Schweizerische Eidgenossenschaft
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Bundesamt für Energie BFE

Schlussbericht August 2009

Studies and support for the EGS reservoirs at Soultz-sous-Forêts

April 2004 – May 2009

Auftraggeber:
Bundesamt für Energie BFE
Forschungsprogramm Geothermie
CH-3003 Bern
www.bfe.admin.ch

Kofinanzierung:
Staatssekretariat für Bildung und Forschung SBF
CH-3003 Bern
www.sbf.admin.ch

Auftragnehmer:
Deep Heat Mining Association, c/o Häring GeoProject
Im untern Tollacher, CH-8162 Steinmaur

Autoren:
Sandrine Portier
François-D. Vuataz
CENTRE DE RECHERCHE EN GEOTHERMIE CREGE
Rue Emile-Argand 11
CH-2009 Neuchâtel
www.crege.ch

BFE-Bereichsleiter: Gunter Siddiqi
BFE-Programmleiter: Rudolf Minder
BFE-Vertrags- und Projektnummer: 152'769 / 102'187

EGS Pilot plant

6th FP of the European Commission – EC Contract N°SES6-CT-2003-502706

Project financed by
State Secretariat for Education and Research — SER/SBF
Swiss Federal Office of Energy — OFEN/BFE

Studies and support for the EGS reservoirs at Soultz-sous-Forêts

Final report April 2004 – May 2009

Edited by Sandrine Portier and François-D. Vuataz

Centre for Geothemal Research - CREGE, c/o CHYN, University of Neuchâtel, Switzerland

The assembled contributions of all members of the Swiss EGS R&D group

Keith Evans[1,2], Benoît Valley[1,3]

[1] Engineering Geology, Swiss Federal Institute of Technology (ETH), Zurich

[2] Keith Evans Consulting, Zurich

[3] presently at MIRARCO (Laurentian University), Canada

Markus Häring

Häring GeoProject, Steinmaur

Robert J. Hopkirk

Polydynamics Engineering, Männedorf

Clément Baujard, Thomas Kohl, Thomas Mégel

GEOWATT AG, Zurich

Laurent André[4,5], Sandrine Portier[4], and François-D. Vuataz[4]

[4] Centre for Geothermal Research, c/o CHYN, University of Neuchâtel

[5] presently at the BRGM, Orléans, France

August 2009

Impressum

Date : August 2009

Project: EC Soultz project N° SES6-CT-2003-502706

Realisation : Swiss EGS R&D Group

Financing : State Secretariat for Education and Research (SER/SBF) and Swiss Federal Office of Energy (OFEN/BFE)

Address and coordinates :

Deep Heat Mining Association, c/o Häring GeoProject

Im untern Tollacher, CH-8162 Steinmaur

Tél. +41 44 854 00 74

haring@geothermal.ch

Citation :

Portier S. & Vuataz F.-D. (eds.), 2009. Studies and support for the EGS reservoirs at Soultz-sous-Forêts. Final report April 2004 – May 2009. Project financed by State Secretariat for Education and Research (SER/SBF) and Swiss Federal Office of Energy (OFEN/BFE).

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Executive summary

Preamble

This report describes the work performed by the Swiss EGS R&D group involved in the EC Soultz project phase entitled: **Studies and support for the EGS reservoirs at Soultz-sous-Forêt.** This project, part of the 6th FP of the European Commission (EC Contract N°SES6-CT-2003-502706), started on April 1, 2004 and lasted until May 31, 2009. The principal declared target set for the current phase of the integrated European geothermal project at Soultz-sous-Forêts (Alsace, France), was to install and operate a power plant, enabling the deep reservoir / heat exchanger to be operated, evaluated and improved under realistic conditions.

The Deep heat Mining Association (ADHM), c/o Häring GeoProject at Steinmaur , was acting as an Assistant contractor to the EEIG Heat Mining and the partner No 6 within the EC project, representing the Swiss EGS R&D team. This group included subcontractors: GEOWATT AG, Engineering geology at ETH-Zürich, Keith Evans Consulting, Polydynamics Engineering, Häring GeoProject and the Centre for Geothermal Research (CREGE) at the CHYN (University of Neuchâtel). The financing of the Swiss scientists was entirely funded by the State Secretariat for Education and Research and by the Federal Office of Energy. The Swiss scientists have been participating to several Work Packages as defined by the EC project:

WP 1 : Short- and medium-term tests of the 3-well reservoir/heat exchanger system

WP 2 : Long term tests of the 3-well reservoir/heat exchanger system

WP 3 : Development and upscaling: technical and economic design of larger industrial EGS units

WP 5 : Methodology of stimulation for EGS

The results of this project phase are gathered within six main sections written by the different scientists of the Swiss EGS R&D group:

Section 1: Exchange of findings by M. Häring

Section 2: The “state of the art” of EGS stimulation methods by R. Hopkirk

Section 3: Interpretation of logging data from the deep reservoir at Soultz by K. Evans and B. Valley

Section 4: Seismo-hydraulics studies by K. Evans

Section 5: Evaluation of the production/injection performance of the boreholes and reservoir development strategies by C. Baujard, T. Mégel and T. Kohl

Section 6: Modelling geochemical impact of forced fluid circulation in the deep geothermal reservoir and results of chemical stimulation tests performed on site by S. Portier and F.-D. Vuataz.

The publication/communication materials derived from the performed works –that are available- are listed and referenced at the end of the document. A CD-R clipped on the back cover contains the pdf files of the final report and additional materials.

Section 1: Exchange of findings

The contribution of Häring GeoProject (HGP) concentrated on liaisons with national and international energy producers in order to keep track with industry demand in the field of EGS R&D and to build up and maintain contacts with industry research groups. HGP has established regular contacts with key players in the Swiss, German and Australian energy industry. The feedback from these sources is, that industry is well aware of the limited potential of hydrothermal developments, and that the really large potential of geothermal resources lies in EGS.

Section 2: The "state of the art" of EGS stimulation methods

The contribution of Polydynamics Engineering has been focused on the state of knowledge and understanding of how an underground heat exchanger can be created within a deep, hard rock formation by favourably modifying the hydraulic conductivity of existing and potential fluid flow paths through the rock mass. The work performed has taken the form of a deliverable report that gives an overview of how this "stimulation" process has developed as a result of the work at the European research site near Soultz-sous-Forêts between 1987 and 2007.

It was originally scheduled for issue at the end of the first year of the current project phase (i.e. in the Springtime of 2005), but it was felt that since so much activity was still necessary to connect the three deep 5000 m boreholes to a satisfactory degree, it could only fulfil its purpose if the experiences from the extended activity could also be described. The vast amount of data generated during the project has still not been fully analysed and some of the analysis work is still continuing.

This is not a scientific paper, rather taking the form of a brief history of the international EGS research and development, relating the background knowledge of geothermal stimulation – effectively the state of the art - at the start of the Soultz project. This is completed by a survey of the lessons learned at Soultz. Together, these blocks of information result in the current state of understanding and are accompanied by projections of some future needs and possible trends. However, there are citations to bibliography and several Appendices.

The Appendices contain scientific publications, based upon work done on behalf of the Soultz project, which are relevant to the stimulation theme and which help to improve the perspective view. In order to be able fulfil this latter condition, the texts included have all been written in the last five years.

Section 3: Interpretation of logging data from the deep reservoir at Soultz

The work conducted by Engineering Geology, ETH Zürich has been focussed on the analysis of sonic borehole images obtained from GPK3 and GPK4. The objective was to improve our understanding of natural fracturing of the Soultz reservoir, and to constrain the in situ stress state from the analyses of breakouts and drilling induced tension fractures that occur over extensive sections of the boreholes. Results provide the identification of multi-scale fracturing in the Soultz-sous-Forêts basement, the linear characterisation of the state of stress to 5 km depth, the stress heterogeneity within the Soultz granite (i.e. the deviations of stress orientation from the linear trends) as deduced from variations in the orientation of wellbore failure and the laboratory measurement of the uniaxial compressive strength of the Soultz granite.

Fractures imaged on sonic televiewer logs run in deep boreholes GPK3 and GPK4 were analysed. Particular attention was paid to the sections above 2000 m where the holes are less than 20 m apart. Four major sets of fractures were identified on the basis of orientation. Fractures had mean true sizes of 15 to 40 m diameter. Spacings appeared to follow log-normal laws with arithmetic mean values of 1 to 6 m. The distribution of fractures along the wells shows distinct clustering, reflecting the intersection of the well with fracture zones composed of an anastomosed network of fractures delimiting shear lenses. Large variations in both the internal structure and the thickness of fracture zones occur over distances of 10 to 20 m. These variations are believed to have a significant influence on the hydraulic behaviour of the zones by channelling the flow. The spacings of the fracture zones range from 40 to 400 m. The size of such structures cannot be specified with our data set. Microseismic imaging shows they can extend over distances of several hundred metres.

Observations of breakouts and drilling-induced tension fractures (DITFs) in two 5 km deep boreholes of the European Enhanced Geothermal Project of Soultz-sous- Forêts, France, were combined with the analysis of pressure data from stimulation tests in all 3 deep wells to obtain a description of the state of stress in the granite down to 5 km depth. The orientation of the maximum horizontal principal stress was found to be at 169°±14°. The magnitude of the minimum principal horizontal stress in the lower reservoir lay on the linear trend defined from stress tests above 3.5 km. The magnitude of the maximum principal horizontal stress was constrained using the distinct depth ranges where tensile (i.e. DITFs) and compressive (i.e. breakouts) failure occurred. The resulting constraints on SHmax magnitude support the conclusion derived from the appearance of both normal and strike-slip fault plane solutions of induced microseismic events that SHmax = 1.0Sv.

Stress heterogeneity was studied by examining the deviation of the orientation of SHmax from the mean direction. Stress variations were seen to occur at all scales and follow a self-affine scaling law. Examination of short-wavelength (<50 m) variations of the DITF orientations in the sections where the wells are about 20 m apart shows that they are correlated with natural fractures, but usually not correlated between wells. This suggests that fractures are for the most part not much larger than 40 m in diameter, in agreement with the results of the study of fracture size. Large wavelength variations are also seen and are principally associated with fracture zones.

Uniaxial compressive strength (UCS) and static Young's modulus tests were performed on 12 samples of Soultz granite having different degrees of alteration. UCS values ranges from 100 to 130 MPa for unaltered granite, and were unaffected by the strength of the pervasive alteration. Samples with weak vein alteration had UCS values that lay near the lowest values measured for the samples that had only pervasive alteration, and one sample that had high vein alteration had a UCS about 8 MPa lower than this. The Young's modulus of 'unaltered' Soultz granite was found to be 54±2 GPa, regardless of the degree of pervasive alteration. However, two samples with vein alteration showed a significantly lower modulus of 39 GPa.

Section 4: Seismo-hydraulics evaluation

The work carried out by Keith Evans Consulting concerns three research themes: evaluation of the state of stress in the Soultz granite to 5 km depth, petrophysical properties of the Soultz granite from laboratory tests; and source parameter studies of the microseismicity generated during the 1993 injections at Soultz.

Estimates for the magnitude of the minimum principal horizontal stress, Shmin, in the lower reservoir at Soultz were obtained from analysis of the downhole pressure records of the first hydraulic stimulations of the three wells penetrating the lower reservoir. The results indicate Shmin levels that lie on the extrapolation of the linear trends defined from tests conducted above 3.6 km.

The petrophysical properties of the Soultz granite were investigated by mineralogical analysis and poro-elastic testing of three samples: two with pervasive alteration and one with vein alteration. The density of all samples lay in the range 2.65-2.70 gm/cc, and connected porosity at atmospheric pressure was measured as 0.25-0.30%. Cyclical loading of the saturated samples to 70 MPa under partially-drained conditions in a testing machine indicated that the Biot's coefficient at atmospheric pressure was approximately 0.5, and that it declined with increased confining stress, perhaps to as low at 0.1 at 70 MPa effective confinement. The precise pressure dependence was somewhat uncertain owing to an increasing degree of undrained conditions at high stress due to decreasing permeability.

Source parameters of microearthquakes induced during the first stimulation of the upper reservoir at Soultz were used to evaluate the spatial variation of the b-value of the Gutenberg-Richter magnitude-frequency relation within the reservoir. Significant variations in value from 0.8 to 1.2 were found. Regions with lower b-values tended to host larger magnitude events and, provisionally, higher stress-drop events.

The Soultz administration had requested that K. Evans serve as chairperson of the newly-conceived Seismo-hydraulics working group at Soultz. Since its inception in April 2005, there have been seven meetings of the seismo-hydraulics working group. The objective of the workgroup was to provide a forum to discuss issues of contention in the interpretation of seismic and hydraulic data. Thus, most meetings featured focussed discussion of a couple of themes. However, in the past year, the focus has changed towards the production of summaries documenting the progress, accomplishments and lessons-learned in seismics and hydraulics since work began at Soultz in 1987.

Section 5: Evaluation of the production/injection performance of the boreholes and reservoir development strategies

The works performed by GEOWATT AG consist in evaluations of performances of the borehole of the Soultz project and of an evaluation of conducted reservoir development strategies. Numerical code development and prediction of stimulation results were also conducted. Special attention was paid to the evolution of the borehole injectivity/productivity indexes, which is quantified, using the borehole simulator HEX-B and characterized, using the reservoir simulator HEX-S. It appeared that the injectivity/productivity indexes of the boreholes GPK3 and GPK4 almost continuously increased during the last 3 years, thanks to the multiple stimulation campaigns realised in the reservoir of the Soultz-sous-Forêts site.

A major task during an EGS reservoir development is the evaluation of the success of specific stimulation activities. Typically the so-called productivity index PI and injectivity index II is used to characterise the hydraulic performance of a borehole. These values have been supplied in the units "litres/second/MPa" and are derived from hydraulic tests, where the pressure at reservoir depth is needed. If downhole data are not available the downhole pressure at reservoir depth must be calculated using wellhead data. This was done with the borehole simulator HEX-B which takes into account the dynamic change of fluid density in the borehole due to the time history of fluid salinity and temperature exchange with the borehole wall during hydraulic tests (Mégel, 2005). Most of the hydraulic tests conducted within this project period have been evaluated. An extended version of the software, called HEX-B2, is installed at Soultz for on-site use.

The crucial task in the development of a subsurface heat exchanger is the controlled creation of permeability in a given host rock. In close vicinity of a borehole the permeability of fractures can be improved by acidification. However, to achieve in a volume of several hundred meters diameter a sufficient permeability, the method of hydraulic over-pressurising of existing fractures and bringing them to fail is seen as the most promising technology. Hydraulic stimulation of existing fractures is a massive intervention into a local physical equilibrium. Therefore the development of instruments and methods for planning stimulation strategies is of paramount importance. The understanding of the dynamic hydro-mechanical processes in a fractured reservoir is essential for the development of tools with predictive capabilities. In the framework of this project phase the reservoir stimulation code HEX-S has been used (Kohl & Mégel., 2007). Two purposes have been pursued: first the evaluation of the codes effectiveness to predict stimulation processes and second the evaluation of the stimulation concept proposing the simultaneous injection into both boreholes (dual injection).

Another part of the reservoir modelling was focused on the code FRAChem, an adaptation of the numerical code FRACTure allowing hydro-chemical transport processes computations. This activity was developed with the CREGE. The main effort of GEOWATT AG included modifications of the numerical meshes of FRACHEM code to improve the calculation time and the treatment of complex geometries.

The Soultz Working group Modelling WG 5, constituted of different European research teams working on reservoir modelling, was chaired by Thomas Kohl since 2005. The purpose of this working group was to share information and data, and to exchange points of view on reservoir processes and mechanisms and to discuss different simulation approaches. The Working group usually met once a year. Some publications concerning modelling efforts in Soultz have been published by the entire Modelling Workgroup. For example, contributions of the working group were presented at two EHDRA meetings during the last years (Baujard et al., 2007; Kohl and Baujard, 2008). One of the most important activities is the position paper for the EU (Baujard et al., 2008) with milestones of the past efforts and future perspectives of the modelling at Soultz.

Section 6: Modelling geochemical impact of forced fluid circulation in the deep geothermal reservoir and results of chemical stimulation tests performed on site

In order to forecast the behaviour of an enhanced geothermal reservoir under exploitation, interaction between flow, heat transfer, transport and chemical reactions must be evaluated. For this purpose, coupled reactive transport modelling can provide useful information, by simulating chemical reactions likely to occur in the system coupled to reactive transport, at large time and space scales. FRACHEM, a thermo-hydraulic-chemical coupled code, was developed especially to forecast the evolution of the EGS project at Soultz-sous-Forêts, Alsace (France).

Geochemical simulation with the code FRACHEM has been pursued by the CREGE (c/o CHYN, Univ. of Neuchâtel). The main task is to forecast the behaviour of the Soultz fractured reservoir during short-term fluid injection - production operations. This code FRACHEM has been implemented with new minerals and some capabilities have been added to the code. Simulation of porosity and permeability evolution were carried out for short and long time periods, all along the fractures between the injection and the production wells. During the simulation of fluid circulation, the coupled processes of a single and also two fractured zones between two wells were investigated to predict the geochemical evolution and to quantify the impact on the reservoir. Results of numerical simulations for a long-term circulation confirm the role played by carbonates on the evolution of reservoir porosity and permeability. Due to their fast reaction rates, carbonate minerals are responsible for most of the reservoir evolution. Silicates and pyrite behaviour is also simulated between two wells, but their influence on the permeability evolution of the fracture zone is minor.

Benchmarking between FRACHEM and TOUGHREACT, as well as between FRACHEM and SHEMAT have shown that the three codes give modelling results in a rather good agreement.

Finally, a review of the chemical stimulation methods in geothermal wells has been realised and the effects of chemical treatments performed in the Soultz wells have been simulated.

Additional material

The publication/communication materials derived from the performed works –that are available- are listed and referenced at the end of the document.

Introduction

This project, part of the 6th FP of the European Commission (EC Contract N°SES6-CT-2003-502706), started on April 1, 2004 and lasted until May 31, 2009. The phase of the European geothermal project at Soultz-sous-Forêts, entitled “EGS Pilot Plant”, started in April 2004 for a period of three years, with an extension of 18 months. The EC project was managed by an industrial consortium (EEIG Heat Mining) and nine scientific partners from France, Germany, Norway and Switzerland were taking part. The principal declared target set for the current phase of the integrated European geothermal project at Soultz-sous-Forêts (Alsace, France), was to install and operate a 1.5 MWe power plant, enabling the deep reservoir / heat exchanger created during the period 2001–2003 to be operated, evaluated and improved under realistic conditions. However, on the site of Soultz-sous-Forêts, successive delays during the programme did not make possible to carry out the planned long-term circulation tests and restricted the possibility to obtain exploitation data to calibrate the simulation results obtained by the numerical models.

The Deep heat Mining Association (ADHM), c/o Häring GeoProject at Steinmaur , was acting as one of the nine Assistant contractors to the EEIG Heat Mining and the partner No 6 within the EC project, representing the Swiss EGS R&D team. This group included subcontractors: GEOWATT AG, Engineering geology at ETH-Zürich, Keith Evans Consulting, Polydynamics Engineering, Häring GeoProject and the Centre for Geothermal Research (CREGE) at the Centre of Hydrogeology of the University of Neuchâtel. The financing of the Swiss scientists was entirely funded by the State Secretariat for Education and Research (SER, Project OFES No 03.04.60) and by the Federal Office of Energy (OFEN/BFE, Project No 150’649). The Swiss scientists have been participating to several Work Packages as defined by the EC project:

WP 1 : Short- and medium-term tests of the 3-well reservoir/heat exchanger system

WP 2 : Long term tests of the 3-well reservoir/heat exchanger system

WP 3 : Development and upscaling: technical and economic design of larger industrial EGS units

WP 5 : Methodology of stimulation for EGS

The Deep Heat Mining Association (Partner 6) was team leader of the Swiss EGS R&D Group and coordinator of the Work Package 5 (Methodology for stimulation of EGS).

DHMA’s main activities during this project have included active participation in the EHDRA (European Hot Dry Rock Association), which is responsible for driving the scientific activities and their quality control during the project and participating in three working groups (WG1 “Corrosion and Scaling”, WG4 “Seismo-hydraulics” and WG5 “Modelling”), the coordination of the Swiss EGS R&D Group activities, as well as the accounting and the administrative work. As in the previous project phase, some efforts were also put into collecting and archiving of data from present and previous HDR/EGS projects.

During this project phase, interesting scientific progresses were realised and new applied methods were developed. Simultaneously, a particular effort was made to transfer the knowledge to the scientific community, by means of participations to congresses, publications in their proceedings and papers in specialized journals.

Moreover, a PhD thesis started at the beginning of this phase has been achieved:

Valley B., 2007. The relation between natural fracturing and stress heterogeneities in deep-seated crystalline rocks at Soultz-sous-Forêts (France). Ph.D. thesis, ETH-Zurich, N° 17’385.

During this project, the Swiss scientists participated to several congresses and workshops, where they presented papers and posters, i.e. but not exclusively:

Annual Meetings of the Geothermal Resources Council, USA;

Annual Workshops on Geothermal Reservoir Engineering, Stanford, USA;

Annual EHDRA Scientific Meetings, Soultz-sous-Forêts, France;

European Geothermal Conference, EGC2007, Unterhaching, Germany;

World Geothermal Congress WGC2005, Antalya, Turkey.

Finally, several articles were published in scientific journals such as Geophysical Journal International, Geothermics and Journal of Geophysical Research.

Composition of the Swiss EGS R&D group

Institution	**Scientists**	**Work Packages**
Deep Heat Mining Association (DHMA), Steinmaur (Participant No 6) Häring Geoprojekt Polydynamics Engineering CREGE	 Dr Markus Häring Dr Robert Hopkirk Dr François-D. Vuataz	Administration, Co-ordination WP 3 WP 5
Engineering Geology, ETH-Zurich	Benoît Valley, PhD student (until August 2007) Dr Keith F. Evans	WP 5
Keith Evans Consulting, Zurich	Dr Keith F. Evans	WP 5
GEOWATT AG, Zurich	Dr Clément Baujard Dr Thomas Kohl Dr Thomas Mégel	WP 1 WP 2 WP 3 WP 5
Centre of Hydrogeology, University of Neuchâtel (CHYN) and Centre for Geothermal Research (CREGE)	Dr Laurent André, Postdoctoral scientist (until February 2006) Dr Sandrine Portier, Postdoctoral scientist (since February 2006) Dr François-D. Vuataz	WP 1 WP 2

Under the title **Studies and support for the EGS reservoirs at Soultz-sous-Forêts**, this report encompasses numerous tasks and methods around the fields of geology, geophysics, geochemistry, numerical modelling and reservoir engineering. The results are gathered within six main sections written by the different scientists of the Swiss EGS R&D group:

Section 1: Exchange of findings by M. Häring

Section 2: The "state of the art" of EGS stimulation methods by R. Hopkirk

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Section 1: Contribution from Häring GeoProject

The contractual part of Häring GeoProject (HGP) was limited to administrative and legal tasks, which could be fulfilled with minimal expenditure.

Since the start of the project in 2003, the Swiss Federal Office of Energy (SFOE) has contributed a total of CHF 666'000.-. by end of 2008, which is 93% of the total SFOE commitment of CHF 714'000.-. The total project budget is 1.71 Mio CHF, to which the State Secretariat for Education and Research (SER) contributes 1 Mio CHF.

By the end of 2008 1.41 Mio CHF have been paid out to the individual researchers and institutions. A comprehensive audited financial report will be presented after completion of all project related works.

HGP was not meant to provide scientific work. The contribution of HGP concentrated on liaisons with national and international energy producers in order to **keep track with industry demand in the field of EGS R&D** and to build up and maintain contacts with industry research groups.

HGP has established regular contacts with key players in the Swiss, German and Australian energy industry. The feedback from these sources is, that industry is well aware of the limited potential of hydrothermal developments, and that the really large potential of geothermal resources lies in EGS. This contrasts to vocal proclamations of smaller project development groups, particularly in Germany, which claim that the future of geothermal power production is a success story with hydrothermal systems alone.

Particularly the experiences in the Basel project demonstrate how difficult it can be to successfully stimulate a reservoir in tight formations. Despite the fact that the Basel project will be blocked politically for an undetermined length of time, the post stimulation flow tests that are being carried out in the course of 2009, will be of great importance for the understanding of reservoir creation processes. Most recent low rate production tests reveal that the hydraulic stimulation has increased the injectivity by 3 to 4 orders of magnitude! These results are preliminary and will be reviewed as soon as the remaining tests are concluded.

Beside Soultz-sous-Forêts, the other major EGS project with more than one deep well is the Habanero project of Geodynamics in South Australia. Sustained circulation tests have failed until now, but it has to be considered, that the Habanero reservoir is highly overpressured and circulation is difficult not because of poor productivity but because of the high pressures at surface. The contact with Geodynamics is well established by direct recurring visits of Keith Evans and HGP to their wells and/or offices.

The exchange of findings between the different project teams in France, Australia and Basel is not always straight forward, as there are investors which, on one hand, would like to protect their know-how, but on the other hand need the exchange with scientific institutions for a fruitful discussion and research. HGP strives to keep this exchange as open as possible.

Section 2: Contribution from Polydynamics Engineering

FOREWORD

The following report is a project deliverable (Report No.D6) entitled the "State of the Art" of EGS stimulation methods, written by R.J. Hopkirk for the Deep Heat Mining association. It is a required documentation associated with Work Package 5.

This report is intended to communicate an overview of the state of knowledge and understanding of how an underground heat exchanger can be created within a deep, hard rock formation by favourably modifying the hydraulic conductivity of existing and potential fluid flow paths through the rock mass. It should also give an overview of how this "stimulation" process has developed as a result of the work at the European research site near Soultz-sous-Forêts between 1987 and 2007.

It was originally scheduled for issue at the end of the first year of the current project phase (i.e. in the Springtime of 2005), but it was felt that since so much activity was still necessary to connect the three deep 5000 m boreholes to a satisfactory degree, it could only fulfil its purpose if the experiences from the extended activity could also be described. The vast amount of data generated during the project has still not been fully analysed and some of the analysis work is still continuing.

This is not a scientific paper, rather taking the form of a brief history of the international EGS research and development, relating the background knowledge of geothermal stimulation – effectively the state of the art - at the start of the Soultz project. This is completed by a survey of the lessons learned at Soultz. Together, these blocks of information result in the current state of understanding and are accompanied by projections of some future needs and possible trends. However, there are citations to bibliography and several Appendices.

The Appendices contain scientific publications, based upon work done on behalf of the Soultz project, which is relevant to the stimulation theme and which help to improve the perspective view. In order to be able fulfil this latter condition, the texts included have all been written in the last 5 years.

1. BACKGROUND AND HISTORICAL DEVELOPMENTS

1.1 Concepts

The first programme aimed at creating a man-made heat collection system in a deep, hard rock environment started some 35 years ago at Fenton Hill, New Mexico on a site situated on the edge of a caldera and were carried out by the Los Alamos Scientific Laboratory.

The experimental activities at Fenton Hill triggered interest in the concept of Hot Dry Rock geothermal energy, as it was then called, all over the World, resulting in research projects being pursued in:

Great Britain – Rosemanowes in Cornwall

Germany – Falkenberg and Bad Urach

Japan – Hijiori and Ogachi

France – Le Mayet-de-Montagne in the Massif Central

and in Sweden- Fjällbakka.

The attraction of HDR was that it offered a possible means of tapping into and exploiting the Earth's own vast geothermal heat store, not just in regions of volcanic anomaly, but anywhere.

The initial approach to extracting thermal energy from hot rocks was to create a flow path between two wells in the form of a large artificial fracture, and to use this as an underground heat exchanger. A heat extraction circuit would be completed by appropriate surface installations. Water would be injected at the surface into one well and recovered at the other. The underground heat exchanger, irrespective of its geometry, would have to exhibit two features: a large surface area for heat exchange between rock and water and a low hydraulic resistance to enable enough water to flow through and carry away the heat with an acceptably low pumping effort (see section 1.3). In this early concept the artificial fracture was to be generated and manipulated using techniques borrowed from the oil and gas industry, that is to say: hydraulic fracturing.

A first successful demonstration of power generation was made at the Fenton Hill research site using a flow path believed to consist largely of a pre-existing fracture zone connecting two wells and to which connections had been made. In this first project phase the inter-well connection was made easily, the system apparently reacting in a manner corresponding to the initial physical expectations and providing encouragement to move on towards deeper rock and higher temperatures.

Connections were indeed made later at greater depths (4000 m), but with less clear implications. Observations and analyses of these and of further injection experiments, including those at the British Rosemanowes Quarry research project, revealed a great deal of valuable information about the interactions between hydraulic pressures and the deformations of fissured host rock and in particular the significance of the in situ stress field. There it was realised that the hydraulic overpressure stimulation intended to fracture the rock created not just one large, artificial fracture in a virgin rock mass, but rather opened and joined pre-existing fractures and planes of weakness formed by ancient, healed or filled fractures. It was during this period (late 1970's and early 1980's) that the first work on applying and refining the techniques of micro-seismic event location were undertaken in order to follow the development of the damage zone due to the hydraulic pressurisation and fluid injection.

Stimulation of the host rock by the application of hydraulic pressurisation to a length of uncased well has been the principal technique employed on all fractured rock research and development projects to date, although experiments have also been pursued with the use of chemicals:

- in the form of explosives or weapon/rocket propellants to apply high pressures with maximum efficiency to the host rock;
- in the form of selected chemicals, acids or chelatants for instance, to clear natural blockages or those induced by drilling and completion from the active flow paths.

In 1986 the European Economic Commission decided to fund a new, European-wide research project for which a site near Soultz-sous-Forêts in northern Alsace was selected. This site qualified or the purpose, because it was centrally located and because it was a region geologically well known, having been the home of the Pechelbron oil field.

The hydraulic overpressure technique has also been employed for all initial stimulations at Soultz. However, because of the social nuisance caused by the larger acoustic energy releases during and after water injection for stimulation, efforts were then concentrated upon examining ways of avoiding such disturbances. Some considerable success has been obtained in the current project phase by augmenting the effective permeability of the host rock mass and its fracture system using experimentally a variety of chemical additives to injection water.

Further relevant contributions and discoveries were made during the research activities at Fjälbakka, at Falkenberg, at Le Mayet-de-Montagne at the Hijiori and Ogachi sites and at Soultz itself and, more recently during stimulations in connection with commercially oriented pilot plants, in the Cooper Basin in Australia and in Switzerland at Basle.

At most of the research projects it proved possible to create a fluid circulation system and in several cases to circulate fluid for extended periods (of up to four years) with some heat extraction. Each of the projects has contributed to a greater understanding of the physics and chemistry involved in accessing and extracting the heat from the host rock mass, but the sum of knowledge is still not enough to satisfy the needs of an energy utility company searching to use geothermal energy for power production. It is not yet possible to design and build a power plant, for any commercial purpose demanding a given thermal or electrical power delivery. Nor is it yet possible to determine the risk of failure, or the risk of having to abandon the original plan. This weakness has been underlined by the difficulties encountered recently during some of the projects in Australia and in Switzerland, but which have nevertheless yielded valuable information.

1.2 Special features of the Soultz site and system

It has been the experiences at Hijiori and in particular at Soultz, that have stimulated the realisation that the bedrock beneath a site must not necessarily consist of Hot Dry Rock, but that more frequently Hot Wet Rock will be encountered. This leads to the more general generic description as "Hot Fractured Rock". By extending conceptually the use of stimulation techniques from engineering a man-made heat collection system on a virgin site to extending and re-injecting into existing natural geothermal reservoirs, one arrives at the generic term for an "Enhanced Geothermal System" or, as some may prefer, an "Engineered Geothermal System" – both abbreviate to "EGS".

