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Seismic Monitoring at the United Downs Deep Geothermal Power Project, Cornwall, UK

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ABSTRACT

The United Downs Deep Geothermal Power project is the first development of its kind in the UK. It is located near Redruth in west Cornwall and is part-funded by the European Regional Development Fund (ERDF) and Cornwall Council. Two wells have been drilled to intersect a target fault structure that, it is hoped, will provide enough natural permeability to allow circulation between the wells at flow rates between 20 and 80l/s. The wells intersect the fault at vertical depths of approximately 2,200m (injection well) and 4,500m (production well). The bottom-hole temperature is expected to be in the region of 190^{O}C which should support electricity generation of between 1 and 3WMe (net). Drilling began in November 2018 and was completed at the end of April 2019. The production well reached a depth of 5,275m (MD) and the injection well 2,393m (MD). During post-drilling well testing and long-term circulation of the system it is expected that low level seismicity will be induced by pressure changes in the fracture system. In order to serve both as an engineering tool and to address public concerns over induced seismicity, a comprehensive seismic monitoring system has been installed and the project will operate a monitoring and control protocol in order to protect the surrounding community from disturbance. Background monitoring started in May 2018, approximately 6 months before the start of drilling. The real-time monitoring has detected and located a number of small natural events ranging in magnitude from 0.5 to 2.3 and four induced events with magnitudes less than 0, associated with drilling mud losses.

1. INTRODUCTION

It has been known for decades that the heat-producing 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 and they were confirmed by heat flow studies and geothermal assessments carried out in the 1970s and 1980s.

Heat flow in the Cornish granite (shown inset in Figure 1) is approximately double the UK average, at more than 120mW/m^2 (BGS 2019).

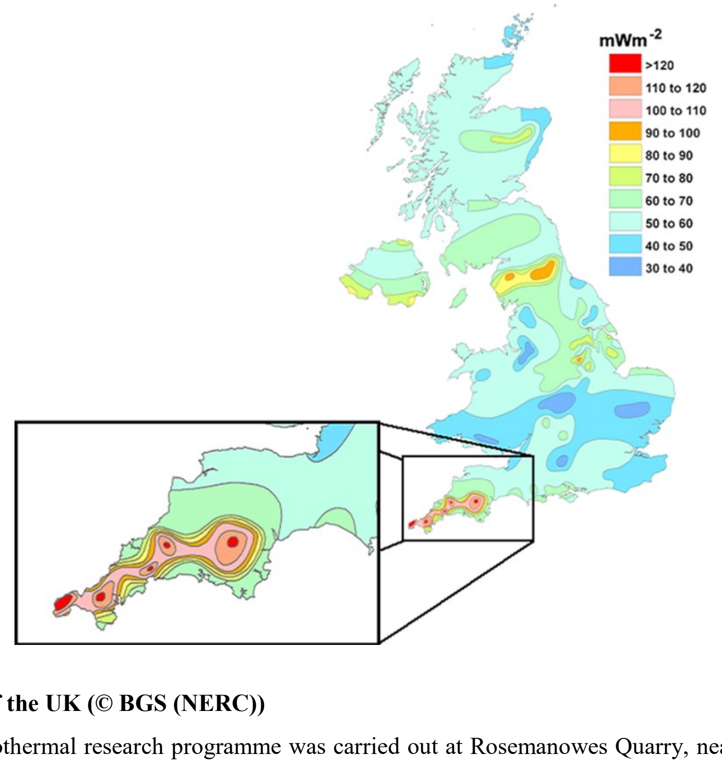

Figure 1: Heat flow map of the UK (© BGS (NERC))

A Hot Dry Rock (HDR) geothermal research programme was carried out at Rosemanowes Quarry, near Penryn in west Cornwall, from the late 1970s until the early 1990s. This was located on the Carnemenellis granite, one of several surface outcrops of the granite. There are many references to this work, for example Parker (1989), Richards et al (1994) and Parker (1999). This project made a significant contribution to the understanding of HDR reservoir development, in particular the importance of permeability enhancement by the shear stimulation of favourably aligned natural joints and fractures.

In the early 1990s European funding was withdrawn and research in Cornwall stopped. For the next 15 years there was no interest in deep geothermal in the UK, either technically or from government, but by 2008 a number of companies and organisations had begun to take an interest in Cornwall again as a potential geothermal resource.

In 2009 a study was undertaken by Geothermal Engineering Limited (GEL) into potential geological targets and drilling sites within a data-rich 400km^2 area of west Cornwall that included the Carnmenellis granite outcrop, the original HDR research site, and a number of now-abandoned mines.

