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# Rate of penetration of geothermal wells: a key challenge in hard rocks

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## ABSTRACT

A drilling data compilation of wells drilled in granite formations across Europe is presented. The review presented in this paper was performed in the Framework of the ThermoDrill project that aims at developing a new drilling system suitable for drilling hard and abrasive rock types and able to withstand the extreme temperature and pressure conditions involved in geothermal drilling. The new system is based on high pressurized fluid-jetting. This paper summarizes the analysis performed while compiling relevant information, linking the Rate of Penetration (ROP) with drill site information, ROP being the key drilling parameter to be improved in the framework of the ThermoDrill project. For each well, the ROP is compared and analyzed thus leading to a proposed mean ROP value for drilling in granite. A normalized ROP is then proposed and discussed. Additionally, a correlation between ROP and lithology is proposed for wells where detailed lithological information is available.

## 1. INTRODUCTION

Rate of Penetration (ROP) is the speed at which a drill bit breaks the rock under it to deepen the borehole. It is a significant parameter when drilling a geothermal well. Any improvement in the drilling speed has a serious impact on drilling costs and therefore on the overall business plan of a given deep geothermal project. As different types of formation are encountered during the drilling process, the bit design and cutting mechanism play an important role in optimizing the rate of penetration. Therefore, different drilling techniques have been developed over the past few decades. Jet-assisted drilling, a combination of high-velocity water jetting and conventional rotary drilling, is considered as a promising and cost-effective one. The most critical parameters of its applicability are the high-pressure generation, the selection of the fluid system, related safety issues and the design of the drill bit. In the ThermoDrill project (Eisner, 2016), an interdisciplinary team of research institutions and industrial partners from all across Europe have joined forces to further improve this jet-assisted drilling technology. The main goal of ThermoDrill is the development of an innovative drilling system based on the combination of conventional drilling with water jetting to achieve a minimum of 50% ROP improvement in crystalline and hard clastic rock. Many geothermal projects in Europe exploit or plan to exploit hard rocks such as granite (Soultz-sous-Forêts, France; Haute-Sorne, Switzerland), or both sandstone and granite (Rittershoffen, France; Insheim, Germany). Thus, the main technical challenge of the ThermoDrill project is to find a way to reduce the tension of the rock ahead of the drill bit, supposedly allowing the bit to erase and break the rock surface easier and faster.

Rate of Penetration in hard rocks is the key parameter to be improved in the framework of the ThermoDrill project. Thus, based on high quality datasets provided by the end user partners from several deep geothermal and gas wells, a geothermal drilling database has been set-up. Published and unpublished drilling parameters from several sites located in the Upper Rhine Graben area (Soultz-sous-Forêts, Rittershoffen, Insheim, Basel) and from the Bohemian massif (Neuhauser, bohemian granites) were gathered. ROP data from 18 wells in hard rocks were analysed and compared versus depth.

## 2. SITE AND WELLS DESCRIPTIONS

The drilling data of the following wells have been analyzed (see map in Figure 1):

- 4 sites in the Rhine Graben :

  - Soultz-sous-Forêts (France) geothermal wells GPK2, GPK3 and GPK4,
  - Rittershoffen (France) geothermal wells GRT-1 and GRT-2,
  - Insheim (Germany) geothermal wells GTI1, GTI1b and GTI2,
  - Basel (Switzerland) geothermal well BASEL-1,
- 5 wells in Bohemian granite and gneiss (Austria).

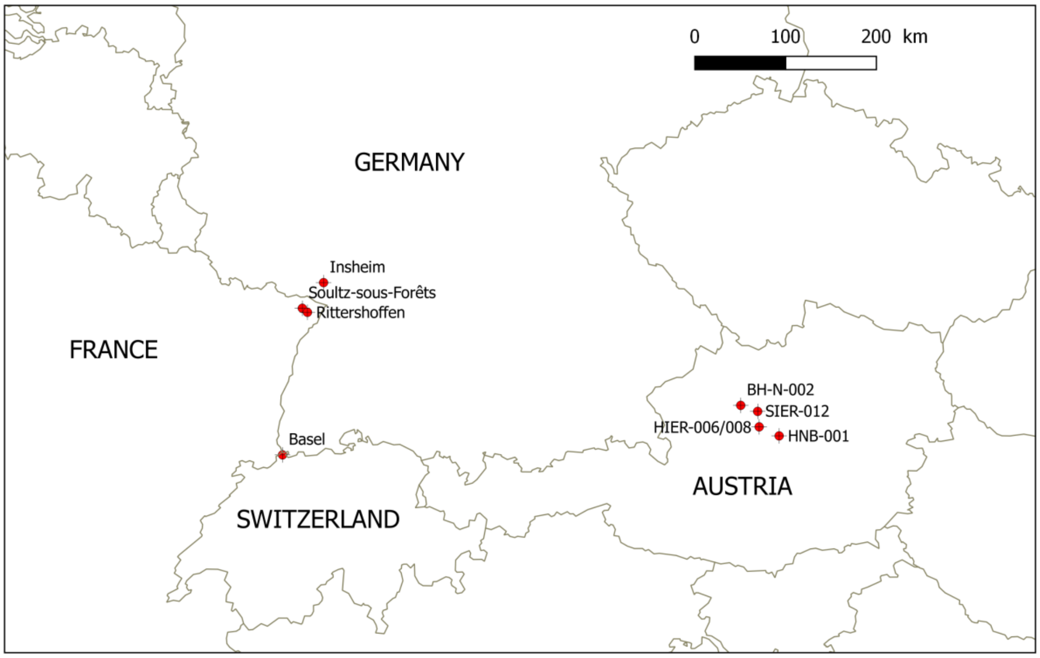


**Figure 1: Map showing the well sites**

The provided data focuses only on hard rocks, i.e. granite or deep sandstone (only for wells GRT-1 and GRT-2). The depth range of available data, drilling diameter and maximum inclination of each well may vary (see Table 1).

