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HEAT AND FLUID FLOW AT THE SOULTZ HOT DRY ROCK SYSTEM IN THE RHINE GRABEN

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ABSTRACT

Hot-Dry-Rock (HDR) is a concept for using Earth's heat as an energy source. An artificial underground heat exchanger at a depth of 3.0 to 3.5 km was created in the granitic basement of the Rhine Graben, close to the town of Soultz in France, by hydraulically connecting two deep boreholes over a horizontal distance of 500 m with the hydrofrac technique. During a 4-month circulation test, over 240,000 m^3 of water were injected and produced at flow rates of 20 to 25 l/s and with outflow temperatures above 140 °C. The net output of thermal power exceeded 10 MW. The experiments indicate that the circulation system in the underground is hydraulically open.

Numerical models of coupled heat and fluid flow help to understand the observations. At the regional scale, previous models suggested deep fluid circulation from East to West through a sandstone aquifer across the Rhine Graben causes a heat flow anomaly at Soultz. This is in contradiction to recent geochemical analyses of pore-fluids. Models of the regional flow-system that agree with the pore-fluid chemistry now predict deep flow through the granitic basement. These models show that in the area of the HDR heat exchanger fluids generally move upwards.

The results of the regional simulations are incorporated as boundary conditions in a local 3-D model of the underground heat exchanger at Soultz. This model consideres two flow regimes: (1) flow in the artificially fractured (stimulated) volume of the granite and (2) flow channeled along natural faults. The stimulated volume is a heat exchanger in the classical HDR concept: it is the hydraulic connection between injection and production wells and provides the surface for heat exchange between the fluid and the the fractured rock. Additionally, the hydraulic fracturing of the granite created a connection with the regional fault system of the graben. Although not part of the HDR concept, this extension of the system improves the long-term heat extraction process because the regional fault system acts as a large heat and fluid reservoir. The numerical models are used to predict the performance of a pilot plant that is planned to utilize an underground heat exchanger at 200 °C over a period of more than 30 years.

1. INTRODUCTION

By hydraulically connecting two deep boreholes with the hydrofrac-technique (Baumgärtner et al., 1998), an artificial underground heat exchanger at a depth of 3.0 to 3.5 km was created in the granitic basement of the Rhine Graben at the European HDR project site near the town of Soultz-sous-Forêts in France. The goals of our project are to create a numerical model of this underground heat excanger, to understand observations made so far, and to predict the long-term performance of a future power plant. As a first step, the regional flow and temperature field across the Rhine Graben is simulated with a 2-D model. In a second step, the results of this model are used as boundary conditions for a local 3-D model of the heat exchanger at Soultz.

2. THE REGIONAL FLOW AND TEMPERATURE FIELD

Soultz-sous-Forêts is the center of the largest anomaly of surface heat flow density in central Europe. With a background value of 80 mW m^{-2} for the Rhine Graben, heat flow density exceeds 140 mW m^{-2} at the Soultz site (Schellschmidt and Clauser, 1996). This anomaly is located about 70 km north of the Kaiserstuhl volcano which is associated with a minimum in crustal thickness and a maximum of mantle He-isotope concentrations in the upper Rhine Graben. The surface heat flow density anomaly at Soultz is not a signal associated with processes at great depth (e.g., rifting) but the result of a redistribution of heat by advection due to fluid flow in the upper crust.

Figure 1 shows the position of a cross section of the Rhine Graben including the HDR site at Soultz. Based on seismic profiles, geological structures along this cross section were translated into a 2-D finite difference grid. Temperature data from boreholes were projected into the plane of the profile. The data was averaged (weighted with the distance of the borehole to the cross section) on a 4.0 km x 0.3 km grid.

The resulting temperature field is shown in Figure 2 together with the numerical model of the simplified geological cross section. High temperatures characterize the area of the HDR site (X=20 km). The general trend, showing lower temperatures in the center of the graben (X=40 km), is in part a result of the high radiogenic heat production of the granite in combination with the topography of the basement. This temperature field is used for the calibration of the numerical models.

