Ref. Ares(2022)4768586 - 29/06/2022

D8.1 Petrophysical interpretation report

Deliverable No	D8.1
Work package No. and Title	WP8 Petrophysical interpretation report
Version - Status	V1.0
Date of Issue	30/05/2022
Dissemination Level	PUBLIC
Filename	D8.1 Petrophysical interpretation report

This project has received funding from the European Union's Horizon 2020 research and innovation action under grant agreement No 101006964

DOCUMENT INFO

Authors

Author	Organization	e-mail
Andrew Kingdon	BGS	aki@bgs.ac.uk
Mark Fellgett	BGS	markf@bgs.ac.uk
Shahin Jamali	IEG	shahin.jamali@ieg.fraunhofer.de
Alex Hall	BGS	ahall@bgs.ac.uk

Document History

Date	Version	Editor	Change	Status
30/05/2022	V0.1	Andrew Kingdon	Table of contents	Draft
07/06/2022	V0.3	Andrew Kingdon	Completion of key sections	Draft
28/06/2022	V0.4	Shahin Jamali	Revision	Draft
29/06/2022	V0.5	Mark Fellgett	Revision	Draft
29/06/2022	V0.6	Shahin Jamali	Revision	Draft
29/06/2022	V0.7	Andrew Kingdon	Summary	Final Draft
29/06/2022	V0.8	Mark Fellgett	Summary Revision	Final Draft
29/06/2022	V0.9	Shahin Jamali	Final Revision	Final
29/06/2022	V1.0	Andrew Kingdon	Final	Final

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Drilling conditions are dependent upon geological variability which can be understood prior to and the drilling process through geological and geophysical parameters. WP9 will study the geological factors that determine drilling performance based on data derived from a variety of legacy boreholes and the impacts of geological information on the optimisation of the drilling process.

This report describes the collation of necessary petrophysical data from legacy well datasets that will be needed to inform such modelling. Necessary parameters for inclusion are listed, then datasets are assessed against this list to determine the most appropriate test datasets. An optimal dataset has been identified. Then as a first step towards real-time modelling of drilling performance this report describes as test application of ML analysis to detect anomalies in petrophysical data. Later stages of this work will extend this analytical process to inform an understanding of the geological effects upon the drilling process in real-time.

1. INTRODUCTION

Drilling to significant depth (>400 m) is an expensive process. Whilst the deep subsurface offers potential of significant resources to decarbonise energy production, making the economic case for initiating a project is hard due to uncertainties caused by limited subsurface data. Finding ways to minimise cost of drilling is a key requirement for more effective costs estimation for future low carbon drilling projects, such as deep geothermal wells which are the focus of this report.

A key factor on the cost of drilling is the nature of the geology to be drilled through. Not only are some rock much harder to drill through than others (“drillability”) requiring different drilling parameters but as drilling progresses through one unit into another with different drilling properties, there is a possibility that damage to the bit and drilling system at such interfaces. For example the variation in properties between lithologies can cause excessive wear of the bit, or other effects. Optimising the drilling conditions requires a clear model of the thickness and properties of the drilling formation to allow the drill parameters to be optimised for minimum wear across the interfaces between as well as through various lithologies. This report describes the firsts application of understanding the geological parameters and their impact on optimising the drilling process.

Sudden changes in lithological properties, including excessive pore pressure, is a major issue when planning and implementing a drilling programme. Whilst rock strength/hardness has a direct effect on drill bit performance, this is quite quickly recognised at surface. The three drilling parameters that the driller has most control over is Weight on Bit (WOB), Revolutions Per Minute (RPM) and Flow (by pumping drilling fluids or air). Torque is exponential (mostly) to controlling these three parameters. Excessive torque, is a vital indicator that something is wrong, leading to problems. Knowing precisely where torque effects are being generated in a wellbore would be hugely beneficial as they are not always at the bit/formation interface. Sudden changes in formation strength are also a major issue, especially when going from hard to soft, as it can easily lead to formation damage and stuck drill strings (excessive mud weight – hydrostatic pressure is also an issue). Freeing stuck drill strings can be a major source of lost time, optimising drilling parameters to avoid these situations is liable to result in significant overall time savings. Advances in sensor technologies and data assimilation in real-time has the potential to greatly reduce risks associated with deep drilling in new “fields” with minimal offset well data.

