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CHPM (Combined Heat, Power and Metal extraction) 2030 deliverable (D1.2): report on data availability for south-west England

Minerals and Waste Programme

Internal Report IR/16/030

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

INTERNAL REPORT IR/16/030

CHPM (Combined Heat, Power and Metal extraction) 2030 deliverable (D1.2): report on data availability for south-west England

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Wheal Cotes tin mine, St Agnes, Cornwall.

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Foreword

This report is a published product of the 'CHPM2030' project - an EC-funded, Horizon2020 project which aims to develop a novel and potentially disruptive technology solution that can help satisfy the European needs for energy and strategic metals in a single interlinked process. Working at the frontiers of geothermal resources development, minerals extraction and electro-metallurgy, the project aims at converting ultra-deep metallic mineral formations into 'orebody-engineered geothermal systems' that will serve as a basis for the development of a new type of facility for 'Combined Heat, Power and Metal extraction' (CHPM).

The project will help provide new impetus to geothermal development in Europe by investigating previously unexplored pathways at low-TRL. This will be achieved by developing a roadmap in support of the pilot implementation of such system before 2025, and full-scale commercial implementation before 2030. This will include detailed specifications of a new type of future engineered geothermal system (EGS) facility that is designed and operated from the very beginning as a combined heat, power and metal extraction system.

In the technology envisioned, the metal-bearing geological formation will be manipulated in a way that the co-production of thermal energy and metals will be possible. As part of this, we will investigate how fluid chemical conditions can be optimised to facilitate recovery of specific metals, anticipating variable market demands at any given moment in the future. Four geographical areas have been chosen for detailed investigation based on pre-existing data and potential for CHPM development in mineralised areas in the United Kingdom (UK), Portugal, Romania and Sweden. This report summarises information relevant to the investigation area in the UK.

The project aims to provide proof-of-concept for the following hypotheses:

1. The composition and structure of orebodies have certain advantages that could be used to our advantage when developing an EGS;
2. Metals can be leached from the orebodies in high concentrations over a prolonged period of time and may substantially influence the economics of EGS;
3. The continuous leaching of metals will increase system's performance over time in a controlled way and without having to use high-pressure reservoir stimulation, minimizing potential detrimental impacts of both heat and metal extraction.

Acknowledgements

The authors would like to thank a number of people in south-west England for their support in this project. Gary Tubridy, Will Wills and Ben Kaack of Avalon Sciences Ltd are thanked for allowing access to the HDR site in Cornwall and also for making available data relating to the HDR deep-boreholes. Richard Crocker of Lantoom Ltd and Debbie Palmer of Colas Ltd are both thanked for providing samples of Cornish granite from their properties. Access to the Herodsfoot mine was kindly granted by its owner Richard Humphries.

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Summary

This report provides a summary of key information available for south-west England, which is relevant for development of enhanced geothermal systems in the region. South-west England is a geologically complex region with a long and significant history of metal mining, producing primarily tin (c. 2.8 million tonnes) and copper (c. 2 million tonnes). The geology of the region is largely the result of Variscan tectonics and associated felsic magmatism. The current surface expression of the Cornubian Batholith comprises six large granitic plutons. From west to east these are: the offshore Isles of Scilly (120 km^2), Land's End (190 km^2), Carnmenellis (135 km^2), St Austell (85 km^2), Bodmin (220 km^2), and Dartmoor (650 km^2). These granite bodies were intruded into a series of Devonian (410–355 Ma) green schist facies metasedimentary rocks, locally known as 'killas' during the late Carboniferous and early Permian (295–270 Ma). The granites of south-west England are texturally and compositionally complex, although broadly they comprise peraluminous, S-type granites of the two-mica variety. They are enriched in elements that include K, F, B, Li, Sn, Th, U and Rb. However, it is their enrichment in K, Th and U that is responsible for their heat-production via radioactive decay.

Mineralisation in south-west England is wide-spread and can be broadly divided on the basis of its timing relative to granite emplacement as: (1) *pre-granite* orebodies of the sedimentary-exhalative type, and shear-zone hosted Au-Sb type; (2) *granite-related* mineralisation, comprising greisens and sheeted vein complexes, and polymetallic sulfide lodes and; (3) *post-granite* mineralised Zn-Pb-Ag veins (so called crosscourses).

Fluids associated with granite-related mineralisation are magmatic in origin, and ranged in temperature from about 400°C for Sn-W greisens to about 280°C for Sn-Cu polymetallic lodes, with salinities ranging between 5 and 15 wt. % NaCl. Post-granite mineralisation is dominated by Pb and Zn rather than Sn and Cu, and formed from lower temperatures fluids (c. 130°C), with higher salinities of about 26 wt. % NaCl. Warm (up to 55°C), high-salinity groundwaters have been found at depths of up to 820 metres depth, primarily issuing from crosscourses and lodes in mines at the northern edge of the Carnmenellis granite. These flows occur in mines in both the granite and in the killas. Some of the crosscourse flows have been discharging for more than 30 years, suggesting that a large reservoir of saline, thermal water exists at depth.

The south-west of England is structurally complex with at least three different episodes of deformation identified. Permeability in the south-west is fracture dominated. Therefore, it is the large NW-SE-trending fault structures that are potentially most important for enhanced geothermal systems in terms of fluid flow. Principal stress orientations are about 30° off parallel from that of the NNW-SSE and ENE-SWS-trending joints sets observed in the Carnmenellis granite. The

maximum *in-situ* stress ($^{\sigma}$H) is about 70 MPa in the NNW-SSE direction, whilst the minimum *in-situ* stress ($^{\sigma}$h) is about 30 MPa in an ENE-WSW direction.

Previous geothermal research in the south-west of England peaked between the 1970s and 1990s. The south-west region was of interest because of the high heat flows present in the Cornubian granites (c. 115–139 mWm^{-2}). These high heat flow values suggest high temperatures (c. 185–220°C) at depths of 5 km or more.

In 1984 an extensive programme of work, funded by the UK Department of Energy (DEn) and the Commission of the European Communities (CEC), was undertaken by the British Geological Survey (BGS) to assess the UK's geothermal potential. Over the same time period (1977–1984) the Camborne School of Mines (CSM) was assessing the feasibility of creating HDR geothermal systems at a test site at the Rosemanowes quarry, on the Carnmenellis granite, in Cornwall. It was assumed that the behaviour and characteristics of a HDR system could be modelled using geochemistry, geophysics and physical properties testing. Between 1985 and 1989 the Department of Energy and the Commission of the European Communities funded a detailed geochemical investigation of the HDR site at Rosemanowes. These investigations were undertaken by the BGS, the then NERC Isotope Geology Centre (NIGC), the University of Bath (UoB) and CSM. In 1987 an informal working group (the UK Hot Dry Rock Geochemistry Group) was established to align the geochemical programme more closely with the work being undertaken by CSM at the Rosemanowes test site.

In summary a huge amount is already known about the geology, mineralisation fluid history and geothermal potential of south-west England. A significant body of data underpins this knowledge base, the majority of which is freely, or openly available. However, there are limitations. For example, much of this data, with the exception of the HDR datasets, only relates to the upper 1,000 m of the crust. This has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths. There are also 'gaps' in the data (e.g. very limited deep-geophysical data), and some data sets have not been updated since their creation in the 1970s and 1980s.

1 Introduction

During the last 50 years geothermal energy research in the UK has been limited, partly due to a lack of high-enthalpy resources, but also because of the availability of cheap fossil fuels during the 1980s and 1990s. Research has focussed on three main aspects: (1) a nationwide appraisal of heat flow; (2) energy generation from hot-brines in deep, hyper-saline aquifers (HSA) and; (3) energy generation from enhanced geothermal systems (EGS) in hot dry rocks (Busby, 2010).

Heat flow measurements (Lee *et* al., 1987; Downing and Gray, 1986; Rollin, 1995; Rollin *et al.*, 1995 and; Barker *et al.*, 2000) place UK background heat flow at about 52 mW m^2, with elevated values associated with buried granites in north-eastern England and radiogenic granites in south-west England. The average UK geothermal gradient is approximately 26°C km^{-1}, although locally it can exceed 35°C km^{-1}.

The radiogenic granites of south-west England were assessed for their HDR geothermal energy potential as part of the HDR project during the 1970s and 1980s. This programme of work was largely undertaken by the Camborne School of Mines to assess the performance of an EGS in the Carnmenellis granite, in south-west England. The test site operated a set of deep (between 2–2.5 km) boreholes to assess the feasibility of developing a full-scale commercial HDR system at about 5–6 km depth.

South-west England was chosen as a potential pilot study site for the CHPM2030 project because of the large amount of data that are available for south-west England, the region's status as a historically important orefield, and because of the history of geothermal research in the region.

2 Geology

The geology and metallogenesis of south-west England is complex and has been the subject of extensive scientific research for more than two centuries. It was during the eighteenth century (c. 1778) that William Pryce first attempted to synthesise the geology, mining practices and metallurgy of the region. A number of important papers followed in the early to mid-nineteenth century (Phillips, 1814; De La Beche, 1839; Henwood, 1843) that sought to explain the role of granite and circulating fluids in the formation of south-west England's mineral deposits. This extensive metallogenic province, covering the county of Cornwall and part of the county of Devon from Land's End to Dartmoor, a distance of some 150 km is termed the 'Cornubian Orefield'. Significant advances were made during the twentieth century in understanding the formation of the Cornubian Orefield, with the publication of numerous papers by Dines (1934 and 1956) and Hosking (1950, 1951, 1952, 1964, and 1969). Geoscience research during the past forty years has sought to refine many of the earlier theories and concepts by the application of geochronology (Chesley *et al.*, 1993; Chen *et al.*, 1993; Clark *et al.*, 1993; Clark *et al.*, 1994; and Darbyshire, 1995), isotope studies (Rouse and Colman, 1976; Darbyshire and Shepherd, 1994; and Shail *et al.*, 2003) and fluid inclusion research (Williamson *et al.*, 1997; Gleeson *et al.*, 2000; 2001; Williamson *et al.*, 2000; and Müller and Halls, 2005). Regional geological mapping by the British Geological Survey at 1:50 000 scale, and airborne geophysical (i.e. magnetic and radiometric) and remote sensing (i.e. LiDAR) surveys, flown as part of the TELLUS South West project, have further contributed to the geological knowledge base. Comprehensive reviews of the geology of south-west England can be found in Selwood *et al.* (1998), LeBoutillier (2002) and Shail and Leveridge (2009), and references therein.

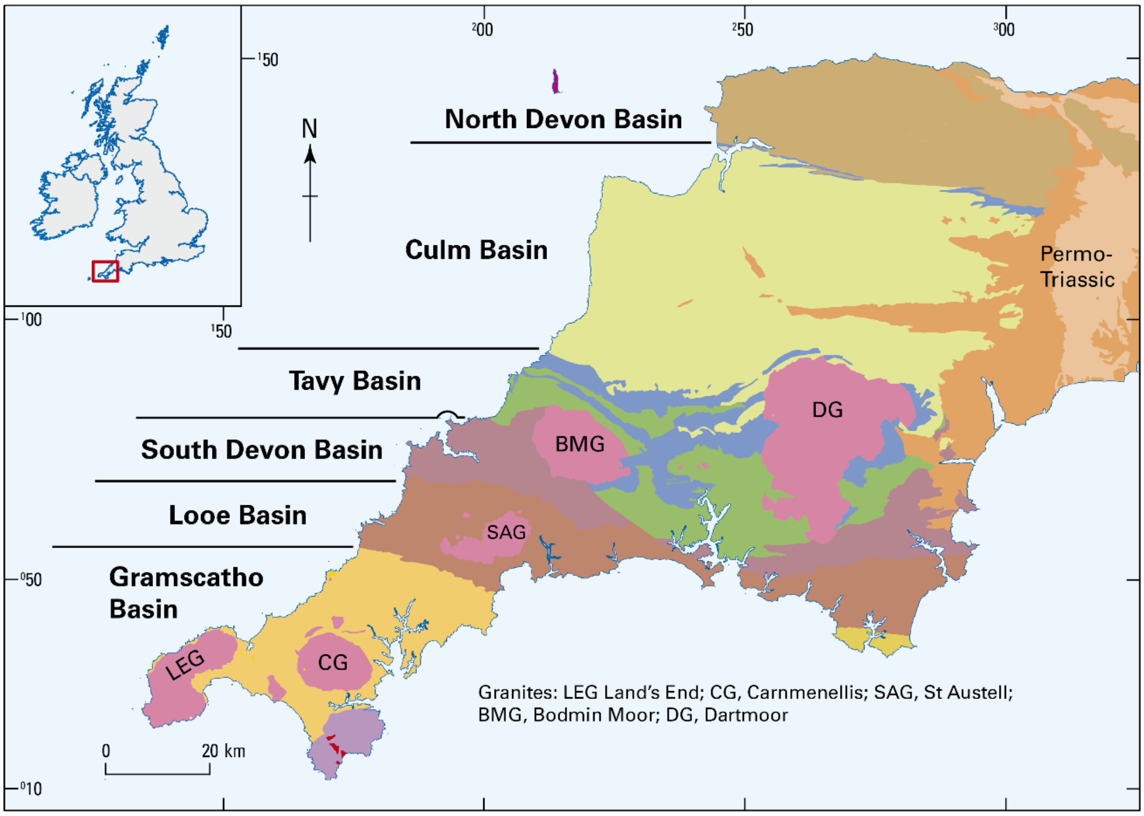

Figure 1. Simplified geological map of south-west England showing the distribution of sedimentary basins and the location of the granites (re-drawn from BGS mapping data and Shail and Leveridge, 2009).

