A Multi-proxy Approach for Fracture Network Quantification of Regional Fold and Thrust Structures for Geothermal Reservoir Characterisation

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Introduction

As part of the EU H2020 MEET project, Göttingen University is researching the potential for the conversion of the gas power plant that provides heating to the campus, to a geothermal powerplant. The reservoir itself is situated below a Creatceous sedimentary cover, in the Variscan basement, and due to the complexity of the structures not much could be interpreted from the seismic study undertaken in 2015. Due to the lack of a research well, and little in the way of seismic interpretation for the reservoir, the focus is on characterising an analogue site. The analogue site is based in the Western Harz Mountains in the Clausthal Culm Fold Zone (CCFZ), Germany, a sequence of Lower Carboniferous flysch deposits folded during the Variscan Orogeny.

The planned reservoir is relying on the primary permeability of the fracture network related to the folding and thrusting caused during the Variscan orogeny. Ideally one might suspect the large scale fold hinge and thrust zones to be target zones, but due to the drilling location being fixed due to the demo-site already being active, any future drilling will be blind. This means all structural and lithological settings should be covered in the analogue characterisation.

Due to the structural complexity of the analogue region, a detailed real structural model and fracture network is not feasible and likely not representative of the reservoir below Göttingen. Therefore, the methodology outlined below will allow for a more holistic approach to outcrop analogue characterisation in view of the creation of a conceptual geological model to then be used for reservoir modelling and process simulations.

By characterising the main features of the fold and thrust system and the main lithological relationshipsinto packages, the general trends in fracture network characteristics, such as intensity, connectivity and orientation sets can be assigned and quanitified.

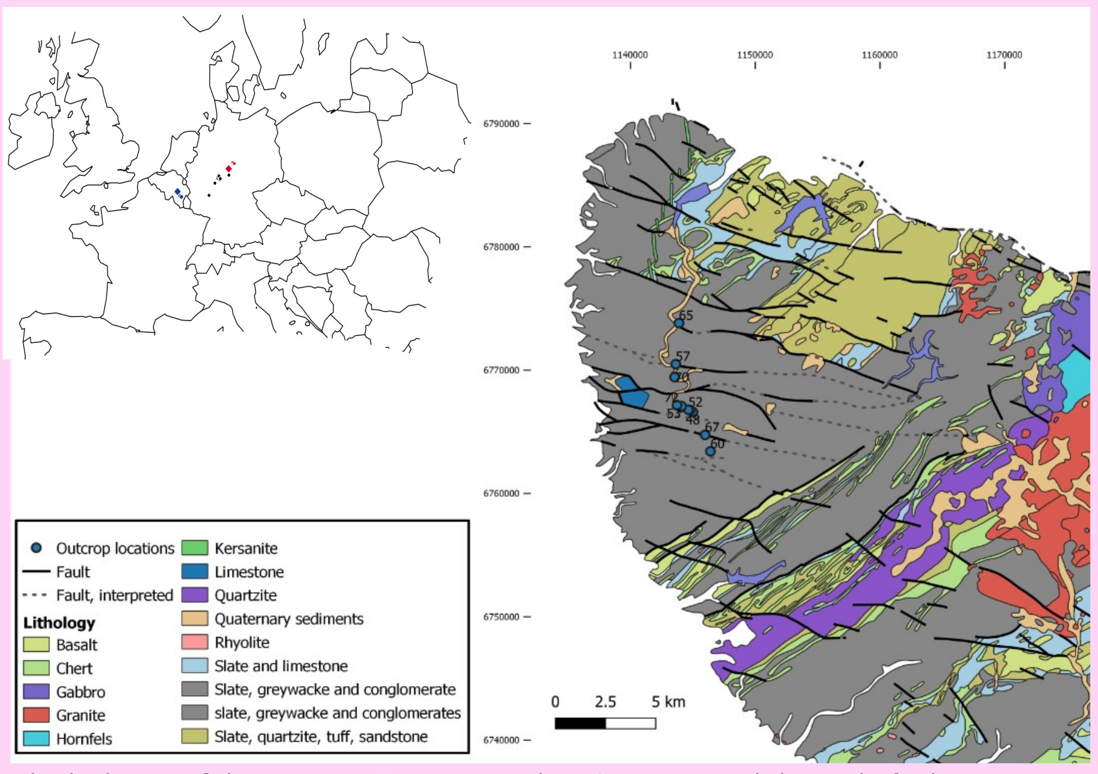

Fig 1. A Geological map of the western Harz mountains, Germany and the main fault structures

Methods

Through an intense field sand literature study involving structural mapping, field sketches and the collection of Unmanned Aerial Vehicle (UAV) images for the creation of outcrop models a deeper understanding of the overall structures within the CCFZ were realised. The main areas within the fold and thrust structure could then be divided into 4 structural settings (as seen in Fig.2), and the lithological relationships into 3. A total of 29 outcrops were analysed and given a number corresponding to the structural and lithological situation that they represent.

