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Applying Variscan Metasediments as an EGS Reservoir - A Conceptual 3D-Structural Model as a First Approach

Katherine Ford, Bianca Wagner, Bernd Leiss, Max Zeuner, Julien Floch, Lorraine De Céris, Graciela Sosa

Geoscience Centre of the University of Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany

katherinealexandra.ford@uni-goettingen.de

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ABSTRACT

To explore deformed Variscan meta-sediments as a potential geothermal reservoir for heat supply of the Göttingen University Campus, one of the first approaches is to set up conceptual 3D-structural model within the EU-Horizon-2020-MEET-project (**M**ultidisciplinary and multi-context demonstration of **E**nhanced Geothermal Systems exploration and **E**xploitation **T**echniques and potentials). As a starting point for such a model, firstly the complex structures of the Variscan meta-sediments as seen in the Western Harz Mountains must be understood and characterized from micro to reservoir scale and a 3D real structural model created. To achieve this, various methods of data collection are undertaken from 3D digital data capturing and classic field methods to the digitization of literature data as well as sample collection from surface outcrops to boreholes. This study focuses on the characterization of the fracture network through topological analysis, defining two main parameters, connectivity and intensity and how these parameters change in various structural situations situated along the generalized fold and thrust structure, as a basis for understanding the complexity of the deformation exhibited in the Variscan Fold-and-Thrust belt. The results of this study do show a general trend of increased intensity and connectivity towards the fold hinge and thrust zone but are however more complex than this hypothesis, therefore concluding that a much more detailed study must be conducted before any such conclusions can be made.

1. INTRODUCTION

As the technology and demand for renewable energy increases across the globe, lithologies and tectonic settings not classically thought of having a technical geothermal potential, are receiving more and more attention to be exploited by Enhanced Geothermal Systems (EGS). One of the aims of the EU-MEET-project is to explore and bring about this potential in Variscan crystalline and meta-sedimentary reservoirs (Trullenque et al., 2018, Leiss & Wagner 2019).

The Göttingen University Campus, Germany, was selected as one of the demo sites for the MEET-project, due to the University's interest to convert the natural gas power and heat plant, into a deep geothermal power plant to supply the existing district heating. Until the targeted 2000 m research borehole is drilled and since in the Göttingen area the expected deformed meta-sediments are covered by a Permo-triassic sedimentary cover of 1500 m (Leiss, 2011), the analogue site for this project has been chosen as the Western Harz Mountains (fig.1), where the Variscan fold and thrust belt experienced an uplift to the surface mainly during the Cretaceous. From interpolation of comparable units in the Rhenish Massif with the Harz Mountains, it is likely that the boundary that separates the Variscan autochthonous from the allochthonous zone is striking through the subsurface of the area of Göttingen, just 40 km south west from the Harz (Leiss et al., 2016). This paired with the reasonable outcrop situation makes the Western Harz a suitable analogue for the Variscan meta-sedimentary basement of Göttingen University Campus.

The area of data collection is focused in what is known as the Clausthal Culm Fold Zone (Clausthaler Kulmfaltenzone, CCFZ), situated just NW of the boundary previously mentioned, in the autochthonous zone. Lithologically speaking it is characterised by Early Carboniferous, syn-orogenic, pre-flysch and flysch deposits. Flinty slates and alum slates are overlain by argillaceous slates, which grade into thick greywackes. This distal shelf facies has been termed the "Culm facies". The post-orogenic granite body (known as the Oker Granite) has caused the Culm facies surrounding this to be partly subjected to contact metamorphism. Tectonically this zone is characterised by NW-verging folds (NE-SW fold axes), with penetrative fold axial parallel cleavage. These fold structures are mostly broken up by parallel striking thrusts (Mohr, 1998*),* giving the classic Hercynian fold and thrust structures seen throughout Western Europe. Younger WNW-ESE strike slip faults affect the CCFZ heavily and are well known by locals for their abundance of ore minerals, often termed "The Upper Harz Veins".

To understand and comprise the complex structural parameters that may be found in the expected slate and greywacke units beneath the surface of Göttingen, a 3D conceptual structural model of the Variscan basement must be created as the first step. This contribution will focus on the interactions and changes of different structural parameters across the typical Variscan fold and thrust belt outcrop scale. To accomplish this, intensive field campaigns and photogrammetry sessions are undertaken for detailed data collection on changes in parameters such as the fracture network, mineralization and lithology across the primary fold and thrust structure. The data collection is comprised of samples taken from outcrops at the surface and subsurface, as well as drill cores. Based on the presented conceptual model created from real structural situations and the following petrophysical and chemical parameterisation derived from lab experiments, reservoir models and EGS-exploitation strategies can be developed.

