Chemical composition of zircons from the Cornubian Batholith of SW England and comparison with zircons from other European Variscan rare-metal granites

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Abstract

Zircon from 14 representative granite samples of the late-Variscan Cornubian Batholith in SW England was analyzed for W, P, As, Nb, Ta, Si, Ti, Zr, Hf, Th, U, Y, La, Ce, Pr, Nd, Sm, Gd, Dy, Er, Yb, Al, Sc, Bi, Mn, Fe, Ca, Pb, Cu, S, and F using EPMA. Zircons from the biotite and tourmaline granites are poor in minor and trace elements, usually containing 1.0–1.5 wt% HfO_2, <0.5 wt% UO_2 and P_2O_5, <0.25 wt% Y_2O_3, <0.2 wt% Sc_20_3 and Bi_2O_3, and <0.1 wt% ThO_2. Zircon from topaz granites from the St. Austell Pluton, Meldon Aplite and Megiliggar Rocks are slightly enriched in Hf (up to 4 wt% HfO_2), U (1– 3.5 wt% UO_2), and Sc (0.5–1 wt% Sc_2O_3). Scarce metamictized zircon grains are somewhat enriched in Al, Ca, Fe, and Mn. The decrease of the zircon Zr/Hf ratio, a reliable magma fractionation index, from 110-60 in the biotite granites to 30-10 in the most evolved topaz granites (Meldon Aplite and Megiliggar Rocks), supports a comagmatic origin of the biotite and topaz granites via long fractionation of common peraluminous crustal magma. In comparison with other

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European rare-metal provinces, the overall contents of trace elements in Cornubian zircons are low and the Zr/Hf- and U/Th-ratios show lower degrees of fractionation of the parental melt.

Key words: zircon, chemical composition, Cornwall, rare-metal granite

Introduction

Zircon is one of the most common accessory minerals in granites and is often used as a petrogenetic indicator (Wark and Miller, 1993; Hoskin and Schaltegger, 2003; Hanchar and Watson, 2003; Gagnevin *et al.*, 2010), in provenance studies (Hoskin and Ireland, 2000; Belousova *et al.,* 2002; Grimes *et al.*, 2007) and for geochronology (Davis *et al.,* 2003; Crowley *et al.,* 2008). In spite of an apparently simple chemical composition ($ZrSiO_4$), the zircon lattice is able to accommodate substantial amounts of several minor and many trace elements. Such substitutions are influenced by the: (i) evolving composition of the crystallizing melt, in particular the content of fluxing elements (F, Cl, P) and P-T conditions (Bea e*t al.,* 1994; Sano *et al.*, 2002; Thomas *et al.,* 2002; Nardi *et al.,* 2013) (ii) trace-element composition of the source (Hoskin and Ireland, 2000; Belousova *et al.*, 2002) and geotectonic setting (e.g. A- vs. S-type granites, Breiter *et al.,* 2014).

The Cornubian Batholith of SW England is a classic location for the study of rare-metal granites (e.g. Černy *et al.*, 2005) and has been extensively studied (e.g. Manning and Exley, 1984; Stone and Exley, 1985; Charoy, 1986; Willis-Richards and Jackson, 1989; Jackson *et al.,* 1989; Chappell and Hine, 2006; Müller *et al.,* 2006 and references therein). However, accessory mineral chemical data is relatively scarce: tourmaline (London and Manning, 1995), topaz (Manning and Exley, 1984), radioactive minerals (Jefferies, 1984, Ward *et al*., 1992), Nb-Ta minerals (Scott *et al*., 1998) and REE-minerals (Jefferies, 1985). As far as

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zircon is concerned, the only published analyses are those from the Land´s End pluton where Müller *et al.* (2006) reported Zr/Hf=29–46 and variable contents of Th, U, Y, REE, and Fe, but without any systematic trend.

The purpose of this article is: (i) to describe and interpret the minor and trace-element mineral chemistry of zircons from different granites of the Cornubian Batholith and (ii) to compare the chemistry of these zircons with those from other European rare-metal granites.

The Cornubian Batholith

The Cornubian Batholith of SW England is a WSW–ENE trending, 250 km long × 20–40 km wide composite granite intrusion extending from the Isles of Scilly in the west to Dartmoor in the east (Willis-Richards and Jackson, 1989). Modelling of gravity anomaly data suggests a minimum batholith thickness of *c.* 6-7 km and implies that >40,000 km^3 of magma was generated and emplaced over a 25 Ma period in the Early- Mid-Permian (295-270 Ma) (Willis-Richards and Jackson, 1989; Chen *et al.*, 1993; Chesley *et al.*, 1993; Taylor, 2007). Granite magmatism occurred in the footwall of the Variscan Rhenohercynian / Rheic suture, was approximately contemporaneous with mantle-derived lamprophyres and high-K basalts (e.g. Leat *et al.* 1987; Stimac *et al.,* 1995; Dupuis *et al.*, 2015), and strongly influenced by a transtensional tectonic regime established following Variscan convergence (Shail and Leveridge, 2009).

At the current exposure level, the batholith comprises >90% biotite granite, >3% tourmaline granite and >1% topaz granite with minor aplites and pegmatites (Hawkes and Dangerfield, 1978; Willis-Richards and Jackson, 1989; Manning *et al.*, 1996). Six major plutons crop out from east to west on the Cornubian mainland: the Dartmoor, Bodmin Moor, St Austell, Carnmenellis, Tregonning-Godolphin, and Land's End granites (Figure 1). The seventh pluton is situated further to the west on the Isles of Scilly, approximately 40 km WSW of the Land's

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End Granite. Other expressions of magmatism include granite stocks, rhyolite / microgranite dykes locally termed 'elvans' and rare rhyolite lavas.