The study concluded that the best potential host for a geothermal reservoir would be one of the northwest-southeast striking fault zones that are present throughout Cornwall. The target chosen for a proof of concept was the Porthtowan Fault Zone (referred to as the PTF), which extends from coast to coast and is mapped along the northeast side of the Carnmenellis granite. It is a structural zone of significant length, and its linearity suggests that it is near-vertical and likely to persist to depth. It was also observed in some of the local mines.

The selection of potential drilling sites was focused not only on proximity to the granite but also on locations from which it would be possible to drill a deviated well into the PTF which, in practice, meant within 1km. Other important selection criteria included the availability of a site that could accommodate a large drilling rig, good road access, availability of a grid connection, sparse population, local authority planning policy and land ownership. Several sites were considered and the one chosen was a brownfield site within the United Downs Industrial Estate, about 2 miles east of the town of Redruth.

Simple heat flow modelling was carried out to predict a geothermal gradient in the region of United Downs. There was a high degree of confidence in these predictions, not only because of the earlier heat flow work but also because of the direct measurements made to a depth of 2,600m at the Rosemanowes HDR site, only 7km away. At a vertical depth of 4,500m the temperature was predicted to be between 180^{O}C and 220^{O}C, with 90% confidence.

2. THE UDDGP DEVELOPMENT CONCEPT

The UDDG concept is novel in several respects and relies on a number of key factors.

Experience from HDR and EGS systems has shown that close well spacing increases the possibility of short-circuits and, as a result, poor long term temperature performance. The UDDGP concept relies on establishing circulation over a large vertical distance through the natural fracture system within the Porthtowan Fault zone. If the permeability is high enough, the large well separation (2,000m) should enable sufficient flow rate and heat transfer area for commercial energy extraction.

Establishing circulation between wells so far apart depends on the presence of significant, connected, fracture permeability at great depth. Such permeability has been observed before in other places but in the UK it remains to be tested. This is the greatest uncertainty that has to be addressed in the UDDGP project. If the PTF proves not to contain such fracturing, the concept will fail. However, if it does contain such fractures then the concept will not only succeed at United Downs but will also be repeatable at other locations in Cornwall, which is the ultimate goal.

In the previous HDR research project in Cornwall, the injection well was originally beneath the production well, with the expectation that injected water would migrate upwards, and circulation was driven by injection pressure. One of the surprising outcomes of that work was that injected water migrated downwards by shear stimulation on favourably oriented joints (Pine and Batchelor 1984) and, as a result, a significant percentage of the injected water was lost. This was partially, but not fully, addressed by the drilling of a third well, below the original two.

By contrast, circulation in the UDDGP system will be driven by a downhole pump in the production well. This pump will create a pressure sink, drawing water towards it not only from the injection well, but also from the far-field. In this way it is hoped that the system can operate at a generally low pressure level and that 100% recovery will be achieved. Furthermore, it is predicted that the onset of shearing on some fractures will occur at pressures as low as 5MPa, so that even moderate pressure around the injection well is likely to cause shearing, and it may well extend some distance into the natural fracture system.

The stress regime at United Downs is expected to be very similar to the Rosemanowes HDR site and, therefore, downward migration of this injected fluid is also to be expected. It could also potentially be driven downwards by increasing the injection pressure temporarily. The injection well is therefore above the production well, as shown schematically in Figure 2.

The combination of factors that allows the injection well to be much shallower than the production well also has a benefit in terms of the cost of drilling which is a significant factor in the proof of concept.

Based on temperature estimates and possible fracture characteristics, the project aims to produce water to surface at a target temperature of 175^{O}C and circulate at a flow rate between 20 and 80 l/s. This would produce between 1 and 3MWe (net) using a conventional binary power plant

The drilling rig was mobilised during October 2018 and drilling of the production well (UD-1) started on 8th November. Casing points were reached in late November (250m), late December (900m) and late March 2019 (4,000m). The well reached its total depth of 5,275m (MD) on 26th April. Geophysical logging runs were made before the 4,000m casing point and at TD.

The pre-drilling geological prognosis estimated the top of granite to be 500-700m below surface, based on inverted gravity data and estimations from surrounding mine workings. In practice, the contact zone between Killas and ‘true’ granite was within 100m of the prediction but its nature was more complicated than expected.

