Proceedings World Geothermal Congress 2020
Reykjavik, Iceland, April 26 – May 2, 2020

Geological Overview of the United Downs Deep Geothermal Power Project, Cornwall, UK

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Keywords: Deep geothermal, Cornwall, United Downs, Variscan, Deep drilling, UK

ABSTRACT

The United Downs Deep Geothermal Power (UDDGP) project is the first geothermal power project in the United Kingdom. It aims to develop the geothermal resources in the heat-producing granites that lie beneath Cornwall in SW England. Financial support has come from the European Regional Development Fund and the local authority (Cornwall Council) who, together, have provided £13m of the £18m project budget.

The project aims to produce 1 to 3 MW electricity from two deep wells drilled into early Permian granite which underlies much of SW England (the Cornubian Batholith). The batholith is formed of high heat production fractured granite which offers great potential for exploitation of geothermal resources due to the elevated temperature gradients.

Fluid will be circulated between an injection well at 2.5km depth and a production well situated 2km directly below it. Both wells are planned to intersect a permeable fault structure known to be associated with episodic fluid transport since the Permian, as well as contemporary groundwater circulation to several km depth. Temperatures at the production depth of ~4.5km are in the region of 190^0 C.

The target fault structure is a >15km long NNW-SSE oriented complex strike-slip fault zone several hundred metres wide as mapped at surface and in shallow mine workings. Along with many sub-parallel structures in SW England it acted as a transfer fault during Variscan thrust faulting (Carboniferous), although inheritance from pre-orogenic Devonian rifting is possible. In the early Permian these structures also acted as transfer faults during NNW-SSE regional extension, during which the Cornubian Batholith was emplaced. Microgranite dykes and magmatic-hydrothermal mineralisation (W-Sn-Cu-Zn-AS metal lodes) are associated with the batholith and occur in and around the United Downs site. The area basically represents a 'fossilised' major Early Permian geothermal complex whose rich mineral deposits became the focus of a world-leading mining industry.

From surface the wells prove marine low-grade metasediments of Upper Devonian age containing a range of intrusive bodies, overlying granite with many intersections of strike-slip faults. The configuration, physical and flow properties of these structures at depth, within the target fault zone, will be crucial for the success of the project. Pre-drill uncertainties associated with the geological conditions at depth will be reviewed and the latest understanding of the geological conditions presented.

This paper summarises the geological setting of the project and the new geological understanding provided by the wells which will explore at depths never before achieved in onshore UK. A wealth of new information will be acquired.

1. INTRODUCTION

The United Downs Deep Geothermal Power (UDDGP) Project is the first deep geothermal power project in the United Kingdom. It is located near Redruth, in Cornwall, and is part-funded by the European Regional Development Fund and Cornwall Council. The drilling of two wells, a 5057 m TVD (true vertical depth) production well (UD-1) which is the deepest onshore well in the United Kingdom, and a 2205 m TVD injection well (UD-2), was completed in June 2019. Both wells are deviated WSW at depth to intersect the NNW-striking, steeply-dipping, Porthtowan Fault Zone (PTF), within the high heat production granites of the Cornubian Batholith. The project builds upon the work of the pioneering CSM 'Hot Dry Rock' Geothermal Project (1974-1991) that was located 7 km SSW of United Downs at Rosemanowes in the Carnmenellis Granite e.g. Parker, (1989).