Biotite granites

The biotite granites are commonly porphyritic, and are mainly monzogranites with subordinate syenogranites (Willis-Richards and Jackson, 1989; data from Exley and Stone, 1964). They are classified as S-type granites (sense Chappell and White, 1974), usually containing K-feldspar phenocrysts, around 5 to 10 modal % biotite (mol. Fe/Fe+Mg ~0.68), up to 4 modal % muscovite, 1 modal % tourmaline and a wide variety of accessory minerals including andalusite, sillimanite, zircon, monazite, uraninite, xenotime, apatite, ilmenite, rutile, anatase, brookite, spinel, fluorite, topaz and garnet (Exley and Stone, 1964, 1982; Jefferies, 1984, 1985; Charoy, 1986; Stimac et al., 1995; Chappell and Hine, 2006). The granites are peraluminous with an aluminium saturation index (ASI) of 1.1-1.4 (Willis-Richards and Jackson, 1989) and silica-rich with a limited range of compositions (SiO_2=70 to 76 wt.%; Darbyshire and Shepherd, 1985, 1987), with an average of 72.35 wt.% (n=54; Chappell and Hine, 2006). They contain elevated As, B, Be, Co, Cs, F, Ga, Li, P, Pb, Rb, Sn, Ta, U and Zn.

A textural distinction can be made between the older (>290 Ma) biotite granites of the Isles of Scilly, Carnmenellis and Bodmin plutons, which largely comprise small phenocryst, coarse-grained granite ± variably porphyritic medium-grained granite, and the younger (<286 Ma) biotite granites of the Land's End, Dartmoor and St Austell plutons that are characterised by variably porphyritic, larger phenocryst, coarse-grained granite (Figure 1). The older biotite granites also have sparse or absent microgranitoid enclaves, more aluminous compositions, lower femic elements, steeper REE patterns, more negative εNd, higher NH_4^+, and biotite/muscovite ratio <1 (Stone, 1997, 2000).

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Tourmaline granites

The tourmaline granites are characterised by tourmaline rather than biotite as the dominant ferromagnesian mineral; they are usually monzogranites and syenogranites and contain either K-feldspar or quartz phenocrysts. Detailed descriptions of the mineralogical and textural variations exhibited by the tourmaline granites are provided by Manning *et al*., (1996). Tourmaline granites occur widely as minor dykes and sills, hosted by biotite granite and immediately adjacent host rocks. Larger bodies have been recognized in the St Austell, Dartmoor and Land's End plutons (Hill and Manning, 1987; Knox and Jackson, 1990; Manning *et al*., 1996; Müller *et al.,* 2006). The mineralogy of the tourmaline granites is broadly similar, with quartz, alkali feldspar, plagioclase (typically $\leq An_7$), biotite and tourmaline (Stone *et al*., 1988; Henderson *et al*., 1989). Accessory minerals usually comprise apatite, monazite, zircon, topaz, and Nb-rich rutile.

Topaz granites

The topaz granites are typically medium-grained, equigranular and aphyric, and characterised by euhedral-subhedral topaz contents of up to 3% and lithium-rich micas (Manning and Hill, 1990; Stone, 1992; Manning *et al*., 1996). They are classified as alkali feldspar granites due to their plagioclase composition ($<An_5$). Topaz granites occur principally in the Tregonning Granite and the Nanpean and Hensbarrow stocks within the St Austell Granite where they are commonly associated with topaz-rich aplites and pegmatites. At Megiliggar Rocks, a series of sub-horizontal topaz granite sheets hosted by slates occur in the roof zone of the Tregonning Granite (Stone, 1975, 1992). The Meldon Aplite is a 3.5 km long, 15–20 m thick, fine-grained topaz granite dyke that crops out in the north-western aureole of the Dartmoor Granite (Edmonds *et al*., 1968). Plagioclase, commonly euhedral and unzoned, is almost pure albite

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(An_{1-4}). Li-micas are zinnwaldite and lepidolite (Stone *et al.*, 1988; Henderson *et al.* 1989); tourmaline is normally schorl, but includes a substantial component of the Li-rich end-member elbaite (London and Manning, 1995). The diverse accessory mineral assemblage variably includes apatite, amblygonite, zircon, ilmenorutile, Mn-ilmenite, Nb-Ta rutile, columbite-tantalite and cassiterite (Manning, 1983; Manning *et al.*, 1996; Scott *et al.*, 1998; Stone & George, 1985).

Samples and analytical methods

Fourteen zircon-bearing samples of granite were obtained from all the plutons of the Cornubian Batholith except the Isles of Scilly and Bodmin Moor plutons (Figure 1, Table 1). Minor intrusions sampled were the Meldon Aplite, Cligga Head Granite, Megiliggar Rocks intrusive sheets (Tregonning Granite roof complex) and an elvan dyke, termed here the Legereath Zawn Elvan, that pre-dates the Tregonning Granite and has been interpreted as a possible expression of the Godolphin Granite, the 'Legereath granite porphyry' of Stone (1975).

Polished thin sections were made from all samples in order to establish the relations between the zircons and rock-forming minerals. Back-scattered electron (BSE) images were taken, prior to analysis, to study the internal zoning of individual mineral grains and their relative position to rock-forming minerals. Zircon and associated minerals such as monazite, xenotime, and uraninite were analyzed using an identical set-up to include all of the elements identified in at least one of the above-mentioned minerals. Elemental abundances of W, P, As, Nb, Ta, Si, Ti, Zr, Hf, Th, U, Y, La, Ce, Pr, Nd, Sm, Gd, Dy, Er, Yb, Al, Sc, Bi, Mn, Fe, Ca, Pb, Cu, S, and F in oxide minerals were determined using a CAMECA SX100 electron probe microanalyser, equipped with five WD spectrometers, hosted by Masaryk University and the Czech Geological Survey, Brno. Minerals were analyzed at an accelerating voltage and beam

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current of 15 keV and 40 nA, respectively, and with a beam diameter ranging from 2 to 5 µm. The following standards were used: U - metallic U, Pb - PbSe, Th - ThO_2, P - fluorapatite, Y - YAG, La - LaB_6, Ce - $CeAl_2$, Pr - PrF_3, Nd - NdF_3, Sm - SmF_3, Gd - GdF_3, Dy - DyP_5O_{14}, Er - YErAG, Yb - YbP_5O_{14}, Al - almandine, Si, Ca, Fe - andradite, Mn - rhodonite, W - scheelite, S - barite, F - topaz, As, Cu - lammerite, Nb - columbite, Ta - $CrTa_2O_6$, Ti - titanite, Zr - zircon, and Sc - $ScVO_4$. Empirical formulae of zircon were calculated on the basis of 4 atoms of oxygen in a formula unit (4 O apfu).

