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Stress field rotation in the EGS well GRT-1 (Rittershoffen, France)

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ABSTRACT

The stress state in GRT-1, a recent deep geothermal well drilled in Northern Alsace (Upper Rhine Graben, France) has been investigated based on drilling-induced fractures (DIF) observed on borehole acoustic logs. Some of those fractures are compressive fractures, known as Breakouts, and others are tensile fractures, called DITFs in this study. They are used to estimate the orientation of the stress field because they occur respectively in the direction of Shmin and SHmax.

At a small scale, SHmax orientation follows a cyclic profile repeating every 50 m MD along the borehole. Those small cycles participate to a more global trend, where the orientation of SHmax tend to reach the regional orientation (N145°E) in weaker layers (as clays or marls), and turn clockwise toward N50°E in hard rock layers (as dolomite and sandstone).

Finally, this study shows that the entire stress state of the sedimentary layer is decoupled from the basement one: the orientation of SHmax is N155°E in the basement, but is globally N20°E in the sedimentary layer.

1. INTRODUCTION

Analysis of stress induced wellbore failure is a powerful method to characterize the state of stress of a rock mass (Zoback et al., 1985, 2003). Knowledge of the stress state in a recent deep geothermal well drilled in Northern Alsace (Upper Rhine Graben, France) has been investigated based on drilling-induced fractures observed on borehole acoustic logs. A new geothermal doublet located at Rittershoffen was drilled within deep fractured rocks lying at the interface between the Triassic clastic sediments from Buntsandstein and the Paleozoic granite (Baujard et al 2015, Genter et al 2015a, b). Many geological and geophysical data have acquired in the open-hole section of the well in order to characterize the natural fracture system as well as the present-day stress field. Based on borehole acoustic image logs, high quality datasets have been interpreted in terms of drilling-induced tension fractures.

Previous studies have characterized the regional stress field of the Upper Rhine Graben, with its magnitude and orientation (Heidbach et al 2008). At regional scale, in our area of interest, the orientation of the maximum horizontal stress component is NW-SE. In the nearby Soultz-sous-Forêts geothermal site, the stress field was characterized in the deep basement (1,5 to 5 km depth) by various methods such as hydraulic tests, borehole image logs and induced seismicity by Cornet et al (2007), Cornet (2013), Valley (2007) and Sahara et al (2014). In-situ stress orientation of the Soultz-sous-Forêts geothermal field were inferred from breakouts and drilling-induced tensile fractures (DITF) patterns observed I the deepest boreholes GPK3 and GPK4 (Valley, 2007, Valley and Evans, 2007). At Soultz, the mean maximum horizontal stress orientation values range between N164E and N185E. Stress heterogeneity have been also outlined from variations in stress orientation indicated by wellbore failure in two boreholes of the Soultz-sous-Forêts EGS site (Valley and Evans, 2007). Localized major stress orientation variations correlate with the occurrence of two most prominent fracture zones or faults, showing some evidence of natural permeability, observed at 2.0 and 4.7 km depth. The lowermost stress perturbation extends over several hundred metres and is characterised by SHmax rotations of up to 90° and changes in the mode of failure from compression (breakouts) to tension (DITFs) (Valley and Evans, 2007).

This study proposes an analysis of the evolution of the orientation of SHmax with depth, using the DITFs orientation, in the lower part of sedimentary Triassic layers and the upper part of the granite Paleozoic basement (Brudy and Zoback, 1999).

Besides the study of the evolution of stress orientation with depth between the bottom of the basin and the top basement, we focused our analysis on stress heterogeneity, Thus, the goal of this study is to find any correlation between the rotation of the stress field and the presence of natural fractures or major changes in the geomechanical unit composition (lithology).

The structural analysis focuses on the vertical well GRT-1, owned by a company named ECOGI. This well has been drilled up to 2580 m Measured Depth (MD), in October-December 2012, in Rittershoffen, at 6 kilometers of the geothermal site of Soultz-sous-Forêts (Figure 1). GRT-1 is the first well of a doublet drilled for industrial thermal application. The second deviated well GRT-2 has been drilled in 2014 down to 3200 m MD and the geothermal power plant is now in activity.