Previous numerical models of coupled heat- and fluid-flow for the Rhine Graben suggested that deep circulation of meteoric water through the Buntsandstein aquifer causes the thermal anomaly at Soultz (Clauser and Villinger, 1990; Person and Garven, 1992). The circulation is driven by flow from the topographically higher flanks, i.e. the Vosges Mountains in the West and the Schwarzwald (Black Forest) in the East. Fluid flow, especially coming from the Schwarzwald, is forced to greater depths and thus carries heat to a horst beneath Soultz. These models are in agreement with the thermal anomaly; however, the regional temperature field shown in Figure 2, not available at that time, is not compatible with this flow field. While the high temperatures at Soultz are reproduced, discrepancies to the observations occur, especially at the flanks of the graben.

Recent analyses of pore water also indicate that fluids in the sandstone aquifer are not diluted by meteoric waters flowing from East to West (Aquilina et al., in press). The results suggest that the aquifer fluids in the deeper part of the graben represent the primary brine, i.e. old evaporated sea water (Fig. 3). As one example of this analysis, Figure 3 shows salinity along an E-W profile across the Rhine Graben. The salinity increases from the Vosges Mountains in the West towards the Soultz site. This agrees well with the concept of meteoric water circulating at the western graben flanks. However, salinity increases abruptly from 20 g/l to 100 g/l at the Soultz site, and from there towards the East the values increase by more than 100%. This is in contradiction to previous flow schemes with meteoric water flowing from the East to the West.

As a consequence of these chemical pore water analyses, regional flow models have recently been revised to allow deep circulation in the granitic basement. The model shown in Figure 2 was expanded to a depth of 15 km. A higher permeability is attributed to the upper 600 m of the granitic basement where borehole measurements have shown that horizontal fractures occur only in this layer. The resulting flow system is schematically shown in Figure 4.

Similar to previous models and in agreement with the chemical analyses, shallow circulation through the sandstone aquifer occurs at the western flank of the graben, forced by the topography of the Vosges Mountains. This convection is not efficient enough to produce the observed heat flow density anomaly at Soultz. East of Soultz, free convection produces small circulation cells within the aquifer and the altered layer of the granite. The cells occur at greater depth because higher temperatures decrease the fluid viscocity and the critical Rayleigh number is exceeded. A flow pattern from East to West through the Buntsandstein aquifer does not develop. Water penetrates the granitic basement in the East, driven by the topography of the Schwarzwald. Water that reaches the permeable aquifer at shallow depth forms no circulation cells and rises to the surface. This causes a temperature high similar to the observations (Fig. 2, X=55 km). In deeper parts of the graben, circulation cells develop and form an obstacle for fluids trying to enter the aquifer. Thus, the water is forced to flow beneath the deepest part of the graben filling. Rising from great depths, these fluids carry enough heat to produce the observed heat flow density anomaly at Soultz. Flow rates in the granite are not high but the moving volume is sufficient. The flow scheme shown in Figure 4 is in good agreement with both the observed temperatures and the results of chemical pore fluid analyses.

The concept of rising water in the granitic basement at the HDR site is also in agreement with the temperatures measured in the Soultz boreholes (Fig. 5). The temperature gradient of 100 K/km in the top sediments drops to 10 K/km in the drilled granitic section (1.4 to 3.8 km). The thermal anomaly detected at the surface of the Soultz area is limited in depth to the thickness of the sediment cover (1.4 km). This large near-surface gradient is the result of convective heat transport partly in the Buntsandstein aquifer, where the gradient is decreased slightly, but mainly from deep parts of the granitic basement, where the gradient is accordingly low. The local 3-D model of the HDR heat exchanger is imbedded in this regional flow system.