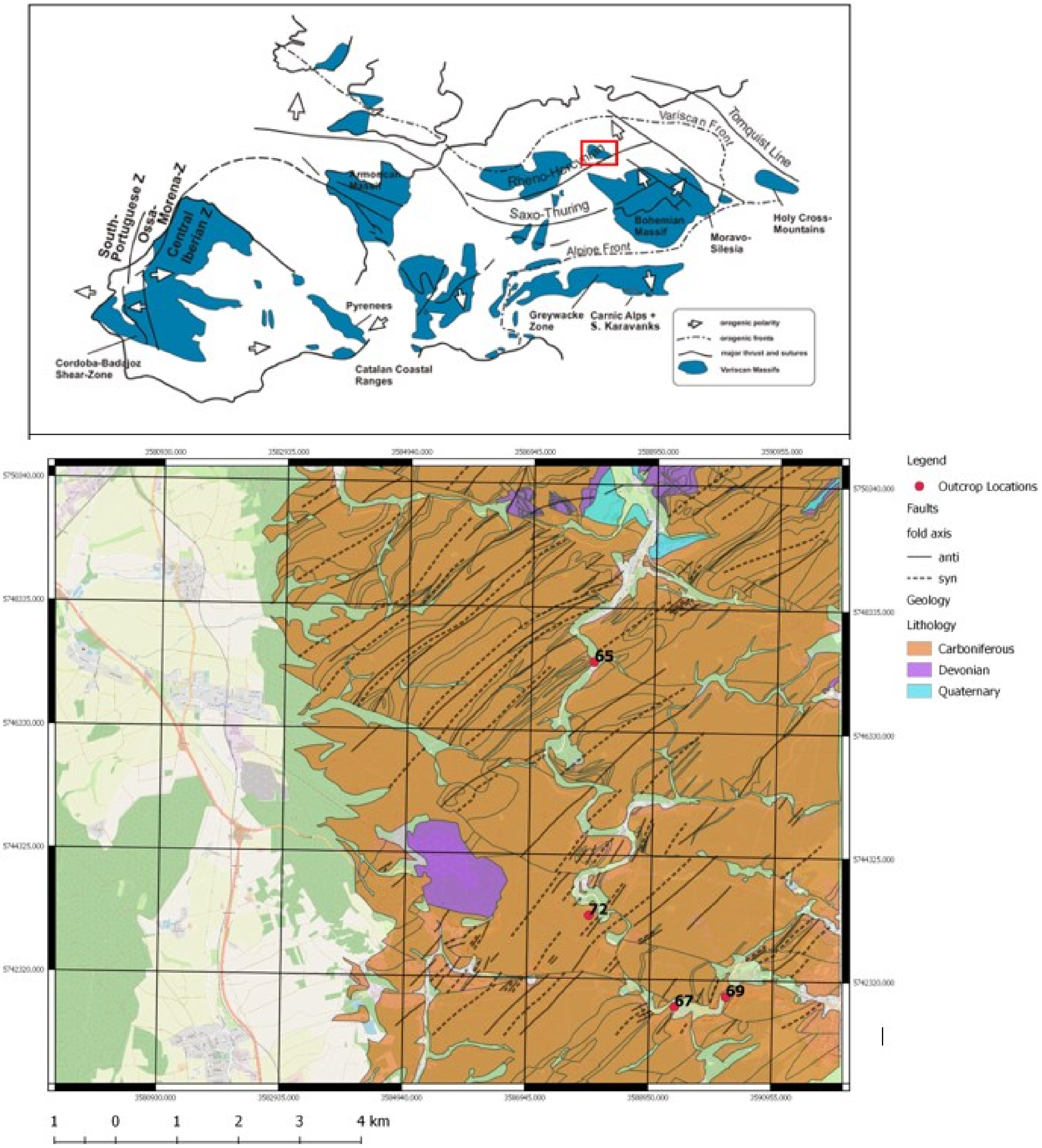

Figure 1: Top – European scale map of the Hercynian belt (Schätz, 2004), red box indicates the location of the Harz Mountains. Bottom - geological and terrestrial map of field area with indication of sample locations and number (red points).

2. METHODS

Outcrop selection is an important part of the process to defining characteristic structures of an analogue site, especially one as complex as the CCFZ. To begin this process, it is important to understand the main structures of the analogue site. To do this, extensive literature research and an exploratory field campaign must be undertaken to view as many outcrops as possible. In the Western Harz, the majority of outcrops are located at roadsides or in abandoned and active quarries, so in general are reasonably accessible. Once a view of the overall structure has been realized, a more focused outcrop selection can take place. In the case of the CCFZ there are so far four main features of the fold and thrust belt that are the focus of this study, the normal limb, the overturned limb, the thrust zone and the hinge zone.

As previously mentioned, classical fieldwork is a very important part of characterizing the structures in any geothermal analogue site, especially one with such a complex deformational history. This section will focus predominantly on the parameterization and characterization of the fracture networks using topological analysis by collecting field data from different structural situations. The methodology used for the collection of fracture parameters and the generation of fracture traces maps in the field has been taken from Watkins et al., 2018. The basis of the methodology is to create "circular scanlines" in different structural situations as outlined previously.

The steps are as follows:

- Once the outcrop has been chosen, an area of representative characteristics and a relatively flat surface should be chosen to perform this methodology. This may not always be possible due to accessibility of the chosen outcrop, but an effort should be made. Once this has been chosen, a circle of a known diameter is drawn onto the outcrop surface and a photo taken with a good quality camera (Fig. 2a, b).
- The next step is to measure the orientation of all the visible fractures that intersect the circle and note if they are mineralized, partially mineralized, or not visibly mineralized (Fig. 2c).
- Using the photo taken in the field, a fracture trace map can be created using any digitising software, in this case QGIS was used. The fractures (including any plane with visible movement along it) from the photo are digitised and categorised by the level of mineralization visible (as in the previous step). (Fig. 2d).