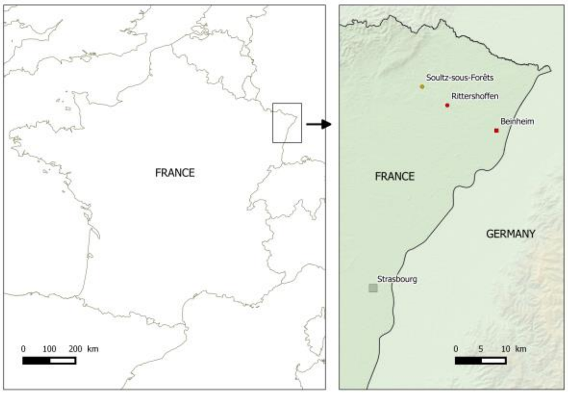

Figure 1: Location of Rittershoffen, (Northern Alsace, France).

The investigated depth interval corresponds to the section of the well GRT-1 which has been imaged by an Ultrasonic Borehole Imager (UBI): from 1460 m MD, in the Middle Keuper (Upper Trias), to 2550 m MD in the deep massive Paleozoic granite. The top basement has penetrated at 2200 m MD. The stress field characterization has been done in GRT-1 only inside the $12^{1/4}$ and $8^{1/2}$ inches borehole section.

2. PRINCIPLE – METHODOLOGY

2.1 Drilling Induced Tensile Fractures (DITFs)

The first step of this study is to get the orientation of SHmax at several depths in the well. To determine SHmax, the classical method is to use Drilling Induced Fracture (DIF) orientations (Davatzes and Hickmann 2005).

As this area has undergone a polyphasic tectonic history with many compressive and extensive structural events from the granite emplacement in Carboniferous to Recent times, the resulting natural fracture network intersected by the well is quite complex and not necessarily representative of the present-day stress field. For that reason, natural fractures are not used to determine the actual stress orientation. In the contrary, drilling a borehole into a rock mass creates a local modification of the actual stress state that usually induces the formation of tiny fractures at the surface of the borehole wall. Some of those fractures are compressive fractures, known as Breakouts, and others are tensile fractures, called DITFs in this study (Figure 2). The reason why DIFs are commonly used to get actual stress field orientation is that Breakouts occur in the direction of the actual minimal horizontal stress Shmin and the DITFs in the direction of the actual SHmax. At the studied depth (~2 km deep), Breakouts are much less present than DITFs, and DITFs are thinner, so their orientation is more accurate. For this reason, DIFTs are the only drilling induced borehole failure that has been investigated for this study.

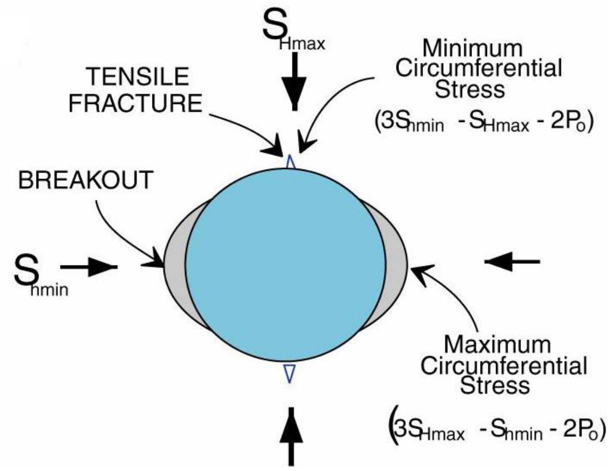

Figure 2: Schematic explanation of Breakouts and Drilling Induced Tensile Fractures formation principle. (Davatzes and Hickmann 2005).

Axial Drilling Induced Tensile Fractures (A DITFs):

There are different kinds of DITFs, some of them are called A DIFTs for “Axial” DITFs (Figure 3). They form vertical thin lines along the borehole surface, they occur symmetrically and they correspond to segments of the well where the stress field is well-aligned to the borehole: the two horizontal principal stresses Shmin and SHmax are in a plan orthogonal to the borehole and the vertical principal stress Sv is collinear to the borehole.