3. LOCAL 3-D MODEL OF THE HEAT EXCHANGER

Numerous hydraulic experiments in Soultz indicate that the fracturing of the granitic basement in GPK1 and GPK2 on the one hand produced a volume of enhanced permeability between the two boreholes, and on the other hand hydraulically connected this stimulated volume to the regional fault system (Jung et al., 1995). The modeling of the underground heat exchanger is thus based on two flow mechanisms: flow in the artificially stimulated volume and channeled flow along natural fault zones. The modelling strategy is two-fold: (1) calibration of the hydraulic model and simulation of the flow field, and (2) coupling of fluid and heat flow for the prediction of a long-term thermal behavior of the heat exchanger.

Step (1a) The fault system is translated into a 2½-D grid, i.e. 2-D elements connected in a 3-D space. Figure 6 shows the geometry of typical fault systems observed at the western flank of the Rhine Graben: parallel and transverse to the graben flank, and parallel to the present-day stress field. To be as realistic as possible, a detailed assessment is done for the Soultz site by comparing flow logs with temperature logs to identify those fractures that are associated with thermally relevant flow. Then, structural logs (providing images of the borehole wall) are used to determine the geometric characteristics (strike and dip) of the chosen fractures (Helmut Tenzer, pers. comm., 1998).

Figure 7 shows typical flow logs for GPK1 and GPK2. In general, these flow logs were similar for all hydraulic experiments, independent of flow direction or pumping rate. For identified flow zones (arrows in Fig. 7), relative flow rates, strike and dip are listed in Table 1. The geometry of the major flow zones (solid arrows in Fig. 7 and bold text in Table 1) is assessed in detail using AutoCAD® for visualization

The translation of this fault system into a 2½-D finite element (FE) grid is shown in Figure 8. We use adaptive grids that are refined automatically during the numerical simulation in places where large gradients occur. This model of channeled flow on fault zones is used to assess the strongest hydraulic signals observed during circulation tests, both in the near- and far-field around the boreholes, and to reproduce break-through times for tracers used in these experiments.

Step (1b) The stimulated volume around the boreholes is connected to this grid as a limited 3-D equivalently porous body. The area of enhanced porosity and permeability within the granite, which is created by the hydraulic stimulation from both boreholes, is shown in Figure 9. Connecting these 3-D bodies to the 2½-D grid of the fault system allows a good match to the observed tailing of tracer recovery, improves the hydraulic connection to the fault system, and represents a short but slow, direct connection between the boreholes.

Step (2) After calibrating the hydraulic model in Step (1) with observations made so far, coupled heat- and fluid-flow is simulated by integrating this model into a 3-D matrix with thermal properties (Fig. 9).

Considering the two flow regimes (one in an equivalent porous medium and the other in faults zones) is important for a realistic simulation of the heat exchange process in the underground. The stimulated zones provide the pathways and the large internal surface for an efficient heat exchange between rock and fluid. This heat exchanger may change in time by effects of over-pressure, reduced permeability or cooling during long-term heat-mining (several decades). However, the observed connection of the system to the regional fault zones will have a significant influence on this development. For a realistic performance prediction of a future power plant at Soultz, the regional flow field is thus incroporated into the numerical simulations.

5. SUMMARY AND CONCLUSIONS

Earlier models of the regional fluid flow system across the Rhine Graben at Soultz had to be revised because they are in contradiction to new geochemical pore-water analyses. The Buntsandstein aquifer fluids are not diluted by meteoric waters coming from the Schwarzwald, and convection in the Buindsandstein alone is not the cause of the thermal anomaly at Soultz. Models of the flow system are in agreement with the regional temperature field and the observed pore-water chemistry if deep circulation in the granitic basement is allowed. In the area of the Soultz heat exchanger (3.0 - 3.5 km deep), fluids are generally flowing upwards.

