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How structural geology can contribute to make geothermal projects successful

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ABSTRACT

In most geothermal reservoirs, particularly in man-made reservoirs, fluid transport is through rock fractures, that is, the host-rock permeability is fracture-controlled ("fractured reservoirs"). The permeability of a geothermal reservoir can be increased through stimulation, either by shearing and opening of existing rock fractures or by creating new hydraulic fractures in the reservoir rock, resulting in Enhanced Geothermal Systems (EGS).

Here we show how structural geology can contribute to maximise the likelihood of success in geothermal projects, particularly as regards EGS projects. To obtain information on the geometry of existing fracture systems, so as to be able to estimate the potential permeability of man-made geothermal reservoirs, we analyse outcrop analogues, that is, outcrops of the same rock types as those supposed to host the man-made reservoir at geothermal depths.

We focus on rock heterogeneity and anisotropy, mainly mechanical layering, that is, changes in the mechanical properties, particularly rock stiffness (Young's modulus) and how these heterogeneities influence fracture propagation. Because of such rock heterogeneities, the local stress field can be very different from the regional stress field. We therefore show how numerical models help to understand the local stress fields as well as the connectivity of existing and newly created fracture systems and therefore the fluid transport in geothermal reservoirs.

We also present results of a case study on the prognosis of fracture systems and permeability in the Buntsandstein in the Northern German Basin. Our field results indicate that even very thin layers (cm-scale thicknesses) of shale, for example, may be responsible for arrest of many joints in sandstone-shale sequences such as the Buntsandstein.

1. INTRODUCTION

In man-made geothermal reservoirs subsurface heat exchangers are created in which water is repeatedly injected, heated and pumped up in order to produce heat and electricity. Commonly doublet-systems are used that consist of injection and production wells. The temperature of the produced water should be more than 100 °C for a period of tens of years. In continental areas with normal geothermal gradients this temperature is reached at depths of several kilometres.

For geothermal reservoirs to be of economic use, a necessary condition is that there is a high flow rate in the order of 10-50 l/s of hot water through the rock (Schulz and Röhling 2000, Schulz et al. 2003). In most geothermal reservoirs, particularly in man-made reservoirs, fluid transport is through rock fractures, that is, the host-rock permeability is fracture-controlled ("fractured reservoirs"; Nelson 1985). The permeability of a geothermal reservoir can be increased through stimulation, either by shearing and opening of existing rock fractures or by creating new hydraulic fractures in the reservoir rock ("reservoir stimulation"), resulting in Enhanced Geothermal Systems (EGS). To stimulate a reservoir successfully the existing fracture system and the current stress field need to be known as accurately as possible.

In this paper we show how structural geology can contribute to maximise the likelihood of success – so that a flow rate high enough for economic use is obtained – in geothermal projects, particularly as regards EGS projects. We first discuss methods of structural geology that we regard as necessary for successful geothermal exploration. Then we present results of a case study on the prognosis of fracture systems and permeability in the Buntsandstein in the Northern German Basin.

2. STRUCTURAL GEOLOGY AND GEOTHERMAL EXPLORATION

The main aim of structural geology in geothermal exploration is to predict the geometry of the existing fracture system, estimate possible fluid flow, and, based on this information, suggest suitable stimulations for the particular reservoir. In the following chapter we discuss methods of structural geology that are important for understanding permeability development in fractured reservoirs (Fig. 1). Without this understanding it is difficult to generate and maintain permeability in man-made geothermal reservoirs.

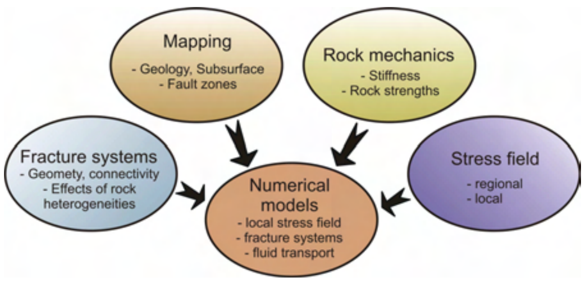

Figure 1: Methods of structural geology in geothermal exploration (see the text for details).

2.1 Geological Mapping

Early in geothermal exploration, the potential drilling sites should be mapped geologically in detail, combined with studies of aerial photographs and satellite images. In addition, any possible information should be obtained on the rocks and geological structures in the subsurface, for example from existing boreholes in the vicinity and results from seismic campaigns, in order to build three-dimensional geological models of the sites. Fault zones are of particular importance for the permeability of EGS because they can be barriers to fluid transport or, by contrast, form preferential flow paths, particularly during and just following fault slip.

