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The importance of tectonic inheritance and reactivation in geothermal energy exploration for EGS resources in SW England

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ABSTRACT

Exploration for Enhanced Geothermal System (EGS) resources has long sought natural deep fractured reservoirs. The Upper Rhine Graben is the most studied area for these targets including the successful geothermal plants at Soultz-sous-Forêts, Bruchsal, Insheim, Landau and Rittershoffen (Genter et al., 2010; Vidal et al., 2017). Previous geothermal projects, such as the Hot Dry Rock project at Rosemanowes (1977-1991) in Cornwall (SW England), targeted areas that lacked major faults and fractures (Barker et al., 2000). The Upper Rhine Graben was incepted during Eocene-Oligocene rifting in a NNE-SSW orientation that underwent Miocene sinistral reactivation (Schumacher, 2002). However, structural inheritance from dextrally reactivated Variscan ENE-WSW faults during the Miocene may also contribute to the reservoir (Bertrand et al., 2017).

Geothermal energy exploration is currently experiencing a revival in SW England, targeting EGS resources within deep granite-hosted fault zones. Two deep wells have been drilled at the United Downs Deep Geothermal Power Project to depths of approximately 5.0 and 2.5 km near Redruth and Eden-EGS Energy have advanced plans for deep geothermal wells near St Austell.

The geology of SW England comprises several E-W-trending Devonian-Carboniferous sedimentary basins that were deformed during the Variscan orogeny (Carboniferous) and intruded by the Cornubian Batholith (Early Permian). The region is characterized by a complex fault network including major NW-SE fault zones (first-order) that have traces lengths >10 km and usually comprise multiple faults across a broad zone of deformation. These are prospective EGS targets due to their inferred down-dip persistence, Cenozoic reactivation (Holloway & Chadwick, 1986; Cooper et al., 2012; Anderson et al., 2018), near parallelism with contemporary σ_H (Batchelor & Pine, 1986) and are known for low magnitude (<M4) seismicity persisting to the present day. Second-order faults, defined based on trace length rather than their kinematic relationships, typically have trace lengths <10 km and exhibit a range of orientations, may be an important consideration for EGS resources in the region.

The Cornubian Batholith has the highest measured heat flow in the United Kingdom and most prospective for EGS resources (Busby & Terrington, 2017). Based on airborne radiometric data, the granites are high heat-producing with 13.3% of the granite outcrop (1239 km^2) showing values >6 μW^{-3} (Beamish & Busby, 2016). Granite emplacement post-dates the inception of both first- and second-order faults within the host rocks, but the granites demonstrate inheritance of both fault sets. Intra-granite structures indicate episodic fault reactivation from the Permian through to the Cenozoic (Holloway & Chadwick, 1986; Shail & Alexander, 1997). Furthermore, a persistent hydrothermal mineralization record in the region demonstrates that both first- and second-order faults have previously been episodically open for fluid flow and geothermal activity.

Herein, the fault network is assessed across different plutons to demonstrate the ubiquity of first-order NW-SE faults and investigate the interaction of second-order faults. By analyzing data from Yeomans et al. (2019), different age plutons are shown to have variable lineament populations. Whilst initial research regarding tectonic inheritance requires further work, the available data appear to indicate an evolving stress regime in the Early Permian. We also present a proposed workflow for generating new EGS targets as part of a staged modelling process. A key aspect of this process is the incorporation of data from regional and outcrop scale modelling to determine if the regional structural framework is representative of the target reservoir. This will allow modelling to be adapted from regional to local scales to best identify and subsequently refine geothermal energy targets.

1. INTRODUCTION

Exploration for Enhanced Geothermal Systems (EGS) resources has long sought natural deep fractured reservoirs. The most studied area for these targets is the Upper Rhine Graben which includes the successful geothermal plants at Soultz-sous-Forêts, Bruchsal, Insheim, Landau and Rittershoffen (Genter et al., 2010; Vidal et al., 2017). Conversely, previous geothermal projects, such as the Hot-Dry Rock project at Rosemanowes (1977-1991) in Cornwall (SW England), had targeted areas that lacked major faults and fractures (Barker et al., 2000). The Upper Rhine Graben area is a NNE-SSW trending Eocene-Oligocene rift that underwent Miocene sinistral reactivation (Schumacher, 2002). However, there is also a component of structural inheritance from Variscan ENE-WSW faults with a dextral sense of movement (Bertrand et al., 2017).

SW England is in a period of renewed geothermal energy exploration, targeting EGS resources within deep granite-hosted fault zones. The United Downs Deep Geothermal Power Project has drilled two wells to depths of approximately 5.0 and 2.5 km near Redruth and Eden-EGS Energy have advanced plans for deep geothermal wells near St Austell. These geothermal resources are key to renewable energy targets set out by the UK Government and are backed locally by the Cornwall Council who list renewable energy as one of “10 opportunities” for growing the local economy (Cornwall and Isles of Scilly Local Enterprise Partnership, 2018)

Targeting fault-controlled geothermal reservoirs requires a strong understanding of the structural geology of the region. The structural framework in SW England is complex with multiple reactivation episodes and it is essential that a greater understanding of the fault network is achieved to better explore for, and de-risk, future geothermal energy projects. The GWatt Project, a £1.8m research project funded by the UK Natural Environment Research Council, aims to address these and other issues related to the development of deep geothermal energy in SW England (Rochelle et al. 2020; Ledingham et al. 2020). In this paper, we outline our proposed approach for geothermal energy exploration in SW England, which will use multi-scale analyses to better understand the fault network and kinematic relationships of different reactivation episodes. These ultimately contribute towards generating a robust prospectivity model at both regional and local scales for targeting future geothermal resources.