Embedded in these regional modelling results, a 3-D local model of the heat exchanger is created. As results from hydraulic experiments demand, two flow regimes are considered: (1) flow in the artificially stimulated volumes of enhanced permeability around the open hole sections of GPK1 and GPK2, and (2) channeled flow along natural fault zones. A detailed analysis of the hydraulic experiments has identified hydraulically active sections (25% or more relative flow rate) in both holes, and provided depths and orientations for these fault zones. These results, in combination with geometrical analyses, show that there is no direct connection of GPK1 and GPK2 through a natural fault zone. All channeled pathways form indirect connections, resulting from the intercept of fault zones. This indicates that the two boreholes are connected to two different regional fault systems.

The stimulated areas have been created around the open-hole sections of the boreholes with the hydro-fracuring technique. As these areas of increased permeability overlap, they form a direct connection between the holes which can be treated as an equivalent porous medium. We assume that this connection is reponsible for the observed low relative flow rates (15% or less).

The modelling strategy is as follows. (1a) The channeled fluid flow on fault systems is simulated with a 2½-D model to match strong hydraulic signals from experiments and the tracer break-through times. (1b) The stimulated areas are added as equivalently porous 3-D volumes to the 2½-D grid to fit weaker hydraulic signals and the tracer tailing. (2) This hydraulic model is placed within a 3-D matrix with thermal properties in order to consider the coupling of fluid- and heat-flow.

The stimulated areas represent the actual heat exchanger of the classical HDR concept. In Soultz, they also created a connection to the regional flow system. This will be of advantage for the long-term development of the heat exchanger. The numerical models will be used to predict the performance of a future HDR power plant in Soultz.

REFERENCES

Aquilina, L., A. Genter, P. Elsass, and D. Pribnow, Evolution of fluid circulation in the Rhine Graben: constraints from the chemistry of the present fluids, in I. Stöber and K. Bucher (eds): *Hydrogeology of crystalline rocks*, Kluwer, in press.

Baumgärtner, J., A. Gerard, R. Baria, R. Jung, T. Tran-Viet, T. Gandy, L Aquilina, and J. Garnish, Circulating the HDR reservoir at Soultz: maintaining production and injection flow in complete balance, *Proceedings of the Twenty-Third Workshop on Geothermal reservoir Engineering, Jan 26-28, 1998,* Stanford University, 11-20, 1998.

Clauser, C., and H. Villinger, Analysis of conductive and convective heat transfer in a sedimentary basin, demonstrated for the Rhine Graben, *Geophys. J. Int., 100,* 393-414, 1990.

Person, M., and G. Garven, Hydrologic constraints on petroleum generation within continental rift basins: theory and application to the Rhine Graben, *Am. Assoc. Petrol. Geol. Bull., 76,* 468-488, 1992.

Jung, R., J. Willis-Richards, J. Nicholls, A. Bertozzi, and B. Heinemann, Evaluation of hydraulic tests at Soultz-sous-Forets, European Hot-Dry-Rock site, World Geothermal Congress, Florence, May 18-31, 2671-2676, 1995.

Pribnow, D., and C. Clauser, Heat and mass transport in the upper Rhine Graben: regional and local models for a Hot-Dry-Rock system, *4th International HDR Forum,* Strasbourg, 1998.

Schellschmidt, R. and C. Clauser, The Thermal Regime of the Upper Rhine Graben and the Anomaly at Soultz, *Z. angew. Geol. 42,* 40-46, 1996.

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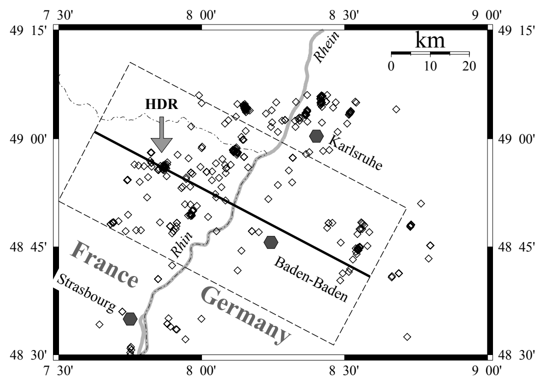

Figure 1. Position of the cross section (solid line) with locations of boreholes with temperature data (diamonds). Borehole data within a distance of less than 20 km (dashed-line box) were projected into the plane below the profile. Cities are labeled with large solid hexagons.