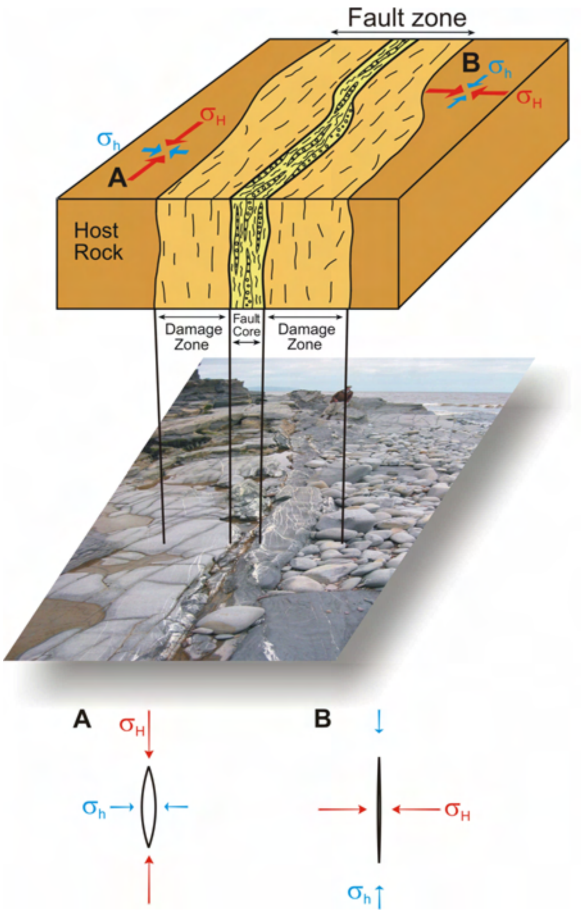

Figure 2: Schematic illustration of the main units of a fault zone (see the text for explanation) compared with a normal fault in limestone at Kilve, Bristol Channel, UK (Gudmundsson et al. 2002, Brenner and Gudmundsson 2004b). In the field example, view is along strike of the normal fault, the hanging wall is to the right. In the fault core, along the fault plane, there is a dense network of calcite veins. The veins extend for a distance of only a few metres from the fault plane into the damage zone. The inserted sketches indicate the sensitivity of fractures to the current stress field. In a stress field A where the maximum principal compressive stress is parallel to the fracture, the fracture tends to open up and fluid transport is enhanced. In a stress field B, however, where the maximum principal compressive stress is perpendicular to the strike of the fracture, the fracture tends to close and fluid transport is inhibited.

Fault zones commonly consist of two major hydromechanical units, namely a fault core and a damage zone (Fig. 2; Caine et al. 1996). The fault core, primarily composed of breccia or gouge, is formed through repeated slip on the fault plane. In an active fault zone (during fault slip – commonly accompanied by earthquakes), the hydraulic conductivity of the fault core is commonly increased by several orders of magnitude (Gudmundsson 2000). For that reason earthquakes may have dramatic effects on hot springs and wells in geothermal fields, such as occurred during two M6.6 earthquakes on strike-slip faults in the South Iceland Seismic Zone in June 2000 (Bergerat and Angelier 2003) that increased the flow of hot water to the surface by some hundreds of litres per second, equivalent to 100 MW thermal power (Orkustofnun, Icelandic National Energy Authority, Homepage www.os.is). When a fault is not active, however, the fault core is commonly very tight and rather a barrier to fluid transport (Gudmundsson et al. 2002). The fault damage zone, occurring on both sides of the fault core, consists mainly of fractures of various sizes that are typically subparallel to the main fault plane (Gudmundsson 2000). Here, the permeability depends mainly on the interconnectivity of the fracture systems and the local stress field.

2.2 Fracture Systems

Fluid flow in a fractured reservoir is largely, and may be almost entirely, controlled by the permeability of its fracture network. For fluid flow to occur from one site A to another site B in a reservoir there must be at least one interconnected cluster of fractures that links these sites. The condition that such a cluster exists is commonly referred to as the percolation threshold (Fig. 3; Stauffer and Aharony 1994). The permeability associated with an individual fracture is mainly controlled by its aperture (opening), that means the volumetric flow rate through a fracture is proportional to the cube of its aperture (the cubic law; de Marsily 1986). Because of possible flow channelling along the widest parts of a fracture (Tsang and Neretnieks 1998), aperture variation is important for the permeability in fluid reservoirs.

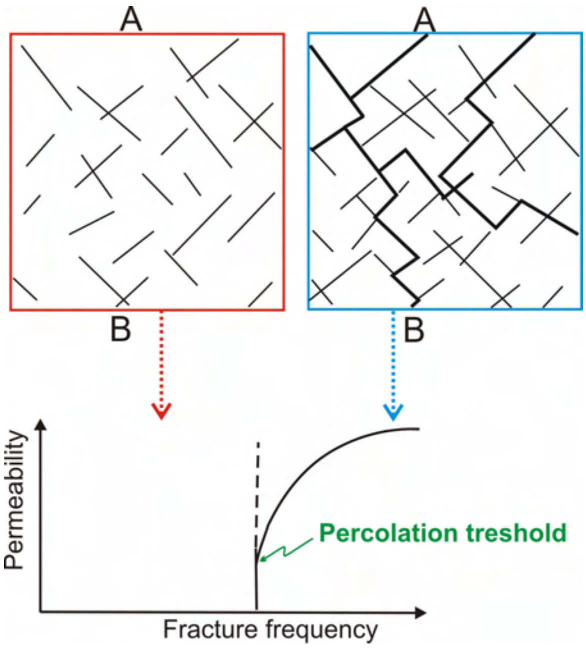

Figure 3: As long as there is no interconnected cluster of fractures between two sites A and B in a fractured reservoir (upper left) the permeability is very low. As soon as there exists such a fracture system (upper right), the reservoir permeability increases rapidly (below): the percolation threshold is reached (modified from Stauffer and Aharony 1994).

Information on the geometry of existing fracture systems is thus necessary so as to be able to estimate the potential permeability of man-made geothermal reservoirs. The resolution of seismic methods is much too poor to obtain this information. Also drill cores from drill holes in the vicinity give only limited information on fracture systems. Therefore, we analyse outcrop analogues (Fig 4), that is, outcrops of the same rock types and same facies as those supposed to host the man-made reservoir at geothermal depths. Such studies in outcrop analogues are also commonly performed in petroleum exploration to understand the reservoir rocks at depth (Gluyas and Swarbrick 2003).

Figure 4: Outcrop in an active quarry in the Middle Buntsandstein (Lower Triassic; Solling Formation) near Bad Karlshafen, Germany (locality indicated on the inset). The rock consists of sandstone layers, several dm thick, interlayered by thin (cm-thick) shale layers. View northeast; the total height of the quarry is ca. 15 m.