1.1 SW England geology

The Upper Palaeozoic geology of SW England (Figure 1) correlates with the Rhenohercynian Zone of Central Europe (Holder & Leveridge 1986). It comprises several E-W-trending Devonian-Carboniferous sedimentary basins that we deformed during Variscan continental collision and were subsequently intruded by the post-orogenic Early Permian Cornubian Batholith (Shail and Leveridge, 2009; Simons et al., 2016). It has a complex fault network that has recently been regionally mapped in a study utilizing airborne geophysics (Yeomans et al., 2019). Major NW-SE structures (first-order faults) usually have trace lengths >10 km and comprise multiple faults across a broad zone of deformation (Dearman 1963; Holloway & Chadwick, 1986; Nixon et al., 2012). These are prospective EGS targets due to their inferred down-dip persistence, Cenozoic reactivation (Holloway & Chadwick, 1986; Cooper et al., 2012; Anderson et al., 2018), near parallelism with contemporary σ_H (Batchelor & Pine, 1986), and are known for low magnitude (<M4) seismicity persisting to the present day. Second-order faults, defined based on trace length rather than their kinematic relationships, typically have trace lengths <10 km and exhibit a range of orientations, may be an important consideration for EGS resources in the region. The second-order faults in the Gramscatho Basin, in the south of the region, typically strike ENE-WSW, whilst those in all the basins farther north strike E-W; a similar structural framework is revealed in offshore data (Shackleton, 1984; Hillis & Chapman, 1992; Alexander et al., 2018)

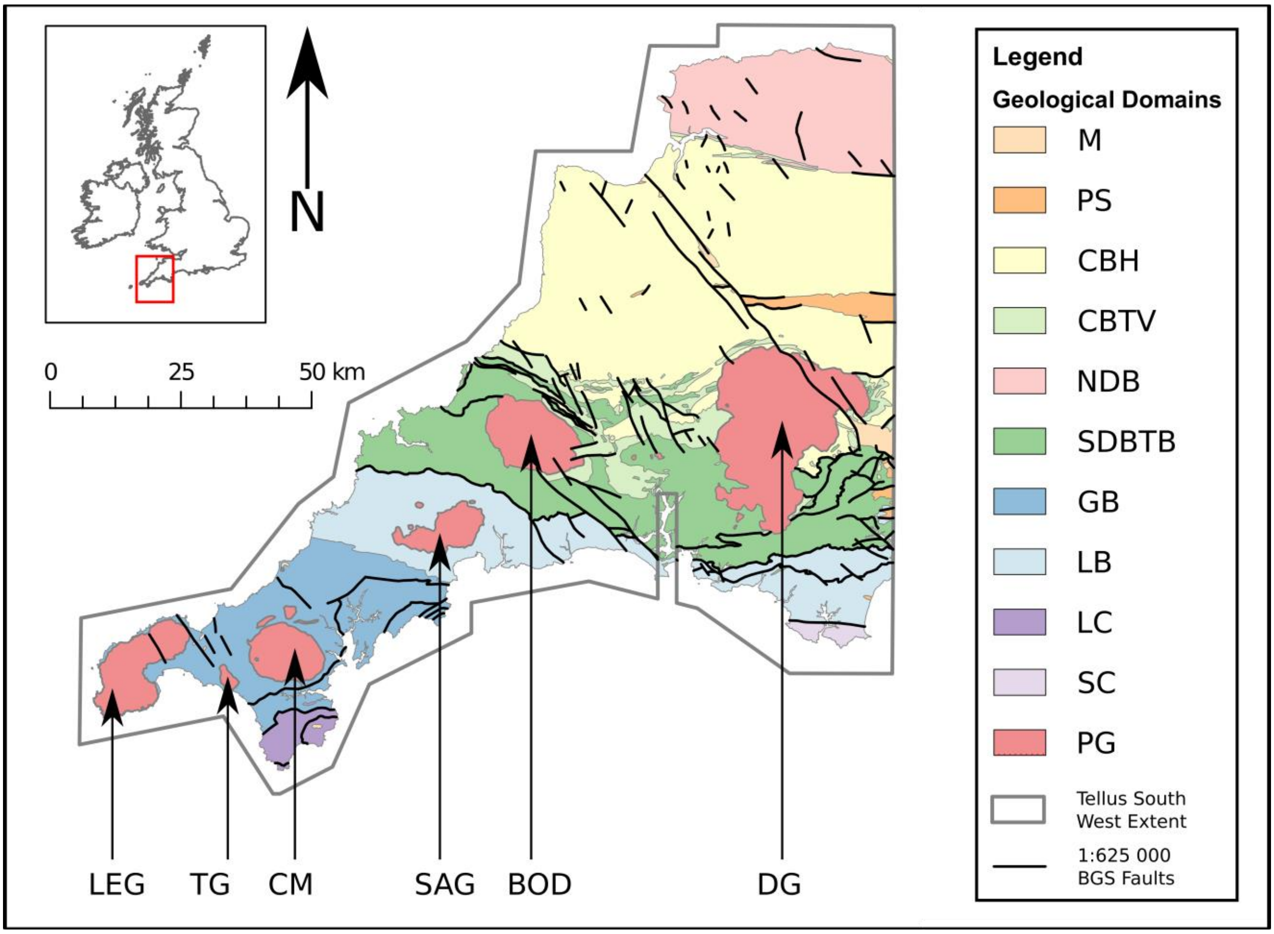

Figure 1 Regional geology of SW England showing the Devonian-Carboniferous basins (GB – Gramscatho Basin, LB – Looe Basin, SDBTB – South Devon Basina and Tavy Basin, CBTV – Culm Basin Teign Valley Group, CBH – Culm Basin Holsworthy Group, NDB – North Devon Basin); Permian Granites (PG); Permian Sandstones (PS); Mesozoic & Younger (M); Lizard Complex (LC) and Start Complex (SC). The Permian Granite plutons include the Land's End Granite (LEG), Tregonning-Godolphin Granite (TG), Carnmenellis Granite (CG), St Austell Granite (SAG), Bodmin Granite (BOD) and Dartmoor Granite (DG). Overlay linework shows the 1:625 000 faults from the British Geological Survey and the grey outline of the Tellus South West airborne geophysical survey.

The Cornubian Batholith has the highest measured heat flow in the United Kingdom and most prospective for EGS resources (Busby & Terrington, 2017). Based on airborne radiometric data, the granites are high heat-producing with 13.3% of the granite outcrop (1239 km^2) showing values >6 μW^{-3} (Beamish & Busby, 2016). The granites post-date the inception of both first- and second-order faults in the region but demonstrate structural inheritance of both fault sets. Intra-granite structures indicate episodic fault reactivation from the Permian through to the Cenozoic (Holloway & Chadwick, 1986; Shail & Alexander, 1997). Furthermore, a persistent hydrothermal mineralization record in the region demonstrates that both first- and second-order faults have previously been open for fluid flow and geothermal activity.