**Table 1: Well parameters**

| Well name | Year | Max. inclination | Drilling Diameter | Depth from (m MD) | Depth to (m MD) | Main Lithology |
|---|---|---|---|---|---|---|
| GPK2 | 2002 | 26° | 8''1/2 | 1427 (data available from 3219m only) | 5057 | Granite |
| GPK3 | 2003 | 25° | 12''1/4 to 4592m, 8''1/2 below | 1418 | 5099 | Granite |
| GPK4 | 2004 | 34° | 12''1/4 to 4767m, 8''1/2 below | 1418 | 5258 | Granite |
| GRT-1 | 2012 | 5° | 8''1/2 | 2212 | 2582 | Sandstone/granite |
| GRT-2 | 2014 | 39° | 8''1/2 | 2493 | 3196 | Sandstone/granite |
| GTI 1 | 2008 | 21° | 8''1/2 | 3517 | 3654 | Granite |

| | | | | | | |
|---|---|---|---|---|---|---|
| GTI 1b | 2009 | 33° | 8’’1/2 | 3456 | 3848 | Granite |
| GTI 2 | 2010 | 22° | 8’’1/2 | 3496 | 3858 | Granite |
| Basel 1 | 2006 | - | 9’’7/8 to 4850m, 8’’1/2 below | 2557 | 5009 | Granite |
| GASP-002 | 2013 | 22° | 8 ½” | 1970 | 2009 | Crystalline / Granite |
| HIER-008 | 2015 | 31° | 8 ½” | 2770 | 2832 | Crystalline / Granite |
| HNB-001 | 2015 | 27° | 8 ½” | 3520 | 3555 | Crystalline / Granite |
| SIER-012 | 2015 | 23° | 8 ½” | 2155 | 2185 | Crystalline / Granite |
| TAX-001 | 2013 | 27° | 8 ½” | 1895 | 1955 | Crystalline / Granite |

For each site, a short overview of the geological context is proposed.

### 2.1 Soultz-sous-Forêts

The Soultz geothermal site is based on EGS technology and is located at the western rim of the Upper Rhine Graben (Alsace, France). It is one of the most well-known geothermal projects worldwide because it mainly benefited from public funding from Europe, France and Germany. Several deep wells have been drilled in a deep-seated granitic basement: 4 wells were drilled in destructive mode (GPK1 to 3.6 km and GPK2, GPK3, GPK4 to 5 km).

In the last 30 years, the project focused on reservoir exploration and exploitation, on technology development of the downhole pump and on energy production (Genter et al., 2010). Highly saline natural brine (100 g/L, Na-Cl based) is circulated within the deep and fractured granitic reservoir. The brine is pumped to the surface at 165˚C with long shaft pump technology and re-injected at ~70˚C into the reservoir. The site operates a new binary plant which produces 1.7MWe gross power (Genter et al., 2016).

The present-day stress field is known from borehole image logs mainly interpreted in terms of drilling induced tensile fractures or breakouts. The maximum stress Sv (overburden) is vertical, generating a normal stress regime. In the deepest part of the site, the maximum horizontal stress SHmax and Sv are quite closed in terms of magnitude. Thus this depth section could be mainly controlled by a strike-slip regime. It could be shown that the orientation of the maximum horizontal stress is N170°E (Valley, 2007).

### 2.2 Rittershoffen site

A geothermal project was initiated in 2010 less than 10 km from the Soultz site, in Rittershoffen (Alsace, France). It is the first industrial deep geothermal project in France aiming at producing overheated water from natural geothermal resources embedded at the interface between the Triassic clastic sedimentary layers and the top crystalline fractured basement of the Upper Rhine Graben (Baujard et al., 2017) using an Enhanced Geothermal System (EGS).

In the framework of this project, a geothermal doublet has been drilled, targeting a deep seated fault zone in the granitic basement. It is designed to produce hot water at 170°C and to deliver a heat power of 24 MWth to the “Roquette Frères” bio-refinery located in Beinheim, thus covering around 25% of the industrial heat needs. The heat is delivered using a 15 km transport loop. The location of the Rittershoffen project is shown in Figure 3 1.

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 (Hehn et al., 2016). 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. Hehn et al. (2016) 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.