We focus these studies on rock heterogeneity and anisotropy, and how these heterogeneities influence fracture propagation. Important fracture parameters include attitude, aperture, and fracture interconnectivity. Three-dimensional reconstructions of fracture systems obtained in outcrop analogues make it possible to estimate the permeability of the reservoir at depth. In idealised fracture networks the volumetric flow rate can be calculated using equations based on the cubic law (Bear 1993). Even if the apertures of fractures at the surface are larger than those of fractures at depth, the typical power-law for a particular fracture system can be obtained so that the apertures of reservoir fractures and the associated fluid transport can be estimated (Gudmundsson et al. 2002).

For comparison with fracture systems in man-made geothermal reservoirs we also study palaeogeothermal fields, exposed as mineral vein systems in deeply eroded fault zones, for example in volcanic rocks in Iceland (Gudmundsson et al. 2002) as well as in sedimentary rocks in the British Bristol Channel Basin (Brenner 2003, Brenner and Gudmundsson 2004a, b). Such studies indicate that in comparatively homogeneous and isotropic rocks, interconnected networks of mineral veins (which are hydrofractures, i.e., fractures generated by internal fluid overpressure, Gudmundsson and Brenner 2001) may develop (Fig. 5a) that may generate a temporary high permeability. In heterogeneous, e.g., layered, rocks, by contrast, many hydrofractures become arrested, especially at contacts between layers with very different mechanical properties (Fig. 5b). Fractures that are restricted to single layers are referred to as stratabound, whereas fractures that are not so restricted are non-stratabound (Odling et al. 1999). A reservoir where most fractures are stratabound is less likely to develop interconnected fracture systems than a reservoir with non-stratabound fractures. Thus, a reservoir with mostly stratabound fractures may not reach the percolation threshold needed for significant permeability.

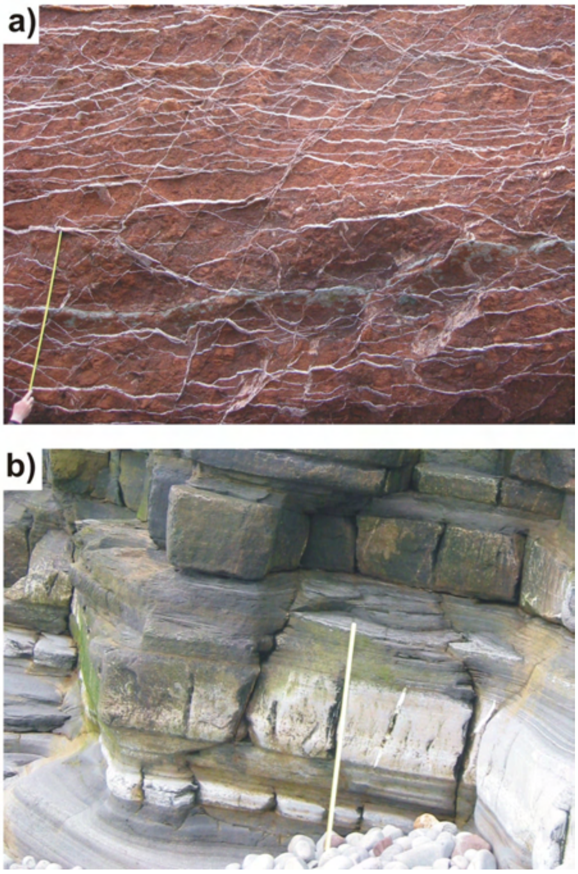

Figure 5: Studies of fracture systems in exposed palaeogeothermal fields can help us understand the permeability development in stimulated reservoirs. a) Comparatively homogeneous rocks, such as this thick mudstone at Watchet, Somerset Coast, Southwest England, may develop interconnected networks of mineral veins (here of gypsum) or other hydrofractures. View south; the visible part of the measuring tape is 1 m long. b) In mechanically layered rocks, such as this succession of limestone and shale at Kilve, Somerset Coast, many hydrofractures, such as these mineral veins of calcite, become restricted to certain layers. The calcite veins presumably became arrested when their tips tried to propagate from the stiffer limestone layers into the much softer shale layers. View east; the measuring steel tape is 1 m long.

2.3 Rock Mechanics

Perhaps the main factor that decides if fractures can propagate through reservoir rocks is the mechanical layering, that is, changes in the mechanical properties, particularly the rock stiffness (Young's modulus; Economides and Nolte 2000; Gudmundsson and Brenner 2001, 2004; Gudmundsson et al. 2002, Brenner 2003, Brenner and Gudmundsson 2004a; Gudmundsson and Philipp 2006). Mechanical layering may coincide with the sedimentary layering, that is, changes in grain size, mineral content or facies. For example, in the German Buntsandstein, sandstone layers may be considerably stiffer (have higher Young's moduli) than shale layers (Bell 2000). We therefore need to analyse mechanical rock properties (Young's modulus, Poisson's ratio, tensile strength etc.) on samples from drill cores or outcrop analogues to predict fracture propagation in a reservoir.

The velocity of a propagating fracture is slow compared with the velocity of seismic waves. Therefore we use static rather than dynamic moduli to characterise the elastic response of the host rock. The static moduli are always lower than the dynamic moduli (Bell 2000), but recalculations of static moduli from dynamic moduli are not possible exactly. Also, to assess the rock mechanical properties affecting fracture propagation at depth one must take into account that existing fractures in a rock layer may significantly lower the in situ moduli (Priest 1993).

2.4 Stress Field

Because fault slip and related fluid transport depends on the current stress field (see section 2.1), the local stress field in the reservoir must be known. In addition, the stress field determines if and how fractures propagate, and become opened up rather than closed (Fig. 2), and thus if fluid transport occurs. When the maximum horizontal compressive stress s_H is parallel to the fracture strike, fractures tend to open up and fluid transport is enhanced. If, however, the maximum horizontal compressive stress s_H is perpendicular to the strike of the fractures, many fractures will close and fluid transport is inhibited.