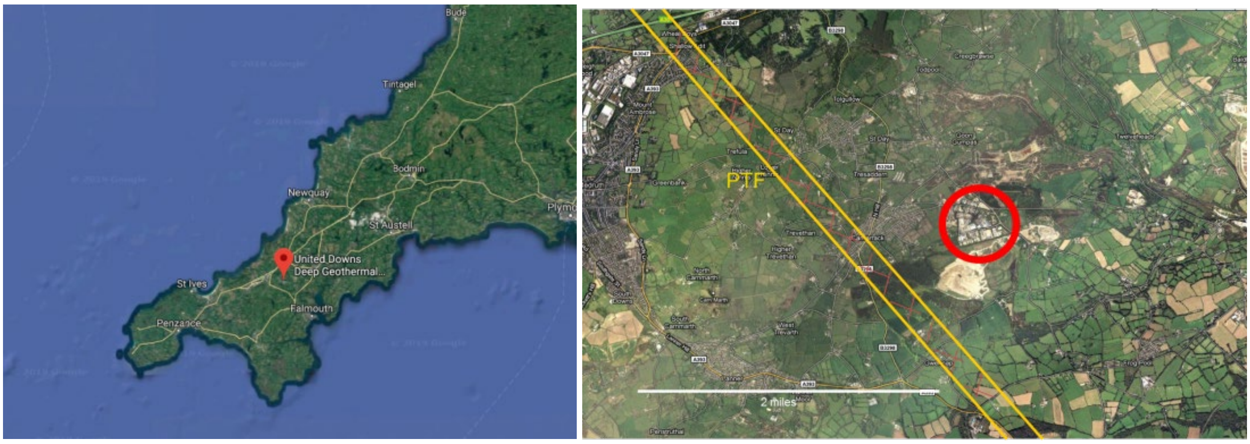


Figure 1: The location of UDDGP in relation to Cornwall and the PTF target. Map data ©2019 Google.

The concept being tested at United Downs is novel, and relies on a well separation of more than 2000 m. Reasons for this are twofold: 1) to eliminate the risk of 'short circuiting' the system and the associated effects on temperature performance, as often experienced in HDR or EGS projects and 2) to establish a more economically and commercially viable method of developing deep geothermal as a resource.

The geological objectives are to test the key criteria for commercial geothermal development: (1) will bottom hole temperatures be similar to those predicted from near-surface flow data? ; (2) can the PTF be intersected at depth? And (3) can fluid circulation through the fracture system be achieved between the injection and production wells?

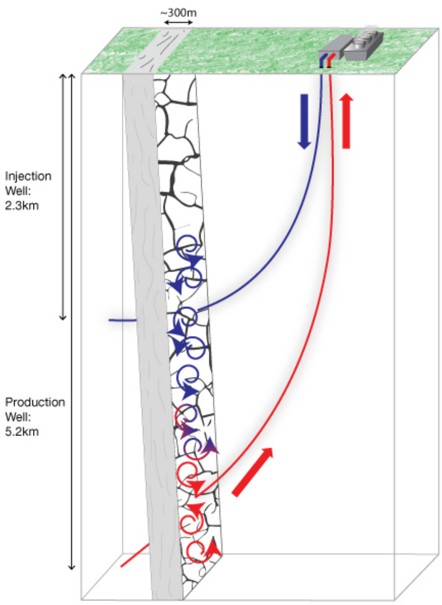


Figure 2: Concept image of the United Downs deep geothermal system.

1.1 Regional Geology

SW England is a Variscan Massif surrounded by Permian and younger offshore sedimentary basins as described by Evans, (1990). The pre-Permian geology largely comprises Devonian and Carboniferous successions that accumulated on the northern passive margin of the Rheic Ocean or its successor basin (Shail and Leveridge, 2009). A SSE-dipping suture is imaged on deep seismic reflection profiles to the south of Cornwall and was associated with late-Devonian Variscan convergence and the ensuing Carboniferous continental collision and low-grade regional metamorphism of the northern lower plate (Alexander et al., 2019). The end-Variscan crustal architecture comprised SSE-dipping thrust faults and NNW-SSE striking steeply dipping transfer faults (Hillis & Chapman, 1992).

Variscan convergence ceased in the latest Carboniferous and was replaced by an extensional regime that persisted through much of the Early Permian (Shail and Leveridge, 2009; Alexander et al., 2019). NNW-SSE crustal extension and thinning was accommodated by the reactivation of Variscan thrust and transfer faults and was accompanied by the generation and emplacement of the granites of the Cornubian Batholith *c.* 293-274 Ma (Chen et al., 1993; Simons et al., 2016). ENE-WSW striking steeply dipping extensional faults, developed in both granites and their host rocks during ongoing extension, are compartmentalised by

NNW-SSE transfer faults, and host microgranite-rhyolite dykes and W-Sn-Cu-As-Zn-Pb magmatic-hydrothermal vein (lode) mineralisation (Shail & Alexander, 1997).

Many of the NNW-SSE transfer faults were reactivated, and new faults were formed, during Triassic ENE-WSW crustal extension (Shail and Alexander, 1997). During this episode, the migration of basinal brines from Permo-Triassic successions resulted in the widespread precipitation of quartz-chalcedony-hematite infills and kaolinitic wall-rock alteration within granite-hosted fracture zones (Scrivener et al., 1994). These NW-SE to NNW-SSE striking fault zones displace earlier ENE-WSW striking magmatic-hydrothermal lodes and are locally termed ‘cross-courses’; they have also experienced selective post-Triassic reactivation and fluid migration (e.g. Psyrillos et al., 2003) and are considered prospective deep geothermal targets.

