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Geothermal fluids of the Carnmenellis Granite, Cornwall, UK

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INTRODUCTION

Until relatively recently, deep geothermal energy research in the UK was limited to the Hot Dry Rock programme of the 1980s (3 boreholes in Cornwall, to 2-2.5 km) but drilling technology advances now make drilling to >5 km achievable within realistic budget constraints. In recent years significant industry investment in SW England (Figure 1) has led to two deep geothermal projects in radiogenic granites: 1) At United Downs (Carnmenellis Granite); 2) At the Eden Project (St Austell Granite). Two boreholes to ≈ 5 km reached bottom-hole temperatures of >180°C and, in the United Downs area, dissolved lithium concentrations to ≈ 300 mg/L. Work is also ongoing in the same area to investigate the potential for dissolved lithium resources at shallower depths (to ≈ 2 km, where drilling costs/risks are lower) and with lithium concentrations to ≈ 100 mg/L. A key challenge for successful development of these systems is to reduce the geological uncertainties associated with geothermal reservoirs, which requires a better understanding of flow pathways (i.e. 3D fracture network) and the heat transfer medium (i.e. water or brine). It is useful to review our understanding of the geothermal fluids in and around these granites, and we revisit relevant conceptual models with a view to: a) Determining if they are still applicable in the light of recent data, b) Identifying knowledge gaps that might usefully be addressed in ongoing/future studies.

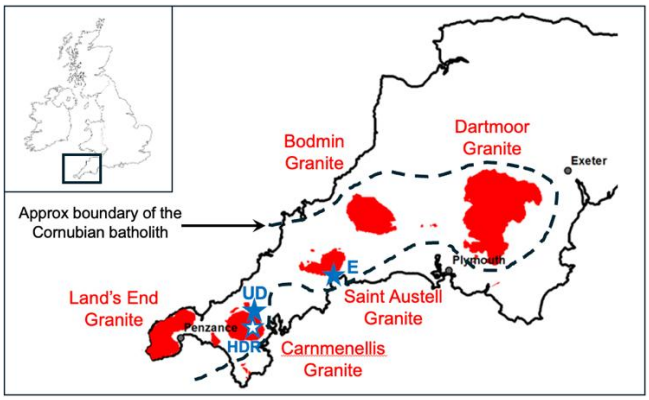


Figure 1: Location of the five main granites in SW England together with the location of geothermal projects (UD = United Downs, E = Eden, HDR = Hot Dry Rock [no longer active]).

1 BACKGROUND GEOLOGY

SW England has a long and complex geological history, including granite genesis and associated magmatic–hydrothermal mineralisation (e.g. Simmons, 2016). The Variscan orogeny initiated emplacement of several granites into already faulted Devonian/Carboniferous sedimentary basins - there are 5 main ones at surface (Figure 1), which are continuous at depth and make up the Cornubian Batholith. This is a major intrusion some 250 km long, 20-40 km wide and 5-10 km thick, underlying much of SW England. Granites were emplaced over some 20 Ma, the Carnmenellis Granite being one of the earliest (293.9 ± 0.6 Ma) and the Land's End Granite one of the latest (274.4 ± 0.4 Ma).

Variscan convergence and granite emplacement caused changes in regional stresses and metamorphism. The net result was fluid movement dominated by fracture flow, in both granites and sediments. Some of the larger fracture zones (‘crosscourse’ structures) connect to the surrounding, unmetamorphosed, basin sediments. They have a long history, with some predating granite emplacement, whilst also showing evidence of displacement after granite emplacement (Shail & Alexander, 1997). They are not individual features, rather they are sub-