This report summaries the data discovery for predicting likely drilling prospects from legacy drilling data. This legacy data is derived from a number of sources. However, the largest component is from hydrocarbon exploration, in particular in the context of this report an example dataset derived from the Equinor Volve field. This data may not geologically be as relevant to geothermal operations. However, rig day rates represent a substantial component of the cost of drilling any well. This report seeks to identify downtime in the drilling process from legacy data based on the respective petrophysical properties and investigate the causes so that these can be minimised to optimise operational time and improve cost models.

Deliverable 5.4 focuses on the processing of drilling parameters and how ML methods can be used to identify anomalous sections of petrophysical data. This report discusses the application of the same algorithmic methods of understanding anomalies in petrophysical data. This report therefore only describes the first iteration of these tasks. In the upcoming processing phase these tools will be applied on a log-by-log basis across a standardised suite of geophysical log data to understand the ability of these data to determine those geological properties that affect the likely drilling parameters.

2. DATA SUMMARY

2.1 Requirement analysis

Characterisation of any drilling operation requires the recording and supply of a number of parameters downhole. To be of use to the project and the requirements of AI models' development, without significant cost to the project, this information needs to be in a format that can be easily interrogated using automated means. Ideally a well will have information on both the drilling and the subsurface geology. This geological information is required to contextualise the drilling information as well as build models to predict subsurface behaviour and its ultimate effect on the overall drilling process. Key datasets for understanding the geological environment include:

- Mudlogging and chipping analysis
- Drill Core
- Conventional geophysical well logs and /or Logging While Drilling (LWD)
- Drilling parameters
- Measurement While Drilling (MWD)
- Records of the drilling process, for example Daily Drilling Reports (DDR)

2.1.1 Mudlogging

The drilling mud is used to enable cutting lift but also lubricates the bit, cools the drilling assembly. It is also critical to prevent fluid ingress into the borehole and in some formations such as evaporites can reduce dissolution. This is achieved by varying the properties of the mud, including its density, salinity and PH. Mudloggers monitor the drilling mud and also the returned cuttings. They also automatically monitor production gases which can be key to the safety of the drilling crew. Mud parameters are increasingly recorded digitally and exported frequently in company specific spreadsheets, pdf's and Wellsite information transfer standard markup language (WITSML). Analysis of chippings forms the simplest methodology of parameterising the geology but, due to the mixed nature of the sample it can be difficult to pinpoint lithological changes from cuttings.

2.1.2 Drill Core

Drill core remains one of the most critical well based datasets for understanding the geology. Information from core can be used to interpret depositional environments, identify key changes in fracturing or cements and understanding the engineering properties of the geology. In addition to this non-destructive analysis through core scanning opens up new datasets to characterise the subsurface. However, drill core is expensive to collect and in some geothermal projects core has not been collected such as the United Downs site in Cornwall UK (Reinecker *et al*., 2021). Even where core is collected it is usually only targeted at specific intervals of interest. As much of the core archive is collected from hydrocarbon exploration boreholes it targets reservoir sections rather than areas that can cause significant issues to drilling such as the thick evaporites in the Zechstein formation in the North Sea.

2.1.3 Geophysical well logs

Given the difficulties in accurately locating rock chippings back into their true downhole depth and a lack of available core, other methods need to be used to understand the geology. One of the key methods used are geophysical measurements taken from wireline logs. Geophysical logging using sensor tools (sondes) lowered down holes recording geophysical parameters using a standardised suite of tools which are used to record variation in sedimentology, structure and stratigraphy. Standard tools record properties at depth increments of 1 – 15 cm with some specialised tools recording every 2 – 5 mm (Kingdon *et al*., 2016). Geophysical logging data has traditionally been recorded at the end of the drilling process with each wells section logged and reported separately and then subsequently integrated into a whole. In hydrocarbon exploration geophysical logs will frequently cover the majority of the well by depth. However, the number of tools and the type of information collected with vary. Usually the wireline logging from hydrocarbon explorations is again focused on the reservoir sections with a reduced number of tools outside of this. This is however also true of the logging at the United Downs geothermal site (Reinecker *et al.*, 2021).