A concept common to the Soultz system, and worldwide to an increasing number of natural geothermal reservoirs of volcanic origin has been adoption of re-injection of the fluid, which has been extracted from the flow paths in the host rock. This represents the essential departure from the original Hot Dry Rock concept, whereby water was pumped via one well into a reservoir volume in the stimulated, but supposedly dry, host rock and recovered from another well. In all the early research projects, this resulted in a continuous loss of injected fluid to the far field in the host rock and a need for make-up water.

In the case of the Soultz project, a slightly different perspective enables us to think in terms of re-injecting what has been produced, rather than producing part of what has been injected. At this site, the natural groundwater level is practically at the surface, so down-hole pumps are employed for fluid extraction and the water thus produced is re-injected after use.

In many less fully saturated sites, the use of down-hole extraction pumps, producing a pressure reduction in the extraction zone(s) should eliminate, or at least greatly reduce the disturbing fluid leakages to the far field experienced as a result of hydraulic overpressures in the earlier research projects. A variety of possible arrangements of injection and production wells are thinkable. These were discussed at length in the first Geothermal Implementing Agreement of the IEA, "Man-made geothermal energy systems - MAGES" between 1978 and 1980.

For the Soultz site a group of three wells, close together on a drilling pad at the surface was selected for the 5'000 m deep system. The wellheads are situated along a line at 10 m intervals and the drilling carried out with the borehole trajectories lying approximately in a vertical plane. This orientation was selected in the light of the state of knowledge of the site – that is to say: knowledge of the orientations of the principal fracture sets and of the stress tensor in the host rock, so as to favour the development of hydraulic connections between the wells.

Directional drilling enabled the distance between the middle well and each of its two neighbours to be about 600 m. The middle well, GPK3, was conceived as the injection well, the other two, GPK2 and GPK4, as extraction wells.

2. SITE AND RESOURCE

2.1 Basic tasks and challenges

In this section we list the challenges facing the developer of an EGS system. These have been encountered in and around the research and development into EGS technology over more than three decades. They are:

1. to create fluid flow paths through the host rock from injection to extraction points of sufficiently low hydraulic resistance so as to reduce the pumping energy demand to an economically acceptable level;

2. to dimension the underground system, so that it exhibits not only favourable hydraulic characteristics, but also provides good access to the geothermal heat in that the fluid sweeps a sufficiently large heat exchange surface in its passage through the underground system;

These two challenges must be successfully met for there to be any chance of economic operation. The quantitative criteria for success will of course depend upon the demands for thermal energy quality and quantity posed by the planned exploitation.

3. to limit the level of disturbance or nuisance from induced seismic activity. It is not possible at present to predict quantitatively what intensity of surface motion will result from injecting fluid and thus deforming the host rock. On a purely qualitative basis the tendency of a site to be able to exhibit greater or smaller strain energy releases could be undertaken, but this alone is not good enough in a populated area.

2.2 Potential uses foreseen for the resource (temperature)

Possible sites for EGS plants are chosen for a multiplicity of reasons, geotechnical, political, ecological, demographic and economic. The detailed host rock characteristics will, however vary greatly. The best method of stimulation to employ will vary from site-to-site and must be determined during a preliminary site investigation programme.

Naturally the first questions to be asked by an interested power utility company, industrial or residential user are:

What energy demands do we wish/need to satisfy - electrical base load, process heat, space heating or a combination of these?

Where are easily accessible geothermal resources available in our territory, which might be worth investigating?

For satisfying which type of demand is each resource most suitable – how much energy at which temperature can we expect to extract?

At this point it is worth reminding oneself that, for an EGS geothermal exploitation it is not just the available temperature, which will be important, but also the operating lifetime of the stimulated system. Temperature is of course vital, as is the achievable through flow rate, but the ideally most economic mode of operation of the plant will depend on other factors as well. One can imagine that the economic optimum could involve setting the operating conditions to moderate levels, so that useful power or heat production can be maintained for as long as possible before capital has to be invested in to be re-developing or abandoning the site. The possible flow rate and temperature gain of the carrier fluid together determine the instantaneous rate of power extraction. However, these will have to be adjusted within the limits of the physical dimensions (accessible rock volume, generated flow path heat exchange area) and connections to the natural fluids outside the accessed region. All of these points cannot be covered right at the start of the construction work and the detailed site investigations, but in preparing to access and stimulate the source, certain questions can be posed and which certain tools are, or will become available, to help in answering them.

From the experiences described in chapter 1 and bearing in mind the considerations above, it becomes apparent that it will be necessary at any given site to provide certain information as early as possible to enable the appropriate economic decisions to be made during the development of an EGS plant on the new site:

- what will be the best way to attack the task of underground data acquisition at the start of the project?
- is the site finally suitable from all points of view including all the environmental aspects and that of potential nuisance from induced seismic activity?
- what could the hydraulic/ heat exchange system be like; how much thermal or electrical power could be produced to satisfy the demand?
- how will the system and its performance develop with time during operation?

At present a number of the tools, ideally necessary to enable these questions to be answered at the ideal time (i.e. as early as possible) in the investigation in order to provide input for strategic or tactical commercial decisions, are not yet available, or are still under development. The data required are as follows:

- the undisturbed rock temperature profile with depth;
- a measure of the anisotropy of the stress field
- at least one measurement of minimum principal stress, preferably a profile against depth types, orientations and positions of intersected fractures
- presence of major fractures, failure zones and block boundaries in or near the zone of interest
- chemistry and mechanical properties of fracture fillings
- water chemistry, including dissolved and non-dissolved gases
- morphologies of the faces of filled and unfilled fractures

Once some data have been collected and analysed, the nature of the thermal resource can to some extent be determined. What is learned here must serve the process of deciding upon system development strategy.

3. STIMULATION TECHNIQUES

Over the past 35 years many field experiments have been undertaken to discover how to create paths for the circulation of working fluid in an underground, hard rock heat collection system, offering low fluid flow impedance and high heat extraction potential. In all cases, some sort of connection between two or three boreholes has been achieved, but during those research projects, efforts to optimise for this combination of low hydraulic impedance and large swept heat exchange area were not pursued actively. There were other challenges to meet. Thus it has first been during the project at Soultz and particularly in its current phase, that some progress has been made. This has been simply because the target of the current phase has been to create a scientific prototype pilot plant: an operating unit designed to produce some energy, but offering at the same time a basic unit for examining, analysing system behaviour including operational reliability and economics.

The basic techniques employed have all for several decades been employed by the oil and gas industry for optimising access to hydrocarbon resources and some of them also for improving access to drinking water aquifers. These are:

a) Hydraulic stimulation – the injection of pressurised water into a borehole at a depth offering a suitable rock temperature for exploitation.

b) Chemical stimulation – the injection of chemical solutions, principally of aqueous solutions of single or mixed acids or chelatants.

c) Stimulation by means of explosives or propellants – blasting, controlled gas pressure generation and perforation.

The principal difference between their use for an EGS system today and their employment in hydrocarbon, or water reservoirs is given by the host rock itself – the difference between the characteristic material behaviour, in their *in situ* stress environments, of sedimentary and crystalline rocks – and by the types of effect targeted.

The targets set by the design of the underground heat collector in hard rock will continue to involve joining two or more active wells in various geometrical arrangements by improving or stimulating the hydraulic conductivity of fractures and fracture networks. The choice of techniques available to a project developer is the same each time: in effect, adaptations of the same techniques as are available to the developers of petroleum, hydrological or purely volcanic geothermal resources. The task is to decide which combinations and which sequences of operations are best employed on each site.

3.1 Hydraulic stimulation

Stimulating a rock mass hydraulically involves the use of pressurised fluid at a point or in a depth range along the length of a borehole, where direct access to the host rock is available to force a route into pre-existing fissures intersecting the borehole wall. It appears that stimulation occurs mostly via the shearing of some of these fractures. In the initial stages of field research, it was simply tension failure, which was expected. Although the creation of tension failure is possible, it is easier (i.e., it requires vastly less fluid pressure) to initiate shear failure in fractures favourably oriented with respect to the local stress field in the host rock (see *Pine and Batchelor*, 1984). The stress tensor field in hard rocks is almost always anisotropic and shearing can be initiated as a result of pore pressures being elevated by stimulation pressures very close to the minimal principal stress. The study of fracture behaviour during and as a result of shear failure is a task, which for many years has occupied and is still occupying research teams (*Barton*, 1976, *Barton & Chouby*, 1977, *Barton & Bandis*, 1990, *Chen et al.*, 2000).

There appears to be a good correlation between fractures and fracture zones outcropping on the borehole wall, which take or yield fluid during low-pressure flow tests prior to stimulation and those, which become permanently stimulated (for example: *Evans,* 2005). This raises three main points:

1. flow paths resulting in the completed heat exchanger/reservoir are predetermined by the initial fracture distribution and the stress field;

2. fissures, which have opened in shear, cannot fit together again and remain propped open, giving access to further potential zones of fluid migration;

3. There are at present no tools available to predict rapidly and efficiently in advance where and of what capacity, at greater distances away from the borehole being stimulated, a useful flow path / heat exchange surface can be generated. However, the data acquired during the detailed site investigation in and around the deep boreholes can by means of detailed, integrated analysis alone, or with the help of mathematical modelling, provide an excellent starting point.

This last point, (3), is particularly relevant to the pre-planning and design of the underground works in a commercial project.

One other very useful technique is, however, already developed, proven and available. This comprises the observation, location and analysis of acoustic (micro-seismic) signal emissions from fractures successively opening during the stimulation process itself. This can only be used, of course, once fluid is being injected during the stimulation process. But then, additional analysis of the individual seismic source mechanisms and fault plane solutions reveals some of the characteristics of the fluid-bearing structures in the rock.

In several of the HDR research projects, including that at Soultz (and also during some of the latest commercially oriented activities, notably at Basel), the acoustic signals emitted by the micro-seismic movements arising during the opening of the fractures in the deep host rock have disturbed the local population. This point has received much attention during the Soultz project.

3.2 Chemical enhancement treatments

New and innovative stimulation technologies are emerging that will modify some of the previously tried and more or less proven methods. Still, in other cases, we see enhancements arriving, which improve the performance of the existing techniques. It appears that the future challenge will be for the petroleum industry to find more cost-effective ways to improve well productivity. It appears that well stimulation will remain a dynamic part of the petroleum industry.

Challenges in sandstone acidizing still exist, although great improvements have been made in the last decade. Factors that contribute to these challenges include: multiple types of co-existing formation damage; uncertain rock mineralogy; multiple fluids and pumping stages; complex chemical reactions between fluids and formation minerals; and fast reaction kinetics at elevated temperatures. Others are: inadequate zonal coverage; limited active acid penetration; rock deconsolidation due to acid-rock interactions; acid emulsion and sludge tendencies; corrosion; and health, safety and environmental (HSE) concerns. These factors contribute to the low success rate of sandstone acidizing treatments especially in acid-sensitive, and clay- and carbonate-rich sandstone formations at high temperatures.

Deleterious side-effects of acidizing in sandstone formations—such as clay swelling, fines migration, gel formation or particle precipitation—may be minimized or avoided altogether by designing hydrofluoric acid (HF) stimulation treatments with compatible chemical and physical properties. Smectite and mixed illite-smectite clays are among the most water-sensitive clays, while illites and chlorites are less prone to ion exchange. Also of concern when acidizing sandstone in the presence of illite, potassium feldspars, sodium feldspars, and zeolites, because these compounds can contribute to the formation of matrix-blocking precipitates.

Clay swelling can occur when acidizing fluids exchange ions with formation minerals, choking off production by obstructing the matrix, unless care is taken to sustain the salinity of the injected fluid after ion exchange. Many water-sensitive clays contain potassium chloride (KCl) and sodium chloride (NaCl) ions that can be exchanged with ions in injected fluids to lower the salinity of the fluid. For example, when a 3% ammonium chloride (NH_4Cl) acidizing fluid flows across a typical ion-exchanging clay, the fluid becomes 3.3% NaCl, a brine too weak to prevent clay swelling, thus requiring a 5% NH_4Cl or equivalent solution.

The acid treatments were developed for improving the productivity of oil and gas wells. The technology was partially adapted to geothermal wells, most often to remove the mineral scaling deposited in the wells after several years of exploitation. Nevertheless, acid treatments also allow the enhancement of the fracture network within the host rock. They have been successfully used in geothermal granitic reservoirs like Fjällbacka or Beowawe (*Epperson*, 1983). In recent years, the reliability of acidizing sandstone intervals has been significantly improved. In the USA, about 90 percent of wells treated have responded with two- to four-fold production increases.

Recently, this technology has been applied to the Soultz reservoir. The three 5-km deep wells (GPK2, GPK3 and GPK4) were treated with different amounts of chemicals and the injectivity of each well was differently affected. If encouraging results were obtained with GPK2 and GPK4, the injectivity improvement of GPK3 well is apparently less marked but the diagnostic for this well was not really performed[1].

Nevertheless, the high reactivity and a weak flow prevent the penetration of acid in the far field between the wells. This high reactivity also involves the risk of creating "wormholes", able to increase the porosity but not always the permeability of the medium.

The increase of acid concentration augments the reactivity in the vicinity of the injection well and creates a new porosity. But the high acidity of the solution has also the disadvantage to decrease the solution pH and to augment the risk of damaging the casing.

The answer could be an increase of the flow to force the acid transport farther in the formation or the use of another acid (e.g. HF), which will dissolve silicate minerals. The result will be an enhancement of the fracture network and of the fractures' connectivity.

Finally, simulators have been developed to track the propagation of reaction fronts and to gain insight into the effectiveness of acid injection as a well stimulation technique. Reactive transport modelling was used to simulate injectivity recovery by acid injection (see Appendix 3(a)). The predicted amount of scaling minerals dissolved by acid was consistent with the estimated amount.

3.3 Explosives and propellants

As the other stimulation techniques, the explosive stimulation aims at reducing the impedance of the formation surrounding the borehole. Three principal techniques can be distinguished:

The perforation makes use of shaped charges, which punch through casing, cement and into the formation. Such explosives have been used by the oil industry for improving oil reservoir flow rates since shortly after World War II. At this time, in the 1950's field gun/missile fuels became available and specially shaped, safe-to-handle charges and the down-hole guns to fire them were and still are being developed. Currently, their use for selective penetration of drill-hole casing at multiple access points is increasing in popularity and has recently undergone major developments, resulting in a co-operative project between the QinetiQ Group and Shell Technology Ventures, licensed to GEODynamics Inc. (see GEODynamics website: www.perf.com). Nevertheless, the penetration of these charges is limited to a few feet and the technique helps create connection to a nearby permeable reservoir zone rather than stimulate fractures in the far field.

The more promising technique, "bore shooting", was also quite common in the oil and gas industry up into the 1950's, but was replaced by hydraulic fracturing. In bore shooting (originally so called because it used to be common practice to fire a shotgun into a dry well), canisters of explosives are lowered to the planned production zone where the detonation shatters the formation. Fracture lengths of up to approximately 13 m away from the borehole have been reported, but the resulting debris has to be removed from the well before using it. Much know-how was gained on the reactions of rock to underground explosions during the American "Plowshare" Programme for investigation of the peaceful uses of nuclear weapons technology in the 1960's. At this time, a major research programme was undertaken at Sandia Laboratories in the USA to increase understanding and avoid the effects of "overcharging" and the formation of a plastically deformed zone of rock in the near field around the borehole surrounded by a stress shell at some distance. *Johanssen & Persson* (1970) give an overview of relevant theory of explosives in their book.

In fact the third technique was a development of the bore shooting. This involves producing pressure pulses of controlled shape and amplitude ("tailored pressure pulses") and has proved to be a key factor to more successful explosive stimulation of rock formations. For this purpose attention was turned to solid propellants, originally of military origin, as are used in casing/borehole wall perforation, rather than explosives as such. For geothermal applications with generally hotter

[1] *It can be also noted that the likely origins of the very limited efficiency of all the methods (including hydraulic stimulation) used for trying to improve the injectivity of the GPK3 well seem rather specific and are still a subject of discussion.*

environment than found in most oil and gas fields these had (and the modern products still have) the added advantage of being less unstable at higher temperatures. Both Gas Fracturing and Perforation can be more reliably carried out using propellants than with true explosives and in addition the propellants tend to be less temperature sensitive and less dangerous during handling.

A major problem in transferring the explosive stimulation technique from the oil field to geothermal wells is the high temperature. Above 180 °C, chemical, physical and mechanical limitations on the equipment and explosive become serious. One early reported use of explosives for the stimulation of a geothermal well took place under contract to the Los Alamos National Laboratory in 1981 in the Geyser's Field in Northern California. The application of up to 5 tons of the high temperature tolerant explosive HITEX II in a dry steam well was successful with respect to the functioning of the explosive, although production rates decreased due to a debris plug from a preceding test (*Mumma*, 1982).

The Sandia work was much appreciated by the HDR community and was applied at the Rosemanowes Quarry geothermal research project during the late 1970's and early 1980's (*Batchelor*, 1979) with co-operation from national research laboratories both in UK and USA. Here, construction, development and testing of a 5m long explosive tool for use in an open-hole section in granite at 2000m depth were undertaken with complete success (*Batchelor*, 1982). Self-propped fractures were created in the vicinity of the borehole, allowing a more effective subsequent hydraulic stimulation. For this experimental programme a safe-to-handle explosive device was developed using carefully sized and centralised charges of TATB, a very stable, machine-workable solid material. Special attention was given to limiting peak explosive pulse pressure and additionally, to developing and testing reliable detonation mechanisms (*Halladay & Batchelor*, 1981).

In-hole explosive techniques in general are principally of use in creating access to natural fractures or porous zones at limited distances in the near field of the drill-hole, as is also the case in oil wells. Hydraulic enhancement is generally necessary to create the far field access. In the case of the Rosemanowes project, it was found ultimately, on account of stress field anisotropy, fracture orientations and vertical stress gradient, that stimulation via hydraulic over-pressuring was more economical, being effective both at near and at far field distances from the bore-hole.

Developments with propellants, which burn at a slower rate than explosives, have continued in the petroleum industry with some success, the technique becoming known as "Gas Fracturing", "High Energy Gas Fracturing" or "Controlled Pulse Fracturing" (viz. *Fram*, 1991; *Hollabaugh & Dees*, 1993). Economics of the operation are still questionable and in addition, neither of the two papers cited here were concerned with crystalline rock.

Sandia Laboratories also continued their efforts to produce substantial cracks radiating out in all directions from a borehole with an experiment in the volcanic tuff at the Nevada test site, aimed at geothermal applications, but using methods originally developed for gas production fields. By this means, a water-filled hole was connected to four surrounding wells by fractures created by propellant combustion in direction both parallel and normal to the minimum principal stress. The inter-well connections were all flow tested and were finally mined out for direct examination (see *Chu et al.*, 1987).

Thus, one can see that explosive, or rather propellant driven stimulation techniques do exist and have been intensely studied, but have (not yet) made much progress in the deep geothermal energy world. But their usefulness, particularly with respect to local selective stimulation or restoring the production level in the case of locally impaired reservoir access, continues to increase within existing industries. It has shown itself capable of enhancing connectivity to the surrounding reservoir in the near field of a borehole and this possibility of selective stimulation could prove useful. It is for this reason that this section has been included. Such techniques have not been considered at all during the R & D work at Soultz, but it is felt necessary to note that the experiences with explosives and propellants, the successes and the disappointments do form today a part of the knowledge about host rock stimulation.

4. EXPERIENCES AVAILABLE BEFORE THE SOULTZ PROJECT

Prior to the drilling and stimulation of the Soultz wells, hydraulic stimulation in an open-hole length at the lower end of a borehole was used in all other EGS investigations. During the pioneer work at the Fenton Hill site in New Mexico, USA and in the Rosemanowes Quarry work in Cornwall, UK a number of vital discoveries were made:

- location of micro-seismic acoustic events of rock moving and breaking due to application of hydraulic pressure showed where changes were taking place;
- by studying in detail the structure of the acoustic records used to locate rock damage migration (*Batchelor, Baria and Hearn*, 1983), from the migration itself (*Pine and Batchelor*, 1984) and at the same time by taking into account the low stimulation overpressures applied at the surface, it appeared that the principal rock joint fracturing was taking place on existing joint surfaces and that the mechanism must be shear;
- the degree of anisotropy in the rock stress tensor was an important factor in determining if and which fractures were most likely to fail in shear;
- the direction of the principal stresses in the rock, the crack orientations and their historical development determined the direction of migration of hydraulically induced damage and once known, should determine where subsequent wells must be to make connections possible.

From these developments came the realisation that it was the essentially interconnected, if not initially very conductive, members of the local fracture network, which formed the bulk of the potential flow paths and which should be activated by stimulation. Those fracture families most favourably oriented to experience shear deformation and opening when the stress tensor in the rock was disturbed by hydraulic overpressure, must be intersected by both production and injection wells. This resulted at the Rosemanowes site in 1982/83 in the drilling of the spirally oriented well RH15, designed for the first time in order to:

- cross the region in which a cloud of micro-seismic disturbances had been located, spreading out from an existing well, which had previously subjected to hydraulic overpressure and;
- cut preferentially within that region that group of cracks, which due to their orientation to the principal stresses in the *in situ* stress field, would be more easily opened by the hydraulic treatment.

The HDR/EGS work in the USA and in the UK in the period between 1975 and 1990 brought the realisation that in deep geothermal situations many new measuring instruments were needed to study the site's characteristics before and after stimulation. These would need to be able to withstand much higher operational temperatures and pressures than was possible at that time. Thus work was triggered to develop high temperature electronic components, micro-seismic sensors and production logging tools.

Also, towards the end of this period viewing the borehole at depth and in the form of high-resolution images was just becoming possible with, for instance, ultrasonic borehole imagers.

In parallel to this came on one hand experience from the hydrocarbon industry, whereby stimulation was used to improve access to oil-bearing reservoirs and on the other hand the mass of research work performed for safety considerations in connection with underground nuclear waste disposal. In this context, fractured media were examined and geo-statistical modelling techniques led to considerations similar to those relevant, for a completely opposite reason, to the HDR/EGS world – percolation of fluids through networks of fissures in hard rock, in addition to percolation through porous media.

All of this knowledge was available and much of it was consequently applied and further expanded during the project at Soultz. It must be noted here, that the completion of several of the international R & D projects overlapped with the start of the work at Soultz, so that full documentation was not available at that time (see for example *GeothermEx & Princeton Economic Research,* 1998).

Furthermore a recent study has been made for the US Department of Energy (*Tester et al.*, 2006) in which each aspect of EGS, including stimulation, has been reported for every one of the international R&D projects up until the Australian commercial project in the Cooper Basin.

5. LESSONS LEARNED AT SOULTZ

The published paper included in Appendix 1 gives a compact and useful historical overview of the Soultz project, from the choice of the site and the formulation of the European geothermal research project in 1984 up until March 2008 and helps to picture the sequence of events as a whole.

Presence of enough water was found at the Soultz site, to encourage and enable unproblematic re-injection of the produced water. This would have been possible in the earlier research projects, where fluid losses were a concern, but then greatly reduced fluid flow circulation rates would have been achieved. The Soultz installations are unique so far, since an in-line triplet of wells with two production wells and between them, an injection well has been created and tested, a geometry, which furthers the development of a recirculating system.

The task of site characterisation via measurement had to be to be undertaken at Soultz with some of the new tools, which were under development at the time and provided a welcome testing ground for them – for instance the ultrasonic borehole wall-imager. One point received much development effort, namely: having realised the significance of the *in situ* rock stress field, a reliable method had to be found to measure it. This had received attention in France (*Cornet & Valette*, 1984) and during the UK Rosemanowes project (*Batchelor and Pine*, 1986) and was studied for Soultz work (*Baumgärtner & Rummel*, 1989; *Rummel & Baumgärtner*, 1991). It was decided to employ hydraulic pressurization with the mini-frac technique. This proved to be difficult at first, since conventional rubber packers became so unreliable at only moderate temperatures. The mini-frac tests, made in an interval between two packers, were enabled by designing packers with soft aluminium sealing surfaces. A modified version of this concept was also built and successfully installed in series in a group and inflated with cement to support the casing above the open-hole stimulation interval at the base of the borehole. The significance of the tensorial stress field, its amplitude and orientation, continued to be investigated however, as reported in *Cornet & Jones*, 1994 and *Cornet & Bérard*, 2003.

Drilling, stimulation, measurement and testing were undertaken here in deep wells drilled into crystalline rock, which were strongly deviated from the vertical. In inclined, directionally drilled wells, the open-hole length can be particularly subject to breakouts, which can preclude later work or measurements in the well, unless a cleaning operation is carried out. Such breakouts can also occur in long open-hole lengths in any well. Their avoidance, by any reasonable means, would be desirable.

Casing deformations and cracks were experienced in two of the Soultz wells, namely in GPK2 and GPK4, in each case shortly after completion. It is possible, but not at present confirmable, that longitudinal water movement is occurring behind the casing of the injection well, GPK3.

The use of a heavy fluid to generate an increased pressure gradient in the water column within the well at the start of stimulation, encouraging preferential opening of connections towards the bottom of the hole and higher temperatures, is potentially useful. It was tried on both GPK2 and GPK3 with some success. Connections between the two wells were achieved around 5000m, although in circulation testing these did not carry the major proportion of the flow.

More was learned from the experiment undertaken during the stimulation of GPK3, namely the simultaneous application of pressure to GPK2 in order to generate a concentrated stress disturbance in the rock mass between the two boreholes and promote their connection.

It was possible to confirm that knowledge of the stress field orientation is indeed useful in planning the trajectories of subsequent boreholes. It was apparent, that induced shear was the principal failure mechanism, requiring rather moderate hydraulic overpressures during stimulation. Also the overall directions of joint damage migration were always close to the normal to the minimum principal stress direction, taking account of directional scatter due to variations in the relative orientations of stress tensor and critically stressed fracture sets.

The large number of stimulation tests undertaken at several depths in the major boreholes at the Soultz site, were accompanied by hydraulic flow tests at various times before, during and after each stage of the process. This allowed the degree of hydraulic system improvement in the host rock to be followed. A logical procedure was developed for deciding on the details of the injection and testing to be undertaken during each stimulation, very concisely described in Appendix 5(a) and (b).

The intensive integrated analyses of systematically collected geological, petrologic, mineralogical, geophysical and rock mechanics data collected from all boreholes at every stage of the project and which formed vital parts of the research programme, have enabled an invaluable and coherent picture to be built up, characterising the site region in great detail. These data were in addition combined with fluid flow, temperature and micro-seismic records. A major step in understanding of the site was achieved after many years of integrated data analysis in 2005, with the publication of the two papers given as Appendices 4(b) and (c), followed in 2008 by the overview, Appendix 4(a).

During the stimulation process itself, the monitoring and locating of micro-seismic events could now be added to the generic picture provided by the integrated data analyses in moving towards a more specific view. This technique still offers the only way at present available of seeing the migration of the damage front during stimulation, observing the direction and rates of the migration and locating at least some of the developing fluid flow paths. It is however noted that, on the one hand some evidence has appeared of flow paths developing without acoustic signals being emitted and on the other hand, events have been detected (and felt) long after any substantial stimulation overpressures have either decayed during a shut-in period or have been reduced by allowing fluid production.

Knowledge of the location of the rock volumes in which fractures have been disturbed was useful throughout the project. In the shallow circulating system at around 3700 m depth between GPK1 and GPK2, the well locations were such as to allow overlapping clouds of micro-seismic locations to be generated from the two open hole regions. In the 5000 m deep triplet system consisting of the deepened GPK2, together with GPK3 and GPK4, each subsequent well was directionally drilled into a target volume designated by the zone disturbed by the stimulation of the previous well. Some detailed information on the micro-seismic investigations, enabling an overview to be gained of the efforts undertaken and results achieved by the Soultz team, are included in Appendix 2(a), (b),(c) and (d). It is noted, that the original choice of the historical oil field region near Soultz as site for the geothermal R&D project, did not only mean that a considerable amount of information was available concerning the regional geosphere, but that some of the existing petroleum wells could be adapted to provide attractively distributed points of installation for the micro-seismic acoustic detectors.

Micro-seismic events can however definitely be big enough to be felt by and to be a nuisance to certain neighbours at certain nearby locations. At the European test site at Soultz, this was also socially problematic, so tests were undertaken to discover if other approaches to stimulation could be more acceptable, yet equally effective.

At present one is still unable to make quantitative predictions of seismic energy releases to be expected from stimulation activities on any particular site.

The controlled experimental programme of chemical stimulation, which was undertaken for this purpose, has confirmed that chemical treatment can be useful in the hard rock environment, apparently for two reasons: to clear out drilling chippings and mud sediments from the exposed borehole wall and to clean out the accessible flow paths in the near field of the well. Thus, selecting and applying the appropriate chemical treatment can improve the connections between the well and the activated flow paths in the host rock. Any effects induced specifically in the far field could not be demonstrated at the time of stimulation, nor indeed up to the end of the currently closing project phase. It appears that this will only become possible with the use of greater quantities of chemical (e.g.: acid) and of longer periods of injection, with simultaneous application of hydraulic pressure to force the fluid flow. More experience with such techniques and with the selection of treatments to match the site water/rock chemistry is still needed.

Confusion in the interpretation of the chemical treatments in GPK4 arose, until temperature logs revealed that two water leakage points had appeared in the lowest 375m of the cemented casing. The casing shoe is at a measured depth (MD) of 4757m, so the upper of these leakage points is at around 600 m TD above the foot of the borehole. The reason for the leakage point is not known with absolute confidence. It seems likely however, that a natural slip plane has been activated and caused a casing/cement failure. It is suggested that this connection point to GPK4 yields a significant part of the circulation flow entering GPK4 from GPK3 and is itself insensitive to the chemical treatments.

The temperature of fluid produced from GPK4 during the 5.5 month circulation test in 2005 was 120°C in contrast to the 160°C produced from GPK2, that is to say, water from shallower sources is captured from the leakage points in GPK4. This experience underlines the importance, at least during the stimulation process, of repeatedly running flow and temperature logs, in order to maintain an overview, enabling the later behaviour of the system to be understood. The background to chemical stimulation techniques, a description of the test programmes and a report on the analyses up until the present are contained in Appendix 3(a), (b) and (c).

The Soultz scientific project has provided requirements and opportunities for the development of mathematical models prediction of behaviour of the underground hard rock system. Progress has been strong in the 20 years of experimental and theoretical activity at the site. In effect the models themselves, the mathematical formulations of processes being simulated, geometrical representations and the capabilities and speeds of calculation have advanced more rapidly than the ways of procuring data to verify the models' correctness. The two papers included in Appendix 6 give an overview of the numerical models used or developed by the various active modelling groups and of their applications during the project. The most valuable uses of the ever more capable modelling tools have tended to be clarification or confirmation of multi-parametric system behaviour to explain or replace measurements.

While uncertain geometries and distributions of physical properties can only be treated with statistical approaches, guaranteed accurate predictions will remain difficult. Confidence has increased, but efforts will continue to improve acquisition and descriptions of data. One spin-off result of the model development work is that now models of specific, definable situations and processes, including transient geochemical reactions, in the underground have become really useful.

The research and development project at Soultz has provided opportunities for international (outside Europe) co-operation in several domains, notably for example, with the University of Utah (geochemistry and choice of tracers) and with the University of Sendai (applications and evaluation techniques of micro-seismic signals). In each of these cases much was discussed and learned by both sides.

6. NEEDS AND OUTLOOK FOR THE FUTURE

We have discussed the developing philosophy of EGS technology and, as is usual in nearly all new domains of science and engineering, we are forced to admit that we are at a point where the more we learn, the more questions arise, which we must learn how to answer.

The initial euphoric dream dating from around 1970 of easily enabling geothermal energy to become accessible from everywhere on earth lately seems to have retreated to become a more modest, but also more rational target for the future.