vertical zones of increased fracture density some 200-300 m wide and that extend over many km, including offshore (Yeomans et al., 2021). Crosscourse structures have likely been associated with hydrothermal fluid flow throughout their lifetime, and mineralisation along them reflects this long history. Fluid inclusion studies indicate a significant Ca-enriched water input in the past, likely from the sedimentary basin rocks adjacent to the granites (Figure 2). They are key conduits of present-day fluid flow and are exploration targets for both geothermal waters and dissolved elements (such as lithium, [Li]) (e.g. Reinecker et al., 2021). Key aspects in terms of geothermal fluid flow are: 1) High temperature (e.g. >300°C) fluid flow in the immediate vicinity of the granite bodies and coincident with granite emplacement. This led to locally-important, economic mineralisation (e.g. tungsten and tin); 2) Wider-ranging high to medium temperature (e.g. 150-300 °C) fluid flow coincident with granite emplacement and cooling, along broadly WSW-ENE trending fractures. This led to notable widespread economic mineralisation (e.g. copper and tin), with most fractures sealed by this mineralisation; 3) Longer range lower temperature (<150°C) fluid flow post-dating granite cooling, potentially driven by warmth in the granites as a result of their relatively high K, U, Th contents. This was largely controlled by NNW-SSE trending fractures, commonly containing silica, calcite and some economic mineralisation (e.g. iron, lead, antimony). These fractures commonly cut across the course/direction of the main economic mineralisation in SW England, often displacing mineral veins, and were named “crosscourses” by local miners.

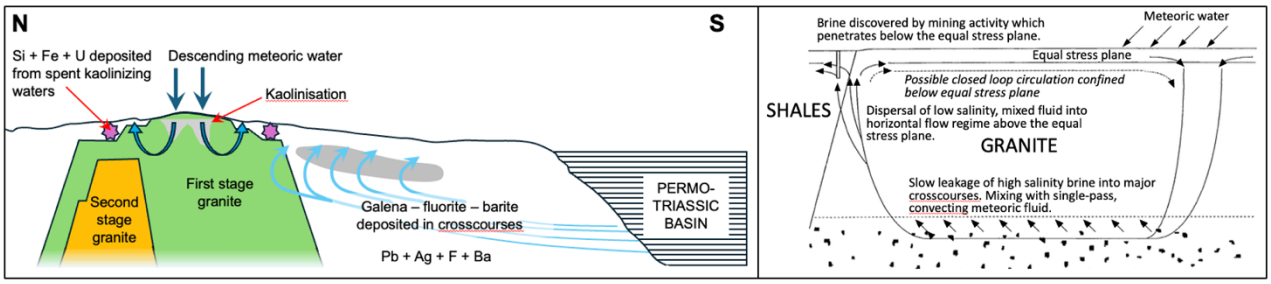


Figure 2: Left: Schematic diagram to represent the development of crosscourse mineralisation in south-west England. Right: Hydrothermal circulation cell model. (Both after Bromley et al., 1989).

2 GEOCHEMISTRY OF SURFACE WATERS

Groundwaters are of meteoric origin, generally oxic, & have low TDS (e.g. Smedley et al., 1989). Their major ion concentrations reflect the lithology of their host rocks – groundwaters for the major granites in SW England share similar chemistry and are predominantly Na-Cl or Na-Ca-Cl type, whilst those from the surrounding thermally-metamorphosed sediments are Na-Ca-Mg-Cl-HCO_3 waters. Major ion compositions are predominantly a function of water-rock interaction processes, the larger range of metasediment-water compositions probably reflects greater lithological variation. The pH of groundwater samples circulating through granite (4.3 to 7.2) is typically lower than that of groundwater in the metasediments (4.7 to 8.0), although near-surface oxidation of sulphide or minerals may locally give rise to lower pH. Downwelling of near-surface waters through fractures is the likely mechanism of recharge of deep geothermal waters.

3 PALAEO-FLUID FLOW THROUGH CROSSCOURSE STRUCTURES

The alteration along crosscourses, and mineralisation within them, reflects a long history. Typically, this was at lower temperatures (<150°C), though there can be local evidence of higher temperature fluids close to WSW-ENE faults. Typical infilling phases include silica, calcite (often Fe-rich) and fluorite. Alteration of host granite in the fracture zones is highly variable - commonly ranging from virtually none to almost complete alteration of feldspars to clays (e.g. kaolinite) and silica. Experimental simulations of alteration at >100°C also identified (smectitic) clays as reaction products (Rochelle et al., 2025).