### 2.3 Insheim site

The Insheim site is located in the Upper Rhine Graben in Germany, about 30 km North of Soultz-sous-Forêts, France. Since 2012 the operator, Pfalzwerke geofuture GmbH generates 4.8 MW of electric power from a geothermal power plant using a single fault system in the crystalline rock for heat extraction covering the needs of approximately 8000 households. In 2008 and 2009 two wells, one injector and one producer, were successfully drilled to a depth of about 3800 meters (see Table 3 5). In autumn 2010 a lateral drain was drilled out of the injection well at approximately 2500 meters, aiming at better distributing the flow between the two injection branches and thus minimizing the induced microseismic activity (Teza et al., 2011; Baumgärtner and Lerch, 2013).

The geothermal reservoir in Insheim was tapped with a temperature of more than 165 °C. Drilling-induced fractures, breakouts from micro-resistivity image, and borehole ellipticity indicate a near N-S maximum horizontal stress direction.

### 2.4 Basel site

Basel is situated at the south-eastern end of the Rhine Graben, a failed rift feature cutting from north-east to south-west through central Western Europe. Geothermal information show throughout the region an increased heat flow of at least 100 mW/m$^2$ with up to 130 mW/m$^2$.

Basel is not only situated at the south eastern end of the Rhine Graben but also at the northern front of the Jura Mountains, the outermost expression and youngest part of the alpine fold belt. The peculiar coincidence of north-northwest trending compression and west-northwest extension creates a seismically active environment.

Well Basel 1 was drilled in 2006 to a depth of 5009 m (Häring et al., 2008). The well is cased down to a depth of 4638 m. The open hole section is drilled with a 9 7/8“ diameter down to 4850 m and 8 ½“ diameter to the along hole end depth of 5009 m. According to temperature logs, which were obtained shortly after reaching the final depth, the reservoir temperature was still disturbed due to the cooling effects of the drilling mud. Various extrapolation methods provided an estimate of the reservoir temperature of 195°C at 5 km depth in the granite. This geothermal site has been abandoned after some acceptability issues triggered by the occurrence of a seismic event following the stimulation operations.

This part of Europe is characterized by strike-slip faulting dominated by compressive forces of the alpine collision. Strike slip faulting along the graben boundary fault system led to vertical hydraulic circulation in various locations. The regional stress field is characterized by strike-slip faulting with SHmax striking in a NNW direction. The maximum horizontal stress direction could be determined in well Otterbach 2 (N140°E± 16°) and in well Basel 1 (N144°E ± 14°) from the drilling induced fractures (Valley and Evans, 2006). The natural fractures identified in the basement section of Basel 1 show an average strike of 163°.

### 2.5 Bohemian site

The Bohemian Massif is in the geology of Central Europe a large massif stretching over central Czech Republic, eastern Germany, southern Poland and northern Austria. The massif encompasses a number of Mittelgebirges and consists of crystalline rocks, which are older than the Permian and therefore deformed during the Variscan Orogeny.

The bedrock of acid gneiss and granite (granodiorite, diorite) is weathered to brown soil. In flat areas and valleys the groundwater had more influence on soil formation; in such places gley soils may be found too.

The basement rocks and terranes of the Bohemian Massif are tectonically part of three main structural zones that differ in metamorphic degrees, lithologies and tectonic styles. This tectonic subdivision was formed during the Variscan Orogeny.

## 3. RESULTS

### 3.1 ROP and normalized ROP comparison

The raw ROP values for all wells are shown in Figure 2 and Figure 3. Depths are measured depths (MD) from surface, as the all trajectories were not available for all wells. Basic geological information was added when available. The given limits are not exact as they may differ from one well to another.

Globally, highest ROP values are recorded in zones where the granite is altered. This is the case for example in the porphyritic granite with vein alteration of Soultz-sous-Forêts, in the granitic section of GRT-2, which is much more fractured than GRT-1, the top of the granitic section of Basel-1, or the top of each granite interval in the Bohemian granite. More in detail, it is interesting to observe that fractured zones are often associated with high ROP values (see for example GPK3 at 4700 m MD, GRT-1 at 2370 m MD, or the cataclastic fracture zones in Basel-1).