A brief chronology of major geological events in south-west England, from oldest to youngest, includes: (1) The development of a series of middle Palaeozoic (410–345 Ma), east-west trending volcano-sedimentary basins (from east–west these are the: North Devon Basin; Culm Basin; Tavy Basin; South Devon Basin; Looe Basin and; Gramscatho Basin) (Figure 1) that have been inverted, deformed and subjected to low-grade metamorphism (Parker, 1989; Shail, 2014); (2) Variscan continental collision, during the mid-Carboniferous (331–329 Ma), resulted in significant crustal shortening and the development of NNW-trending thrust sheets (Parker, 1989; Shail, 2014); (3) Crustal extension and orogenic collapse during the late Carboniferous and lower Permian that resulted in extensive granitic magmatism (295–270 Ma) and associated hypothermal (300–600°C) Sn-W greisens, and mesothermal (200–300°C) Sn-Cu mineralisation hosted by E-W-trending mineral lodes. Following granite emplacement widespread Pb-Zn mineralisation developed in N-S-trending crosscourses, many of which are re-activated NNW-trending thrust sheets (Parker, 1989; LeBoutillier, 2002; Shail *et al.*, 2014) and; (4) Cyclic periods of uplift, erosion and sedimentation throughout the Jurassic and Cretaceous (Parker, 1989; Shail *et al.*, 2014) resulting in the current landscape (e.g. exposure of granite roof zones at the existing land surface).

Emplacement of the Cornubian batholith into largely Devonian sedimentary rocks caused large-scale heating and thermal alteration. These metamorphic rocks in south-west England are locally known as ‘killas’. Although these rocks are not economically important in themselves, fractures within them host a significant proportion of the region’s mineral deposits (e.g. polymetallic mineral veins, or ‘lodes’). The ‘killas’ comprises a series of Devonian (410–355 Ma), marine deposited sandstones, siltstones, mudstones and rare carbonates that were regionally metamorphosed to sub-green schist facies during the Variscan Orogeny. As a result of granite emplacement, the low-grade regional metamorphism has been locally overprinted by higher-grade contact metamorphism, to produce a series of aluminosilicate and/or cordierite-bearing slates (Selwood, *et al.*, 1998).

The current surface expression of the Cornubian Batholith is six large granite plutons. From west to east these are: the offshore Isles of Scilly (120 km^2), Land’s End (190 km^2), Carnmenellis (135 km^2), St Austell (85 km^2), Bodmin (220 km^2), and Dartmoor (650 km^2) (Figure 1). The subsurface extent of the Cornubian Batholith is estimated to be about 250 km in length and has an approximate width of between 40 and 60 km (Willis-Richards and Jackson, 1989; Scrivener, 2006). However, there is uncertainty about the true size of the Cornubian Batholith because current models are based on a small amount of data (e.g. gravity measurements and a very limited number of deep drill holes). Similarly there is some uncertainty about the true thickness and shape of the granite plutons. 2D-gravity modelling of the Carnmenellis, St Austell and Bodmin granites indicates they are tabular bodies with an estimated thickness of between three and four kilometres, whilst the larger Dartmoor pluton is estimated to be about nine kilometres thick (Taylor, 2007). However, seismic refraction data suggest that the depth of the base of the batholith (i.e. its lower contact with the killas) is variable, ranging from about seven and eight kilometres beneath the Bodmin and Carnmenellis granites, respectively, to about ten kilometres beneath the Dartmoor granite (Brooks, 1984; Shail *et al.*, 2014).

Radiometric dating (U-Pb in monazite and zircon) suggests that the extensive granitic magmatism observed in south-west England occurred over an about 20 million year period, between about 293 Ma and 274 Ma, although separate intrusive episodes can be identified in some of the individual plutons (Chen *et al.*, 1993; Chesley *et al.*, 1993; Clark *et al.*, 1994). In terms of age, the plutons can be broadly divided into two groups: (1) the older (>290 Ma) Bodmin Moor, Isles of Scilly and Carnmenellis granites and; (2) the younger (<286 Ma) Land’s End, St Austell and Dartmoor granites (Figure 2).

Compositionally the granites are all peraluminous, S-type granites that are enriched in elements such as K, B, F, Li, U, Th, Sn, Rb and Pb. An interesting feature of Cornubian granites is their high uranium content (with an average of about 12 ppm for all plutons), which is largely controlled by the distribution of accessory minerals such as uraninite and monazite (Chappell and Hine, 2006; Scrivener, 2006). Importantly it is the radioactive decay of uranium, thorium and potassium in the Cornubian granites that is responsible for their high heat production through radioactive decay (Chappell and Hine, 2006).

The granites of south-west England can be categorised mineralogically into three broad groups: (1) biotite granite; (2) topaz granite; and (3) tourmaline granite. However, minor variants also exist, including Li-mica granite and fluorite granite (Exley *et al.*, 1983; Floyd *et al.*, 1993; Manning *et al.*, 1996). Textural variations are also used to distinguish sub-classes of the granites e.g. fine-grained tourmaline granite (Manning *et al.*, 1996) (Figure 2). The older granites (Bodmin Moor, Isles of Scilly, and Carnmenellis) can be distinguished from the younger granites (Land’s End, St Austell and Dartmoor) by their texture, composition (peraluminosity), isotopic signature ($^{\varepsilon}$Nd) and rare earth element (REE) patterns. These differences may reflect increased mantle-melting and possibly increased amounts of crustal melting during formation of the younger granites, probably in response to higher temperatures in the lower crust. However, it remains unclear why temperatures increased, and if this change was transitional, or an abrupt change in response to a discrete tectonic event (Stone, 1995; 1997; 2000a; 2000b; Shail *et al.*, 2014).

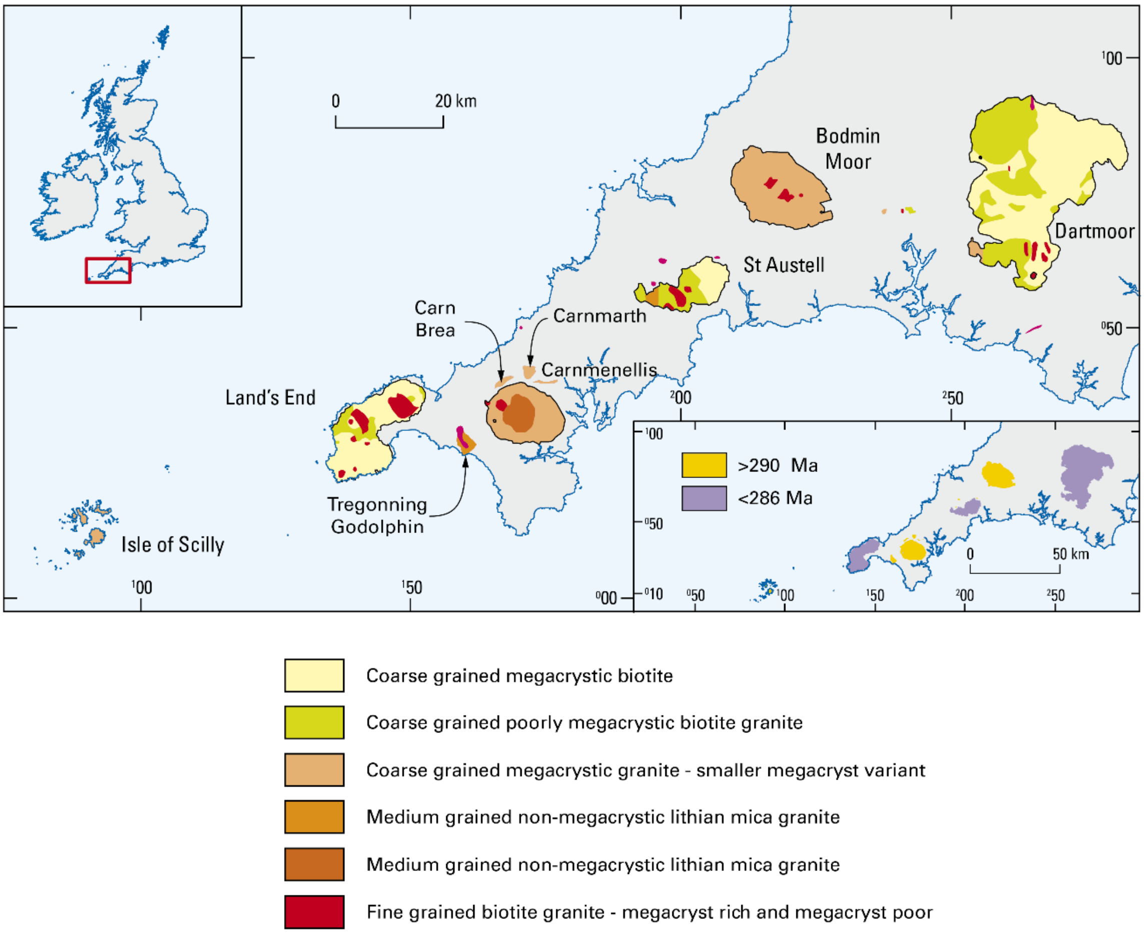

Figure 2. Map showing the principal mineralogical and textural variations in the Cornubian Batholith. It combines subdivision into biotite and lithian-mica granites with a textural scheme based primarily on mean matrix grainsize and the size and abundance of alkali feldspar megacrysts - compiled from Exley and Stone (1964, 1982) Stone and Exley (1985), Hawkes and Dangerfield (1978), Dangerfield and Hawkes (1981), Exley *et al*. (1983), Floyd et al. (1993), Manning *et al*. (1996), Manning (1998) and Shail *et al.* (2014). In-set map shows the distribution of granite ages: Dartmoor, St Austell and Land's End (in purple) are <286 Ma, whereas Bodmin, Carnmenellis and Isle of Scilly (in yellow) are older (>290 Ma).

2.1 SUMMARY

The region has been studied for more than 200 years and thus a large amount of data exists that describes the relationship between magmatism and mineralisation. Complimentary geological mapping and airborne geophysical surveys have further refined the interpretation of the geological evolution of the region. The abundance of magmatism and mineralisation across south-west England warrants its status as a globally significant metallogenic province.

2.2 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- Extensive body of academic literature.
- Good understanding of the geological evolution of the region.
- Continuous digital geological mapping at 1:50,000 scale.
- Complimentary regional datasets (e.g. LiDAR, airborne geophysics, etc.).
- 3D model of the geology at 1:625,000 scale.

2.3 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF THE GEOLOGY OF SOUTH-WEST ENGLAND:

The majority of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m). There has also been no regional deep geophysical investigation. As a consequence, this presents uncertainty in terms of extrapolating information and data at surface to any significant depth.