Sibson et al. (1975) suggest that fluid flow along the faults was related to seismic pumping, with Scrivener et al. (1994) also suggesting density driven circulation. Scrivener et al. (1994) also suggest that extensional vein deposition was characterised by mixing of basinal brines with meteoric fluids at structural intersections, which lead to the deposition of the silica- and iron-oxide-rich assemblages in crosscourses. Mixing of waters could also lead to the zonation recorded in minerals. The episodic nature of events is evidenced at a range of scales: 1) Metre-scale: Multiple infilling events, leading to banded silica precipitates, 2) Centimetre-scale: Repeated brecciation and the formation of ‘cockade’ textures with several generations of silica deposition around rounded clasts, 3) Micron-scale: Individual minerals showing multiple growth zones. Hence, there is much evidence for fluid flow through crosscourse structures over geological timescales. There is also evidence for fracture reactivation and repeated pulses of geothermal waters, leading to banded/zoned fracture-filling phases. Existing conceptual models for the evolution of palaeo-fluid flow through crosscourse structures appear broadly sound,

and appropriate as a starting point to understand present-day conditions where groundwater movement could exploit similar structures.

4 PRESENT-DAY FLUID FLOW THROUGH CROSSCOURSE STRUCTURES

Previous chemical analyses of surface waters do not show a clear signature of deep thermal water input. Only subsurface samples show this (e.g. springs in deep mines), but these cannot be revisited as the mines are now inaccessible. TDS concentration data (from the 1980s/90s) for brines from the South Crofty mine ranged from 9–14 g/L, with temperatures of 35–42ºC. However, concentrations up to 32 g/L and temperatures up to 55ºC were observed in other thermal brines in the area (Smedley et al., 1989). These authors note enhanced ^{4}He values, and U series geochemistry, suggesting that brines may have components with ages 10^4–10^6 years. That said, the presence of tritium in some samples suggests a substantial component of modern recharge water which may have circulated to depth in the mineralised areas via fractures and lodes.

Evidence from mining activity, underground sampling in mines, and microseismic studies from both the UK HDR project (Pine and Batchelor, 1984) and the United Downs Deep Geothermal Power (UDDGP) project (Farndale and Law, 2023; Reinecker et al., 2021; BGS unpublished data) identify crosscourses as major conduits for subsurface water flow. There is evidence for downward migration through crosscourses (to at least 3 km) - likely ongoing for millions of years *in some areas*, as evidenced by the formation of large amounts of kaolinite in the near surface (e.g. the china clay mining area of the St Austell Granite). However, studies of deep groundwater movement in thermogenic granites, including the Carnmenellis granite (Durrance et al., 1982; Sams and Thomas-Betts, 1988), identified possible hydrothermal circulation cells – driven by locally elevated temperatures at depth (Figure 2). Thus, zones of ascending water are expected, and the presence of warm springs in mines is a strong indicator of upward water flow *in some areas*. The lack of evidence for thermal springs or other similar surface hydrothermal manifestations, points to the return leg of the circulation loop being in the subsurface, with any near-surface indicators of it being massively diluted by surface meteoric water.

Gregory and Durrance (1987) used the helium (He) content of surface spring waters as a more sensitive tracer of deep hydrothermal waters and found enhanced concentrations in the United Downs area. Recent analysis of waters from deep boreholes in the area indicate increasing dissolved He concentrations with depth: 1) At 600-800 m, exsolved gases contain 1.2-1.3 % He (Cornish Lithium GWDD001 borehole, Strauch et al., 2024); 2) At 4-5 km and after water was flashed, gases contain 3.4% He (GEL UD-1 borehole, unpublished GEL data). These limited data also appear consistent with the hydrothermal circulation model in Figure 2. Furthermore, it could be (tentatively) suggested that the elevated He concentrations in surface spring waters and the (historic) warm/Li-enriched springs in mines both align with structural trends in the area, which are potentially beneficial in terms of finding exploration targets and subsequent geothermal development.