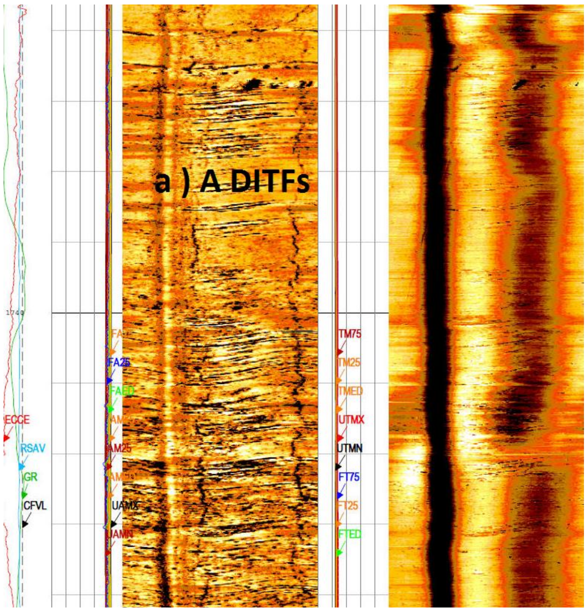

Figure 3: Example of A DITFs in GRT-1. The amplitude of the UBI is on the left, and the transit time on the right.

En Echelon Drilling Induced Tensile Fractures (E DITFs):

Another sort of DITF is called E DITFs for “en Echelon” DITFs. They form short inclined little fractures along the borehole (Figure 4). The middle of the fracture is still in the direction of SHmax and corresponds to segments of the well where the stress field is not well-aligned to the borehole: when Sv is not really collinear to the borehole. This orientation difference varies between 10° to 20°. As GRT-1 is mostly vertical (maximum deviation is 8.8°), E DITFs occur when Sv is not vertical anymore.

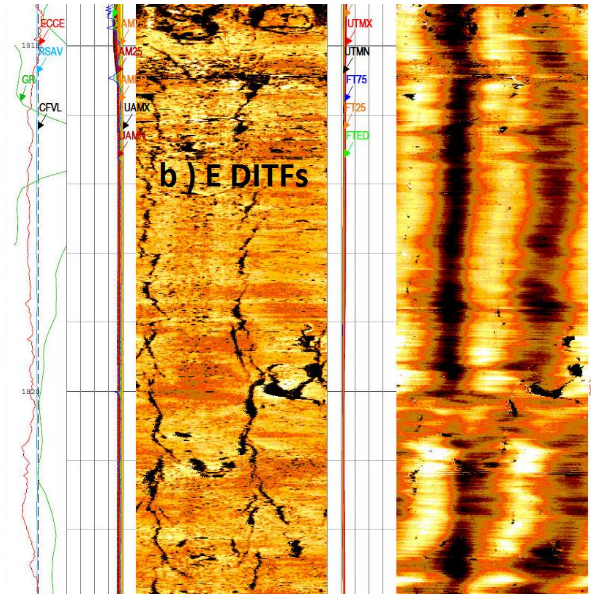

Figure 4: Example of E DITFs in GRT-1. The amplitude of the UBI is on the left, and the transit time on the right.

Petal Centerline Fracture:

The last sort of DITF is called Petal Centerline DITFs (Figure 5, Davatzes and Hickmann 2005). They are also formed during the drilling operation but some meters into the rock mass below the drill bit, due to the decompression of the rock, and are then crossed by borehole later. They are still aligned to SHmax, but the borehole doesn’t always cross them in a manner that they appear symmetrically opposed in the borehole.

It is sometimes difficult to distinguish the DITFs from some natural fractures which have almost the same dip. It is also hard to distinguish Petal Centerline DITFs and A DITFs. For this reason, Petal Centerline DITFs are integrated in A DITFs in this study. Making this association still allows making the differentiation between the borehole sections where Sv is collinear to the borehole axis or not.