3 Fluids

Academic research in south-west England during the past 30 years has focussed on the nature of mineralising fluids, and their role in metal transport and ore deposit formation. Fluid inclusion (i.e. fluids trapped during mineral growth) studies have been invaluable in revealing the composition (salinity), temperature and in some cases the pressure of the mineralising fluids. Complimentary stable isotope studies (e.g. O, H, He and S) have also provided useful information on the source of the mineralising fluids (e.g. He signatures suggest a mantle-derived volatile component) (Shail *et al.*, 2003). Studies of shallow groundwaters (down to c. 100 m), as part of the HDR programme have provided insights into water-rock interaction over short time intervals and at shallow depths. Similar studies of deep, thermal spring waters from disused mines provide information on fluid circulation and mixing. When combined these data (e.g. shallow groundwater and mine water composition, and fluid inclusion studies) have enabled important conclusions to be drawn regarding palaeofluid circulation in both the granites and country rocks of south-west England (Smedley, *et al.*, 1989).

Broadly two dominant fluid types have been implicated in the formation of mineralisation in south-west England:

(1) Moderate to high salinity ($NaCl+CO_2$), high temperature magmatic fluids that produced the granite-related mineralisation (e.g. polymetallic Sn-Cu lodes); and

(2) High salinity ($NaCl+CaCl_2$), lower temperature basinal fluids that formed the younger, post-magmatic mineralisation (e.g. crosscourses) (Table 1).

Table 1. Summary of fluid inclusion data for mineralising fluids (Smith *et al.*, 1996[1] and Gleeson *et al.*, 2001[2]).

Mineralisation style	**Temperature**	**Salinity**	**Composition**
Greisen[1]	450–350 °C	5-10 wt. %	$NaCl \pm CO_2$
Polymetallic lode (Sn-Cu)[2]	280–200 °C	3–15 wt. %	NaCl
Polymetallic lode (Pb-Zn)[2]	c.220 °C	0–5 wt. %	NaCl
Crosscourse[2]	c.130 °C	26 wt. %	$NaCl \pm CaCl_2$

Stable isotope studies (i.e. Cl, O, H, He and S) on fluids taken from inclusions in the mineralisation have provided useful insights in to the origin of mineralising fluids. For example, isotopic studies of main stage, polymetallic lodes indicate that mineralising fluids were principally magmatic in origin, whilst fluids associated with later crosscourses are distinctly non-magmatic, having a strong sediment-derived fluid signature (Wilkinson *et al.*, 1995; Gleeson *et al.*, 1999; Banks *et al.*, 2000; Shail *et al.*, 2003).

Warm (up to 55°C), high-salinity groundwaters have been found at depths of up to 820 metres, primarily issuing from crosscourses and lodes in mines at the northern edge of the Carnmenellis granite. These flows occur in mines in both the granite and in the killas. Some of the crosscourse flows have been discharging for more than 30 years, suggesting that a large reservoir of saline, thermal water exists at depth (Smedley *et al.*, 1989). These deep spring waters 31–55°C, mildly acidic to neutral (pH 5.4–7.7), and compositionally they are dominated by Na, Ca and Cl (Smedley *et al.*, 1989) (Table 2). Stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}D$) isotope studies indicate that these waters are not derived from seawater, but are more likely diluted palaeobrines which have flowed through crosscourse structures within the granite and killas. Their chemical and isotopic signatures also indicate mixing and dilution by circulation of local meteoric water (Alderton and Sheppard, 1977; Smedley *et al.*, 1989).

Table 2. Summary of mine water compositions (n.r., 'not reported').

Parameter	**South Crofty (420 level)**	**South Crofty (420 level)**	**Wheal Jane**	**Clifford United**
Source	Smedley *et al.*, 1989		Alderton and Sheppard, 1977	
Depth	690	690	198	448
pH	6.79	5.38	7.70	n.r.
Temperature (°C)	45.3	34.3	31.5	52
Total dissolved solids	14,099	10,454	9,934	9,189
Na	3,210	1,890	2,073	2,043
K	138	66.8	127	111
Mg	51.6	94.8	29.5	32
Ca	1,670	1,630	1,326	1,166
Cl	8,750	6,500	6,110	5,628
SO_4	107	240	118	124
HCO_3	n.r.	n.r.	23.8	n.r.

Low salinity, shallow groundwaters from within the granite and killas show considerable compositional overlap. However, slight differences can be observed in both the major cation (i.e. Ca, Mg, Na and K) and anion (i.e. HCO_3, SO_4, Cl and NO_3) contents of these waters. Granite-related shallow groundwaters are more acidic (pH 4.3–6.9) and are dominated by Na, K and Cl, whilst killas-related groundwaters are more alkaline (pH 4.9–8.0), and have compositions dominated by Ca, Mg and HCO_3. The higher overall concentration of elements (e.g. Ca, Mg, Cl, etc.) in killas-related groundwaters suggests that that the killas is more reactive, or possibly more soluble, than the granite. The abundance of minerals such as calcite, dolomite, chlorite and clays in the killas may account for these higher concentrations by dissolution and precipitation, and ion exchange reactions. Element enrichment and depletion patterns suggest that shallow groundwater compositions are strongly controlled by lithology. For example, granite-related waters typically have higher Ba and Rb contents, which likely reflects dissolution of alkali feldspar (Smedley *et al.*, 1989; Smedley and Allen, 2004).

Previous studies suggest that palaeo-fluid flow in and around the Carnmenellis granite can be divided in to four main stages (Figure 3): (1) Expulsion of early magmatic fluids associated with the emplacement of the granite, which led to the formation of sheeted Sn-W greisens in the granite roof zone and overlying metasedimentary rocks. Hydrothermal convection of formation waters starts to occur in response to the thermal anomaly created by the granite emplacement. (2) Copper, zinc and sulfur are leached from the host rocks. Formation waters are drawn down through the granite as the system begins to cool, resulting in the deposition of Cu-Zn-sulfides in veins. (3) Main-stage, polymetallic lodes are emplaced within the granite roof zone by further expulsion of magmatic fluids. (4) Formation waters start to circulate through the granite in response to cooling of the system, resulting in the deposition of Cu-Zn-sulfides in steeply dipping fissures (Smedley, *et al.*, 1989). Post-magmatism basinal brines circulate through N-S-trending structures within the granite and killas, mixing with meteoric waters. These fluids deposited Pb-Zn-rich mineralisation within the so called crosscourse veins (Scrivener *et al.*, 1994; Gleeson *et al.*, 2000; 2001).

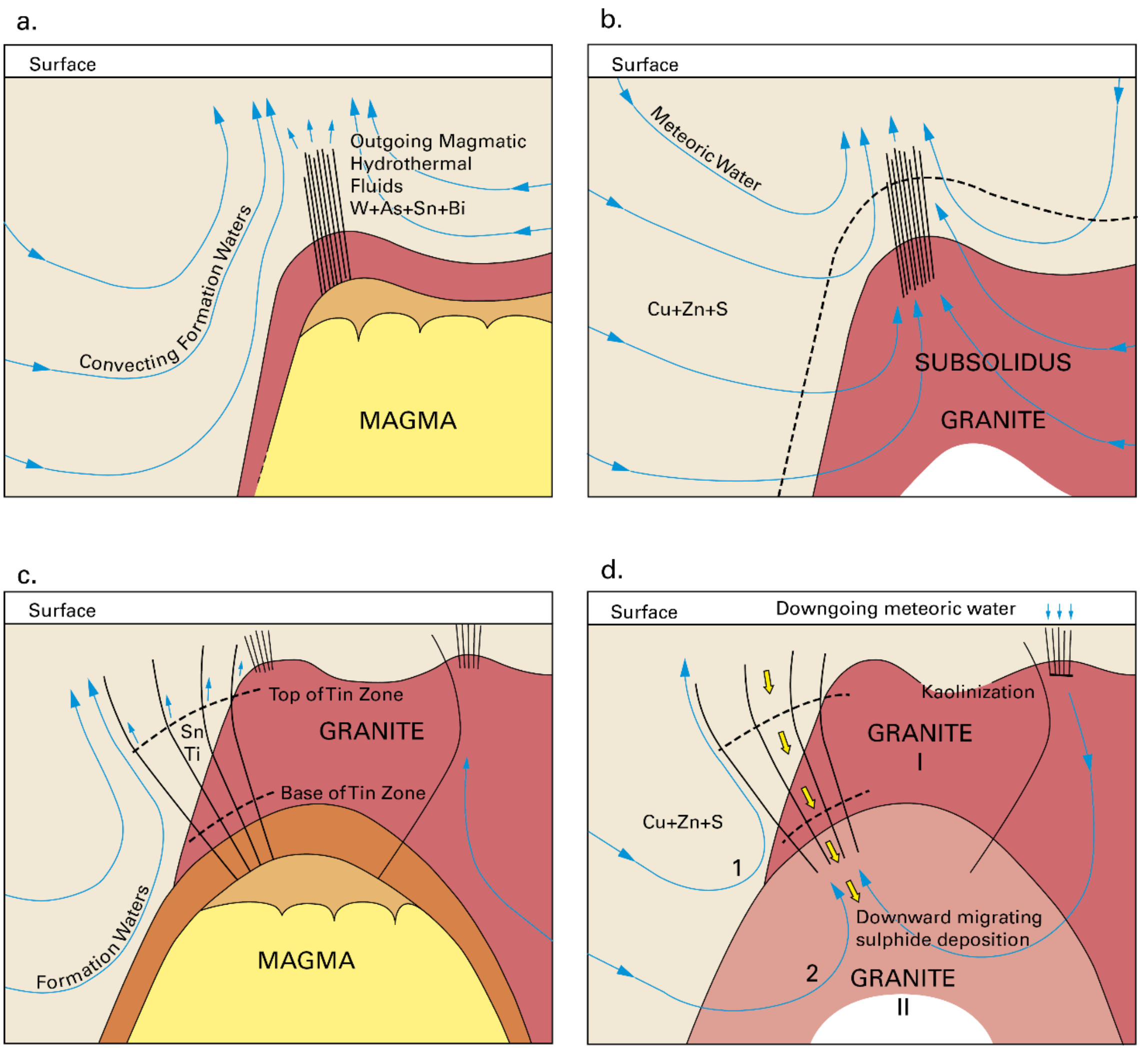

Figure 3. Schematic diagram illustrating fluid flow regimes in relation to emplacement of the Carnmenellis granite. (a) Expulsion of magmatic fluids forming Sn-W greisens and generation of hydrothermal convection in overlying groundwaters. (b) Leaching of metals and sulfur from the host rocks. Cooling of the system permits meteoric waters to pass down into the granite pluton. (c) Main stage, polymetallic lodes form in the roof zone of the granite pluton by expulsion of magmatic fluids. (d) Meteoric waters circulate through the granite as the system cools. Cu-Zn sulfides are deposited in a series of lodes (re-drawn after Smedley, *et al.*, 1989).

3.1 SUMMARY

Fluids associated with both Sn-W greisen and Sn-Cu polymetallic lode mineralisation in south-west England are primarily of magmatic origin, In contrast fluids associated with post-granite crosscourse mineralisation are distinctly non-magmatic and derived from sedimentary basins, possibly with a local meteoric water component. Saline mine waters (known to extend to depths of at least 820 metres) are considered to be palaeobrines that have been diluted by local meteoric water. These mine waters exploit N-S-trending crosscourse structures in the granite and killas.

Active fluid flow and mixing has, and continues to, play an important role in the formation of the Cornubian Orefield.

3.2 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- Mineralising fluids, saline mine waters and shallow ground waters are reasonably well characterised (e.g. by fluid inclusion, stable isotope, geochemical studies etc.).
- Significant amounts of data have been generated as part of the HDR programme (e.g. water chemistry, stable isotopes, and fluid inclusions).
- Fluid circulation is reasonably well understood in the shallow subsurface.