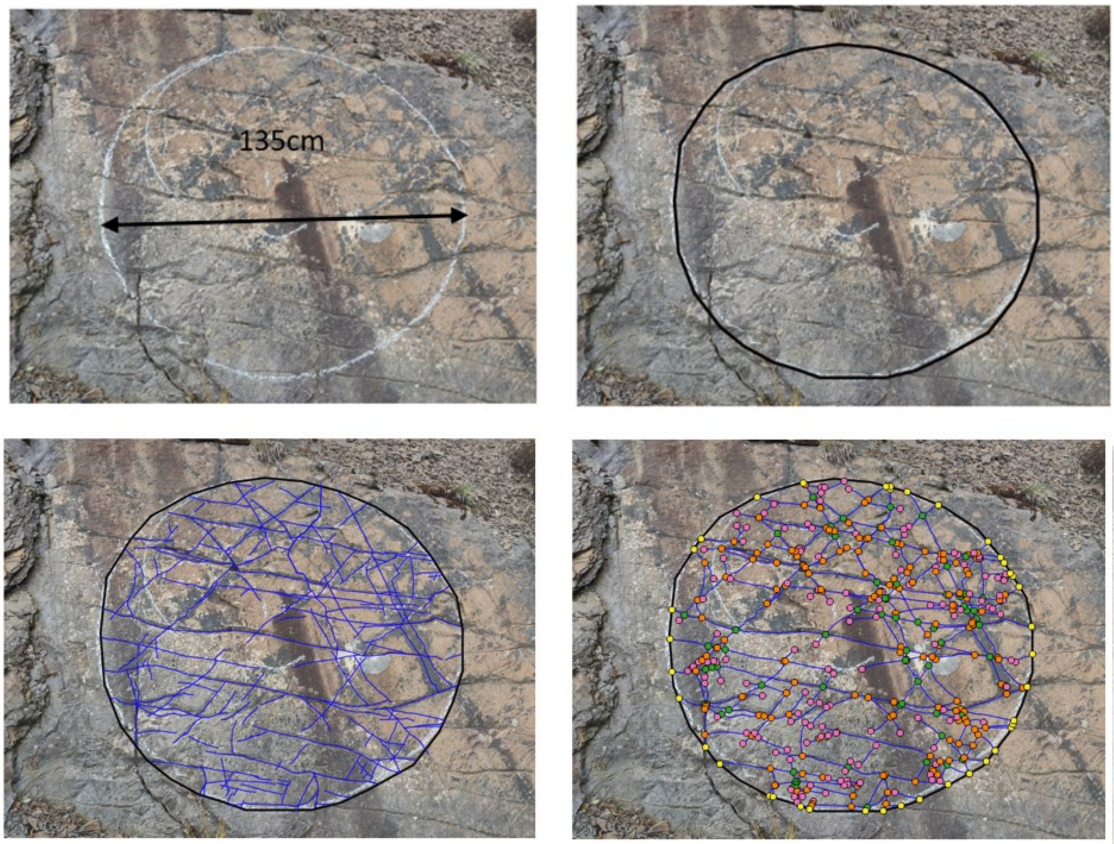

Figure 2: a, b, c and d Diagram showing the methodology for creating fracture trace maps from field photographs as explained above.

2.1 Topological Analysis

Using the methodology explained by Nixon & Sanderson (2015) a study using fracture topology can be used to quantify parameters such as connectivity between fractures from the 2D fracture trace maps.

In two-dimensions, a fracture network consists of a system of branches and nodes that can be used to define both geometrical features, such as length and orientation, and the relationship between elements of the network – topology. The basis of this methodology is on the interactions of fractures or "nodes". The main node types are isolated (I), abutting (Y) and crossing (X) (Fig. 3). Although topological analysis can only yet be done in 2D, it can be used on all scales from micro to reservoir scale.

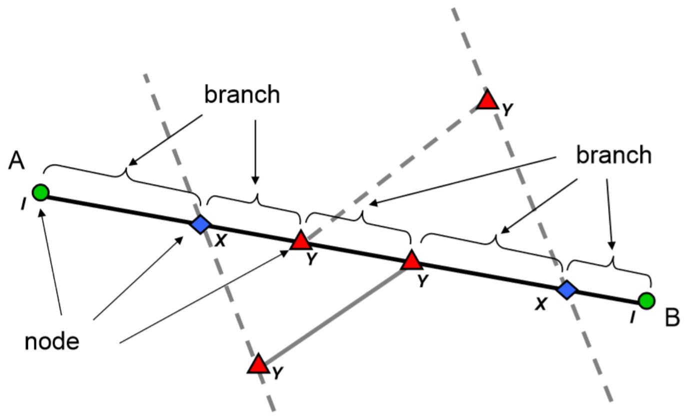

Figure 3: A fault trace (A-B), intersected fault traces (dotted lines) and the relationship with nodes I, Y and X and associated branches. Taken from Nixon & Sanderson (2015)