UAV images were taken to allow for a view of areas that would otherwise not be accessible from foot. This allowed for 1-30m scale fracture network characteristics to be analysed. At each outcrop a circle of known diameter was drawn, a picture taken for analysis of fracture network characteristics on the metre to centimetre scale.

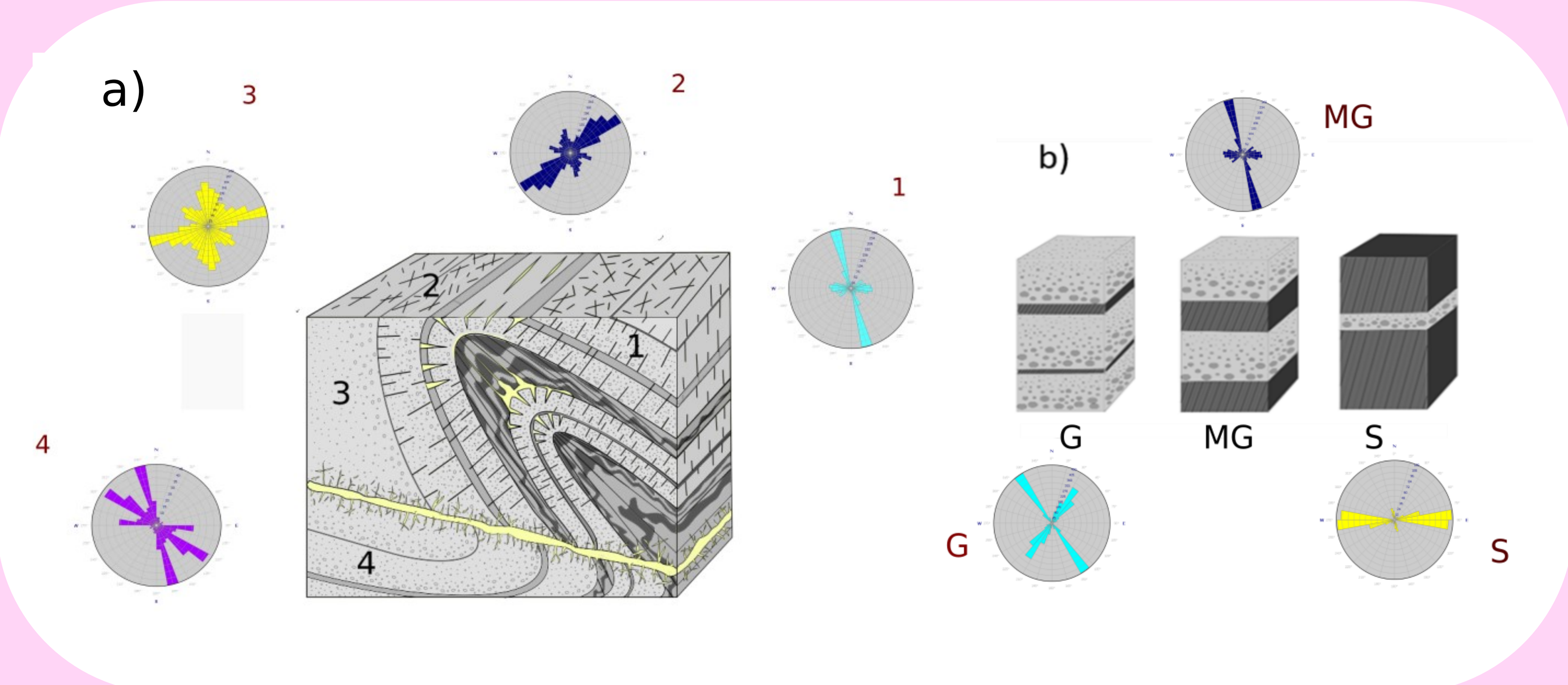

Fig.2 a) A conceptual diagram of the four main fold placements 1- normal limb, 2 - hinge zone 3 - overturned limb, 4 - low angle forelimb. b) conceptual blocks of the three main lithological relationships G - Large greywacke beds with slate intercalations, MG - greywacke beds with thicker slate layers S - majority slate with some greywacke layers. As well as rose diagrams of the strike orientation of fractures at each of these situations.