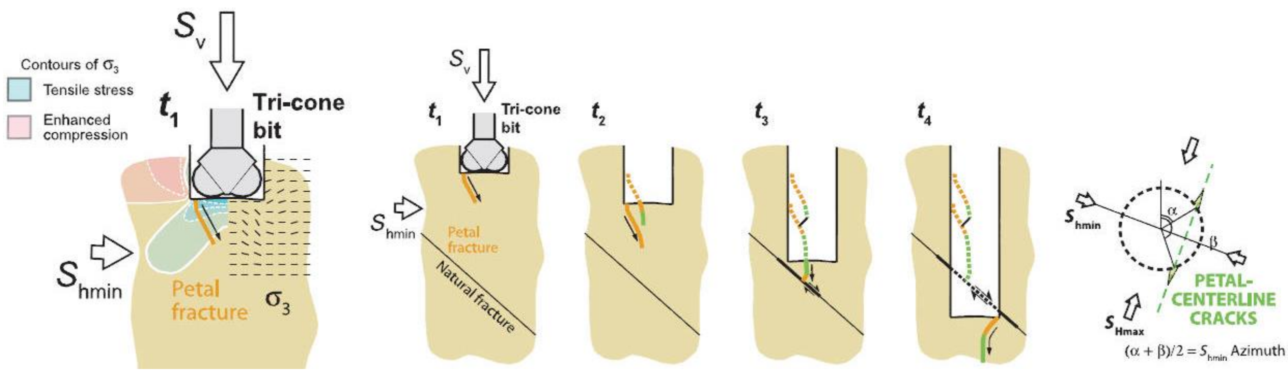

Figure 5: Schematic explanation of Petal Centerline Induced Fracture formation principle. (Davatzes and Hickman, 2006)

Picking strategy:

The DITFs have been picked visually by hand on a software, using available images of the GRT-1 from and Ultrasonic Borehole Imager (UBI). The acoustic image logs were acquired at a vertical resolution of 1 cm and an azimuthal resolution of 2°. A section of the UBI is missing between 1900 m MD and 1930 m MD because it corresponds to the depth of a change in drilling diameter: from 12.25 inches to 8.5 inches. This section is known to be naturally fractured but no UBI can visually attest it. Before the picking, the UBI has been corrected by the deviation of the well. DITFs have been picked and separated in 4 categories: Major and Minor A DITFs and E DITFs. As the qualification Major or Minor is only visual and qualitative, they have been grouped in A DITFs and E DITFs for this study. The DITFs database obtained has then been exported for a forthcoming treatment.

Natural fracture data were interpreted by Dezayes et al (2014) and Vidal et al (2016). Lithology and stratigraphy are given from Aichholzer et al (2015).

2.2 Treatment

The goal of this study is to find if there is a correlation between the rotation of the stress field and the presence of natural fractures or a change in the lithology (geomechanical unit). So the aim of the treatment was to compare the raw azimuth of DITFs, with the mean azimuth of DITFs for different lithological segmentation of the studied interval by taking into account the location of the major natural fractures crossed by the GRT-1 borehole.

Moving average:

First, the graphical representation of raw DITFs azimuths is too cloudy because the azimuths are too scattered. To solve this visualization issue, a moving average has been applied on the DITFs orientations. A moving window of 10 meters has been used, and each DITF has been weighted by its length. This moving average process is not optimal because it skews the distribution by artificially adding points at transitions between two clusters of strongly different DITF orientations. Nevertheless, it has only been used for visualization, and helps to see azimuthal trends or vertical evolutions where DITF orientations are smoothly rotating.

Depth interval segmentation:

Secondly, the studied interval has been discretized with three degrees of refinement related to lithology: ages, sub-ages, and formations. For each segment, a mean of DITF orientations has been calculated, weighted by the corresponding length of each individual DITF.

All the results are not presented here. It has been decided to focus on the global behaviour of all DITFs orientation (A and E) on the more refined depth interval discretization (Figure 6).

Natural Fracture selection:

Finally, the major natural fractures have been selected. It has been decided to keep only the larger fractures, because they could probably create stronger stress field perturbations. The picking of natural fractures has been done in a previous study (Dezayes et al 2014, Genter et al. 2015b, Vidal et al 2016). Due to their physical acoustic contrast with the surrounding rocks, natural fractures are detected on the UBI. Fractures visible on both transit time and amplitude, thus showing an apparent free aperture, are interpreted as locally opened fractured. However, it is again not optimal because when a fracture shows a free aperture in a UBI, it means that it is open in the direct vicinity of the borehole wall but it can be plugged or sealed in the far field. More detailed about fracture characterization is given by Vidal et al (2016).

A and E DITFs comparison:

The two major discriminating parameters are the orientation and the length of the DITFs. It has been decided not to treat differentially A and E DITFs orientation here, but to focus on length proportion of A or E DITFs among the same depth interval segments as for the All DITFs orientation study. For this purpose, the total length of A DITFs by depth interval has been compared with E DITFs length in the corresponding depth section. The ratio between A and E DITFs has been calculated, so that values of the ratio below 1 correspond to formations where there is more E DITFs than A DITFs and values above 1 correspond in the contrary to sections where A DITFs are more represented than E DITFs.