Once the trace maps have been created, the topology of the networks can be analysed. Each node can be represented by a point, with different colours to visually represent the node types. Once the number and proportion of node types are established, these numbers could be used to identify the number of lines and branches, therefore the number of connections per branch using these equations (Sanderson, 2015): I and Y nodes represent the tip of a line, the number of lines (NL) is given by:

$NL=1/2(NI+NY)$ *(eq1)*

A branch will have two nodes, an I-node contributing to one branch, a Y-node to 3 branches and an X-node to 4 branches. The number of branches (NB) is indicated by:

$NB=1/2(NI+3NY+4NX)$ *(eq2)*

The ratio of branches to lines will be:

$NB/NL=(NI+3NY+4NX)/(NI+NY)$ *(eq3)*

Branch classifications stem into three topological groups, I-I (isolated), I-C (partially connected) and C-C (fully connected). This is used to plot onto a ternary branch diagram for the proportion of branch types, i.e. if the data plots towards the C-C corner of the diagram it has a high proportion of connected branches, therefore a higher connectivity.

To establish the number of connections (CB) per branch:

$CB=(3NY+4NX)/NB$ *(eq4)-*

This will give a value of between 0-2 and is a good indication of connectivity.

The proportion of any branch being isolated (PI) or connected (PC) is given by:

$PI= NI/(NI+3NY+4NX)$ *(eq5)*

$PC = (3NY +4NX)/(NI+3NY+4NX)$ *(eq6)*

Therefore, the probability of each branch type (PII, PIC, PCC) is:

$PII = PI^2$ *(eq7)*

$PIC = PI *PC$ *(eq8)*

$PCC = PC^2$ *(eq9)*

2.2 Fracture Intensity

For an estimation of fracture intensity within the circle scanlines, the number of intersecting fractures were recorded, and using this equation from Watkins et al., 2018:

$I= n/(4r)$ *(eq10)*

where I is the estimated fracture intensity (m/m2), n the number of fracture intersections with the circle, and r is the circle radius (m). Estimated fracture intensity, in this case, is given as fracture length per unit area in 2D.

3. RESULTS

This section will focus on the description and analysis of the collected fracture maps using the topological methods discussed in the previous section. As mentioned, localities for data collection were chosen based on a number of factors but most importantly, the structural situation and position in the generalized fold and thrust structure, which are explained in Fig.4 and their locations shown on Fig.1.