In geothermal exploration any information available on the stress field at the potential reservoir site and its surroundings should be compiled. This information may be from borehole breakouts, hydraulic fracturing experiments, overcoring and flat-jack measurements, and focal mechanisms of earthquakes (Amadei and Stephansson 1997), and indicate the current regional stress field. Because of rock heterogeneities, however, the local stress field can be very different from the regional stress field. In fact, because of rock heterogeneities as regards the mechanical properties the stress field can be extremely heterogeneous, whatever the scale of observation, and have great effects on fracture propagation (Gudmundsson and Brenner 2001, 2004; Gudmundsson and Philipp 2006). Since we cannot obtain information on the local stress field in sufficient detail using stress measurements, we need numerical models to understand the effects of heterogeneous mechanical rock properties on the local stress field and thus on fracture propagation.

2.5 Numerical Modelling

Numerical models divide ('discretise') the problem into an equivalent system of small units ('elements'). For each element algebraic solutions (resulting in numerical approximations) are obtained for a specific set of differential equations, consisting of constitutive equations that describe the behaviour of the deforming material (e.g., as linear elastic) and conservation laws (including the 'conservation of mass' and the 'conservation of momentum'), and specific boundary conditions (applied stresses or displacements). The solutions for the elements are then combined into a solution for the entire body. Numerical solutions can be found for complex geometries and apply also to large strains, and heterogeneous and anisotropic mechanical properties. Therefore numerical models are used to simulate physical problems when analytical solutions become too complex. Simply speaking, numerical models can be regarded as calculation experiments using idealised materials and applied loads.

Numerical models may help to understand local stress fields and thus fracture propagation in heterogeneous reservoirs. This gives information on the connectivity of existing and newly created fracture systems and therefore on possible fluid transport in a geothermal reservoir. In the next section we present several indealised numerical models on hydrofracture propagation in layered reservoirs.

3. NUMERICAL MODELS

All the numerical models presented in this section are run using the commercial boundary-element program BEASY. Detailed information on the boundary-element method (BEM) can be found in Brebbia and Dominguez (1992), whereas further information on the modelling software is available at the BEASY company homepage (www.beasy.com). The models are two-dimensional using the so-called plane-strain option so as to include the third dimension mathematically (Brebbia and Dominguez 1992).

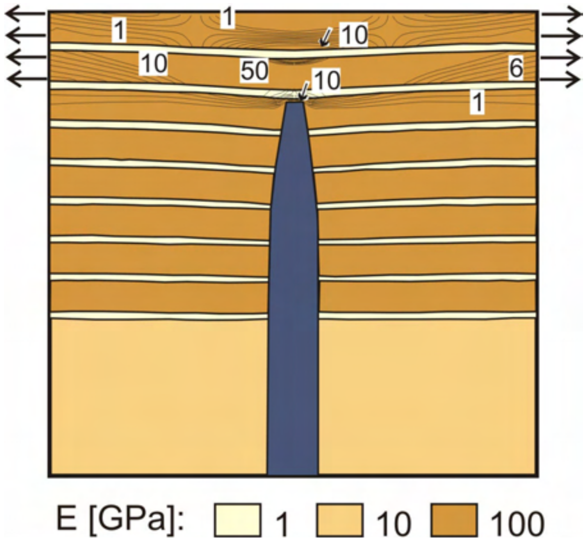

Figure 6: Numerical model of a hydrofracture with an internal fluid overpressure of 10 MPa propagating through a mechanically layered reservoir. The Young's moduli of the layers are indicated with different colours: the thin layers are very soft, the thicker layers very stiff. The reservoir is subject to external tension of 3 MPa. Contours represent the magnitudes of the minimum principal compressive stress (maximum principal tensile stress) s_3. The tensile stress concentrations in the stiff layers become very high, but soft layers could be stress barriers to hydrofracture propagation.

Figure 6 shows a simple model of an idealised hydrofracture subject to an internal fluid overpressure of 10 MPa propagating through a mechanically layered reservoir. The lowermost layer has a moderate Young's modulus E of 10 GPa, all the thin layers in the strongly layered part above are very soft, with a Young's modulus of 1 GPa, the thicker layers are very stiff, their Young's modulus being 100 GPa. Poisson's ratio is 0.25 in all the layers in all the models, which is a typical value for many rocks (Bell 2000). The reservoir is subject to a typical external tensile stress of 3 MPa. As a result we show the deformed model (50 times exaggerated) and contours of the magnitudes of the minimum principal compressive stress (maximum principal tensile stress), s_3. The tensile stress concentrates in the stiff layers and reaches magnitudes higher than 50 MPa in a large area in the stiff layer next to the hydrofracture tip.

Where the tensile stress concentration is higher than the typical in situ tensile strength of rocks of 0.5 – 6 MPa (Haimson and Rummel 1982), new fractures could be induced. In the soft layers, however, tensile stresses are suppressed and rarely reach values higher than a few MPa. This indicates that, whereas the hydrofracture could easily propagate through the stiff layers, in the soft layers the local stress field is unfavourable to hydrofracture propagation, that is, the soft layers could be stress barriers to hydrofracture propagation.

The model in Figure 7 has the same layering as the model in Figure 6. Here, however, the reservoir is subject to a reasonable external compressive stress of 15 MPa. Here, tensile stresses, indicated again by contours of the magnitudes of the minimum principal compressive stress (maximum principal tensile stress) s_3, still become concentrated in the stiff layers. In this model, however, the concentration of tensile stresses in the stiff layers is much lower than in the earlier model. In both these models it can be observed that the tip of the hydrofracture becomes rounded and rather blunt when meeting with the soft layer, whereby hydrofracture propagation becomes unlikely (cf. Gudmundsson and Brenner 2001, Brenner and Gudmundsson 2004b).

