A Review of Downhole Field Methodologies Applied for the Hydrogeological Exploration of Lithium Enriched Groundwater

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Abstract

This paper focusses on the type of hydrogeological testing and sampling methods applied at two UK geothermal lithium exploration sites, to define their extent and extraction potential. The results highlight the value of combining different hydrogeological, geophysical, and geochemical techniques to further the interpretation of geothermal structures. Hydraulic testing and samples from packer isolated intervals provided higher precision and higher confidence data that form the basis needed for exploration. Combing geophysical methods such as pumped impellor, Electrical Conductivity (EC), temperature, and Acoustic Televiewer (ATV) logging, provided higher resolution data, which has proved useful for the identification of controlling structures and refinement of conceptual models.

Keywords: Geothermal Lithium, Packer Testing, Geophysics

Introduction

This paper reviews the application of downhole exploration and hydrogeological testing methods for the exploration geothermal lithium brine resources for extraction, with reference to two UK case studies. In both case studies locations for exploration had already been determined based on historical records and other methods of non-intrusive exploration. The exploration boreholes in this review were part of early intrusive investigations to define this resource and plan further exploration.

Mining hydrogeologists are familiar with a number of methods to characterise the variability of hydraulic properties and flowing fractures vertically in deep rock strata. This paper explores a selection of such methods applied to geothermal lithium investigation, and how those methods provided both the requisite sampling and in combination, provided useful insights for understanding subsurface structures and flows.

The Emergence of Geothermal Lithium Resources

Increasing domestic production of lithium, amongst other minerals, is a key aim in UK's Critical Minerals Strategy for meeting future demand for battery supply. With demand exceeding supply internationally and uncertainty in complex supply chains for minerals that are generally produced outside the UK, sometimes in regions of geopolitical instability, the UK aims to strengthen its supply of critical minerals (Gov. UK 2023)

Currently the main international sources of lithium are typically brines from shallow salt lake deposits (salars) and hard rock mining. The grade of lithium found in geothermal brines is typically orders of magnitude less than such sources, yet internationally it has recently gained interest, due to the lower costs of exploration, development, and potentially, extraction. Advancements in Direct Lithium Extraction (DLE) methods, together with concerns over the environmental sustainability of existing methods has also facilitated increased interest in geothermal supplies.

The genesis and chemistry of each geothermal source is likely to be unique, and as such exploration requirements tailored as this understanding develops. Geothermal brines have the potential to be enriched in other valuable minerals such as borates, magnesium, and potassium, that could also be extracted, but they can also contain minerals that hinder the extraction process and reduce its economic value (Vera *et al.* 2023). The temperature of the fluid may be sufficient that geothermal energy can be produced and opportunity to extract the lithium is a by product to an existing process.

Practically a geothermal lithium operation can be expected to comprise of a deep abstraction well or wells, a processing plant and similar number of injection wells for the re-injection of brine once the lithium is removed. As the re-injected fluid remains saline it needs to be injected back into a suitable environment, often at similar depths as the fluid that was extracted for processing.

Hydrothermal Lithium in the UK

Through involvement with UK lithium geothermal projects in Cornwall (Cornish Lithium Plc) and County Durham (Northern Lithium Ltd), SRK has had the opportunity to apply experience in deep hydrogeological testing and sampling methods used in mine projects to geothermal lithium exploration. Hydrothermally enriched lithium groundwater in the UK is related to low-enthalpy systems developed in areas with slightly elevated geothermal gradients or where structures provide a pathway for fluid upwelling from deep within the earths crust. In the case of the North Pennines and Cornwall, the elevation in lithium is associated with the granite rock which underlies these areas.

In the North Pennines, interest in the Weardale Granite began in the early 1980s when saline water was found in Cambokeels Mine (Manning *et al*, 2007). Chemical analysis suggested these waters had originated from deep within the Weardale Granite through ascent via the main mineral vein fracture system. Subsequent investigations occurred for the purposes of geothermal exploration of targeted mineral veins, such as the Slitt Vein, and these supported the geothermal potential within the granite (Younger and Manning, 2010). The lithium analysis collected from these investigations became of interest to Northern Lithium Ltd, who commenced intrusive exploration in 2022.