In upper borehole sections or sections without reservoirs, the typical geophysical logging suite that is acquired includes:

- Temperature to measure the temperature of the formation
- Gamma Ray to measure the natural gamma rays given off by the formation allowed geological correlation between formations with the relatively low natural levels of radioactivity, for example carbonate rocks and clastic sediments, and relatively high natural levels of radioactivity for example mud rocks made up from a high proportion of clay materials. Sometimes spectral gamma ray tools are used which allows identification of radioactive decay from Uranium, Thorium and Potassium which allows a more accurate lithological understanding of rock materials.
- Sonic (velocity) which will certainly incorporate compressional (P-Wave) logs but may also include Waveform Sonic to measure Shear waves (S-Waves) and Stoneley wave

The primary objective of the logging in these upper zones are stratigraphic identification and correlation, often with a focus on marker horizons. The primary measurements of these sections are qualitative with interpretation undertaken by comparison of geological successions with other equivalent sections with limited recording of quantitative parameters

Zones of detailed investigation for example hydrocarbon reservoir zones are typically logged with a much more complete logging suite. As well as stratigraphic correlation this logging suite allows an understanding of the quantitative parameters which facilitate geological parameterisation. This highlights the properties that affect the behaviour of these rocks in the subsurface including porosity, permeability, and capacity to inhibit or facilitate the movement of fluids.

Detailed list of parameters measured by geophysical logging:

- Temperature
- Gamma Ray (GR) / Spectral Gamma Ray
- Sonic (velocity) which will certainly incorporate compressional (P-Wave) logs but may also include Waveform Sonic to measure Shear waves (S-Waves) and Stoneley wave
- Density logs which uses gamma-gamma Compton scattering to measure a proxy of formation bulk density
- Neutron logging that exploit neutron scattering to estimate total porosity for the formation
- Direct resistivity (Laterolog) or Induction resistivity to measuring the formation resistivity at different depths of investigation including micro-resistivity measurements to understand mudcake and mud filtrate invasion effects.
- NMR logging, measures the induced magnet moment of hydrogen nuclei (protons) contained within the fluid-filled pore space of porous rocks). Unlike other logging tools (e.g., acoustic, density, neutron, and resistivity), which respond to both the rock matrix and fluid properties and are therefore influenced by mineralogy, NMR-logging measurements respond to the presence of hydrogen protons that occur primarily in pore fluids, so NMR effectively responds to the volume, composition, viscosity, and distribution of these fluids. It is used to determine porosity fractions and permeability.

2.2 Digital Well data

Deep wells in the are increasingly drilled using instrumented drill assemblies or tools fitted behind the drill bit in the Bottom Hole Assembly (BHA) assemblies with mud pulse links in order to transmit information back to the surface in near real time. This allows accurately recording of digital data throughout the drilling process which is transmitted to the drill floor. This process is known as Measurement While Drilling (MWD) and Logging While Drilling (LWD).

MWD is an effective continuous recording of the drilling parameters collected at bit during the drilling process. These are usually supplied to end users in combination with rig derived parameters (ROP, weight on bit etc). LWD records an array of geological parameters. Many of these measurements are similar or identical to those collected by conventional geophysical logging with the expectation that reproducing these measurements makes data integration efficient.

However, these sensors typically record a reduced set of parameters compared to a standard downhole geophysical log. This is due to vibration of the sensors caused by the drilling process alongside the acoustic interference of the drilling process itself. This results in some logs such as sonic velocity being impossible to collect. This information is available to operators much quicker than standard geophysical logs which are only collected at the end of each well section.

2.3 Petrophysics Data requirements for OptiDrill

Given the above constraints the ideal well for the OptiDrill project requires to consist of the following data including:

- A deep well
- Digital well data
- MWD incorporating ROP
- LWD with detailed geological information
- Digital daily drilling reports

Given the limited level of geothermal drilling activity in onshore Europe, there is a scarcity of any relevant data, much less a full dataset that is freely and readily available for research studies. Also, the legislation (e.g. UK Continental Shelf act 1964) and conditions attached to well data transfers associated with these data can be complex. As a trans-European project, it is essential for the OptiDrill project that data can be accessed in all partners nations and transferred to those partners to work on simultaneously with minimal restrictions over its use.

Given these competing demands, it has become rapidly apparent that these attributes necessitate the project focus on existing hydrocarbon wells and their respective datasets. It was felt that the easiest way to learn from the dataset was to utilise such a fully instrumented dataset in the first instance, and then transfer these understanding to a more incomplete historic data.

These wells are available from National Data Repositories such as the UK NDR from the North Sea Transition Authority (NSTA), DISKOS from the Norwegian Petroleum Directorate, and NLOG operated by Netherland's ministry of economic affairs and climate policy. Data access to NDR is determined by national rules but in the case of these NDR, the OptiDrill project partners have been able to negotiate access (DISKOS) or are able to openly access the data (UK NDR and NLOG). It was found that data discovery was simplest in the first instance for using DISKOS and a series of wells were identified from the Equinor Volve Field (Equinor, 2022).