Results

Zircon crystal shape

Zircon from the biotite granites and Legereath Zawn Elvan forms mostly columnar crystals, internally homogeneous (Fig. 2a, b, c) or fine oscillatory zoned (Fig. 2d). It is usually located within, or at the surface of, mica flakes and is often associated with xenotime (Fig. 2e) or monazite (Fig. 2a). In the Legereath Zawn Elvan, and in the coarse-grained biotite granite from Carnmenellis and Land´s End plutons, zircon forms aggregates with rutile (Fig. 2c, f, g). Strongly zoned zircons with a light core and a darker rim are typical for the biotite and topaz granites of the St. Austell pluton (Fig. 2h, i). The rims of these crystals are enriched in Hf and U but, due to strong metamictization, have low analytical totals which result in a darker colour in back-scattered electron images (compare Nasdala *et al.*, 2009).

The most differentiated topaz granites contain mainly patchy zoned and metamict zircons (St. Austell, Fig. 2j) associated often with monazite (Megiliggar Rocks, Fig. 2k) or columbite (Meldon Aplite, Fig. 2l).

Zircon chemical composition

Altogether, 68 analyses of zircon were obtained from 14 thin sections.

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Zircon ($ZrSiO_4$) ideally contains 67.3 wt% ZrO_2 and 32.7 wt% SiO_2. In reality, the content of both elements decreases due to variable substitution by a wide range of minor and trace elements. In the samples studied, ZrO_2 was as low as 43.4 wt% (0.80 apfu Zr) and SiO_2 as low as 21.9 wt% (0.76 Si apfu).

Hafnium is crystallochemically similar to zirconium and so there is substantial substitution in zircon from all rock types. Zircon from the biotite and tourmaline granites analysed usually contains 1.0–1.5 wt% HfO_2 (0.01–0.015 apfu Hf) but this increases to 2.0–3.5 wt% HfO_2 (0.02–0.035 apfu Hf) in the topaz granites, reaching a maximum of 7.35 wt% HfO_2 (0.073 apfu Hf) in the Meldon Aplite.

The Zr/Hf ratio in zircon is, in general, considered a reliable indicator of magma fractionation (e.g. Linnen and Keppler, 2002) and therefore was chosen as the index against which to compare variations in all other elements. The atomic Zr/Hf ratio ranges from 110–60 in the biotite granites to 30–10 in the Meldon Aplite and Megiliggar Rocks topaz granite. Nevertheless, the Zr/Hf ratios vary considerably, not only among different granite types, but also among single zircon grains in the same thin section (Fig. 3).

The radioactive elements **thorium** and **uranium** are ubiquitous components. The U content usually varies from less than 0.1 to 1.0 wt% UO_2 (0.0005-0.007 apfu U). The highest contents, up to 3.6 wt% UO_2 (0.029 apfu U), were found in the St. Austell topaz granites. The Th content is usually lower than 0.1 wt% ThO_2 (0.0005 apfu Th) and high concentrations were found only rarely with a maximum at 3.17 wt% ThO_2 (0.027 apfu Th) in a fine-grained biotite granite from the Dartmoor pluton. Atomic U/Th ratios usually range between 3 and 15, but in the fine-grained Dartmoor biotite granite and St. Austell topaz granite often exceed 100.

Yttrium and HREE are also generally common in granitic zircon due to isostructural mixing between zircon and xenotime, $ZrSiO_4 \leftrightarrow YPO_4$. The content of Y is usually lower than 0.4

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wt%, only rarely exceeding 0.5 wt% Y_2O_3. The highest values, up to 3.0 wt% Y_2O_3 (0.06 apfu Y), were found in the fine-grained Dartmoor Granite. **Ytterbium** is the most common REE: usually 0.05–0.20 wt% Yb_2O_3, maximally 0.7 wt% Yb_2O_3 (0.008 apfu Yb) (Fig. 4).

LREE are much less compatible in the crystal lattice of zircon than HREE and their content only sporadically exceeded 0.05 wt% of appropriate oxide (=the detection limit of microprobe).

Scandium is present in the majority of zircons, typically around 0.05–0.20 wt% Sc_2O_3, but in more fractionated granites reaches more than 0.5 wt%, and a maximum of 1.5 wt% Sc_2O_3 (0.046 apfu Sc) in the St. Austell topaz granite.

Bismuth is a rare element, but commonly present at around 0.10–0.15 wt% Bi_2O_3. The highest content occasionally found in the St. Austell topaz granite is 0.55 wt% Bi_2O_3 (0.005 apfu Bi).

The content of **phosphorus** usually varied between 0.2–0.8 wt% P_2O_5 (0.005–0.02 apfu P) but, in differentiated granites, increased substantially to 5.5 wt% P_2O_5 (0.16 apfu P) in one grain from the St. Austell topaz granite.

The content of **arsenic** is lower than that of P: usually 0.05–0.10 wt% As_2O_5, with a maximum of 0.46 wt% As_2O_5 (0–008 apfu As) in the St. Austell topaz-zinnwaldite granite.

W and **Nb** were found in a single strongly metamictized zircon grain from the St. Austell topaz granite (0.47 wt% WO_3 and 0.55 wt% Nb_2O_5).

The contents of **Al**, **Fe**, **Mn**, and **Ca** is usually lower than detection limit of EPMA, but each of these elements may be enriched up to □1 wt% (Mn up to 0.4 wt%) of the corresponding oxide in metamictized grains.