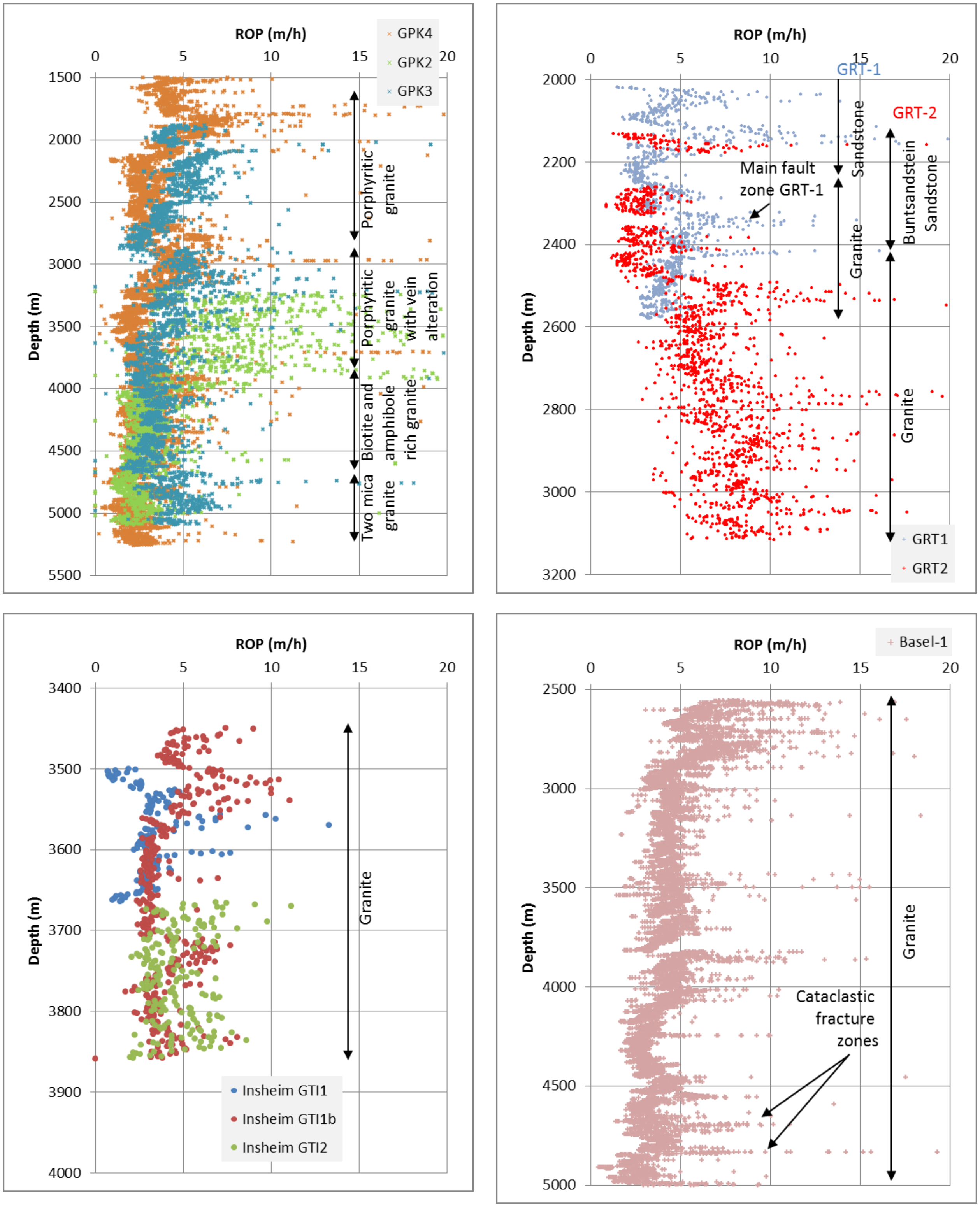


**Figure 2: ROP values of the drill sites in the Rhine Graben: Soultz-sous-Forêts (upper left); Rittershoffen (upper right); Insheim (lower left) and Basel (lower right)**

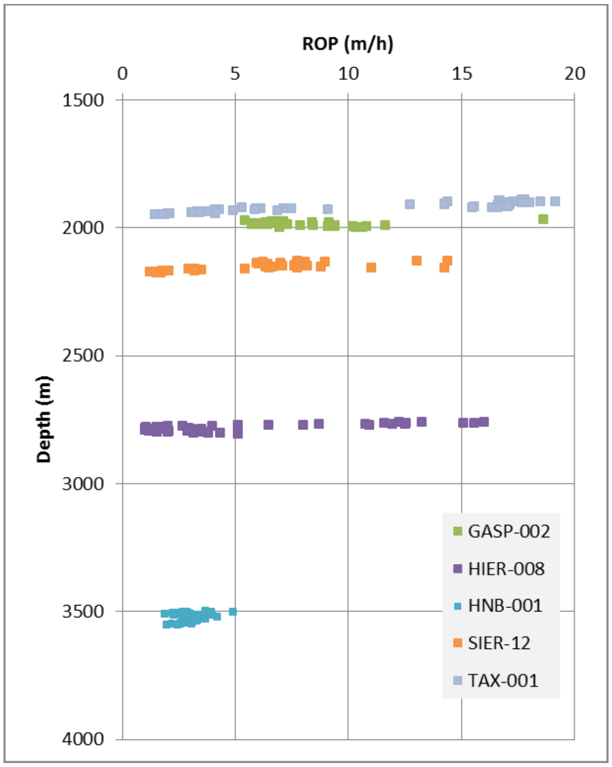


**Figure 3: ROP values of the available drill sites in the Bohemian basin.**

All ROP data are compared in Figure 4. This figure shows that most ROP values in granite are located in the interval 2-7 m/h. A decrease of ROP with depth can be observed: the ROP for medium deep granites (between 2000 and 3500 m depth) can be estimated between 3 and 7 m/h and, for deeper granites (below 3500 m), the ROP can be estimated between 2 and 4 m/h. This is also coherent with the fact that ROP are higher where the granite is altered, which is more likely in the top section of the granite.

The ROP values in granite were normalized by Weight On Bit (WOB) and by hole diameter when the data were available (see Figure 5), according to:

$$ROP_{norm} = \frac{ROP \cdot \pi \cdot r^2}{WOB}$$

With $ROP_{norm}$ *[m3/h/hton]* being the normalized ROP, *ROP [m/h]* being the raw ROP, *r [m]* being the hole radius, and *WOB [ton]* being the Weight on Bit. The result is a volume of removed rock per hour per ton. This graph shows that normalized ROP mainly ranges in the interval of 0.005-0.03 m3/h/ton. As for the raw ROP data, a decrease of normalized ROP with depth can be observed.

