Comparative petrology & geochemistry of high heat-producing granites in Australia & Europe

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To better understand the origin, tectonic setting and generation of high heat-producing granites (HHPG) and provide target criteria for the exploration of granite-hosted Enhanced Geothermal Systems (EGS), Australian examples are being studied and compared with better known European analogues that are being re-examined.
Three areas of long-standing interest for EGS in Europe are Cornwall, UK; Soultz-sous-Forêts, France; and the Erzgebirge, Germany. These areas have higher than average heat flow (at surface and depth), and concentrations of the main heat-producing elements Uranium (U), Thorium (Th) and Potassium (K) in granitic rocks.
The Big Lake granite suite of the central Australian Cooper Basin (Gatehouse et al., 1995), is a pre-eminent HHPG target for EGS development in Australia. The Big Lake Suite granites are Australia's hottest with temperatures of >250ºC at ~4km depth (Habanero 1, (Baisch et al., 2006). The Soultz-sous-Forêts and Cooper Basin systems have in common an insulating sediment cover of several kilometres.

Keywords: high heat-producing granites (HHPG), Cooper Basin, Cornwall, Soultz-sous-Forêts, Erzgebirge, Uranium, Thorium, Permo-Carboniferous, intraplate.

Background

The development of EGS in the Cooper Basin was started by Geodynamics Ltd in 2002 with the aim to be the first Australian Company producing electricity from EGS sources. Their first geothermal well (Habanero 1) encountered granite at depth. The granite (Big Lake Suite) is situated in the Nappamerrie trough (Meixner et al., 2000; Sun, 1997) and intruded into the Cambrian – Ordovician Warburton Basin (Gatehouse et al., 1995). The Big Lake Suite Granite is covered by a ~3km thick sedimentary package consisting of the Cooper (Late Carboniferous – Middle Triassic), Eromanga (Early Jurassic) and Lake Eyre (Early Tertiary - Holocene) Basins. U/Pb series dating of zircon of granite intersected at depth in two wells established a Permo-Carboniferous age ranging between 323±5 Ma and 298±4 (Gatehouse et al., 1995).
The Cornubian batholith in Cornwall (SW England; Fig. 1) is comprised of six plutons ranging in age from 293.1±1.3 Ma to 274.5±1.4 Ma, based on U/Pb dating of magmatic monazites (Chen et al., 1993). Two plutons of interest are the Carnmenellis and Land's End granites (Fig. 2) as they contain the highest levels of U and Th (Table 1). During the 1970's and 1980's the Rosemanowes area of the Carnmenellis granite was a test site for the Department of Energy, European Commission and Cambourne School of Mines investigation into EGS technology as it has the highest heat flow in England, over 120 mW/m^2 (Tenzer, 2001).
Soultz-sous-Forêts (Fig. 1) has been the European test site for EGS since 1987, with temperatures of 200°C at 5 km depth (Antics and Sanner, 2007).
The granites of the Erzgebirge region (Fig. 1), like Cornwall, are associated with Tin (Sn), Tungsten (W), Lead (Pb), Zinc (Zn), Fluorine (F), Barium (Ba) and U mineralisation, with the high U and Th contents and crustal heat flow values giving added prospectivity as a clean energy resource.

Tectonic History

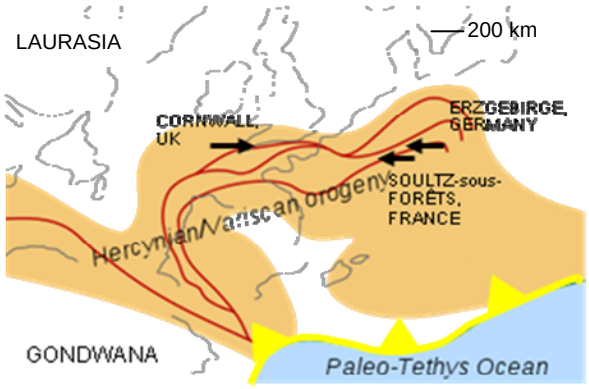


Figure 1: Location of the Hercynian/ Variscan mountain chains in the middle of the Carboniferous period. Red lines are sutures. Yellow line is subduction zone (triangles point in direction of subduction) (Scotese, 2001). Adapted from Matte (2001) and Zeigler (1990).