5 PRESENT-DAY GEOTHERMAL WATER COMPOSITION

Fluids from the UD-1 borehole provide the best evidence we have for the composition of deep geothermal water in the area (i.e. endmember composition). Indeed, Li/Cl relationships show a clear trend linking data from the near surface, springs in mines, and boreholes (Figure 3). That the chemistry of some mine springs (at <1 km deep) is relatively close to the 5 km deep geothermal water, and that the springs retain some heat, suggests that the water expelled into the mines had risen relatively rapidly. The range of Li & Cl concentrations indicates variable degrees of dilution, suggesting that upward pathways for the movement of deep water are isolated/channelised. Dilution by relatively recent water is supported by 'intermediate' concentrations of environmental tracers (SF6, CFCs, tritium). There is good evidence therefore, for the presence of a subsurface mixing zone between deep geothermal waters and near-surface groundwater.

δ^2H and δ^{18}O for present-day deep waters from the UD-1 borehole indicate a meteoric source (Rochelle et al., 2019). The deep geothermal water is isotopically heavy relative to present-day surface waters but does not show a significant shift away from the meteoric water line towards heavier δ^{18}O values, and the data suggest that it has been in the subsurface for an extended period of time. Rochelle et al. (2019) considered whether the palaeo-waters were from a time when the UK experienced a warmer climate, and drew on (limited) data for waters in the Wessex Basin (e.g. Edmunds, 1986) to *tentatively* suggest that water at United Downs may have been recharged during the Neogene. Additional analyses are needed to confirm this, but it appears to have been at depth for a very long time. Thus, input of geothermal water to springs in mines indicates relatively fast upward flow compared to the length of time the waters spent in the deep subsurface.

Measured temperatures range from ≈ 185°C for the bottom of UD-1 (5 km deep), though ≈ 60-90°C for the HDR boreholes (up to 2.6 km) to ≈ 40-70°C for the Cornish Lithium boreholes (GWDD001/2, 600-800 m; GWDD003, 1.7 km) and springs in mines (low 100s m deep). A range of aqueous geothermometers were applied to water

chemistry data, but most gave inconsistent results – likely because their calibration relies on higher temperature water-mineral equilibration. More consistent results were obtained using Na/K ratios (Michard, 1990) based on a range of crystalline basement areas (Figure 3). Samples from the UD-1 borehole lie on an extrapolation of the Michard (1990) dataset. Data for waters from Cornish Lithium boreholes (e.g. GWDD003), plus also historic data for springs in mines, lie at broadly similar Na/K ratios to UD-1, but at much lower temperatures. Whilst we cannot definitively rule out addition of K or removal of Na as a way to generate these compositions, a simpler explanation would be relatively fast ascent and cooling of the waters - such that they underwent little or no re-equilibration with minerals lining the fractures. The Michard (1990) geothermometer suggests (minimum) temperatures between 130-200°C, and this is broadly consistent with bottom hole temperature of the UD-1 borehole.