All the results are presented as graphs or tables in the next section.

3. RESULTS

3.1 All DITFs orientation

The Figure 6 summarise the resulting A DITFs orientation for one set of depths segmentation. It represents the azimuth of All DITFs corrected by a moving average, the mean azimuth of All DITFs for different the lithostratigraphic formations and the major natural fractures encountered in the well.

The Table 1 represent the ratio of A DTIFs length on E DITFs length for the more refined depth interval set: lithological formations.

From the bottom well section in the deep-seated granite to the sedimentary part in the Keuper formations, the main observations in terms of stress orientation derived from the DIFTs, can be done:

- At 2,500 m, in the unaltered granite, average SHmax is N20W;

- At 2,450 m, in the unaltered granite, SHmax is N10°W;

- At 2.390 m, in the unaltered granite, SHmax is N30°E. This zone is just below the largest and the most permeable fracture zone of GRT-1;

- From 2,980 m to 2210 m, within the highly hydrothermally altered and fractures granite as well as in the rubefied granite, SHmax is scattered but with an average orientation of N20°E±7°. This section contains the highly concentration of larger natural fractures;

- From the top basement, 2,210 m and 2,160 m, in the Annweiler sandstone, SHmax value is variable with N030°E in average. This interval is poorly fractured;

- From 2,160 m to 1,920 m in the Vosgian sandstone, SHmax value varies from N18°E to N25°E. This interval is poorly fractured except at 1,990 m where a fracture zone crosses the borehole;

- The borehole radius changes from $8^{1/2}$ to $12^{1/4}$ inches at 1,920 m depth. From 1,900 m to 1,800 m in the Upper Buntsandstein, the main SHmax orientation rotates anticlockwise form N40°E (1,900 m), N35°E (1,850m) and N27°E (1,810m). There is no large fracture in this depth section.

- From 1,810 m to 1,770 m depth in the Lower Muschelkalk layers (sandstone, dolomites), SHmax varies from N25°E to N18°E respectively.

- Around 1,760 m depth, severe mud losses related to the occurrence of a large fracture was observed during drilling operation. At that depth, SHmax is N20°W.

- From 1,700 m to 1,500 m depth, in the Upper Muschelkalk, and the Keuper formations, SHmax is quite stable and is oriented N10°E.