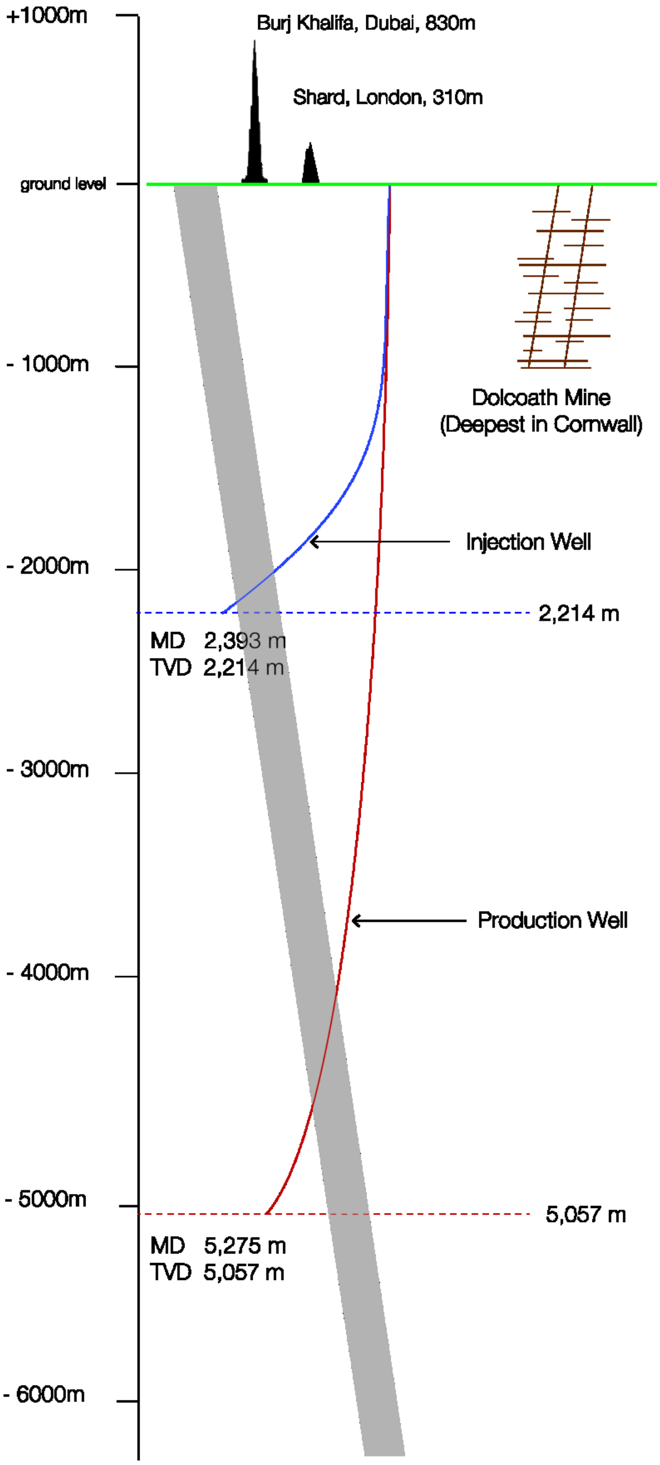

Figure 2: Schematic of the UDDGP concept showing idealized well intersections with the PTF

In the top 1,000m of UD-1 a number of predicted mineral lodes and cross-course structures (NNW-SSE striking features) were encountered. More importantly, the target fault structure was intersected in the 8 ½" open-hole section between approximately 4,100m and 4,700m.

The rig was skidded to the second well location on 6th May and drilling of UD-2 commenced on 11th May. Casing points were reached in late May (804m) and mid-June (1,820m) and drilling was finished at the end of June with the well at a depth of 2,393m. This was shallower than originally planned and was partially the result of a drill bit disintegrating downhole. Since the well had already penetrated almost 300m into the fault zone and an injection test showed that there was permeability, it was decided not to attempt a fishing operation and continue drilling.

At the time of writing (July 2019) the drilling rig was being demobilised and preparations being made for a period of well testing to determine the reservoir characteristics and estimate the long term sustainable energy production from the system.

3. SEISMIC MONITORING

The seismic monitoring networks installed at the 1980s Hot Dry Rock geothermal research project in Cornwall, and at other HDR and EGS sites since then, have provided valuable information about the distribution of injected water and the shape and size of the geothermal reservoir. There is therefore an engineering imperative for installing such a system at UDDGP to understand how the reservoir develops within the PTF.

However, there is also an 'environmental' imperative to carry out monitoring because of public concern over induced seismicity, specifically relating to unconventional oil and gas developments; the so-called 'Fracking' projects. Although the UDDGP concept depends on pre-existing natural fractures, there is still a degree of mistrust about any projects that involve deep drilling and the circulation of water underground. As a result there is a need both for seismic monitoring and for a monitoring and control protocol. This was also a condition in the planning consent for the project.

