients by the Pitzer equations. These two species are unlikely to vary due to fluid-rock interactions in the probable case of a closed circuit. It is therefore possible to start with an average fluid composition to calculate for each aqueous species an activity coefficient depending only on temperature. The chemical activity is then described as:

$$a_i = \gamma_i(T)*m_i$$

$$\gamma_i(T) = A_0+A_1T+A_2T^2+A_3T^3+A_4T^4$$

where a_i is the chemical activity of species i, γ_i its activity coefficient, m_i its molality, T the fluid temperature and A_i the coefficient determined in this study. Because of code performances and numerical stability of the model, it is necessary to simplify as much as possible the conceptual model. Therefore, only commonly observed minerals are taken into account and trace elements are not included in the model. Trace elements that are present in relatively large amounts are assimilated to other elements having a similar behaviour and a much higher concentration. For example, strontium is assimilated to calcium, being 30 times more concentrated, respectively. Similarly, bromide is assimilated to chloride (600 times more concentrated) and lithium is assimilated to sodium (50 times more concentrated).

Even with these simplifications, the determinations of the $\gamma_i(T)$ functions remain dependent of the current state of the hot brines modelling and the available analyses data. The primary code used in this study was TEQUIL which allows modelling of the H_2O-Na-K-Ca-H-Cl-OH-SO_4-HCO_3-CO_3-SiO_2-CO_2 system from 0 to 300°C. The first step was to estimate the concentration of the species not analysed. The total dissolved carbon was calculated by equilibrium with calcite at 165°C. The sulphate content given by the analyses leads to high anhydrite oversaturation at 165°C. Knowing that the Soultz altered granite contains almost no anhydrite but pyrite, the difference between the analysed sulphate and the equilibrium concentration with anhydrite was supposed to

represent the sulphide concentration. The activity coefficients of the species not included in TEQUIL, such as Mg, Fe, F and sulphide, were calculated at 25°C using EQ3/6 and at 165°C by equilibrium with dolomite, pyrite and fluorite. They were then interpolated for temperatures between 65°C and 200°C. The aluminium behaviour still remains uncertain as the only accurate assumption is its equilibrium with montmorillonite and K-feldspar at 165°C. Its molality and the $\gamma_{Al}^{+++}(T)$ function where extrapolated. This activity coefficients calculation method has been introduced in CHEMTOUGH.

The thermodynamic model allows the fluid saturation indexes to be calculated for different minerals. However, saturation does not automatically bring precipitation, because for every mineral there is a maximum oversaturation index below which it does not precipitate. This oversaturation index can widely vary for a given mineral, as a function of the physical conditions (pressure, temperature), as well as suitable mineral deposition sites. Additionally, some reactions can be just too slow to be interesting for our study or can be totally superseded by faster reactions. To build a model coupling transport and reaction, the dissolution kinetics must be taken into account and the available reaction surfaces must be estimated. After being tested with CHEMTOUGH, the geochemical model should be coupled with FRACTure (Kohl et al. 1995), which adds thermo-elasticity and turbulent flows modelling. This part of the project will be carried out by D. Baechler (Inst. of Geophysics, ETH-Zurich).

During the recent deepening of the production well GPK2 in Soultz, mineral scaling was collected on the internal wall of the deep casing. On most of the casing there was only a thin layer which can possibly have been deposited after the circulation test, but at the diameter increase of the casing, the amount of mineral deposit is more important. These deposits were analysed and are registered in an unpublished report of the Laboratoire de Géochimie et Métallogénie de l'Université P. et M. Curie in Paris. They are composed of quartz, calcite, aragonite, siderite, as well as iron oxides and iron hydroxides. The precipitation of the carbonates can be due to local degassing of CO_2, even if they are undersaturated in the fluid at temperatures below 165 °C. The precipitation of other minerals can be explained by a drop of critical oversaturation indexes. Moreover, limited deposits of galena (lead sulphide) were observed in the surface heat exchanger during the 4-month flow test.

4. CONCLUDING REMARKS

Presently we are working on modelling the kinetics of the reaction. We are also using the CHEMTOUGH code as a new method of calculating activity coefficients. It is planned to carry out the first kinetic simulation in a few months, followed by testing of the coupled model before the end of 2000. The elaboration of these coupled processes modelling aims first to understand reservoir evolution and behaviour during future long-term flow tests in Soultz-sous-Forêts. Moreover, geochemical brine modelling can be useful for future Enhanced Geothermal Systems where hot brines circulate as a closed loop in fractured crystalline basement.

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Table 1: Compilation of selected physical and chemical data from six Hot Dry Rock reservoirs

HDR SITES	Bad Urach	Fenton Hill	Hijiori	Ogachi	Rosemanowes	Soultz-sous-Forêts
Rock type	Metatexite occasionally altered along joins and veins	Biotite granodiorite	Granodiorite widely altered	Granodiorite altered along the cracks	Granite occasionally altered along joins and veins	Granite altered along the veins
Reservoir depth (m)	3300	3500	2200	711~719 & 990~1027	2400	3200~3600
Well	Urach 3	EE-2	HDR-3	Production well	RH15	GPK-2
Well depth (m)	3325	4010	2303	1100	2780	3876
Sampling date	1978	27-Jul-1992	November 1991	1993	15-Aug-1988	16-Nov-1997
Production test	None (a)	3.5 months	3 months	22 days	5.5 months	4 months
Type of sample	Downhole	Wellhead	Wellhead	Wellhead	Downhole	Wellhead
Injected fluid	None (a)	Fresh water closed loop	Fresh water	Fresh water	Fresh water (TDS < 0.1 g/kg)	Formation fluid
Rock temperature (°C)	143	327	250-270	170-230	99.8	165
Fluid temperature (°C)	143	182	167	108	99.8	142
pH	4.2	na	na	na	8.8 (25°C)	4.8
Redox potential (mV)	na	na	na	na	na	~ -250
TDS (g/kg)	na (~ 2.5)	3.434	1.4	1.25	0.419	101