The content of **fluorine** is usually lower than the EPMA detection limit but, in some zircons from F-enriched topaz-bearing rocks (Meldon, St. Austell), may be enriched up to 1.6 wt% F (0.17 apfu F).

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The contents of Mg, Cu, Pb, and S are negligible; Ta is in all cases lower than the detection limit.

Associated minerals

Apatite, rutile, monazite, xenotime and uraninite occur in most samples (Table 3). **Monazite** forms homogeneous isometric grains up to 100 µm in diameter. It is usually enriched in Th and U: 6–10 wt% ThO_2 (0.05–0.09 apfu Th) and 0.5–2.3 wt% UO_2 (0.005–0.020 apfu U). Only the monazite from the Legereath Zawn Elvan is U and Th-free. Monazite appears to be younger that zircon when in mutual contact.
Xenotime forms short columnar crystals up to 50 µm (Fig. 2b) or irregular grains, usually older than the associated zircon. As well as a significant content of Y (0.75–0.80 apfu Y), xenotime contains HREE: up to 5.7 wt% Dy_2O_3 (0.066 apfu Dy), 5 wt% Yb_20_3 (0.055 apfu Yb), 4.0 wt% Er_2O_3, 3.0 wt% Gd_2O_3 and 1.1 wt% Sm_2O_3. The contents of thorium are lower, and uranium higher, than in the associated monazite: up to 1.5 wt% ThO_2 (0.012 apfu Th) and 3.8 wt% UO_2 (0.030 apfu U).
Uraninite appears as small (<20 µm) isometric late interstitial grains. It usually contains 1.5–3.7 wt% ThO_2 (0.03–0.08 apfu Th) and 2.8–3.7 wt% PbO (0.07–0.09 apfu Pb).

Discussion

Substitution in zircon

The tetravalent elements Hf, Th, U, and Ti substitute in the zircon crystal lattice for zirconium. The trivalent elements Y and REEs enter the zircon structure as the “xenotime component” (P^{5+}+(Y, REE)$^{3+}$↔Si^{4+}+Zr^{4+}) because xenotime and zircon are isostructural and have similar lattice parameters (Speer, 1982). Also Sc, and occasionally Bi, substitute in zircon as their respective phosphate components $ScPO_4$ (pretulite) and $BiPO_4$ (ximengite)

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(Bernhard *et al.,* 1998; Shi, 1989). Positive correlation between P and the sum of REE+Y+Sc+Bi, with the ratio P/M^{3+} close to 1, supports this interpretation (Fig. 5). Trivalent Al is present only in metamictized zircons with partially destructed and hydrated structure and probably substitutes for Si: $(AlOH)^{2+} \leftrightarrow (SiO)^{2+}$ (Geisler *et al.*, 2003; Nasdala *et al.*, 2009).

Fractionation of the Cornubian granites

The Zr/Hf ratio in zircon is a good indicator of granite fractionation (Linnen and Keppler, 2002). Breiter *et al.* (2014) compared the zircon atomic Zr/Hf ratio with the grade of fractionation of parental granites and were able to divided granites into three groups: common granites containing zircon with Zr/Hf>55, evolved granites containing zircon with Zr/Hf=25–55, and strongly evolved granites with zircon with Zr/Hf<25. According to this classification, the coarse-grained biotite granites from Dartmoor, Carnmenellis, Cligga Head, Land´s End, and St. Austell plutons and the Legereath Zawn Elvan are “common granites”, whilst the Dartmoor fine-grained biotite-tourmaline granite, St. Austell topaz granites, Meldon Aplite and Megiliggar topaz aplite/pegmatite are “evolved granites”. This is in good agreement with generally accepted petrological/geochemical classification of the Cornubian Batholith as comprising, at the current exposure level, predominantly less evolved biotite (±tourmaline) granites and minor more evolved topaz granites (Manning and Hill, 1990).

The genetic relationship between biotite granites and topaz granites in SW England remains controversial. The topaz granites have been variably interpreted as the: (i) result of progressive fractionation of the biotite granite magma (Stone, 1975; Taylor and Fallick, 1997), (ii) product of partial melting of lower crustal residues after generation and extraction of previous biotite granite magmas (Manning and Hill, 1990), or (iii) product of partial melting of metasomatically enriched lower crust (Stone, 1992).

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When evaluating these models, the approximately coeval (<1 Ma) emplacement of biotite (Godolphin) and topaz (Tregonning) granites in the same area (Clark et al., 1994) must also be considered.

Melting of a crustal residuum, as proposed by Manning and Hill (1990), is unlikely because such melting will produce a subaluminous, P-poor, A-type melt (Eby, 1990; Bonin, 2007) and not a strongly peraluminous P-rich melt required to form the topaz granites.

Enrichment of the lower crust with F- and Li-bearing fluid during the short period between production of both principal types of granites is highly speculative; moreover the topaz granites are enriched not only in F and Li, but also in Sn, Nb, Ta, W, etc. The Cornubian biotite and topaz granites are chemically and mineralogically similar to late-Variscan composite plutons in Massif Central, France, and Western Erzgebirge, Germany/Czech Republic, where the direct link between the less differentiated biotite granites and spatially associated Li-mica–topaz granites is well established (Raimbault *et al.*, 1995; Förster *et al.*, 1999; Breiter, 2012). Therefore, the origin of the topaz granites via pronounced fractionation of the biotite granite-magma seems to be the most probable.