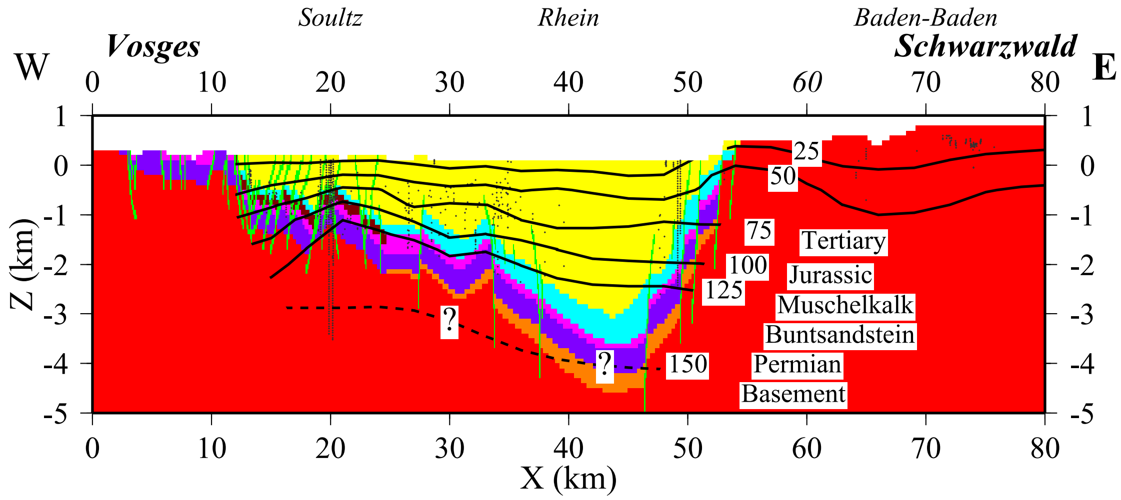

Figure 2. Numerical model of the geological structures based on seismic profiles along the cross section shown in Figure 1 together with temperature contours from borehole measurements. Subvertical structures are fault zones. The projected temperature data positions are marked with dots (746 values from 174 boreholes). Temperature contours are labeled in °C. The 150 °C contour is dashed because temperatures this high have only been measured at Soultz (X=20 km).

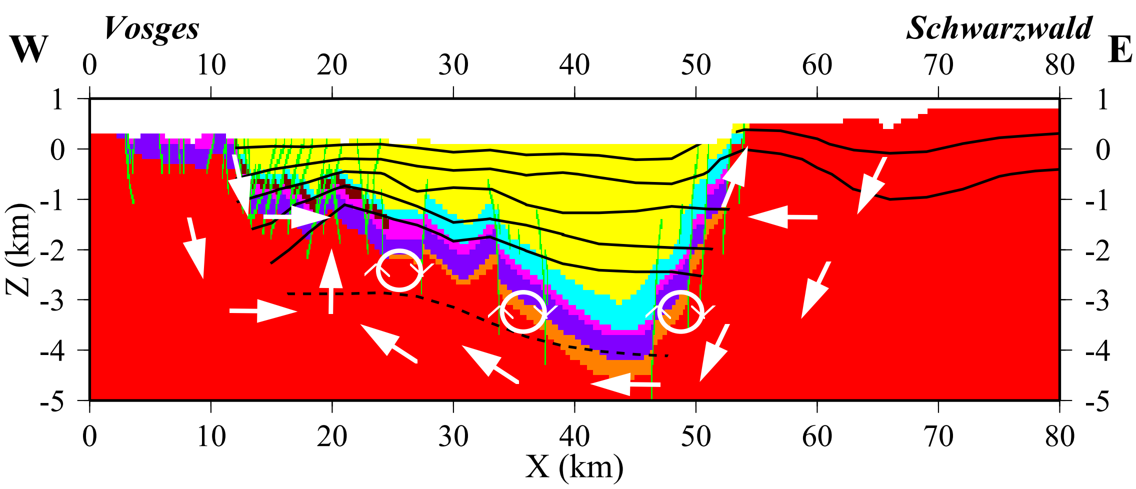

Figure 4. Schematic flow field including the granitic basement. The arrows indicate the direction of flow and are not related to the velocity. The numerical model is 15 km deep.