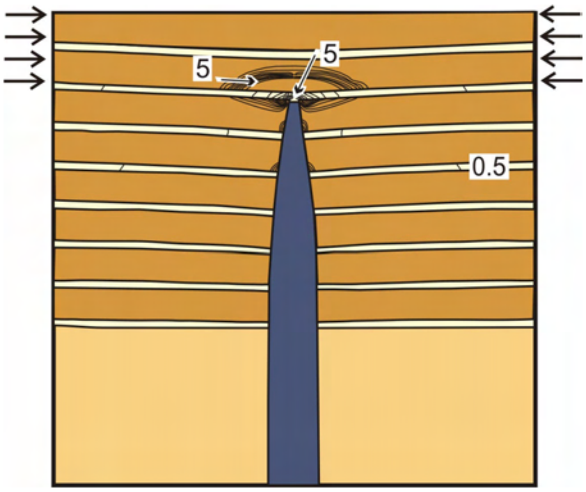

Figure 7: Numerical model of a hydrofracture with an internal fluid overpressure of 10 MPa propagating through a mechanically layered reservoir. The layering is the same as in the model in Figure 6. The reservoir is subject to external compression of 15 MPa. Contours represent the magnitudes of the minimum principal compressive stress s_3. The tensile stress concentrations in the stiff layers are much lower than in the model of a reservoir subject to external tension (Fig. 6).

In the next numerical model (Fig. 8) there is again a hydrofracture with an internal fluid overpressure of 10 MPa propagating through a layered reservoir. In this model, however, the layering of the reservoir is opposite to that in the earlier models: the thin layers are very stiff (E = 100 GPa), the thicker layers very soft (E = 1 GPa). The reservoir is again subject to an external compressive stress of 15 MPa. First (Fig. 8a) we present the contours of the magnitudes of the minimum principal compressive stress s_3 as for the models in Figures 6 and 7. The tensile stresses again concentrate in the stiff layers; the magnitudes are similar to the low tensile stress concentrations in the earlier model of a reservoir subject to external compression (Fig. 7). For this model we also present the contours of the magnitudes of the maximum principal compressive stress, s_1. The compressive stresses clearly concentrate in the stiff layers as well. This is not surprising since from Hooke's law it follows that, for a given strain, the stress concentration – both of tensile and compressive stresses – in a stiff material will be greater than in a soft material. In fact, in this model the compressive stress concentration in the stiff layers becomes very high. Under these loading conditions, therefore, the stiff layers may become stress barriers to hydrofracture propagation. In this model, where

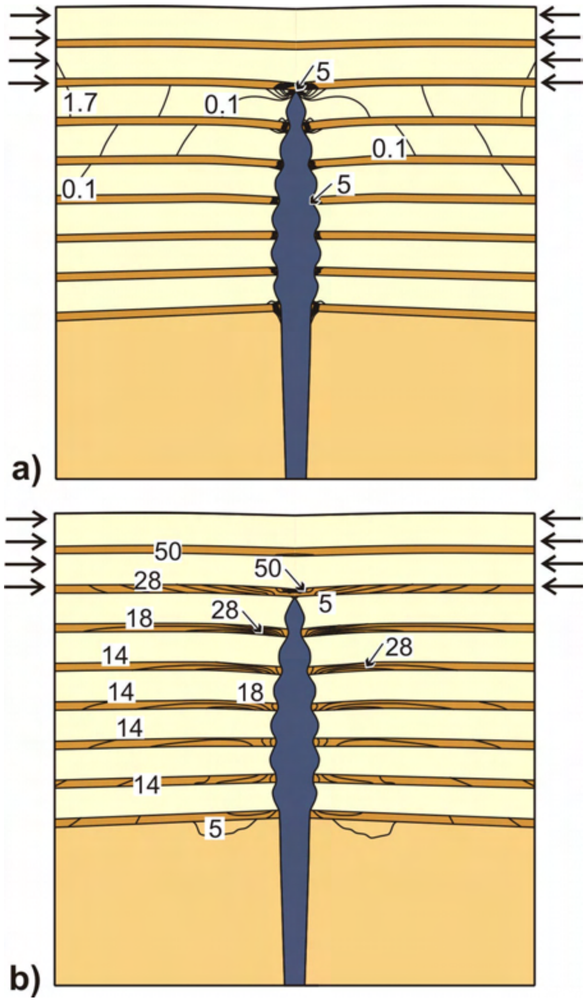

Figure 8: Numerical model of a hydrofracture with an internal fluid overpressure of 10 MPa propagating through a layered reservoir. The colour code for the Young's moduli of the layers is as indicated in Figure 6. Here, however, the thin layers are very stiff, the thicker layers soft. The reservoir is subject to external compression of 15 MPa. a) Contours of the magnitudes of the minimum principal compressive stress s_3. Observe that the tensile stress concentration in the stiff layers is similar to the low tensile stress concentration in Figure 7. b) Contours of magnitudes of the maximum principal compressive stress s_1. The compressive stress concentration in the stiff layers becomes very high. Under these loading conditions, therefore, the stiff layers may become stress barriers to hydrofracture propagation. In addition, observe the strong aperture variation of the hydrofracture between the layers: the aperture (which is shown 50 times exaggerated) is much higher in the soft layers than in the stiff layers.

the soft layers are much thicker than the stiff layers, one can also observe a strong aperture variation of the hydrofracture between the layers: the aperture is much larger in the soft layers than in the stiff layers. Also, the hydrofracture tip is rather narrow at the contact with the stiff layer above.