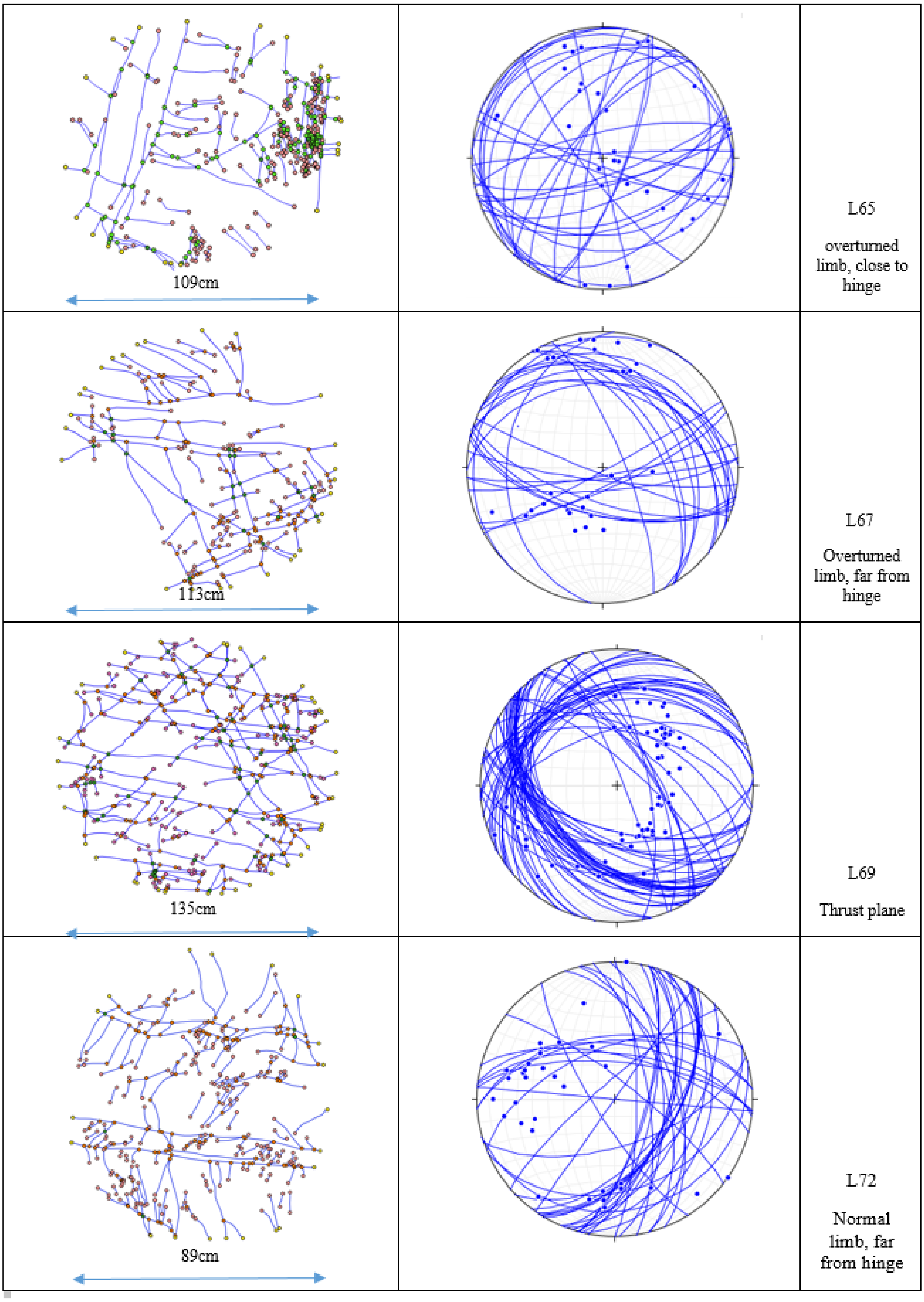

Figure 4: Fracture trace maps and stereonet projections from each sample location. I node – pink, Y node – orange, X node – green, intersection with circle - yellow

After the creation of the fault trace maps, the number and type of fracture intersections were collected in table 1 and the percentage of each node type calculated. The percentages of node type vary heavily throughout the different sample locations. For example, the highest percentage of X nodes can be found at L69 with almost 19% of the fracture intersections counted, as X nodes, but only 1.48% in L72, with a range of 14.52%. The percentage of Y nodes ranges from 35.91% to 45.40%, with a 9.49% range, and the I nodes range from 35.65% to 62.61%, giving a range of 26.96%, indicating a higher change in the number of I nodes in comparison to Y and X nodes across the sample locations. By plotting the percentages of each node type into a triangular plot, the dominance of nodes can be established by the placement of each point as seen in Fig.4. All locations are considered "Y node" dominated systems but L69 is the outlier with the highest percentage of X nodes by 8.1% and the lowest percentage of I nodes by 15.9%, and L72 being the outlier for the highest percentage of I nodes by 4.4%, and lowest percentage of Y nodes (by 1.7%) and X nodes (by 0.6%). The distribution across the sample locations is shown in Fig.5.

Table 1: Table of number and percentage of node types for each sample location.

	I	Y	X	TOTAL	I %	Y%	X%
L65	198	135	7	340	58.2	39.7	2.1
L67	110	80	23	213	51.6	37.6	10.8
L69	128	163	68	359	35.7	45.4	18.9
L72	211	121	5	337	62.6	35.9	1.5

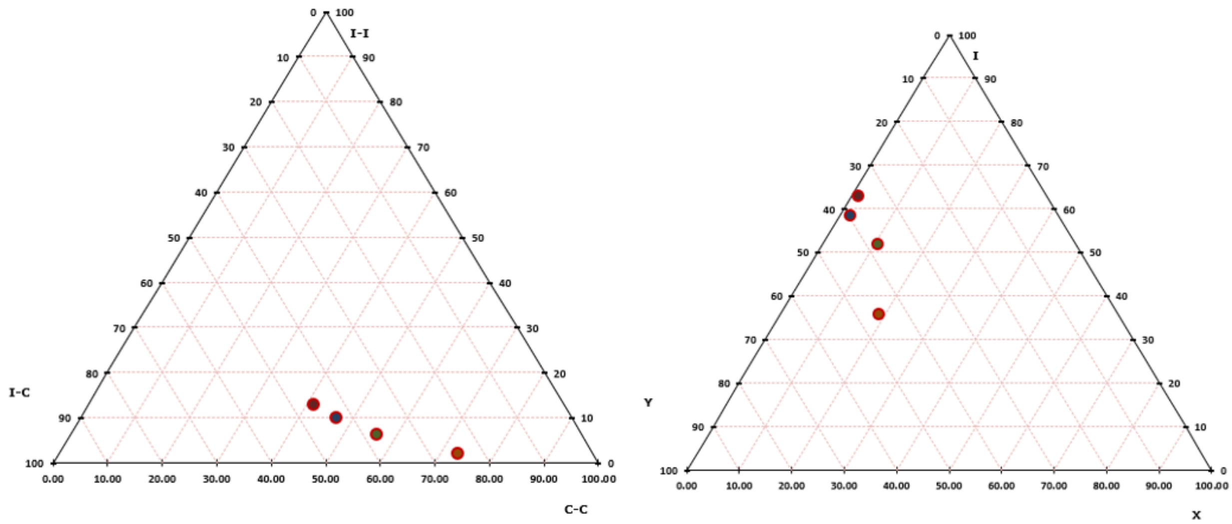

Figure 5: Triangular plots of topological data. Left; plot of branch type probability. Right; plot of percentage of node types. Blue - L65, Green -L67, Orange - L69, Red - L72

To further analyze the fracture interactions, these numbers were put into equations that give a value for the level of connectivity in a sample area (given as CB, connections per branch) shown in table.2. These CB values as expected range heavily, from 1.29 in L72 to 1.71 in L69, meaning the most connected system is L69 and the least, L72. This gives an overall connectivity value but does not take into account the level of connectivity for individual branches, therefore by calculating the probability of a branch being isolated, partially connected, or completely connected, gives another level of characterization to the fracture network. The probability of a completely isolated branch (PII) ranges from 0.021 – 0.126, a wide range of results, but not as large as the range of the probability of a completely connected branch (PCC: 0.414 – 0.733). All locations show that there is a higher probability of a branch being completely connected than partially connected or isolated, but the highest probability of a branch being completely connected is highest by far at L69 and lowest probability in L72 followed closely by L65. This is visually represented in Fig.5 showing the distribution of the probability of different branch types in the sample locations.