1.2 Heat Flow

It has long been known that the granites of SW England represent a potential geothermal resource. Historical records and measurements made in deep tin and copper mines, and the first-hand experience of the miners, demonstrated elevated temperatures later confirmed by heat flow studies and geothermal assessments carried out in the 1970s and 1980s (Francis, 1980; Downing and Gray, 1985). In 1974 systematic heat flow studies in SW England showed anomalously high heat flow values across the Cornubian Batholith (*c.* 120 mWm^{-2}) almost double the UK average (Tammemagi & Wheildon, 1974; Tammemagi & Wheildon, 1977; Francis, 1980; CSM Report 2B-25, 1986). More recently, these heat flow values have been revised and corrected for paleoclimatic effects (Beamish and Busby, 2016).

2. DRILL SITE SELECTION

The project feasibility study carried out in 2009 included geological evaluation of locations in west Cornwall with the best potential for deep geothermal resource exploitation. Two main criteria were applied in geological site selection. Firstly, locations of high surface heat flow and, secondly, locations with a high degree of natural fracturing and thus potentially good fracture permeability within the granite.

Heat flow data is well documented across SW England and is, in general, spatially related to granite depth as interpreted from gravity data (Fig 3). Therefore, the heat flow combined with granite depth became a key constraint in site selection.

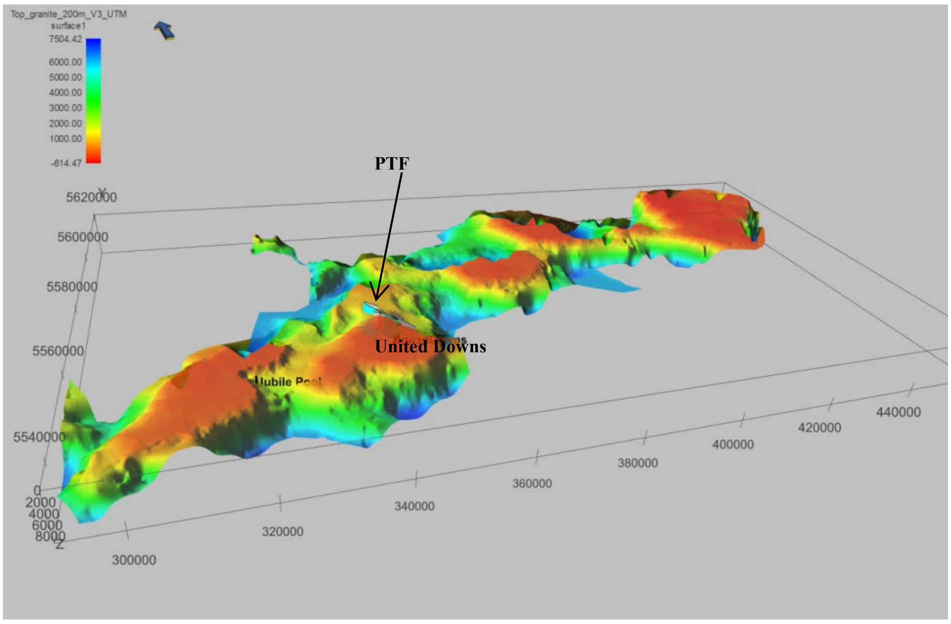
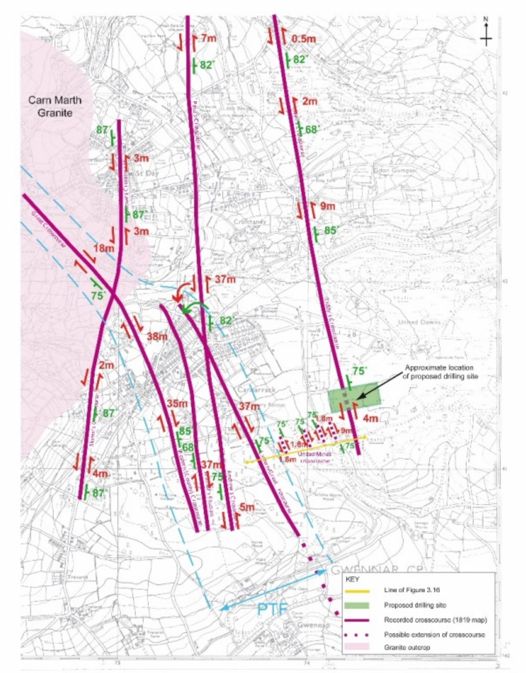


Figure 3: RMS model showing interpreted depth to granite from gravity data interpreted by Willis-Richards and Jackson (1989).