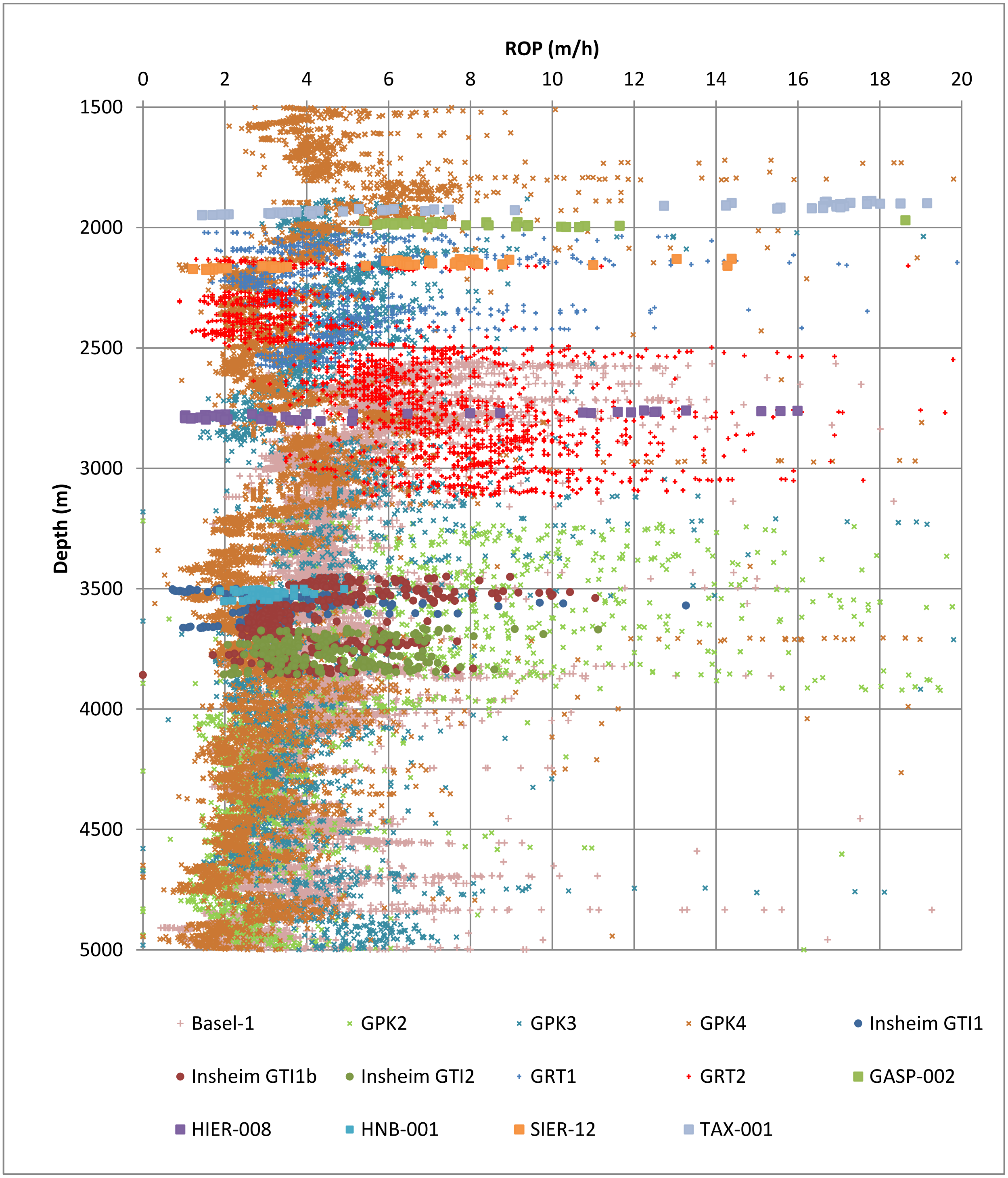


**Figure 4: Comparison of ROP values of the available drill sites**

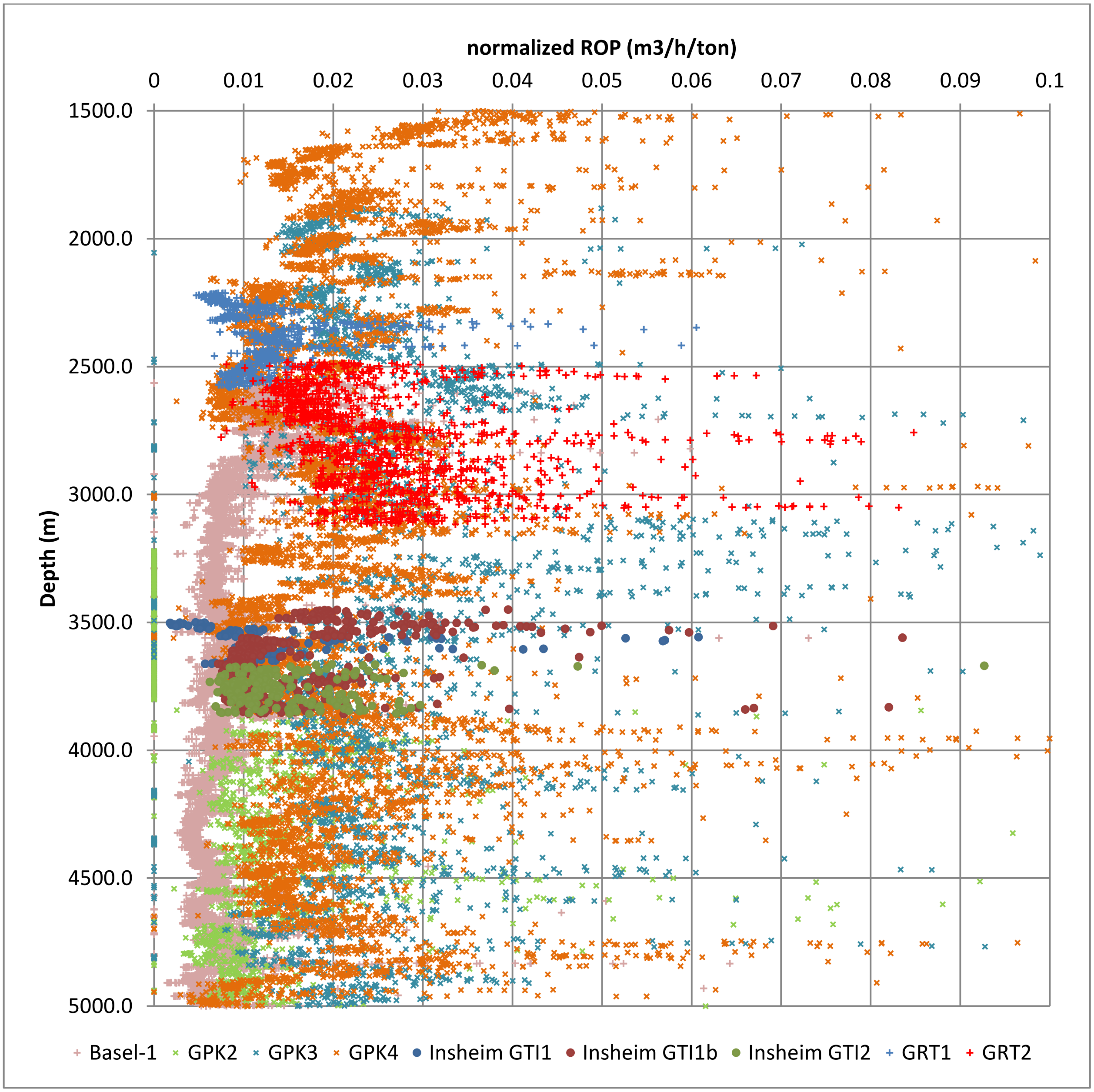


**Figure 5: normalized ROP values for the available drill sites**

**3.2 ROP vs Lithology**

The ROP database exposed in part 3.2 shows a global decrease of the rate of penetration with increasing depth. This trend has been correlated to the degree of granite alteration. Indeed, with decreasing depth, the granite get more hydrothermally altered, its rheological characteristics are changed, making it easier to drill. But as the alteration process can take various forms, the relation between granite lithology and ROP has to be analyzed more closely.

In this section, the a priori link between granite alteration and ROP will be detailed, using ROP and granite lithological data of the geothermal wells of Soultz-sous-Forêts (GPK1, GPK2, GPK3 andGPK4) and Rittershoffen (GRT-1).

The general idea is to cross the ROP log of one well with the corresponding lithology encountered in the granite. Practically, the treatment of the data was done as follows:

- Gathering the granite ROP values for one well. Some wells have been drilled in several times and in different diameters. The reaming ROP has not been used; the initial drilling ROPs have been used instead.
- Filtering the ROP values. Some extreme ROP values have to be filtered because they may distort the calculated average ROP. Drilling operations can artificially make extremely high ROP values for one meter:
  - For example, when the tool touches the bottom of the hole, the count of the tool penetration starts, but the elasticity of the steal tool strings allow the surface strings (where ROP is measured) to go down some dozens of centimeters more. This can lead to an artificial progression of more than one meter per minute.