Similarly, lithium was first discovered in the 'hot springs' in deep Cornish mines in the late 19^{th}-centuary derived from deep, permeable structures. Cornish Lithium is evaluating the economic viability of extracting lithium from these waters through regional exploration and targeted drilling campaigns.

Hydrogeological Characterisation Requirements

Tapping concentrated geothermal features inevitably involves deep investigation, to intercept higher grade fluids prior to dilution in shallower groundwaters. The projects in Cornwall and the Pennines were able to use historical mining or geothermal projects to initially target exploration. However, deep saline aquifer systems have limited prior characterisation with which to define possible resource extents and behaviours.

Key requirements at the exploration phase are the determination of economic lithium grades in the fluid, the sufficiency of flows from the generating structures, and the sustainability of this supply. A viable project only exists if all these elements are present. First round exploration boreholes aim to provide the information for the first of those two elements directly and supporting information for long-term supply sustainability. Supply sustainability highly depends on the connection to the underlying geothermal system that is generating the enriched fluid, thus measurements which characterise the wider geological and hydrogeological conceptual model are important, combined with sound understanding of the regional geological and structural systems.

To be an economically feasible project, it is likely that the processed or spent brine will require disposal by re-injection at the site or nearby. Approach to injection site selection is highly site specific, however practical considerations may limit the distances injection wells can be sited from abstractions. As such, detailed hydrogeological conceptual understanding of the geothermal reservoir and structural controls can be critical to minimise grade dilution at abstraction wells.

Aims of Downhole Hydrogeological Testing

Primary testing requirements for downhole exploration are those that directly determine the grade and flow of the resource in that exploration borehole. These are:

- Obtaining representative brine water quality samples, for a given depth or depth interval.
- Obtaining permeability /flow for the same interval.

Together these can be used to infer the overall solute volumes per day that can be obtained.

Several additional aims help build the conceptual model of the hydrothermal system. These include:

- Detection of key or controlling features. Both in terms of boundary and supply.
- Extent of geothermal alteration.
- Measurement of temperature and salinity profiles in-situ.
- Measurement of hydraulic gradients, both vertical and horizontal.
- Measurement of rock or fracture properties such geothermal alteration, aperture, fills and orientations and linkage of properties to target host features.
- Recording of variations of fluid in the test interval overtime.

Downhole Field Investigation Approach

The test methodology utilised is outlined in Table 1 with reference to the methodology applied at the Pennines investigation area. Similar methods have been applied in Cornwall.

In the early exploration stages orientated core drilling is recommended over rotary drilling methods due to the additional geological data that can be obtained. Fracture surfaces can be examined for traces of flow, hydrothermal precipitates and alteration as the core arises to target testing intervals. The resultant smoothness of the borehole wall formed from diamond core drilling lends itself high resolution acoustic televiewer (ATV). Diamond drilling works well with wireline packer systems to isolate intervals for hydraulic testing and water sampling, however, fluid introduction through the core drilling process needs to be taken account of.

A hydraulic through the bit packer system was selected (IPI – SWiPS®) so that the drill string would not have to be removed during testing. This enables more rapid packer deployment than conventional gas inflated or other wireline packers. The improved speed means that completing numerous single packer tests concurrent with drilling is economically viable, and therefore this was selected as the primary mode for this investigation. Straddle packer testing has also been conducted for follow-up measurements on targeted sections.