3.3 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF FLUIDS IN SOUTH-WEST ENGLAND:

- Much of the primary data that exists is related to the shallow sub-surface (<1,000 m, and often <200 m). Hence little is known about fluids existing at depths below 1,000 m, both in terms of chemistry and circulation.
- Mine water data are largely restricted to sites concentrated around the Carnmenellis granite.

4 Mineralisation

The Cornubian Orefield has a complex, protracted (c. 100 Ma), multi-stage history of polymetallic mineralisation. Mineralisation comprises a variety of styles, ranging from Devono-Carboniferous syngenetic mineralisation, to recent placer and kaolin deposits. Although historically the south-west region was major metal producer, the Drakelands Sn-W deposit (operated by Wolf Minerals Ltd) is the only active metal mine in south-west England. It is hosted within and around a dyke-like body of porphyritic granite, known as the Hemerdon Granite that forms a cupola to the south-west of the main body of the Dartmoor Granite. The deposit is one of the world's largest tungsten deposits containing 35.7 million tonnes at a grade of 0.18% WO_3 and 0.03% Sn (Wolf Minerals, 2015). The Drakelands operation has a production capacity of more than 3,000 tonnes of tungsten concentrate per annum (Wolf Minerals, 2015). There is a long history of mineralisation-related research in south-west England, with a particular focus on granite-related hydrothermal tin and tungsten-bearing deposits.

4.1 HISTORICAL PRODUCTION

Historically, the south-west region was a major metal producer. Mineral deposits in the region were predominantly exploited for tin, tungsten, arsenic, zinc, lead and copper (Dines, 1956; Shail *et al*., 2014; Burt *et al*., 2015). Approximate quantities of metal production in south-west England are shown in Table 3.

Table 3. Estimated total mineral and metal production from south-west England. After Dines (1956), Alderton (1993) and South Crofty PLC (1988-1998). Adapted from LeBoutillier (2002).

Mineral or metal (Tonnes)	
Sn metal	2,770,000
Cu metal	2,000,000
Fe ore	2,000,000
Pb metal	250,000
As (as As_2O_3)	250,000
Pyrite	150,000
Mn ores	100,000
Zn metal	70,000
W (as WO_3)	5,600
U ore	2,000
Ag ore	2,000
Ag metal (from sulphide ore)	250
Co-Ni-Bi ores	500

Sb ores	300
Mo metal	Minor
Au metal	Minor
Barite	500,000
Fluorite	10,000
Ochre/umber	20,000
Kaolinite (china clay)	150,000,000

4.2 MINERALISATION IN SOUTH-WEST ENGLAND

Four main stages of mineralisation have been identified in south-west England, forming over about a 100 Ma period between the early Permian and the late Triassic. The mineralisation can be broadly divided on the basis of its timing relative to granite emplacement as:

(1) *Pre-granite* orebodies of the sedimentary-exhalative type and shear-zone hosted Au-Sb mineralisation;

(2) *Granite-related* mineralisation, comprising greisens and sheeted vein complexes and polymetallic sulfide lodes and;

(3) *Post-granite* mineralised Zn-Pb-Ag crosscourses (highlighted in Table 4). Figure 4 provides an overview of the fluid chemistry of these mineralisation syles.

Pre-granite mineralisation comprises: (1) stratiform mineralisation that contains sub-economic enrichments in base metals (Scrivener *et al.*, 1989; Scrivener, 2006); and (2) metamorphogenic quartz-carbonate veins that typically contain Sb-As-(Au) (Clayton *et al*., 1990). The main commodities associated with the early stratiform mineralisation are iron and base metals. Orogenic shear-hosted Au-Sb-Ag mineralisation is limited to basinal argillaceous lithologies with significant volumes of basic volcanic rocks. It is also spatially associated with NNW-trending shear zones (Stanley *et al*., 1990). Fluid chemistry and structural data indicates that the quartz-Au-Sb veins were precipitated early from CO_2-rich metamorphic fluids with fluid inclusion homogenisation temperatures (Th) in the range 315–280 °C (Clayton *et al*., 1990).

Granite-related mineralisation formed largely during the early to mid-Permian. These mineral deposits were historically of the greatest economic importance and were exploited for tin, tungsten, arsenic and base metals. *Granite-related* mineralisation includes skarns and pegmatites, greisens and sheeted vein deposits, and the main-stage polymetallic deposits. Localised skarn deposits have resulted from the thermal alteration of calc-silicate minerals that have been altered by boron-rich fluids (Scrivener 2006). Volumetrically these skarns are insignificant, thus reflecting the lack of carbonate-rich rocks in the region.

Greisen occurrences are restricted in extent, but common immediately adjacent to all plutons, including the Isles of Scilly Granite (Grant and Smith, 2012; Sullivan *et al*., 2013; Shail *et al.*, 2014). Greisen wall rock alteration is characterised by the development of secondary mica around sheeted veins and in stockworks. It occurs in the granite (endogranite) and the surrounding host rocks (exogranite). Endogranitic greisens occur at St. Michaels Mount (Floyd *et al*., 1993), Cligga Head (Hall 1971; Jackson and Moore 1977), and Hemerdon (Beer and Scrivener, 1982), while exogranitic greisens occur in the Tregonning and St Austell granites (Dominy *et al*., 1995). The greisens comprise closely spaced quartz-tourmaline veins up to 0.1 m wide that host wolframite, cassiterite, stannite, arsenopyrite and other sulfides. Fluid inclusions indicate that the greisen-bordered veins were precipitated over a wide range of temperatures (Figure 4). Greisens represent the earliest occurrence of significant fracture controlled magmatic-hydrothermal mineralisation in south-west England (Shail *et al.*, 2014). Greisen bordered, sheeted veins and quartz-(feldspar)-wolframite lodes formed within 2–3 Ma of granite emplacement, and overlap with muscovite cooling ages for the host/adjacent pluton (Chen *et al*., 1993; Chesley *et al*., 1993).

Polymetallic lodes containing cassiterite and chalcopyrite, and subordinate arsenopyrite, sphalerite, galena and localised wolframite post-date the greisen bordered, sheeted veins. These lodes were historically the main source of tin and copper in the region. The complex structure and mineralogy of these deposits, and their strong spatial association with granite bodies, reflect the protracted magmatic-hydrothermal activity associated with their formation (Scrivener 2006). These polymetallic lodes are generally orientated E-W and developed between 269–259 Ma, although there is a suggestion that this reflects the dating of more than one paragenetic episode (Chen *et al*., 1993; Clark *et al*., 1993). These lodes mark the final contribution of magmatic-hydrothermal fluids to mineralisation in south-west England (Shail *et al.*, 2014).

Table 4: Summary of mineralisation styles in the south-west England (Cornubian) orefield (adapted from Andersen, *et al*. 2016).

Pre-granite mineralisation	**Main ore minerals**				
1) Rifting and passive margin development (early Devonian-Carboniferous) sedimentary-exhalative (SedEx) mineralisation	Haematite	Siderite	Galena	Sphalerite	
2) Variscan convergence and continental collision (late Devonian-Carboniferous) shear zone hosted Au-Sb + base metal mineralisation	Gold	Bournonite	Sphalerite	Chalcopyrite	Tetrahedrite
Granite-related mineralisation					
3) Early post-Variscan extension and magmatism (early Permian)					
a) Magnetite-silicate skarns developed in metabasaltic hosts	Magnetite	Cassiterite			
b) Sulfide-silicate skarns developed in calc-silicate granite hosts	Cassiterite	Arsenopyrite	Pyrite	Chalcopyrite	Pyrrhotite
c) Greisen-bordered sheeted vein complexes	Wolframite	Cassiterite	Chalcopyrite	Sphalerite	Bismuthinite
d) Quartz-tourmaline veins and breccias	Cassiterite	Haematite			
e) Polymetallic sulfide lodes	Cassiterite	Chalcopyrite	Wolframite	Arsenopyrite	Sphalerite
Post-granite mineralisation					
4) Episodic intraplate rifting and inversion (late Permian – Cenozoic)					
a) Crosscourse Pb-Zn ± F, Ba mineralisation	Galena	Sphalerite	Arsenopyrite	Chalcopyrite	

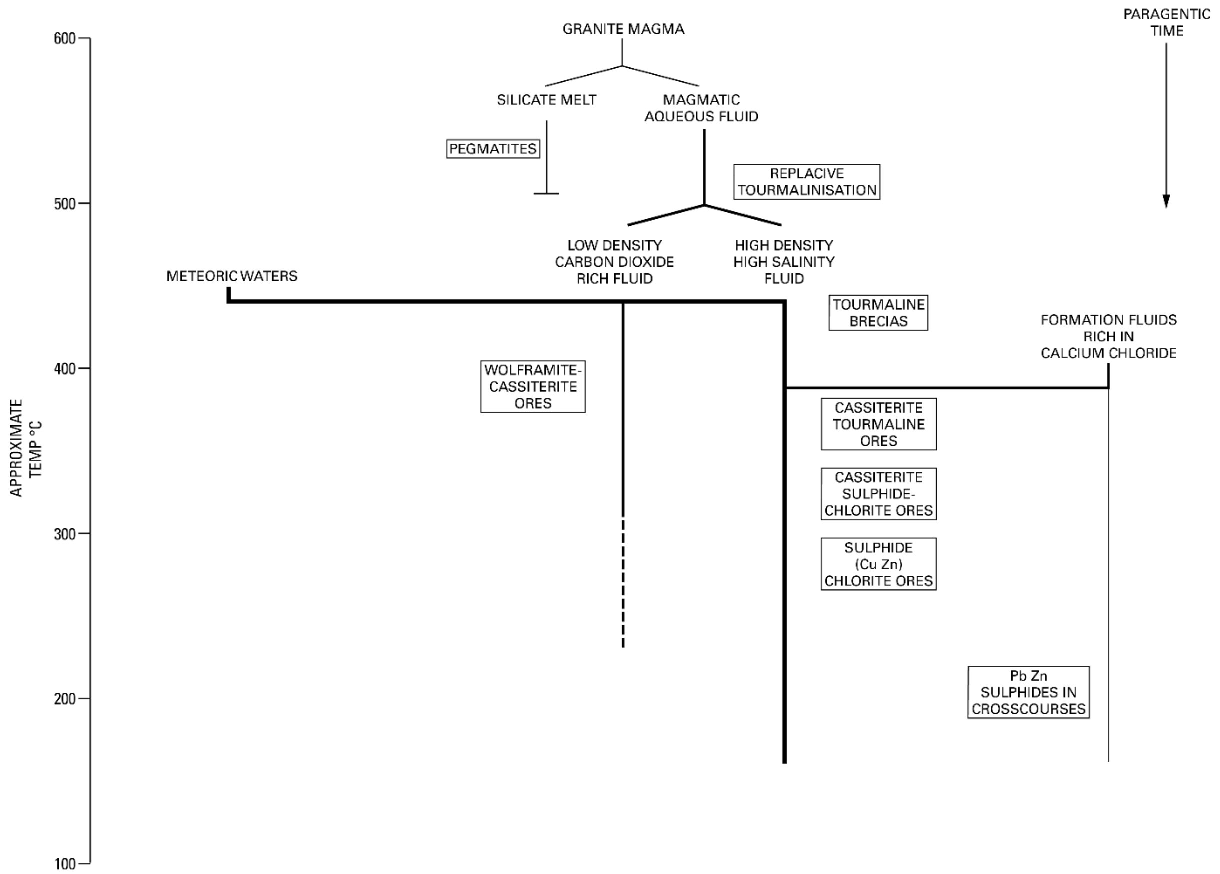

Figure 4. Overview of the evolution of mineralising fluids in south-west England (after Leveridge *et al*., 1990).

Post-granite mineralisation formed by east-west extension during regional extension-driven subsidence in the Permian resulted in the formation of north-south-trending fracture systems. Subsequent fracture-controlled ingress of metal-complexing basinal fluids from Permo-Triassic sedimentary successions into the Variscan basement resulted in the stripping of metals from metalliferous source rocks, and the formation of what is known as 'crosscourse' mineralisation (Scrivener *et al.,* 1994). This comprises polymetallic veins dominated by lead, zinc and copper, which locally host antimony-bearing minerals. The north-south-trending crosscourse mineralisation postdates the granite related Sn-W-Cu mineralisation by 30–40 Ma (Scrivener *et al*., 1994). The crosscourse veins were primarily exploited for lead, zinc, silver, fluorite and baryte, typically within Devonian and Carboniferous successions.