The target is an assembly of enough knowledge - consisting of physical understanding and of techniques - for reducing the geological risk factor on an already apparently well-chosen site (i.e. a site which is in the right place to tap into and make use of a known thermal resource). To achieve this, the intention to reduce uncertainties even further to a level where a project, including the creation of the underground heat exchanger, approaches the predictability of a more conventional power plant engineering task.

If the resources are to be used commercially, there will be a number of conditions to be fulfilled. At present a power plant based on a virgin EGS requires per MWh of mined energy much more detailed information than has been needed historically for a hydrocarbon reservoir development. Obtaining this information requires measurement equipment, which is reliable under remote operating conditions at elevated temperatures and pressures and often also requires improved techniques for rapid and reliable interpretation of the measurements – and of course: careful financial planning and adequate financing.

This detailed site evaluation down to operating depth demands time, which in the presence of one or several large drill rigs, becomes very expensive. This is especially the case now, when the petroleum explorers are using more drilling and field service resources than ever before.

Here then, in the acquiring of knowledge on how to evaluate each sort of site and the parallel development of improved measurement techniques and instruments lies one major R&D challenge in the domain of EGS for the next few years.

Another major task is the undertaking of a number of detailed investigations at promising and likely sites, as far as possible using and testing the new methods, with the intention of building operational pilot plants. Only by this means can a large enough body of data, experience and understanding be assembled to start the geothermal industry moving into a way of thinking in some way analogous to that prevailing in the hydrocarbon industry.

These might involve the use of, as yet undefined, techniques of host rock tomography and of improved techniques of *in situ* stress measurement in order to obtain rapidly a reliable picture of the positions and orientations of potential flow paths and the relative orientations and amplitudes of the stress tensors. Developing such techniques will be particularly challenging.

In the current project ("phase II"), just finishing at Soultz, some work in this direction has been and is still being done by IFP (Institut français du pétrole) in co-operation with the Baker-Hughes Group. Here, novel Vertical Seismic Profiling signal pre-processing and interpretation is employed to obtain reliable 3-D structural information from signal mutations at major fault planes. Strings of three-component sensors are used in the wells and a wide range of sites employed for the offset surface sources. A patent for the data handling and conditioning techniques has been applied for. A large-scale measurement campaign was carried through in two stages in the boreholes EPS1, GPK1, GPK3 and GPK4 with many source locations. The theoretical studies and the evaluation work has had a promising start since 2007, but progress, in view of examining and optimising procedures for error correction and conditioning the very large mass of data, is proving to be very slow. Even if the work is technically successful, the evaluation procedure for a given site will have to be accelerated for commercial use. However, the target of the initiative is attractive and the

Soultz campaign will certainly form a solid base for further work on three-dimensional VSP surveys.

Since host rock stimulation could become more reliable by operating selectively on pre-chosen, promising depth zones in the boreholes, the availability of tomography techniques to help making such zone pre-selections will become important.

One can hope for success from the VSP work. Otherwise, some other, as yet undefined alternative approach must be tried. The requirements are defined. Several attempts have been made in the past to use potentially useable ground investigation techniques to produce 3-D images of rock structures over several hundred metres and for improved stress measurement and evaluation. Both new and existing methods of interest should continue to be actively sought and investigated and co-operative development programmes set in motion.

Finally, the question of recognising and defining the best stimulation technique on a given site requires much more work.

Until now, the principal technique used in the deep man-made geothermal projects has been hydraulic stimulation of the whole open-hole section of a well. Some experiments have been made with other techniques, both on the major research projects themselves and also in external, associated experiments: some with explosives with only small success rates; some with controlled high pressure gas pulses and some with chemical leaching techniques – these latter, with a modest degree of success, at Soultz.

It certainly appears that connections with flow paths outside the very near field around a borehole and extensions of those flow paths to greater distances require in the first instance some sort of mechanical or hydraulic creation mechanism. In this way the transport of sufficient concentrations of active chemicals to successively enhance the flow capacity of inter-well transport paths can be assured.

It is suggested that particular attention be paid here to enable moves towards selective stimulation, using for example, modern high-pressure gas perforation, depth selective pressurization systems (which are robust and not temperature sensitive) and active chemical enhancement. This could lead to fully cased wells and also to the use of fully cemented, pre-stressed casings.

A final outstanding task to be mentioned here is that of learning how reasonably to predict and handle the risk of nuisance and anxiety concerning safety and potential damage to property from ground vibrations during stimulation and long term operation. This has been a source of worry during the Soultz R & D project and the initial stimulation attempts at the commercially based EGS project in Basel at the end of 2006. It continues to consume effort and time.

7. CONCLUDING REMARKS

Current economic conditions in general and the increased effort now needed for finding and exploiting new resources dictate that oil field operators now have to consider optimizing well and reservoir productivities. Achieving the goal of long-term, low-cost sources of hydrocarbons has already begun to demand a significant succession of technological advances in the area of well stimulation. Here also, notably in the oil shales, local stimulation, coupled with micro-seismic event monitoring has migrated from the EGS world into the range of techniques used in hydrocarbon resource development (see, for example: *Fischer, K., 2006*).

It is apparent that such advances will affect many different petroleum production sites around the world, from old, mature fields, where extracting the remaining reserves, often significant, but which have become economically unattractive, to the brand new, major ultra-deep water projects that are being evaluated today. The challenge will be to increase productivity, and then to maintain that increased productivity throughout the life of the field to provide improved total recovery of hydrocarbons from the reservoir.

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9. APPENDICES

APPENDIX 1 – the project

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Section 3: Contribution from Engineering Geology / ETH-Zürich

ABSTRACT

Fractures imaged on sonic televiewer logs run in deep boreholes GPK3 and GPK4 were analysed. Particular attention was paid to the sections above 2000 m where the holes are less than 20 m apart. Four major sets of fractures were identified on the basis of orientation. Fractures had mean true sizes of 15 to 40 m diameter. Spacings appeared to follow log-normal laws with arithmetic mean values of 1 to 6 m. The distribution of fractures along the wells shows distinct clustering, reflecting the intersection of the well with fracture zones composed of an anastomosed network of fractures delimiting shear lenses. Large variations in both the internal structure and the thickness of fracture zones occur over distances of 10 to 20 m. These variations are believed to have a significant influence on the hydraulic behaviour of the zones by channelling the flow. The spacings of the fracture zones range from 40 to 400 m. The size of such structures cannot be specified with our data set. Microseismic imaging shows they can extend over distances of several hundred metres.

Observations of breakouts and drilling-induced tension fractures (DITFs) in two 5 km deep boreholes of the European Enhanced Geothermal Project of Soultz-sous- Forêts, France, were combined with the analysis of pressure data from stimulation tests in all 3 deep wells to obtain a description of the state of stress in the granite down to 5 km depth. The orientation of the maximum horizontal principal stress was found to be at 169°±14°. The magnitude of the minimum principal horizontal stress in the lower reservoir lay on the linear trend defined from stress tests above 3.5 km. The magnitude of the maximum principal horizontal stress was constrained using the distinct depth ranges where tensile (i.e. DITFs) and compressive (i.e. breakouts) failure occurred. The resulting constraints on SHmax magnitude support the conclusion derived from the appearance of both normal and strike-slip fault plane solutions of induced microseismic events that SHmax = 1.0Sv.

Stress heterogeneity was studied by examining the deviation of the orientation of SHmax from the mean direction. Stress variations were seen to occur at all scales and follow a self-affine scaling law. Examination of short-wavelength (<50 m) variations of the DITF orientations in the sections where the wells are about 20 m apart shows that they are correlated with natural fractures, but usually not correlated between wells. This suggests that fractures are for the most part not much larger than 40 m in diameter, in agreement with the results of the study of fracture size. Large wavelength variations are also seen and are principally associated with fracture zones.

Uniaxial compressive strength (UCS) and static Young's modulus tests were performed on 12 samples of Soultz granite having different degrees of alteration. UCS values ranges from 100 to 130 MPa for unaltered granite, and were unaffected by the strength of the pervasive alteration. Samples with weak vein alteration had UCS values that lay near the lowest values measured for the samples that had only pervasive alteration, and one sample that had high vein alteration had a UCS about 8 MPa lower than this. The Young's modulus of 'unaltered' Soultz granite was found to be 54±2 GPa, regardless of the degree of pervasive alteration. However, two samples with vein alteration showed a significantly lower modulus of 39 GPa.

1. INTRODUCTION

The contribution of Engineering Geology centred on the doctoral work of B. Valley which was entirely supported by the contract. The focus of the Ph.D. was modified during the course of his studies in response to project needs. The original intention stated in the work plan was to investigate the mechanisms underpinning permeability enhancement (stimulation) in both the Soultz and Basel 5000 m deep reservoirs through the integrated analysis of borehole logs, geologic, hydraulic and microseismic data. Early in the project it was realised that the task of relating geologic structures to microseismic patterns would not be possible within the timeframe of the project. Thus, this aspect of the work was replaced by a study of fracture scaling constrained by correlating data from closely-spaced boreholes, as communicated in the Annual Report for 2005. More recently it became clear that the Basel EGS project, by its proprietary commercial nature, lay outside the scope of work conducted within the present contract. This, together with discussions with the Soultz coordinators and the desire to avoid duplicating work being conducted with other contractors, led to the doctoral work focussing on the interpretation of logging data from the deep reservoir at Soultz, with particular regard to fractures and the state of stress. Thus, the contributions of Engineering Geology that are presented in this report are:

Multi-scale fracturing in the Soultz-sous-Forêts basement from borehole images analyse.

1. The linear characterisation of the state of stress at Soultz to 5 km depth
2. Stress heterogeneity within the Soultz granite (i.e. the deviations of stress orientation from the linear trends) as deduced from variations in the orientation of wellbore failure.
3. Laboratory measurement of the uniaxial compressive strength of the Soultz granite

The work was for the most part was supervised internally within the ETH by K. Evans, except for topic 1 which was supervised externally by A. Genter and C. Dezayes of BRGM. B. Valley's thesis was accepted for the degree of Dr. sc. by the ETH Zürich on August 2007. The full document of this PhD thesis is on the attached CD-R. The scientific publications derived from the performed works are listed and referenced at the end of the report.

The objective and results of the work performed on the four topics is summarised in the following four sections.

2. WORK CONDUCTED

2.1 Multi-scale fracturing in the Soultz-sous-Forêts basement from borehole images analyses

This study was based upon the identification of fractures on more than 7 km of Schlumberger borehole ultrasonic reflectivity (UBI) logs from boreholes GPK3 and GPK4. An important objective of the analysis was to explore ways in which the fracturing observed at the 30 cm diameter scale of the borehole walls could be used to infer properties and geometry of structures at the reservoir scale (i.e. up to 2 km). Innovative methods were developed that exploited the small (i.e. <20 m) separation of the wells from the surface to 2.5 km depth in order to quantify the spacing and the size of the structures identified in each of the holes.

Fractures identified on acoustic borehole images were classified according to a fracture typology developed by the BRGM that is based upon the characteristics of their traces. This typology has been used to characterise fracture in all Soultz wells and is described in Table 1. The orientation and frequency distributions of fractures observed in each of the two deep wells is shown in Fig. 1. Four major sets of fractures were identified on the basis of orientation. Fracture spacing appeared to follow log-normal laws with arithmetic mean values of 1 to 6 m, although this could be an artefact of selective sampling of what is actually a power law due to the limited resolution of the televiewer (Genter et al., 1997). The size of the fractures was evaluated by determining the subset of fractures that extended between the holes above 2.5 km depth, where the holes are less than 20 m apart. The fractures were assumed to be perfectly planar and penny shaped, and have lengths that followed a negative exponential distribution. This analysis suggested the fractures had mean true sizes of 15 to 40 m diameter.

Table 1. Fracture typology developed by BRGM. Modified version after Maqua (2003).

		1st digit	
		transit time characteristics	
2nd digit	persistance on amplitude image	open 1	close 2
	fully visible (>80%) **1**	11	21
	good visible (50-80%) **2**	12	22
	poor visible (0-50%) **4**	14	24
	uncertain **5**	15	25

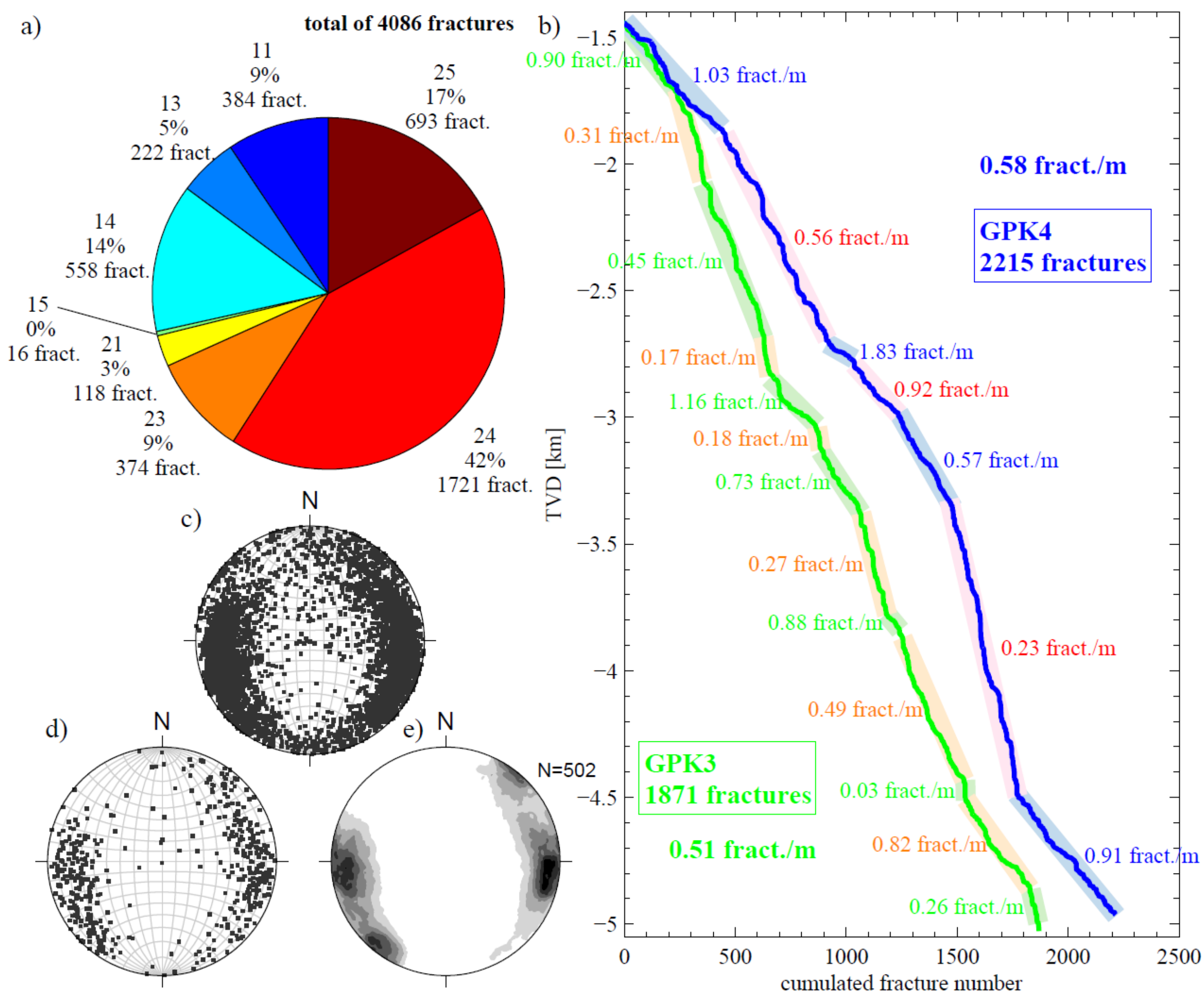

Figure 1. Presentation of the entire fracture data set from GPK3 and GPK4. a) Repartition of the fractures in the different types defined by the typology (see text for details). b) Cumulative number of fractures vs. depth. GPK3 is displayed in green and GPK4 in blue. Fractures frequencies are also displayed for various sections. c) Stereographic projection of the poles of all GPK3 and GPK4 fractures (lower hemisphere, equal area). d) poles of fractures of types 11 and 21 (80%–100% of the sinusoidal trace on reflectivity image) of GPK3 and GPK4 (lower hemisphere, equal area). e) Weighted contouring of the fracture density of fracture data presented on d). Weighting is performed for a Terzaghi correction (e.g. Priest , 1993, p. 71).

The distribution of fractures along the wells showed distinct clustering, reflecting the intersection of the well with fracture zones, which are composed of an anastomosed network of fractures delimiting shear lenses. Large variations in both the internal structure and the thickness of fracture zones were seen in their expression in wells only 10 to 20 m apart. The spacing of the fracture zones along the wells range from 40 to 400 m.

Collectively, the results are consistent with the notion that strain accommodation in the basement of the Upper Rhine Graben during its long tectonic history generated discontinuities at various scales. The inner architecture of the Upper Rhine Graben is made of tilted blocks delimited by faults whose length range from about 2 km to 20 km. Examples in the Soultz area are the Pechelbronn fault, the Surbourg-Kutzenhausen fault or the Hermerswiller-Soultz fault. Such faults build local horst and graben systems, have throws of 100 to 500 m, and typical spacings of 800 m to 3 km or even more. All of structures intersected by the boreholes are considered to be fracture zones rather than faults. Fracture zones are intermediate scale shear structures with a spacing ranging from about 40 to 400 m and sometimes less. The size of such structures cannot be determined from the image data. However, microseismic imaging shows they can extend over distances of at least several hundred metres (e.g. Evans et al., 2005). A length range of 50 − 500 m is considered to be a reasonable estimate.

The fracture zones and faults are the key hydrological elements of the geothermal reservoirs. The faults are thought to be structures of very large hydraulic capacity that form a connected network which governs large-scale fluid movement through the basement under natural conditions. However, due to their sparse distribution, few if any will be intersected by the wells. Fracture zones are also permeable features that have lower capacity than the faults but are more frequently intersected by boreholes. Moreover, experience has shown that the transmissivity of fracture zones can be increased by stimulation. Thus, stimulation of fracture zones can be used to link the boreholes to more significant hydrological structures such as faults. However, the heterogeneous architecture of the fracture zones may play a major role in their hydraulic behaviour by channelling the flow. This may explain the fact that only a limited number of fractures zones show clear permeability at the borehole wall. The orientations of the fractures zones were estimated at borehole wall and seem to be similar to the orientation of the small scale fractures, i.e. dominantly N–S striking dipping at about 60° to the west or to the east. East dipping fractures zones dominate in the upper part of the basement while west dipping structures dominate at the level of the deep reservoir. Single fractures that are not part of fracture zones do have enough connectivity to be hydraulically significant.

2.2 The linear characterisation of the state of stress at Soultz to 5 km depth

2.2.1 Introduction

The state of stress is a key parameter that must be prescribed to permit quantitative simulation of reservoir behaviour. Many studies of stress have been conducted for the upper reservoir, but none have carefully examined the data from the lower reservoir. Thus, observations of breakouts and drilling-induced tension fractures (DITFs) in the two 5 km deep boreholes GPK3 and GPK4, were combined with the analysis of pressure data from stimulation tests in all 3 deep wells to obtain a description of the state of stress in the granite down to 5 km depth.

An evident depth-partition in the style of failure is observed, with DITFs occurring predominantly and almost continuously above 2.2 km depth whereas breakouts predominate below 3.6 km. The DITFs can be divided into those aligned with the borehole axis, called axial-DITFs (A-DITFs), and those which form a small angle to the axis, called en-echelon-DITFs (E-DITFs). The latter indicate that one principal stress is not precisely aligned with the borehole axes, which is vertical for depths above 2.2 km. However, the E-DITFs are always fairly steep and deviate wit equal frequency to the east and to the west, suggesting that although local deviations from verticality of the 'sub-vertical' principal stress occur, reflecting stress heterogeneity as discussed later, on average one principal axis is vertical and the two orthogonal axes are horizontal. In the following we describe the results of the analysis for each attribute of the stress characterisation

2.2.2 Orientation of maximum principal horizontal stress, SHmax-orientation

The orientation of SHmax inferred from breakouts and DITFs in sections of the borehole that are within 15° of vertical is shown in Fig. 2. High confidence data are very consistent and collectively indicate an orientation of the maximum horizontal stress, *SHmax*, in the 5 km deep reservoir of N169°E±14°. This is in accord with previous results from the 3.5 km reservoir.

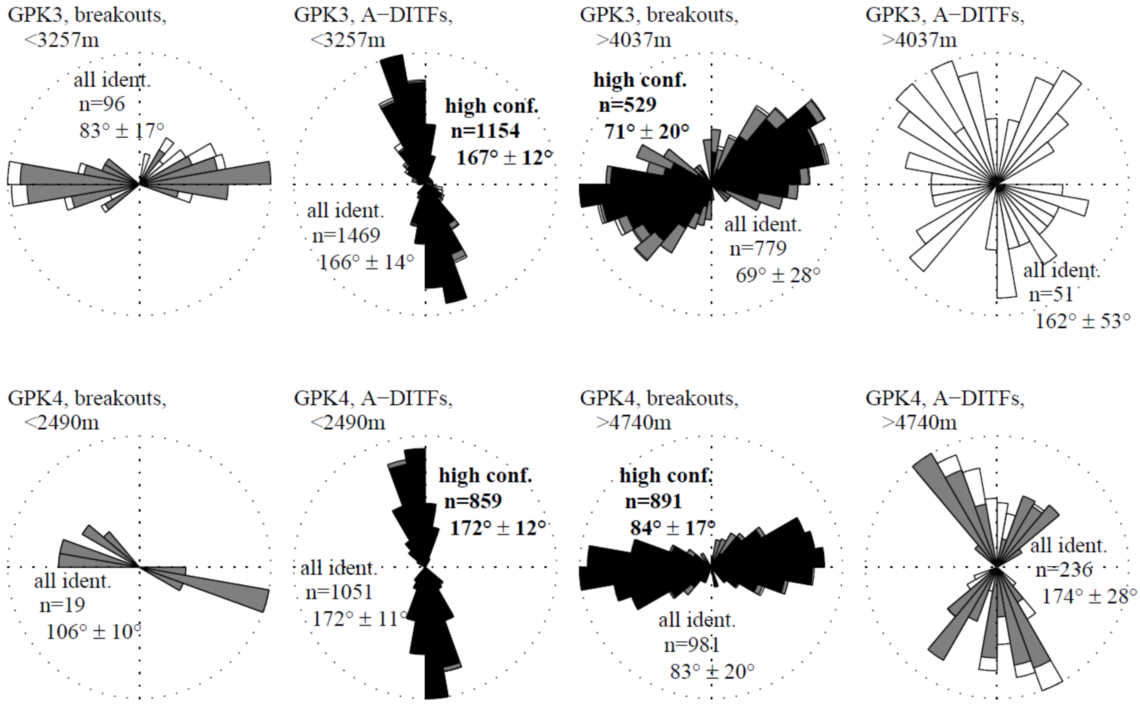

Figure 2. Circular histograms of breakout and A-DITF orientations along subvertical sections of GPK3 and GPK4. Sectors filled with black denotes high confidence data; grey denotes medium confidence data, and white is for low confidence data. The circular mean direction and single standard deviation are given.

2.2.3 Vertical stress magnitude, Sv

The magnitude of *Sv* was taken equal to the integrated density profile. This was estimated between zero and 898 m depth from regional density log surveys and lithology density estimates, between 898 m and 3600 m from gamma-gamma density logs run in well GPK1 at the site, and below 3600 m by taking the mean value from that logs run in the granite section above 3600 m. The results indicate an Sv profile for the granite described by:

Sv[MPa] = $-1.30+25.50z$[km] with a standard error equal to $\pm(0.98z$[km]$+0.6)$

2.2.4 Minimum horizontal principal stress magnitude, Shmin

The *Shmin* magnitude profile was estimated from the maximum pressures attained at the top of the injection intervals for all large-volume, high-rate injection tests conducted in the upper (to 3600 m) and lower (to 5000 m) reservoirs. This aspect of the work was conducted by KE Consulting, and is reported in this partner's section. Six estimates of *Shmin* at depths between 2000 and 4489 m TVD were obtained that were well-fit by the following linear trend (Fig. 3):

$Shmin$[MPa] = $-1.78 + 14.09z$[km] with an uncertainty of $\pm$ $(0.45z$ [km] $+ 1.82)$

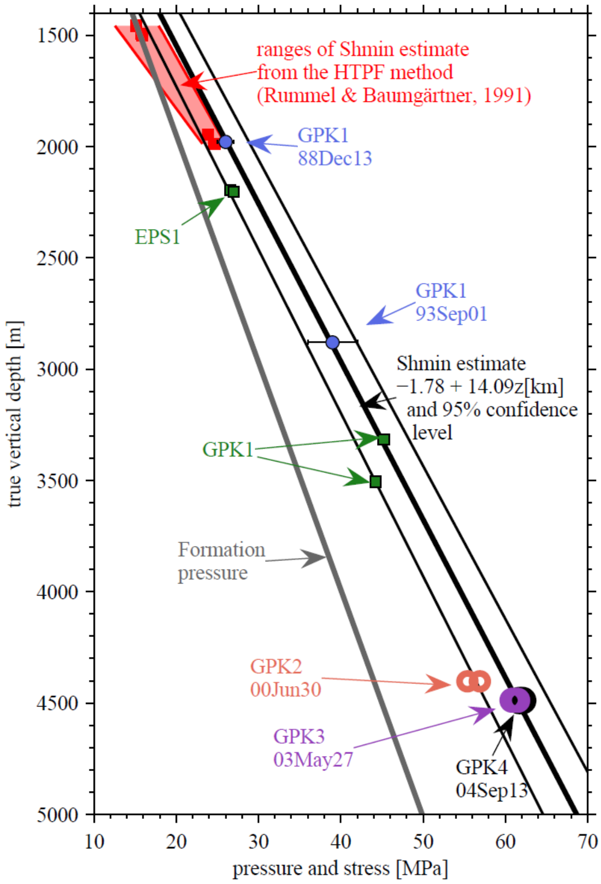

Figure 3. Estimates of *Shmin* from small-volume injection tests (squares) and large volume injection tests (circles). The well ID and, for the large volume injections only, the test number are indicated. The best-fitting linear trend to these data and the 95% confidence limits are denoted by the thick-black and thin-black lines.

2.2.5 Maximum horizontal principal stress magnitude, SHmax

Bounds on the profile of *SHmax* for the depth range 1400–5000 m were obtained from the observation that DITFs occurred primarily above 2.2 km, whereas breakouts occurred almost exclusively below 3.6 km. The analysis of the conditions for each type of wellbore failure to occur, or not occur as the case may be, used compressive strength estimates derived from uniaxial compressive strength (UCS) tests performed as part of the contract and reported in Section 2.4. The analysis also used drilling-related cooling stress estimates obtained from temperature sensors inside the logging sondes, and also MWD (measurement while drilling) estimates of mud temperature inside the drill bit. The resulting bounds limit *SHmax* to the range 0.7–1.2·*Sv* in the lower reservoir below 3.6 km, although the absence of breakouts near 3.5 km limits *SHmax* to be less than 1.0*Sv* (see Fig. 4) The results per se do not impose tight constraints on the magnitude of *SHmax*, and the best working hypothesis remains *SHmax* = 1.0Sv, as imposed by the observation of strike-slip and normal fault plane solutions. A corollary of the analysis is that the coefficient in the effective stress law for tensile failure is less than 0.8, possibly significantly so. *SHmax* estimates were also computed from measurements of the width and depth of the breakouts using two recently applied formulae (Barton & Zoback, 1988; Diederichs et al, 2004), and the results compared with the strict bounds obtained from the presence or absence of failure. Neither yielded an improvement on the bounds. However, it is clear that variations in the width of breakouts occur that are systematic and probably reflect stress heterogeneity.

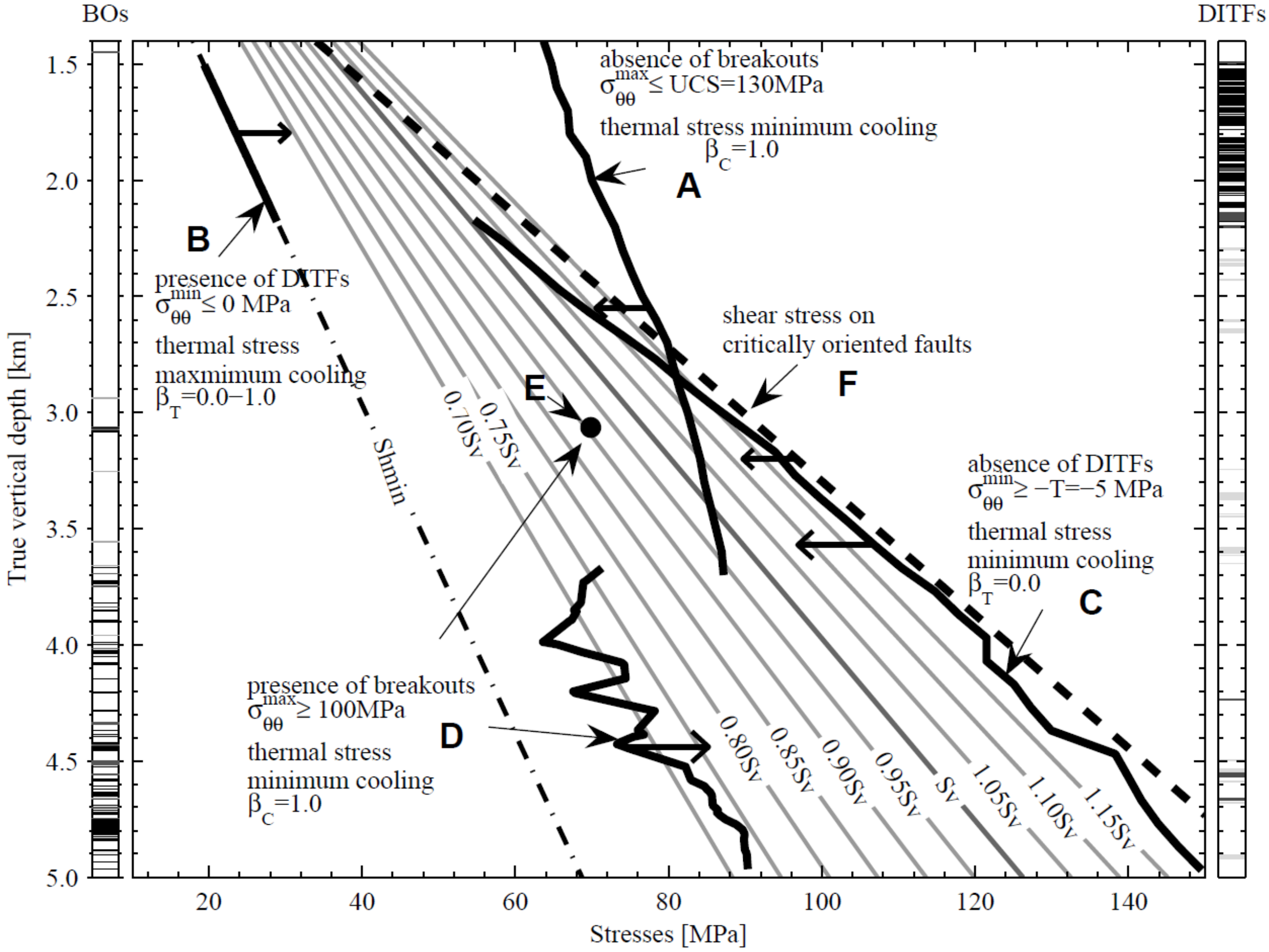

Figure 4. Constraints on *SHmax* magnitude placed by the presence or absence of DITFs and breakouts in GPK4. The arrow on the bounds indicates whether they are upper or lower limits. Contours of *SHmax* given as various fractions of *Sv* are shown to provide a reference background. Conservative values were used for all parameters used in deriving the bounds so as to yield absolute limits. The distributions of breakouts and DITFs along the well are shown at left and right respectively.