Previous geothermal drilling to 2600 m at the Rosemanowes ‘Hot Dry Rock’ site and deep mine data had shown the stress field at depth to be anisotropic (strike-slip) with σ_H aligned NW-SE (Batchelor and Pine, 1986). Injection tests coupled with microseismicity in the Rosemanowes wells implied that fluid flow was also anisotropic, being focused on structures with an approximate NW-SE trend. The NW-SE to NNW-SSE striking ‘cross-course’ fault zones were therefore targeted due to their perceived enhanced permeability, and the feasibility study identified one of these structures crossing Cornwall from the north coast at Porthtowan towards Falmouth Bay on the south coast. Surface maps (BGS) combined with detailed observations from metal mining records and aeromagnetic data suggested a strike length >15 km for the Porthtowan Fault Zone (PTF).

No suitable seismic data was available at United Downs with which to map the sub-surface geometry of the PTF but, on the basis of its trace length, and by analogy with similar structures elsewhere in SW England and also N France, it was considered to have a down-dip persistence >5 km and a long geological history. Mine records provided additional evidence of the PTF character: (1) details of the near-surface (0-300 m) geometry of individual faults within the zone; (2) locations of warm groundwater springs in mines close to the PTF whose geochemistry indicates mixing between deeper older and younger shallower fluid sources during fracture-controlled circulation (Edmunds et al., 1989); (3) locations of subsurface hydrocarbon seeps close to the fault zone whose organic chemistry supports a probable Jurassic source and implies long-range fault-controlled migration on structures such as the PTF (e.g. Baba et al., 2018).

Conceptually, at surface the PTF is interpreted as a ~400 m wide zone or 'envelope' within which there are several braided fault strands with relays, overstep, and jogs, and with opposing dips and senses of displacement on individual strands (Fig. 4). This is characteristic of strike-slip faults as seen in outcrop and as observed on the Cornish coast for structures of PTF trend.



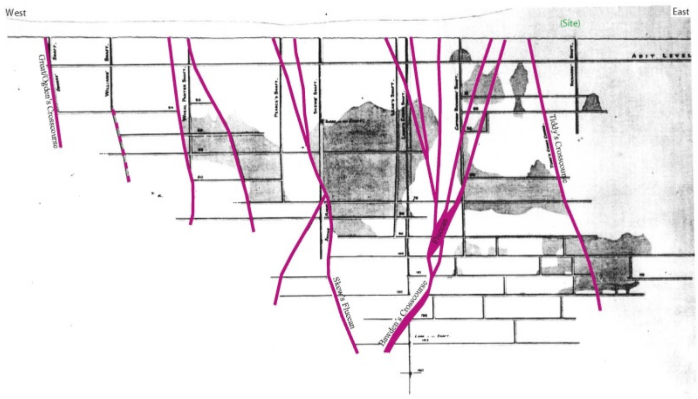


Figure 4a: Map of the PTF structures as seen from surface mapping and mine data. Lateral offsets shown in red, dip directions and magnitudes in green. The PTF envelope is outlined with blue dashes, with the drill pad location shown as a green rectangle. The location of the cross-section shown in Figure 4b is shown in yellow.

3. DATA ACQUISITION

During drilling of UD-1 and UD-2 an extensive programme of cuttings sampling and description was undertaken, and continuous MWD data was acquired including gamma, together with all the normal drilling parameters including mud temperature, losses, ROP, torque, and gases. Real-time interpretation of this data was crucial to the identification of formation character and especially identification of the PTF intersections in UD-1 and UD-2.

Comprehensive openhole wireline logging suites were performed in the 12.25" and 8.5" intervals of UD-1, including ultrasonic and micro-resistivity image logs and full waveform sonic for the identification of fractures. In the 17.5" interval limited logging was carried out (caliper, temperature and gamma).

3.1 Sampling Strategy

Cuttings were collected every 10 m throughout the main sections of both UD-1 and UD-2 and every 5 m through the "zone of interest" within the PTF. Each bulk sample weighed approximately 1000 g and was split equally between GEL and the BGS (British Geological Survey). An extra bulk sample was taken at each interval for analysis on site. These were washed and dried to remove drilling mud from the cuttings before they were examined. Certain intervals throughout the wells were heavily kaolinised, and during such sections extra precautions had to be taken when handling the samples to ensure that the cuttings remained representative.