Packer isolated test intervals were sampled using a submersible pump, with inline flow through cell and logging multi-parameter water quality to obtain real-time transient readings. This process acted as a constant rate abstraction test (CRT), as well as enabling purging for sampling. The combination of packer isolation and purging equipment was selected over grab-sample methods to obtain stabilisation of the real-time monitored water quality parameters to verify sample data. This was used to confirm interference from drilling or injected fluids had been removed. Prior to the CRT phase, shut in pressure tests were also undertaken to obtain in-situ pressure of packer isolated zones and short constant pressure/head injection tests (CHT) were performed for confirmation of transmissive zones and verification readings for hydraulic conductivity (K).

Wireline geophysical methods were conducted following borehole completion. Methodologies used included ATV, impellor, electrical conductivity (EC), temperature, nuclear magnetic resonance, and resistivity logging. ATV is beneficial in conjunction with extracted core as it allows in-situ definition of structures, reducing misinterpretation of fractures in the core caused by the core handling. It also allows for interpretation of fracture aperture and orientation.

The main aim of other geophysical methods was to provide high resolution data to attempt to identify permeable structures or geothermal inflows (via EC or temperature signatures). Impellor, EC and temperature logging under pumped conditions is a procedure that aims to generate sufficient drawdown in the borehole such that flow is induced from all key fractures the borehole intersects (described further in Moltz *et al*. 1994).

Review of Performance of Testing Methods

In both test sites core drilling provided a wealth of information in terms of confining structures, hydrothermally altered rock, hydrothermal precipitates, evidence of water movement on fracture planes (via freshness/ staining / infill) and discontinuity of fracture surfaces. Visible hydrothermal alteration was often coincident with increases in salinity and lithium content, however this was not always the case, indicating that the enriched fluid had permeated through adjacent fracture systems.

Data obtained from packer isolated sections provided the principal data for confirmation of both chemistry and hydraulic conductivity variation vertically in the boreholes due to reliability and capability to undertake QA/QC measurements (Figure 1).

Single packer isolated interval carried out concurrent with drilling, enabling full testing coverage of the borehole proved to be key. This allowed for rapid repeat tests to refine intervals. Whilst a preconception of target depth or structures can be useful, testing the entire borehole is critical for a data led, non-biased conceptual model. Characterising extents of any non-productive zones is equally important for well design and contemplating potential reinjection depths.

Shorter term injection CHT tests generally proved more useful for both comparative measurements between packer intervals at a field level, as in most cases the same test pressures can be reapplied. The packer CRTs were taken over longer periods, with greater influence of vertical drainage into test section observed and potential boundary effects sometimes encountered. Therefore, the analysis of hydraulic properties was more involved and more subjective. This ambiguity makes the pumped CRTs less useful for relative comparisons. It also highlights how the simple extrapolation of total well yield from the summation packer isolated intervals could lead to overestimates in productivity if vertical flow influences are not appropriately account for in the analysis.

High head gradients can exist in geothermal zones; therefore, it is not uncommon to find strong interflows between structures in an open borehole under ambient conditions. Figure 2 shows this situation in a highly productive zone of one of the exploration boreholes. The discrete depth of a set of hydraulically active structures is well correlated between pumped and ambient EC, temperature, and impellor logs (shown by numbered horizontal red lines in Figure 2). The ambient impellor logging also shows a strong upward flow, generally from the set of structures at positions 3 and 4 to those at 1 and 2, higher in the borehole. Head pressures obtained during single packer shut-in phases illustrate the pressures in the intervals relative to ground level. These show progressively increasing groundwater pressure at depth and are consistent with the upward flows observed in the ambient impellor to the structures located at positions 1 and 2. Full

Table 1 *Field methods utilised in lithium exploration boreholes*

Field methodology	Main data targeted
Pumped samples via inflatable packer isolation	Depth dependant water samples for laboratory testing
Constant head injection (CHT) and constant rate abstraction tests (CRT) in packer isolated sections	Hydraulic conductivity (K) measurements (at same intervals)
Ambient and pumped impellor, electrical conductivity (EC) and temperature logging	Detection of location of discrete structures via flow, salinity or heat changes
Acoustic televiewer logging	Determination of in-situ fracture properties
Core sample logging	Immediate indication of rock properties (for test targeting). Lithology and confining layers. Determination of hydrothermal alteration. Fracture surface properties
Nuclear Magnetic Resonance (NMR) and Resistivity logging	Used to evaluate if useful high resolution information for hydraulic active fractures could be obtained