Regionally, the European granites were emplaced in an extensional environment between 334-270 Ma following collision of Laurasia and Gondwana to form the supercontinent Pangaea (Willis-Richards and Jackson, 1989). This collisional event, known as the Variscan (Hercynian) orogeny, resulted in an extensive rift system within the northern foreland of the Variscan

orogenic belt following termination of orogenic activity (Wilson et al., 2004).

Cornwall

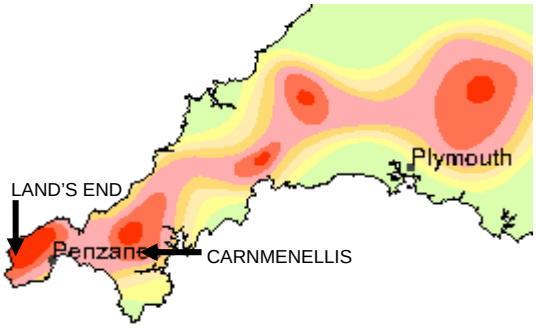


Figure 2: Heat flow map of Cornwall, UK, showing the location of the Carnmenellis and Land's End plutons. Heat flow of >120 mW/m^2 (deep red), to 60-70 mW/m^2 (green). Adapted from British Geological Survey GIS heat flow map, 2010.

The Cornubian batholith was emplaced at the end of the Variscan orogeny terminating a period of regional, back-arc continental extension during the Devonian and Early Carboniferous, (Darbyshire and Shepherd, 1985).
This orogenic event caused crustal thickening (Willis-Richards and Jackson, 1989) and has been suspected to have caused anatectic melting (Clark et al., 1993).
Figure 1 shows that at the time of emplacement the Cornubian granites were over 1350 km away from the nearest active plate margin (bounding the Neo-Tethys), suggesting they are not subduction related.

Soultz-sous-Forêts

The Soultz-sous-Forêts granites lie within the Upper Rhine Graben, a tectonically reactivated region associated with Oligocene crustal extension and thinning (Genter et al., 2003). These granites were emplaced slightly prior to those in Cornwall following the Variscan orogeny, from 334 +3.8/-3.5 Ma (U/Pb monzogranite) to 319.8±0.6 Ma (^{40}Ar/^{39}Ar), (Cocherie et al., 2004 and Stussi et al., 2002).

Erzgebirge

The Erzgebirge granites were also intruded from the Late Carboniferous to Early Permian during large-scale extension following orogenic collapse (Förster et al., 1999b). In addition, wrenching was associated with granite emplacement (Edel et al., 2007).
Förster and Förster (2000) concluded that peak orogenic metamorphism occurred 350-340 Ma, followed by rapid uplift and cooling between 340 and 326 Ma with the oldest, post-collisional, granites intruded to a depth of 3-6 km at 325 Ma (Förster et al., 1999b).

Table 1 is a summary of relevant information for these areas of HHPG.

Granite Petrography

Cooper Basin

The samples studied from the Big Lake Suite have varying degrees of alteration, with alteration increasing with decreasing depth. Unaltered samples consist of quartz (31%), K-feldspar (31%) and plagioclase (31%), with minor biotite (5%) and accessory phases (2%). Accessory phases indentified are magnetite, apatite, thorite/huttonite, zircon, monazite and xenotime with some fluorite.
The altered samples show varying degrees of sericitisation, ranging from minor replacement of the feldspars to complete replacement and the formation of illite. Biotite has altered to chlorite, after which chlorite is replaced by illite. Fresh biotite still exists in the altered samples, but is restricted to small inclusions in quartz. The illite from the Big Lake Suite alteration assemblage occurs as two main textures: 1) pseudomorphic and 2) cryptocrystalline.

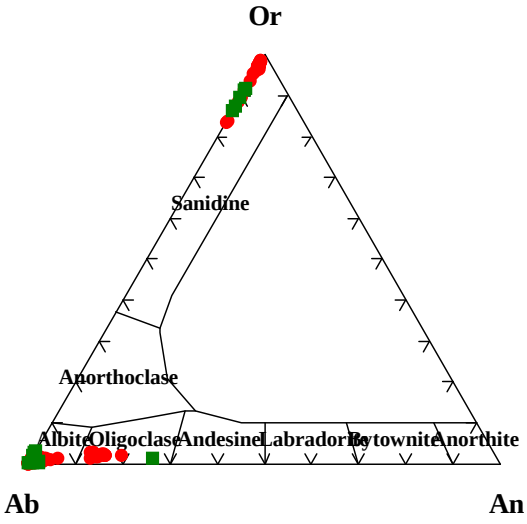


Figure 3: Feldspar classification diagram showing the feldspar composition. Cooper Basin (●) and Soultz–sous–Forêts (■) (Komninou and Yardley, 1997; Stussi et al., 2002).