The contacts between the layers may also have great effects on fracture propagation. This we explore in the last numerical model (Figure 9). Again, a hydrofracture propagates through a layered reservoir. In this model, however, the fluid overpressure of the hydrofracture (10 MPa) is the only loading. The Young's moduli of the layers are the same as in the first models (Figs 6 and 7). In this model, we added a discontinuity with a stiffness of 0 MPa/m at the contact between two layers above the hydrofracture. This discontinuity represents a weak (non-welded, the tensile strength across the contact being negligible) contact (Priest 1993), as are common close to the surface. The width of the discontinuity is half the total width of the model. The results show that the discontinuity opens up due to the approaching hydrofracture. In this case, if the hydrofracture propagated through the next two layers, it would reach the open discontinuity which may capture the upward-propagating fracture. The resulting arrested fracture is, because of its peculiar shape, referred to as a T-shaped fracture (Economides and Nolte 2000).

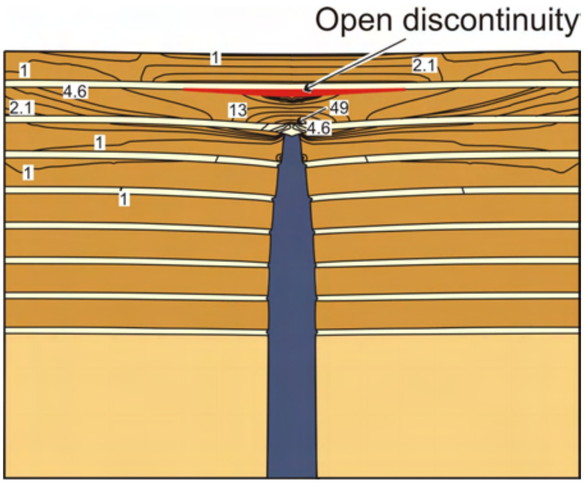

Figure 9: Numerical model of a hydrofracture propagating through a layered reservoir. In this model the only loading is the fluid overpressure of the hydrofracture (10 MPa). The Young's moduli of the layers are as in Figure 6 (see also the colour code in Fig. 6); contours represent the magnitudes of the minimum principal compressive stress s_3. In this model, a discontinuity with zero stiffness, representing a weak contact, is added between two layers above the hydrofracture. This discontinuity opens up due to the approaching hydrofracture. In this case, if the hydrofracture propagated through the next two layers, it would reach the open discontinuity and form a so-called T-shaped fracture, which would lead to fracture arrest.

4. BUNTSANDSTEIN IN NORTHERN GERMANY

In this section we present results of field studies performed in the Middle Buntsandstein (Lower Triassic) in Northern Germany. We investigate the fractures (joints and faults) in the Solling-Formation so as to predict possible permeabilities within this horizon. The Middle Buntsandstein has a good geothermal potential (Schulz and Röhling 2000) and will be used in the near future to provide hot water for heating the "Geozentrum Hannover" (Project GeneSys; e.g., Orzol et al. 2004).

The Middle Buntsandstein consists of several fining-upward cycles, the Solling-Formation being the uppermost unit of the Middle Buntsandstein. Each formation starts with thick basal sandstones and continues with interbedded sandstone and shale layers (Röhling 1991). Upwards, the thicknesses of the sandstone layers decrease, the thicknesses of the shale layers increase. We selected several outcrops that represent different facies typical for the Middle Buntsandstein (Hoffmann et al. 2006; Philipp et al. 2005, 2006). Details on the field studies can be found in a recently submitted diploma thesis (Hoffmann 2006) and several Bachelor theses (Bartelsen 2005, Oelrich 2005, Thaeter 2005).

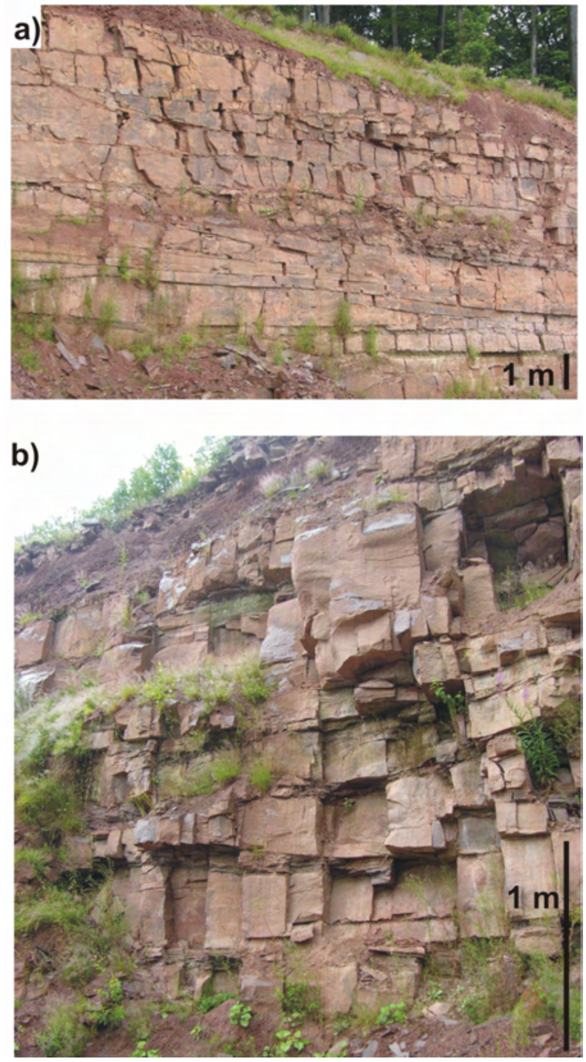

Figure 10: Details of the Buntsandstein outcrop in Bad Karlshafen (cf. Fig. 4). a) View east; scale indicated. Most joints are restricted to individual sandstone layers (cf. Fig. 11a); the outcrop wall itself is rather smooth. b) View north; scale indicated. Many joints propagate through several layers (cf. Fig. 11b).