Great care was taken to preserve full grain size representation throughout the samples with material being sieved using a series of sieve sizes. Selected samples were weighed to obtain the grain size distribution. Bulk samples did not account for particles below

63 µm, therefore specific samples were taken to include the finer size range. As well as rock samples, mud samples were collected every 12 hours and kept in the dark to avoid rapid degradation of polymers.

3.2 Mineral Identification

Initial mineral identification for each sample was undertaken through optical assessment, and automated SEM (QEMSCAN) and XRD analysis were employed on selected samples. Further mineral analysis will be carried out on the cuttings in order to obtain a full understanding of the variation within the granite and the mineralogy of infilled fractures.

3.2.1 QEMSCAN

A QEMSCAN (4300, EVO 50) operating in Fieldscan mode with an analysis spacing of 10 µm was used for quantitative modal mineralogical and textural analysis using methods outlined by Pirrie et al. (2004). Samples were analysed from different grain size distributions. For the coarse fraction, cut and polished epoxy resin blocks coated with carbon were used. However this technique was not possible for the deeper samples due to the occurrence of graphite in the cuttings. Samples measuring <500 µm were also analysed using a 'sprinkle' amount on the stub mount.

3.3 Wireline Logging

Baker Hughes (BHGE) ran a full suite of wireline logs for the 12 ¼" and 8 ½" sections in UD-1 (Table 1). In the 17 ½" interval only temperature, spectral gamma and caliper logs were run by European Geophysical Services (EGS).

17 ½" (250 – 900 m(MD)	**12 ¼" (900 – 4000 m(MD)**	**8 ½" 4000 – 5200 m(MD**
Fluid Temperature & Electrical Conductivity		
Spectral Gamma	TTRM (Temperature/Tension/Resistivity/Mud)	TTRM
Caliper	DSL (Digital Spectra Log)	DSL
	CN (Compensated Neutron)	CN
	ZDL (Dual Spectrum Density)	ZDL
	XMAC (Cross Multipole Array Acoustilog)	XMAC
	RTEX (Laterolog)	RTEX
	ORIT (Directional Survey)	ORIT
	UXPL (Ultrasonic Xplorer)	UXPL
	STAR-HD (Simultaneous Acoustic and Resistivity Imager)	
	MIT (Multi-Finger Caliper)	

Table 1: wireline log data collected in UD1

Additional wireline logs will be obtained in UD-1 during the autumn of 2019, including static temperature and caliper logs, together with a sidewall coring programme. A full suite of wireline logs will also be run in the 8.5" open hole section of UD-2 providing crucial data for the full interpretation of the PTF at depth.

4. PRELIMINARY FINDINGS

4.1 Lithological variation in UD-1

The upper 210 m of the United Downs Site comprises highly deformed, low-grade regionally metamorphosed and deformed mudstones of the Upper Devonian Mylor Slate Formation (Leveridge et al., 1990). It has a subhorizontal foliation along which late Variscan, pre-granite, metamorphic quartz veins occur on a millimetric scale. A contact metamorphic assemblage of white mica and biotite developed during granite emplacement and was variably greisened and tourmalinised by the migration of fracture-controlled magmatic-hydrothermal fluids. Traces of the magmatic-hydrothermal W-Sn-Cu-Zn oxide-sulphide mineralisation formerly exploited from steeply dipping lode systems within the slates at United Downs occur in heavy mineral assemblages.

Coarse resolution gravity data and local mine records indicated that the top granite batholith would be encountered at *c.* 500 m depth. Extensively greisened and kaolinised microgranite was penetrated from ~210 m (MD) in both UD-1 and UD-2. Surface mapping carried out by the BGS (1989) indicates moderately NNW-dipping microgranite-rhyolite (elvan) dykes in the vicinity of the United Downs site but the thickness intersected in the wells is consistent with a body that is subvertical and/or has a more irregular geometry at depth. The syn-emplacement interaction of ENE-WSW striking extensional faults with NNW-SSE striking strike-slip faults at the eastern margin of the PTF may have influenced the microgranite geometry.

Below 800 m a variety of granite types persist to the bottom of UD-1 (5057 m TVD). Whilst there are mineralogical and textural variations, almost all unaltered types plot within the monzogranite field (Figure 5). Muscovite is always dominant over biotite and, whilst there may be minor secondary white mica, the granites correspond to the two-mica (G1) and muscovite (G2) granite types as defined by the recent re-classification of Cornubian granites (Simons et al., 2016). The accessory mineral assemblage comprises tourmaline, apatite, ilmenite, rutile, monazite, zircon, topaz and fluorite with allanite recognised in the deeper granites.