2.3 Stress heterogeneities in the Soultz granite inferred from analysis of wellbore failure to 5 km depth

Stress heterogeneity is thought to play an important role in many aspects of crustal mechanics, including the influencing of the space-time distribution and scaling of earthquakes. As such, it is likely to have some influence on the reaction of rock masses to massive fluid injection such as at HDR sites. Unfortunately, too little is known about the magnitudes of spatial variations of stress in the crust, primarily because heterogeneity is so difficult to measure. Breakouts and drilling-induced tension fractures (DITFs) observed in boreholes offer one the best direct methods of studying stress heterogeneity since they provide perhaps the best indication of the orientation of the principal stresses. DITF occur more or less continuously to 2.2 km depth in the 5 km deep boreholes, GPK3 and GPK4, and breakouts similarly occur below 3.6 km. Collectively, they indicate a mean orientation for the maximum horizontal principal stress (SHmax) at the site of N169°±4°. However, significant systematic variations in the orientation of the breakouts and

DITFs from their respective means are evident, which reflect the heterogeneity of the stress field along the trajectory of the holes. In this section the deviations are described and explanations for their occurrence sought. A novel feature of the study arises from the 20 m separation of the holes between 1400 m and 2400 m, where DITFs cover 55% of the borehole lengths, which allows the lateral coherence of the variations to be examined.

The variations are seen to occur at all scales, from relatively abrupt changes over a couple of metres, to gradual variations over scales of several hundred metres. Deviations in *SHmax* orientation from the mean of more than 90° occasionally occur. The variations of SHmax-orientation along the boreholes follows power law scaling with an index close to -2.0, indicating self-affine behaviour where variations appear progressively 'rougher' at shorter scales.

Two large long-wavelength (>100 m) variations occur in GPK3 at 2.0 and 4.7 km, and correlate with the two most prominent fracture zones penetrated by the wells. The lowermost variation occurs over a borehole length of ~400 m and is centred on a major fracture zone in GPK3. Deviations of SHmax-orientation from the mean of up to 90° and changes in the mode of failure from compression (breakouts) to tension (DITFs) are seen. The uppermost variation occurs where the wells are separated by only 20 m, and is only partly correlated between wells, indicating high spatial gradients in stress about the perturbing fracture zone (see Figure 5).

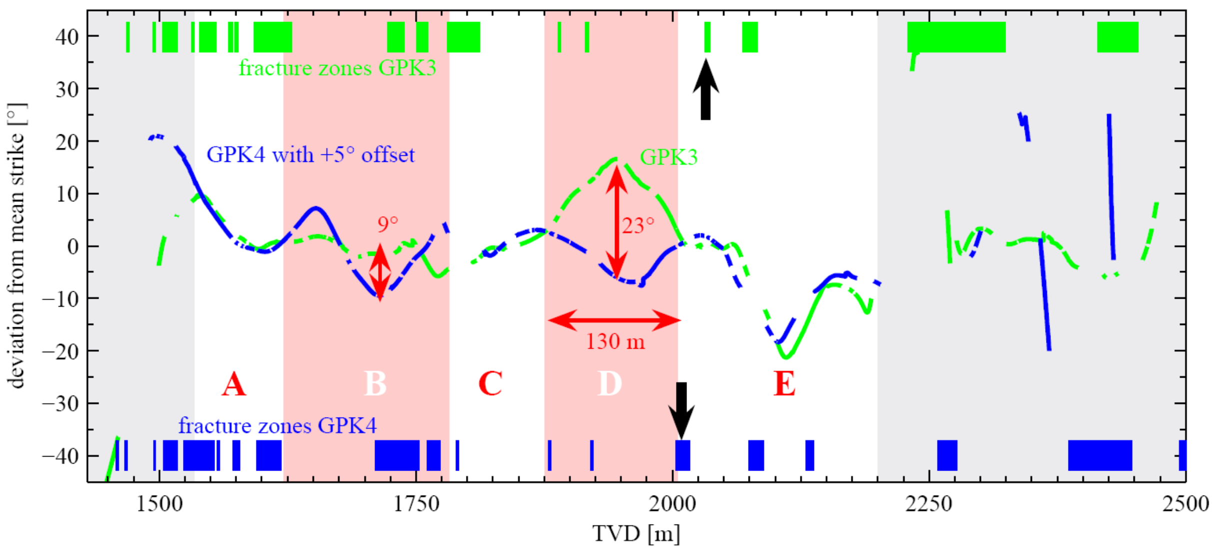

Figure 5. Superposition of the long wavelength components of the strike variations from GPK3 (green) and GPK4 (blue). In the upper part of the wells. Note that the curve for GPK4 has been shifted by 5° to compensate for the apparent systematic discrepancy in orientation measurement between the two holes. The two curves are essentially identical in zones A, C and E denoted by the white bands, but deviate significantly from each other in Zones B and D (light red bands). The distribution and width of fracture zones intersected in the two wells are shown at the top (GPK3) and bottom (GPK4) of the figure. Black arrows point to the major fracture zone crossed by the boreholes at about 2100 m.

Short wavelength variations in orientation occur more or less continuously and are usually associated with natural fractures, as are pauses in wellbore failure, and terminations of DITFs or their transformation from one sort to another, such as axial (A-DITFs) to en-echelon (E-DITFs). Little coherence is seen for short-wavelength variations between wells. These observations suggest the variations reflect the stress perturbations associated with slip of the fractures at some time in the past. Almost all fractures associated with stress perturbations are 'critically stressed' under the linear stress characterisation described in the earlier section (Figure 6). E-DITFs are often seen to form parallel to natural fractures, which typically dip at 50–70°. The parallel geometry suggests partial relaxation of shear stress from near critical level on the associated natural fractures, and can be explained as due to slip induced by momentary pressurisation as they are penetrated by the drill bit. Low shear stress levels on at least some of the fractures may also be pre-existing.

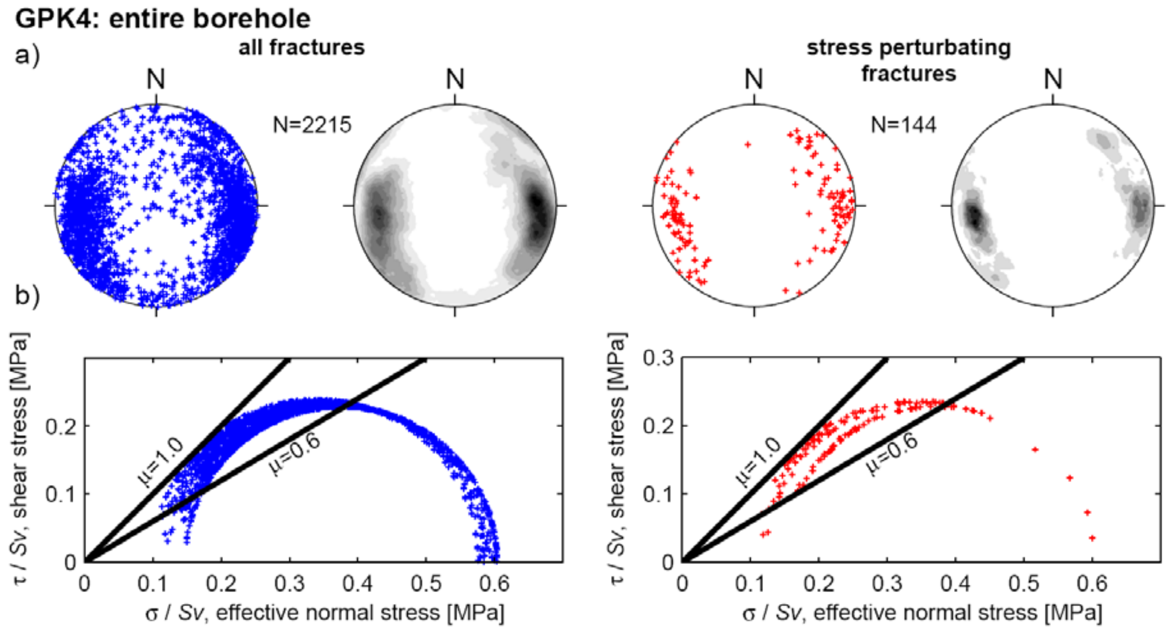

Figure 6. a) Stereographic plot of poles to all natural fractures identified in GPK4 (left) and the subset that were associated with stress perturbations (right). b) Mohr circle plots of the shear and effective normal stresses resolved on fracture sets in a). The stress was taken as given by the linear characterisation for Soultz and the pore pressure as ambient.

2.4 Determination of the uniaxial compressive strength of Soultz granite from laboratory tests on core

Uniaxial compressive strength (UCS) tests on 12 samples were performed in order to provide the data required to estimate SHmax. These were the first UCS tests performed on Soultz granite. A by-product of the tests were the estimation of static Young's modulus. There are several existing determination of Young's modulus against which the measured estimates can be compared to. The twelve samples were prepared by cutting 190 mm length sections from 78 mm core taken from borehole EPS1 and grinding the ends to produce a right circular cylinder that was as close as possible to the ISRM norms (Bieniawski & Bernede, 1979). The samples were selected so that they presented various degrees of pervasive and vein alterations, as described in Table 2. The tests were performed at constant strain-rate of about 0.075mm/min and comprised three loading cycles that reached progressively higher loads until the ultimate UCS was reached. Two of the tests were discarded due to incorrect loading cycles.

Table 2. Classification of alteration of the granite samples tested in uniaxial compression.

Pervasive alteration	
None (N)	Unaltered biotite K-Feldspar and plagioclase. This case is never met.
Low (L)	Biotites are black showing only little alteration into chlorite, plagioclases are milky and K-feldspars are grey or pink.
Medium (M)	Biotites become greenish showing advanced alteration into chlorite, plagioclase show beginning of greenish coloring reflecting alteration in epidote and K-Feldspars are less pink and more reddish.
High (H)	Biotites are totally transformed into chlorite, plagioclases are dark green trough transformation in epidote and K-Feldspars are reddish to orange.
Vein alteration	
None (N)	No visible trace of vein alteration.
Low (L)	Small fractures present a yellowish halo of vein alteration which does not penetrate the whole sample.
Medium (M)	Former biotites and plagioclases are yellowish, reflecting alteration to illite. No major fractures cross the sample.
High (H)	The sample is traversed by fractures and biotites and plagioclases are totally altered to illite.

The results of the tests are presented in Figure 7. UCS values ranges from 100 to 130 MPa for unaltered granite, and is unaffected by the strength of the pervasive alteration. Samples with weak vein alteration had UCS values that lay near the lowest values measured for the samples that had only pervasive alteration, and one sample that had high vein alteration had a UCS about 8 MPa lower than this. The Young's modulus of 'unaltered' Soultz granite was found to be 54±2 GPa, regardless of the degree of pervasive alteration. However, two samples with vein alteration showed a significantly lower modulus of 39 GPa.

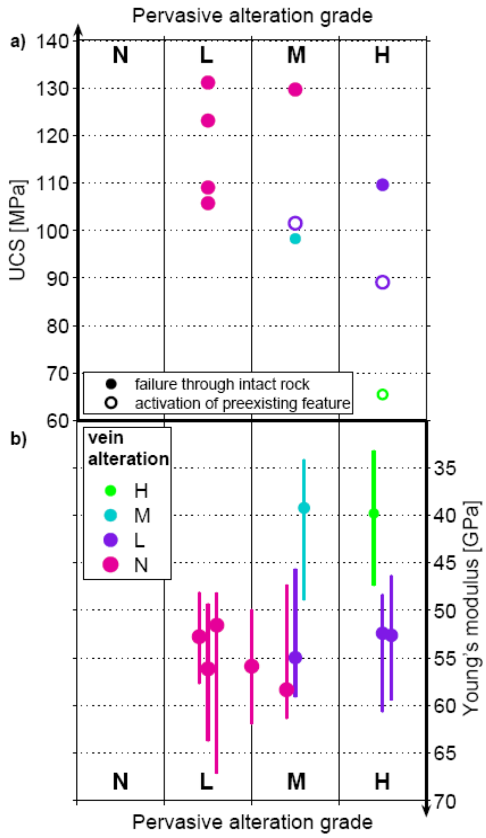

Figure 7. Illustration of the effect of the two types of alteration on the test results. The degree of pervasive alteration is indicated by the column, and the degree of vein alteration is denoted by both the colour and the size of the circles a) Results for UCS . Tests where sample failure occurred in intact rock are denoted as closed circles whereas those that involved activation of a natural fracture are indicated by open circles. b) Results for E-modulus. The ranges extend from Emin to Emax, and the circles denote Eavg.

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Section 4: Contribution from Keith Evans Consulting

ABSTRACT

Estimates for the magnitude of the minimum principal horizontal stress, Shmin, in the lower reservoir at Soultz were obtained from analysis of the downhole pressure records of the first hydraulic stimulations of the three wells penetrating the lower reservoir. The results indicate Shmin levels that lie on the extrapolation of the linear trends defined from tests conducted above 3.6 km.

The petrophysical properties of the Soultz granite were investigated by mineralogical analysis and poro-elastic testing of three samples: two with pervasive alteration and one with vein alteration. The density of all samples lay in the range 2.65-2.70 gm/cc, and connected porosity at atmospheric pressure was measured as 0.25-0.30%. Cyclical loading of the saturated samples to 70 MPa under partially-drained conditions in a testing machine indicated that the Biot's coefficient at atmospheric pressure was approximately 0.5, and that it declined with increased confining stress, perhaps to as low at 0.1 at 70 MPa effective confinement. The precise pressure dependence was somewhat uncertain owing to an increasing degree of undrained conditions at high stress due to decreasing permeability.

Source parameters of microearthquakes induced during the first stimulation of the upper reservoir at Soultz were used to evaluate the spatial variation of the b-value of the Gutenberg-Richter magnitude-frequency relation within the reservoir. Significant variations in value from 0.8 to 1.2 were found. Regions with lower b-values tended to host larger magnitude events and, provisionally, higher stress-drop events.

1. INTRODUCTION

The original work plan had four elements:

Assess the reasons for the difference in the hydraulic and seismic response of the upper (i.e. 3.5 km) and lower (i.e. 5 km) reservoirs at Soultz.

Determine the state of stress in the lower reservoir.

Perform a critical stress/permeability analysis for the lower reservoir, data permitting.

Participate in reservoir characterisation of the Basel reservoir if requested.

In 2005 SER/BFE were notified that task 3 could not be conducted because of data limitations, and that the Soultz administration had requested that K. Evans serve as chairperson of the newly-conceived Seismo-hydraulics Workgroup at Soultz, a task that had not been foreseen. It was proposed that task 3 be replaced with a laboratory determination of poro-elastic properties of the Soultz granite and support for K. Evans's costs in chairing the new workgroup. Original Task 1 was absorbed into the more general remit of the workgroup. More recently, it has become clear that the demands of the Basel project were negligible. Thus, this provisional task was replaced by work begun in earlier phases of the project on source parameters and scaling of seismic events generated in 1993 during stimulation of the upper reservoir. Thus, the contributions from KE Consulting that are presented in this report are:

Evaluation of the state of stress in the Soultz granite to 5 km depth.

Petrophysical properties of the Soultz granite from laboratory tests

Source parameters of microseismic events induced during the 1993 GPK1 stimulation

Activities the Seismo-hydraulics work group

Attendance at other Soultz Workgroup and EHDRA meetings

It should be noted that there is considerable overlap between the work conducted by KE Consulting and that performed by Engineering Geology. Almost all of the work reported in this section has been or will be published with the academic affiliation. The Annexes contain scientific publications based upon performed work.

2. WORK CONDUCTED

2.1 Evaluation of the state of stress in the Soultz granite to 5 km depth

This task was conducted in collaboration with Engineering Geology. This part describes the estimation of minimum principal stress datapoints for the lower (4.5-5.0 km deep) reservoir. The full stress profiles are presented in the partner's section.

No formal, hydraulic stress tests were conducted below 3.5 km from which Shmin could be estimated. Thus, the approach proposed by (Cornet and Bérard, 2003) was adopted which assumes that the maximum pressure attained at the casing shoe during large stimulation injections provides a direct measure of Shmin at that depth. This approach must be considered as tentative since it assumes the following conditions were met during the stimulation injections:

1. Pressure-limiting conditions were reached that are controlled by jacking and not shearing.

2. Near-wellbore pressure drops (i.e. entrance losses) due to flow focussing are negligible.

3. The minimum stress prevailing at the time of maximum pressure reflects the ambient stress and is not elevated by poro-elastic effects.

Violation of assumption 1 results in underestimation of the ambient minimum stress, whereas 2 and 3 would result in overestimates. These conditions appear to have been met for the large injections into the shallower reservoirs at 2.0 and 3.0 km, since the suggested Shmin profile of Cornet and Bérard (2003), which is based on maximum pressures during large volume injections, does not differ greatly from that determined from the small-volume injections. Here the method was applied to the first stimulation injection conducted in each of the three 5 km wells. The attainment of pressure-limiting conditions could be demonstrated in all three cases by evaluating steady-state pressures prevailing at two different flow rates. Furthermore, for two of these injections, flow rates were cycled up and down, thereby allowing the reversibility of the pressure response to be demonstrated. In these cases it is clear that jacking was the underlying pressure-limiting method, and hence that assumption 1 was satisfied. The validity of assumptions 2 and 3, however, remains uncertain, although it is likely that any overestimation in Shmin arising from the violation of assumption 3 is unlikely to exceed a couple of MPa (Evans, 2005).

The records of pressure and flow rate obtained during the initial hydraulic stimulations of the three 5 km deep wells are presented in Figs. 1-3. The maximum pressures inferred at the casing shoe during the injections are indicated on the figures and listed in Table 1. In all cases these pressures were measured downhole by a sensor located slightly above the casing shoe. The data were corrected to values at the casing shoe depths. It is evident that all data show pressure-limiting behaviour. The three datapoints from the 03May27 stimulation of GPK3 are from a sequence when the flow rate was stepped from 50 l/s to 70 l/s for 2 hrs and then back to 50 l/s. The small, reversible changes in pressure that accompanied the flow rate steps indicates that jacking was occurring, as required for the Shmin estimation procedure to be valid.

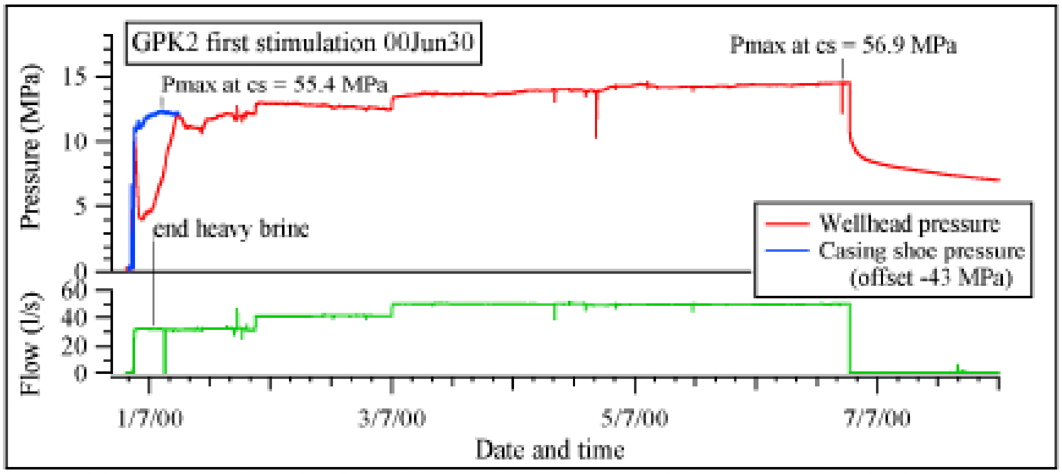

Figure 1. Pressure and flow during the first stimulation of GPK2 after deepening. The casing shoe lies at 4402 m TVD. The times at which the downhole pressure points listed in Table 1 were measured are indicated. The large difference in the wellhead and downhole pressure curves at the start is due to the use of a heavy brine slug.

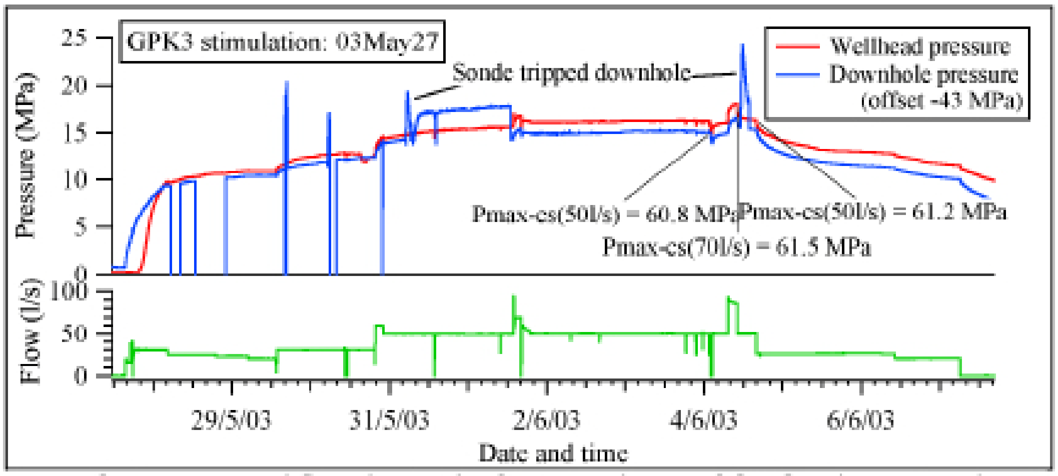

Figure 2. Pressure and flow during the first stimulation of GPK3. The casing shoe is located at 4488 m TVD. Times when the downhole pressure sonde was tripped downhole for logging are indicated, as are the times when datapoints in Table 1 were taken. The downhole pressure sonde is malfuctioning prior to 13:00 on 1/6/00 but is believed to be operating accurately thereafter.

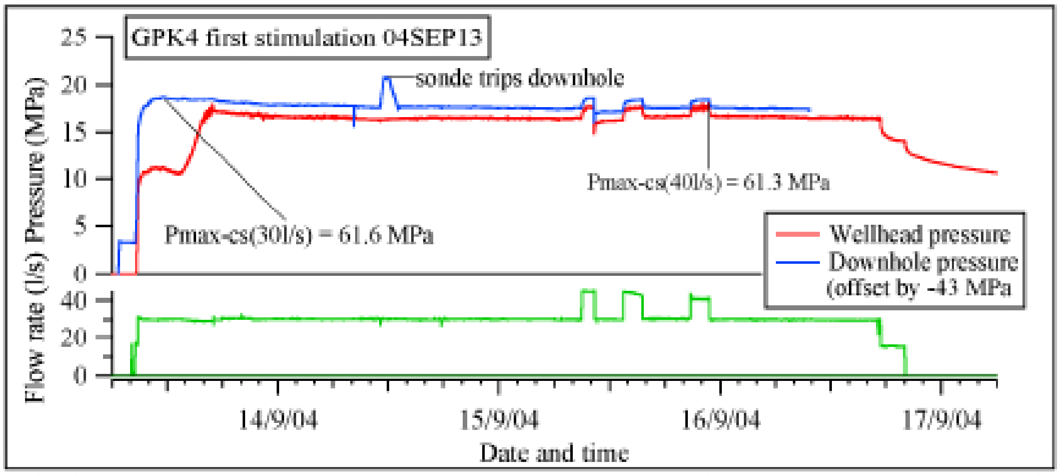

Figure 3. Pressure and flow during the first stimulation of GPK4. The casing shoe is located at 4489 m TVD.

Table 1. Maximum pressures recorded at the casing shoe during the stimulation injections of the three deep wells. The data denote the pressures prevailing at the end of injection stages with different flowrates.

Borehole	Injection test ID	Depth of casing shoe [m TVD]	Max. pressure at casing shoe [MPa]	Flow rate at max. press. [l/s]
GPK2	00JUN30	4402	55.4	31
GPK2	00JUN30	4402	56.9	50
GPK3	03May27	4488	60.8	50
GPK3	03May27	4488	61.5	70
GPK3	03May27	4488	61.2	50
GPK4	04SEP13	4489	62.1	30
GPK4	04SEP13	4489	61.7	40

The resulting estimates of Shmin are plotted as a function of depth in Figure 4, together with estimates from small- and large-volume tests in the upper reservoir. In fitting the data with a linear trend, only estimates obtained from large-volume injection tests were used because these are less sensitive to local stress heterogeneities. The Shmin estimates fall close to a linear trend, with the exception of the data points for GPK2 which are too low by about 4 MPa. It is noteworthy that pressure was continuing to slowly increase at the end of this stimulation (Weidler et al., 2002). This can be interpreted as indicating that the jacking pressure was not reached, although other explanations are possible. Because of this complexity, the GPK2 injection pressures were excluded from the fitting process. The resulting best-fit linear trend obtained from the casing-shoe injection pressures of the two GPK1 injections, the GPK3 and 4 injections is given by:

$Shmin = -1.78 + 14.09\, z[\text{km}]$ with an uncertainty of $\pm\,(0.45 z[\text{km}]+1.82)$ (1)

The uncertainty level is derived from the 95% confidence bounds on the linear best fit process, and is ±2.5 MPa at 1400 m depth and ±4.1 MPa at 5 km depth. This profile is very similar to that proposed largely on the basis of data from the shallow reservoir to 3.6 km in earlier studies (Cornet et al., 2007).

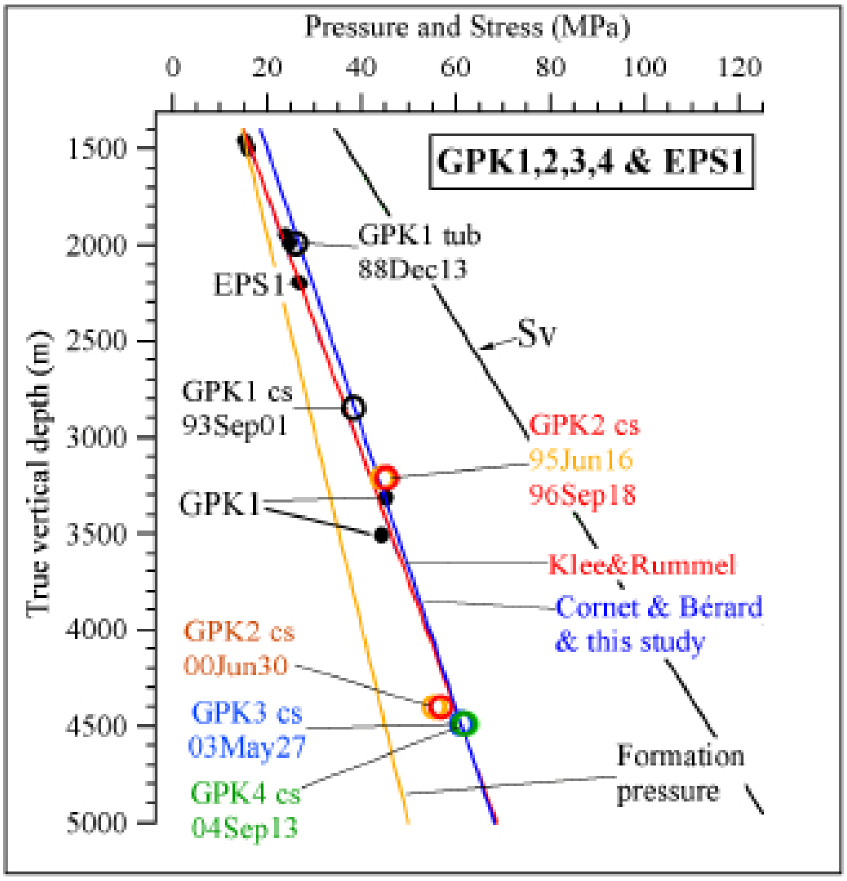

Figure 4. Datapoints defining the profile minimum principal horizontal stress, Shmin. The test number that defines the point is indicated. The best-fit linear trend that passes through the datapoints from large injections is denoted as 'Cornet & Bérard & this study'. The profile of Klee and Rummel extrapolated to the lower reservoir is also shown.

2.2 Petrophysical properties of the Soultz granite from laboratory tests

2.2.1 Introduction

Prior to this study there had been no laboratory determinations of the poro-elastic properties of the Soultz granite. The absence of estimates of Biot's coefficient is particularly notable, since several published studies of the hydromechanical behaviour of the rock mass have been forced to assume values (Evans, 2005; Shapiro et al., 1999). Thus, a laboratory study of the poro-elastic properties of several samples of Soultz granite was undertaken. Two samples of unaltered Soultz granite (samples 1 and 5b) and one of altered granite (sample 1) with diameter 54.3 mm and nominal lengths 107 mm were prepared at the ETH. All three samples contained large K-feldspar blasts, several centimetres in size, within the granitic matrix, and thus are decidedly inhomogeneous. The precise mineralogical compositions were determined by B. Valley at the ETH by inspection and thin section analysis and the results are listed in Table 2. Also listed are the density and porosity of the samples, measured by weighing dry and then wet, after saturating with water in a vacuum for several days. The saturated samples were then sent in sealed containers to the Technical University of Graz who performed the loading tests under contract.

Table 2. Petrophysical and mineralogical data for the tested samples

Sam-ple	Well	Depth	Alter-ation	Poro-sity	Dens-ity	Modal volume fractions			
		(m)		(%)	kg/m³	k-fel-spar	Plagio-clase	biotite	quartz
1	EPS1	1792.68	Perva-sive	0.25	2670	0.22	0.32	0.08	0.48
3	EPS1	1994	Vein	0.24	2650	0.32	0.45	0.07	0.16
5b	GPK1	3524	Perva-sive	0.31	2660	0.30	0.30	0.15	0.25

2.2.2 Sample preparation and testing

The tests at Graz were conducted by M. Blümel using an MTS machine. The samples were jacketed whilst still saturated, and then placed in the load train. The end-caps of the load train contained hydraulic lead-throughs (drill holes) that connected to an open, vertical stand pipe (Fig. 5). This arrangement was intended to try to keep the fluid pressure in the sample at atmospheric pressure during the loading cycles (i.e. maintained drained conditions), although this would be realised only if the load was applied sufficiently slowly to maintain drained conditions throughout the sample. The arrangement also allowed the water expelled/imbibed from the sample during the cycles to be estimated by measuring the change in head in the stand pipe with a pressure sensor. This water volume is a measure of the change in total connected pore volume of the sample, although it is only an exact measure if the deformation is fully drained. The samples were removed from immersion in water for 10-15 mins during their jacketing and installation in the load train. Once installed, the hydraulic system was filled with water, and the samples left for 2 days under 2 m of water head to re-saturate. Then the samples were subjected to two 'seasoning' cycles of hydrostatic pressure (i.e. confining and axial loads kept the same) to 20 MPa so that the jacket seated onto the sample. After seasoning, the strain gages were affixed to the jacketed sample. Two axial strains were measured with a pair of diametrically-opposite clip-on gages, and circumferential strain was measured with a chain (Fig. 5).