  - The crossing of a highly fractured zone can also create really high and punctual values of the ROP.
  - A normal filtration of 5 percent didn't suppress all the extreme values because the ROP follows a highly asymmetrical distribution. For those reasons, it was decided to filter some upper and lower percentiles of the ROP values. The filtration window was adjusted manually for each studied well, from one to ten percentiles, for extremely low and high values.
- Gathering lithological values for each well. The lithology of the granite is usually summarized in many different categories, depending on their composition, their colour and their degree of alteration. The number of categories has sometime been reduced to ensure that every category contains a reliable number of ROP values for the average calculation.
- Crossing the ROP value with the corresponding lithology intervals. The minimum, maximum and average value of the filtered ROP is computed for each lithological category. A table summarises the results, sorted by increasing average ROP.

The main hard rock lithologies are deduced from cuttings analyses in the various boreholes (Dezayes et al., 2003). The main rock facies correspond to massive unaltered granite (GRAN), K-Feldspar rich granite (MFKR), fine grained two-mica granite (GR2M) or low density granite (LEG1, LEG2), paleo-weathered granite rich in Fe-oxides (HEMA, RUBE), Biotite-rich porphyritic granite (MELA), K-feldspar depleted granite (GRAD), propylitic low alteration granite (PROP), xenolith-rich granite (XENO), granite artificially enrichment in biotite due to drilling process (NGRN) and massive sandstones (GRES).