In addition to the styles of mineralisation described above, there are a number of less significant types of mineralisation that are not described in this report. These include: syn-granite tourmaline-tin veins (Scrivener 1982; Bromley 1989); tourmaline breccias (London *et al*., 1995; Müller and Halls 2005); post-granite, low temperature manganese and iron replacement deposits; and gold-carbonate veins (Jackson *et al*., 1989). Following granite emplacement, descending meteoric water resulted in alteration of feldspar, leading to high levels of kaolinisation in the St Austell and Dartmoor granites. This has not been discussed in this report as it is not metallic mineralisation. However, the following references provide a good overview of this late-stage alteration: Sheppard (1977), Bray and Spooner (1983) and Bristow and Exley (1994).

4.3 SUMMARY

The south-west of England is a historically important mining region and has produced a significant range and volume of metals. However, the region is best known for its tin and copper production. Mineralisation in south-west England can be categorised into four broad styles that have been related to the timing of granite emplacement (i.e. pre-granite, granite-related, and post-granite). The most significant mineralisation in south-west England from an economic perspective is related to magmatic-hydrothermal activity associated with granite emplacement. Importantly a significant, and growing, body of research and data exists on mineralisation in south-west England.

4.4 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- A large amount of data (e.g. geochronology, fluid composition, mineralogy, geochemistry, etc.) has been generated from ore deposit research in south-west England.
- A good understanding is developing of how magmatism, fluids and large-scale structures have interacted to produce economic mineralisation. This data and knowledge has implications for engineered geothermal systems.

4.5 LIMITATIONS IN OUR UNDERSTANDING OF THE MINERALISATION IN SOUTH-WEST ENGLAND:

- There is significant uncertainty about the form and scale of mineralisation below 1,000 m.
- The distribution of data coverage is generally skewed towards areas where economic mineralisation has been exploited or commercial mineral exploration has occurred.

5 Structure and stress-field measurements

South-west England is a structurally complex region whose geological past has been dominated by Variscan tectonics. British Geological Survey mapping, academic research and seismic surveys have led to the identification of three main deformational phases associated with Variscan orogenesis. Two phases are related to crustal shortening (D_1 and D_2) whilst the third (D_3) is associated with crustal extension during orogenic collapse (Alexander and Shail, 1996; Leveridge *et al.*, 2002). The D_1 deformation event (c. 385 Ma) is characterised by: (1) large-scale (10s km), NW-SE-trending strike-slip faults; (2) a NNW-trending mineral lineation; and (3) E-W-trending folds. Structures associated with the second deformation event (D_2) are similar to those formed during D_1, but D_2 structures are generally more steeply dipping. The D_3 event (c. 305–300 Ma) occurred in response to orogenic collapse and associated crustal extension. It resulted in the development of steep to gently inclined WNW-ESE-trending extensional faults (Alexander and Shail, 1996; Leveridge *et al.*, 2002). Regionally extensive NNW-SSE-trending crosscourse structures formed during the Permian in response to a period of crustal extension (Scrivener *et al.*, 1994; Shail and Alexander, 1997).

In south-west England both granite and the killas have inherently poor permeability (Heath *et al.*, 1985). Accordingly, fluid circulation in the region is largely controlled by regional-scale structures (e.g. NW-SE-trending faults) (Figure 5) and fractures (Heath *et al.*, 1985; Bromley *et al.*, 1989; Smedley *et al.*, 1989). Fractures in the granite are primarily the result of magma chamber processes, for example cooling and hydro-fracturing (caused by the movement of magmatic fluids). In contrast fractures in the killas are principally the result of granite emplacement. Local zones of high-fracture density, in both granite and killas, may also be associated with episodes of late faulting. However, the permeability and connectivity of these fractures, particularly at depth, remains enigmatic (Heath *et al.*, 1985).

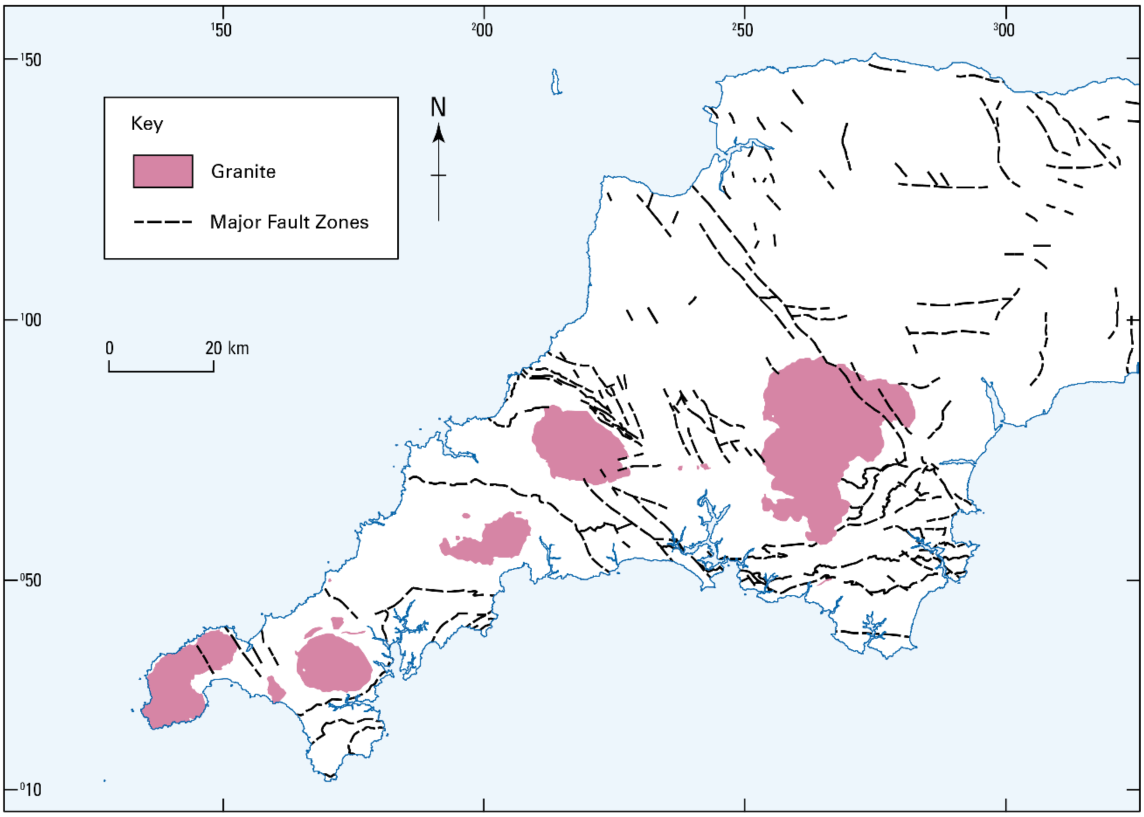

Figure 5. Map of the distribution of major NW-SE-trending faults and granite bodies in south-west England (drawn from BGS mapping data).

A relatively small number of stress field measurements were made on the Carnmenellis granite, during the 1980s. Both hydraulic fracture tests and overcoring tests were conducted at the Rosemanowes HDR test site at depths of 0–2,000 m and 800 m, respectively. All of the tests were successful in achieving 'breakdowns' (i.e. the point at which the fluid pressure is high enough to fracture the rock), in only one of the tests was the hydraulic fracture fully characterised using microseismic monitoring. A series of overcoring tests were also conducted in the South Crofty mine (on the edge of the Carnmenellis granite) at a maximum depth of 790 m. A similar, but unrelated, set of stress field tests (i.e. hydraulic fracturing and overcoring) were carried out at Carwynnen quarry, also on the Carnmenellis granite. Although the hydraulic fracture tests and overcoring were conducted at much shallower levels, 700 m and 34 m, respectively the two studies confirmed the presence of two joint sets in the Carnmenellis granite: one trending NNW-SSE-trending and the other ENE-WSW. The results from both studies show that the *in-situ* stress orientation is about 30° off parallel from that of the natural joint sets observed in the granite. The studies also demonstrated that maximum *in-situ* stress (σ_H) is approximately 70 MPa in the NNW-SSE direction, whilst the minimum *in-situ* stress (σ_h) is about 30 MPa in the ENE-WSW direction (Figure 6). It was found that stress magnitude and orientation at depth are relatively consistent across the Carnmenellis granite, and are fairly consistent with measurements from the rest of the United Kingdom. Importantly it was found that shearing along these natural joints was more likely than dilation, unless very high injection pressures were used (Pine and Batchelor, 1984; Evans, 1987; Cooling *et al.*, 1988; Haimson *et al.* 1989; Turnbridge *et al.*, 1989).

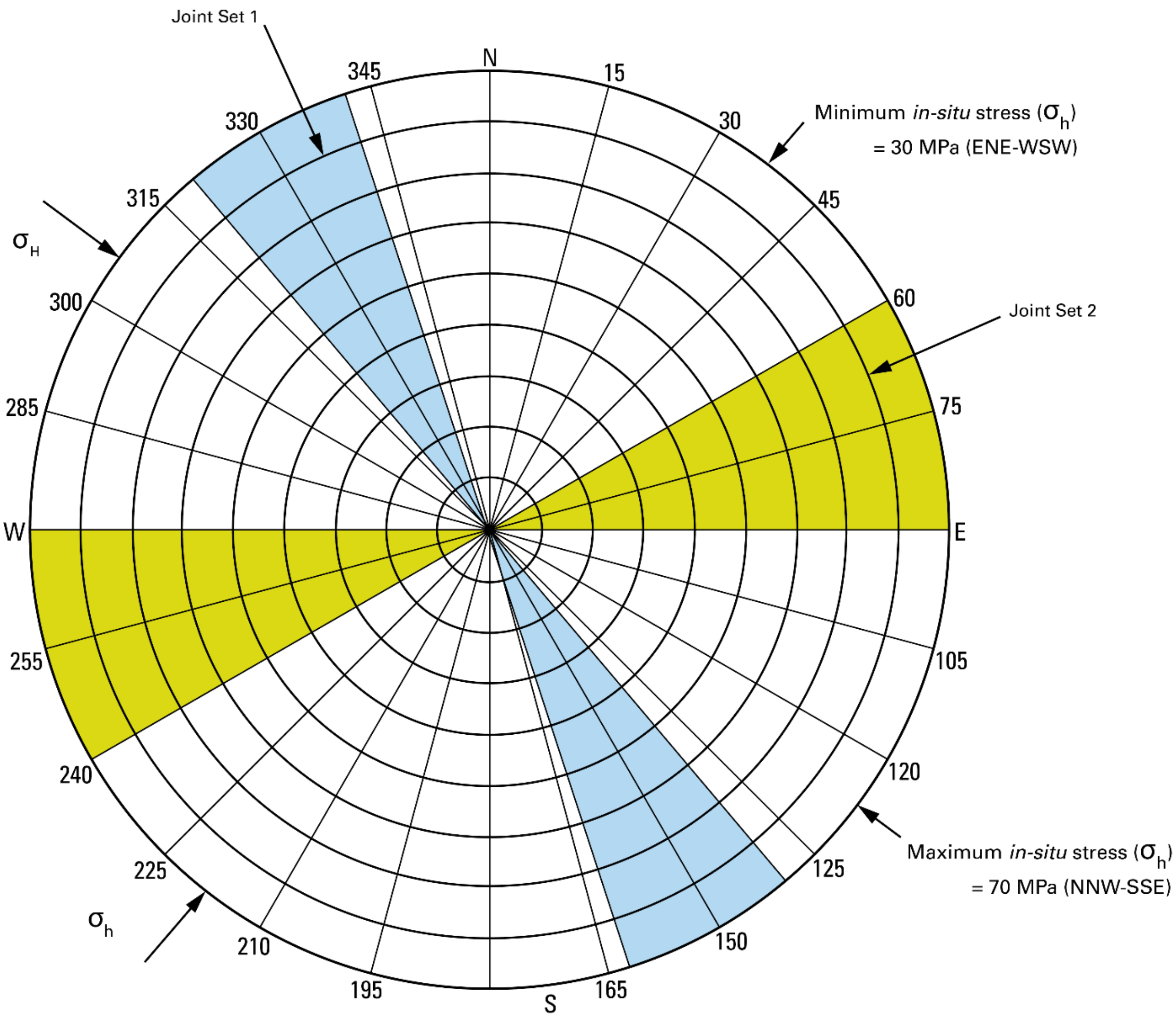

Figure 6. Principal stress orientation and magnitude in the Carnmenellis granite as determined by *in-situ* hydraulic fracture tests at the Rosemanowes HDR test site (re-drawn from Pine and Batchelor, 1984).