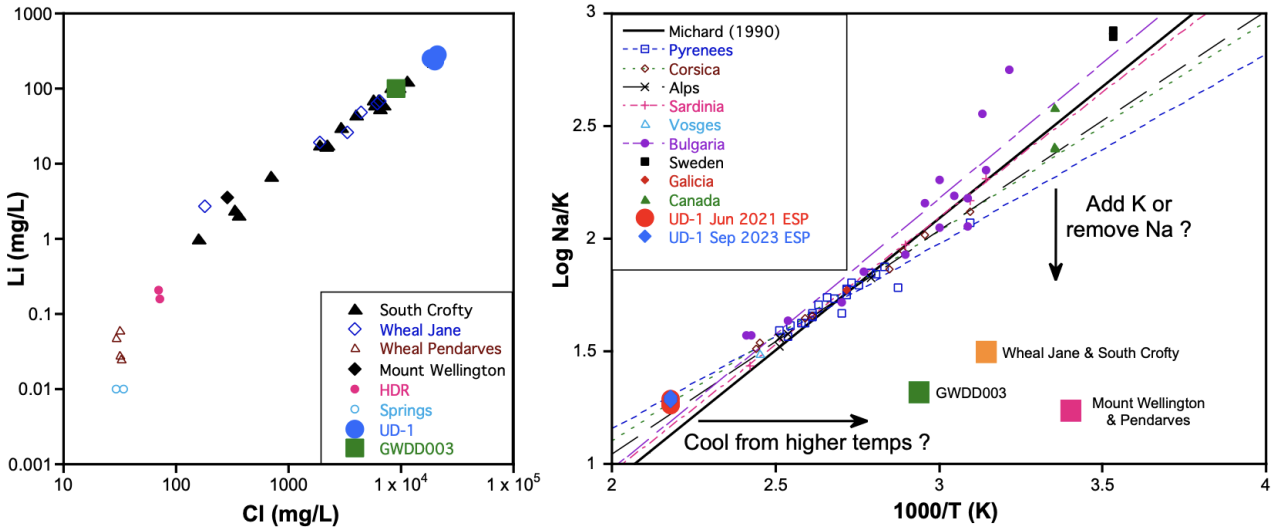


Figure 3: Left: Li/Cl relationships for surface springs, a range of mine waters, and deep borehole waters (UD-1 = United Downs borehole [4-5 km], GWDD003 = Cornish Lithium borehole [1.7-1.9 km], HDR = Hot Dry Rock [~2km, but waters diluted]). Right: Log Na/K concentrations of crystalline basement waters versus temperature, non-Cornwall data from Michard (1990).

Mineral saturation state calculations were undertaken for water samples from initial testing of the UD-1 borehole (using PHREEQC, currently unpublished data). Gas data were limited, and some estimations had to be made - which increases uncertainties, especially for carbonates. However, saturation states for other key minerals pass close to zero around 200-210°C. This is encouraging, as it correlates reasonably well with a measured UD-1 bottom hole temperature of ≈ 185°C, and suggests that the initial waters produced from UD-1 do show chemical equilibrium with a range of minerals likely to be present at 5 km in the Carnmenellis Granite. Further sampling and analysis of borehole fluids will reduce uncertainties and allow for more detailed interpretation.

6 SUMMARY

Geothermal development in Cornwall has seen a major step forward recently, with both the UK's first powerplant, and significant exploration for dissolved mineral resources – both targeting deep groundwaters held within fracture zones in c. 290 Ma old thermogenic granite. Recent industry projects, scientific studies, and information from the 1980s, provide much data on fluid chemistry within the upper 5 km of the northern central and northern edge of the Carnmenellis granite. This allows us to revisit older conceptual models of fluid circulation in and around the granites and see if they remain robust in the light of new data – in particular, whether large-scale hydrothermal circulation is ongoing through the fracture network in the granite.

The UD-1 borehole samples water from a crosscourse at a depth of 4-5 km, and provides the best example thus far, of endmember geothermal fluids. It confirms it is an old, meteoric-derived, NaCl-dominated water at about 185°C, a TDS of ≈ 35 g/L, and is enriched in elements such as lithium (≈ 280-300+ mg/L). Sections of some fracture zones allow relatively fast thermally-driven advection of the deep groundwater to shallower levels, creating mixing zones with local surface groundwaters and intermediate water chemistries. These carry a diluted deep geothermal signature, but can still have commercially attractive Li concentrations (≈ 100 mg/L) at 1-2 km depth. Springs in mines also carry a similar signature. However, near-surface ground water massively dilutes rising geothermal water, and its signature is not readily discernible in local spring waters. That said, enhanced dissolved helium concentrations are observed in some surface springs, and appear the best surface indicator, so far, for the presence of rising deep geothermal waters in some areas – such as beneath United Downs.

Recent data do appear broadly consistent with existing conceptual models of hydrothermal fluid circulation in the thermogenic, fractured Carnmenellis Granite. Ongoing studies will continue to investigate waters, gases and minerals within the fracture-dominated flow pathways in Cornish granites, adding quantitative information to these models. Through these studies, we aim to produce additional datasets and a deeper understanding of geothermal fluid transport in SW England.

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