Table 2: Table of branch analysis. NL - number of lines, NB - number of branches, CB - connections per branch, PI - probability of isolated node, PC - probability of connected node, PII - probability of isolated branch, PIC - probability of partially connected branch, PCC – probability of fully connected branch.

	NL	NB	CB	PI	PC	PII	PIC	PCC
L65	166.5	315.5	1.372	0.314	0.686	0.098	0.215	0.479
L67	95	221	1.502	0.249	0.751	0.062	0.187	0.564
L69	145.5	444.5	1.712	0.144	0.856	0.021	0.123	0.733
L72	166	297	1.290	0.355	0.645	0.126	0.229	0.414

Another parameter that can be analysed using this data collection method is estimated fracture intensity seen in table.3. In this case it is given as fracture length per unit area in 2D. The range of values is from 5.973 m/m^2 (L67) the lowest level of intensity -11.481 m/m^2 the highest level of intensity (L69), almost doubling of values. Although intensity can be correlated with connectivity in the case of L69 (11.481 m/m^2 estimated intensity and a connectivity value of 1.712 CB both the highest values over the sample locations), it is important to note that although the level of intensity may be high in a sample area, this does not indicate a well connected system. As can be seen with L72, with a relatively high intensity value of 10.393 m/m^2, but as seen from table.2 a low connectivity value of 1.290 CB.

Table 3: Table of estimated fracture intensity measurements at each location given as fracture length per unit area in 2D.

Location	Circle diameter/m	N. Fractures	Intensity/ m/m^2
L65	1.09	30	6.881
L67	1.13	27	5.973
L69	1.35	62	11.481
L72	0.89	37	10.393

4. DISCUSSION

This section will focus on the interpretation of the data above and discuss how these known parameters change across the generalized Variscan fold and thrust structure found in the CCFZ, what this means in terms of geothermal exploration and how this will be the basis for future work in the characterization of the metasedimentary Variscan reservoir beneath Göttingen.

As previously discussed, the sample locations were purposefully chosen to represent different structural situations throughout the generalized fold and thrust structure to compare the levels of connectivity and intensity of fractures and evaluate their dependency on structural situations. As can be seen from the data there is a clear difference in connectivity and intensity values throughout the sample locations (Table.4).

4.1 Fracture Intensity

Heterogeneity of deformation is expected in a fold and thrust belt. As the majority of the strain is taken up in the hinge of an anticline and in the thrust plane, an increase in fracture intensity towards the fold hinge and thrust fault is anticipated (Watkins, 2018). This is mostly evident from the results shown in the previous section, with the highest level of estimated fracture intensity being highest at the sample location located on a thrust plane (L69) and lowest located far from the hinge zone (L67). The anomaly in this case is L72, with a high intensity but located far from the hinge zone in the normal limb. This is unexpected but can be explained due to the heterogeneity of the lithology. At this location there is evidence for flexural slip of the greywacke beds due to the presence of thin mud/silt stone layers. This has caused the formation of many small fractures oblique to the bedding plane and has can be seen from the tracemaps in fig.4.

Table 4 : Table comparing the intensity and connectivity values to the structural situation of the sample location

Structural situation	Location	intensity m/m^2	connectivity/CB
Overturned limb close to hinge	L65	6.881	1.372
Overturned limb further from hinge	L67	5.973	1.502
Thrust plane	L69	11.481	1.712
Normal limb far from hinge	L72	10.393	1.289