Electron Probe Microanalysis (EPMA) data shows no compositional differences between the different illite textural types. Although illite does not show compositonal differences between the textural types, there are two compositionally distinct illites - the first is a pure illite with low (<1%) to no Fe_2O_3T, and the second is an Fe-bearing illite (up to 7% Fe_2O_3T). The feldspars from the Cooper Basin are mainly partly albitised oligoclase, with the K-feldspar being microcline. Microcline occurs in some instances as graphic intergrowths with quartz indicating eutectic crystallisation of the granite. In some samples, the quartz from the Cooper Basin granites exhibits

undulose extinction, with some grains exhibiting planar deformation features.

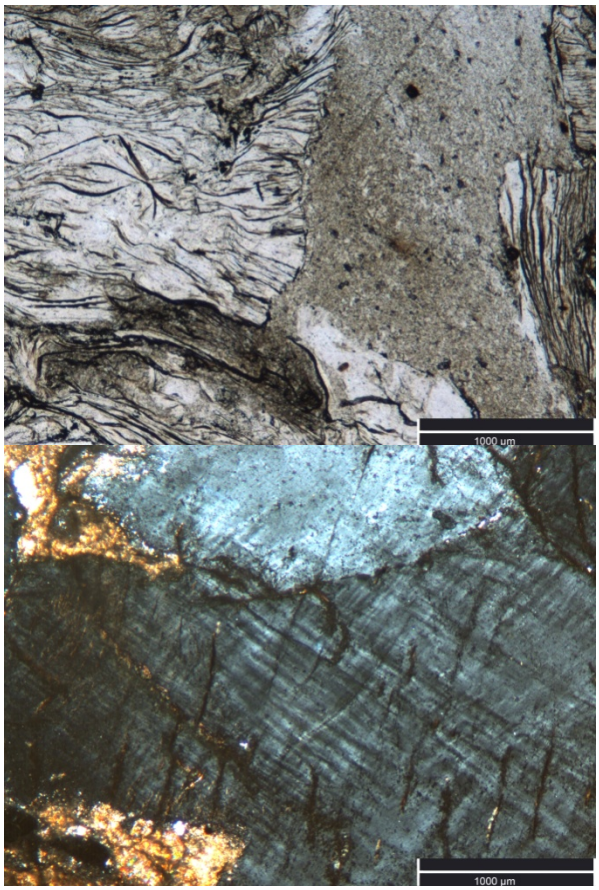


Figure 4: Photomicrographs of two illite textures (top), and planar deformation features in quartz (bottom) in Big Lake Suite granites.

Cornwall

The Carnmenellis granites generally contain around 34% quartz, 32% K-feldspar, 22% plagioclase, 6% biotite, 4% muscovite, 1% tourmaline and 1% accessory phases including andalusite, cordierite, ilmenite, zircon, monazite and uraninite (Charoy, 1985; Chappell and Hine, 2006).The radioactive mineral assemblage important for hosting Th and U are predominantly monazite, apatite, xenotime, zircon and uraninite (hosting ~90% of total U) (Jefferies, 1984; Martel et al., 1990), all of which are commonly associated with apatite and ilmenite (Jefferies, 1984).

Soultz-sous-Forêts

These granites have a normative composition of around 43% plagioclase (37% albite, 6% anorthite), 25% K-feldspar, 22% quartz, 6% biotite, 2% hornblende, and <1% of other minerals including titanite, apatite, magnetite and hematite (Stussi et al., 2002).
The accessory mineral phases important for hosting U and Th are relatively unknown, and will be investigated as part of this study.

Erzgebirge

The normative composition of the Erzgebirge granite is 36% quartz, 32% plagioclase, 29% K-feldspar, 2% biotite and <1% muscovite, with the remainder in accessory phases including apatite, zircon, monazite, opaques, xenotime and uraninite (Förster et al., 1999b).
Förster and Förster (2000) noted that ~90% of U and Th is bound in accessory minerals; 30-90% of U is fixed in uraninite, with the remainder present in monazite, xenotime, zircon and thorite; monazite hosts 80-90% of the Th budget, followed by allanite and thorite.