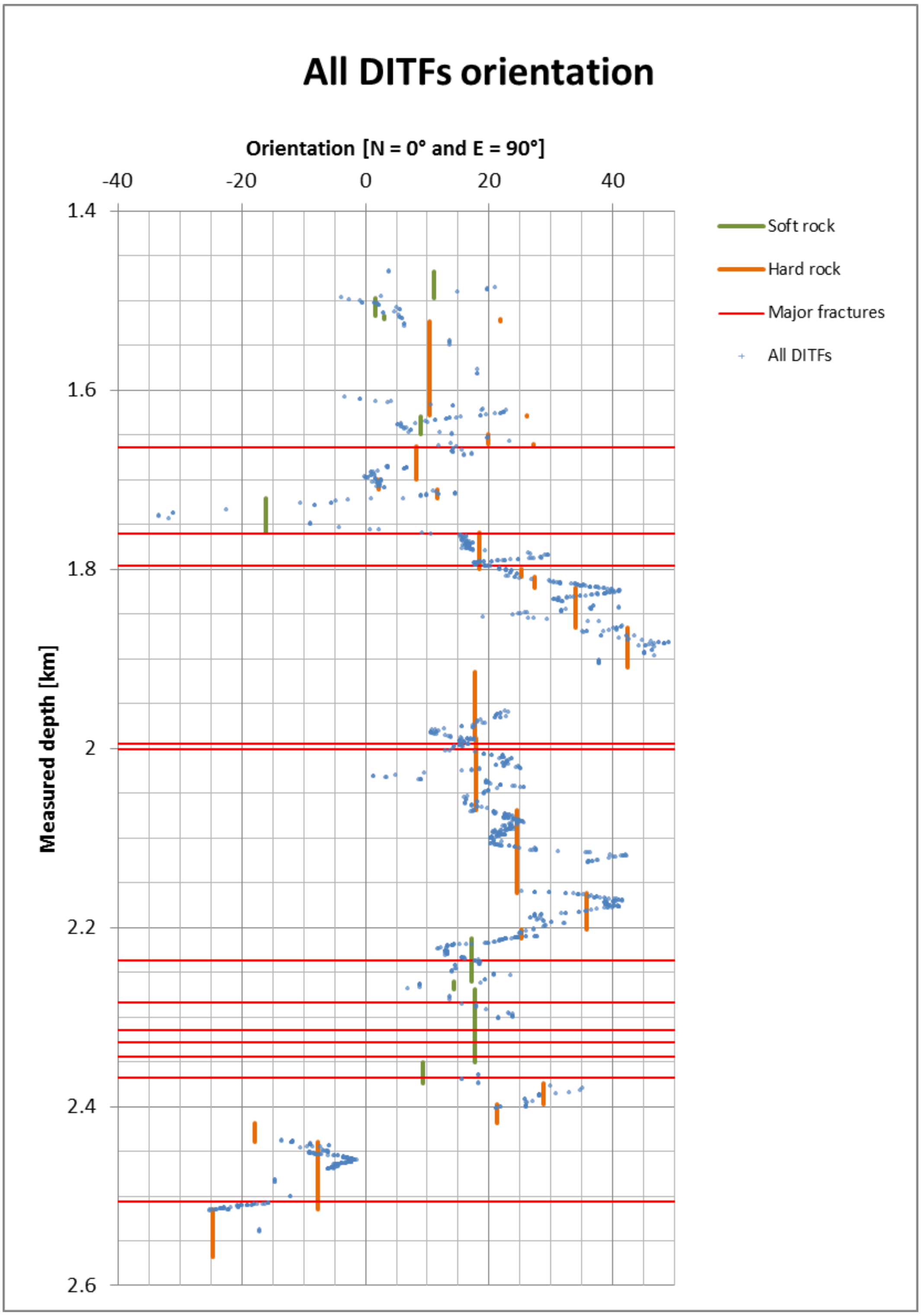

Figure 6: All DITFs orientation compared to the detailed lithostratigraphy units. DITF orientations are represented as blue crosses. Mean orientation are represented by vertical segments (green for soft rocks and orange for hard rocks) and major natural fractures are shown as horizontal red lines.

Table 1: Comparison between A and E DITFs cumulated length on depth intervals corresponding to lithological formations (bt: biotite, ms:muscovite).

Formations	Dominant lithology	All DITFs length	A DITFs length	E DITFs length	A/E DITFs length
Marnes Irisées supérieures	Marl	8.29	6.49	1.8	3.61
Argiles de Chanville	Clay	15.51	13.12	2.39	5.49
Marnes Irisées moyennes	Marl	5.39	3.91	1.48	2.64
Grès à Roseaux	Sandstone	0.98	0	0.98	0.00
Marnes Irisées inférieures	Marl	20.89	18.55	2.34	7.93
Dolomie Limite	Dolomite	0.37	0.37	0	+ infinity
Argile de la Lettenkohle	Clay	21.17	16.16	5.01	3.23
Dolomie Inférieure	Dolomite	2.39	0.91	1.48	0.61
Calcaire à Térébratules	Limestone	1.18	1.18	0	+ infinity
Couches à Cératites	Limestone	24.84	17.12	7.72	2.22
Calcaire à Entroques	Limestone	12.25	6.31	5.94	1.06
Dolomie à Lingules	Dolomite	9.37	2.5	6.87	0.36
Marnes Bariolées	Marl	31.24	29.09	2.15	13.53
Dolomies - Calcaires Ondulées - Couches à Myacites	Dolomite	36.93	13.04	23.89	0.55
Grès Coquillier	Sandstone	6.86	3.48	3.38	1.03
Grès à Voltzia	Sandstone	11.79	5.09	6.7	0.76
Couches intermédiaires	Sandstone	46.64	17.47	29.17	0.60
Couches de Karlstal 12.25	Sandstone	37.85	27.03	10.82	2.50
Couches de Karlstal 8.5	Sandstone	36.25	30.19	6.06	4.98
Couches de Rehberg	Sandstone	70.83	31.16	39.67	0.79
Couches de Trifels	Sandstone	55.04	8.76	46.28	0.19
Grès d'Annweiler	Sandstone	40.33	0	40.33	0.00
Permien anté - Annweiler	Sandstone	14.73	12.33	2.4	5.14
Rubefied granite	Granite	54.8	31.6	23.2	1.36
Weathered rubefied granite	Granite	4.97	3.44	1.53	2.25
White altered granite	Granite	18.48	15.22	3.26	4.67
Pink altered granite	Granite	8.2	8.2	0	+ infinity
Light grey bt/ms sound granite	Granite	45.32	44.26	1.06	41.75
Pink bt/ms sound granite	Granite	4.45	1.34	3.11	0.43
Pink-grey bt/ms sound granite	Granite	2.91	2.91	0	+ infinity
Light grey bt/ms sound granite	Granite	46.29	14.19	32.1	0.44
Pink-grey bt/ms sound granite	Granite	4.51	1.81	2.7	0.67
TOTAL		701.05	387.23	313.82	