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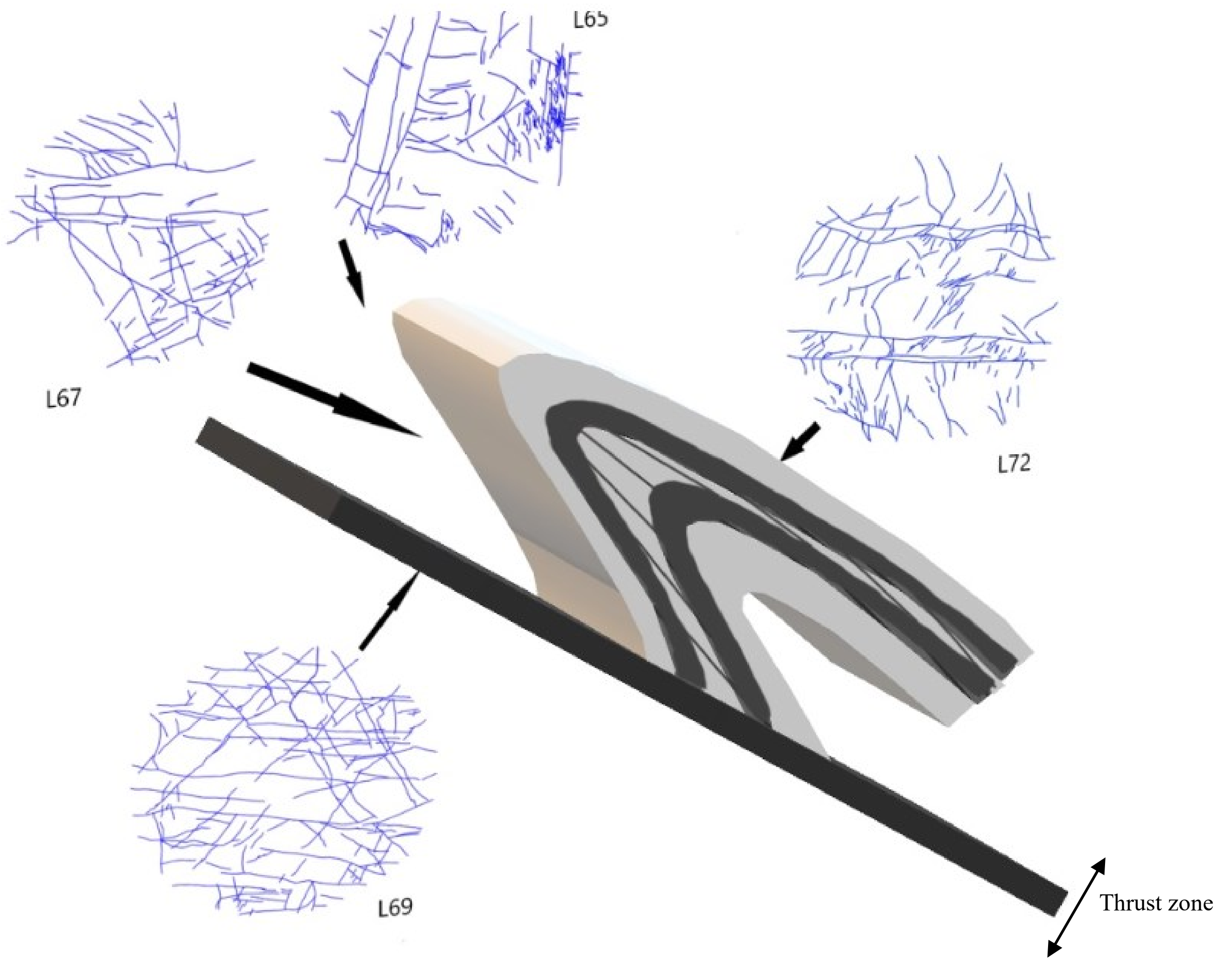

Figure 6: Conceptual 3D diagram of fold and thrust structure with bedding and cleavage planes exhibited in the CCFZ and the retrospective position of the sample locations along this structure. dark grey bands – greywacke, light grey bands – slates. Not to scale.

In this study, all planes with perceived movement along them or that were considered "open" were taken as "fractures" as these planes can be exploited through EGS so should be included in studies that mean to characterise EGS reservoirs, therefore some cleavage planes and bedding planes have also been included in this study. At L72, this may also explain the higher levels of fracture intensity.

4.2 Fracture Connectivity

Connectivity is a very important parameter to define in terms of facture network characteristics for reservoir analysis, as has been shown in the previous section, fracture intensity can be high but this does not necessarily indicate a well-connected system. Connectivity in this study is defined by the number of connections (Y or X nodes) per branch (0-2) and can be further analyzed by defining the probability of types of branch connections. As seen in Fig.5 there is a correlation between increased fracture connectivity and how close the sample area is to the hinge zone, however the anomaly in this is L67, which is relatively further from the hinge zone, with a higher level of connectivity than the sample location next to the hinge zone L65. In this case, L65 had strong mineralization within the cleavage planes, it was clear that these planes are somewhat connected due to this, but in 2D it was not possible to define these planes as connected, this may have caused the lower connectivity value using this methodology. L69 has the highest connectivity value of 1.712, with L72 having the lowest at 1.289, again showing the general trend of increased connectivity towards the hinge and thrust zones seen in table.4 and visually represented in fig.5.

Connectivity may be an indication of an increase in number of deformation events, as connectivity is controlled by oblique fractures intersecting each other through either a cross cutting or abutting relationship, but more analysis should be done on the relative ages of the fracture sets, this is discussed further in the following section.

4.3 Geothermal Relevance

As previously mentioned, the main output of this research is the 3D conceptual structural model of the complex fold and thrust system located in the Western Harz Mountains. To achieve this, a detailed understanding of the complexity of the deformation styles using data collected from varying scales; reservoir scale (km), outcrop scale (m) and microscale (cm or less) is necessary. In a reservoir, the fracture network acts as a form of natural permeability that can be enhanced through EGS, therefore before stimulation takes place, the system must be characterized for a clearer understanding of the outcomes of stimulation.

An interesting characteristic to note is the natural anisotropy of the reservoir rocks, namely the bedding planes and cleavage. Due to the competence comparison between the main lithologies, they deform in very different ways, and the slate layers often seem to act in a more "ductile" manor than greywackes, allowing slipping between bedding planes, as there is movement exhibited along the bedding and cleavage planes, they were also included in this study as this is evidence for reactivation through stimulation.