The principal regional structural events during the formation and reactivation of NNW-SSE fault zones in SW England are:

1) Initial development in Devonian-Carboniferous successions, and the underlying pre-rift basement, as NNW-SSE transfer faults during Variscan collision and thrust-faulting (Shail & Alexander, 1997); continued development during strike-slip dominated deformation at the end of the collisional history (late Carboniferous).

2) Formation / reactivation as strike-slip transfer faults in Devonian-Carboniferous successions and underlying basement during latest-Carboniferous – Early Permian extension; partially influence granite magma transport from lower / middle crust and emplacement as thick (*c.* >7 km) composite laccolith in upper crust. Continued movement during batholith construction propagates NNW-SSE fault zones into partially / wholly crystallised granites; collectively, these and their continuation in the host rocks segment and/or act as transfers to the ENE-WSW to E-W trending extensional faults controlling emplacement of rhyolite-microgranite sheets and granite-related magmatic-hydrothermal W-Sn-Cu-Zn-Pb mineralisation (Shail & Alexander, 1997).

3) Variable minor reactivation during Mid-Permian strike-slip episodes that may be accompanied by the latter stages of magmatic-hydrothermal mineralisation (Shail & Alexander, 1997).

4) Reactivation and development of new faults during late Permian–Triassic rifting (ENE-WSW stretch). Major Mid-Late Triassic regional fluid flow, involving migration of brines from Permo-Triassic 'red-bed' successions, primarily along NW-SE to N-S striking faults, resulting in local 'cross-course' base metal mineralisation (Scrivener et al., 1994; Shail & Alexander, 1997)

5) Jurassic-Early Cretaceous regional inversion driven by rifting; granites exhumed by >1.5 km. Migration of basinal fluids, including hydrocarbons, into granites and surrounding host rocks (Psyrillos et al., 2003; Baba et al., 2018)

6) Variable, but poorly constrained, Cenozoic strike-slip reactivation. Evidence strongest in the Sticklepath-Lustleigh Fault Zone where strike-slip movements accompanied Palaeocene magmatism and later mid-Cenozoic accumulation of sedimentary kaolins in strike-slip pull-apart basins (Holloway & Chadwick, 1986)

7) Re-activation in contemporary in-situ stress regime to give earthquakes <M4 (Musson, 2000).

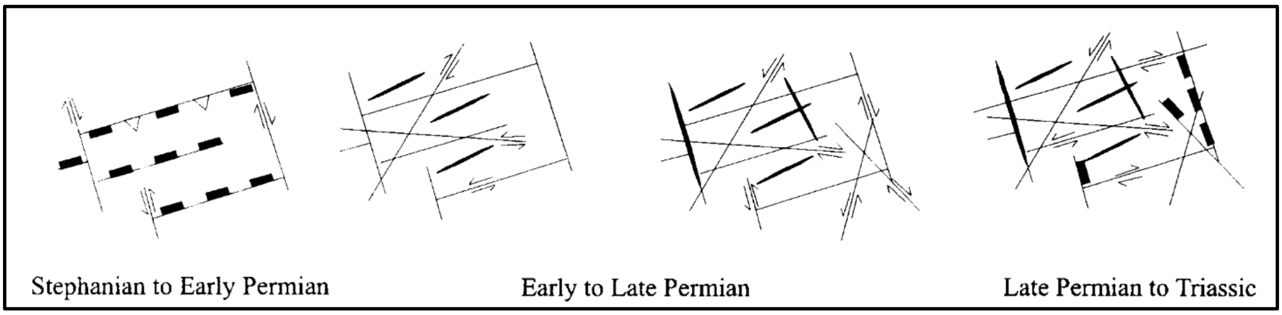

Figure 2 Tectonic evolution of SW England showing the beginning of extensional reactivation of Variscan thrusts in the Stephanian to Early Permian through strike-slip overprinting in the Early to Late Permian and subsequent ENE-WSW extension during the Late Permian to Triassic (Shail & Alexander, 1997)

2. LINEAMENT DETECTION AND ANALYSIS

Structural mapping in SW England is hampered by poor inland exposure. Coastal outcrops often provide excellent opportunities but often the orientation of the coastline will influence mapping as features parallel to the coast may be under-sampled or entirely unseen. These limitations have significantly influenced the mapping of structures across the different map districts in SW England. Furthermore, more detailed structural data exists for recently surveyed districts compared to those surveyed in the late 1800s and early 1900s leading to a disparity in the 1:50 000 mapping and in digital data products.

Given the limitations of field mapping, modern remote sensing techniques such as Landsat and aerial photography allowed a new means of mapping regional structures. Early work by Moore & Jackson (1982) made use of imagery from Landsat 3 using the MSS instrument (79 m pixel resolution). Regional lineaments were interpreted manually at an approximate regional scale of 1:500 000 and, despite problems relating to image processing, a number of significant features were identified (Figure 3A). Further follow-up work was conducted using multi-seasonal imagery and combined Synthetic Aperture Radar imagery with Landsat MSS data concluding that winter scenes provide more detail due to the low sun angle and suppress noise from agricultural land-use (James & Moore, 1985).

The Landsat TM sensor introduced with the launch of Landsat 4 increased the pixel resolution to 30 m. This allowed a significant increase in mapping resolution to 1:250 000 and was exploited by Smithurst (1990) to map regional lineaments across SW England (Figure 3B). A more detailed study by Rogers (1997) followed using Landsat 5 data which manually mapped lineaments from processed data using a variety of resolutions and directional filters (Figure 3C). It was found that the higher resolution data (40 m pixels) resulted in significant anthropogenic artefacts and the data was coarsened to smooth out these features resulting in a pixel resolution of 150 m (Rogers, 1997).

Remote mapping of structure has also been conducted using geophysical data and an elevation model in the Tiverton area where Pennsylvanian turbidites were mapped from variations in a local gravity survey and the off-sets between interpreted lithologies were used to infer faults (Leslie et al., 2007). The technique was effective but has not been applied extensively, resulting in areas that are structurally over-interpreted compared to adjacent areas.