There is a strong similarity between the granite types encountered in UD-1 and those encountered to a depth of 2600 m at the HDR Rosemanowes Site, 7 km to the SSW.

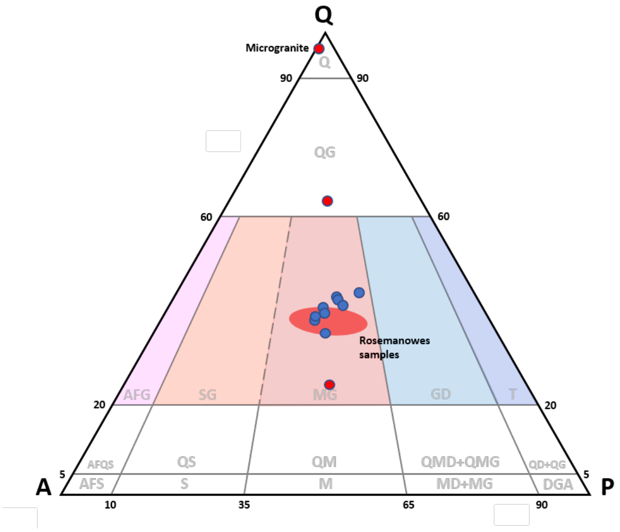


Figure 5. QAP classification of UD-1 granites (coarse cuttings 720-5275 m analysed by QEMSCAN). Almost all samples plot within the monzogranite field and are similar to the granites in the nearby Rosemanowes HDR site (red elliptical field). UD-1 samples in red have anomalous compositions due to cuttings representivity or alteration (microgranite).

4.2. Radioelement Classification

The granites were classified on their radioelement concentrations from the Baker Hughes DSL spectral gamma ray tool into five different types: Microgranite, Granite A, Granite B, Granite C and Granite D. The Th concentration was a significant parameter for defining these granite types (Figure 6); Th concentrations vary by *c.* 22 ppm compared to *c.* 4 ppm U between three main granite types. Step changes in Th were previously used to classify granites at the Rosemanowes HDR site, within the Carnmenellis Granite (Parker, 1989).

The radiogenic accessory minerals determined by QEMSCAN include monazite, allanite, zircon and apatite. Monazite and allanite both have high Th:U ratios (Adams et al., 1959; Lucas, 1994) and their distribution may exert a dominant control on the radioelement-defined granite types; allanite was first detected when high-Th granite was encountered.

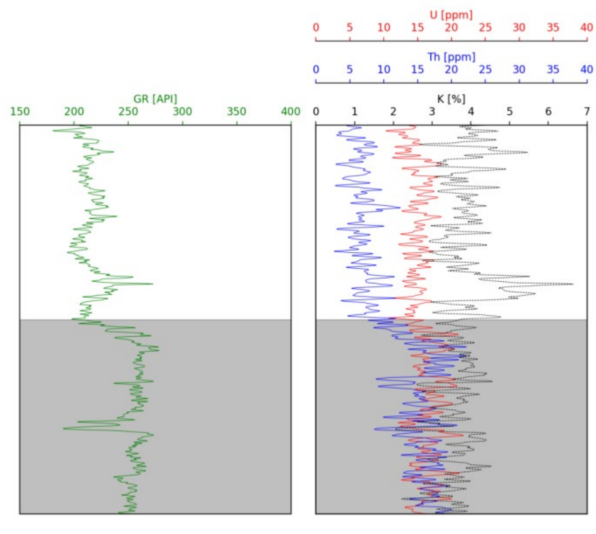


Figure 6: the boundary between two granite types in UD-1 where a sustained increase in Th occurs (shaded white/grey).

4.3. Heat Flow Analysis

Uncertainties exist surrounding the heat budget and heat flow of the Cornubian granites. Spectral gamma data from Rosemanowes well RH 15 (2600 m - Carnmenellis Granite) indicated a decrease in U and Th concentrations with depth (Lucas, 1994) and geophysical modelling has reduced the interpreted volume of the Cornubian granites (CSM Report 2C-7, 1989; Tombs, 1977; Willis-Richards and Jackson, 1989; Taylor, 2007). These present major challenges for modelling the high surface heat flow values of the granite (Batchelor, 1977; Francis, 1980, CSM Report 2B-25, 1986; Sams and Thomas-Betts, 1988; CSM Report 2C-7, 1989). Further research using data from UDDGP will address uncertainties relating to the surface heat flow, where the heat production and thermal conductivity will be investigated.