Granite Petrology

Cooper Basin

The Cooper Basin granites are peraluminous I-type granites based on mineralogy, but because of alteration it is difficult to distinguish between fractionated I-, A- or S-type (Fig. 5). The occurrence of hornblende, relative abundance of biotite and absence of distinctive aluminosilicate phases, suggests the granite suites are more likely fractionated I- to A-types. The Cooper Basin granites have a wide range in ACNK (Al_2O_3 / ($CaO + Na_2O + K_2O$) molar) values from weakly (1.04) to strongly (1.98) peraluminous. The range in peraluminosity reflects the high degree of alteration in these samples, with significant leaching of calcium causing some samples to exhibit strongly peraluminous compositions. In contrast to most of the European granite examples, the Cooper Basin granites do show stronger “within plate” tectonomagmatic affinities (Fig. 6). However, Gatehouse et al. (1995) postulated that the Cooper Basin granites may be related to the Alice Springs Orogeny of central Australia, but based on available ages, the granites were emplaced at the end and after the 332–320 Ma climax of uplift in Central Ausralia (Veevers, 2009). The Cooper Basin granites range from less fractionated with lower total REE and small Eu anomalies to more fractionated with higher total REE and larger Eu anomalies (Figs 7 & 8).

Cornwall

The Cornubian granites have been described as S-type in character (Chappell and Hine, 2006, Fig. 6), reflecting a metasedimentary crustal source. Specifically, the granites are believed to have been derived by partial melting of aluminium-rich pelitic metasedimentary rocks deposited during the Carboniferous and Devonian in a tensional back-arc ensialic setting (Willis-Richards and Jackson, 1989). The Cornubian granites are highly evolved and strongly peraluminous, reflected by the presence of muscovite and cordierite (Charoy, 1995 and Stone, 1995). Recent fieldwork on the Land’s End pluton

confirmed Tammemagi and Smith's (1975) observations of abundant K-feldspar megacrysts in places. Some plutons have subhorizontal flow fabrics (e.g., St Austell granite) suggesting some granitic magma emplacement in sill-like or laccolithic bodies, and mineralogical and age variations indicate the batholith has been incrementally built.

Soultz-sous-Forêts

The Soultz-sous-Forêts granites have been classified as S-type according to tectonic discrimination diagrams (Fig. 6), however they are noted to have hornblende (Stussi et al., 2002) and oxidised K-feldspar, suggesting possible I- or A-type classification. They are also peraluminous and porphyritic, with K-feldspar megacrysts up to 80 mm in diameter. These granites are thought to have originated from either crustal partial melting of enriched metamorphic greywacke, granulite and amphibolite, or meta-igneous rocks of appropriate composition; however, a minor mantle contribution can't be excluded due to the negative εNd values (Stussi et al., 2002). Subhorizontal magma fabric oriented to the NE was also noted suggesting either a laccolithic body or the roof of a diapir-like intrusion, in association with post-magmatic fracturing (Stussi et al., 2002).

Erzgebirge

The Erzgebirge granites are more varied, with mildly peraluminous transitional I- to S-types and strongly peraluminous S-types both present (Förster et al., 1999b, Fig. 5).
Förster et al. (1999b) also noted some granites have peraluminous A-type chemical affinities, consistent with the intraplate setting of this magmatism.
Förster and Förster (2000) recognised that the surface heat flow is higher where the granites occur, contributing 70-90 mW/m^2 to the surface heat flow - two to four times higher than would be estimated from the average composition of the continental bulk crust.

Table 1: Compositions of targeted HHPG for EGS. Sources: Charoy (1985), Chappell and Hine (2006), Jefferies (1984), Martel et al. (1990), Tammemagi and Smith (1975), Willis-Richards and Jackson (1989), Chen et al. (1993), Müller et al. (2006), Förster H.J. (1999), Förster and Förster (2000), Förster et al. (1999a), Förster et al. (1999b), Hooijkaas et al. (2006), Stussi et al. (2002), Uysal and van Zyl (unpubl. data), and Taylor and McLennan, (1985).