From the images taken in the field, a 2D fracture trace map was created in QGIS. The shapefiles could then be georeferenced accurately using the Jupyter Notebook script written by (Luijendijk, 2020). Once the fracture networks are correctly georeferenced, they can be analysed using NetworkGT, a Python plugin used primarily for the topological analysis of 2D fracture networks (Nyberg, Nixon, & Sanderson, 2018)

The connectivity value is plotted using IYX topology (Sanderson, 2015)

The intensity is measured as dimensionless intensity (P22)

The orientations are measured as the strike measurement, or fracture trace orientation

Results

To evaluate the relationship between placement on the fold and the level of connectivity, intensity and fracture orientation, measurements from multiple outcrops with the same structural or lithological situation have been used to show that these relationships are statistically more valuable. As can be seen in the Fig 3-5, there is a notable change in the connectivity, intensity, and dominance of fracture orientation sets across the fold structure.

Using the percentage of IYX nodes in varying fracture networks (Fig.3a) there is a clear distinction between most structural situations. The outcrops noted as a forelimb structure (1), and those as a low angle forelimb (2) notably have the lowest connectivity. The hinge zone (3) and overturned limb (4) outcrops have a wider spread, but in almost all plot below 1 & 2 . The lithological situations Fig.3b) are slightly more spread, generally showing that outcrops with mostly slate (S), or mostly greywacke (G) seem to have a higher connectivity over those with a mix of the two.

Dimensionless intensity values (P22) show a similar trend to connectivity for the structural situations as well as the lithological. In fig.4a, 1 showing a wider spread of P22 values, 2 showing the highest average, and 4 the smallest. There is a slight overlap, but the mostly notable is between 1 and 2. The lithological situations (Fig.4b) still show a trend, with S having the highest average P22 value, followed by MG, and G with the lowest.

Orientation set dominance is relatively clear (Fig.2), in situations 1,3 and 4 the dominant set is running perpendicular to the fold axis. In situation 2 however, there is a clear dominance of axis parallel fractures. In terms of lithology, the only noticeable difference is with the slate group, with the dominant group being NEE-SWW, corresponding to the orientation of the cleavage.

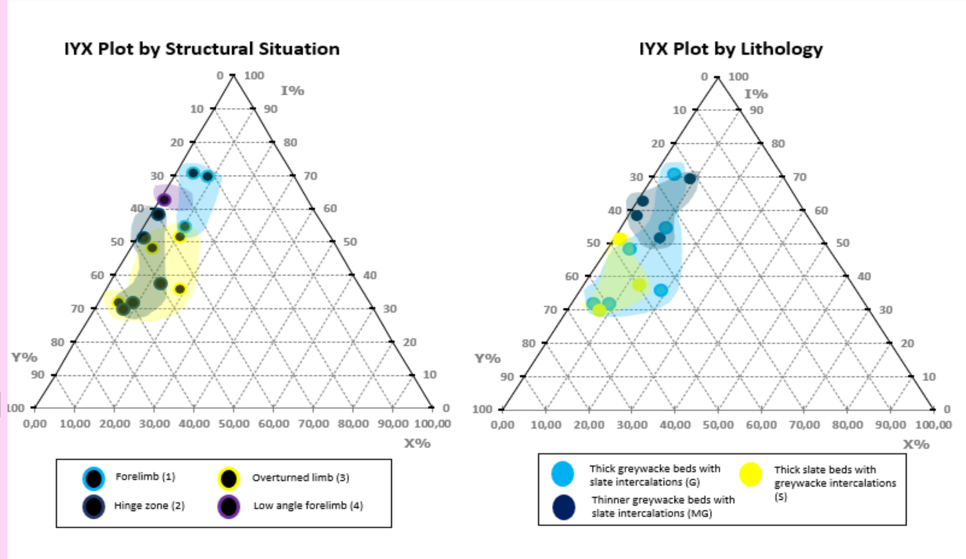

Figure 3 - Triplot diagrams showing the percentage of IYX nodes in each fracture network sample colour coded by structural situation (a) and lithological situation (b)