3.1 Monitoring and control protocol

In 2016 Cornwall Council adopted a set of guidelines to provide advice to renewable energy projects within the county, following a period of consultation with stakeholders and potential developers. During the consultation period geothermal developers advocated that surface ground vibrations should be used as the basis for controlling induced seismicity, rather than event magnitudes, which was the approach that had been adopted by the UK Oil and Gas Authority to manage unconventional oil and gas projects. The Planning Authority accepted that this was a more appropriate and robust approach and adopted it in their guidelines.

Within its planning framework Cornwall Council uses British Standards (BS) to define operational limits on the ground vibrations associated with industrial processes such as mining, tunneling and quarry blasting. The British Standard most relevant to the UDDGP is BS 6472-2:2008 - A guide to evaluation of human exposure to vibration in buildings, Part 2: Blast-induced vibration (BS 6472-2:2008). These standards relate to Peak Ground Velocity (PGV) measured at surface.

Accordingly, UDDGP's Monitoring and Control of Induced Seismicity (MACIS) protocol is based on Peak Ground Velocity (PGV). Four relevant PGV levels are considered in the determination of trigger points for making changes to project operations.

There are three 'Operating States':

A **Normal** operating state is the default situation, and will continue as long as there is no induced seismicity or if any measured seismicity results in a PGV of less than 0.5mm/s.

A **Caution** operating state will be triggered if any seismicity results in a PGV of 0.5mm/s or above, without it reaching a level sufficient to trigger an **Action** operating state.

An **Action** operating state will be triggered if any of the following conditions occurs:

- three or more events with PGV of 2mm/s or above within a 12 hour period;
- a single event with PGV of 4mm/s or above outside working hours; or
- a single event with PGV of 8.5mm/s or above within working hours

In the protocol it is noted that 2mm/s is generally regarded as the limit of human perception (BS 6472-2:2008) and working hours are defined as 8am-6pm Monday to Friday and 8am - 1pm on Saturday, whereas Sundays and public holidays are defined as outside working hours.

Although the MACIS protocol is defined in terms of ground motion it is nonetheless operationally convenient to utilise equivalent magnitudes as a preliminary alert mechanism for possible increases in ground vibration. Since event magnitude calculation requires the merging of results from multiple sensors it helps avoid false alerts resulting from localised vibration sources at surface, such as other human activity, road traffic or weather conditions.

A base Ground Motion Prediction Equation (GMPE) has therefore been used to estimate the 'equivalent magnitude' of events at a depth of 2.5km that would generate the relevant PGV levels discussed above at surface, at the +1σ level. The GMPE is adopted from Douglas et al (2013) and has a standard functional form (Equation 1) accounting for first-order effects of magnitude scaling, near-source saturation, geometrical spreading, and anelastic attenuation

$$Ln\,Y = a + bM + cln\sqrt{R_{hyp}^2 + h^2} + dR_{hyp} \quad (1)$$

where M is the moment magnitude (Mw), R_{hyp} is the hypocentral distance and Y is the response variable corresponding, in the UDDGP case, to PGV. The constants a, b, c, d and h are regression coefficients obtained by Douglas et al (2013) from the compilation and analysis of induced seismicity data from a mix of geothermal and hydrocarbon production activities. It is the intention that this GMPE and the regression coefficients be continually reviewed for suitability as data is collected at UDDGP.

For reference, a predicted PGV of 0.5mm/s would result from a magnitude 0.5 event, at the +1σ level of the base GMPE. The equivalent magnitudes for the other three relevant PGV levels are 1.4, 1.8 and 2.3, respectively, also at the +1σ level of the base GMPE.

The MACIS protocol represents a conservative approach. Even the highest PGV trigger point is much lower than the value likely to be required to cause cosmetic damage to buildings, which is estimated to be 15mm/s by BS 6472-2:2008.

3.2 Target specification of the monitoring system

The key performance requirements of the monitoring system were:

- A complete microseismic catalogue down to at least magnitude 0.0 at a depth of 5km within the immediate vicinity of the operations. Within a larger 10km by 10km monitoring area a minimum of magnitude 1 was considered acceptable.

- Event locations within the immediate vicinity of the operations should have depth location uncertainty (95% confidence) less than 250m and better than 500m in the larger 10km by 10km area. In both cases it is acknowledged that the epicentre location uncertainty will be lower than the depth uncertainty.