Further remote mapping of geological structure was conducted by Nixon et al. (2011) using aerial photography of a small section of wave-cut platform at Westward Ho!, NW Devon. The study focused on the strike-slip fault network exhibited on the platform and was complemented by later work off-shore using multi-beam bathymetry (Nixon et al., 2012)

Most recently, regional lineament mapping has been conducted using Object-Based Image Analysis methods on airborne geophysical data (Yeomans et al., 2019). This study took an integrated approach to lineament detection and combined airborne magnetic, radiometric and LiDAR data in a single analysis to create a comprehensive and composite lineament network based on geophysical, geological and geomorphological properties (Figure 4).

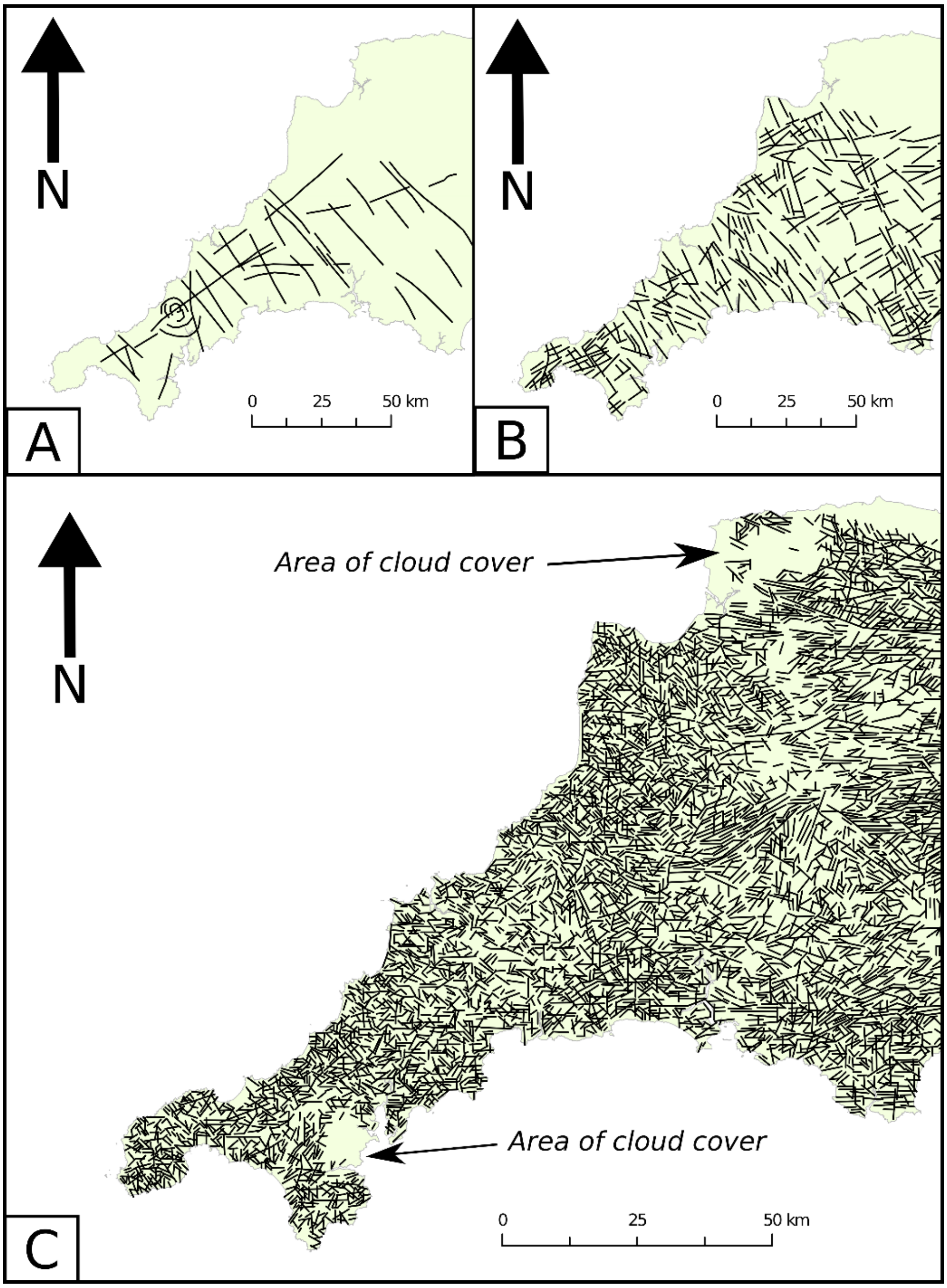

Figure 3 Previous lineament studies making use of early Landsat data. (A) shows lineaments derived by Moore & Jackson (1982) for mineral exploratio purposes. (B) shows linemaents from Smithurst (1990) using Landsat 5 data at 1:250 000 scale. (C) shows the comprehensive study by Rogers (1997) using Landsat 5 data at a similar scale to Smithurst (1990) but with greater data density.

2.1 Regional lineament analysis for geothermal potential

At the regional scale, the lineament map produced by Yeomans et al. (2019) shows a broad picture of the structural geology of SW England. Figure 4 illustrates the different orientation populations of structures across the region with some clearly defined changes between different geological domains.

The faults displayed largely mimic the main orientations described by Shail & Alexander (1997). Of these, there are an abundance of NW-SE faults that are EGS targets. These NW-SE structures are designated as 'first-order' faults in terms of their average strike trace length of >10 km which, in some cases, can relay into other faults to define zones >100 km (Cooper et al., 2012; Anderson et al., 2018). The remainder are considered 'second-order' faults based on their shorter trace length and are often markedly oblique, or orthogonal, to the contemporary σ_H.

Whilst the consistent mapping of regional geological structures has been vastly improved through recent semi-automated lineament detection, dip-direction, dip and kinematics are often poorly constrained, especially for first-order faults. What can be inferred is that these structures are likely to have had episodic extensional and both dextral and sinistral strike-slip movement (Holloway & Chadwick, 1986; Shail & Alexander, 1997).