Detailed field studies focused on the effects of the sedimentary layering on the propagation of fractures, particularly on joints. In Bad Karlshafen there are several active quarries with dm-scale sandstone layers, interbedded with cm-scale shale layers (Figs 4 and 10). In these outcrops an orthogonal joint system can be investigated (Hoffmann et al. 2006; Philipp et al. 2005, 2006). One joint set has a trend of about N80E (in the following referred to as the EW-joint set), the other joint set is trending N10W (in the following NS-joint set; Philipp et al. 2005). Looking at an NS-trending wall in the quarry (Fig. 10a) one notices that most of the EW-joints observable in this wall are restricted to individual sandstone layers. This was confirmed with quantitative measurements of many joints (Fig. 11a; Oelrich 2005, Philipp et al. 2006). The wall of the quarry itself, however, is rather smooth. This characteristic is caused by the fact that the wall is formed by big NS-trending joints that propagated through many layers (Philipp et al. 2005).

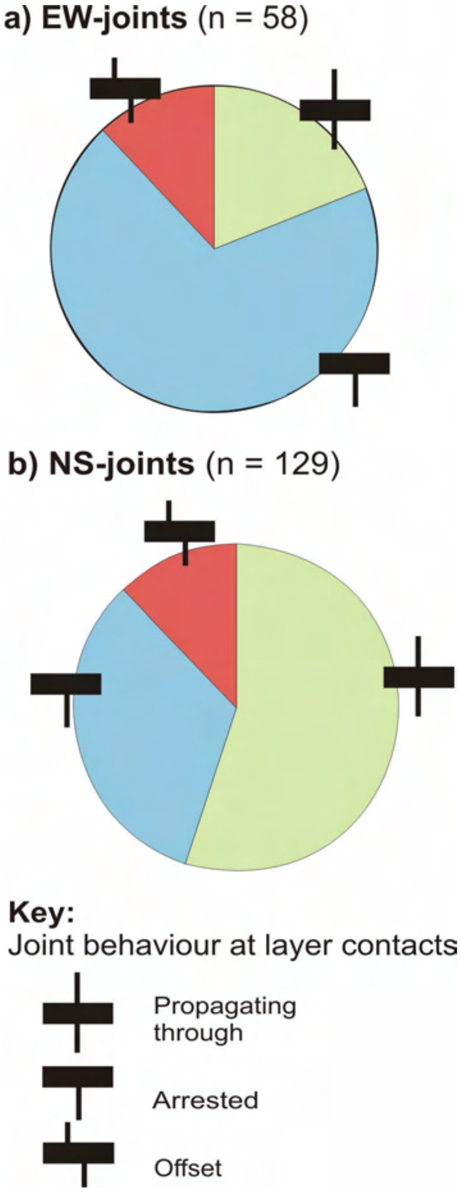

Figure 11: Measurements of joint behaviour at layer contacts of sandstone and shale layers show that in the NS-trending joint set (a) most joints propagate through the layer contacts. EW-trending joints (b), however, are mostly arrested at layer contacts and are restricted to individual sandstone layers. Compare this figure to the field photographs in Figure 10 and the schematic illustration of the joint system in Figure 12.

Looking at an EW-trending wall of the outcrop (Fig. 10b) this effect becomes clearer. Since most of the EW-trending joints are restricted to individual sandstone layers (Figs 10a, 11a), parts of the wall are more prominent than others (Fig. 10b). Most of the NS-trending joints observable in this wall propagate through several layers (Fig. 11b), as had been expected from the characteristics of the outcrop walls (Philipp et al. 2005, 2006).

5. DISCUSSION

Our field studies show that orthogonal joint systems exist in the Middle Buntsandstein. In several Buntsandstein outcrops in Northern Germany (Philipp et al. 2005, 2006), in which orthogonal joint systems are common, we have observed, taking the abutting of younger joints against older joints into account, that an N-S joint set is the older and mostly non-stratabound, whereas an E-W joint set is the younger and mostly stratabound. The field results indicate that even very thin layers (cm-scale thicknesses) of shale, for example, may arrest many joints in sandstone-shale sequences such as in the Buntsandstein (Figs 10 and 11). Layer contacts between sandstone and shale layers are also often open and form discontinuities that have fluid flow properties similar to horizontal fractures. The two joint sets and some open layer contacts thus may form rather interconnected systems of fluid pathways (Fig. 12).

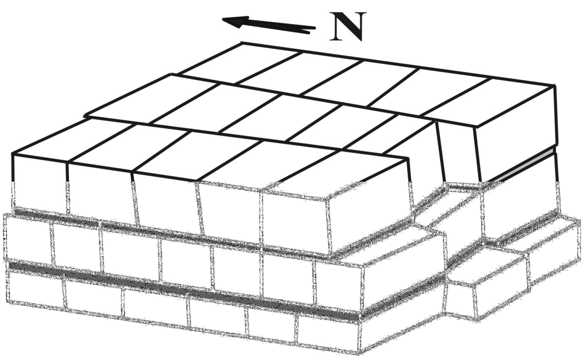

Figure 12: Schematic illustration of the orthogonal joint system in the Buntsandstein outcrop in Bad Karlshafen (Figs 4, 10, and 11). Sandstone layers are pictured in white, shale layers in grey. Together with comparatively open layer contacts, which form discontinuities, the joint sets form an interconnected system of fluid pathways.