It was felt that these targets could probably be achieved using a surface network of broadband seismometers, although it was considered fairly close to the limits of performance. The key factor would be achieving a sufficiently low background noise-floor within a quite heavily populated area. If acceptable noise levels could not be achieved then it might be necessary to deploy shallow borehole sensors in some or all stations within the network. This would ensure the requirements were met, but would add to the overall complexity and cost of the project.

The approach was therefore to initially deploy a small network of surface seismometers at carefully selected sites as a base-case. After evaluating the system performance the decision could then be made whether to replace some or all stations with borehole sensors. In most cases the noise floor was found to be low and the performance requirements could be met with the surface array. However the decision was subsequently made to aim, ultimately, for a small sub-array (4) of borehole stations which should increase the overall diagnostic capability of the system by detecting events well below the minimum requirement.

4. SYSTEM DESCRIPTION

The surface sensors are Guralp 6T lightweight tri-axial force-feedback broadband seismometers. These have a flat frequency response between 1Hz and 100Hz. They are analogue instruments and digitisation takes place using low-noise Guralp 24-bit digitisers. In the UDDGP system we use both DM24 units and the newer Minimus compact digitisers. The data sampling rate during the background monitoring phase was 200Hz, but this was increased to 500Hz at the start of drilling. The increased sample rate was also in preparation for the planned addition of the borehole sensors.

The seventh station (GEL07) was a trial installation of a tri-axial low-frequency (4.5Hz) borehole geophone unit at approximately 80m depth on the UDDGP site. This is Geospace Technologies Inc GS-One LF tri-axial unit. This is also an analogue instrument and signals initially pass through a low-noise amplifier before being digitized by the same Guralp digitiser units as the surface stations.

Data transmission uses dedicated 4G/LTE mobile modems at each station. The data transfer protocol is SEEDlink and continuous data records are stored in a headerless SEED format (miniSEED) archive, along with separate instrument response (RESP) files. The archive data is then made accessible to the BGS and other partners using a commercial file-sharing service.

At most stations the equipment is powered by 12V deep-cycle batteries, with continuous recharging via solar-panels. However at some sites mains power is available and is used to charge 12V back-up batteries that power the equipment. An example of a surface seismometer site (GEL04) and the UDDGP borehole site (GEL07) are shown in Figure 3.

Figure 3: Photographs of two UDDGP microseismic stations. A) a broad-band seismometer station powered by 12V deep-cycle batteries, with continuous recharging via solar-panels. B) a borehole geophone station using mains power and backup batteries. The wellhead standpipe is blue and the black conduit carries the geophone cable underground into the instrumentation cabinet.

There are also currently three strong-motion devices capable of recording unsaturated signals in the case of large events. These are Kinemetrics ETNA-2 units, which are tri-axial force balance accelerometers with a bandwidth from DC to 200Hz and a system dynamic range ~139dB at 100Hz sampling rate. These also stream real-time data back to the central acquisition system via the SEEDlink protocol.

Figure 4 below shows the layout of the microseismic monitoring system, which currently consists of eight stations. GEL07 is the borehole sensor at the UDDGP drill site and the red 500m radius circle shows the approximate location of the subsurface target. For reference, the red square is the 10km x 10km overall monitoring area.

The data acquisition and processing system used in the UDDGP project runs on a remotely hosted server, which removes the need for a physical data centre and provides easy internet access to the data. The incoming SEEDlink data streams are first merged by the data acquisition system into a data ring-buffer. Signal conditioning and event-detection algorithms are then applied. Short sections of the waveform data (40s) are extracted around the event detection times (triggers) and these data are used for subsequent data processing. This involves picking of Compressional (P) and Shear (S) wave phase arrival times, event location and the calculation of source parameters, such as magnitude. The data is then available in real-time via a relational database and via a web portal.

Although Moment Magnitude (Mw) is frequently used to express microseismic event magnitudes UDDGP have decided to routinely use a Local Magnitude (ML), which is consistent with the approach adopted by the BGS for the UK natural seismicity catalogue (Luckett et al 2019, Kendall et al 2019).

Following Luckett et al (2918) the addition of an exponential term to the standard local magnitude scale reduces the overestimation of magnitude at short distances and improves consistency with results from the BGS national network. This new scale can therefore be used at all distances with a smooth transition between short and long distances. The BGS is now using this exponential term (Equation 2) when calculating all local magnitudes (M_L) for UK earthquakes.

$$M_L = Log(A) + 1.11Log(r) + 0.00189r - 1.16e^{-0.2r} - 2.09 \tag{2}$$

Where A is the displacement amplitude in nanometers and r is the hypocentral distance in kilometers, respectively.