A hydrothermal alteration scale was defined as follows: low alteration grade (HLOW), moderate alteration grade (MOD), high alteration grade (HHIG), extreme alteration grade (HEXT) and fracture zones deduced from logs (NEWF).

The following tables expose the results.

**Table 2: ROP distribution versus granite lithology in GPK1.**

| Lithology | Interval length | Average ROP | Min ROP | Max ROP |
|---|---|---|---|---|
| - | m | m/h | m/h | m/h |
| LEG1 | 13 | 1.22 | 0.91 | 1.58 |
| HEXT | 34 | 1.23 | 0.86 | 2.73 |
| HEMA | 78 | 1.29 | 0.86 | 3.53 |
| LEG2 | 43 | 1.66 | 1.09 | 2.73 |
| MELA | 166 | 1.83 | 0.86 | 5.34 |
| PROP | 134 | 2.08 | 1.03 | 5.00 |
| HHIG | 107 | 3.45 | 0.92 | 10.12 |
| GRAN | 839 | 3.54 | 0.92 | 9.55 |
| HMOD | 224 | 3.65 | 1.22 | 10.64 |
| HLOW | 254 | 3.95 | 1.52 | 10.89 |
| MFKR | 26 | 5.14 | 4.10 | 7.16 |

**Table 3: ROP distribution versus granite lithology in GPK2.**

| Lithology | Interval length | Average ROP | Min ROP | Max ROP |
|---|---|---|---|---|
| - | m | m/h | m/h | m/h |
| XENO | 14 | 2.03 | 1.28 | 4.89 |
| GR2M | 66 | 2.82 | 1.27 | 6.54 |
| GRAN | 911 | 3.27 | 1.28 | 9.78 |
| HLOW | 453 | 3.47 | 1.28 | 9.82 |
| MELA | 135 | 3.57 | 1.54 | 6.34 |
| GRES | 15 | 3.70 | 1.86 | 5.59 |
| HMOD | 200 | 3.74 | 1.28 | 9.84 |
| HHIG | 104 | 4.55 | 1.75 | 9.52 |
| HEXT | 2112 | 4.80 | 1.78 | 9.77 |
| MFKR | 6 | 5.00 | 4.03 | 5.62 |

**Table 4: ROP distribution versus granite lithology in GPK3.**

| Lithology | Interval length | Average ROP | Min ROP | Max ROP |
|---|---|---|---|---|
| - | m | m/h | m/h | m/h |
| MELA | 60 | 3.46 | 1.94 | 6.55 |
| GRAN | 1873 | 3.84 | 1.88 | 8.88 |
| HLOW | 477 | 4.15 | 1.88 | 8.84 |
| HMOD | 269 | 4.65 | 1.90 | 8.92 |
| GR2M | 188 | 4.93 | 1.89 | 7.66 |
| GRAD | 7 | 5.17 | 4.67 | 5.69 |
| HHIG | 69 | 5.38 | 2.00 | 8.73 |

**Table 5: ROP distribution versus granite lithology in GPK4.**

| Lithology | Interval length | Average ROP | Min ROP | Max ROP |
|---|---|---|---|---|
| - | m | m/h | m/h | m/h |
| NGRN | 718 | 2.49 | 1.24 | 7.86 |
| NEWF | 703 | 3.20 | 1.22 | 7.68 |
| HEXT | 138 | 3.44 | 1.70 | 8.02 |
| HLOW | 995 | 3.45 | 1.45 | 7.97 |
| MELA | 165 | 3.50 | 1.98 | 7.92 |
| GRAN | 1444 | 3.57 | 1.22 | 8.10 |
| HMOD | 779 | 3.95 | 1.74 | 7.96 |
| HHIG | 336 | 4.20 | 1.25 | 7.94 |
| GR2M | 56 | 4.20 | 3.05 | 7.71 |

**Table 6: ROP distribution versus granite lithology in GRT-1.**

| Lithology | Interval length | Average ROP | Min ROP | Max ROP |
|---|---|---|---|---|
| - | m | m/h | m/h | m/h |
| RUBE | 54 | 3.13 | 2.20 | 5.10 |
| HMOD | 84 | 4.51 | 2.80 | 7.30 |
| GRAN | 384 | 4.54 | 2.50 | 10.40 |
| HLOW | 12 | 4.81 | 3.90 | 5.40 |
| HHIG | 126 | 5.16 | 2.40 | 10.80 |
| HEXT | 24 | 5.37 | 3.40 | 10.60 |

For every well, there were a few extremely low and high values of ROP. As the proportion of extreme values was not the same for each well, no global filtering has been applied. The filtered percentiles have been adjusted case-by-case:

- for GPK1 the lowest and the 6 highest percentiles have been removed;
- for GPK2 the lowest and the 10 highest percentiles have been removed;
- for GPK3 the lowest and the 3 highest percentiles have been removed;
- for GPK4 the lowest and the 3 highest percentiles have been removed;
- For GRT-1 the lowest and the highest percentiles have been removed.