Many field observations in palaeogeothermal reservoirs (Fig. 5) and other outcrops show that in heterogeneous, anisotropic, e.g., layered, rocks many fractures become arrested at layer contacts. Many dykes are arrested at contacts between lava flows and pyroclastic layers (Gudmundsson and Brenner 2001) or at bedding contacts in sedimentary rocks (Baer 1991). Mineral veins and joints (many of which are hydrofractures) may also become arrested, some with blunt tips, at contacts in mechanically layered rocks (Gillespie et al. 2001, Brenner and Gudmundsson 2004a, b). Also hydraulic fractures in petroleum engineering become arrested at depths of several kilometres (Economides and Nolte 2000).

Fracture arrest is primarily controlled by local variations in the stress field, mainly due to three factors: discontinuities (fractures and contacts), changes in host rock mechanical properties (particularly Young's modulus), and stress barriers. These factors are related in that changes in stiffness and stress barriers are common at contacts (discontinuities) between different rock types

(Gudmundsson and Brenner 2001). Some fractures may be arrested by slip at contacts (Cooke and Underwood 2001), but field observations show that there is no slip at bedding contacts associated with many arrested veins, joints (Brenner and Gudmundsson 2004a), and dykes (Gudmundsson 2003).

Field observations also show that different types of fractures react differently to host-rock layering. Fractures formed at great depths are generally less likely to become stratabound (cf. Odling et al. 1999), but different fractures also seem to "feel" the rock layers and contacts differently. For example, mineral veins are much more often non-stratabound than joints (Brenner 2003). Also, the sedimentary and the mechanical layering are not always correlated. If a layered rock mass has essentially the same Young's modulus throughout, and if the layers are welded together so that there are no weak or open contacts, the layers will function mechanically as a single layer.

It is unlikely that a fracture system studied in a surface outcrop is exactly the same as the fracture system that will be encountered at depth in a geothermal reservoir (Philipp et al. 2005, 2006). First, the investigated outcrops are commonly located at some distance away from the potential reservoir so that the tectonic history of the rocks may be different. Second, joints may also result from tectonic uplift and associated unloading. Even if such joints may not occur at depth, however, there may be weaknesses in the reservoir rock (where the fractures would form when unloading) at which places fractures could be created in a reservoir. Third, in excavating a quarry or road cut the stress field is changed locally (Hudson and Harrison 1997). Still, surface outcrops allow us to investigate the reservoir rock three-dimensionally in a unique way. In particular, the effects of rock heterogeneities (mostly the mechanical layering) on fracture propagation can be studied in detail. Using this information we can make predictions as to the fracture system at depth, even if fracture frequencies and apertures may be different from the surface analogues. In addition, it is possible to estimate how man-made hydraulic fractures would propagate or how the existing fractures are likely to become interconnected through stimulation. In order to make predictions, all available information from field studies and on the reservoir at depth should be used to develop numerical models.

To obtain the mechanical properties of the reservoir rocks (as we need to do to build realistic numerical models) several assumptions need to be considered. Young's modulus, Poisson's ratio, and some rock strengths generally increase with depth – rock samples taken in surface outcrops would thus yield too low results. In typical small laboratory samples, however, there normally occur very few fractures or cracks so that laboratory Young's moduli and rock strengths reach higher values than in situ. For example, the in situ tensile strength of most rocks is in the range 0.5-6 MPa (Haimson and Rummel 1982, Amadei and Stephansson 1997); laboratory measurements are higher by one order of magnitude (Bell 2000). For the numerical models we often use extreme values for the Young's moduli as to investigate the full range of common rocks (Figs 6-9). Typical values for Young's modulus are, as used here, between 1 and 100 GPa (Bell 2000). The range of Poisson's ratios for bedrocks is, as compared with Young's modulus, narrow. Poisson's ratios of the rocks that commonly constitute fluid reservoirs have a range between 0.2 and 0.35 (Bell 2000). Therefore we focus the numerical models on the variation of Young's modulus.

The numerical models presented in this paper are very simple. They were selected so as to highlight general features of hydrofracture propagation in strongly layered reservoirs. It is, however, possible to run models on real fracture systems as observed in the Buntsandstein outcrops (e.g., Hoffmann 2006), also in three dimensions and adding more complexities so as to obtain very reliable model predictions.

Using field studies combined with information on the potential man-made geothermal reservoir at depth and numerical models, as described above, it is possible to decide on the optimum localities for drilling sites and the best drilling and stimulation strategies. Suitable sites may, for example, be fault zones with many natural fractures that have propagated through many layers and that are favourably orientated in relation to the current local stress field so as to generate man-made geothermal reservoirs with high permeabilities. Structural geology can thus contribute to maximise the likelihood of success in geothermal projects.

5. CONCLUSIONS

1. Structural geology can contribute to maximise the likelihood of success in geothermal projects, particularly as regards EGS projects.

2. To obtain information on the geometry of existing fracture systems so as to be able to estimate the potential permeability of man-made geothermal reservoirs, we should analyse outcrop analogues, that is, outcrops of the same rock types as those supposed to host the man-made reservoir at geothermal depths.

3. Even very thin layers (cm-scale thicknesses) of shale, for example, may be responsible for arrest of many joints in sandstone-shale sequences, such as in the German Buntsandstein.

4. Numerical models can help us understand the local stress fields as well as the connectivity of existing and newly created fracture systems and therefore the potential fluid transport in geothermal reservoirs.

5. Many hydrofractures become arrested at layer contacts (are stratabound), particularly at contacts between layers with contrasting mechanical properties. Which layers become stress barriers to fracture propagation depends on the external loading conditions. In tension, soft layers tend to arrest hydrofractures – in compression, stiff layers may be stress barriers.

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