Although there were some concerns about sensor deployment within a quite heavily populated area the general background noise-floor that has been achieved is quite low, typically <0.3μm/s. However there are frequent noise events at individual stations, which can randomly correlate within the event detection window. Therefore the system can suffer from bursts of false triggers. We are continuing to work on this aspect of system performance and hope to improve on event/noise discrimination once there is a reasonable sample of geothermal related seismicity to calibrate the system against. Nonetheless the overall noise-floor is better than anticipated.

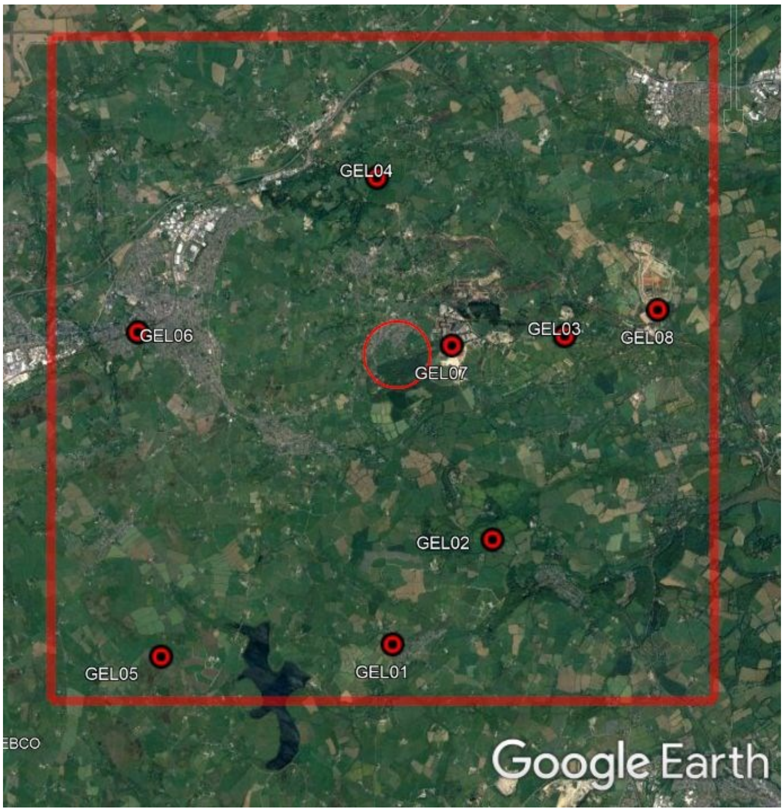

Figure 4: Google Earth image showing the layout of the eight microseismic stations, where GEL07 is the borehole sensor on the UDDGP drill site. The red 500m radius circle indicates the approximate location of the subsurface target and the red square the 10km x 10km overall monitoring area.

The system became operational for background monitoring in May 2018, providing approximately 6 months of data before the start of drilling. During the background monitoring period the detected seismicity mainly consisted of blasting associated with quarrying to the South-East of the monitoring area and a cluster of approximately 20 natural earthquakes over a few days in September 2018. These occurred within a previously documented earthquake swarm area (near Constantine) that periodically becomes active. The event depth range is approximately 7.5 -> 8.5km and magnitudes between 0.5 -> 2.3. Several of these were also detected and located by the BGS national network. There were also a few more distant regional and national natural events detected by the system.

Significantly there was no seismicity detected within the UDDGP monitoring area during this background monitoring phase.

The Constantine natural seismicity also provided an opportunity to verify the sensitivity of the system with a deep seismic source, even in the absence of seismicity within the UDDGP area. During the design phase numerical modelling had been used to predict magnitude sensitivity based on assumptions of background noise and seismic attenuation.

Figure 5 below shows the predicted sensitivity at 8km depth based on the 5-stations operational at the time of the Constantine seismicity. This predicts a detection limit of approximately magnitude 0.5, which is very similar to the smallest detected events within the Constantine swarm. This implied that the system was performing as expected but, more importantly, that the absence of seismicity within the UDDGP area was a genuine observation and not due to a lack of network sensitivity.