4.3.1. Heat Production

The Cornubian Batholith is composite and the primary control on radioelement (U, Th, K) content is the temperature and degree of source rock partial melting and fractional crystallisation processes affecting individual magma batches (Simons et al., 2016). The secondary control is the leaching of radioelements during multiple episodes of fluid-rock interaction; this particularly effects the near-surface distribution of U and all elements in zones of intense kaolinization.

A preliminary high-resolution heat production profile has been calculated using the equation of Bücker and Rybach (1996):

$$A[pW\ /\ m^3] = \ 0.0158(GR[API] - 0.8)$$

where *A* is the heat production and GR is the total gamma count in API units. This method is reliable up to 350 API and has an estimated error below 10%. A composite log based on the Halliburton LWD and Baker Hughes DSL total gamma data was used to avoid data issues resulting from tool calibration and corrections. These data will later be refined in accordance with quality control checks to produce a higher accuracy heat production profile using the equation from Rybach (1976) and spectral gamma and density data.

The initial findings indicate a stepped increase in radioelement concentration and therefore heat production between Granite A, B and D. Localised packages of Granite C show decreases in heat production as a result of lower U and more notably Th concentrations. In general, there is an increase in radioelement concentration with depth, which has significant implications for heat flow modelling as previous spectral gamma from the Carnmenellis granite in Rosemanowes well RH-15 (2600 m) implied U and Th decrease with depth (Lucas, 1994).

Further work will involve portable X-ray Fluorescence Spectrometry (pXRF), laboratory XRF and ICP-MS to further characterise the variation in radioelements with depth. Further to this, electron microprobe and LA-ICP-MS will be carried out to understand the host minerals of U and Th within the granite.

4.3.2. Thermal Conductivity

Preliminary calculations of the thermal conductivity of the granite have been derived from the QEMSCAN mineralogical data using a harmonic mean mixing model (Fuchs et al., 2018). Values range between 2.48 – 3.73 W/(m K) and are primarily controlled by variations in quartz content. Further investigations into the clay fraction have been carried out using the geophysical log data and mud consistency reports. This has shown intervals of high kaolinite content in the upper parts of UD-1. Kaolinite has a low vertical thermal conductivity of 1.25 W/(m K) and a high anisotropy of 2.67 (Hantschel & Kauerauf, 2009). This would significantly change thermal conductivity of the granite and may allow kaolinite-rich zones to act as a thermal blanket, depending on their lateral extent.

Further work will involve thermal conductivity measurements to investigate the roles of the temperature dependence, kaolinite distribution and granite anisotropy on thermal conductivity values.

4.4 Structure of the PTF

Interpretation of the UD-1 ultrasonic image log data (UXPL) between 900 – 5000 mTVD in conjunction with the cuttings analyses, openhole logs, and drilling data has revealed a high degree of structural and lithological complexity both within the PTF envelope and in the adjacent granitic host rock. Given the large volume of log data (~4km) the discussion here is preliminary and further refinement of understanding will take place. However, it can be said that the image log structural interpretation is broadly consistent with the conceptualisation of the PTF as described in Section 2.

The eastern margin of the PTF was encountered close to the prognosed depth and is seen in the UXPL data as a zone of enhanced fracture intensity (hanging wall fault damage zone) and as a cluster of steeply NE-dipping to sub-vertical faults. The dominant fracture strike is NW-SE at the intersection depth, with subsidiary strike populations E-W, NNW-SSE and NNE-SSW.

The western margin of the PTF was interpreted some 500 m (TVD) deeper in the (30° inclined) UD-1, which implies an orthogonal width of *c.* 350 m for the PTF envelope at depth. It coincides with a significant decline in fracture intensity along with a change in fault dip direction in the footwall, towards the SW. The structure as described above is essentially an interval of brittle fracture deformation closely aligned with the PTF as seen at surface. In addition, the UXPL image also reveals a strong background fabric in the granite starting *c.* 200 m (TVD) deeper than the eastern margin and coincident with the presence of graphite in the cuttings, which also reduce in size from this depth. This fabric strikes sub-parallel with the PTF with variable but generally steep dips and is tentatively interpreted as a mylonitic foliation in the granite – perhaps a ductile precursor of the 'brittle PTF' described above. Alternatively, the fabric could be a primary flow or compositional texture coincident with the PTF envelope.