The 15/9-F-9 A, Data form Norwegian NDR DISKOS was chosen as the first well for analysis. This was because it met the full requirements set out above. Another well which matched these requirements was the UK well 43/25d-03 for the Southern North Sea Endurance structure. Both of these recent well datasets represented the ideal data sets that could be used and therefore do not represent the majority of the available well datasets.

A number of additional well data sets were made available by BGS for the use of the OptiDrill programme including two open files datasets, the UKCS Hutton well datasets and the RGGE Swanworth and Metherhills stratigraphic wells. These wells are more typical of those resources that you can typically get hold of from legacy data however they have been made available under open government license meaning they can be reused by any project partner for any reason provided the data source is acknowledged. Consequently, such wells are likely to be the focus of any subsequent publications.

2.4 Historical drilling process parameters

The aim of OptiDrill is to optimise the drilling process and also identify those factors that are affecting the non-productive time taken to drill that are not directly related to the drilling process. Initially the focus has been on the optimisation of ROP value with depth as this is an expression of how the drilling process is progressing.

There can be significant changes in ROP caused by changes in hole size. Subsequently, absolute values of ROP are not useful to the project. However short wavelength variations in ROP will be a result of variations in factors such as geological, mud properties, or borehole condition.

3. PETROPHYSICAL MODELLING

Petrophysical modelling calculates parameters based on geophysical logs, such as porosity, water saturation, and lithology. For the wells of interest conventional petrophysical interpretation has been undertaken to understand geological parameters. These have then been compared with ML based anomaly detection.

Staff changes have meant undertaking the anomaly detection process upon the geophysical logs suites has made limited progress so far. The process of understanding the anomaly detection for drilling related data (reported in D5.4) has taken precedence as this provides the linkages within the instrumentation actions within the OptiDrill project. In this workstream a processing algorithm has already been applied to drilling information to better understand the drilling process.

3.1 Common petrophysical models

Given the requirements for hydrocarbon drilling the predominant use of petrophysical models is in calculation of sources rock properties and reservoir rock properties, calculations of minimal importance to geothermal drilling. Petrophysical software frequently come preloaded with functions and /or workflows to derive petrophysical parameters but these are very largely based on zones of interest for hydrocarbon exploration such as clastic silicate or carbonate reservoirs or assessment of hydrocarbon source rock quality.

Key parameters of interest to the process of geothermal drilling are rock strength and the capacity to be drilled, as this determines vibration and bit wear. Some petrophysical models predicting rock strength exist but are not widely used. This is due to the need for core samples to ground truth such models on a site by site basis. There is a pronounced need for models that predict the responses of the risks to drilling enabling these rocks to be drilled most effectively. Training of ML models will ultimately be needed to understand the appropriate drilling operations necessary to drill these sediments with maximum efficacy.

4. PETROPHYSICAL ANALYSIS

In order to reduce bias in analysis the geophysical logs supplied have been input directly into the ML workflow rather than derivations based on common petrophysical calculations. Data formats have caused problems here as the geophysical logs for the Equinor wells are provided in binary DLIS format. This is a standard format in the logging industry which cannot yet be read by the existing Python library. Currently these files have to be converted from DLIS to LAS 2.0 format in order to be useable within the current workflow. Adding this functionality to the workflow in the future would require additional work, though other DLIS to LAS converters are available.

Gamma Ray values were recorded in the MWD/LWD logging suite, so an illustrative example is demonstrated here, attempting to visualise the relationship between drilling rate anomalies and gamma ray. Although no convincing patterns are discernible here, the future use of more petrophysical parameters may yield more meaningful insights.

4.1 ROP-GR Anomaly detection

Identical pre-processing was applied to the data as for the drilling parameters analysis. As GR is used for depth matching of geophysical logs it is also the most repeated geophysical measurement downhole. As a result a larger proportion of the data was removed in the pre-processing stage. Whether this is an issue is unclear without further experimentation. However, the pre-processing parameters may be altered for future analyses – for example by reducing the number of identical values to remove from the data.

Figure 1 GR values for the F-9A well with respect to depth prior to data cleaning. Note the step change as the hole section changes, along with the visible artifacts in the data in the final hole section.