4. INTERPRETATION

4.1 All DITFs orientation

One can notice that the global variations of SHmax orientation can be divided in cycles of fifty meters depth below 1,600 m MD. In those cycles, the orientation of SHmax by increasing depth rotates clockwise first and then anticlockwise. Similar cycles can be observed from 1,600 m to 2,500 m MD. The nature of lithostratical units and the natural fracture occurrences cannot clearly be related to this cycle frequency. The resulting global rotation of SHmax can be either clockwise or anticlockwise. The variations of these resulting global rotations are discussed in the following paragraphs.

Considering only the DITFs orientations represented as blue crosses in Figure 6, one can notice that there are many variations along the studied depth interval. The global orientation oscillates between N0°E and N20°E at 1,500 m MD. It can be noticed that this mean orientation is slightly different than the one measured in the basement at Soultz-sous-Forêts (Valley, 2007). In Figure 6 the variations of the orientations of SHmax are correlated with the lithology. Indeed, it appears that SHmax orientation rotates clockwise eastward until N30°E in hard rock formations, for example in Grès à Roseaux (sandstone [1,521 m MD; 1,523 m MD]) and Calcaire à Térébratules (limestone [1,659.5 m MD; 1,662 m MD]). Then, in weaker rocks, the orientation comes back anticlockwise to N0°E or N160°E, for example in Argiles de Chanville (clays [1,497 m MD; 1,517 m MD]) and Marnes Bariolées (marls [1,721 m MD; 1,758.5 m MD]).

From 1,750 m MD to casing shoe at 1,920 m MD (the end of the section in 12”1/4 inches), SHmax follows a global trend: the orientation of SHmax is rotating clockwise from N15°E at 1,750 m MD, to N50°E at 1,900 m MD in Couches de Karlstal (sandstone [1,865.5 m MD; 1,989 m MD]).

The Couches de Karlstal interval is cut in two parts by the casing shoe (1,920 m MD). Nevertheless, from the 12.25 to the 8.5 inches sections, SHmax has rotated anticlockwise from N50°E to N20°E. No reliable UBI are available for this diameter changing section (1,920 +/- 20 m MD), but the casing shoe has been placed at this depth because this interval is known for its high fracture density. So if the lithology can’t explain this stress rotation, maybe it can be related to this corresponding but not documented fracture zone.

Between 1,900 m to 2,275 m MD, another clockwise rotation of SHmax can be noticed. The global rotation is slower than the one between 1,750 m and 1,900 m MD, but it also goes from N20°E to N40°E.

At 2,200 m MD, the orientation is sharply turning anticlockwise again to N20°E. The pattern is similar than the rotation shown at 1,900 m MD. Here it corresponds precisely to the change between Grés d’Annweiler (unweathered and hard Sandstone [2,161 m MD; 2,202 m MD]) and the rubefied granite (weak and weathered crystalline rock mass). So the orientation of SHmax shows again a clockwise rotation Eastward in hard rocks, and the anticlockwise rotation Westward in weaker rocks.

This behaviour is reproduced once more between 2,200 m and 2,400 m MD: SHmax rotates clockwise from N15°E in weathered rubefied granite, to N30°E in unaltered granite.

Below 2,400 m MD where the unaltered granite basement is reached, the orientation of SHmax comes back anticlockwise from N30°E to N160°E: this latter value fits with the stress field orientation given between 1,500 to 5,000 m for the stress state in the basement at Soultz-sous-Forêts (Valley, 2007; Valley and Evans, 2007).