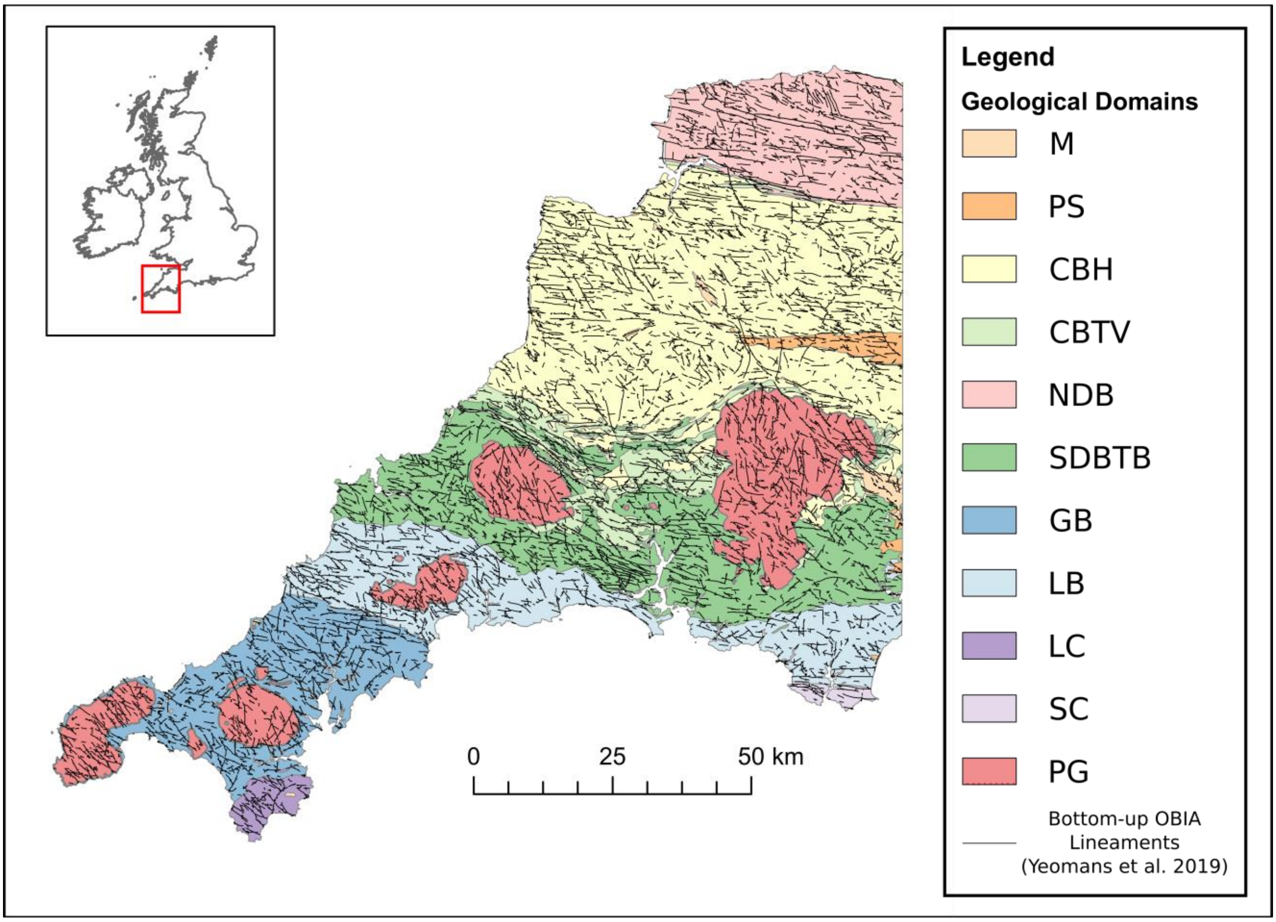

Figure 4 Regional geology with lineament data from Yeomans et al. (2019) overlain. These data form the basis for further analysis of lineaments at the pluton scale. Devonian-Carboniferous basins (GB – Gramscatho Basin, LB – Looe Basin, SDBTB – South Devon Basina and Tavy Basin, CBTV – Culm Basin Teign Valley Group, CBH – Culm Basin Holsworthy Group, NDB – North Devon Basin); Permian Granites (PG); Permian Sandstones (PS); Mesozoic & Younger (M); Lizard Complex (LC) and Start Complex (SC).

3. GRANITE-HOSTED FRACTURE NETWORKS IN SW ENGLAND

Accessible outcrop occurs in coastal areas, hilltops, quarries and underground exposures. Of these, coastal exposures are perhaps the best suited to characterize fault zones at outcrop scale. Regional geophysics provides further constraint and lineament mapping conducted by Yeomans et al. (2019) is considered an essential tool for assessing the fracture network at a regional scale. By combining regional and outcrop scales, it is anticipated that a comprehensive understanding of the fracture network can be compiled for fault-hosted geothermal reservoir targets. However, the other problematic aspect of modelling the fracture network in SW England is projecting surface observations to depth. In this section, all three aspects of this modelling process are briefly discussed.

3.1 Regional scale

By isolating lineaments that cut the major granite plutons, the orientations of these can be reassessed to determine different sub-populations. A subset of the lineaments generated by Yeomans et al. (2019) has been created for each pluton and presented as rose diagrams in Figure 5. All plutons show a dominant NW-SE trend; however, there is considerable variation between different plutons with the Carnmenellis (CM) and Bodmin (BOD) granites showing lineaments oriented in almost all orientations compared to the

Land's End (LEG) pluton. The St Austell (SAG), Tregonning-Godolphin (TG) and Dartmoor (DG) plutons show a range of orientations but the ENE- to NE-trending lineaments are less prevalent.

The LEG, TG and CM plutons are hosted by the Gramscatho Basin which represents elements of the Devonian distal passive margin incorporated into the Variscan orogenic wedge (Shail & Leveridge, 2009). It preserves a slightly different structural history and inheritance relative to the Looe, Tavy and Culm basins that formed farther north as part of the Devonian-Carboniferous proximal passive margin. The CM and BOD plutons exhibit similar lineament populations despite being hosted, respectively, by the Gramscatho and Tavy-Culm basins with differing host rock lineament populations. The Cornubian Batholith was emplaced over a *c.* 20 Ma period (Chen et al., 1993; Chesley et al., 1993) and the temporal link between pluton age and lineament population characteristics may reflect evolving stress regimes during batholith construction; three age/lineament population groups can be identified:

1) Earliest group, c. 292 Ma, comprising the CM and BOD plutons showing second-order NE-SW lineaments.

2) Intermediate group, c. 285-280, comprising the SAG, DG and TG plutons in which second-order NE-SW lineaments are subordinate with possible minor E-W component.

3) Latest group, *c.* 279-275 Ma, and possibly younger, developed in the LEG pluton that shows a distinct lack of NE-SW lineaments and dominated by NW-SE trend which may overprint earlier lineament populations in older granites.