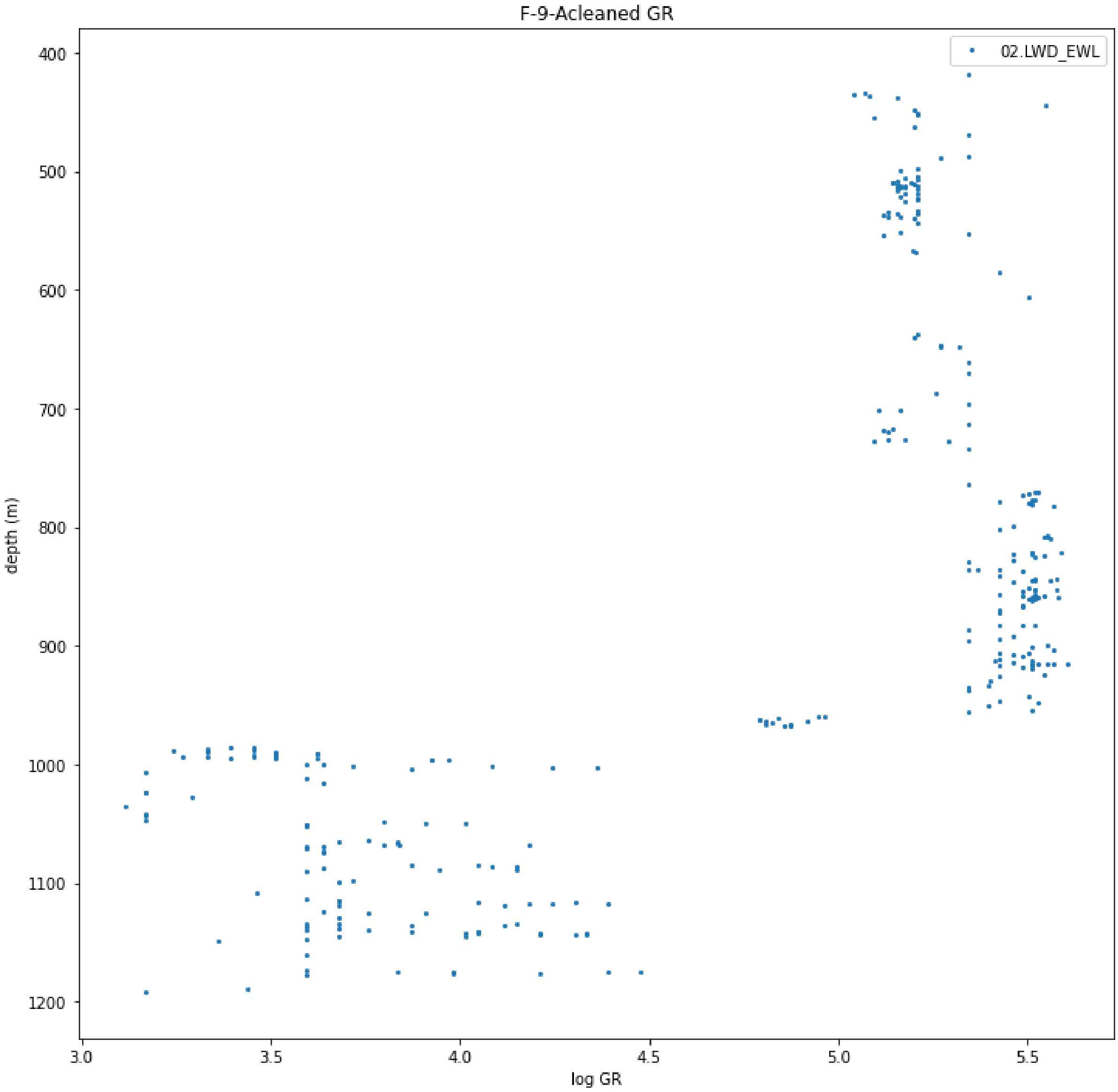

Figure 2 GR-Depth show in plot after pre-processing of the gamma-ray log to remove duplicated values.

As with the drilling anomaly analyses in D5.4, isolation forest method was used to automatically label anomalous points within each dataset, where both the ROP and GR values were considered as contributors to whether a point was an anomaly or not. Although this example was more illustrative than that of the drilling parameters, we do still see some potential points of interest:

- There are numerous anomalies towards the top of the wellbore. The GR value actually appears to be the driving factor for these anomalies, as the ROP in this section is relatively constant.
- Unlike the drilling parameters analysis, anomalies do not occur around hole section changes.
- Although the relative changes in GR are greater in the bottom hole section, ROP alone seems to contribute to whether a point is labelled as anomalous here.
- Even more significantly, the relatively constant GR values around areas of non-drilling time reduce the tendency of these areas to be flagged as anomalous. The drilling parameter analysis labelled these areas as so due to the start/stop nature of the drilling. So, using petrophysical properties in tandem with drilling parameters may actually help to moderate ‘outside effects’ and help to automatically label points which are truly anomalous and not just different because drilling recently stopped or started.