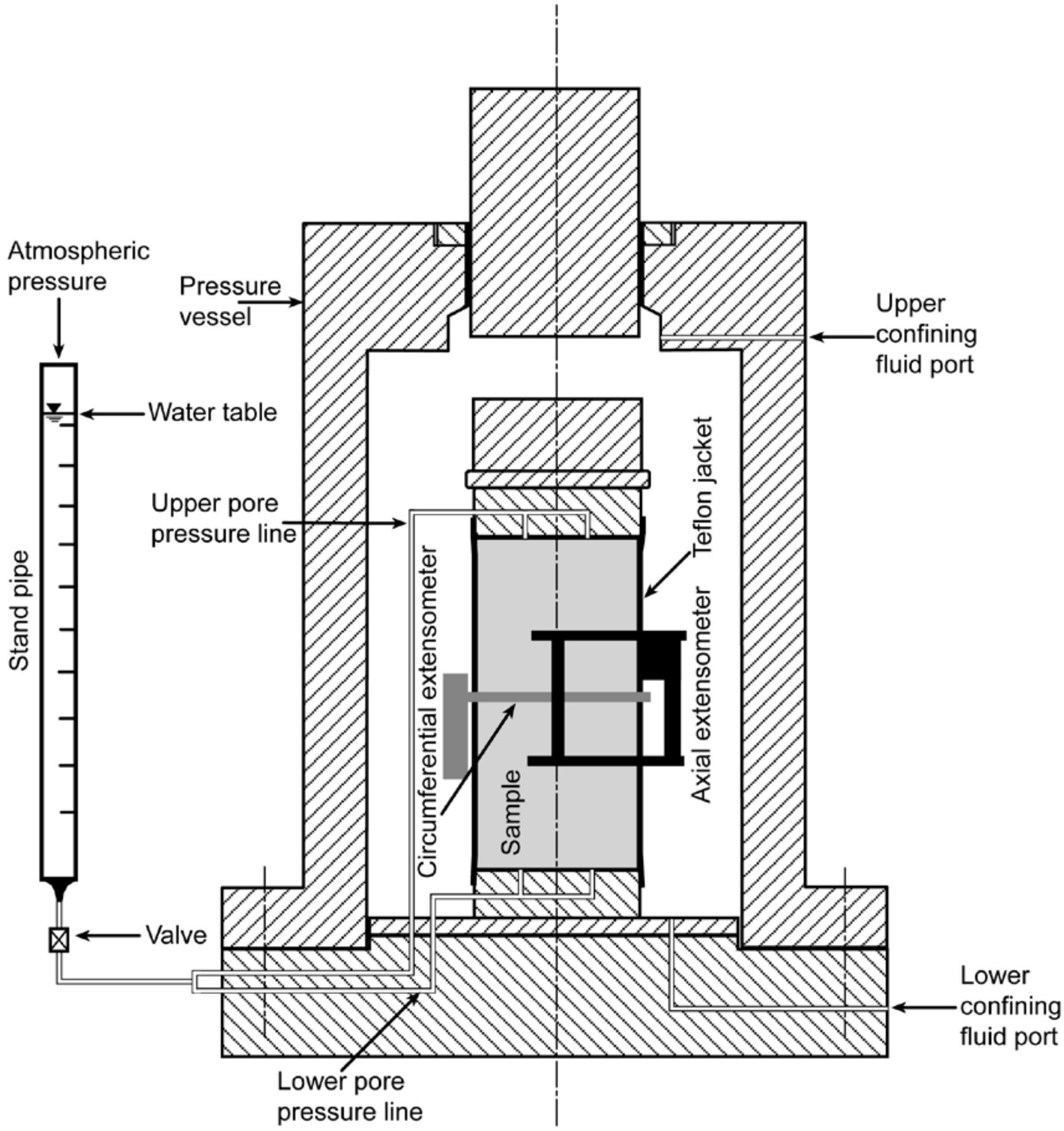

Figure 5. Set-up for the poro-elastic tests of the Soultz granite. The Sample is jacketed, but fluid can drain through the ports in the end caps. Two axial and a circumferential strain gage are attached to the sample after jacketing and seasoning.

The records from the test of sample 5b are shown in Figure 6. Each sample was subjected to two complete cycles of hydrostatic loading to 70 MPa in steps of 10 MPa. Pressure at each step was held constant for 6-10 mins before ramping to the next level at a rate of ~3 MPa/min. A single complete cycle took 2-3 hrs. The circumferential strain was corrected for the effect of the jacket thickness, and the axial gages corrected for a measured change in offset with pressure (i.e. the gages were tested unaffixed to a sample in the pressure vessel). Since the loading is hydrostatic, the strains recorded by the two axial and the circumferential gages should be the same, assuming the rock is isotropic. However, they were found to differ significantly, suggesting a calibration problem. Two sets of gages were used: one set for Samples 3 and 5b, and another for sample 1. To measure the calibration factors, identical hydrostatic tests were run on a sample of fused quartz, a material whose elastic constants are precisely known. The tests were run for the gage set used to test samples 3 and 5, but not for the other gage set. The calibration coefficients for each gage derived from the quartz tests differed from the original calibrations by 40-60% , indicating the latter were is error. Thus, the quartz calibration coefficients were used in analysing the data from the Soultz granite tests. However, the coefficients are only strictly valid for samples 3 and 5b, the calibration coefficients of the gage set used to test sample 1 remaining undetermined. As is evident from Fig. 6, the strains derived from the three gages using the quartz-derived calibrations agree reasonably well except for the initial pressure step which is due to jacket seating. Close examination of the data, however, shows that the circumferential gage suffers from significant hysteresis which affects the strain at the top and bottom of cycles. Thus, volume strains used in the calculations of elastic constants were computed from the average of the two axial strains (i.e. $\varepsilon_V = (3\varepsilon_A + 3\varepsilon_B)/2)$) rather than using all three gages (i.e. $\varepsilon_V = 2\varepsilon_C + (\varepsilon_A + \varepsilon_B)/2$).

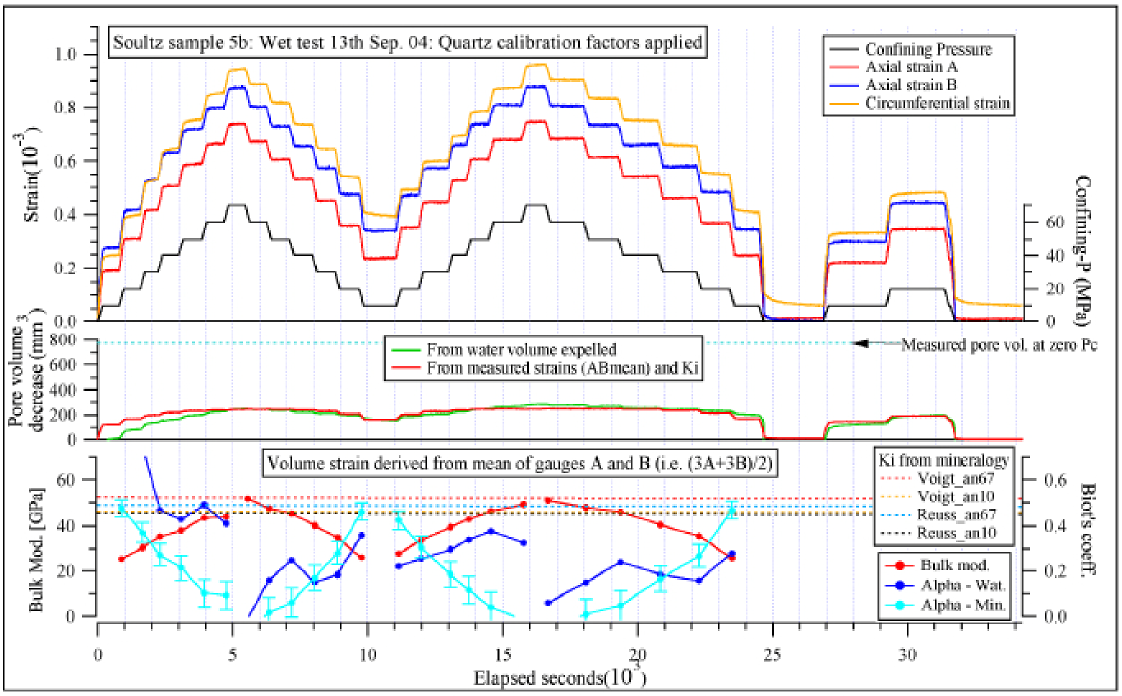

Figure 6: The upper frame shows records from the tests on unaltered sample 5b with strains calibrated using coefficients from the tests on quartz samples. The middle frame compares the pore volume change derived from the strain with the measured change in pore fluid volume. The lower frame compares Biot coefficient estimates derived from the measurements of fluid volume change with estimates derived from the inferred bulk modulus and the mineralogically-defined intrinsic modulus estimates.

2.2.3 Intrinsic bulk modulus, K_i, estimates from mineralogy

The computation of poro-elastic properties requires estimates for the intrinsic bulk modulus of the solid skeleton, K_i of each of the samples tested. The values were estimated by B. Valley of ETH from the mineralogy listed using the method of (Brace, 1965). Volume fractions for the key mineralogical components in the sample listed in Table 1 were used to derive upper and lower bounds on the bulk modulus of the aggregates. The principle uncertainties in the analysis stem from two sources. One is mineralogical in nature, and is the relative quantity of anorthite (as opposed to albite) that is present in the plagioclase feldspar fraction. Anorthite is 30% stiffer than most common rock-forming minerals and those has a disproportionate effect on aggregate modulus. Upper and lower bounds were set at 10% and 67% anorthite fraction, implying 90% and 33% of the plagioclase feldspar was albite. The second uncertainty is geometric in nature and arises from uncertainty as to the precise distribution of heterogeneous stresses and strains that develop inn the sample under deformation. Here upper and lower bounds are given by the internal deformation of the sample conforms to constant strain (Voight average of weighted mineral bulk modulii) and constant stress (Reuss average of weighted mineral compressibilities). The resulting bounds on the aggregate intrinsic bulk modulus (which are slightly pressure-dependent) are plotted for Sample 5b in the lower frame of Figure 6. The upper bound on stiffness is generally given by the Voight average with 67% anorthite and the lower bound by the Reuss average with 10% anorthite. For calculation purposes the intrinsic modulus of each of the 3 samples is taken as the mean of the four bounds and is essentially 50 MPa with a range of variation less than ±10 MPa.

2.2.4 Derivation of Biot's coefficient

Estimates of Biot's coefficient, α, as a function of confining pressure were derived in two ways. The first used a relation between a sample volume change, ΔV, for a load step and the resulting change in pore volume, ΔV_P, given by

$$\alpha = \Delta V_P / \Delta V.$$

In applying this relation, the net change in sample volume for each loading step was estimated from the product of the nominal sample volume V and the measured volume strain, ε_V. The pore volume change, ΔV_P, was taken as given by the fluid volume expelled/imbibed during the load steps, an assumption that is strictly true only if the sample deformation is fully drained. The curve of fluid expelled during the test of Sample 5b is shown in the middle frame of Fig. 6. Also shown is the curve of pore volume change predicted from elastic theory for the hydrostatic loading of an isotropic, homogeneous rock with and bulk modulus, K, and an intrinsic bulk modulus, K^i. This curve was derived from the relation (e.g. (Walsh, 1965)):

$$\Delta V_P = \Delta P_c(K^{-1} - K_i^{-1}).$$

The first term represents the change in volume of the sample, and the second is the change in volume of the solid constituent. There is reasonable agreement between the curves, especially since the Soultz samples are most certainly not homogeneous mono-crystalline materials, except for the first few loading steps which are probably affected by jacket seating. However, close inspection shows that the correspondence is also markedly poorer for points after a reversal in loading direction, reflecting hysteresis effects. The resulting estimates of Biot's coefficient are plotted in the lower frame of Fig. 6. The first point in each of the four segments should be ignored because they are effected by hysteresis. The points all lie between 0.1 and 0.4 with the estimates from the loading cycles being slightly higher than for the unloading cycles. No pressure dependence is evident for the loading cycles, and a weak dependence for the unloading cycles.

The second approach to estimating Biot's coefficient dispensed with the measurements of expelled fluid volume and used instead the pressure-dependent estimates of bulk modulus, K, derived from the volume strain and the estimates of intrinsic bulk modulus, K_i, derived from the mineralogy. From these values, Biot's coefficient can be estimated from:

$$\alpha = (1 - (K/K_i))$$

The values of bulk modulus for each of the loading/unloading steps for the test of Sample 5b are plotted in the lower frame of Fig. 6. Again, the first point of each cycle is affected by hysteresis and should be ignored. The values show stiffening with depth, and are consistent with an asymptote set by the intrinsic modulii estimates. The resulting estimates of Biot's coefficient are also shown in the lower frame of Fig. 6. The intrinsic modulus was taken as the mean of the four estimates for the different aggregates and assumptions. The values lie between 0.1 and 0.5, which is essentially the same as the estimates derived from expelled fluid volume measurements. However, the estimates show a clear pressure dependence with higher values corresponding to lower confining stresses. The estimates are also reasonably symmetric between loading and unloading cycles, although the tendency towards lower values for the unloading cycles that was prominent in the expelled fluid volume estimates is slightly manifest.

A possible explanation for the asymmetry in the Biot's coefficient estimates for loading and unloading cycles is that it reflects lower permeability of the sample under higher confining stress. It should be recalled that the confining stress was cycled between 10 and 70 MPa, and it is certain that the permeability of the sample was considerably lower at 70 MPa that at 10 MPa. Thus the time required for equilibration of pore pressure in the sample after a change in confining pressure is longer for higher pressures. Moreover, this equilibration time and the underlying permeability would show hysteresis since they reflect the closure and opening of the connected microcrack system within the sample. It is clear from the records of strain and expelled fluid volume that the steps were not long enough for the curves to stabilize, and that the degree of disequilibrium prevailing at the end of the steps, the time when the datapoints from which the Biot's coefficients and bulk modulus estimates were taken, was greater at higher confining pressure. Greater disequilibrium would lead to under underestimation of Biot's coefficient by both methods and over-estimation of bulk modulus. Thus, the low values of Biot's coefficient derived from the bulk modulus estimates at high confining pressure may be underestimates. However, at low confining stress, the strain and expelled fluid volume curves approach stability (i.e. the last unloading step of the first cycle), suggesting drained conditions were reasonably approximated. Thus, the Biot's coefficient values of 0.4-0.5 obtained at lower confining pressure are not considered to be significantly low.

2.3 Source parameters of microseismic events induced during the 1993 GPK1 stimulation

2.3.1 Introduction

In September 1993, the upper reservoir at Soultz was stimulated for the first time by the injection of 20,000 m^3 of water into well GPK1 between 2850 and 3600 m depth. Microseismicity was recorded with an array of downhole sensors. Source parameters for these events were computed by (Jones and Evans, 2001) from spectral analysis of the waveforms. By fitting a long-period flat level and a constant-slope, high-frequency roll-off to the displacement spectra, estimates of moment and source radius were obtained from which the stress drop of the events were estimated.

The results of (Jones and Evans, 2001) were used to investigate the spatial variation of microearthquake scaling within the reservoir. The moments of the events were transformed to moment-magnitudes using the relation given by (Hanks and Kanamori, 1979), and then a 3-D grid defined on the seismic cloud such that each element contained a sufficiently complete set of events to allow the slope, b, of the Gutenberg-Richter magnitude-frequency plot to be deduced. The b-values were then graphed in 3-D. The analysis was done by S. Wiemer of the ETH under contract, using his software ZMAP (Wiemer, 2001). An example of the results is shown in Figure 7. This shows an approximately north-south vertical section through the microseismic cloud shown by the red dots which denote hypocentres of events. The b-value derived from the frequency-magnitude of seismicity in the neighbourhood of a point is shown by the colour scale. It is evident that significant variations of b-value occur in different parts of the reservoir. The underlying cause of the variation is uncertain, although the variation of the b-value of natural seismicity has been linked to stress, with lower b-values tending to occur in regions characterised by high differential stress. In Fig. 7 we also plot the stress drop of events having a moment larger than 10^9 Nm. These are denoted by the blue circles with the circle size reflecting the magnitude of the stress drop. It is evident that high stress drop events tend to occur in regions of low b-value. Work is ongoing to validate the estimates of source size (and hence stress drop) obtained by (Jones and Evans, 2001) which were derived from an automatic curve-fitting routine.

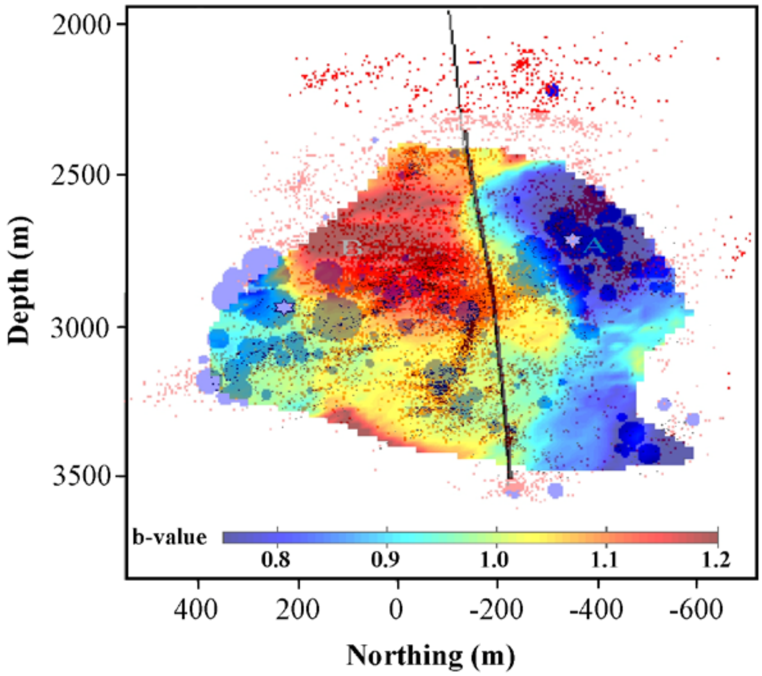

Figure 7. North-south section through the microseismic cloud (red dots) with the b-value shown in the colour scale. Significant variations in b-value occur. The locations of high stress-drop events are shown by the large circles with the symbol size scaled to the stress drop. The high stress-drop events tend to occur in regions of low b-value.

2.4 Activities of the seismo-hydraulic workgroup

Since its inception in April 2005, there have been seven meetings of the seismo-hydraulics workgroup (see Table 3). The objective of the workgroup was to provide a forum to discuss issues of contention in the interpretation of seismic and hydraulic data. Thus, most meetings featured focussed discussion of a couple of themes. However, in the past year, the focus has changed towards the production of summaries documenting the progress, accomplishments and lessons-learned in seismics and hydraulics since work began at Soultz in 1987. Work in drafting these reports is on-going and will be concluded in the next project phase. Progress reports were presented at the 2008 Scientific Meeting at Soultz.

Table 3. Meetings of the Seismo-hydraulics workgroup

Date	*Location*	*Objective*
29 Apr 05	Soultz	Organisational meeting.
2 Jun 05	Soultz	Discussion of several issues in seismics.
16 Sep 05	Strasbourg	Discussion of several issues in reservoir hydraulics.
19 Jan 06	Soultz	Discussion of reservoir geomechanics with Cornet.
11 Dec 07	Soultz	Begin formulation of summary paper of accomplishments in hydraulics and seismics.
16 May 08	Soultz	Discussion of seismics issues for position paper.
26 Aug 08	Soultz	Discussion of the fidelity of downhole instruments and the outcome of seismic hazard studies.

2.5 Attendance at other Soultz workgroup and EHDRA meetings

K. Evans also attended some meetings of the Modelling workgroup and the Borehole Geophysics and Tectonics workgroup since there is clear overlap with the activities of the Seismo-hydraulics workgroup. In addition, K. Evans was requested to attend the last four EHDRA meetings since the preparation of a document summarising the Soultz project was on the agenda.

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Section 5: Contribution of Geowatt AG

ABSTRACT

The presented works consist in evaluations of performances of the borehole of the Soultz project and of an evaluation of conducted reservoir development strategies. Numerical code development and prediction of stimulation results were also conducted.

The methodology of work using different numerical tools is presented in introduction. In a second step, the conducted works are exposed and the content of the 18 technical notes that were delivered to Soultz EEIG since 2005 is detailed. The timeframe of the different tests treated by GEOWATT AG is also given. The results obtained or emphasized by the conducted works are then exposed, with respect to the work packages classification. Special attention is paid to the evolution of the borehole injectivity/productivity indexes, which is quantified, using the borehole simulator HEX-B and characterized, using the reservoir simulator HEX-S. It appears that the injectivity/productivity indexes of the boreholes GPK3 and GPK4 almost continuously increased during the last 3 years, thanks to the multiple stimulation campaigns realised in the reservoir of the Soultz-sous-Forêts site.

Finally, the publication/communication materials derived from the performed works –that are available- are listed and referenced at the end of the document.

1. INTRODUCTION AND METHODOLOGY OF WORK

The use of geothermal energy via the EGS technology is based on a successful creation and operation of a subsurface heat-exchanger. At the Soultz site different reservoir stimulation and characterisation tests have been carried out, mainly for GPK3 and GPK4. An overview is given in Figure 1.1. The work performed by GEOWATT AG in the framework of the Swiss EGS R&D group can be summarised in 4 major tasks:

- Evaluation of the production/injection performance of the boreholes

A major task during an EGS reservoir development is the evaluation of the success of specific stimulation activities. Typically the so-called productivity index PI and injectivity index II is used to characterise the hydraulic performance of a borehole. These values have been supplied in the units "litres/second/MPa" and are derived from hydraulic tests, where the pressure at reservoir depth is needed. If downhole data are not available the downhole pressure at reservoir depth must be calculated using wellhead data. This was done with the borehole simulator HEX-B which takes into account the dynamic change of fluid density in the borehole due to the time history of fluid salinity and temperature exchange with the borehole wall during hydraulic tests (Mégel, 2005). Most of the hydraulic tests conducted within this project period have been evaluated. The results are given in the appended technical notes; a summary of the technical notes is tabulated in the next section of this report. An extended version of the software, called HEX-B2, is installed at Soultz for on-site use.

- Evaluation of reservoir development strategies and prediction of stimulation results

The crucial task in the development of a subsurface heat exchanger is the controlled creation of permeability in a given host rock. In close vicinity of a borehole the permeability of fractures can be improved by acidification. However, to achieve in a volume of several hundred meters diameter a sufficient permeability the method of hydraulic over-pressurising of existing fractures and bringing them to fail is seen as the most promising technology. Hydraulic stimulation of existing fractures is a massive intervention into a local physical equilibrium. Therefore the development of instruments and methods for planning stimulation strategies is of paramount importance. The understanding of the dynamic hydro-mechanical processes in a fractured reservoir is essential for the development of tools with predictive capabilities. In the framework of this project phase the reservoir stimulation code HEX-S has been used (Kohl & Mégel., 2007). Two purposes have been pursued: Evaluation of the codes effectiveness to predict stimulation processes and evaluation of the stimulation concept proposing the simultaneous injection into both boreholes (dual injection).

- Workgroup Modelling (WG 5)

The Soultz Workgroup Modelling WG 5 is constituted of different European research teams working on reservoir modelling. This workgroup is chaired by Thomas Kohl (GEOWATT AG) since 2005. The purpose of this Workgroup is to share information and data, and to exchange points of view on reservoir processes and mechanisms and to discuss different simulation approaches. The Workgroup usually meet once a year; the last results/developments or issues concerning modelling activities of the different teams are exposed.

Some publications concerning modelling efforts in Soultz have been published by the entire Modelling Workgroup. For example, contributions of the workgroup were presented at two EHDRA meetings during the last years (Baujard et al., 2007; Kohl and Baujard, 2008). One of the most important activities is the position paper for the EU (Baujard et al., 2008) with milestones of the past efforts and future perspectives of the modelling at Soultz.

- Support for the development of the FRAChem code

Another part of the reservoir modelling was focused on the code FRAChem, an adaptation of the numerical code FRACTure allowing hydro-chemical transport processes computations. This activity was developed with the CREGE.

2. CONDUCTED WORKS

2.1 Evaluation of the production/injection performance

Since 2003, the data of several hydraulic tests performed in Soultz (production, injection, acidization or stimulation) has been evaluated with the borehole simulator HEX-B. The results have always been sent to Soultz. The timeframe of the different tests treated is shown in the next figure.

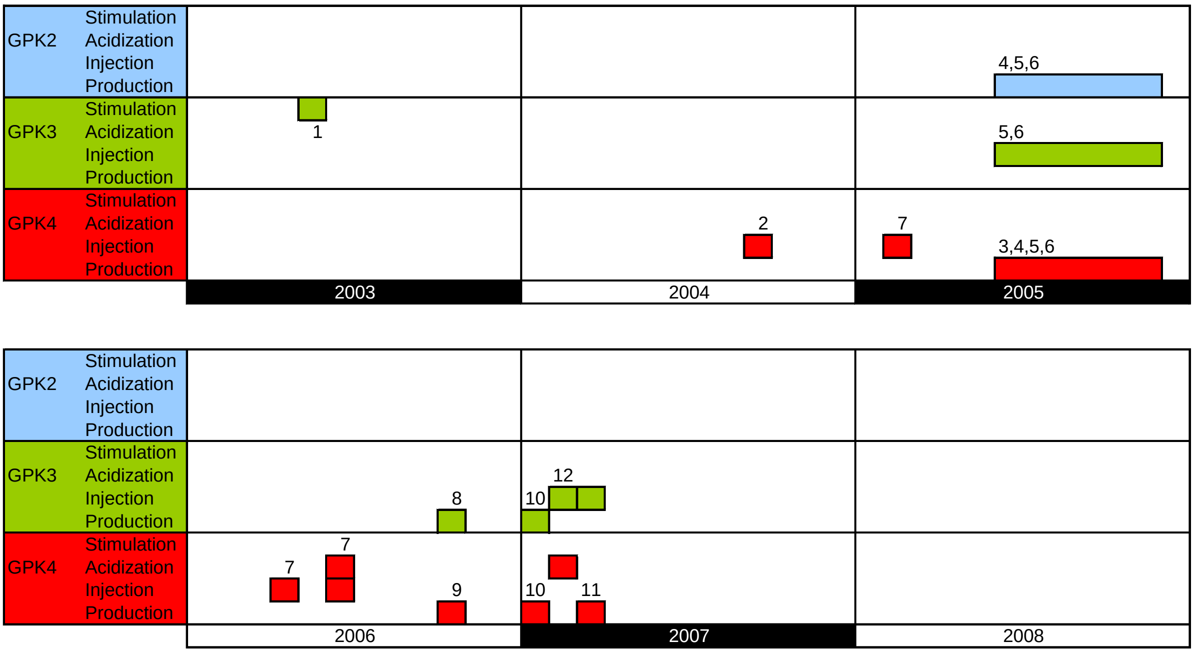

Figure 1. Timeframe of the different tests treated by GEOWATT AG. The length of the tests is only indicative. The indicated numbers point on the various technical notes, see next tables.

The correction/interpretation of these tests is reported in several technical notes. The technical notes are listed in Table 1. Different kinds of work can be distinguished:

- Derivation of downhole parameters from borehole model and surface parameters, in case of downhole sensor breakouts or if no sensor was used
- Quantification of stimulation/acidization success. As HEX-B allows deriving the downhole parameters, it can compute the injectivity or productivity (ratio flowrate per pressure change) of the well for any well history (even if the equilibrium was not reached) at the beginning of the test. The corrections then allow to compare two similar tests realised in different initial pressure conditions, and thus to quantify the success of reservoir developments operations.
- HEX-B was also used to predict the production temperatures (i.e. quantify the heat losses in the borehole) for different flowrates, in order to dimension the surface installations at best.

Table 1. List of data correction/interpretation carried out with HEX-B. The numbers on the first column correspond to the number referenced in the previous figure.

	Name of note	*Date, name of test*	*Borehole*	*Content*
1	TN2	14.1.2005 **03MAY27**	GPK3	Correction of downhole pressure GPK3 of stimulation test 03May27: extended corrections of the measured values at 4544m and 4244 m MD. These results have also been presented at the WGC2005 (Mégel, 2005). 2 data files sent to Soultz with the calculated pressures at the depth of the downhole tool (2 depths) and for 4544 m MD (corresponds to the casing shoe).
2	TN4	24.9.2004 **04SEP08**	GPK4	Pressure, temperature, injectivity index and fracture failure pressure during the low rate injection test 04Sep08 at GPK4. Calibration of the initial state with the measured values at 6.9.2004. Very good fit of the measured downhole values for temperature and pressure during the test over 350'000 s (~100 hours).
3	TN8	13.7.2005 **05JUL05**	GPK4	On 4th July 2005 a 2 days production test has been carried out at GPK4. Production was enabled only by buoyancy (thermosyphon). Interpretation of the measured values at wellhead/surface for pressure, flow rate and temperature.
4	TN10	25.7.2005 **05JUL11**	GPK2 GPK4	Productivity index for GPK2 and GPK4, production was enabled only by buoyancy (thermosyphon). This technical note is a prolongation of TN8.
5	TN11	11.08.2005 **05JUL11**	GPK2 GPK3 GPK4	Injectivity index for GPK3, on 11th July 2005 the circulation test 05jul11 has been carried out, with GPK3 as the injection borehole and GPK2 and GPK4 as production boreholes.
6	TN16	11.8.2006 **05JUL11**	GPK2 GPK3 GPK4	Analysis of the 180 days lasting circulation test by calculation of downhole pressures for 4500 m TVD and the corresponding apparent injectivity/productivity indices, as discussed in the paper for the scientific meeting Soultz 2006 (Mégel et al., 2006).
7	TN17	26.5.2006 **06MAY26**	GPK4	Analysis of the success of the acidification test with the test 06April24 prior and test 06May29 after acidification. Improvement of injectivity by nearly 30%.
8	TN19	26.09.2006 **06OCT09**	GPK3	Calculation of downhole pressure from a production test realised in well GPK3 on 09.10.2006.
9	TN20	7.11.2006 **06OCT24**	GPK4	Production test of GPK4. Data Files only
10	TN21	8.2.2007 **07JAN15**	GPK3 GPK4	Calculation of productivity index from a production test realised in well GPK3 and GPK4 on the week of 15.01.2007.
11	TN22	14.3.2007 **07MAR05**	GPK4	Calculation of the productivity index from a production test realised in well GPK4 on the week of 05.03.2007. Increase of the productivity index from 4 l/s/MPa to 5 l/s/MPa.
12	TN23	21.3.2007 07FEB07 07MAR11	GPK3	Calculation of the injectivity index from two injection tests realised in well GPK3 on 07.02.2007 and 11.03.2007, quantification of the injectivity improvement due to OCA injection which was preformed between both tests. The increase of injectivity due to OCA injection in GPK3 is estimated as 7%.
	TN9	1.4.2005	GPK4	Thermal previsions in GPK4, calculations for injections of 10 l/s and 15 l/s during 12 hours and 24 hours to evaluate the cooling effect *(en français)*.
	TN18	27.11.2006	GPK2 GPK4	Calculation of production temperatures of wells GPK2 and GPK4 at various production flowrate in order to allow dimensioning of an ORC conversion unit. Various production flowrates are tested for each well.

2.2 Evaluation of reservoir development strategies and prediction of stimulation results

Different modelling activity has been carried out to improve reservoir development schemes that are based on numerical implementation of physical processes of hydraulic and fracture mechanics. This was done on mainly three aspects:

- Since the complexity of the behaviour of a fractured reservoir cannot be represented from well testing and logging data alone, sophisticated modelling approaches are required. As such, the numerical code HEX-S can be used to validate/invalidate conceptual geometrical and parameter conditions (Kohl and Mégel, 2007).
- As example of its future applications and capabilities, the reservoir simulation HEX-S was used to evaluate the impact of different reservoir assessment strategies, like dual-well stimulation. The impact of the use of heavy brine during the initiation phase of a hydraulic stimulation using the borehole simulator HEX-B (Mégel et al., 2006).
- The code HEX-S was also used to predict the results; this was realised for the first stimulation of the well GPK4, for which the locations of the microseismic events were predicted (Kohl and Mégel, 2007).

This field of activity lead to several publications/talks. They are listed below (for technical notes released for Soultz EEIG) and at the end of the document for the more open contributions.