5.1 SUMMARY

The south-west of England is a structurally complex region whose geological past has been dominated by Variscan tectonics, which resulted in at least three episodes of deformation. The permeability of rocks (i.e. granites and metasedimentary rocks) in south-west England is inherently very low, and as such faults and fractures are locally and regionally important in terms of fluid flow. In particular the presence of large-scale, NNW-SSE-trending crosscourse structures are an important consideration for the design of any EGS system in south-west England. However, the permeability and connectivity of these features, particularly at depth, remains enigmatic. Assessment of the stress field in south-west England shows it is comparable to other parts of the

UK. Two joint sets occur in the Carnmenellis granite and analysis has determined the relative *in-situ* stress orientation and the maximum and minimum *in-situ* stress values.

5.2 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- I*n-situ* stress measurements have been made at depth (up to 2,000 m) in south-west England.
- Relative to many other onshore parts of the UK the stress field in south-west England is fairly well constrained.
- Consistency in the approach used for making *in-situ* stress field measurements in south-west England means the results of different survey are directly comparable.

5.3 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF STRESS IN SOUTH-WEST ENGLAND:

- Whilst existing data provide a good indication of the stress field in the upper 2 km of crust in south-west England, uncertainty about the type of lithologies which occur at greater depth and their structural characteristics means the validity of extrapolating these measurements to the target depths of an EGS system is a consideration.
- Only a small number of deep (specific ~2,000m) stress measurements are available for south-west England. This is a particular issue given that significant heterogeneity in stress orientation and magnitude may exist.

6 Deep sub-surface temperatures in south-west England

6.1 UNITED KINGDOM OVERVIEW

Between 1977 and 1994 the UK government funded an assessment of potential geothermal energy resources. This programme considered three main elements: (1) appraisal of heat flow; (2) potential of hot-brines from deep hyper-saline aquifers (HAS) for direct heat production; and (3) the potential of EGS, which included the HDR Programme. A catalogue of sub-surface temperatures, heat flow estimations, thermal conductivity measurements and geochemical data was compiled by BGS (Burley and Edmunds, 1978). It was subsequently updated by Burley and Gale (1982), Burley *et al.* (1984) and Rollin (1987). The findings of this work were summarised by Downing and Gray (1986a, 1986b), BGS (1988), Parker (1989, 1999) and most recently in Barker *et al*. (2000).

A heat flow map (Figure 7) of the UK was generated and subsequently revised (Downing and Gray, 1986a, b; Lee *et al*., 1987; Rollin, 1995; Rollin *et al*., 1995; and Barker *et al*., 2000). The map shows two areas of enhanced heat flow that are associated with the radiogenic granites of south-west England (Cornwall) and the buried granites of northern England. Temperatures at 5 km depth were estimated to be as high as 180–190°C in Cornwall, and up to 130–170°C in northern England, but rarely exceeded 95°C elsewhere. The average geothermal gradient is 26°C km^1 but locally it can exceed ≈ 35°C Km^{-1} (Busby, 2010). The average UK heat flow is approximately 55 mWm^{-2}.

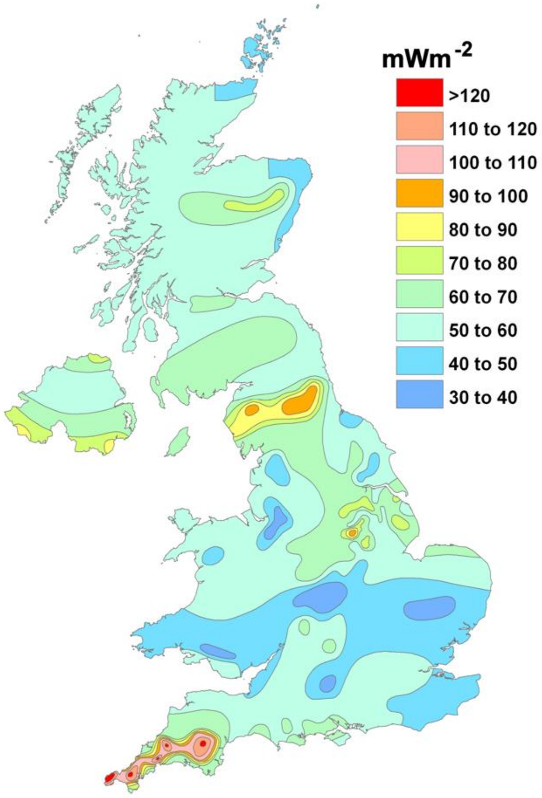

Figure 7. Heat flow map of the UK (after Busby, 2010).

6.2 SOUTH-WEST ENGLAND OVERVIEW

Of specific interest to this project are the data for the south-west region of the UK, in particular Cornwall where the geothermal gradient is estimated to be highest. Barker *et al*. (2000) noted that the average heat flow in the Cornubian granites of south-west England is ≈ 120 mWm^{-2}. Heat production values for the Cornubian granites can be found in Wheildon *et al*. (1981) and Thomas-Betts *et al*. (1989). Beamish and Busby (2016) have re-assessed the quality of these original data sets, and in addition have recalculated the heat flows in accordance with our improved understanding of paleoclimate. This has resulted in revised values that are higher than the original estimates, with the consequence that temperatures at depth are also greater i.e. at 5 km they range from ≈ 185°C for the Dartmoor granite to ≈ 220°C for the St Austell granite, (Figure 8) which is an increase of between 6 and 11 per cent. The vast majority of the temperature data comes from shallow wells (about 100 m), with additional data available from some former mines e.g. Geevor mine at about 400 m and South Crofty at about 600 m. As such, these estimated temperatures are based on a model that assumes constant heat production to a depth of 5 km. There are only very limited (historic) temperature data available from depths below 600 m, largely comprising data from the former HDR Project at Rosemanowes Quarry, near Redruth, on the Carnmenellis granite. Here three deep wells were drilled, the deepest being a 2,600 m vertical well, plus several shallow boreholes (300 m). Barker *et al*. (2000) reported that measured temperatures were ≈ 80°C at 2,100 m depth (in well RH12) and ≈ 100°C at 2,600 m (in well RH15). The revised heat flow data from Beamish and Busby (2016) gives slightly higher, estimated, subsurface temperatures of ≈ 84°C, and ≈ 102°C at 2,100 m and 2,600 m, respectively. Unfortunately, UK government funding was withdrawn from the HDR project before it could investigate conditions at 5–6 km, and it closed in 1994. Although its three deep wells are still accessible, it is unclear if any temperature measurements have been obtained since the close of the project. To date no other deep wells have been drilled in the region.

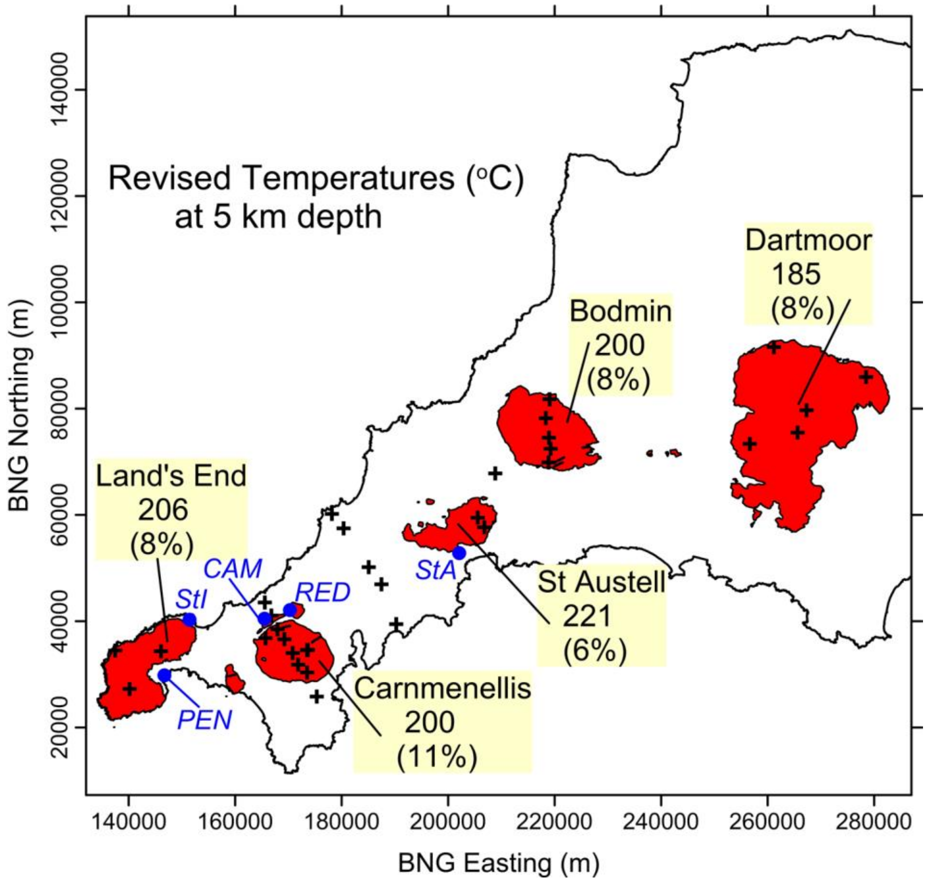

Figure 8. Revised estimated granite-related average temperatures (°C) at a depth of 5 km and the percentage increases (in brackets) over previously published estimates. Locations of five towns, are shown in blue; PEN = Penzance; StI = St Ives; CAM = Camborne; RED = Redruth and; StA = St. Austell (after Busby and Beamish, 2016).

6.3 SUMMARY

A significant body of data exists from a British government funded assessment of the potential geothermal energy resources in the UK, over a period spanning three decades. South-west England, specifically Cornwall, was estimated to have the highest geothermal gradient in the UK. Temperatures at 5 km depth in the Cornubian granites are estimated to be in the range of ≈ 185°C–220°C. However, it is important to note that these estimates are based on modelled heat flow and heat production. Data from depths of >600 m is very limited, but the measured temperature from one of three deep wells in the Carnmenellis granite was ≈ 100°C at 2,600 m. It is notable that these three well are still accessible.

6.4 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- A significant dataset exists from investigation of the geothermal potential of the UK. However, some of this data may be only available in analogue format.
- Three deep boreholes are still accessible within the Carnmenellis granite, meaning there is potential for new measurements to be taken to validate existing data and new models and estimates.

6.5 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF DEEP SUB-SURFACE TEMPERATURES SOUTH-WEST ENGLAND:

- Despite a significant body of data there is still significant uncertainty about the temperatures that might exist at the depth of an EGS system as most estimates and models are based on extrapolation of near surface historical data.
- Selected historical data is only available in analogue format.
- The HDR project ceased in 1994, with little associated work taking place during the subsequent 22 years.