The Cornubian biotite granites contain 66–169 ppm Zr (Chappell and White, 2006) and the topaz granites less than 30 ppm Zr (Manning and Hill, 1990). Assuming melting temperature at or slightly above 800 °C, the biotite granites were Zr-saturated, and the topaz granites strongly under saturated at the source (Watson and Harrison, 1983). This implies no Zr/Hf fractionation during partial melting. All aforementioned models assume generation of both granite types from a similar protolith, i.e. the biotite granite-magma and the topaz granite-magma started their evolution with the same Zr/Hf ratios (identical with the protolith). The substantially lower Zr/Hf in the topaz granites, in comparison with those in the ‘common’ biotite granites, documents a comparatively longer/more intensive fractionation path of the former. However, this is not a proof that topaz granites in the St. Austell and Tregonning

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plutons originated via fractionation of a magma batch that formed the immediately adjacent biotite granites. The less evolved members of the topaz granite suite, with lower contents of volatiles and thus more viscous, may be present at deeper levels in the batholith and may not have any surface expression. Such superposition of the more- and less-fractionated portions of a pluton are described in detail in rare-metal granites from Beauvoir, France, and Cínovec, Erzgebirge (Raimbault *et al.*, 1995; Breiter and Škoda, 2012).

Comparison with zircon from other European rare-metal granites

The association of minor and trace elements in granitic zircon is highly variable and principally reflects three factors: (i) composition of the melted source rocks, (ii) PT-conditions of melting, and (iii) degree of fractionation of the granitic melt. The first two factors result in higher contents of Th, Y, and HREE in zircon from A-type granites than in zircon from peraluminous S-type granites (Breiter *et al.*, 2014). The granites of the Cornubian Batholith are differentiated, as represented by their enrichment in volatile agents and some ore elements (e.g. Sn, W, Cu), often termed as “rare metal-” or “tin-” granites (Černý *et al.*, 2005). Strongly differentiated rare-metal granites occur widely in Europe. Examples include the distinctly peraluminous (S-type) late Variscan granites of the Western Erzgebirge (Germany/Czech Republic, Förster *et al.*, 1999; Breiter, 2012) and Massif Central (France, Raimbault *et al.,* 1995), the slightly peraluminous to subaluminous (A-type) late Variscan granites of the Eastern Erzgebirge (Förster *et al.*, 1999; Breiter, 2012), and the Proterozoic Wiborg Batholith in Finland (Haapala, 1995).

Relative to the aforementioned granites, zircons from the Cornubian Batholith are relatively poor in trace elements (Fig. 6). Fig. 6a combines contents of Hf and Y: increasing Hf mirrors the increasing degree of magma fractionation while Y represents the share of the xenotime component (e.g. content of Y and HREE in melt). The Cornubian zircons are also relatively

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poor in both Hf and Y: Zircons from the Beauvoir pluton are more enriched in Hf, and zircons from the A-type granites much more enriched in Y (Breiter *et al.*, 2006, 2014; Breiter and Škoda, 2012).

Figs. 6b, 6c, and 6d show a general increase in Sc, U, and Th with increasing differentiation (as shown by the decrease in the Zr/Hf ratio). The chemical composition of the Cornubian zircons is comparable with the zircons from the S-type granites in the Western Erzgebirge. Zircons from the Beauvoir Granite, France are Sc- and Th-poor, while zircons from both A-type granite series are often Sc-, Th-, and Y-rich with common mixed compositions among zircon, thorite, xenotime and pretulite (Förster, 2006; Breiter *et al.*, 2012, 2014).

The elements F and P play an important role in the transport of ore elements by lowering melt viscosity and forming metal complexes (Linnen, 1998; Keppler, 1993.). Fig. 6e demonstrates the differences between zircons from strongly peraluminous granites (enriched simultaneously in F and P) and zircon from the A-type granites (enriched only in F). In this case, Cornubian zircons are generally poor in both F and P, which again demonstrates a relatively lower degree of differentiation in the Cornubian Batholith in comparison with granites from the Erzgebirge and Massif Central.

The Fig. 6f was proposed by Breiter *et al.* (2014) for classification of zircons from fractionated, often ore-bearing granites. Here, the Cornubian zircons are again similar to the peraluminous granites from the Western Erzgebirge, although having somewhat lower grade of differentiation in terms of U/Th and Zr/Hf ratios.

With respect to W, Nb, Ta, and Bi, their contents in Cornubian zircon are very low (W, Nb, and Ta usually less than detection limit of EPMA). Enrichment of these elements in order 0.X wt%, commonly found in many rare-metal granites (Breiter *et al.* 2006, 2014) are not found in SW England.

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Conclusions

Zircons from the Cornubian granites are relatively poor in minor and trace elements.

The lower Zr/Hf ratio in zircons from the topaz granites, in comparison with those from biotite granites, implies a greater degree of fractionation if the granites shared a similar protolith. The pronounced fractionation of a primary crustal magma seems to be the most probable model of origin of the topaz granites from the St Austell and Tregonning-Godolphin plutons. Nevertheless, some of the less evolved members of the topaz granite suites probably remained hidden under surface exposure.

Cornubian zircons exhibit a relatively lower grade of fractionation in terms of Zr/Hf and U/Th ratio in comparison with other European rare-metal granites.

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Table 1 Studied samples

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Table 2 Typical microprobe analyzes of zircon (wt%) and empirical formulae (in atoms per formula unit) based on 4 oxygen atoms. Contents of Ta, La, and Cu were in all cases under the detection limits of EPMA (u.d.l.).

Table 3 Typical microprobe analyzes of monazite, xenotime, and uraninite (wt%) and empirical formulae (in atoms per formula unit) based on 4 oxygen atoms for phosphates and 2 oxygen atoms for uraninite. Contents of W, As, Nb, Ta, Hf, Al, Cu, and S were in all cases under the detection limits of EPMA (u.d.l.).