Table 2. List of technical notes linked with reservoir assessment

Name of note	*Date*	*Borehole*	*Content*
TN3	23.7.2004	GPK4	Short Note on Strategy Planning for the Stimulating of GPK4: Design of an advantageous injection strategy for GPK4, to improve the borehole wall transmissibility in the deep part of the open hole section. HEX-B calculations for the injection of the brine into GPK4 without exceeding the failure pressures of the fractures, derived from the HEX-B calculations at GPK3. Result was a proposed injection rate and duration.
TN5	24.9.2004	GPK4	Prognosis and conclusions for the 1st Stimulation Phase of the 04sep08 stimulation test at GPK4, 13-16 September 2004: HEX-S calculations of the overpressure and the fracture failure, comparison with measured values. Results presented on different conferences.
TN12	29.7.2006	GPK2 GPK3 GPK4	Proposition of a circulation scheme, discussed with André Gérard.
TN15	26.4.2006	GPK4 GPK3	Proposal for hydraulic stimulation of GPK4 – (GPK3), Microseismic locations density of GPK4 evaluated, identification of the possible hydraulic characteristics of the zone between GPK3 and GPK4, transient hydraulic calculations with HEX-S for 3 stimulation scenarios for GPK4.

3. RESULTS

3.1 Work Package 1 and 2: Code FRAChem improvement

In cooperation with CREGE the code FRAChem for hydro-chemical transport processes has been strongly improved. FRAChem helps to understand the role of long-term fluid-rock chemical interactions due to the circulation through the reservoir (Portier et al., 2007). The restriction of rectangular fracture geometries was modified to a more flexible treatment of arbitrary numerical meshes, which resulted also in a much faster calculation speed. The new extension allows now to combine multidimensional finite element discretisation schemes (i.e. 2D fractures next to a 3D rock matrix). The effects of more complex geometries including also sensitivity analyses have been performed by CREGE.

3.2 Work Package 3: Up-scaling of stimulation/hydraulic testing method

Hydraulic stimulation and testing of a reservoir after a second or third borehole has been drilled leads to more flexibility for reservoir creation strategies. On the other hand it has to be distinguished between single-well tests and multi-well tests for the characterisation of the borehole performances.

A major goal in the creation of the subsurface heat exchanger of an EGS is to increase the permeability between the future injector and producer wells. One concept proposes the simultaneous injection into both boreholes (dual injection). Calculations with HEX-S have been carried out to evaluate the effectiveness of a this concept. The time-dependant pressure development in the reservoir model from a single injection and a dual injection have been evaluated using the boreholes GPK2 and GPK3 as injectors. Both calculations have been carried out for 10 hours of injection. A comparison between both injection strategies shows clearly that the hydraulic pressure in the middle part between the wells increases faster when both boreholes are used as an injector at the same time. Hence the fracture failure pressure in the middle part between the wells will be exceeded faster with a dual injection. This seems to be advantageous with respect to the wish of limited duration of injection tests with limited volumes of injected fluid.

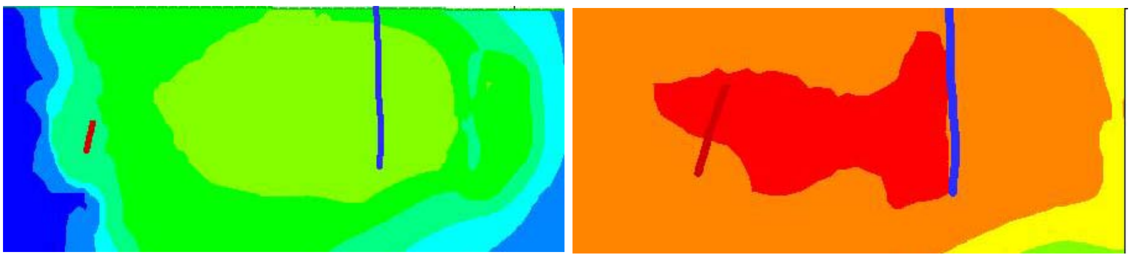

Figure 3. Hydraulic pressure field of hypothetical single versus dual injection tests. The left frame illustrates the effect of a single injection test with GPK3 (blue) as injector and GPK2 (red) as producer. The right frame shows the pressure field of a dual injection test in GPK2/GPK3 (flow is dissipated through external faults). Since a flow rate of 30 l/s is assumed, the pressure field reaches 15 MPa in the centre of both boreholes under dual injection conditions and only 10 MPA next to GPK3 in the single injection mode.

For the determination of hydraulic borehole performances principally it must be distinguished between productivity/injectivity index-values derived from single-borehole tests and from multi-well tests. Due to the mutual hydraulic influence of neighboured boreholes in multi-well tests values from these two kind of tests must not compared.. Values from single-borehole tests are useful for the evaluation of success of stimulation activities, values from multi-well tests are needed to evaluate and predict the performance under a future production operation. However, the turbulent behaviour has to be taken into account if test results are scaled up to operation parameters. The following tables provide an overview to the results of our analyses characterizing the success of stimulation activities at Soultz between 2005 and 2007.

Table 3. Evolution of Injectivity/Productivity indexes in GPK3

		06Oct06	07Jan15	07Feb07	07Feb15	07Mar11
GPK3	Q [l/s]	7	8	24	OCA inj	24
	Inj.			3.5		3.7
	Prod.	5.7(*)	4.15			
	%					+7%
	Source	TN19	TN21	TN23		TN23

(*) not in equlibrium conditions

Table 4. Evolution of Injectivity/Productivity indexes in GPK4

		05Feb22	06April24	06May17	06May29	07Jan15	07Feb21	07Mar05
GPK4	Q [l/s]	26	24	ACID inj	24	7	OCA inj	9
	Inj.	2	3		4			
	Prod.					4.05		5
	%				+25%			+20%
	Source	TN17	TN17		TN17	TN21		TN22

3.3 Work Package 5: Methodology for stimulation of EGS

The hydro-mechanical code HEX-S has been developed to calculate the stimulation processes in a fractured reservoir during massive injection into a borehole. The code takes into account the aperture change of each fracture in the model due to the corresponding overpressure resulting from the injection. The propagation of the overpressure in the reservoir as well as the development of the anisotropic permeability in the fractured reservoir as a result of the fracture apertures is calculated as a time-dependent process. The permeability distribution in a HEX-S model depends essentially on the location, orientation, aperture and extent of the incorporated fractures. HEX-S allows defining an arbitrary number of both, stochastic and deterministic, fracture sets. Experience from various EGS test sites demonstrates that microseismic events often follow planar structures. Since it is assumed that induced microseismic event represents mostly shear failure of a part of a fracture surface area, the locations of the calculated shearing events can be compared with the microseismic clouds, However. mode I events remain unidentified. The time-dependent pressure calculation in HEX-S is performed with a continued development of the FRACTure code. The hydraulic conductivity for each element is derived from the apertures of the intersecting fracture sets by a specific mapping procedure. Thereby, the hydraulic properties of the FE grid are modified after each time-step. HEX-S calculates the pressure in the model and determines the new apertures of the fracture sets.

In TN5 it is demonstrated that the code is not only suited to explain or forecast the hydro-mechanical reservoir behaviour due to massive flow injection but also to design future stimulation tests. It has been concluded that the hydraulic re-stimulation of GPK4 inherits the risk of low further efficiency. A data analysis of the 2004 and 2005 stimulations has shown that the microseismicity does not strongly develop beyond a near subvertical E-W striking plane. This plane was determined from an analysis of located microseismic events condensed into cubes 50x50x50m3 of volume. This zone has certainly a different hydraulic characteristic and will play a key role during future stimulation. However, the characterization is ambivalent with arguments support a characterization as highly conductive zone (1) Fingering of microseismic density; 2) No increase of the density of microseismic events once zone reached and injection continues; and 3) the intersection of this plane with GPK4 above the casing shoe, high fluid-losses have been encountered during drilling). On the other hand also arguments can be found for a characterization as high impedance zone (1) long transients during GPK4 shut-in; 2) High seismic density between GPK4 and aseismic zone and 3) Orientation nearly perpendicular to SHmax). The weak hydraulic connection between GPK3 and GPK4 and the little tracer recovery between GPK3 and GPK4 cannot be used as argument since both facts may be interpreted by one of the extreme hydraulic conditions. The problem of little stimulation success is also seen from GPK3, whereas other stimulation have shown convincing results with 10 times increase of injectivities.

According to our considerations, the seismic risk and the success of stimulation can be optimized as follows:

Short-term injections (1-2 days): This prevents pressure build up in the secondary flow zones (pore pressure) and will reduce the impact of reversed shearing during shut-in. Our simulations indicate that the injectivities are generally immediately increased by the pressure build-up in the vicinity of the boreholes. The effectivity of long term pressure build up at larger distance does not seem to be convincing. A successive re-stimulation by short-term injections should also be conceived.

Slow pressure reduction, avoiding an abrupt shut-in. This would require a continuously reduction in flow rate after maximum pressure (flow) is reached. The time for the reduction should be in the same order like the pressure build-up.

Initial fast and high-pressure rates: the stronger the near borehole is pressurized the better this area is stimulated.

Short term dual injection GPK3 and GPK4: Short transients in the matrix can be anticipated, at much larger pressurized volume. If the danger for seismicity prevails in GPK3, a constant ~10 MPa over pressure should be applied (i.e. injection).

4. LIST OF TALKS AND PUBLICATIONS

Table 3. List of main talks and publications

Location	*References*
Conferences	
EHDRA Meeting	(Kohl and Mégel, 2005; Mégel and Hopkirk, 2005) (Kohl et al., 2006; Mégel et al., 2006) (Baujard et al., 2007; Kohl, 2007) (Kohl and Baujard, 2008)
Stanford Worlkshop	(Baria et al., 2004) (Kohl and Mégel, 2005)
World Geothermal Congress	(Baria et al., 2005; Kohl et al., 2005; Mégel, 2005; Rabemanana et al., 2005)
Geothermal Resources Council	(Kohl et al., 2004)
Workgroup Modelling	(Megel, 2005), (Baujard, 2007)
Others	(Megel, 2004) (Kohl, 2005) (Kohl and Baujard, 2006; Kohl et al., 2006; Mégel and Kohl, 2006) (Kohl and Mégel, 2007; Portier et al., 2007)
Official publications	
Geothermics Journal	(Gérard et al., 2006; Mégel et al., 2006)
GEOTHERMIE.CH	(Mégel and Kohl, 2005) (Kohl and Mégel, 2007)
Other Journal	(Kohl and Mégel, 2007)
Others	(Baujard et al., 2008)
Technical notes	
2004	(GEOWATT AG, 2004; GEOWATT AG, 2004)
2005	(GEOWATT AG, 2005; GEOWATT AG, 2005; GEOWATT AG, 2005; GEOWATT AG, 2005; GEOWATT AG, 2005; GEOWATT AG, 2005)
2006	(GEOWATT AG, 2006; GEOWATT AG, 2006; GEOWATT AG, 2006; GEOWATT AG, 2006; GEOWATT AG, 2006; GEOWATT AG, 2006)
2007	(GEOWATT AG, 2007; GEOWATT AG, 2007)

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Section 6: Contribution from CREGE/CHYN-UniNE

ABSTRACT

In order to forecast the behaviour of an enhanced geothermal reservoir under exploitation, interaction between flow, heat transfer, transport and chemical reactions must be evaluated. For this purpose, coupled reactive transport modelling can provide useful information, by simulating chemical reactions likely to occur in the system coupled to reactive transport, at large time and space scales.

FRACHEM, a thermo-hydraulic-chemical coupled code, was developed especially to forecast the evolution of the EGS project at Soultz-sous-Forêts, Alsace (France). FRACHEM can simulate thermal, hydraulic and fluid-rock interactions within the fractures connecting the injection and the production wells, and determine the dissolution/precipitation reactions of nine minerals in the Soultz granite (carbonates, pyrite, silicated minerals). During the simulation of fluid circulation, the coupled processes of a single and also two fractured zone between two wells were investigated to predict the geochemical evolution and to quantify the impact on the reservoir. Results of numerical simulations for a long-term circulation confirm the role played by carbonates on the evolution of reservoir porosity and permeability. Due to their fast reaction rates, carbonate minerals are responsible for most of the reservoir evolution. Silicates and pyrite behaviour is also simulated between two wells, but their influence on the permeability evolution of the fracture zone is minor.

Economic exploitation of enhanced geothermal systems is dependent to mineral precipitation, respectively dissolution and associated decrease, respectively increase in permeability of the system. These chemical processes may change fluid flow and associated heat extraction from the system. One solution to the problem of permeability decrease consists in injecting reacting fluids into the wells, in order to dissolve the secondary minerals sealing the fractures, to increase the permeability and hence to stimulate the reservoir. Chemical stimulation tests were performed on the Soultz wells. FRACHEM simulations have been tested to forecast the impact of reacting fluid injection, such as acidizing, on amounts of carbonates dissolved and precipitated, and resulting porosity developments.

1. INTRODUCTION

The contribution of CREGE has been mainly focussed on modelling forced fluid circulation and scaling tendencies in fractured granite at Soultz-sous-Forêts EGS geothermal site. The original intention stated in the work plan was to validate the simulations with exploitation data. Early in the project it was realised that this task would not be possible within the timeframe of the project phase. More effort and more time than expected have been concentrated on developing and improving the underground man-made flow and heat exchange system, avoiding as far as possible nuisance from microseismic events. Thus, this aspect of the work was replaced by benchmarking of the code FRACHEM with other coupled codes. Although in response to project needs, the discussions with the Soultz coordinators led to a comprehensive work on the chemical stimulation techniques, with particular regard to acid jobs in geothermal wells. Thus, the contributions of CREGE that are presented in this report are:

- Coupled modelling with the improved version of FRACHEM for potential short- and long-term evolution of the reservoir.
- Benchmarking of the code FRACHEM with validated coupled codes (TOUGHREACT and SHEMAT).

- Review of the chemical stimulation techniques and first guidelines for permeability improvement in the vicinity of the wells at Soultz.

The objective and results of the work performed on the three topics is summarised in the following three sections.

2. WORK CONDUCTED

2.1 Coupled modelling with the improved version of FRACHEM for potential short- and long-term evolution of the reservoir

2.1.1 Introduction

Circulation of geothermal fluids through granitic fractured reservoirs leads to chemical reactions, modifying the porosity and permeability of the rock mass. The goal was to incrementally build a thermo-hydraulic-chemical coupled computer code, FRACHEM, able to simulate forced fluid circulation and scaling tendencies in fractured granite at Soultz-sous-Forêts EGS geothermal site.

Water-rock interactions in reservoirs are driven by the state of disequilibrium that persists among solids and solutes due to changing temperature and stress conditions, as well as advective and diffusive influx of solutes. Water-rock interactions bring about changes to formation composition and texture through a complex chemical reactions network. These reactions can be divided into two types: solid-solute and solute-solute. Reactions of solids and solute are kinetic, i.e., they depend on compositions of solids and water, temperature, pore water pressure, and stress. Speciation among solutes is described by thermodynamic relations that depend on water composition and temperature. Both reaction mechanisms, mediated by formation water, are strongly interdependent. The mass transfer processes are governed by reactive phase compositions, surface areas, water-rock ratios, reaction rates, and fluid residence times. It is the ultimate goal of water-rock modelling to be able to describe quantitatively the evolution of both fluid composition and rock mineralogy in time and space.

Furthermore, coupled thermal-hydraulic-chemical (THC) codes help in studying the potential permeability reduction of fractured media caused by water-rock interactions. Conditions such as large degree of supersaturation, change in temperature, and rate of flow control the quantity and morphology of the precipitating minerals. FRACHEM code can simulate fluid–rock interactions and determine the dissolution/precipitation reactions of nine minerals in the Soultz granite (i.e. carbonates, pyrite, silicates and aluminosilicates). Numerical simulation results of long-term fluid circulation through the 5000-m deep Soultz reservoir are comparable to those determined for the shallow reservoir (3500 m) and confirm the role played by carbonates in the evolution of reservoir porosity and permeability. Moreover, experiments with FRACHEM in simulating short-term fluid flow during hydraulic and/or chemical stimulations have demonstrated that the code could prove as an efficient tool in reservoir engineering and management.

2.1.2 Development of FRACHEM code to simulate the impact of long-term circulations on the evolution of the permeability conditions

The circulation of injected cold brine in the Soultz reservoir is modelled using FRACHEM (Durst, 2002; Bächler, 2003, Rabemanana et al. 2003; André et al., 2005; Bächler and Kohl, 2005). The fluid flow within the granitic reservoir modifies the chemical and thermal equilibrium of the system involving dissolution and precipitation of some minerals.

Reactivity of aluminosilicates

In FRACHEM code, a general kinetic model has been adopted to explain the dissolution/precipitation reactions of minerals. Its overall form is expressed as:

$$v = k_m(T).s_m.\left(1-\left(\frac{Q}{K_m}\right)^{\mu}\right)^{\eta}$$

Positive values of v correspond to dissolution rates, whereas negative values refer to precipitation rates. This equation is adapted to each mineral and the determination of parameters k_m, μ and η are deduced from published experiments, conducted at high temperature in NaCl brines.

Previously, the reactivity of only four minerals (calcite, dolomite, quartz and pyrite) was considered in the simulations. Detailed information on the determination of the reaction laws can be found in Durst (2002). During this phase of the project, bibliographic research attempted on the dissolution-precipitation kinetics of one silicate (amorphous silica), three aluminosilicates (K-feldspar, albite and illite) and one carbonate (siderite) permit to investigate the behaviour of nine minerals when modelling fluid-rocks interactions with FRACHEM code.

Kinetic equations for the newly added minerals (amorphous silica, K-feldspar, albite and illite) can be found in Table 1.

Table 1. Kinetic equations for amorphous silica, K-feldspar, albite, illite dissolution and precipitation used in FRACHEM code.

Reaction rate laws	Sources
Amorphous silica dissolution rate $r_d = 10^{(0.82191-(3892.3/T))}(a_{SiO_2})(a_{H_2O})^2 s\left(1-\frac{Q}{K}\right)$	Rimstidt and Barnes (1980), Icenhower and Dove (2000)
Amorphous silica precipitation rate $r_p = 3.8\times10^{-10}\exp\left(\frac{-50\ 000}{8.314}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right) s\left(\left(\frac{Q}{K}\right)^{4.4}-\frac{1}{(Q/K)^{8.8}}\right)$	Rimstidt and Barnes (1980), Carroll et al. (1998), and Xu et al. (2004)
K-feldspar dissolution rate $r_d = 5.25\times10^{-6}\exp\left(\frac{-51\ 700}{RT}\right)\left[\frac{10^{-0.97}a_{H^+}}{1+10^{-0.97}a_{H^+}+10^{3.04}a_{Na^+}}\right]^{0.5} s\left(1-\frac{Q}{K}\right)$	Blum and Stillings (1995) and Stillings and Brantley (1995)
K-feldspar precipitation rate $r_p = 10^{-12}\exp\left(\frac{-67\ 830}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right) s\left(\frac{Q}{K}-1\right)$	Blum and Stillings (1995)
Albite dissolution rate $r_d = 0.35\ \exp\left(\frac{-89\ 000}{RT}\right)\left[\frac{10^{-0.97}a_{H^+}}{1+10^{-0.97}a_{H^+}+10^{3.04}a_{Na^+}}\right]^{0.5} s\left(1-\frac{Q}{K}\right)$	Hellmann (1994) and Stillings and Brantley (1995)
Albite precipitation rate $r_p = 10^{-12}\exp\left(\frac{-67\ 830}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)\right) s\left(\frac{Q}{K}-1\right)$	Blum and Stillings (1995)
Illite dissolution rate $r_d = \left[2.2\times10^{-4}\ \exp\left(\frac{-46\ 000}{RT}\right)a_{H^+}^{0.6}+2.5\times10^{-13}\exp\left(\frac{-14000}{RT}\right)\right] s\left(1-\frac{Q}{K}\right)$	Köhler et al. (2003)
Illite precipitation rate $r_p = 1.1638T\ \exp\left(\frac{-117\ 000}{8.314T}\right) s\left(\frac{Q}{K}-1\right)^2$	Nagy et al. (1991)

**s: surface area of mineral (m^2)*

Considering the great depth of the Soultz reservoir, the pressure effect on the solubility of minerals has been implemented in FRACHEM code for some minerals. The effect of pressure (P in bar) on the solubility constants of minerals in water can be estimated from the partial volume and compressibility of species involved in the reaction. From litterature data, the equations of the variation of solubility products of calcite and dolomite have been established between 1 and 1000 bars:

For calcite: $$K(T,P) = K(T,P_0).\exp\left[-\left(\frac{-1.5155.10^{-3}T^2+0.1811T-34.477}{83.14.(273.15+T)}\right)P\right]$$

For dolomite: $$K(T,P) = K(T,P_0).\exp\left[-\left(\frac{-3.0751.10^{-3}T^2+0.3405T-62.0860}{83.14.(273.15+T)}\right)P\right]$$

For quartz:

$$K(T,P) = K(T,P_0).\exp\left[7.10^{-10}.T^4 - 5.25.10^{-7}.T^3 + 1.45.10^{-4}.T^2 - 1.74.10^{-2}T + 5.74.10^{-4}.P + 1.713\right]$$

For amorphous silica: $$\frac{(K_{Am.\,Sil.})_{1034\ bars}}{(K_{Am.\,Sil.})_{vapor\ pressure}} = 10^{-\frac{79}{T}+0.3}$$

Where P_0 represents the vapour pressure.

In the Soultz reservoir, at a depth of 5000 m, a pressure of about 500 bars can be estimated. In these conditions, the pressure plays a non-negligible role on the minerals solubility and variations can raise one order of magnitude. At last, the values of equilibrium constants calculated with the proposed equations are in good agreement with values given in SUPCRT92 database (Johnson et al., 1992).

Major results of the base case

The initial application of FRACHEM is the modelling of a 2-D simplified model with a geometry close to the Soultz system. Injection and production wells are linked by fractured zones and surrounded by the granite matrix (Figure 1). The model is composed of 1250 fractured zones. Each fractured zone has an aperture of 0.1 m, a thickness-depth of 10 m, a porosity of 10%, and contains 200 fractures. Initially the temperature was set to the reservoir temperature of 200°C. One of these fractured zones is modelled with the assumption that the fluid exchange with the surrounding low permeability matrix is insignificant. Due to the symmetrical shape of the model, only the upper part of the fractured zone is considered in the simulation. The area is discretized into 222 2D elements.

The size of the elements ranges from a minimum of 0.5 m x 0.05 m near the injection and the production wells to a maximum of 50 m x 35 m. Considering a production rate of 25 $l.s^{-1}$, the fluid was re-injected in each of the fractured zones at a rate of 2 x 10^{-2} $l.s^{-1}$ at a constant temperature of 65°C. During this simulation a constant overpressure of 8 MPa was assumed at the injection well and a hydrostatic pressure at the production well. Dirichlet boundary conditions were applied to the upper, left and right side of the model. Due to the sensitivity of the sequential non iterative approach (SNIA) method on the time discretization, the time step used for this simulation is limited to 10^2 s, meaning that five years of simulation take one day of computer time. The values of thermo-hydraulic parameters and mean composition of fluid and mineral components considered in the simulation are listed in Table 2 and Table 3, respectively.

The fluid does not circulate on the total thickness of the fractured zone but only in the fractures. The real aperture of a fracture represents more or less 10 % of the thickness of the fractured zone (equal to the rock porosity). As a consequence, a factor has been added in the code to constrain the fluid to circulate in the fracture aperture.

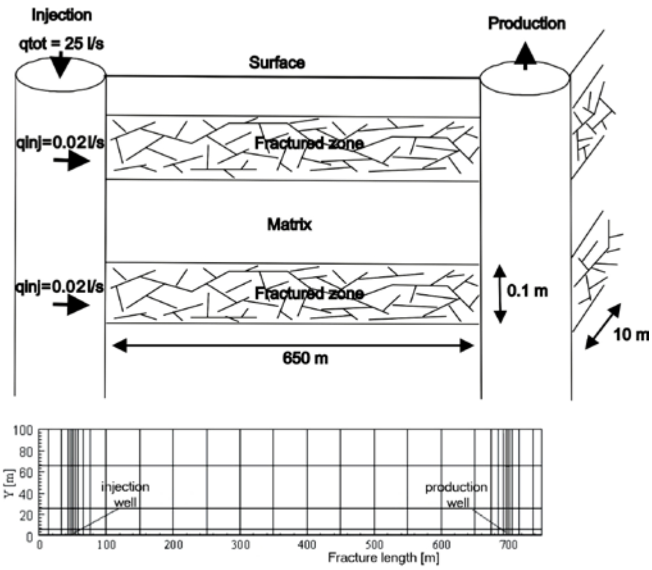

Figure 1. Simplified model and spatial discretization.

Table 2. Values of the thermo-hydraulic parameters for fracture, matrix and fluid.

Parameters	Fracture	Matrix	Fluid
Hydraulic conductivity [m/s]	$7.03\ 10^{-4}$	$9.5\ 10^{-12}$	-
Thermal conductivity [W/m.K]	2.9	3	0.6
Density [kg/m^3]	-	2650	1000
Heat capacity [J/kg.K]	-	1000	4200
Porosity [%]	10	0	-

Table 3. Mean composition of formation brine (pH = 4.9 at 200°C) and mineral components. The fluid composition derived from the chemical analysis of the fluid sampled at the wellhead of GPK2 well on December 1999 at the end of the 40-day production test, after being deepened at 5 km (Durst, 2002). Initial mineral abundances are based on the synthetically identification of hydrothermalized facies (Jacquot, 2000).

Aqueous Species	**Initial concentration of brine [mmol/kg H_2O]**	**Mineral**	**Initial concentration of mineral component [mol/kg H_2O]**
Na^+	1148.00	quartz	8.18
K^+	73.40	calcite	8.3
Ca^{2+}	169.50	dolomite	1.15
Mg^{2+}	3.21	pyrite	2.72
Cl^-	1648.00	Amorphous silica	159.2
S	1.77	K-feldspar	11.54
C	42.76	albite	13.45
Fe^{2+}	2.61	illite	13.12
SiO_2	6.06		
Al^{3+}	$3.7\ 10^{-3}$		

Results show that the most reactive of the silicates is amorphous silica. Its reaction rate is three orders of magnitude larger than that of quartz. In contrast to calcite, the solubility of amorphous silica increases with temperature. As a consequence, it precipitates near the injection well. With increasing circulation time, the zone of amorphous silica precipitation spreads towards the production well; the model shows that after 1800 days it extends over the first hundred metres of the fracture (Figure 2). However, the reaction rate of amorphous silica is one or two orders of magnitude smaller than calcite. Pyrite precipitates all along the fracture, but as with quartz, its reaction rate is negligible in comparison to that of calcite. K-feldspar seems to be the most reactive of the aluminosilicates (Figure 2). Because its solubility increases with temperature, the precipitation of this feldspar occurs close to the injection point but drops off away from it. It is interesting to note how small the dissolution of albite and illite is close to the production well. It is also clear that the main phase of aluminosilicate precipitation occurs at the start of forced fluid circulation, and that it decrease with time (Figure 2). The weak dissolution of aluminosilicates in the fracture keeps the aluminium concentrations low in the circulating fluid, thus preventing the precipitation of these minerals.

In first conclusion, considering a brine circulation of 1800 days, calcite appears to be the most reactive mineral (Figure 2) with about 1300 kg dissolved in the first 50 meters of the fractured zone and about 1500 kg precipitated in the second half of the fracture. Silicates and aluminosilicates tend to precipitate near the injection well but in small quantities. A consequence of these reactions is the impact on the reservoir porosity and permeability. In the vicinity of the injection well, porosity increases of about 30 %, mainly due to calcite dissolution, while porosity decreases by 5 % near the production well (Figure 2). Carbonates reactions seem to control the porosity of the reservoir, at least during the first 1800 days of circulation (Figure 2). Although silicates and aluminosilicates play a secondary role, their impact on porosity and permeability is visible, particularly in the first 10 meters of the fracture (Figure 2). Nevertheless, all these results concerning porosity and permeability depend on the relationship linking these two parameters.

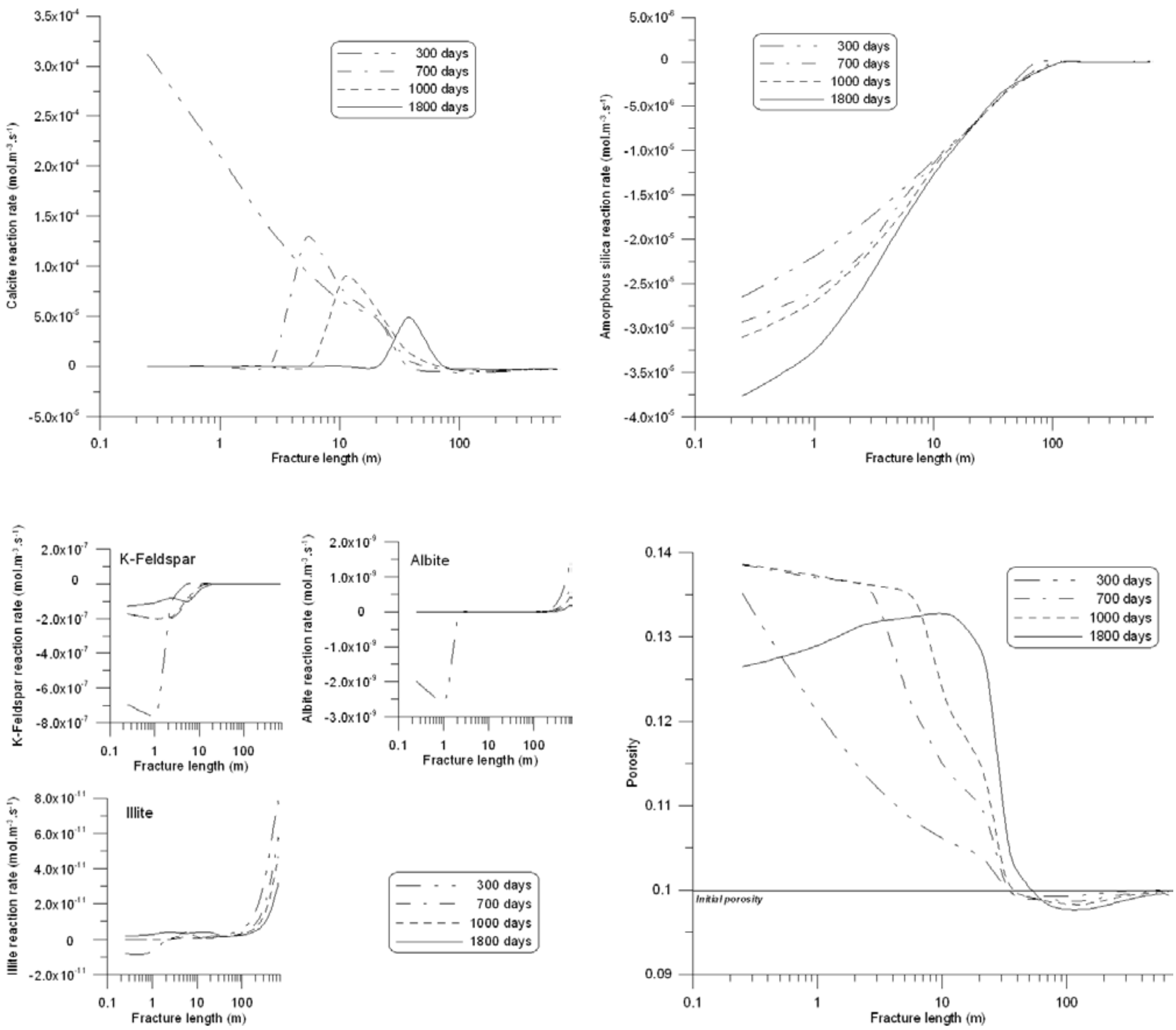

Figure 2. Calcite, amorphous silica and aluminosilicates reaction rates along the fracture and influence of chemical reactions on the fracture porosity.