7 Hot Dry Rock (HDR) research programme

In 1984, a programme of work, funded by the UK Department of Energy (DEn) and the Commission of the European Communities (CEC), was undertaken by the British Geological Survey (BGS) to assess the UK for its geothermal potential. Over the same time period (1977–1984) the Camborne School of Mines (CSM) was assessing the feasibility of creating HDR geothermal systems at a test site at the Rosemanowes quarry, on the Carnmenellis granite, in Cornwall. The assumption was made that the behaviour and characteristics of a HDR system could be modelled using geochemistry, geophysics, and physical properties. Between 1985–1989 the Department of Energy and the Commission of the European Communities funded a detailed geochemical investigation of the HDR site at Rosemanowes. These investigations were undertaken by the BGS, the then NERC Isotope Geology Centre (NIGC), the University of Bath (UoB) and CSM. In 1987 an informal working group (the UK Hot Dry Rock Geochemistry Group) was established to align the geochemical programme more closely with the physical properties and geophysical work being undertaken by CSM at the Rosemanowes test site. The BGS output of this work was series of seven volumes (Edmunds *et al.* 1989; Richards *et al.* 1989; Andrews *et al.* 1989; Smedley *et al.* 1989; Bromley *et al.* 1989; Savage *et al.* 1989 and; Richards *et al.* 1989) that outline the methods and results of geochemical HDR research at the Rosemanowes test site (Edmunds, *et al.*, 1989) (Figure 9). Similar outputs (authored by CSM) that describe the physical properties of the HDR system are not held by the BGS.

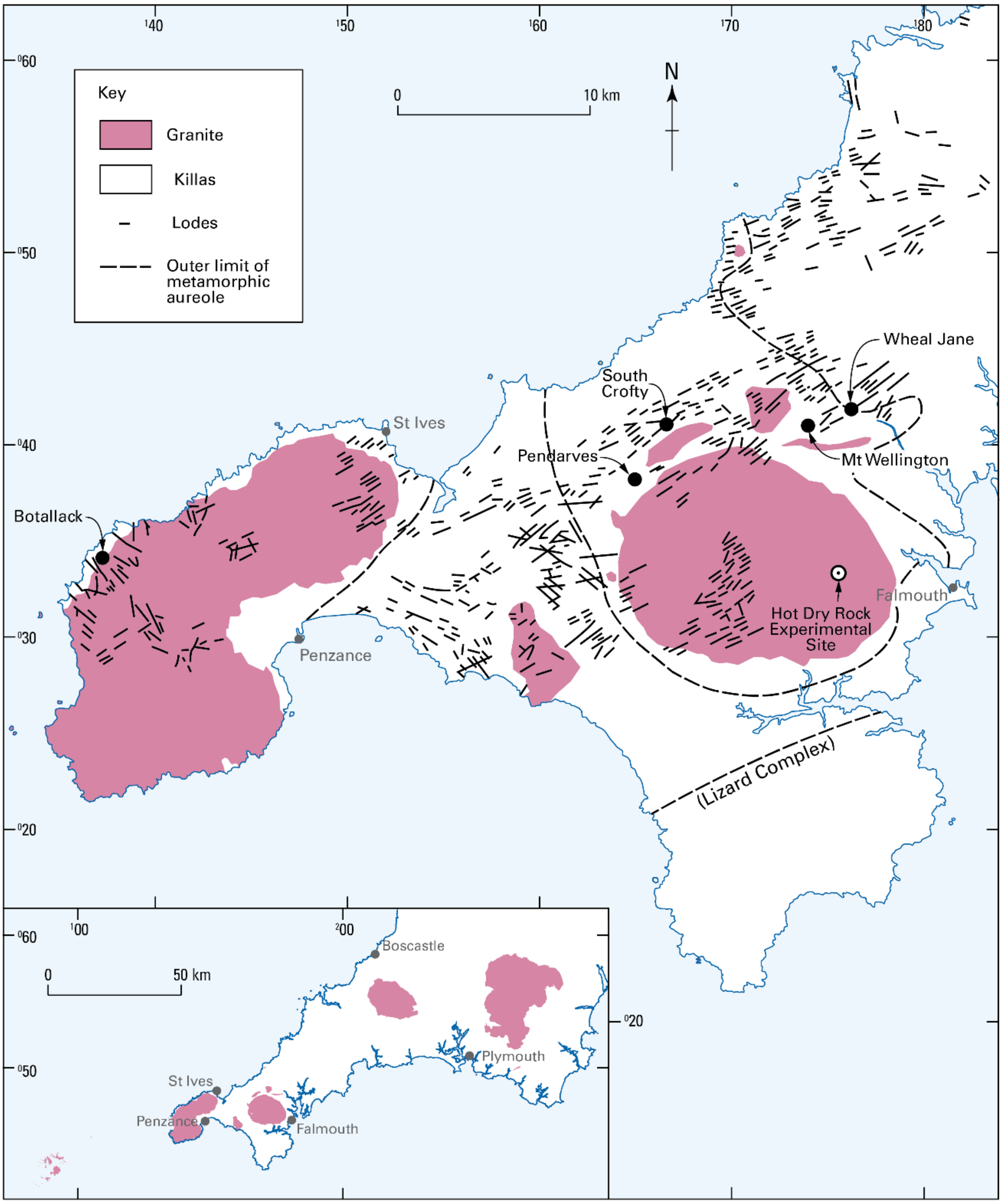

Figure 9. Location of the Rosemanowes HDR test site in relation to the Carnmenellis granite outcrop (re-drawn from Edmunds *et al.*, 1989).

An overview of the aims and main conclusions of each volume is given below along with a schematic of the HDR system at the Rosemanowes test site (Figure 10). Volumes 1 and 2 (Edmunds *et al.* 1989; Richards *et al.* 1989) are not described here as they are primarily, overview-type documents (Volume 1 provides a synopsis of the other 6 volumes, whilst Volume 2 provides an overview of geochemical results collected as part of the HDR programme). Full details of methods used and results obtained are given in each of the volumes.

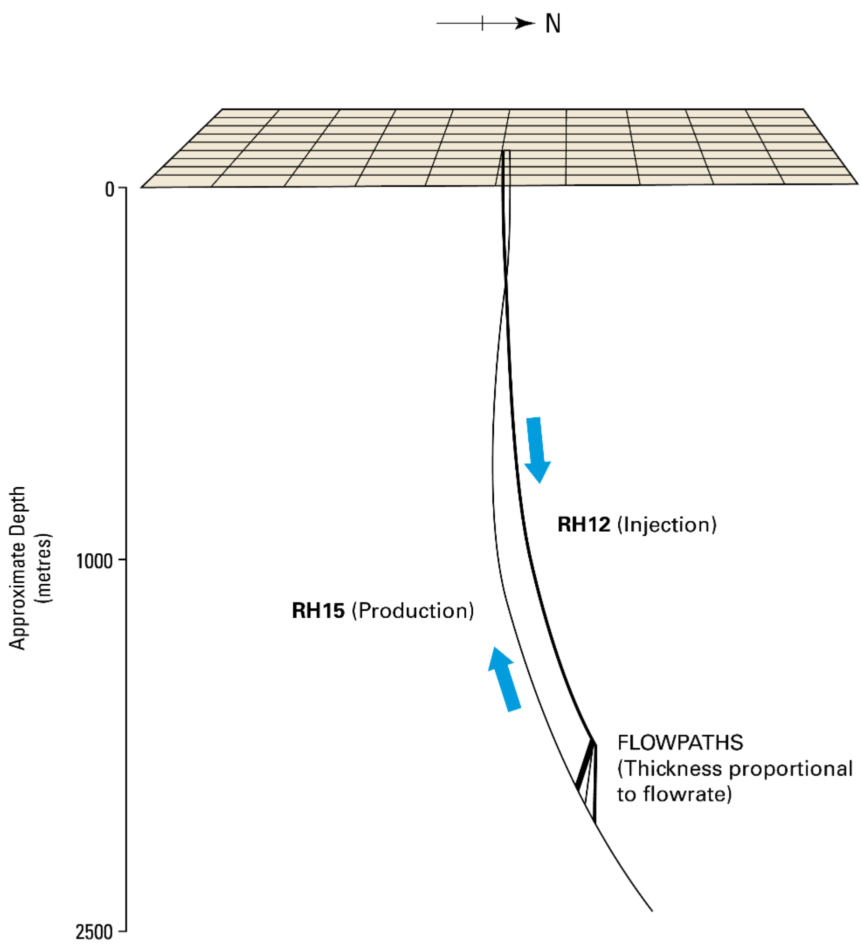

Figure 10. A schematic diagram showing the configuration of the 2 and 2.5 km test wells at the Rosemanowes HDR test site (re-drawn from Edmunds *et al.*, 1989).

7.1 VOLUME 3: THE USE OF NATURAL RADIOELEMENT AND RADIOGENIC NOBLE GAS DISSOLUTION FOR MODELLING THE SURFACE AREA AND FRACTURE WIDTH OF A HOT DRY ROCK SYSTEM (ANDREWS *ET AL*. 1989)

Scope of the report

The movement of natural radioelements (e.g. ^{226}Ra) and radiogenic noble gases (e.g. ^{222}Rn) in the HDR system was investigated to: (1) characterise changes in reservoir surface area; (2) develop a routine monitoring method for determining ^{222}Rn in the HDR return fluids; (3) determine the effect of surface mineralisation and physical conditions on ^{222}Rn flux, and hence upon derived reservoir parameters; (4) estimate the effect of fracture width variation on the radon model; and (5) assess geochemical changes in radioelement chemistry induced by HDR circulation.

Conclusions

- Reservoir surface area showed a general increase as flow tests progressed.
- Tracer transit times of up to 400 hours were observed within fractures.
- Mineralised surfaces, particularly those hosting uranium-rich minerals, dramatically increase the ^{222}Rn flux of the system.
- Uranium mobilisation occurs in the system in response to fluid circulation.

7.2 VOLUME 4: FLUID CIRCULATION IN THE CARNMENELLIS GRANITE: HYDROGEOLOGICAL, HYDROGEOCHEMICAL, AND PALAEOFLUID EVIDENCE (SMEDLEY *ET AL.* 1989)

Scope of the report

Investigation of the hydrogeology and hydrogeochemistry of the Carnmenellis granite helped to explain important processes, such as: (1) granite-water interaction; (2) fluid-flow in granite; and (3) solution-precipitation reactions. Understanding natural fluid flow can be useful to HDR development as it provides an analogue to artificial short-term circulation in the HDR reservoir.

Conclusions

- Groundwater flow in both granite and killas is dominated by fracture permeability; primary permeability in both rock types is low. In particular it is the north-south-tending crosscourse structures that are the most important water-conducting fractures.
- Shallow groundwater compositions show a strong affinity with the local geology and soils. In many cases the element concentrations are very lithology-specific, for example Cl, HCO_3, pH, Na, Ca, Mg levels are highest over the killas, whilst Al, Ba and Rb levels are higher over the granite.
- Saline thermal waters discharging in deep mines (depths down to 820 m) are effectively dilute palaeobrines (formed by long-term water-rock interaction) that have mixed with circulating local meteoric waters.

7.3 VOLUME 5: MINERALOGY AND GEOCHEMISTRY OF THE CARNMENELLIS GRANITE (BROMLEY *ET AL.* 1989)

Aims of the report

In order to fully understand the geological constraints on HDR reservoir development the geology of the region is considered in detail. In particular the following areas of enquiry are of interest: (1) the spatial variation in the petrological and geochemical characteristics of the granites ; (2) the spatial variation in the nature of the fracture system ,and the character of fracture mineralogy and adjacent wall-rock alteration; (3) the mechanisms and products of natural fluid-rock interaction under conditions similar to those pertaining in an artificial reservoir, and which might provide useful analogues for reservoir behaviour; and (4) the prediction of geological conditions at depths of 5–7 km in regions where commercial reservoirs may be developed.

Conclusions

- Rock at depth is likely to be an inhomogeneous mixture of vuggy, pegmatitic granite and magmatic residues (i.e. restite). Thus water-rock interaction would be significantly different from that predicted by experiments on samples of 'average' Cornubian granite.
- The ability to drill an inhomogeneous mixture of granite and restite is likely to be very different from that of standard granite alone.
- Localised zones of argillic alteration, associated with crosscourse structures at depth, may hamper drilling operations.
- North-south-trending crosscourse structures are likely to extend to significant depths and as such represent important zones of increased permeability. However, they may also lead to extensive fluid loss from the HDR system.