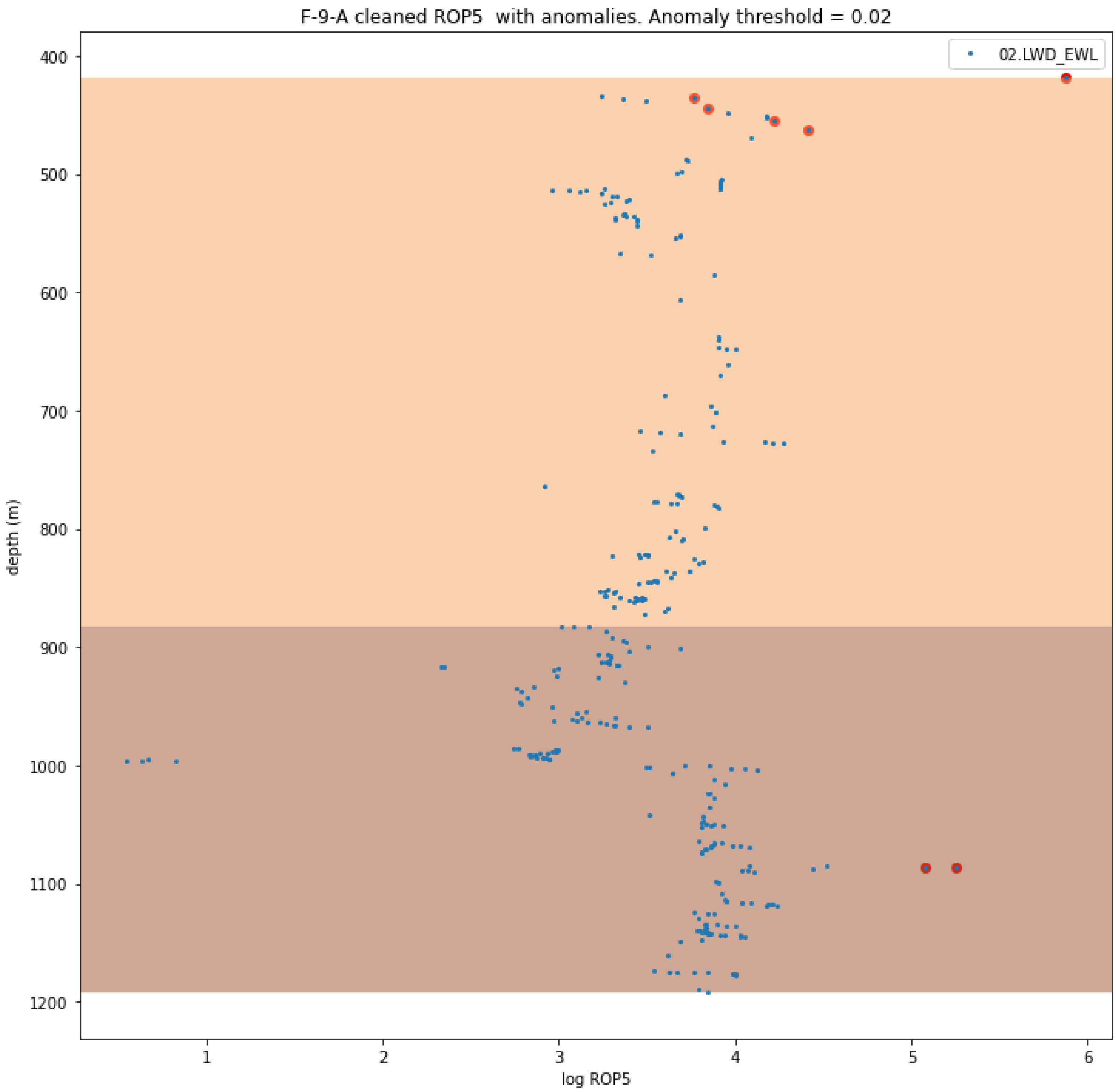

Figure 3: ROP/DEPTH with anomalous points labelled in red. Both the ROP and GR values were considered in this case to determine whether a given point was anomalous.