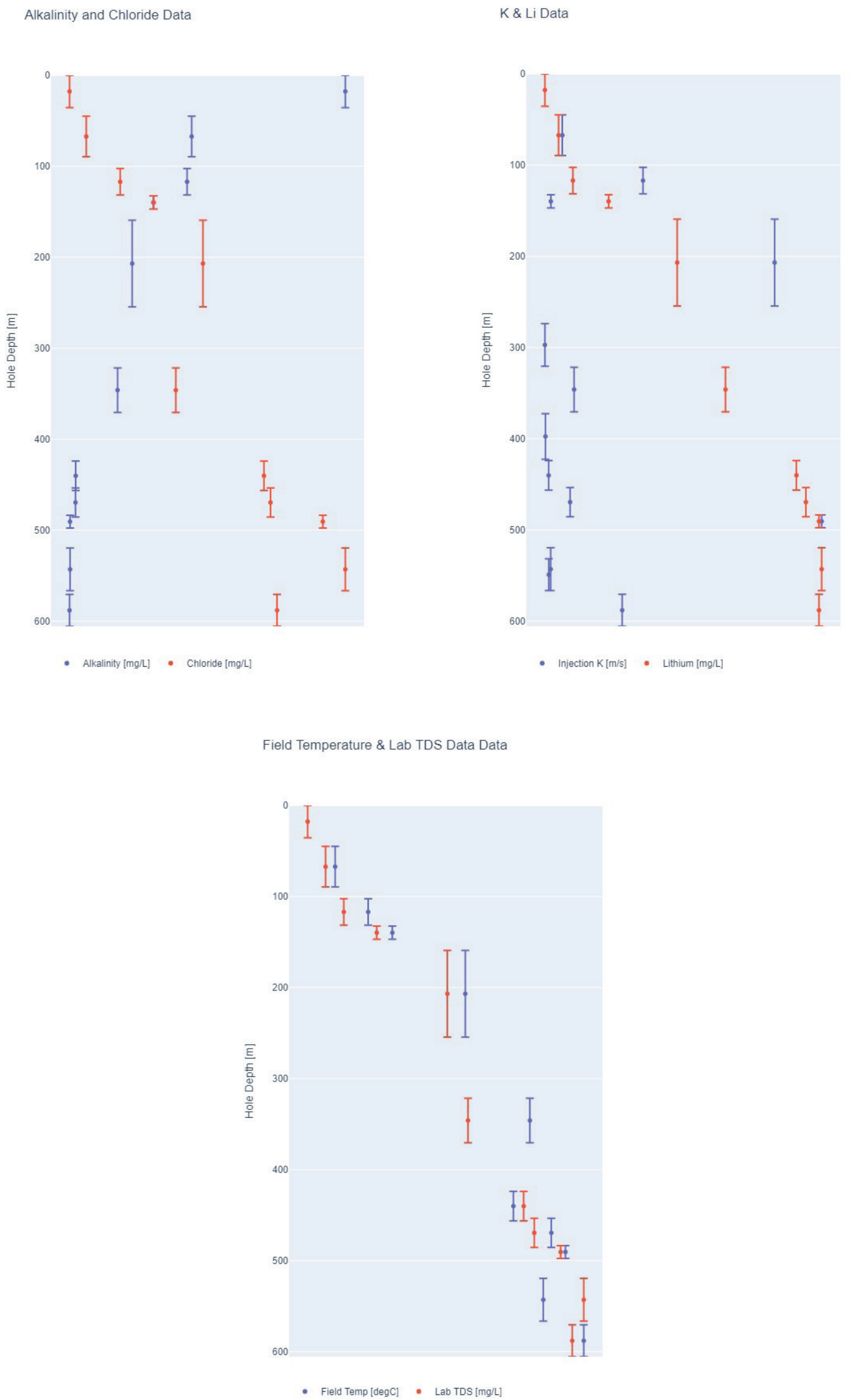

Figure 1 Example of depth dependant hydrogeological data derived from packer testing combined with water quality sampling

account of such ambient flows within the borehole is needed to prevent error when resolving flow proportions for structures solely using pumped impellor observations.