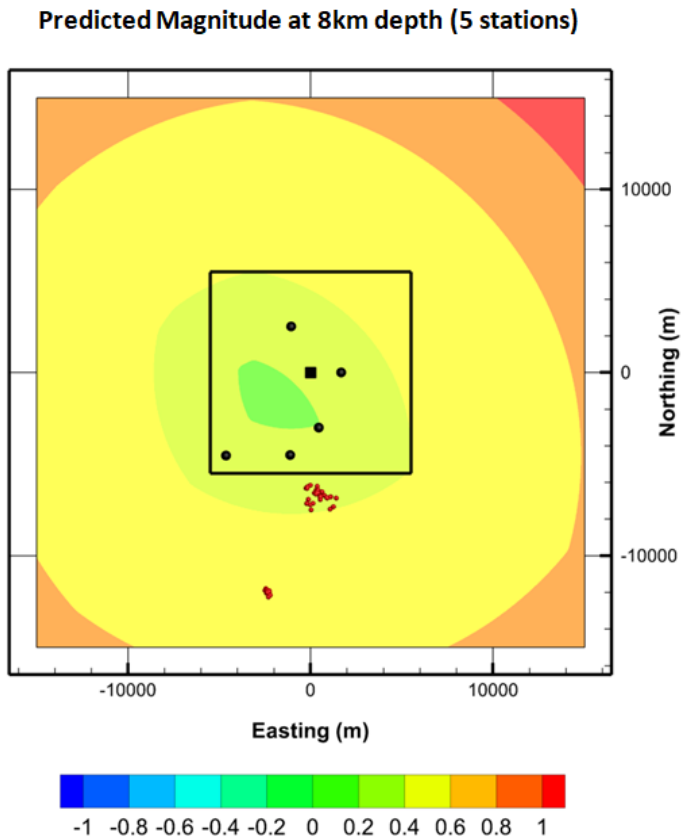

Figure 5: Predicted network sensitivity at 8km depth based on the five-stations operational at the time of the Constantine natural seismicity. Contours are minimum magnitude threshold. The red points to the far South are the Constantine earthquake swarm, where the magnitude threshold is approximately 0.5. The black points are the stations and the black square the UDDGP site. The black box is the 10km x10km monitoring area.

5. MONITORING RESULTS

In the few months prior to the start of drilling, additional sensors were added and the network currently consists of 8 stations (Figure 4).

During most of the drilling of UD-1 there was no observed seismicity, apart from ongoing quarry blasts and occasional regional seismicity. However during the drilling of the final production section of UD-1 a few small events were detected within the UDDGP monitoring area by the real-time detection system. These are shown in yellow in Figure 6 below, along with the previously discussed quarry blasts (white) and the Constantine seismicity (purple). The first event was detected on 5 April and three more on 16 April 2019, with the latter occurring during a period of mud loss.

The local magnitudes (M_L) for the events range between -1.0 -> -0.5 and with low observed ground velocities (<0.015mm/s) recorded on the seismometers. Subsequent re-triggering of the continuous data records using a more refined trigger algorithm identified a further 10 smaller events within the same clusters, with M_L extending below -1.5.

Although this data sample is small it indicates that the sensitivity of the system significantly exceeds the design specification of magnitude 0.0 within the immediate vicinity of the operations.

At the time of writing the current objective is to identify three additional sites for 100m deep borehole stations, which should further increase the network sensitivity within the vicinity of the boreholes. It is hoped that the increased sensitivity will then enable the monitoring to fulfill a valuable diagnostic role during the planed injection testing, as well the primary role in induced seismicity mitigation.

6. CONCLUSION

Preliminary results from the UDDGP drilling are promising. The wells intersect the fault at vertical depths of approximately 2,200m (injection well) and 4,500m (production well). The bottom-hole temperature is expected to be in the region of 190^{O}C, which should support electricity generation of between 1 and 3WMe.

The next phase in UDDGP is to carry out a series of measurements and hydraulic tests in order to evaluate the fault structure, make sure the wells are in good condition, and evaluate the amount of geothermal energy that can be sustainably produced by the system.

This phase is to take place between August 2019 and the end of March 2020.

During well testing and long-term circulation it is expected that low level seismicity will be induced by pressure changes in the fracture system. During these phases the microseismic monitoring system will serve both as a diagnostic engineering tool and to address public concerns over induced seismicity.

The UDDGP Peak Ground Velocity (PGV) based Monitoring and Control of Induced Seismicity (MACIS) protocol will operate throughout these operations in order to help protect the surrounding community from disturbance.