EGS TARGETED GRANITES	AGE (Ma)	LITHOLOGY	SiO_2 (wt%)	K_2O (wt%)	U (ppm)	Th (ppm)
Carnmenellis Cornwall, UK	295-270	Megacrystic biotite and two-mica granites	70-76	4-4.3	4.3-35 (12.1 mean)	11-25 (19.3 mean)
Land's End Cornwall, UK	277-274.5	Early megacrystic biotite granites, younger Li-siderophyllite granites	66-73	3.5-6	6.9-38	4.4-46.2
Soultz-sous-Forêts Upper Rhine Graben, France	334-319	Porphyritic monzogranite	67-69	3.8-4	6.2-14.1	23-37
Erzgebirge, Germany	325-315	Transitional I-, S- and A- type biotite granites, two-mica granites and S- and A- type Li-mica granites	67-77 (biotite) 71-76 (two-mica) 73-76 (Li-mica)	3.8-5.4	9-30.9	10.4-34.3
Cooper Basin, Australia	323-298	Coarse grained two feldspar biotite granite, moderately weathered	-	-	11 - 27	17 - 117
Upper Continental Crust			66	3.4	2.7	10.7

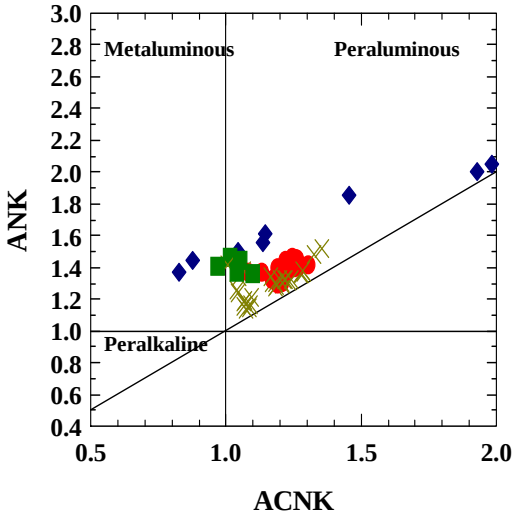


Figure 5: ASI index for granites classification plot according to Shand (1927), Cooper Basin (◆); Cocherie et al. (2004), Soultz-sous-Forêts (■); Chappell and Hine (2006) and Müller et al. (2006), Cornwall (●); and Förster et al. (1999b) Erzgebirge (X).

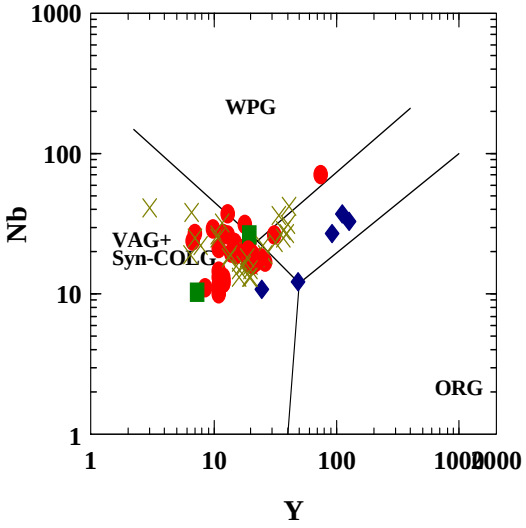


Figure 6: Tectonic discrimination diagram comparing the studied granite suites (Pearce et al., 1984).

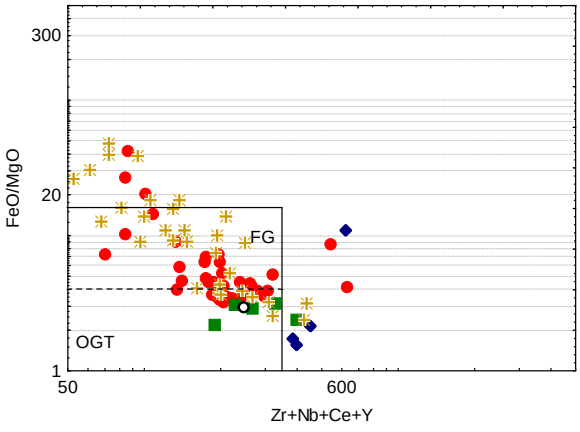


Figure 7: Granite discrimination plot from Whalen et al. (1987) OGT - Other Granite Types (I-, M-, S- type), FG – Fractionated Felsic Granites.