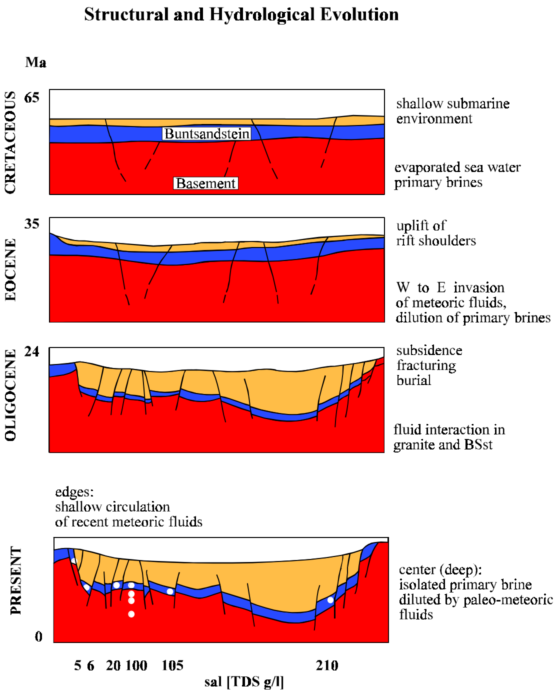

Figure 3. Schematic development of the Rhine Graben (Aquilina et al, in press). White circles mark positions of fluid samples. As an example of the chemical analyses, salinity (sal) is listed (TDS: total dissolved substance). At the HDR Soultz site, 4 samples were taken in different depths, including fluids from the granite.

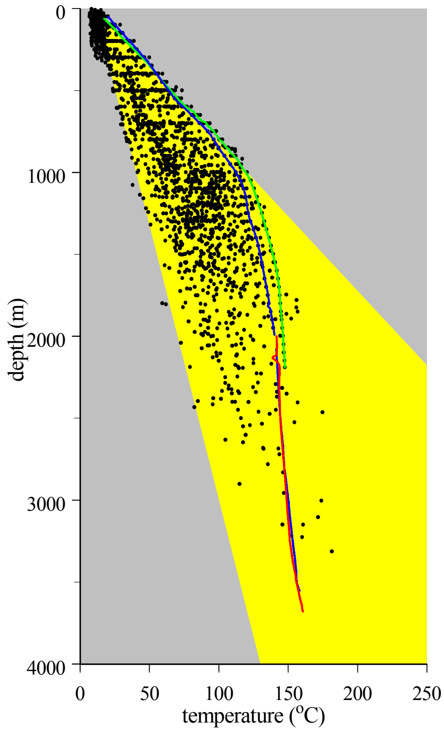

Figure 5. Temperature measured in boreholes in the Rhine Graben (dots) and in Soultz (lines).

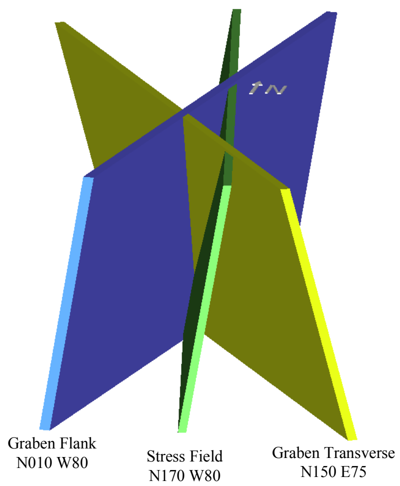

Fig. 6. Geometry of the natural fault system at the western flank of the Rhine graben based on data from the surface, boreholes and drill cores.