As can be seen in Figure 2, a reduced correlation was observed between the vertical position of hydraulic conductivity reported in NMR logs and responses in the temperature, EC and impellor logs. In this borehole the magnitude of hydraulic conductivity reported in NMR logging showed limited correlation with results from packer CHT and CRT tests, however, increases in NMR hydraulic conductivity were overall consistent with the sections of the boreholes that showed the most flow.

The utilisation of packers enabled the collection of discrete purged water quality samples. Purging methods comprised removal of the monitored drilling water losses together with field water quality parameter stabilisation checks. Whilst obtaining purged samples had clear advantages over grab methods in a situation where fluids are introduced in the drilling process, this also meant storage and disposal of large volumes of pumped brine and as well as obtaining appropriate saline resistant pumping equipment.

Conclusions

Several downhole hydrogeological characterisation methods have been successfully applied to geothermal lithium exploration. The results highlight the value of combining different hydrogeological and geophysical techniques to further the interpretation of geothermal structures. Different methods have different strengths, in either data resolution, rapidity, precision, and repeatability, and need careful consideration for an integrated cost-effective approach. For example, the repeatability and high and low transmissivity range of constant head packer tests proved invaluable for determining the relative inflows over the borehole length. The high resolution of pumped impellor, EC and temperature logging helped ascertain discrete inflow positions for review against ATV and extruded core to characterise structures of interest. Observed ambient flows in the borehole were better understood when comparing to section pressures obtained in packer shut in tests. This exploration data continues to provide the basis for the development of early conceptual models, sufficient for the planning of further investigation boreholes and design of optimised test wells.

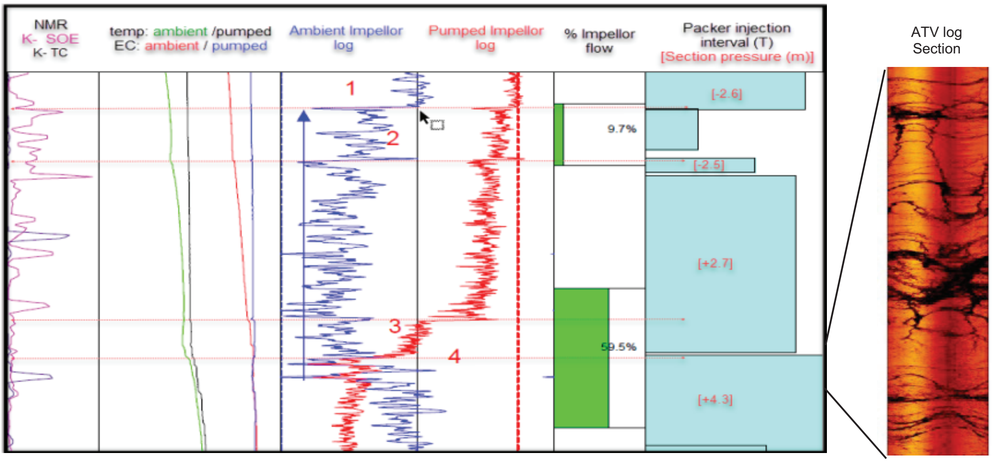

***Figure 2** Example of downhole data comparison, showing from the left: interpretated hydraulic conductivity from NMR, pumped and ambient temperature, electrical conductivity (EC), and impellor logs together with packer isolated CHT transmissivity and section pressure results (in red brackets). A shorter portion of the ATV log is also shown indicating significant fracturing at a depth consistent with changes in the readings position 4*

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