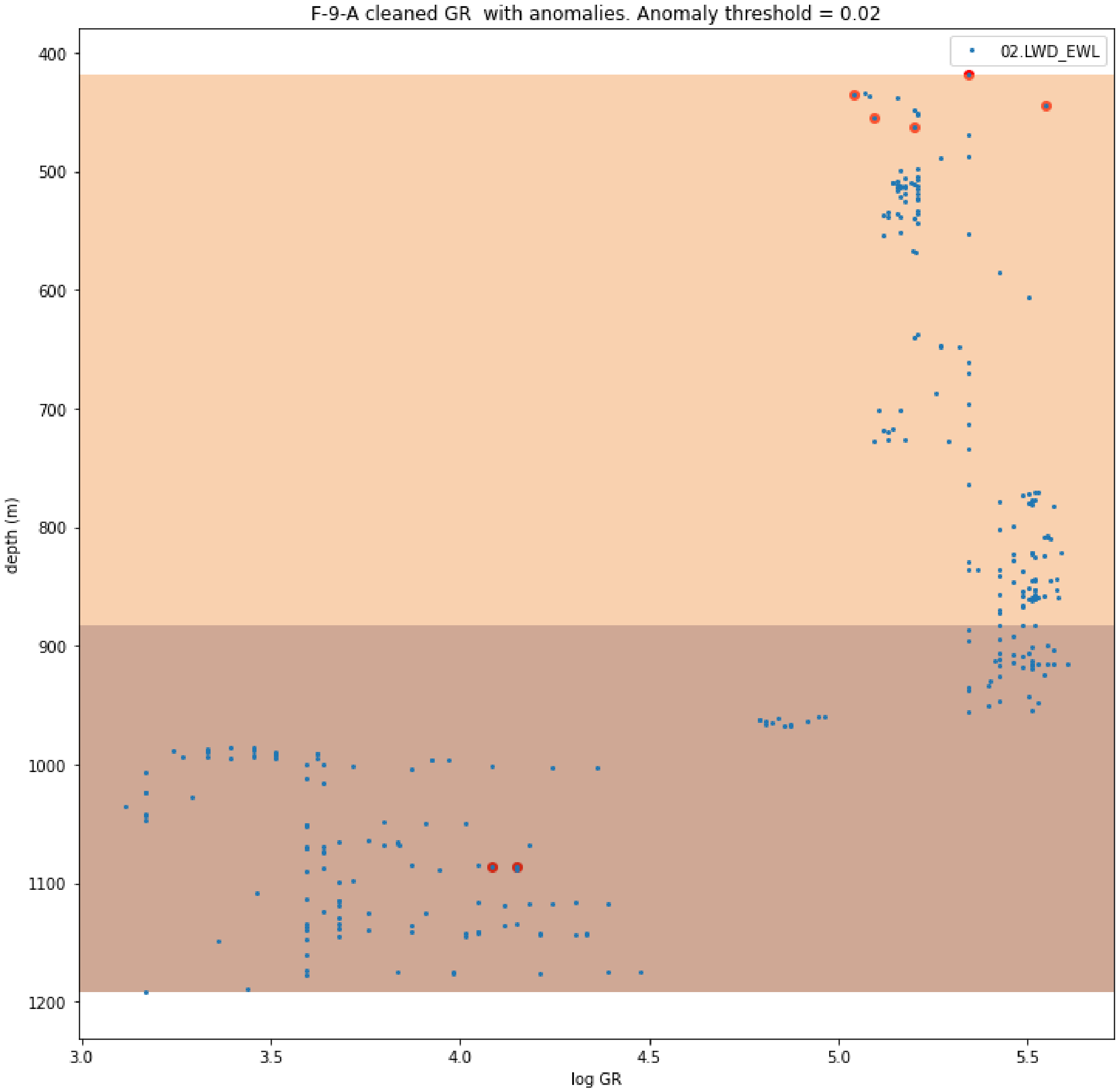

Figure 4: As Figure3 but showing GR. Note the anomalies in the lower hole section where GR does not contribute at all – there are labelled as anomalous solely due to their unusual ROP values.