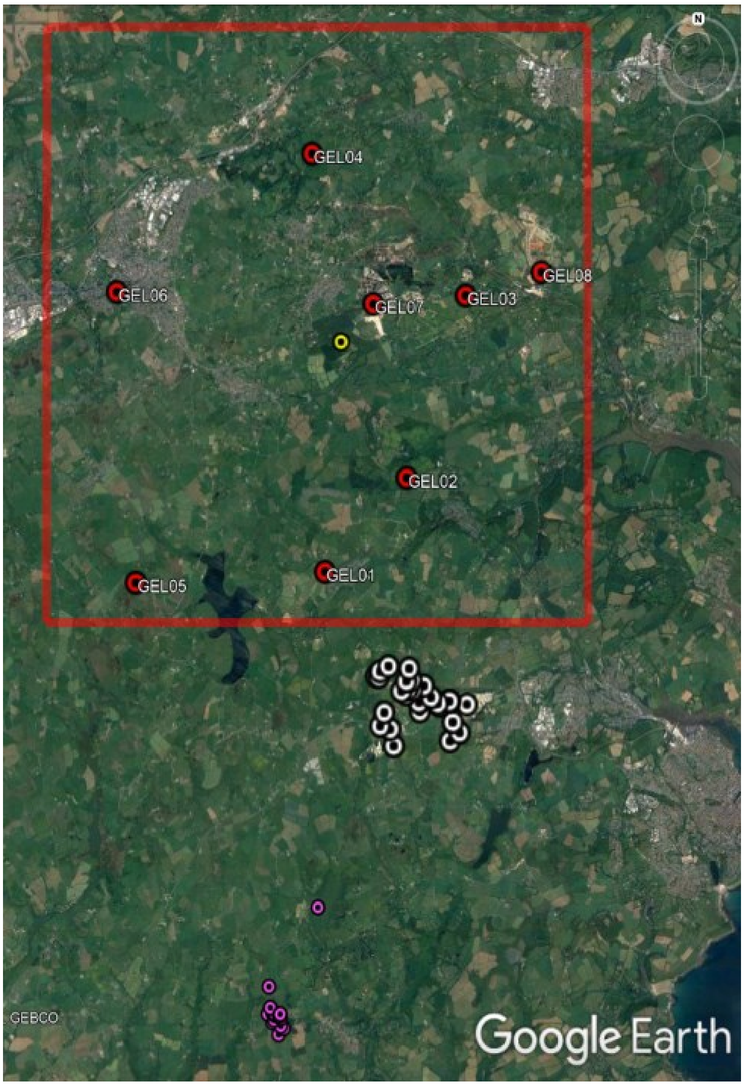

Figure 6: Google Earth image showing the location of the UDDGP associated seismicity (yellow points), where GEL07 is the borehole sensor on the UDDGP drill site. The red square is the 10km x 10km overall monitoring area. Also shown are the quarrying related blasts (white points) and the Constantine swarm (purple points).

REFERENCES

BGS (British Geological Survey) Geothermal energy – what is it? www.bgs.ac.uk/research/energy/geothermal/, (2019)

BS 6472-2:2008 - A guide to evaluation of human exposure to vibration in buildings - Part 2: Blast-induced vibration, British Standards Institute, (30th June 2008)

Douglas, J., Edwards, B., Covertito, V., Sharma, N., Tramelli, A., Kraaijpoel, D., Cabrera, B., Maercklin, N., and Troise, C.: Predicting ground motion from induced earthquakes in geothermal areas, Bulletin Seismological Society of America, 103, 3, (2013), 1875-1897.

Kendall, J., Butcher, A., Stork, A., Verdon, J., Luckett, R., and Baptie, B.: How big is a small earthquake? Challenges in determining microseismic magnitudes, First Break, 37, 2, (2019), 51-56.

Luckett, R., Ottemoller, L., Butcher, A., and Baptie, B.: Extending local magnitude (M_L) to short distances, Geophysical Journal International, 216, (2019), 1145-1156.

Parker, R.: Hot Dry Rock Geothermal Energy, Phase 2B Final Report of the Camborne School of Mines Project, 1–2, (1989), Pergamon Press, Oxford, UK.

Parker, R.: The Rosemanowes HDR project 1983-1991. Geothermics, 28, 4/5, (1999), 603-615.

Pine, R. J. and Batchelor A. S.: Downward migration of shearing in jointed rock during hydraulic injections. International Journal Rock Mechanics, Mining Sciences and Geomechanical Abstracts, 21, 5, (1984), 149-263.

Richards, H., Parker, R., Green, A., Jones, R., Nicholls, J., Nicol, D., Randall, M., Richards S., Stewart, R., Willis-Richards, J.: The performance and characteristics of the experimental hot dry rock geothermal reservoir at Rosemanowes, Cornwall (1985–1988), Geothermics, 23, 2, (1994), 73-109.