Explanation to figures

1. Geological sketch map of studied granite plutons. Summarised from Dangerfield and Hawkes (1981), Manning *et al*., (1996) and British Geological Survey mapping.
2. BSE-images of typical zircon grains and associated minerals (scale bar in all cases 20 μm): **a-** broken homogeneous columnar zircon crystal (gray) with attached monazite aggregates (bright), sample #4957, coarse-grained biotite granite of the Carnmenellis pluton; **b-** crystal of zircon (light gray) with inclusion of monazite (bright), #4959, porphyritic medium-grained biotite granite of the St. Austell pluton; **c-** homogeneous zircon crystal (bright) associated with ilmenite (gray), #4961, Legereath Zawn elvan, Megiliggar Rocks; **d-** oscillatory zoned zircon crystal (grey), #4950, coarse-grained biotite granite of the Dartmoor pluton; **e-** large slightly zoned xenotime crystals (bright) with several associated small zircon grains (gray), #4951, fine-grained biotite granite of the Dartmoor pluton; **f-** small grains of zircon (light gray) associated with monazite (bright), large isometric grain of apatite (Ap) and aggregate of columnar rutile (Rt), #4957, coarse-grained biotite granite of the Carnmenellis pluton; **g-** zircon (bright) associated with columnar rutile (Rt) and isometric apatite (Ap), #4955, fine-grained biotite granite of the Land´s End pluton; **h-** zoned crystal of zircon, core is near the ideal zircon composition (compare anal. 28 in the table 2), while rim is enriched in P, Y, and F (anal. 29 in the table 2), #4959, porphyritic medium-grained biotite granite of the St. Austell pluton; **i-** zoned zircon crystal with bright core (anal.

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37 in the table 2) and darker metamictized U, Al, Sc, F-enriched rim (anal. 38 in the table 2), #4960A, medium-grained topaz granite of the St. Austell pluton; **j-** patchy metamictized zircon, #4960B, medium-grained topaz granite of the St. Austell pluton; **k-** monazite (bright) with associate zircon crystals (gray), #4962, fine-grained two-mica granite, Megiliggar Rocks; **l-** patchy metamictized zircon (gray) associated with columbite (bright), #4952, topaz aplite, Meldon quarry.

3. Chemical composition of zircon from Cornubian granites (in atoms per formula unit): **a-** Zr vs. Hf; **b-** Zr/Hf vs. U; **c-** Zr/Hf vs. Y; **d-** Zr/Hf vs. Sc; **e-** Zr/Hf vs. P; **f-** Zr/Hf vs. F.
4. Chondrite normalized distribution of REE (acc. to McDonough and Sun, 1995) in selected zircon grains
5. Xenotime-type substitution P^{5+}+(Y, REE, Sc, Bi)$^{3+}$↔Si^{4+}+Zr^{4+} in Cornubian zircons
6. Comparison of the contents of minor elements in zircons from SW England and other European rare-metal granites (in atoms per formula unit): **a-** Hf vs. Y; **b-** Zr/Hf vs. Sc; **c-** Zr/Hf vs. U; **d-** Zr/Hf vs. Th; **e-** P vs. F; **f-** U/Th vs. Yb.

Appendix1: Microprobe analyzes of zircon (wt%) and empirical formulae (in atoms per formula unit) based on 4 oxygen atoms. Contents of Ta, La, and Cu were in all cases under the detection limits of EPMA

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Table 1 Studied samples

No.	Locality	Description	Minor minerals	UK Grid Reference
4950	Dartmoor Granite	Coarse-grained porphyritic biotite granite	Zircon, apatite, uraninite	SX 7865 8560
4951	Dartmoor Granite, near the Warren House Inn	Fine-grained tourmaline-biotite granite	Zircon, monazite, xenotime, apatite, uraninite	SX 6763 8095
4952, 4954	Meldon Aplite	Fine-grained topaz aplite-pegmatite dykes	Zircon, apatite, fluorite, uraninite, columbite, thorite, monazite	SX 5707 9204
4955	Land´s End Granite, Porthmeor Cove	Fine-grained biotite granite	Zircon, apatite, rutile, monazite	SW 4252 3764
4956	Land´s End Granite, Geevor mine	Coarse-grained porphyritic biotite granite	Zircon, apatite, fluorite, monazite	SW 3754 3456
4957	Carnmenellis Granite, Holman's Test Mine	Coarse-grained (small phenocryst) biotite granite	Zircon, apatite, monazite, rutile, uraninite	SW 6569 3668
4958	Cligga Head Granite	Fine-grained biotite granite, locally kaolinized	Zircon, apatite, rutile, monazite, xenotime, columbite	SW 7386 5367
4959	St. Austell Granite, Wheal Remfry	Porphyritic medium-grained biotite granite	Zircon, apatite, monazite, rutile, fluorite	SW 9268 5699
4960A	St. Austell Granite, Treviscoe	Leucocratic medium-grained Li-biotite granite (topaz granite)	Zircon, apatite, topaz, rutile, columbite	SW 9462 5560
4960B	St. Austell Granite, Goonbarrow	Leucocratic medium-grained zinnwaldite granite (topaz granite)	Zircon, topaz, apatite, columbite, thorite	SX 0095 5848
4961	Legereath Zawn Elvan, Megiliggar Rocks	Elvan ('Legereath granite porphyry') of Stone (1975), granite porphyry with orthoclase phenocryst and fine-grained groundmass	Zircon, ilmenite, gahnite, arsenopyrite, monazite	SW 6076 2676
4962	Tregonning Granite roof complex sills, Megiliggar Rocks	Medium-grained two-mica granite (topaz granite)	Zircon, apatite, monazite, topaz, xenotime	SW 6081 2671
4965	Tregonning Granite roof complex sills, Megiliggar Rocks	Layered tourmaline aplite/pegmatite	Zircon, apatite, tourmaline, Bi, columbite, pyrite, monazite, rutile, ixiolite, cassiterite	SW 6081 2671

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Table 2 Typical microprobe analyzes of zircon (wt%) and empirical formulae (in atoms per formula unit) based on 4 oxygen atoms. Contents of Ta, La, and Cu were in all cases under the detection limits of EMPA (u.d.l.).