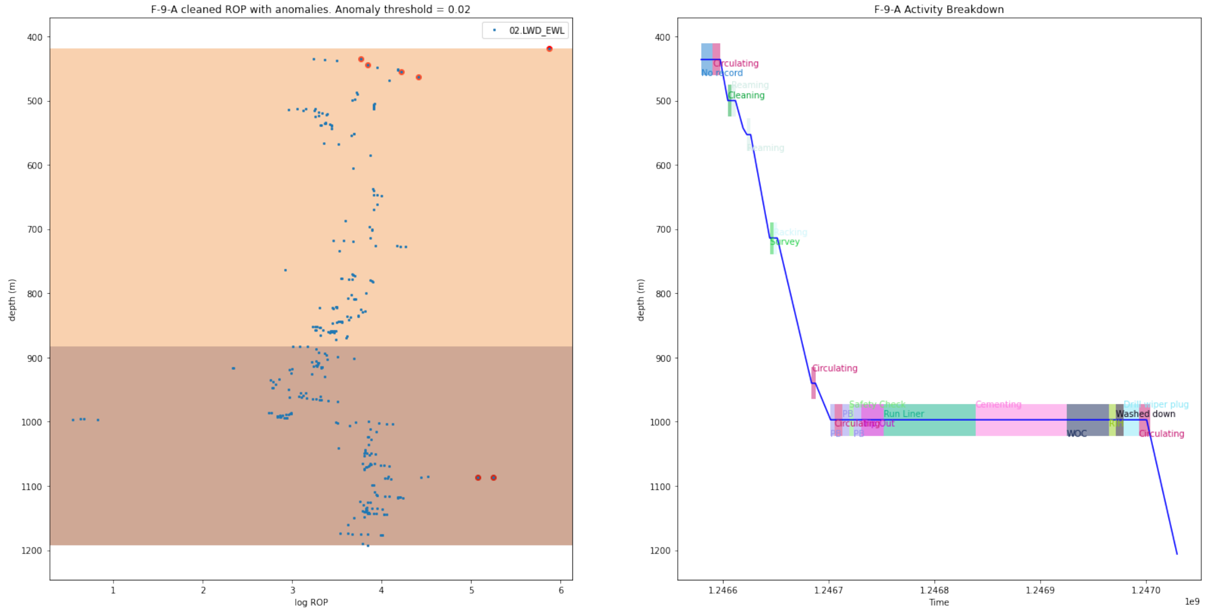

Figure 5: DEPTH-ROP plot with corresponding Gantt chart. The presence of the GR log moderated the previously anomalous ROP values around the long section of non-drilling time is noteworthy. This hints that petrophysical properties may be used as 'noise removal' for datasets of drilling data where the drilling parameters are particularly noisy.

5. CONCLUSION

This report describes what is very much preliminary work to establish the capability of the ML technique to be adapted to anomaly detection for petrophysical parameters. This needs to be optimised by application to parameters relevant to future realistic deep geothermal drilling prospects. Next steps include selection of an appropriate "test geological succession" for a realistic deep geothermal drilling concept.

Once an appropriate prospect (realistic or theoretical) is defined then this can be followed by development of an appropriate petrophysical prospect model. This model will define expected parameters sets and attributed (rock strength, and propensity to be fractured).

OptiDrill WP3 is undertaking research and development of a sensor housing with accelerometers and acoustic sensors that can be added to the existing bottom hole assembly (BHA) to monitor drilling parameters. In addition to providing greater bandwidth for transmission of conventional MWD parameters, this will also measure acoustic emissions (AE) including high and low energy vibration, and telemetering these to the driller in real-time to allow at bit drilling performance to be immediately understood. This provides the potential for AE to provide real-time data from the bit, and potentially ahead of the bit, delivering lithological understanding derived from petrophysical parameters using ML to indicate likely upcoming drilling parameters. By using legacy data to develop petrophysical models of expected lithological parameters, anomalous deviations from such expected parameter can be used to identify unexpected geological conditions such as units which are thicker or thinner than predicted, or that have different responses to monitoring than expected so enabling the driller to adjust the drilling operations to optimise drill system performance across these transitions. As data is developed from WP5 and WP these petrophysical models can be developed and tuned to more accurately predict the likely bottom hole conditions and their expected impacts upon drill system performance using a multi-variable drilling problem detection algorithm.

6. REFERENCES

Equinor, 2022. Volve field data set. https://www.equinor.com/energy/volve-data-sharing

Kingdon, A, Fellgett, M.W. and Williams, J.D.O, 2016. Use of borehole imaging to improve understanding of the in-situ stress orientation of Central and Northern England and its implications for unconventional hydrocarbon resources. Marine and Petroleum Geology, Vol. 73 May 2016, Pages 1–20. https://doi.org/10.1016/j.marpetgeo.2016.02.012

Reinecker, J. Gutmanis, J., Foxford, A. Cotton, L. Dalby, C., Law, R., 2021. Geothermal exploration and reservoir modelling of the United Downs deep geothermal project, Cornwall (UK). Geothermics V977, 102226. https://doi.org/10.1016/j.geothermics.2021.102226