During drilling, the PTF was associated with difficulty holding the well trajectory, an increase in C1 and C2 gases as well as CO_2, and with significant mud losses. These observations were focused mainly on the western side of the brittle PTF, and in its footwall. In fact the most significant mud loss was some 150 m TVD inside the PTF footwall as here defined, implying connectivity despite being in a zone of low fracture intensity. Potentially open fractures were resolved in UXPL images right down to the base of the logged interval at c. 5000 m TVD.

Within the logged 'non-PTF' volume, the UXPL data shows variable and often high levels of fracture development in the granite, with more diverse fault and fracture strikes. The dominant strike is NNW-SSE with secondary NW-SE, E-W and NNE-SSW trends. This reflects the late Carboniferous to early Permian extensional phase when broadly WSW-ENE extensional structures formed, together with the hydrothermal lode mineralisation (Section 1.2). The UXPL shows that this structural grain persists within the PTF volume itself, although subdued compared to the PTF 'overprint'. A complex kimematic relationship involving multiple reactivation phases of both NNW-SSE and ENE-WSW trends during the Permo-Trias and into the Cenozoic is implied by offsetting relationships and regional considerations.

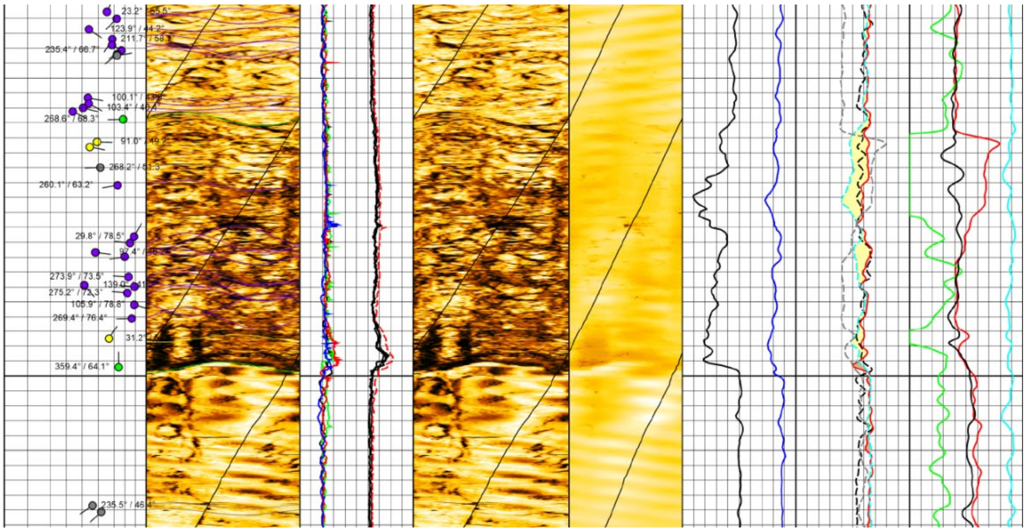


Figure 7. Ultrasonic (UXPL) image log showing a fault zone (~18 m thick) in the granite of UD-1.

5. SUMMARY

Preliminary findings outlined in this paper show that, at the time of writing, two of the three geological key criteria referred to in the introduction to this paper (Section 1) have been met:

1) Bottom hole temperatures are similar to those predicted from near surface flow data. The stepped increase in heat production with depth, driven primarily by Th levels was a surprising but encouraging result for UDDGP. Furthermore, a bottom hole temperature of 180 °C from the production well was ascertained whilst circulating drilling mud. A static temperature log will be run in the autumn of 2019 to confirm the true temperature at 5 km depth following a six month well recovery.

2) The PTF is proven at depth, close to its prognosed position. Results from the UD-1 image logs confirmed that the PTF was intersected at the predicted depths. This is supported by the occurrence of mud losses and gases within or on the shoulders of the PTF envelope. Wireline logs are due to be run in the injection well by the end of 2019 to confirm the geometry of the fault structure. During drilling, encouraging losses within the prognosed PTF zone of interest were observed.

Regarding the third criteria (circulation between the injection and production wells), a six month testing programme in late 2019/2020 will determine the injection, production and circulation characteristics of the PTF and allow an estimate of the sustainable energy that can be produced.

To conclude, an enormous amount of data has been collected during the drilling phase of UDDGP and extensive work will continue to test the viability of the project. At time of writing, the initial results are very promising. UDDGP has taken ten years of detailed planning and it is an exciting prospect that by the middle of 2020 the reality of a new geothermal industry in the UK will be one step closer.

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