Influence of porosity-permeability relationships

All the chemical reactions involved in the simulations have an influence on reservoir properties, but it is quite difficult to determine an adequate relationship between porosity and permeability considering that few field data are available and that the real structure of the Soultz granite is not well known. An estimation of the evolution of reservoir porosity was proposed through three examples of relationships (a gaussian distribution, a non-gaussian distribution and a fractal distribution). The theoretical aspect of each model is first described and then a comparison of the results is presented.

Combination of grain and fracture models (Case 1a)

Considering the alteration of the Soultz granite, the flow can circulate in a medium composed of fractures and grains. A combination of a fracture model and a porous media model was proposed for determining permeability of the fractured zone. The fracture-type model is based on the work of Norton and Knapp (1977), and modified by Steefel and Lasaga (1994), who consider the case of three sets of mutually orthogonal fractures that produce an isotropic permeability, where all the fractures have the same spacing and fracture apertures. The fracture permeability k_F is:

$$k_F = \frac{\Phi_F^3}{324.n_F^2}$$

The porous media-type model is based on that of Kozeny-Carman, which was modified by Bolton et al. (1996):

$$k_G = \frac{R_0^2}{45}.\frac{\Phi_G^3}{(1-\Phi_G)^2}$$

Then, during fluid circulation in the system, minerals precipitation and dissolution imply porosity changes in the fracture, directly tied to the volume changes. The global permeability of the fractured zone is given by:

$$k = \alpha k_G + (1-\alpha)k_F$$

In this model, we assume that the fracture aperture and the thickness of the mineral layer follow Gaussian distributions (Durst, 2002). These variations are calculated for each time step and for each mineral.

Modified grain and fracture models (Case 1b)

An alternative to the previous model is not to assume a Gaussian distribution of the fracture aperture and of the thickness of the mineral layer. This modification entails a different approach to calculating mineral-surface contact areas. In this case (case 1b), the variation of the reactive area depends only on the fracture porosity:

$$\frac{dA_{F,m}}{d\Phi} = A_{F_0}.f_m.\frac{1}{\Phi.(1-\Phi)}$$

A fracture model (Case 2)

The Soultz reservoir can also be considered as a succession of fractured zones. Fracture permeability changes can be then approximated using the porosity change of plane parallel fractures of uniform aperture (cubic law; e.g., Steefel and Lasaga, 1994). The permeability can be adjusted to porosity changes brought about by the precipitation or dissolution of minerals, i.e.

$$\mathrm{k} = \mathrm{k}_0\left(\frac{\Phi}{\Phi_0}\right)^{\mathrm{D}_{f,i}}$$

One of the disadvantages of this law is that zero permeability is only reached under the condition of zero fracture porosity. The fractal exponent $D_{f,i}$ depends on porosity. For porosities ranging from 0.01 to 1, which is supposed to be the case for the fractured zone of the Soultz granite, it is assumed that the permeability variations are calculated from changes in porosity, based on a square law (Clauser, 2003). Thus, permeability values are updated according to the following equation:

$$k = k_0 \left(\frac{\Phi}{\Phi_0} \right)^2$$

The variations of the reactive surface area of each mineral and the global surface area are determined such as defined in case 1a.

The three relationships between porosity and permeability described above were applied to the model set-up presented in Figure 1. The variations of reservoir porosity and permeability forecasted by each method are presented in Figure 3. The three investigated cases give relatively the same results on the variations of reservoir porosity and permeability; only some differences are observed near the injection well in relation with the different calculation modes. It seems that cases 1b and 2 are nevertheless less sensitive to the re-precipitation of minerals like amorphous silica. It is the reason why a porosity decrease is not observed near the injection zone as in case 1a. These differences between the three cases have an effect on permeability calculations, mainly near the injection well (Figure 3). The tendency and the global evolution of this parameter are the same in the three cases, but the permeability increase is less important in case 2 than in cases 1.

As a first conclusion, some hypotheses on the evolution of the reservoir properties can be drawn. Each method gives the same global evolution of the reservoir properties with an increase of porosity and permeability close to the injection well and a decrease in the second half of the fractured zone. For the time being, the limited knowledge of the Soultz reservoir behaviour precludes the choice of a defined porosity-permeability relationship. Only a comparison between simulation results and field data obtained from future circulation and production periods will allow selecting the proper relationship.

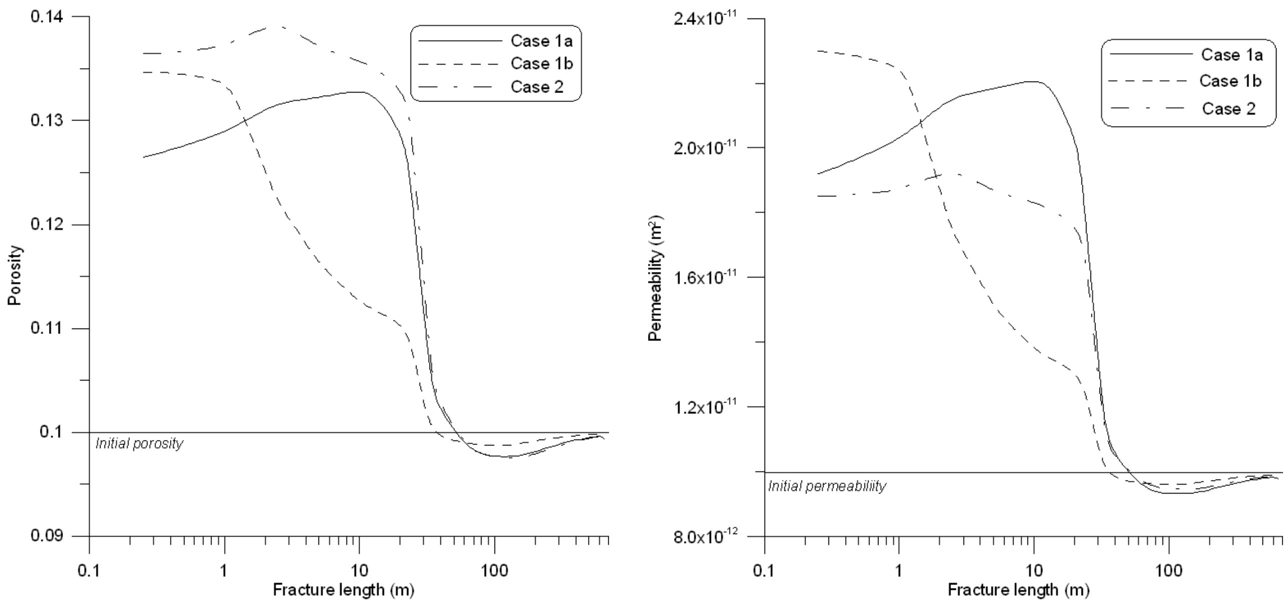

Figure 3. Variations of mean reservoir porosity and reservoir permeability according to different porosity-permeability models. Case 1a: combination of grain and fracture models; case 1b: modified grain and fracture models and case 2: fracture model.

Influence of geometrical model set up

The extension of the code performed in collaboration with Th. Kohl from GEOWATT AG allowed combining multidimensional finite element discretization (i.e. 1D fractures next to a 2D rock matrix). This implementation allowed dividing the calculation time by a factor 2 and it offers the possibility to work with 1D or 2D geometrical models.

Following this improvement, sensitivity analysis has been made concerning the spatial discretization and fracture network density. Simulations results indicate that the permeability variation depends principally on the evolution of the temperature field calculated by FRACTure and not much on the spatial discretization or the fluid flow rate. However changes in the porosity and permeability, and thus in the hydraulic conductivity, impact the fluid velocity and the pressure distribution in the fracture. Mineral precipitation causes the porosity and therefore also the permeability and the hydraulic conductivity to decrease. Lower hydraulic conductivity results in lower fluid velocities. Since the fluid velocities are smaller, the rate of temperature decrease in the fractured zone is lower.

The effects of permeability distributions along the fractured zone on fluid flow and water-rock interactions have been investigated. For the uniform permeability model, an average hydraulic conductivity value ($7.44.10^{-8}$ $m^2.Pa.s^{-1}$) is assigned all along the fractured zone. For the probabilistic model, the distribution of permeability along the fracture zone follows a lognormal distribution, where hydraulic conductivity is distributed between 10^{-6} and 10^{-9} $m^2.Pa.s^{-1}$, with an average value of 8.10^{-8} $m^2.Pa.s^{-1}$. In our models, the permeability has a decreasing tendency with distance from wells in general but it varies widely; thus fracture zones could remain permeable far from well.

The uniform and probabilistic permeability models share a similar pattern in porosity distribution, even though the distribution is less uniform at the vicinity of the wells and towards the production well when the initial permeability contrast is higher. Porosity of the fractured zone is notably increased for the probabilistic permeability cases because the fracture zone permeability becomes higher in the vicinity of the injection well. Several permeability models were developed to test the relationship between distance from wells and fractured zone permeability, on the basis of the conceptual model. A change in the width and transmissivity of the fractured zone results in a change in fluid flow along the fracture zone and then impacts the water-rock chemical interaction.

Similarly, flow of reactive fluids through variable-aperture fractures can lead to geochemical alteration of the fracture surfaces resulting in localized changes in fracture permeability. For a pore fluid that is undersaturated with respect to the minerals forming the fracture surfaces, chemical reactions lead to dissolution and increases in local fracture apertures. Local dissolution rates tend to be positively correlated with fracture aperture, meaning that larger flow rates lead to locally higher flow rates and faster dissolution.

2.1.3 Simulation of the impact of short-term circulations on the evolution of the permeability conditions

Scenarios were proposed to manage the reservoir properties.

Simulation of acid injection

A challenge for the code consists to forecast the effectiveness of the chemical stimulations to enhance the reservoir porosity/permeability. In this domain, the code appears as a tool to investigate the impact of the geochemical processes on reservoir properties.

The response of the model to HCl acid addition was examined. Injected strong acid reacts of course with the carbonates (calcite and dolomite). According to mineralogical data, these compounds represent more or less 5 % of the hydrothermally altered granite. From this proportion and in case of a massive acid injection, all carbonates can be dissolved by acid solution leading to a porosity of about 0.15. For a limited acid injection (10 $L.s^{-1}$ at 2 $g.L^{-1}$), the acid effect is very limited in dissolving carbonates amount and in term of penetration within the reservoir. At this flow, a real impact on reservoir properties is only obtained for extended injections of many days and for high acid concentrations. After an injection of 10 days of a solution at 10 $g.L^{-1}$, the totality of carbonates is dissolved in the first 0.5 metres around the injection well but only 65 % in the range 0.5-1.5 meters. A weak flow has a relative low effect. Better results are obtained with flow of 25 $L.s^{-1}$. This flow was used to inject acid in GPK2 (injection of 12 h at an average concentration of 2 $g.L^{-1}$). The experiment consisted of a succession of injection of fresh water followed by diluted acidified brine at different injection rates. The results showed a decrease of injection pressure in the vicinity of the injection well, as calcite was dissolved and progressively carried away. HCl acid solution injected was prepared with the formation brine, diluted twice with fresh water and acidified to a concentration of 2 $g.L^{-1}$ by addition of concentrated HCl. The pH of the injected solution is close to 1.4, whereas the composition of the brine within the fractured zone is unchanged. The results show that an acid solution dissolves carbonates in the first metres of the fractured zone. After injection of the acidified brine during one day, the injected HCl affects only the first 0.5 meters around injection well with a decrease of about 10 % of the initial calcite amount. The same flow was used to inject acid at 3.2 $g.L^{-1}$ in GPK3 during 24 hours. Modelling results showed that the acid impact does not exceed 0.5 meters around the injection well. But, in this case, the acid amount is not sufficient to dissolve all the carbonates in the range 0-0.5 meters. For GPK4, acid injection lasted 3 days at this flow and at a concentration of 2 $g.L^{-1}$ (more or less 11 tons of acid injected in the reservoir). According to the simulations of this test, injected acid is just sufficient to dissolve half of the carbonates initially present in the range 0-0.5 meters. Dissolution process causes an increase of about 10 % of rock porosity in the short interval 0-0.5 m around the injection well, and 0.2 % in the interval 0.5-1.5 m after 3 days of acid injection. Farther in the fracture, the impact is quasi nil. Nevertheless, it seems that at this flow, acid concentrations of about 7 to 10 $g.L^{-1}$ could have a positive impact up to 7.5 metres from the injection well, and for an injection time relatively limited (5 days). Due to the respective reaction rate of each mineral, it should be noted that dolomite is dissolved only near the injection well and not farther in the fractured zone.

The best results are obtained for long-term injections of high-concentration acid solutions. In these conditions, the impact radius can reach 15 meters around the injection well. Considering these conditions (for example 10 $g.L^{-1}$ and 50 $L.s^{-1}$), it should be noted that the important amount of injected acid is able to dissolve the carbonates (calcite + dolomite) up to 7 metres from the injection well, even for very limited injection times (2.5 days). Finally, a test has been carried out with a short-term acidification at a flow rate of 25 $L.s^{-1}$. The HCl acid concentration was 50 $g.L^{-1}$, which corresponds to a solution of about 1.37 $mol.L^{-1}$. With such solution, a 10-hour injection represents an injected acid amount of about 100 tons. After a half-day injection, all the carbonates in the first 0.5 metres around the injection well are been dissolved and 20 % of carbonates have been consumed between 0.5 and 1.5 meters.

Effect of a reverse circulation period

Another scenario proposed to stimulate the reservoir was attempted with a temporary reverse fluid circulation after a certain period of exploitation. The simulation of fluid-rock interaction showed that calcite is more soluble around the injection well and that an increase of temperature favours calcite deposition towards the production zone. In order to improve porosity and permeability around the production well, the fluid circulation was reversed during 3 months after 300 days of exploitation. It means that the production well was used for injection and vice-versa during this period. Fluid chemistry and mineral components are updated to the situation after 300 days of circulation and the boundary conditions are inverted to this configuration. Figure 4 shows the porosity evolution after 300 days of exploitation and a reverse circulation during three months.

The reverse circulation slightly modifies the reservoir porosity, as this parameter is mainly influenced by carbonates reactions. After 300 days of circulation (continuous line on figure 8), porosity has increased of about 35 % near the injection well and it has decreased of about 0.5 % near the production well. By reversing the circulation during 3 months (dashed line on figure 8), carbonates dissolve near the "new" injection well. As a consequence, an increase of about 9 % of the porosity is observed in the first 10 metres of the fracture, between 650 and 700 m (see zoom on Figure 4). This dissolution involves the increase of calcium in solution and the re-precipitation of calcite further in the fracture between 500 and 650 m. Porosity is not affected in the rest of the fracture. Considering these results, it seems that a temporary reverse circulation could improve the reservoir properties, particularly in the vicinity of the production well.

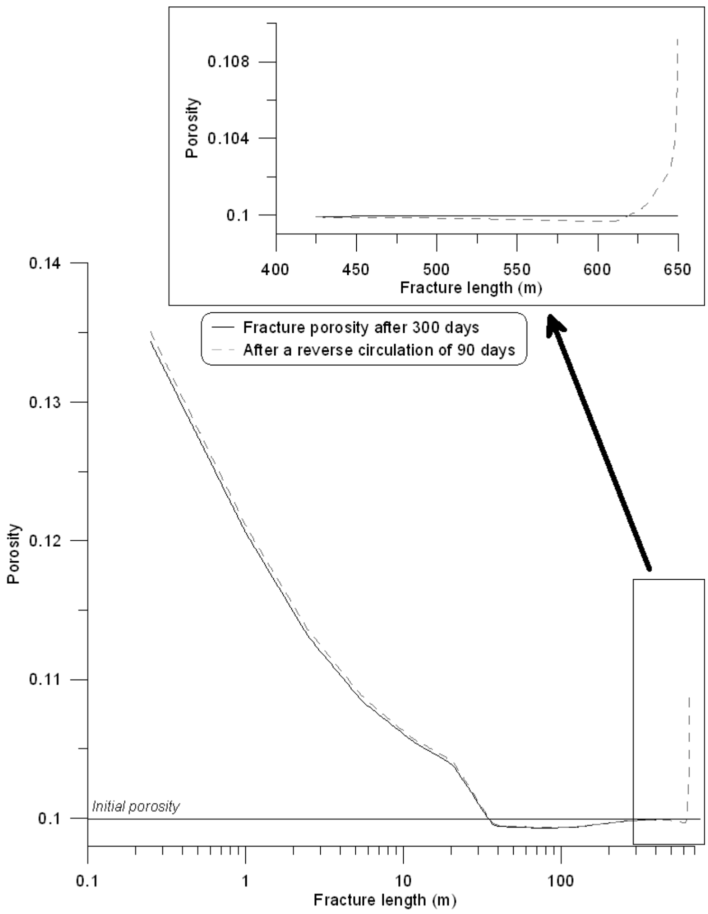

Figure 4. Evolution of mean reservoir porosity after 300 days of exploitation in one direction and 3 months-circulation in inverse direction.

Change in temperature injection

In many geothermal reservoirs silica precipitation is a major process and re-injection temperature is a key parameter (Xu et al., 2004). In order to estimate the sensitivity of the model to the re-injection temperature, it was modified from 65°C to 50°C. The amounts of minerals precipitated and dissolved were compared to the simulation carried out at 65°C. The most important variations concern only the less reactive mineral but without influence on reservoir properties. Among the most reactive minerals, we can note that calcite behaviour is weakly affected by this variation of re-injection temperature. This is explained by the retrograde solubility of calcite, but a variation of 15°C of re-injection temperature does not influence the reservoir performance. Concerning amorphous silica, its weak solubility at low temperature involves an increase of its precipitation of about 20 %. As a consequence, porosity and the reservoir properties are influenced by this increase of precipitation, mainly in the vicinity of the injection well (Figure 5). In the whole fracture, porosity differences between the two simulations do not exceed 2 %. In the vicinity of the injection well however, variations of 3 to 5 % are observed.

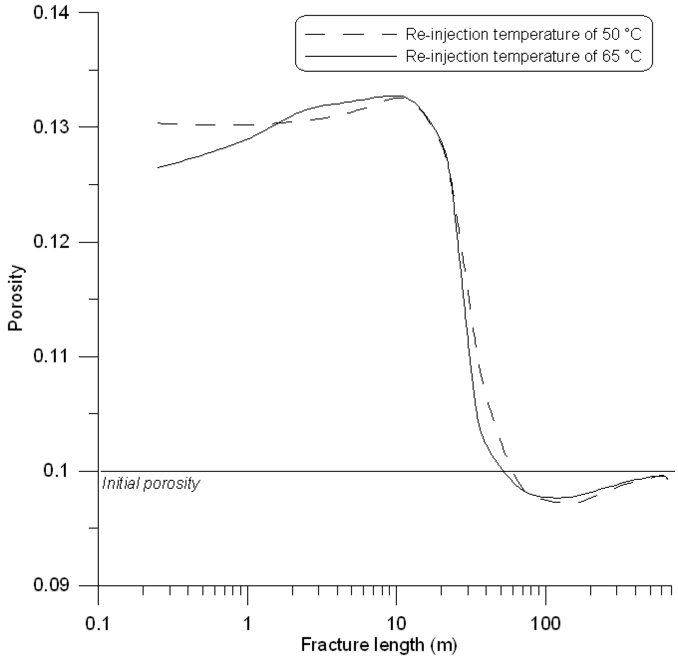

Figure 5. Evolution of mean reservoir porosity after 1800 days of fluid circulation for two different re-injection temperatures of the original brine.

Injection of diluted brine

During a soft acidizing test performed at Soultz, 5814 m^3 of fresh water were injected into the well GPK2. To understand the impact of fresh water injection into the reservoir, a circulation test of one year was simulated using FRACHEM. To this end, the brine was diluted with fresh water by 10% (i.e. 90 % of brine and 10 % of fresh water), the injection temperature and rate were respectively maintained to 65°C and 2.10^{-2} L s^{-1} within the fractured zone. The amounts of precipitated and dissolved minerals were similar for dolomite, quartz, amorphous silica and aluminosilicates (Table 4). Nevertheless, calcite behaviour was different for the two fluids. The diluted brine mainly led to a decrease of the calcite reactivity. After 300 days of fluid circulation, the calcite reactivity decreases by 50 %. As a consequence, the reservoir properties are slightly modified, as shown in Figure 6. These variations mainly occur in the vicinity of the injection well, where calcite and dolomite reactivities are the highest.

Table 4. Comparison of amounts of mineral transfer obtained from initial and diluted brine after 300 days of fluid circulation

Minerals	Amount (kg)	Original brine	Diluted brine
Calcite	Precipitated	362	356
	Dissolved	258	121
Dolomite	Precipitated	0.0	0.0
	Dissolved	170	143
Quartz	Precipitated	0.02	0.0
	Dissolved	0.0	0.07
Amorphous silica	Precipitated	26.2	16.7
	Dissolved	0.5	0.5
Pyrite	Precipitated	0.3	0.0
	Dissolved	0.0	0.02
K-feldspar	Precipitated	0.7	0.5
	Dissolved	0.0	0.0
Albite	Precipitated	0.0	0.0
	Dissolved	0.18	0.18
Illite	Precipitated	0.0	0.1
	Dissolved	0.0	0.0

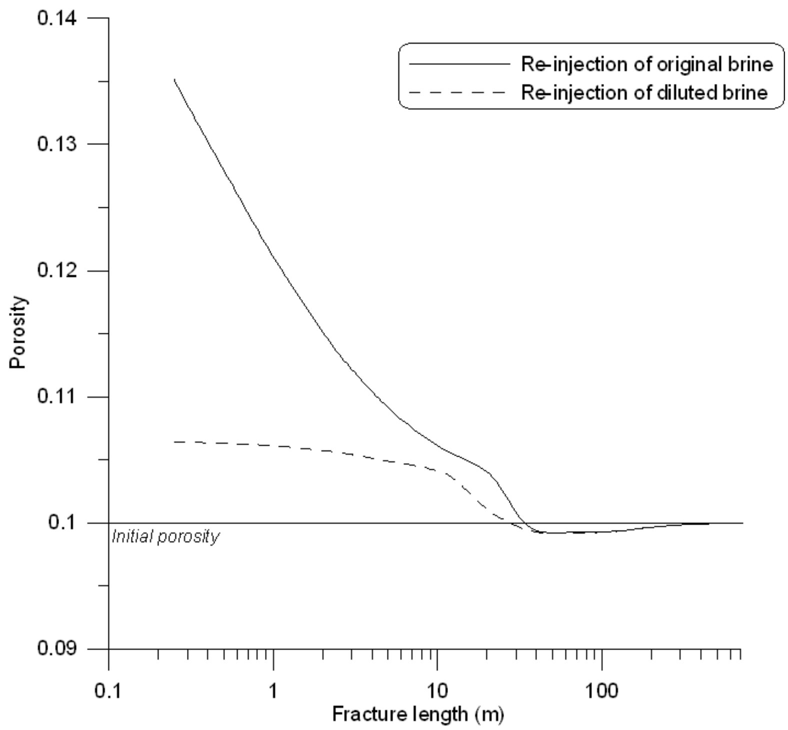

Figure 6. Evolution of mean reservoir porosity after 300 days of circulation of original brine or brine diluted with fresh water (90 % original brine and 10 % fresh water).

First conclusions

The great complexity of the scale formation process results from the large number of species found in a geothermal fluid and from the multiple possible physical mechanisms involved. Scaling occurs due to interaction of geothermal water with rocks deep in the reservoir, resulting in supersaturated water due to the dissolution of minerals. Dissolution may be accelerated by temperature and, sometimes, it may be retrograde depending on the solute. Calcite, silica and metal pyrite deposition are the most common scales.

Through the scenarios presented here, the brine dilution seems to be the most efficient method to maintain the reservoir properties. This method is rather simple, but needs large volumes of make-up water. Although technically more complex, the temporary reverse circulation could also be an interesting method. Then, a combination of these methods could keep the reservoir properties during long-term production. Finally, different chemical stimulation methods can be applied to enhance the permeability in the vicinity of the wells and FRACHEM code could be adapted to evaluate the most efficient reacting fluids.

Reactive transport simulations help in understanding processes at play, especially the various feedbacks between strongly coupled mechanisms. However this study clearly shows that the predictive value of complex coupled THC simulations is mostly qualitative. Unless these simulations are closely integrated with field and laboratory experiments, their predictive ability should be asserted with much caution. Therefore, if THC simulations such as those presented here are to be used in a quantitative manner to plan the design and operation of the Soultz EGS (or any other geothermal system), integration of these simulations with laboratory experiments and field tests is highly recommended. Better understanding of the fundamental physico-chemical principles of forced fluid circulation and heat transport in fractured porous media by numerical modelling, will help to develop better techniques and apply more effective existing ones for preventing formation damage of geothermal reservoirs.

2.2 Benchmarking of FRACHEM with other codes

Three THC simulators were applied and compared to forecast geothermal reservoir evolution. The fact that several coupled numerical models yield similar results is of great importance, since no reliable measured data or adequate laboratory experiments were available at that time for comparison.

2.2.1 Benchmark with TOUGHREACT

Collaboration with the Lawrence Berkeley National Laboratory (LBNL) has been carried out since 2005 to evaluate the performances of both FRACHEM and TOUGHREACT codes. TOUGHREACT is a geochemical model based on the existing code TOUGH2, by introducing reactive transport. TOUGHREACT code has been applied to different problems and recent developments have included the Pitzer formalism which renders now possible its application to solve geochemical processes of highly saline brines.

The goals of this work were to compare two multicomponent reactive transport codes, FRACHEM and TOUGHREACT (Xu and Pruess, 2001; Xu et al., 2004; Xu et al., 2006), to model complex water-rock interactions such as at the enhanced geothermal system at Soultz. This work aims mainly to compare the calculations methods for the determination of activity coefficients of dissolved species, the mineral solubility and the mineral dissolution/precipitation rates at high temperature and pressure. Different aspects of each code and input data were evaluated, including the methods to calculate activity coefficients, the mineral reaction rates, and the equilibrium constants of key minerals. TOUGHREACT offers the choice of either an extended Debye-Hückel (Tr-DH) model or the Pitzer formalism (Tr-Pitzer) to compute activity coefficients of dissolved species and water activity. FRACHEM uses activity coefficients externally calculated using TEQUIL (Moller et al., 1998). Activities of dissolved species computed with these codes for a typical Soultz fluid (ionic strength around 2 molal) were compared. Key differences were found in the activity coefficients of Ca^{2+} and Mg^{2+}, yielding calcite saturation indices lower by up to 1.5 log(Q/K) units when computed with Tr-DH instead of FRACHEM or Tr-Pitzer. However, the effect of increased calcite solubility in the Tr-DH simulations is minimal, because the model assumes an initial reservoir fluid composition reflecting saturation with respect to calcite. This shows that the model conceptualization is as important as the model input data. The Pitzer ion-interaction parameters implemented in TEQUIL are expected to provide more accurate calcite solubilities for applications with Soultz-type fluids, because these parameters were developed specifically for high-temperature geothermal applications at moderate ionic strengths. The relatively recent EQ3/6 Pitzer database, revised and used with TOUGHREACT in this study, is expected to be most accurate for applications below 150°C and very high ionic strengths.

Concerning the minerals reaction rates, a good agreement was observed for calcite, quartz and amorphous silica. For aluminosilicates (K-feldspar, albite and illite), differences in rates reach about two orders of magnitude, but can be explained easily by the fact that FRACHEM takes into consideration the inhibitor effect of Na+, whereas TOUGHREACT does not. The largest differences in reaction rates were observed with dolomite and pyrite. In FRACHEM, kinetic data for these two minerals were determined from extrapolations that may be questionable. As a result some modifications to the future FRACHEM database should be considered.

The equilibrium constants for minerals used with FRACHEM and TOUGHREACT are mostly issued from the same sources. A good agreement is observed for the carbonates (calcite and dolomite) and for silicates (quartz and amorphous silica). The most important differences are observed for aluminosilicates, and these differences mainly result from the assumed form of aluminium in solution. Because reservoir pressures at Soultz are high (estimated to about 500 bar), pressure corrections to the equilibrium constants of carbonates and silica phases were investigated. For these minerals, the variation of equilibrium constants with pressure was implemented in FRACHEM using simple correlations. These correlations show that the equilibrium constants of carbonates increase significantly with pressure. For this reason, consideration should be given to implementing similar correlations into TOUGHREACT.

The second phase of this study involved simulating the Soultz system. The codes were applied to simulate reactive transport processes in the Soultz reservoir, using essentially identical model conceptualizations and input chemical and hydrological data. Three main processes were investigated for a fluid-injection period of 5 years: the evolution of reservoir temperature, the mineral precipitation/dissolution behavior, and the evolution of reservoir porosity. The three codes (FRACHEM, Tr-Pitzer, and Tr-DH) produced similar results. The circulation of cooled fluid in the fracture zone is predicted to affect the temperature of the reservoir within the first 100 m from the injection well. The injection of cooled fluid results in chemical disequilibrium and dissolution/precipitation reactions of several minerals. Carbonates dissolve at the injection well head (because of their retrograde solubility), whereas quartz and K-feldspar precipitate. The dissolved calcite eventually reprecipitates away from the well, leading to an overall permeability decrease, which is predicted to range between 6% (with FRACHEM) and 25% (with Tr-DH and Tr-Pitzer). However, water-rock interactions occur mostly within the first 20 m from the injection well, and the porosity of the reservoir remains essentially unchanged at distances greater than about 100 m from the injection well. These results are consistent with a circulation test performed in 1997 within the shallow reservoir at 3,500 m at Soultz-sous-Forêts.

The initial reservoir temperature was only 165°C, but the mineral composition of the granite was very similar to that in the deep reservoir (5000 m). During this circulation of 140 days, the pressure at the injection well decreased, indicating an increase of the injectivity around the injection well. According to the simulation presented in this report, this process is likely caused by the dissolution of carbonates, the most reactive minerals. It should also be noted that concentrations of dissolved silica in the injected fluid remain below the solubility of amorphous silica, even at a temperature of 65°C, and therefore porosity reduction from silica precipitation is avoided. This occurs because the reservoir temperature is relatively low (200°C), precluding the dissolution of silica at concentrations exceeding the 65°C solubility of amorphous silica (i.e., temperature remaining within a silica precipitation "gap"). Should injection occur in hotter intervals, amorphous silica precipitation in the injection well could be significant.

Although the three models yield similar results, in a qualitative sense, quantitative results differ significantly (e.g., 6% versus 25% predicted porosity decrease at distances varying from about 2 to 20 m from the injection well, depending on the code), (Figure 7). These differences are primarily caused by differences in implemented activity coefficient models and their input parameters, as well as other model input thermodynamic and kinetic data. This study, therefore, highlights the importance of these data in reactive transport simulations, in particular for systems involving brines.