7.4 VOLUME 6: EXPERIMENTAL INVESTIGATION OF GRANITE-WATER INTERACTION (SAVAGE *ET AL.* 1989)

Scope of the report

Investigation of chemical reactions that take place between circulating fluids and reservoir rock in a HDR system is important because: (1) it provides an indication of the evolution of the physical characteristics of a reservoir under development (e.g. temperature), and (2) it provides information about the potential lifetime of a reservoir undergoing commercial operation. Laboratory experiments were undertaken to evaluate the magnitude and rate of water-rock reactions, including: (1) the surface-area dependant release rate of a variety of chemical component from the Carnmenellis granite under likely *in-situ* conditions at EGS depths; and (2) the investigation of the chemical reaction of Carnmenellis granite with possible circulation fluids.

Conclusions

- The concentration (by weight) of elements in the output fluid from laboratory experiments was as follows (from highest to lowest): SiO_2 > Ca > Na > K > Fe > Mn > Rb > Li > Cs > Sr.
- The relative molar release rates of the elements (from highest to lowest) was: SiO_2 > Na > Ca > K > Fe > Mn > Li > Rb > Sr > Cs.
- Changes in pH were only found to affect Al (increased with increasing pH), SiO_2 (increased with increasing pH) and Fe (decreased with increasing pH).
- Use of dilute surface water as an EGS 'top-up' fluid was superior to using seawater, the latter causing potential problematical precipitation of hydrated magnesium sulphate phases.
- Bulk granite dissolution rates vary significantly from 6 x 10^{-10} g m^{-2} s^{-1} (expressed as SiO_2 release) at 60°C to 5 x 10^{-7} g m^{-2} s^{-1} (expressed as Ca release) at 100°C.
- Individual mineral dissolution rates also vary significantly. Experiments at 80°C have generated the following estimated rates of dissolution: 2 x 10^{-11} – 8 x 10^{-10} mol m^{-2} s^{-1} (biotite); 4 x 10^{-11} – 2 x 10^{-10} mol m^{-2} s^{-1} (oligoclase); 2 x 10^{-10} – 4 x 10^{-10} mol m^{-2} s^{-1} (labradorite) and; 1 x 10^{-15} – 2 x 10^{-14} mol m^{-2} s^{-1} (tourmaline).

7.5 VOLUME 7: GEOCHEMICAL PROGNOSIS FOR A HOT DRY ROCK SYSTEM IN SOUTH-WEST ENGLAND (RICHARDS *ET AL.* 1989)

Aims of the report

The geochemical aspects of the design and operation of a commercial HDR geothermal system in granite, in south-west England are reviewed and modelled in order to predict: (1) the composition of the circulation fluid; (2) the potential for chemical problems associated with the wells and surface plant (including effluents); (3) the rates of water-rock reactions in the HDR reservoir, and how this might affect hydraulic performance; and (4) the potential use of geochemistry in characterising the performance of the HDR reservoir during and after its creation.

Conclusions

- The most appropriate circulation fluid is predicted to be a mildly-saline, neutral- to mildly-alkaline local surface water, with low to moderate total sulfur (20–150 ppm SO_4) and low to moderate total sulfide (5–10 ppm H_2S).
- Silica and/or carbonate-based scaling are likely to the biggest issue for wells and surface plant.

- Predicted arsenic (c. 1 ppm), boron (c. 1 ppm), fluoride (c. 10–20 ppm) and silica (c. 300 ppm) concentrations in the circulation fluid mean they could not be discharged straight into the environment without prior treatment.
- Mineral dissolution is likely to result in widening of fractures (by up to 1 mm over a 25 year lifetime) and thus will have an impact on reservoir hydraulics.
- However, the precipitation of secondary minerals (e.g. zeolites, clays and calcite) as a result of granite-water reactions would also have a potentially negative impact on porosity and reservoir hydraulics.

7.6 SUMMARY

The UK HDR geochemistry group was a collaboration between BGS and CSM; it sought to use geochemistry to characterise the behaviour and performance of an engineered geothermal system (EGS). A number of important conclusions were drawn from this work, including: fluid residence time, mineral dissolution rates, surface area modelling, and potential problems related to chemistry (e.g. scaling of surface plant and 'clogging' of the reservoir by the development of secondary minerals).

7.7 HOW SOUTH-WEST ENGLAND CAN POSITIVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- Data associated with the HDR programme is specific to engineered geothermal systems.
- Samples, data and observations gathered as part of the HDR project are derived from boreholes down to about 2.6 km deep. This is currently much deeper than similar boreholes in the UK, and thus provides a useful insight into the deep geothermal environment in south-west England.

7.8 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF SOUTH-WEST ENGLAND:

- Data and interpretation are specific to the Carnmenellis granite.
- Only a small amount of core material from the original HDR programme is available.
- Significant uncertainty remains in terms of actual conditions that might be encountered in a deep (c. 4–6 km) commercial HDR system (i.e. many of the conclusions are based on predictive models).
- Much of the data are only available in analogue format.

8 Data holdings at BGS

The BGS is the world's longest established national geological survey, and is the UK's premier provider of objective and authoritative geoscientific data. It has been gathering geoscience data and information about the subsurface in the UK and other countries for more than 180 years. It is a data-rich organisation with more than 500 datasets in its care, including environmental monitoring data, digital databases, physical collections (e.g. borehole core, rocks and minerals), records and archives. Importantly, a great many of these datasets are openly available, many of which provide complete, seamless UK coverage at a number of scales. Certain other datasets may be subject to confidentiality clauses and/or licencing fees. Information about how to access these datasets can be found here: http://www.bgs.ac.uk/data/home.html?src=topNav.

These national datasets are available to the CHPM2030 project, and can provide a very useful starting point to assess CHPM potential in south-west England. Many of the datasets cover much of the UK, whereas others are specific to south-west England (e.g. geophysical data conducted as part of the TELLUS project (http://www.tellusgb.ac.uk/). Most of the data stored relate to surface exposures or the near-surface environment. Although, the datasets do contain much information about a large number of boreholes and mines, most does not extend below 100 m, and there is limited data below 1,000 m. This places significant constraints on predictions when extrapolating the data to EGS depths (i.e. 4–6 km). The datasets are also of differing ages and levels of detail - reflecting changing national priorities over the past decades. In terms of geothermal development, much of the data are derived from a national programme of work in the 1980s and early 1990s. As a consequence, the data reflect monitoring technology and ideas at that time, and much of the data are in analogue format.

Table 5: Summary of datasets pertinent to CHPM2030 held by the BGS.

Datasets	Description	Scale	Coverage	Access cost	Link
Hydrogeology					
Depth to groundwater	Spatial model showing depth (m) to the phreatic water table.	1:50,000	Great Britain	15p per km^2	http://www.bgs.ac.uk/products/hydrogeology/depthToGroundwater.html
Hydrogeological maps	Spatial model of aquifer potential based on geological formations.	1:625,000	UK	Free	http://www.bgs.ac.uk/products/hydrogeology/maps.html
Permeability	Spatial model showing flow regimes (e.g. fracture flow) and relative flow rates.	1:50,000	Great Britain	10p per km^2	http://www.bgs.ac.uk/products/hydrogeology/permeability.html
Geophysics and remote sensing					
LiDAR	High-resolution LiDAR digital terrain model (DTM) and digital surface model (DSM).	Resolution information on website	SW England	Free	http://www.tellusgb.ac.uk/data/home.html
Airborne magnetics	Airborne survey data showing variation in the magnetic field.	Resolution information on website	SW England	Free	http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html
Airborne radiometrics	Airborne survey data for the radioactive isotopes Th, U, and K.	Resolution information on website	SW England	Free	http://www.tellusgb.ac.uk/data/airborneGeophysicalSurvey.html
Land gravity	A database of over 165,000 gravity observations.	N.A.	Great Britain	Free	http://www.bgs.ac.uk/products/geophysics/landGravity.html
Geophysical borehole logs	An archive of geophysical downhole log data.	N.A.	Various	£30 per hole	http://www.bgs.ac.uk/products/geophysics/boreholeLogs.html

Datasets	Description	Scale	Coverage	Access cost	Link
Geology					
Geological maps	2D lithological and structural mapping (bedrock and superficial).	*1:50,000	UK	**20p per km^2	http://www.bgs.ac.uk/products/digitalmaps/DiGMapGB_50.html
UK3D	A 3D bedrock model of the UK at 1:625,000 scale.	1:625,000	UK	Free	http://www.bgs.ac.uk/research/ukgeology/nationalGeologicalModel/gb3d.html
Boreholes					
Borehole database	A database of over one million records of boreholes, shafts and wells.	N.A.	Great Britain	Free	http://www.bgs.ac.uk/products/onshore/SOBI.html
Borehole scans	Online access to more than one million borehole logs.	N.A.	Great Britain	Free	http://www.bgs.ac.uk/data/boreholescans/home.html
Physical properties					
Rock stress	Online access to almost 1,000 rock stress measurements.	N.A.	Great Britain	Free	http://mapapps.bgs.ac.uk/rockstress/home.html
Discontinuities	Spatial model of discontinuities in bedrock (e.g. fractures and faults).	1:50 000	Great Britain	**30p per km^2	http://www.bgs.ac.uk/products/groundConditions/discontinuities.html
Geochemistry					
GBASE south-west	Geochemical baseline survey of soils and stream sediments.	N.A.	SW England	Free	http://www.bgs.ac.uk/products/geochemistry/GbaseSWproducts.html
Minerals					
Britpits	A database of over 180,000 records of active and inactive mine and quarry workings.	N.A.	UK	***£50 per region	http://www.bgs.ac.uk/products/minerals/BRITPITS.html

Footnotes:

* Other scales available (e.g. 1:25,000; 1:10,000; 1:625,000).

** Commercial rate. Free to use via the BGS web-based viewer: http://mapapps.bgs.ac.uk/geologyofbritain/home.html

*** The full dataset comprises fifteen regions.

8.1 SUMMARY

The BGS maintains a large number of datasets (over 500) that include environmental monitoring data, digital databases and physical collections (i.e. borehole core and rock samples). Many of the datasets offer complete, seamless coverage of the UK at a variety of scales. A good number of these datasets are also freely and openly available.

8.2 HOW SOUTH-WEST ENGLAND CAN POSITVELY CONTRIBUTE TO THE AIMS OF CHPM2030:

- The BGS holds a large amount of information about the geological, geophysical and geochemical properties of the UK.
- Data coverage for the south-west region is very good.

8.3 LIMITATIONS IN OUR CURRENT UNDERSTANDING OF SOUTH-WEST ENGLAND:

- The majority of the data sets only relate to the shallow sub-surface 0–1,000 m).
- Some datasets are incomplete (e.g. rock stress data are restricted in spatial coverage).
- Some datasets are based on old data that have been digitised.

9 Conclusion

This report describes the breadth of information available for south-west England, which is relevant to the development of enhanced geothermal systems, except data held by CSM relating to physical properties testing and geophysics at the HDR test site. South-west England is a geologically complex region with a long and significant history of metal mining, producing primarily tin and copper. The requirement to better understand the economic mineral potential of the region has resulted in almost 200 years' worth of applied and academic research. These studies have generated a huge volume of data that includes: geological mapping, geophysical and geochemical surveys, and numerous reports and peer-reviewed publications. Another potentially important resource in south-west England is geothermal energy. Previous geothermal research in the region peaked between the 1970s and 1990s, and focussed largely on the high heat flows associated with the Cornubian granites. In 1984 this programme of work was undertaken by the BGS to assess the UK's geothermal potential. Over the same time period (1977–1984) the Camborne School of Mines (CSM) was assessing the feasibility of creating HDR geothermal systems at a test site at the Rosemanowes quarry, on the Carnmenellis granite, in Cornwall.

In summary a huge amount is known about the geology, mineralisation, fluid history and geothermal potential of south-west England. A significant body of data underpins this knowledge base, the majority of which is freely, or openly available. However, there are limitations. For example, much of this data, with the exception of the HDR datasets, only relates to the upper 1,000 m of the crust. This has significant implications regarding the accuracy of modelled conditions in an enhanced geothermal system (EGS) at greater depths. There are also ‘gaps’ in the data (e.g. very limited deep-geophysical data), and some datasets have not been updated since their creation several decades ago.

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