Anal.No.	44	36	2	5	28core	29rim	37core	38rim	41
Sample	**4950**	**4951**	**4952**	**4954**	**4959**	**4959**	**4960A**	**4960A**	**4960B**
Locality	Dartmoor	Dartmoor	Meldon	Meldon	St.Austel	St.Austel	St.Austel	St.Austel	St.Austel
WO_3	u.d.l.	0.30	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.47
P_2O_5	0.35	1.57	0.75	0.59	0.30	5.25	0.30	1.07	5.48
As_2O_5	0.06	0.12	0.29	0.11	0.04	0.30	0.06	0.19	0.46
Nb_2O_5	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.55
SiO_2	31.83	22.95	27.35	31.01	31.60	22.78	31.60	25.37	21.91
TiO_2	0.01	u.d.l.	0.02	0.06	u.d.l.	0.03	u.d.l.	u.d.l.	0.09
ZrO_2	63.67	43.37	50.87	60.60	64.22	52.19	63.86	49.17	50.50
HfO_2	1.65	1.79	7.35	3.87	1.47	2.17	1.42	2.12	2.76
ThO_2	u.d.l.	3.17	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.12	u.d.l.
UO_2	0.50	1.68	1.52	0.66	0.13	0.75	0.13	3.60	1.50
$Y2O_3$	0.30	3.02	0.55	u.d.l.	0.13	1.85	0.08	u.d.l.	u.d.l.
Ce_2O_3	u.d.l.	0.12	u.d.l.	u.d.l.	u.d.l.	0.15	u.d.l.	u.d.l.	u.d.l.
Pr_2O_3	u.d.l.	u.d.l.	u.d.l.	0.08	u.d.l.	0.07	u.d.l.	u.d.l.	u.d.l.
Nd_2O_3	u.d.l.	0.11	u.d.l.	u.d.l.	u.d.l.	0.20	u.d.l.	u.d.l.	u.d.l.
Sm_2O_3	u.d.l.	0.11	u.d.l.	u.d.l.	u.d.l.	0.14	u.d.l.	u.d.l.	u.d.l.
Gd_2O_3	u.d.l.	0.18	u.d.l.	u.d.l.	u.d.l.	0.22	u.d.l.	u.d.l.	u.d.l.
Dy_2O_3	u.d.l.	0.42	0.18	u.d.l.	u.d.l.	0.25	u.d.l.	u.d.l.	u.d.l.
Er_2O_3	0.11	0.35	0.14	0.06	0.06	0.25	0.08	u.d.l.	u.d.l.
Yb_2O_3	0.18	0.47	0.27	0.10	u.d.l.	0.32	0.06	0.09	u.d.l.
Al_2O_3	u.d.l.	1.20	0.48	0.13	u.d.l.	1.00	u.d.l.	1.22	1.04
Sc_2O_3	0.05	0.03	0.30	0.31	0.08	0.18	0.06	1.14	1.52
Bi_2O_3	0.13	0.19	u.d.l.	0.18	u.d.l.	0.47	u.d.l.	u.d.l.	0.55
MnO	u.d.l.	0.09	0.47	u.d.l.	u.d.l.	0.10	u.d.l.	0.17	0.11
FeO	0.72	4.08	0.72	u.d.l.	u.d.l.	1.09	u.d.l.	1.09	0.88
CaO	u.d.l.	1.08	1.31	0.33	0.14	1.82	u.d.l.	1.15	1.35
PbO	u.d.l.	0.13	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.
MgO	u.d.l.	0.05	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.07	0.05
SO_3	u.d.l.	0.04	u.d.l.	0.09	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.04
F	u.d.l.	0.74	0.19	u.d.l.	u.d.l.	1.59	u.d.l.	0.74	1.03
Total	99.79	87.34	92.94	98.31	98.44	93.36	97.95	87.53	90.44
W	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.004
P	0.009	0.050	0.022	0.016	0.008	0.152	0.008	0.033	0.161
As	0.001	0.002	0.005	0.002	0.001	0.005	0.001	0.004	0.008
Nb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009
Si	0.987	0.870	0.946	0.980	0.988	0.778	0.991	0.920	0.761
Ti	0.000	0.000	0.001	0.001	0.000	0.001	0.000	0.000	0.002
Zr	0.963	0.802	0.858	0.934	0.979	0.869	0.977	0.870	0.855
Hf	0.015	0.019	0.073	0.035	0.013	0.021	0.013	0.022	0.027
Th	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.001	0.000
U	0.003	0.014	0.012	0.005	0.001	0.006	0.001	0.029	0.012
Y	0.005	0.061	0.010	0.000	0.002	0.034	0.001	0.000	0.000
Ce	0.000	0.002	0.000	0.000	0.000	0.002	0.000	0.000	0.000
Pr	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000
Nd	0.000	0.001	0.000	0.000	0.000	0.002	0.000	0.000	0.000
Sm	0.000	0.001	0.000	0.000	0.000	0.002	0.000	0.000	0.000

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Gd	0.000	0.002	0.000	0.000	0.000	0.002	0.000	0.000	0.000
Dy	0.000	0.005	0.002	0.000	0.000	0.003	0.000	0.000	0.000
Er	0.001	0.004	0.001	0.001	0.001	0.003	0.001	0.000	0.000
Yb	0.002	0.005	0.003	0.001	0.000	0.003	0.001	0.001	0.000
Al	0.000	0.054	0.020	0.005	0.000	0.040	0.000	0.052	0.042
Sc	0.001	0.001	0.009	0.008	0.002	0.005	0.002	0.036	0.046
Bi	0.001	0.002	0.000	0.001	0.000	0.004	0.000	0.000	0.005
Mn	0.000	0.003	0.014	0.000	0.000	0.003	0.000	0.005	0.003
Fe	0.019	0.129	0.021	0.000	0.000	0.031	0.000	0.033	0.026
Ca	0.000	0.044	0.048	0.011	0.005	0.067	0.000	0.045	0.050
Pb	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.003	0.002	0.000	0.000	0.001	0.001	0.004	0.003
S	0.000	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.001
F	0.000	0.088	0.021	0.000	0.000	0.171	0.001	0.085	0.113
Zr/Hf atomic	66	41	12	27	75	41	77	40	31

Table 2 cont.