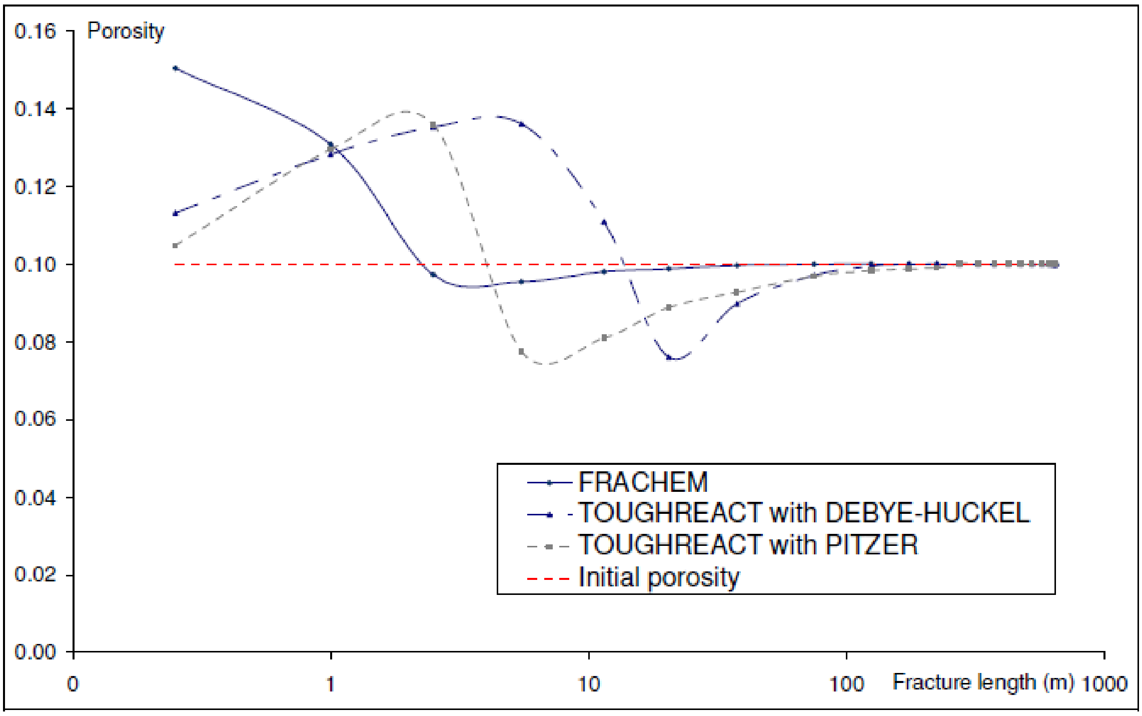

Figure 7. Porosity evolution for the two simulators FRACHEM and TOUGHREACT along the fractured zone after five years of forced fluid circulation, according to the three models.

2.2.2 Benchmark with SHEMAT

The Simulator for HEat and MAss Transport (SHEMAT, Bartels et al., 2003) has been developed in several phases and is today a general purpose reactive transport code for a wide variety of thermal and hydrogeological problems in two and three dimensions. SHEMAT is a finite difference code that solves coupled problems involving fluid flow, heat transfer, species transport and chemical water-rock interaction. It was successfully employed for the prediction of the long-term behaviour of geothermal fluid production systems with operation times of at least thirty years. SHEMAT is in combination with its graphical user interface "Processing SHEMAT" (Kühn and Chiang, 2003) an easy-to-use, general purpose reactive transport code for a wide variety of thermal and hydrogeological problems in two and three dimensions. The "IAPWS Industrial Formulation" (Wagner et al. 2000) is the equation of state used for water. In SHEMAT, the different flow, transport and reaction processes can be selectively coupled. Flow and heat transport are coupled in that the fluid parameters density, viscosity, compressibility, thermal conductivity and thermal capacity are functions of temperature and pressure. Flow and salt transport are coupled via fluid density implemented by a linear approximation.

The current version of SHEMAT offers the user two choices for calculating the activity-concentration relationships underlying the mineral reaction processes: (1) Pitzer's equations (best suited for concentrated brines) or (2) Debye-Hückel's theory (useful for more dilute solutions).

SHEMAT's first chemical speciation module CHEMEQ is a modification of the geochemical modeling code, PHRQPITZ (Plummer et al. 1988). It permits calculations of geochemical reactions in brines and other highly concentrated electrolyte solutions using the Pitzer virial-coefficient approach for activity-coefficient corrections. Reaction-modeling capabilities include calculation of aqueous speciation and mineral-saturation as well as mineral solubility.

To extend the applicability of SHEMAT with a second chemical speciation module, for example to enable re-engineering ore deposits or simulate permeable reactive barriers, the program has now been interfaced additionally to the chemical code PHREEQC (Parkhurst and Appelo 1999). PHREEQC is based on the Debye Hückel ion association approach. Compared to PHRQPITZ and due to the considerably larger thermodynamic data set for the chemistry of dilute aqueous solutions, it allows to study chemical reactions between much more elements.

Collaboration with Aachen University (RTWH) has been carried out between 2006 and 2007. The goals of this work were to compare two geochemical transport codes, FRACHEM and SHEMAT (with similar databases), and to model complex systems like Enhanced Geothermal systems. FRACHEM and SHEMAT codes were applied to simulate reactive transport processes in the Soultz reservoir, using essentially identical conceptual model and input chemical and hydraulic data. Three main processes were investigated for a forced fluid circulation of five years: the evolution of reservoir temperature, mineral precipitation/dissolution behaviour and the evolution of reservoir porosity. Significant differences in models results were found, primarily due to differences in the kinetic models and their parameters. This study highlights the importance of these models in reactive transport simulations, in particular for systems involving brines. Nevertheless, it can be seen from the porosity evolution that the results of FRACHEM and SHEMAT are very similar (Figure 8). Even though the simulators show significant differences with regard to the quantities of minerals precipitated and dissolved it is determined that changes of the hydraulic system are equally well described by both models. FRACHEM and SHEMAT calculate the same temperature development and fluid velocities as well as resulting porosities from the mineral reactions. Thermodynamic equilibrium modelling resulted in comparable species and mineral concentrations in both models (applied activity coefficients and equilibrium constants have been chosen to be consistent for both codes). Thus, the Pitzer approach is well implemented. Finally, assuming an adequate calcite reaction rate in the SHEMAT code should result in a better fit of calcite amounts precipitated and dissolved.

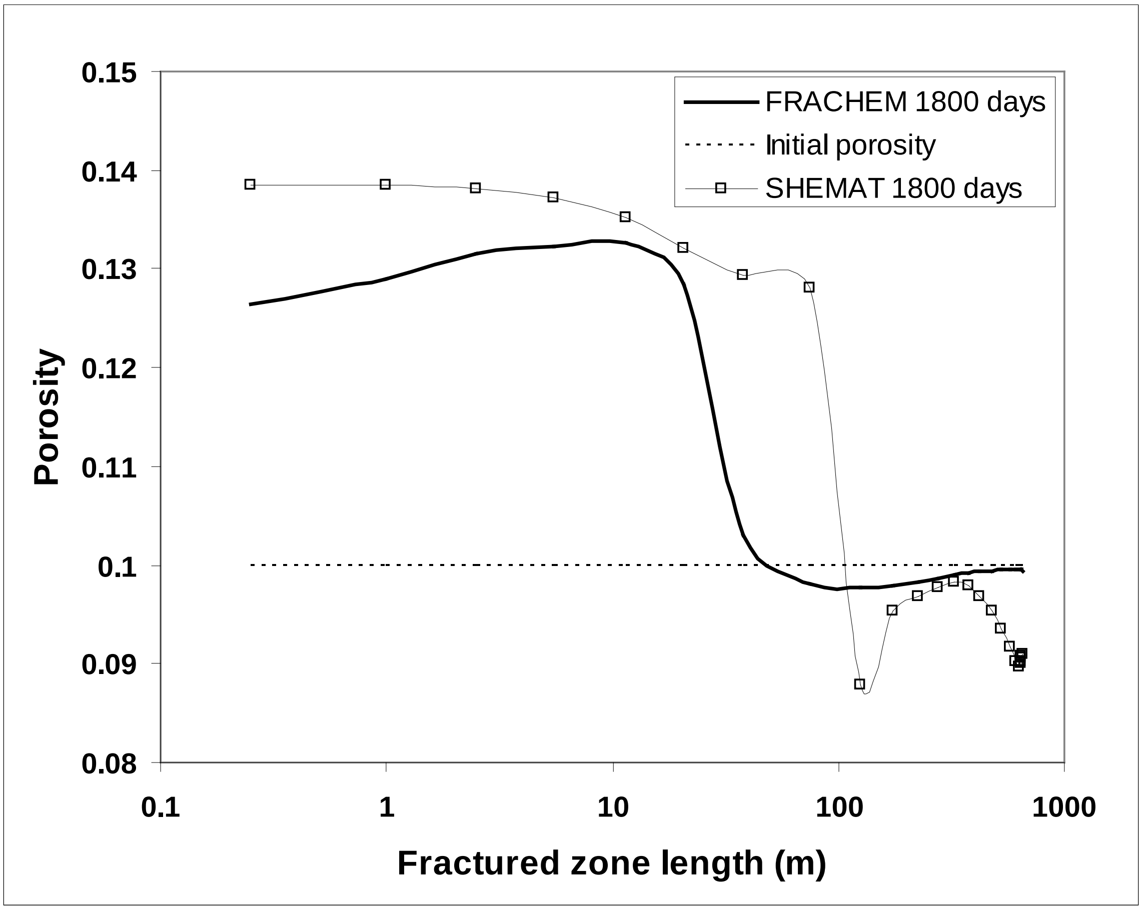

Figure 8. Porosity evolution for the two simulators FRACHEM and SHEMAT along the fractured zone after five years of forced fluid circulation.

2.3 Chemical stimulation techniques applied to geothermal wells and reservoirs

2.3.1 Introduction

Economic exploitation of enhanced geothermal systems is dependent to mineral precipitation and associated decrease in permeability of the system. This inhibits fluid flow and associated heat extraction from the system. One solution to this problem consists in injecting a reacting fluid into the wells, in order to dissolve the secondary minerals sealing the fractures, to increase the permeability and hence to stimulate the reservoir. Recent acid treatments were performed on the Soultz wells.

Geothermal injection wells are prone for having a naturally low injectivity and/or exhibiting serious injectivity losses at various stages of their life. The main reasons for sometime rapid injectivity losses are the need to inject very large amounts of brine per well. The new drilled or completed geothermal injection well differs drastically from the same well after large amounts of heat-depleted (cooled) brine are injected. The damage caused by drilling and completions operations is quite different from the damage caused by a prolonged injection of heat-depleted brine and also require special considerations (O'Sullivan and McKibbin, 1993).

Some field studies involving suspended particles measurement and monitoring in a geothermal operation showed that these suspended particles can eventually result in the plugging of the pore spaces of the reservoir, and thereby, decreasing well injectivity. In addition, various chemical inhibitors can be added during the production of the brine to combat scale (and/or corrosion) problems in the producing brine. Excess amounts of these chemicals may remain in the brine and enter the injection wells. This can damage the well by blocking the pores. The heat-depleted brine has a composition somewhat different from the formation brine and can create incompatibility problems. The stimulation of injection wells generally consists of repairing the near wellbore damage. Chemical methods (acidizing or use of chelating agents) are commonly used for such stimulation in high temperature geothermal fields worldwide.

2.3.2 Principles and practices

Matrix acidizing is suitable to both generate extra production capacity and to restore original productivity in damaged wells. Matrix acidizing of sandstones starts with the careful evaluation of the well and the accurate determination of the nature and severity of the problem. Then, a possible treatment fluid is selected. The first selection criterion is the nature and location of the damage. Then, the potential compatibility problems between the rock minerals and the fluids are examined. The composition of the fluid is further defined by performing flow tests and checking the absence of damaging reactions. Once the treating fluids and the sequence of fluids have been defined, treating parameters, such as volumes, rates, and pressure, are estimated or calculated and simulated. If the extension and severity of the damage are known, and economic evaluation (production prediction vs treatment cost) can be performed and the treatment results can be optimized. Various diverting techniques, including mechanical techniques (such as packers) and various chemical diverting agents allow better fluid placement. To enhance the production (or injection) capacity, most of the damage must be removed, and thus the treating fluid must be injected in the least permeable and most damaged zones. Finally, a comprehensive monitoring of the job effectiveness and a post-treatment evaluation are necessary.

Various types of chemical stimulation methods have been considered. High pH fluids seem to be a logical choice for some wellbore and/or reservoir stimulations. The solid silica, one of the major sources for injector plugging is highly soluble in many high pH fluids. But unfortunately, the native reservoir fluids as well as the injected brine are often highly sensitive to a high pH value. The precipitation of hydroxide and basic carbonate scales is a consequence of the chemical reactions between high pH stimulation fluid and reservoir or injection brine. These scales, particularly the hydroxides, are extremely voluminous in the pores even if their amounts are only very small.

Fluids having a neutral pH can be successfully used in chemical stimulation methods only in a very few and rare instances. There are some neutral pH fluids which could be excellent solvents for certain types of damaging materials. For example ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid (NTA) salts are excellent chelating agents (Fredd and Fogler, 1998). Thus, scales could be removed by solutions of these materials in neutral or near neutral pH water without causing secondary precipitates if properly applied (Rose et al., 2007). The major problem is cost: these compounds are rather expensive and large amounts would be necessary for most stimulation jobs. Low pH fluids, i.e. acids, have by far the best chance to be used for these chemical stimulation jobs. The standard acid treatments are HCl mixtures to dissolve carbonate minerals and HCl-HF formulations to attack those plugging minerals, mainly silicates (clays and feldspars).

The reactivity of the formation-dissolving fluid may be selected (for example with the use of fracture and/or acidizing simulator computer programs) on the basis of the flow rate and formation and fluid parameters. The reactivity of the stimulation fluid can be controlled by varying the rate of reaction, the rate of mass transfer, or both. For example, the rate of reaction can be decreased by changing the type of stimulation fluid, by changing the form of the fluid from a solution to an emulsion, by adding appropriate salts (which change the equilibrium constant for the surface reaction), or by increasing the pH of the stimulation fluid. The rate of reaction can also be decreased by changing the physical processing conditions (e.g., by reducing the pump flow rate and/or pumping pressure, or by cooling the stimulation fluid). A matrix acidizing apparatus for conducting linear core flooding is capable of reproducing different conditions regarding flow rate, pressure, and temperature. The results obtained from the experiments carried out on core samples showed that the temperature activates the reaction rate of HF-HCl acid mixtures in sandstone acidizing. The use of higher concentrations of HF, particularly at high temperatures, may cause deconsolidation of the matrix adversely affecting the final stimulation results. It was also seen that the higher the flow rate the better the permeability response, until certain optimal flow rates are reached.

In general, in creating propped fractures having wormholes in the fracture faces far from the wellbore, simple mineral acids such as HCl, HF, or mixtures of HCl and HF, would be too reactive, and would spend too close to the wellbore. It would normally be necessary to use a less reactive formation-dissolving fluid (Crowe, 1986, Gdanski, 1997). Acids are not the only reactive fluids that will dissolve formation minerals. Non-limiting examples would be organic acids, retarded mineral acids (such as gelled or emulsified HCl), or chelating agents. The reactivities of organic acids, such as acetic or formic acids, could be further adjusted by including varying amounts of sodium acetate or sodium formate respectively. The reactivities of chelating agents, such as EDTA or HEDTA (hydroxyethylethylenediaminetriacetic acid), could be further adjusted by converting them partially or completely into sodium, potassium or calcium salts or by adjusting the pH with for example HCl. These chelant-based materials have low reactivity, low viscosity, but high dissolving capacity (Mella and Rose, 2006).

2.3.3 Case studies in geothermal reservoirs

Over the past years, great improvements in matrix acidizing have taken place for geothermal wells, parallelling the developments in hydraulic fracturing. Provided that the forecasted production/injection results make economic sense, matrix acidizing is still simpler, often less risky, and more economic to implement than hydraulic fracturing. Preplanning and proper job design are essential for a successful matrix stimulation treatment. Different techniques are being used over a variety of reservoir and well conditions. Sophisticated laboratory equipment, expertise, and well testing software can help to identify production or injection damage effects and mechanisms – making it easier to select proper well candidates and optimize job design. Except as may be helpful in adjusting the pH of the fluid system, there are no restrictions on the order of addition of the components in the fluid mixture.

Alternatively, any combination of the components can be premixed on site or at a separate location (to enhance safety on location) and then another component or components may be added later. Standard mixing equipment and methods may be used; heating and special agitation are normally not needed but may be used. The only acid additives necessary in a geothermal acid job are corrosion inhibitor and inhibitor intensifier, as well as high-temperature iron-control (reducing) agent. Corrosion inhibitors of diverse description and composition have been proposed over the years for use with well treating acids. Treatment placement is better ensured through the use of chemical or mechanical diversion methods and technologies, and placement tools (coiled tubing, packers, etc.). On-site quality control is enabled by monitors and software, enabling to determine the evolution of skin with time, and radius of formation treated.

A summary of the main chemical stimulation experiments carried out in geothermal fields is given in Table 5, showing variable results. To date, only a few chemical stimulation experiments and laboratory tests have been attempted in EGS wells and reservoirs. Only limited amount of data were found on the projects at Fenton Hill, USA (LANL, 1977) and Fjällbacka, Sweden (Sundquist et al., 1988; Wallroth et al., 1999).

Table 5. Results of chemical treatments for scaling removal and connectivity development in selected geothermal fields.

Geothermal field	Chemical agents used	Number of treated wells	Variation of the injectivity index before and after chemical treatment ($kg.s^{-1}.bar^{-1}$)	Ref.
Bacman (Philippines)	HCl - HF	2	0.68 to 3.01	(1)
			0.99 to 1.40	
Leyte (Philippines)	HCl – HF	3	3.01 to 5.84	(2)
			0.68 to 1.77	
			1.52 to 10.80	
Tiwi (Philippines)	HCl – HF	1	2.52 to 11.34	(3)
Mindanao (Philippines)	HCl – HF	1	successful	(4)
Salak (Indonesia)	HCl – HF	1	4.70 to 12.10	(5)
Berlín (El Salvador)	HCl – HF	5	1.60 to 7.60	(6)
			1.40 to 8.60	
			0.20 to 1.98	
			0.90 to 3.40	
			1.65 to 4.67	
Las Tres Vírgenes (Mexico)	HCl – HF	2	0.8 to 2.0	(7)
			1.2 to 3.7	
Los Azufres (Mexico)	HCl – HF	1	3.3 to 9.1	(8)
Beowawe (USA)	HCl – HF	1	successful	(9)
The Geysers (USA)	HCl – HF	1	no effect	(10)
Coso (USA)	HCl and NTA*	30	24 wells successful	(11)
Larderello (Italy)	HCl – HF	5	11 to 54	(12)
			4 to 25	
			1.5 to 18	
			successful	
			11 to 54	
Fenton Hill (USA)	Na_2CO_3	1	About 1000 kg of quartz were dissolved and removed from the reservoir but no impedance reduction resulted.	(13)
Fjällbacka (Sweden)	HCl – HF	1	Efficiency of acid injection in returning rock particles.	(14)

References: (1) Buning et al., 1995; (2) Malate et al., 1997; Yglopaz et al., 1998; (3) Buning et al., 1995; (4) Buning et al., 1997; (5) Pasikki and Gilmore, 2006; (6) Barrios et al., 2002 and 2007; (7) Jaimes-Maldonado and Sànchez-Velasco, 2003; (8) Flores et al., 2006; (9) Epperson, 1983; (10) Entingh, 1999; (11) Evanoff et al., 1995; Rose et al., 2007; (12) Capetti, 2006; (13) LANL, 1977; (14) Sundquist et al., 1988; Wallroth et al., 1999.

* NTA: Nitrilotriacetic acid ($C_6H_9NO_6$)

2.3.4 Summary of tests performed at Soultz-sous-Forêts EGS project

Low-pressure pre-stimulation hydraulic tests were conducted in the wells to characterize the natural permeability of the granite. They indicated an initial productivity index of 0.01 $L.s^{-1}.bar^{-1}$ in GPK4, 0.1 $L.s^{-1}.bar^{-1}$ in GPK3 and 0.02 $L.s^{-1}.bar^{-1}$ in GPK2. The first hydraulic stimulations of the three wells were carried out between 2000 and 2005, and resulted in an improvement of the productivity index of wells GPK2 and GPK4 by a factor of approximately 20 and of GPK3 by a factor of approximately 1.5 (Nami et al., 2007). Although the limited performance of hydraulic stimulation, with high costs and public concern about induced seismic events, provided an important set of reasons for undertaking chemical treatments as additional or even alternative method to hydraulic stimulation, the main argument for chemical stimulation was the evidence, based on drill cuttings and cores analysis as well as on geophysical logs, of fracture filling by carbonates and other soluble minerals. The results obtained both from tracer tests (Sanjuan et al., 2006) and pressure interferences based on the hydraulic tests carried out in the open hole sections (Dezayes et al., 2005) have clearly identified the major fluid pathways that take fluid during stimulation and permit to show that some connections occur between the boreholes throughout the natural fractures of the granite basement. The most important fracture zone, oriented N160°E-52°W, appears as a "direct" connection between GPK2 and GPK3 (Dezayes et al., 2005). However, in GPK2, this fracture zone is thinner and less permeable than in GPK3.

Due to the insufficient productivities of GPK2 and GPK4 and the poor injectivity of GPK3 after successive hydraulic stimulations, it was decided to carry out a programme of chemical stimulation on all three wells. Chemical treatments with low-concentrations of HCl were performed in the three wells after the hydraulic stimulations. The objective of this dilute but extended stimulation was to dissolve secondary carbonates (calcite and dolomite) deposited in the fractures. Between May 2006 and February 2007, three operations of chemical stimulation were planned and carried out in GPK4 and one in GPK3. During these operations, solutions of Regular Mud Acid (RMA), nitrilo-triacetic acid (NTA) and Organic Clay Acid (OCA) were successively injected with fresh water into GPK4, but only the OCA treatment was used for GPK3.

Chemical stimulations were performed by injecting acid and reacting solutions from the wellhead through the casing string. The stimulation zones were therefore the whole openhole section of the wells (500 to 650 m length). Corrosion inhibitors were used to protect the inner casing string. The operations were conducted by specialized service companies. Table 6 shows the various chemical treatments conducted in the deep Soultz wells.

Hydraulic tests were performed before and after the chemical stimulations in order to evaluate the change in productivity or injectivity. The productivity and injectivity values are time-dependent; the values in Table 6 are those after 3 days of injection or production. The experience in Soultz shows that there is no significant difference between injectivity and productivity at moderate flows and pressure changes (Nami et al., 2008). Geochemical monitoring was conducted during most of the chemical stimulations. Sanjuan et al. (2007) report on the results obtained on the fluids and deposits collected from the GPK4 and GPK3 during the production tests carried out in 2006 and 2007 after the chemical stimulation operations. This work was done in the framework of the research activities accompanying the construction of the scientific pilot plant (European EGS Pilot Plant Project).

Table 6. Summary of the chemical stimulation operations carried out in the three 5-km deep wells at Soultz-sous-Forêts

Well	Date	Concentration of chemical agents	Results Inj./Prod. increase
GPK2 (production well)	Feb. 2003	One test in 2 steps: HCl 0.09 % and HCl 0.18 %	Wellhead pressure drop and productivity increase (0.5 $L.s^{-1}.bar^{-1}$)
GPK3 (reinjection well)	June 2003	HCl 0.45 %	Injectivity: 0.35 $L.s^{-1}.bar^{-1}$
	Feb. 2007	OCA HT	Weak impact: 0.4 $L.s^{-1}.bar^{-1}$
GPK4 (production well)	Feb. 2005	HCl 0.2 %	Productivity: 0.2 to 0.3 $L.s^{-1}.bar^{-1}$
	May 2006	Preflush: HCl 15 %	
		RMA (HCl 12% - HF 3%)	Max. enhancement of injectivity: 35%
	Oct. 2006	NTA 19 % in caustic soda	The formation of a plug increased wellhead pressure - Productivity: 0.3 to 0.4 $L.s^{-1}.bar^{-1}$ (after RMA and NTA treatments)
	March 2007	OCA HT	Productivity: 0.4 to 0.5 $L.s^{-1}.bar^{-1}$

2.3.5 First results for permeability improvement in the vicinity of the Soultz wells

The chemical stimulation programme performed at Soultz generated an improvement factor of 1.12 to 2.5 of the injectivity/productivity (Nami et al., 2008). The easiest gain was obtained in GPK2 and the most important was observed in GPK4 (GEIE 2007).

Although they were not executed with the same comparable protocol, variable but encouraging results were observed after this series of tests using several chemical stimulation methods in a fractured granitic EGS reservoir. While GPK3 showed weak variations of its injectivity whatever the technique used (hydraulic or chemical), GPK4 presented a real increase of injectivity and productivity after the treatments, and GPK2 also presented a very sensible improvement despite the fact that the acid treatments were limited in terms of time, volume and concentration. Table 2 presents a summary of the chemical stimulation approach and the results obtained so far in the three deep wells of the Soultz EGS project.

These results show that the acids have actively reacted with minerals present in the fractured and porous volumes of the granite. The injection into GPK4 of NTA dissolved in caustic soda solution (pH 12) allowed cleaning of this well and of a part of the fractured areas, and the recovery of significant amounts of drilling wastes (grease, cuttings), rock fragments and hydrothermal deposits. Dissolved and solid Ca-Fe-NTA compounds were also formed. The maximum volumes of calcite dissolved by the RMA and NTA treatments were estimated at about 19.2 and 5.5 m^3 respectively (Sanjuan et al., 2007). The prior use of a caustic soda solution to clean GPK4 before the NTA injection would have probably allowed NTA to extend deeper into the fractures and, consequently, to be more efficient.

The OCA treatment improved GPK4's productivity from 0.4 to 0.5 $L.s^{-1}.bar^{-1}$, but seems not to have made much difference to the injectivity of GPK3. The OCA solution mainly attacks calcite but also silicate, alumino-silicate, iron oxy-hydroxide minerals and Ca-Fe-NTA compounds.

No major improvement in injectivity was observed for GPK3 after successive stimulation operations with HCl and OCA. Even though the distribution and sizes of the fractured areas around GPK3 and GPK4 are probably different, the failure to use a caustic soda solution to clean GPK3 and the neighbouring fractured areas (where it is likely that accumulated debris formed blockages well into the main fracture zone) could partially explain the limited results obtained on this well. It seems that single chemical treatments may not be appropriate for the Soultz wells but that a combination of treatments must be envisaged.

The combination of the RMA, NTA and OCA treatments is possibly at the origin of the significant increase of GPK4 productivity (Figure 9). However, minor microseismic activity (hundreds of events with magnitudes up to 1.5) was observed around 4100 m TVD during the OCA test in GPK4 well (Nami et al., 2008). Flow logs were run and have shown two leak zones in the well casing at 4110 (15-25%) and 4440 m TVD (9-15%, 50 m above the casing shoe), respectively. The leak locations do not correspond to the joints of the casing. The origin of these leaks is not clearly explained but the shearing of fractures could be involved. Except for these two loss zones, the flow is quite constant until a last fluid loss at 4800 m TVD that corresponds to a known highly hydrothermalized fracture zone. In contrast to the previous production tests, the temperature curve of the production test performed after the OCA-stimulation showed a decreasing trend despite the highest production rate (Nami et al., 2008). Apparently, this gain of productivity does not originate only from the openhole section. Thus, the chemical stimulations with RMA, NTA dissolved in caustic soda solution and OCA improved the productivity of the GPK4 well by 30 and 25% respectively, but a part of this gain could be attributed to a simultaneous hydraulic stimulation of two loss zones in the cemented part of the casing, assuming that they were not generated during or after termination of the initial hydraulic stimulation.

From the step rate test performed in GPK4, the pressure response in GPK3 and GPK2 was observed throughout the stimulation operations to follow the connection to GPK4. A sensitive pressure response was measured in the two wells after the stimulation with RMA. The pressure difference in GPK3 is higher than in GPK2 because of its proximity to GPK4. For the same reason, the reaction time is shorter in GPK3. The pressure propagation to GPK2 might be explained by the improved connectivity of a structure between GPK3 and GPK4, reaching another structure connecting GPK2 and GPK3. The great fracture zone connecting GPK2 and GPK3 could form a short-cut circulation pathway and minimize the residence time of the fluids in the reservoir and thereby affect the production temperature. The geochemical monitoring of the fluids discharged from GPK3 and GPK4 also indicates that the proportions of traced fresh water injected in large amounts in 2000, 2003 and 2005 into GPK2, GPK3 and GPK4 are always low (< 10%) compared to the proportions of native geothermal brine (Sanjuan et al., 2007). The existence of at least three fluid flow pathways between the wells GPK2 and GPK3 with different effective fluid velocities, which contrasts with a poor hydraulic connection between GPK3 and GPK4, was highlighted during the fluid circulation loop and the associated tracer test using fluorescein, carried out between July and December 2005 (Sanjuan, 2006).

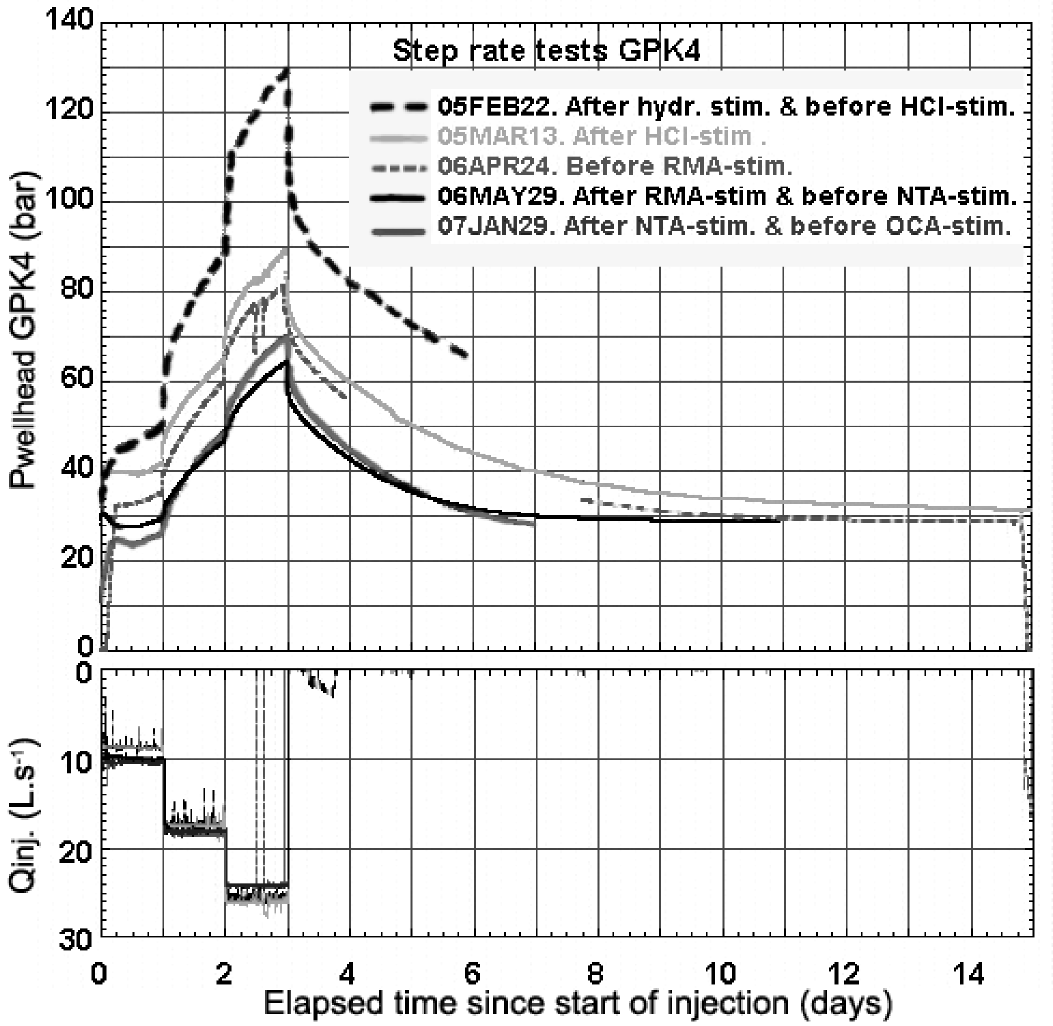

Figure 9. Comparison of GPK4 wellhead pressures and injection rates with time during chemical treatments (step rate tests performed in GPK4 well), (modified after Nami et al., 2007).

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Polydynamics Engineering

Appendix 1 – the project

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