Because of this heterogeneous filter, no global statistics have been calculated for the 5 wells. For the interpretation, every well has to be studied separately

The massive unaltered granite with a porphyritic texture made of K-feldspar mega crystals (GRAN) represents a cumulative length of 5451 m for ROP values ranging from 3.27 to 4.54 m/h. MFKR facies shows ROP values higher than 5 m/h. Two mica granite and biotite-rich granite show also high ROP values ranging between 3.50 and 4.50 m/h. In GPK1 well, some facies variations interpreted as leucogranites (LEG1, LEG2) show low ROP values between 1.22 and 1.66 m/h.

The most hydrothermally altered and fractured granite (HEXT, HIGH, HMOD, HLOW) representing a cumulative length of 6797 m has ROP values ranging from 3.44 to 5.38 m/h which could be in agreement with the occurrence of fracture and hydrothermal alteration (secondary porosity). Surprisingly, in GPK1 well, HEXT facies show a very low ROP of 1.23 m/h. This can be interpreted with the occurrences of secondary deposits within the fracture zones such as secondary quartz. Such precipitation could reinforce the rock strength by an overall silicification process of the altered rock mass and therefore low ROP values are observed.

Thus, in the crystalline basement of the Soultz and the Rittershoffen wells, ROP values are quite high between 3.5 and 4.5 m/h. Hydrothermally altered granites as well as massive unaltered granites also show high ROP values.

## CONCLUSIONS

An attempt of correlating drilling data available from different wells was carried out by comparing raw ROP values from various drilling sites and realized in hard rocks (mainly granite). This showed a trend versus depth, higher ROP values are observed between 2000 and 3500 m depth than at greater depths (>3500 m). For these sites, the ROP ranges from 3 to 6 m/h in the shallower section and between 2 and 5 m/h in the deepest one. The drillability of hard rocks was also investigated according to lithological variations observed in the Soultz and the Rittershoffen wells between 1.5 and 5 km depth. This investigation surprisingly indicated that massive granite and fractured granite have similar ROP values ranging between 3.5 and 4.5 m/h.

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## REFERENCES

Baujard, C., Genter, A., Dalmais, E., Maurer, V., Hehn, R., Rosillette, R., Vidal, J., Schmittbuhl, J., (2017). Hydrothermal Characterization of wells GRT-1 and GRT-2 in Rittershoffen, France: Implications on the understanding of natural flow systems in the Rhine Graben, *Geothermics*, **65**, 255–268.

Baumgärtner, J., Lerch, C., (2013). Geothermal 2.0: The Insheim Geothermal Power Plant - The second generation of geothermal power plants in the Upper Rhine Graben. Abstracts & Papers, *Third European Geothermal Review*, Geothermal Energy for Power Production, June 24-26, 2013, Mainz, Germany, pp. 9-10.

Dezayes, Ch., Genter, A., Homeier, G., Degouy, M., Stein, G. (2003). Geological study of GPK3 HFR borehole (Soultz-sous-Forêts, France). BRGM/RP-52311-FR, 128 p.

Eisner, P. (2016). Simulation of a High-velocity Jet to Predict Its Influence on Crack Initiation and Propagation in Jet-assisted Drilling. *EAGE - 15th European Conference on the Mathematics of Oil Recovery (ECMOR XV)* Amsterdam, August 29th 2016

Genter, A., Baujard, C., Cuenot, N., Dezayes, Ch., Kohl, Th., Masson, F., Sanjuan, B., Scheiber, J., Schill, E., Schmittbuhl, J., Vidal, J., (2016). Geology, Geophysics and Geochemistry in the Upper Rhine Graben: the frame for geothermal energy use, *European Geothermal Congress 2016*, EGC2016, 19-22 September 2016, Strasbourg, France.

Genter, A., Evans, K.F., Cuenot, N., Fritsch, D., Sanjuan, B., (2010). Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of Enhanced Geothermal Systems (EGS). *C.R. Geoscience*, **342**, 502-516.

Häring, M.O., Schanz, U., Ladner, F., Dyer, B.C., (2008). Characterisation of the Basel 1 enhanced geothermal system, *Geothermics*, **37**, 469-495.

Hehn, R., Genter, A., Vidal, J., Baujard, C. (2016). Stress field rotation in the EGS well GRT-1 (Rittershoffen, France). *European Geothermal Congress 2016*, EGC2016, 19-22 September 2016, Strasbourg, France.

Teza, D., Baumgaertner, J., Lerch, C., Gandy, T., Hettkamp, T., Penzkofer, P., Schindler, M., Wahl, G., (2011). Developing and circulating a fault system in the crystalline rock for geothermal power generation in Insheim, Germany. *American Geophysical Union,* Fall Meeting 2011, abstract #S44B-03.

Valley, B., Evans, K.F., 2006. Stress orientation at the Basel geothermal site from wellbore failure analysis in BS1. Report, to Geopower Basel AG for Swiss Deep Heat Mining Project Basel. ETH Report Nr.: ETH 3465/56. Ingenieurgeologie ETH Zürich, Switzerland, 29 pp.

Valley, B. (2007). The relation between natural fracturing and stress heterogeneities in deep-seated crystalline rocks at Soultz-sous-Forêts (France), *PhD thesis*, ETH-Zürich, Switzerland, 260 pp.