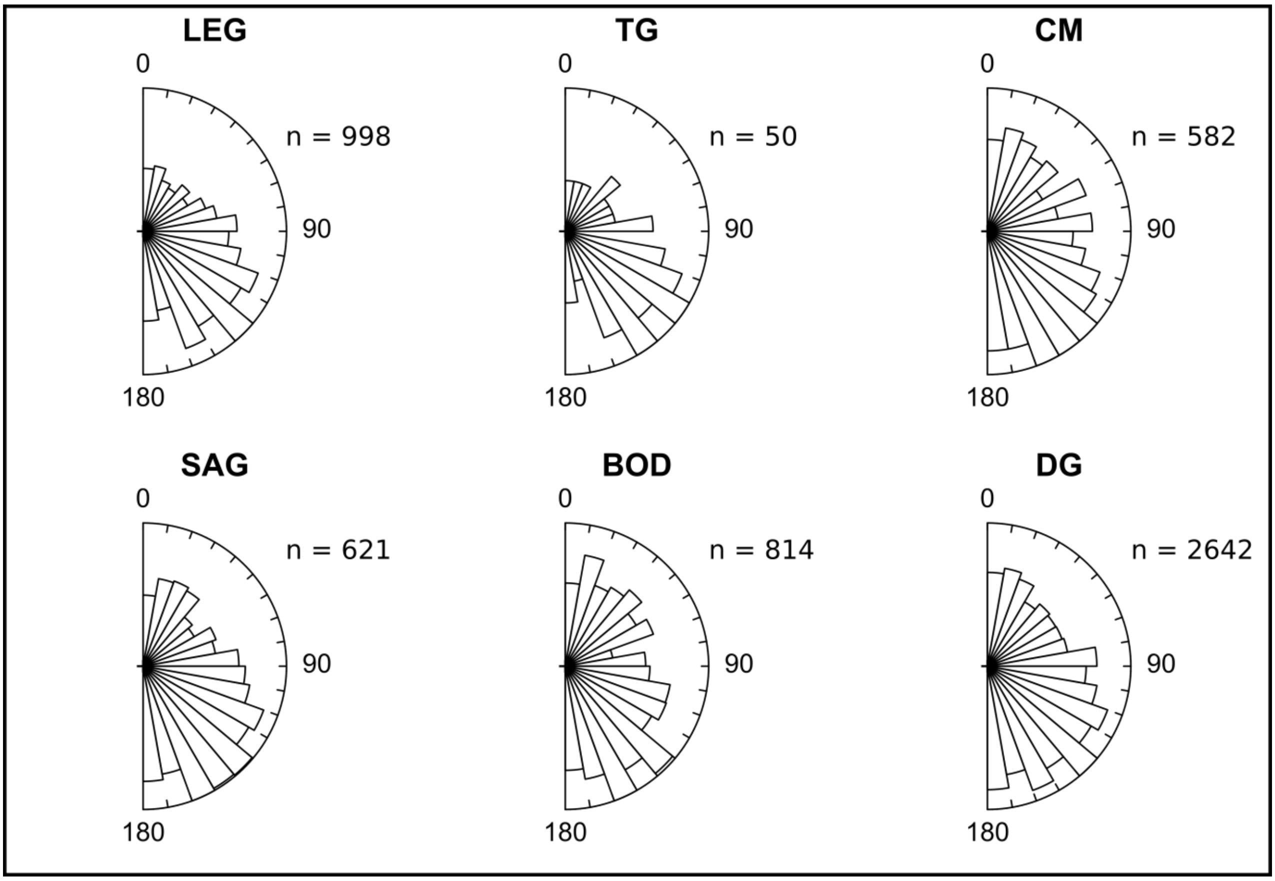

Figure 5 Rose diagrams plotted for each pluton using lineament data from Yeomans et al. (2019). Plutons include the Land's End Granite (LEG), Tregonning-Godolphin Granite (TG), Carnmenellis Granite (CG), St Austell Granite (SAG), Bodmin Granite (BOD) and Dartmoor Granite (DG). All plutons show a dominant NW-SE trend. The older plutons (CM and BOD) show a clear subordinate population of lineaments in NE orientations which is reduced in TG, SAG and DG plutons and almost absent from the youngest, LEG pluton.

3.2 Outcrop scale

Digital outcrop modelling can be used to create highly detailed twins of the field locality which can then be used to create 3D models of the fracture network. By collecting high-resolution data from key localities that have been identified as likely reservoir analogues, the fracture distribution at the local scale, and the fractures within the damage zone, can be better understood.

At the time of writing, we are in the early stages of collecting data from around the peninsula from areas that are likely analogues for the United Downs Deep Geothermal project where the granite is not exposed at surface. Figure 6 shows a UAV-borne photogrammetry image collected in June 2019 from the south coats of the Land's End Granite at Gwennap Head. Inset figures aim to illustrate the 3D nature of the dataset and demonstrate the fracture network observed in the area. The use of UAVs to collect these data allows access to some localities which would previously be inaccessible for standard geological data collection. Gwennap Head provides a reservoir analogue for the major NW-SE fault zones within the granites of the Cornubian Batholith. The area also shows the complexity of cross-cutting relationships with fractures similar to second-order structures seen at the regional scale. The digital outcrop model created at Gwennap Head will provide an excellent means to assess the link between regional and outcrop observations and resolve the scalability problems. These models will ultimately influence future reservoir modelling that will be conducted later in the project.