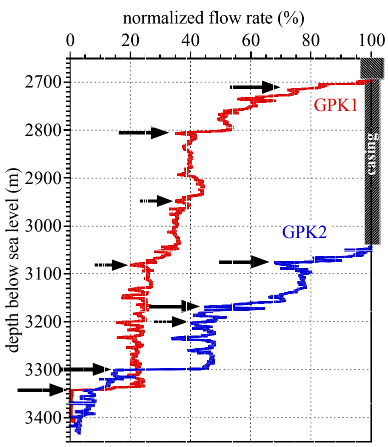

Figure 7. Typical flow logs for GKP1 and GPK2. For comparison, logging depths have been transformed into depths below sea level. Solid arrows mark identified flow zones with 25% flow rate or more; dahed arrows mark 10% or less. Borehole casing is indicated by black boxes (upper, thicker box for GPK1).

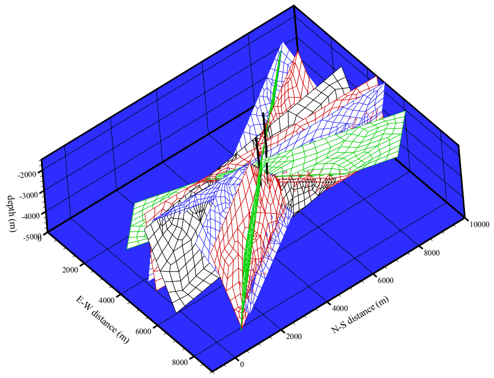

Figure 8. Translation of conceptual model based on data from Table 1 into 2½-D finite element grid.

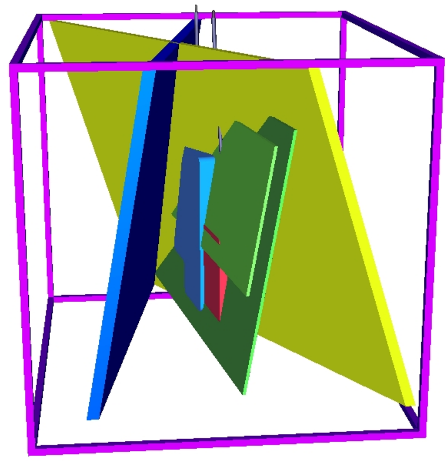

Fig. 9. Modell for coupled simulation of fluid flow in fractures (Fig. 8) and stimulated areas (center boxes) with heat flow density (large box).

Table 1. Characteristics of identified flow zones (after Helmut Tenzer, Stadtwerke Bad Urach). For comparison, logging depths (below well head) have been transformed into depths below sea level. The intercept with the other borehole is calculated geometrically. Zones with relative flow rates of 25% or more are bold (solid arrows in Fig. 7) and considered for further discussion. The flow zone at 2100 mbwh in GPK2 was observed while drilling the hole but is behind the casing now; the 40% flow rate is determined from an older experiment and is not comparable to the other results.

	depth below well head (mbwh)	depth below sea level (mbsl)	relative flow (%)	strike N180= north	dip 90= vert.	intercept with other hole (mbsl)
GPK1						
	2870	**2710**	**25**	**N20**	**W70**	none
	2960	**2810**	**30**	**N05**	**W80**	casing
	3100	2950	10	N20	E80	none
	3235	3080	10	N50	E50	none
	3500	**3340**	**25**	**N05**	**E85**	none
GPK2						
casing	2100	1930	(40)	N150	E75	2810
	3250	**3080**	**25**	**N150**	**E60**	3340
	3350	**3180**	**25**	**N140**	**E85**	none
	3370	3200	10	N150	E75	none
	3470	**3300**	**25**	**N175**	**E70**	3180
	3510	3340	10	N020	E80	none
	3560	3390	5	N160	E80	none