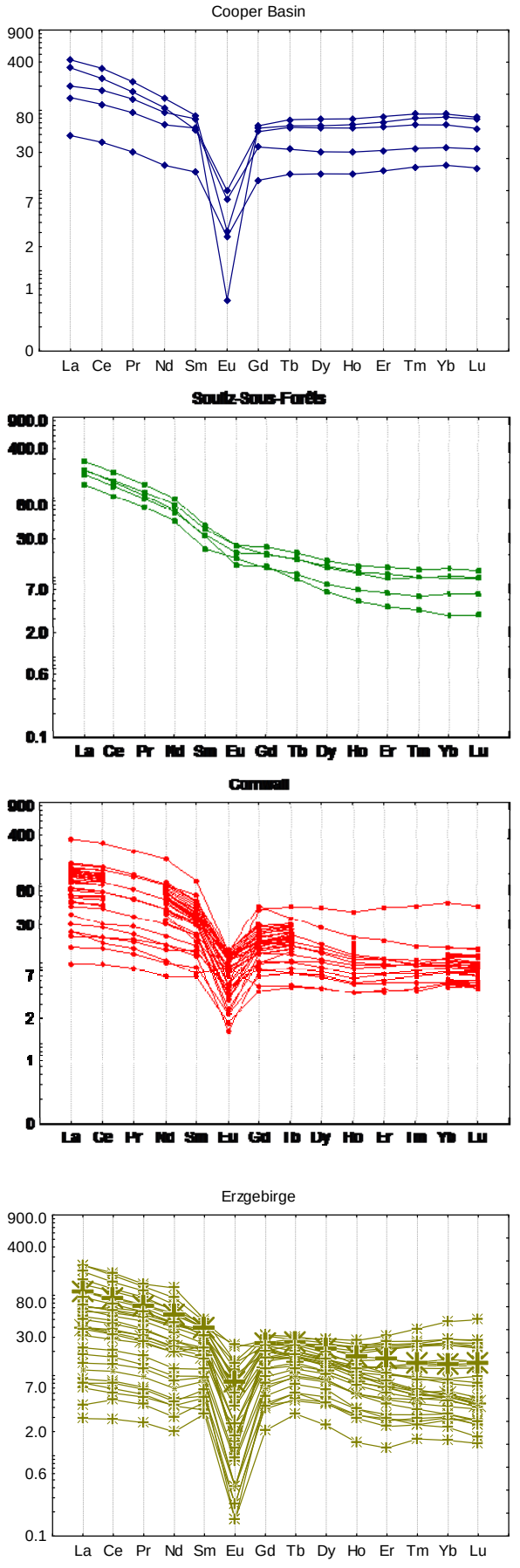


Figure 8: REE Spider plots for the four granite intrusions. Normalisation was performed using McDonough and Sun (1995).

Discussion and Comparison

- Both European and Australian examples of HHPG are Late Carboniferous to Early Permian in age.
- All HHPG in this study were emplaced well in board from active plate margins. The European granites are post-collisional and extension-related, whereas the Cooper Basin granites are also within-plate but may be (temporally) related to intraplate deformation.
- The Cooper Basin, Soultz-sous-Forêts and the Erzgebirge show similar abundances of quartz, plagioclase and K-feldspar, with plagioclase being the more abundant phase in Soultz-sous-Forêts. The Cooper Basin and Erzgebirge are equigranular, whereas Soultz-sous-Forêts and the Carnmenellis are distinctly megacrystic granites.
- It is difficult to use the I- and S- type classification for fractionated granites, but this study suggests all the granites are peraluminous, with the European granites dominantly S-type, but Cooper Basin and Erzgebirge also showing I- and A- type affinities suggesting that crustal source composition may not be a prime control on HHPG generation.
- Literature and field observations indicate that at least part of the Cornubian and Soultz-sous-Forêts granites have sill-like intrusive components but importantly, that all the batholiths discussed here have been incrementally built by a number of intrusions.
- Trace element geochemistry and rare earth element abundances of the Cooper Basin granites show a range from less fractionated to highly fractionated (Eu/Eu* =0.04 to 0.17), whereas Soultz-sous-Forêts show more uniform REE patterns, and a wide range of REE patterns have been described for the Erzgebirge granites. The Carnmenellis has a narrower range in REE than the Erzgebirge. The Cooper Basin, Carnmenellis and Erzgebirge all show strong Eu anomalies indicating fractional crystallisation was important in the production of these granites (Fig. 7).
- Isotope data suggests that all examples have crustal signatures.
- The Cooper Basin granites are more enriched in Th, but there is similar U enrichment for all examples. Currently, the reason for U and Th enrichment is unknown, except for the normal fractional crystallisation processes.

The current conclusion from this study is that the peraluminous, highly fractionated chemistries have promoted the U and Th enrichment of HHPG.

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