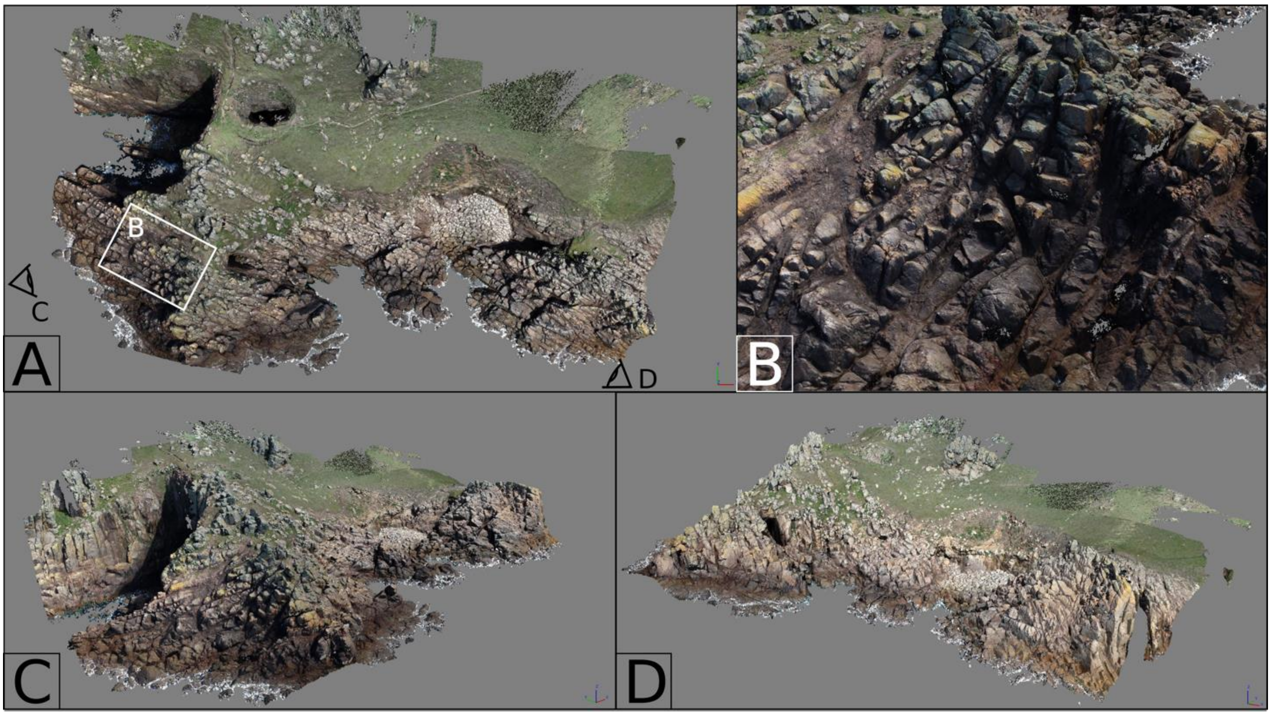

Figure 6 Digital outcrop modelling of the Land's End Granite at Gwennap Head. (A) shows the overall footprint of the field area in plan view. (B) shows the detailed structure observable in the model. (C) and (D) show the 3D nature of the model and help visualize the field area.

3.3 Fractures with depth

The exploration for deep geothermal resources is problematic due to the lack of information on the fracture arrangement at depth. Geophysical data are somewhat useful but often provide broad target zones which are only implicit about fracture density or permeability; these data also decrease in resolution with depth. In SW England, the United Downs borehole doublet has already been drilled, and, including the information from the Rosemanowes geothermal boreholes, present the best means of assessing the deep fracture network. Downhole data logs can provide valuable information on fractures that have been intersected. By using these data, the fracture distribution with depth can be elucidated and help de-risk future drilling projects.

4. FAVORABILITY MAPPING OF NEW EGS GEOTHERMAL TARGETS

Favorability mapping, or prospectivity modelling, is a common method used to define exploration targets in the mining industry. The technique usually makes use of a GIS platform to implement either a data-driven *Weights-of-Evidence*, or knowledge-driven *Fuzzy Logic* approach (Bonham-Carter, 1994). Other data-driven approaches have recently come to the fore, especially those that incorporate machine learning techniques such as the Random Forest™ and Support Vector Machine algorithms (Rodriguez-Galiano et al., 2015).

A variety of algorithms are available for favorability mapping, but ultimately it is the available data and the way that it is processed that will govern successful target identification; better algorithms may just refine these. For example, data quality and the challenge of moving from regional to more local targeting is well documented by studies in Turkey. The regional study of Western Anatolia by Tüfekçi et al. (2009) showed high geothermal potential in graben structures in the region. Further analyses conducted by Yalcin & Gul (2017) in the Akarcay Basin and Cambazoğlu et al. (2019) in the Gediz Graben failed to create clear targets which is likely due to both approaches giving high weights to layers that are strongly correlated with the graben structure (hot spring, fault and lithological data), but lack higher resolution from within the graben to better resolve more local targets.

With respect to data processing, similar input datasets were used by Moghaddam et al. (2014) and Sadeghi & Khalajmasoumi (2014) to model geothermal favorability using *Index Overlay*, and *Fuzzy Logic* methods. The former used a complex fuzzy modelling approach and reported *Fuzzy Logic* to be the best method. Conversely, the latter used a simplistic *Fuzzy Logic* method and found *Index Overlay* to be the best method; however, this may well be a reflection of the simplistic, and limited, data processing used by Sadeghi & Khalajmasoumi (2014) in their modelling approach. In contrast, Sang et al. (2017) made use of a combined *Weights-of-Evidence* and Fry analysis approach. The study incorporated the transformation of some layers using Fry analysis prior to generating a *Weights-of-Evidence* model. The approach was advantageous to the model when compared to a standard *Weights-of-Evidence* analysis due to the directional elements incorporated by Fry analysis which are particularly beneficial when the geothermal targets are structurally controlled and demonstrates the benefit of careful data processing.

4.1 Conceptual geological model

A conceptual geological model is outlined in Figure 7 that shows the first-order structure (P1) and the two-well system designed by Geothermal Engineering Ltd to exploit the vertical fault system. Additional fault planes (P2-4) have been sketched in to illustrate the second-order structures that may be present and could interact with the main P1 target. Considering the approximate NW-SE orientation of σ_H (Batchelor & Pine, 1986), similarly oriented first-order P1 structures are a clear target; however, the interaction of second-order structures is an important consideration. P2 structures are illustrated as vertical and antithetic to P1 but could provide a significant fluid pathway if still open. P3 represent subordinate low-angle structures that may be orthogonal and thus unlikely to increase permeability. P4 are low-angle structures but oblique to σ_H and may result in greater fracture permeability where they intersect P1.