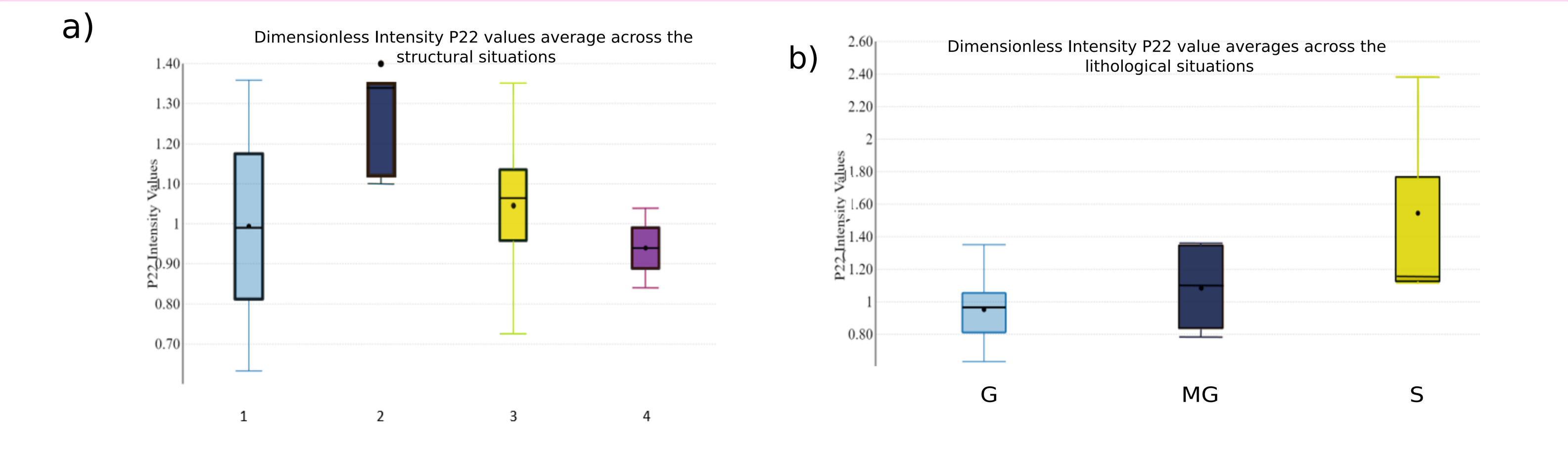

Figure 4 - Box and whisker diagrams showing the average dimensionless intensity P22 values across the structural situations (a), and lithological situations (b)

Discussion

There is a correlation between fracture orientation and connectivity which is visible in the data above. The highest average connectivity appears to be in situation 4, when looking at the orientation spread in this group there is also a wider spread of orientations, the more opposing orientation sets, the more chance of connections between fractures. If the fracture intensity is higher, this also increases the chances of connections, but a variety of fracture orientations is more important in terms of connectivity (Sanderson and Nixon, 2018).

Structural Location	Average Connections per Branch	Average Dimensionless Intensity P22	Most Dominant Fracture Set
1 Forelimb	1,43	0,98	NW-SE
2 Hinge Zone	1,55	1,35	NE-SW
3 Overturned Limb	1,63	1,08	NE-SW
4 Low Angle Forelimb	1,29	0,91	NW-SE
Lithological Situation	**Average Connections per Branch**	**Average Dimensionless Intensity P22**	**Most Dominant Fracture Set**
Thick Greywacke Beds with Slate Intercalations (G)	1,61	0,95210625	NW-SE
Thinner Greywacke Beds with Slate Beds (MG)	1,41	1,0852325	NW-SE
Thick Slate Beds With Greywacke Intercalations (S)	1,59	1,5454	NEE-SWW

Figure 5 -Table of the average value of connectivity, P22 intensity and most dominant fracture set in each lithological and structural situation.

The P22 values increasing towards the hinge zone are to be expected due to the increased level of strain in this zone typically. The wider spread of values in situation 1 are more surprising but could be due to more localised deformation not visible from the outcrop. The higher P22 values in S are mostly likely due to cleavage. As mentioned in Burg, 2018, the thicker the layer, the less fracture intensity is exhibited, which helps explain the lower averages in G. Although the greywacke is more competent, if including cleavages the intensity of fractures will be stronger within the slate layers.

The orientation data shows that the majority of the fractures in situations 1, 3 and 4 are NE-SW striking, this could be related to the uplift of the Harz during the Cretaceous, not to the Variscan. However the dominance of NW-SE striking fractures in the hinge zones, parallel to the fold axis are much more likely to be of Variscan origin.

Conclusions

The general trend of these data indicate towards the hinge zone (2) (Fig.2a) may be more suitable in terms of permeability. The lithologies however, are more complex due to other anisotropies such as cleavage playing a role. There are of course other important parameters such as aperture and length not included in this study but will be so in the future to allow for a more quantitative characterisation.

By comparing the differences in lithology and structural placement and how these impact fracture network characteristics, there can begin a deeper understanding into the suitability of a potential reservoir.

In conclusion, this method is the first step in a holistic approach to the characterisation of complex meta-sedimentary fold and thrust belts for the purpose of reservoir modelling, especially when a detailed structural model on such a scale would not necessarily be beneficial.

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