The explanation of those variations can be the following: the orientation of SHmax is known and stable in the basement. But the sedimentary layer is constrained by a slightly different stress state. When the lithology corresponds to hard rock, this stress state can’t be realised or accommodated. In this case, SHmax rotates from the global stress state to the sedimentary one. In weaker lithologies, clay-rich units, the sedimentary stress state has been accommodated or realised by the deformations of the rock itself. In this case, the sedimentary component of the stress state has been removed and the orientation of SHmax tends to reach the one observed in the basement.

At the top of the granite basement, the uppermost unaltered granite section has to support all the lithostatic stress due to the sedimentary pile, as well as its plastic deformation and its rotating pattern. For that reason, the uppermost part of the unaltered granite has a strongly rotated stress state. But as there is no plastic deformation anymore, all those variations are rapidly overprinted by the granite and the orientation of SHmax rotates with depth reaching the global and regional balanced stress state orientation.

Finally, the sedimentary part shows a totally different pattern for SHmax orientation. The stress state in the basement is decoupled from the sedimentary stress state. This decoupling of stress has already been outlined in Western Europe by Cornet and Roeckel (2012). They showed significant variations with depth of the maximum horizontal principal stress orientation, both in the Rhine Graben and in the North German Basin. They concluded that stress field observed at shallower depths in the sedimentary layers may be decoupled from that which prevails at greater depth in the basement.

No clear correspondence can be highlighted between the cyclic variation of SHmax orientation and the presence of the bigger opened fractures. Maybe the fractures involved in this rotation phenomenon are not the largest ones.

4.2 A and E DITFs distribution ratio

The ration A/E DITFs varies a lot along the borehole for the different lithological intervals (Table 1). It can be noticed that values of the ratio between zero and one, representing intervals where there is more E DITFs than A DITFs, always correspond to hard rock intervals (e.g. ratio of 0.61 for Dolomie Inférieure, 0.60 for Grès à Voltzia, 0.43 for Pink biotite/muscovite massive granite, etc). On the other hand, the highest value of the ratio, representing intervals where there is more A DITFs than E DITFs, doesn't always correspond to weaker rock (e.g. ratio 5.49 for Argiles de Chanville, but ratio of 41.75 for Light grey biotite/muscovite massive granite).

These observations mean that E DITFs are more likely to occur in hard rocks than in weaker rocks. For A DITFs, there is no predominant rule: they can be found either in hard or weaker rocks.

This difference in the A/E DITFs ratio means that the so called "vertical principal stress Sv" is more likely to be really vertical in marls and clays. In other terms, only hard rocks can lead to a rotation of Sv.

This observation matches with the discussion made on global All DITFs orientation. In weaker rocks, the principal stresses orientations tend to reach the global and regional stress state of the Rhine Graben. In those lithological units, the shearing stresses are released because of the plastic deformation of marls and clays. In consequence, Sv tends to be more vertical in clay-rich formations and marls than in dolomite, sandstone, limestone or granite. In the contrary, in hard rocks, there is not enough plastic deformation to accommodate the shear stress. In consequence, the principal stresses rotate to compensate the differences between the upper sedimentary stress state and the basement one, making E DTFs more likely to occur.

CONCLUSIONS

On a global scale, this study shows that the entire stress state of the sedimentary layer is decoupled from the basement one. The first massive unaltered and poorly fractured granite sections between 2,400 m to 2,500 m MD make the interface between the two stress states.

On a larger scale, the orientation of SHmax in the Upper Rhine Graben is globally N145E, and at Soultz N170°E. But the study of the orientation of DITFs has shown that the orientation of SHmax varies a lot, from N150°E to N50°E in the sedimentary layers.

SHmax orientation follows a cyclic profile repeating every 50 m MD along the borehole. Those cycles are not well explained by the presence of major opened fractures or by any change in the geomechanical properties of the lithological units.

Those small cycles participate to a more global trend, where SHmax turn smoothly clockwise from N10°E to N40°E, and then comeback sharply anticlockwise to N0°E or N10°E. This global trend is repeated three times from 1,750 m MD to 2,450 m MD. Such behavior is also not explained by the presence of major opened fractures. But it has been shown that the orientation of SHmax tend to reach the regional orientation in weaker layers (as clays or marls), and turn clockwise toward N50°E in hard rock layers (as dolomite and sandstone).

This result is corroborated by the fact that E DITFs are less likely to occur in weak layers. It also shows that the stress state rotates more in hard rock layers, and is closer to the regional one weaker rock.

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