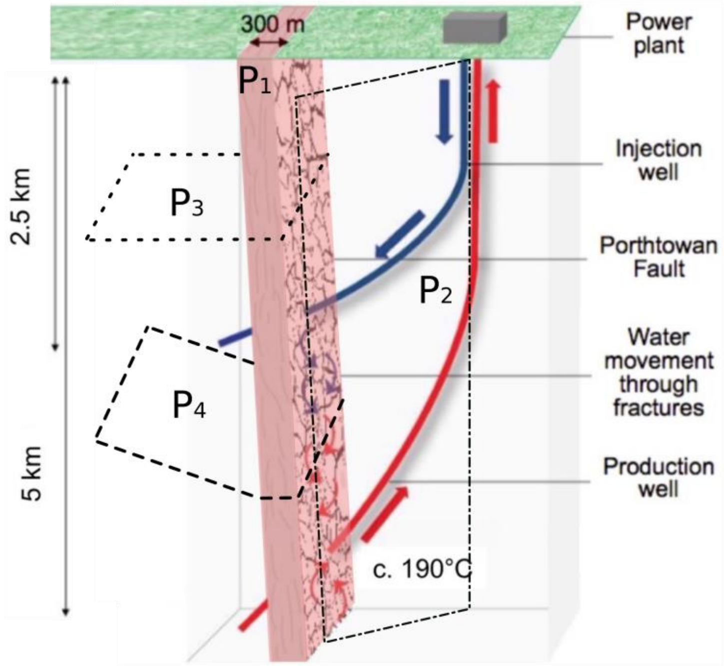

Figure 7 Schematic conceptual geological model based. The model is initially based on original concept for the United Downs Deep Geothermal Power project courtesy of Geothermal Engineering Limited (2014). We develop this to postulate the interactions of the main target and first-order structure (P1) with multiple possible second-order structures (P2-P4).

4.2 Proposed framework

A considered approach to favorability mapping is required to define, and subsequently refine, clear targets. In the case of fault-hosted geothermal resources, a key focus is the structural framework when defining regional targets. Furthermore, to refine targets, higher resolution datasets will help elucidate the scalability of the structural network and whether the same modelling approach can be applied at the local scale. These two problems set out the requirement for a staged modelling approach which can be tailored to the problem at different data resolution and, or, scale of the structural model.

4.1.1 Understanding the structural framework

Exploration for fault-hosted geothermal systems requires a strong understanding of the structural geology of the region. In SW England, understanding the structural geology is complicated by multiple reactivation episodes that are poorly constrained. Multiple lineament detection studies have attempted to map the regional fault network, the most recent being the highest resolution and using multiple datasets to inform the analysis (Yeomans et al., 2019). As shown in Section 3, this is a first step towards understanding the arrangement of major fault systems across the peninsula and at the pluton scale. However, limited kinematic information can be gained from the existing fault mapping. The long strike-extent of the NW-SE fault systems allow the area of interest to be extended to off-shore areas and to the east where later Mesozoic rocks are known. By mapping these areas and building a topological relationship between fault systems, greater certainty can be placed on kinematic interpretations and be projected back to targets on-shore.

The NW-SE faults are inferred to be the major fluid pathways for geothermal fluids in these systems. Historic warm springs are well documented in SW England, particularly in west Cornwall, although their presence is seldom seen due to dewatering of the region through mining. The springs may form a useful dataset to be included as part of a Fry analysis, in a similar approach to Sang et al. (2017), as a means of an indirect test of the influence of different fracture orientations.

4.1.2 Understanding scale

The use of digital outcrop models will be key to understanding any differences in the structural framework between regional favorability mapping and refining targets at a local scale. By comparing regional versus outcrop models, the structural framework can be assessed to discover if it behaves similarly at different scales (and is thus scale invariant, or fractal) or has nuances that need to be accounted for. The main limitation for regional mapping of lineaments is that data resolution may preclude the detection of lineaments at the small scale. Thus, the effect of spatial resolution on analyses must be investigated in detail to attempt to assess whether scale invariance exists, and whether it is fully captured at different resolutions.

Furthermore, it has already been demonstrated herein that some plutons show a different distribution of lineaments from regional lineament mapping. These are provisionally interpreted to reflect evolving Early-Mid Permian stress regimes during 20 Ma of batholith construction that results in greater structural complexity in older plutons. This notable difference may mean that the problem may change temporally and the spatial distribution of different age granites adds another layer of complexity to the modelling.

4.1.3 A staged modelling approach

Conducting a staged modelling process is not an especially novel approach; however, it allows for the reprocessing of data over areas of interest, the incorporation of datasets at higher resolution, or completely new data that is not available at the regional scale. A useful example of this is the demonstration of scalability of prospectivity modelling for orogenic gold in northern Finland (Niiranen et al., 2019). The work implements at Fuzzy Logic methodology to regional, provincial and mine-camp scale prospectivity modelling. Each stage represents a new model developed for the purpose, the difference between regional and provincial models are the fuzzy operator functions used to combine datasets; at the mine-camp scale, more refined data at higher density are used. By adapting the modelling approach for different scales, targets are consistently refined and include appropriate data for the modelling problem. This approach is therefore highly applicable when considering the potential variations in structural framework and available data for identifying future geothermal energy resources.

5. CONCLUSIONS

The structural framework of SW England is complex, and work herein has shown that there is some variability in the structures seen between the different granite plutons. The tectonic inheritance of these granites is difficult to elucidate with a dominant NW-SE trend to lineaments that intersect granite plutons. However, the two oldest granite plutons (Carnmenellis and Bodmin) show a strong NE-SW which becomes weaker tending to insignificant populations in younger plutons suggesting that there has been a change in stress regime. This is in contrast to the expected change in orientation of second-order structures across the Gramscatho-Looe basin boundary. The different Devonian-Carboniferous basin settings for the Gramscatho-hosted Carnmenellis pluton and Tavy-Culm-hosted Bodmin pluton may indicate that the Early Permian was subject to an earlier stress regime and that the inheritance of second-order structures may not be related to basinal setting. However, without further data to determine regional stress regimes during the Early-Mid Permian, the host basin problem for tectonic inheritance is, as yet, inconclusive.

In this paper, we have outlined a framework for better understanding the structural framework, tectonic inheritance and later reactivation of these structures. This is set in the context of identifying new EGS geothermal energy targets in the region and the stages for analysis are summarized as follows:

- Understand the structural framework and the tectonic history of the region
- Multi-scale analysis important to understand the regional stress regimes and the effect on local fault networks to determine if there is a scale invariant structural problem
- Conduct a staged modelling approach that can be adapted from regional to local scales to best identify and subsequently refine geothermal energy targets

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