The main outcome of this study is to understand the changes in fracture intensity and connectivity in comparison to the generalized fold and thrust structure. As discussed, there appears to be a correlation with an increase in both these factors towards the fold hinge and thrust plane, which of course is due to the majority of the stress being accommodated in these areas. In terms of the relevance to the geothermal reservoir model, this gives a good indication that these zones may be a good target for enhancement through stimulation for increased fracture permeability. Of course, this data is not conclusive yet and more analysis must be done into other parameters that affect the permeability of the fracture system, but it is a good starting point for further research.

5. FUTURE STUDIES

This section will focus on the planned future work for further characterization of the Variscan metasedimentary reservoir, from lithological to structural characterization and how these parameters will be defined and compared for the creation of the 3D structural model.

5.1 Structural characteristics

5.1.1 General Structural Overview

To further understand the fold and thrust structures exhibited in the CCFZ, a 3D model of the entire area must be created. This will be done by digitizing literature and field data. The main aim of this will be to understand how the main geometries of the fold and thrust structures change towards the foreland, if there is a dramatic change. This will allow for further characterization of structural situations within the CCFZ for analysis.

5.1.2 Further Characterisation of Structural Situations

For a more detailed understanding of the changes exhibited within the CCFZ in regard to structures, more structural situations must be recognized. For example, the circular scanline method realized by Mauldon et al, 2001, could be done at defined intervals where possible (e.g. sample circles at 2m spacing along a fold structure). Due to the outcrop situation in the Harz mountains this may only be possible at a few locations, however this could be attempted at a larger scale with sample circles taken at every possible outcrop, for comparison.

5.1.3 Fracture Network Parameters

Although this study only focuses on two main parameters, there are many more to be defined using this method. So the next steps will be to analysis the changes in orientation of the fractures, length, density, spacing and level of mineralization. From understanding these parameters, a clearer picture of the characteristics of different fracture sets can be realized, and their changes across the fold and structures understood.

5.1.4 Topological Characteristics

By defining the topological characteristics and geometrical relationships of fractures in a network, one can get a good indication of relative ages of fracture sets (Peacock, 2018). The main relationships are as follows:

Isolated – Identified by an I node, this is where fractures are not physically connected to one another, these fractures have tips within the rock matrix.

Approaching – these are isolated fractures that are close enough to be kinematically related but do not physically touch therefore are not geometrically linked, for example stepping normal faults (Kim, 2004).

Abutting – Where a set of fractures link to form a Y node. These fractures may have formed during the same event, or during separate events depending on further analysis of the interaction. It is common that if one open-mode fracture cross cuts an earlier fracture, it will intersect at a high angle (60°-90°) and is then stopped by the older fracture (Peacock, 2018). In another case, splaying and branching forms Y node interactions, but are an indication of the fractures forming under the same event, they are typically characterized by a low angle interaction (30°) (Peacock, 2018).

Cross cutting – Where a later fracture cross-cuts another to form an X node, or if two sets mutually cross-cut it could be that they developed at the same time (conjugate sets) (Nicol, 1995).

By defining these relationships and comparing them with orientation, a clear indication of relative ages of fracture sets can be defined within each structural situation.

5.2 Lithological Characteristics

The complexity of this reservoir in part is due to the heterogeneity of the lithology. As mentioned, Lower Carboniferous flysch deposits dominate the CCFZ, alternating sequences of fine-coarse grained greywackes and mud/silt stones that have been partially metamorphosed. This heterogeneity causes very complex deformation as the lithologies deform in different ways, the most obvious difference being the formation of cleavage planes within the mud/silt deposits and more dominant jointing in the greywackes due to the competence difference. It is possible that the dominance of a certain lithology may also impact the style of deformation; therefore, the lithological groupings must be characterized and compared to the defined structural situations for further characterization. Three main lithological packages have been identified, greywacke dominant, slate dominant and roughly 50/50. The next steps are to find locations that represent these lithological packages in all defined structural situations, this will give a clearer understanding into the impact lithology has on the fracture network and fold and thrust geometry.

5.3 Mineralogical Characteristics

Another important factor in characterizing a reservoir is to understand the mineralization of the fractures; the type and the level of mineralization can give a good indication into the 3D connectivity of the fracture system and can help characterize fracture sets in terms of relative ages. The next step will be to characterize the level of mineralization of the fractures within the sample locations and identify relationships with other fracture network characteristics, this can help give a clearer indication into relative ages, 3D connectivity and changes in mineralization across the fold and thrust structure. Ongoing fluid inclusion studies will help to identify fluid compositions and quantify temperature and pressure conditions during formation and might help to distinguish the different pre-, syn- and post-Variscan vein generations.

6. CONCLUSIONS

The Variscan Fold-and-Thrust belt represents an extremely complex structural system but offers at the same time a large variety of different predefined planar systems in favour for developing a reservoir. This study represents a first approach to defining the parameters for a conceptual structural model, with lab measurements of the rock physical parameters currently underway. These first results demonstrate that a simple approach as expecting a higher fracture intensity and connectivity in the higher strained fold hinges and thrust planes isn't as clear as originally thought, through field observations. It is clear that a much more detailed characterisation of the complex deformation and potential fracture system exhibited in these systems must be undertaken before a target zone for EGS can be defined. This work will then finally feed into the workflow for the creation of the reservoir model.

7. ACKNOWLEDGEMENTS

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