TDS : Total Dissolved Solids
na : data not analysed or not available

Table 2: Compilation of fluid composition and computation of saturation indexes for six fluids from Hot Dry Rock reservoirs

SITES	Bad Urach	Fenton Hill	Hijiori	Ogachi	Rosemanowes	Soultz-sous-Forêts
Fluid composition (mmol/kg)						
Na	24.3	39.1	13	13	4.38	1064
K	4.09	2.28	3.3E-1	0.45	8.72E-2	86.6
Ca	3.75	0.449	9E-1	0.1	0.344	172
Mg	1.85E-2	4.11E-03	na	na	3.29E-3	5.81
Cl	Large amount	26.9	5.3	1.4	2.06	1564
SO_4	Present	3.93	5.2E-1	1.6	0.775	2.35
HCO_3	na	9.64	1.8	9.2	1.21	*2.42*
F	na	0.895	na	0.35	0.599	0.21
SiO_2	2.61	7.06	4	2.7	1.09	2.33
Fe	1.98	1.43E-02	na	na	3.94E-4	0.537
Al	2.15E-2	4.45E-02		na	7.41E-3	<1.5E-2
Saturation Indexes						
Quartz	nc	0.31	0.15	0.46	0.10	0.03
K-Feldspar	nc	-0.94	nc	nc	-2.24	0 (b)
Na-Feldspar	nc	-1.01	nc	nc	-2.38	-0.39
Ca-Feldspar	nc	-0.53	nc	nc	-2.05	-3.33
Pyrite	nc	<-45	nc	nc	-41.26 (a)	0 (b)
Anhydrite	nc	0.16	-0.21	-1.87	-1.70 (a)	0 (b)
Calcite	nc	0.76	0.57	-2.50	0.40	0 (b)
Dolomite	nc	-2.95	nc	nc	-1.37	0 (b)
Fluorite	nc	-0.16	nc	-1.18	-0.09	0 (b)
Siderite	nc	-3.75	nc	nc	-1.72 (a)	nc
Hematite	nc	14.21	nc	nc	12.72 (a)	nc
Goethite	nc	5.86	nc	nc	5.22 (a)	nc
Illite	nc	-3.03	nc	nc	-3.70	nc
Montmorillonite	nc	-2.73	nc	nc	-3.23	0 (b)

HCO_3 content in italic indicates recalculated data
na : data not analysed or not available
nc : computation not possible with available data
a : computed with an arbitrary redox potential of 0 mV
b : by definition of the fluid model

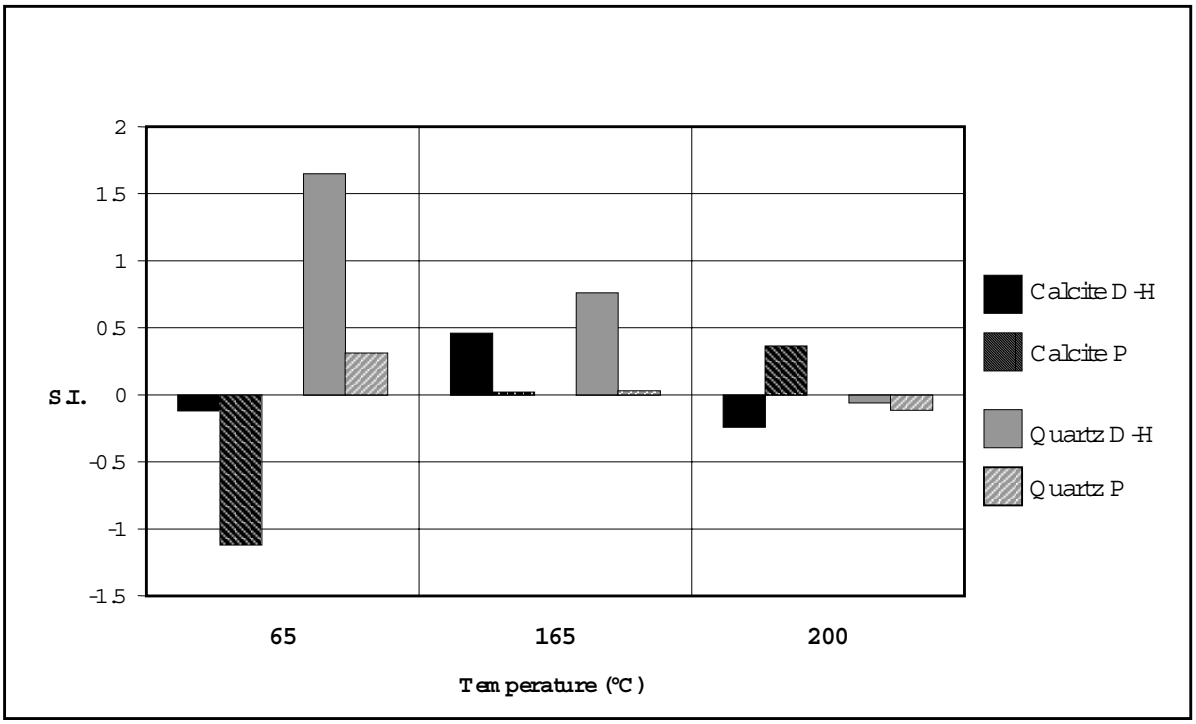


Fig.1 Comparison between saturation indexes (S.I.) calculated with Debye-Huckel (D-H) and Pitzer (P) formalism