Anal.No.	24	21	30	3	11	10	15
Sample	**4957**	**4958**	**4955**	**4956**	**4961**	**4962**	**4965**
Locality	Holman's Test Mine	Cligga Head	Land´s End	Land´s End	Legereath Zawn	Megiliggar	Megiliggar
WO_3	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.
P_2O_5	0.41	0.10	0.85	0.39	0.38	0.66	0.92
As_2O_5	0.07	0.07	0.09	0.05	0.05	0.16	0.15
Nb_2O_5	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.
SiO_2	32.18	32.18	29.65	31.92	31.88	30.84	30.87
TiO_2	u.d.l.	0.24	0.06	0.07	0.50	0.13	u.d.l.
ZrO_2	64.66	64.56	59.20	64.44	63.52	61.91	59.84
HfO_2	1.59	1.84	1.42	1.41	1.18	1.62	3.56
ThO_2	u.d.l.	u.d.l.	0.56	0.11	u.d.l.	0.13	u.d.l.
UO_2	0.23	0.21	0.70	0.40	0.29	1.03	1.04
$Y2O_3$	0.20	u.d.l.	1.23	0.28	0.22	0.41	0.27
Ce_2O_3	u.d.l.	u.d.l.	0.11	u.d.l.	u.d.l.	u.d.l.	u.d.l.
Pr_2O_3	u.d.l.	u.d.l.	0.08	0.06	u.d.l.	u.d.l.	u.d.l.
Nd_2O_3	u.d.l.	u.d.l.	0.11	0.02	0.10	0.05	u.d.l.
Sm_2O_3	u.d.l.	u.d.l.	0.07	u.d.l.	u.d.l.	u.d.l.	u.d.l.
Gd_2O_3	u.d.l.	u.d.l.	0.13	u.d.l.	u.d.l.	u.d.l.	u.d.l.
Dy_2O_3	u.d.l.	u.d.l.	0.18	u.d.l.	0.06	0.10	u.d.l.
Er_2O_3	u.d.l.	0.06	0.16	0.07	u.d.l.	0.09	0.11
Yb_2O_3	0.06	u.d.l.	0.21	u.d.l.	0.09	0.17	0.21
Al_2O_3	u.d.l.	u.d.l.	0.49	u.d.l.	u.d.l.	u.d.l.	0.59
Sc_2O_3	0.12	0.04	0.15	0.10	0.11	0.21	0.54
Bi_2O_3	u.d.l.	0.16	u.d.l.	u.d.l.	0.13	u.d.l.	u.d.l.
MnO	u.d.l.	u.d.l.	0.07	u.d.l.	u.d.l.	0.04	u.d.l.
FeO	0.34	0.07	1.17	0.48	0.73	0.48	0.12
CaO	0.04	u.d.l.	0.46	0.04	u.d.l.	0.18	0.07
PbO	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.
MgO	u.d.l.	u.d.l.	0.08	u.d.l.	u.d.l.	u.d.l.	u.d.l.
SO_3	u.d.l.	u.d.l.	0.05	u.d.l.	u.d.l.	u.d.l.	u.d.l.
F	u.d.l.	u.d.l.	0.08	u.d.l.	u.d.l.	0.08	u.d.l.
Total	100.18	99.70	97.45	100.03	99.45	98.45	98.53

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W	0.000	0.000	0.000	0.000	0.000	0.000	0.000
P	0.011	0.003	0.023	0.010	0.010	0.018	0.024
As	0.001	0.001	0.002	0.001	0.001	0.003	0.003
Nb	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Si	0.988	0.994	0.950	0.984	0.985	0.972	0.971
Ti	0.000	0.006	0.001	0.002	0.012	0.003	0.000
Zr	0.968	0.973	0.925	0.969	0.958	0.952	0.918
Hf	0.014	0.016	0.013	0.012	0.010	0.015	0.032
Th	0.000	0.000	0.004	0.001	0.000	0.001	0.000
U	0.002	0.001	0.005	0.003	0.002	0.007	0.007
Y	0.003	0.000	0.021	0.005	0.004	0.007	0.005
Ce	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Pr	0.000	0.000	0.001	0.001	0.000	0.000	0.000
Nd	0.000	0.000	0.001	0.000	0.001	0.001	0.000
Sm	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Gd	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Dy	0.000	0.000	0.002	0.000	0.001	0.001	0.000
Er	0.000	0.001	0.002	0.001	0.000	0.001	0.001
Yb	0.001	0.000	0.002	0.000	0.001	0.002	0.002
Al	0.000	0.000	0.018	0.000	0.000	0.000	0.022
Sc	0.003	0.001	0.004	0.003	0.003	0.006	0.015
Bi	0.000	0.001	0.000	0.000	0.001	0.000	0.000
Mn	0.000	0.000	0.002	0.000	0.000	0.001	0.000
Fe	0.009	0.002	0.031	0.012	0.019	0.013	0.003
Ca	0.001	0.000	0.016	0.001	0.000	0.006	0.002
Pb	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.000	0.000	0.004	0.000	0.000	0.000	0.000
S	0.000	0.001	0.001	0.000	0.000	0.000	0.000
F	0.000	0.000	0.008	0.002	0.000	0.008	0.000
Zr/Hf atomic	70	60	71	78	92	65	29

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Table 3 Typical microprobe analyzes of monazite, xenotime, and uraninite (wt%) and empirical formulae (in atoms per formula unit) based on 4 oxygen atoms for phosphates and 2 oxygen atoms for uraninite. Contents of W, As, Nb, Ta, Hf, Al, Cu, and S were in all cases under the detection limits of EMPA (u.d.l.).

Mineral	Monazite	Monazite	Monazite	Monazite	Xenotime	Xenotime	Uraninite	Uraninite
Sample	4956	4961	4959	4957	4951	4962	4957	4950
P_2O_5	28.15	28.63	29.43	29.32	31.06	31.35	u.d.l.	u.d.l.
SiO_2	0.62	u.d.l.	0.10	0.22	0.88	0.58	u.d.l.	u.d.l.
TiO_2	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.39	u.d.l.	u.d.l.
ZrO_2	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.44	u.d.l.	u.d.l.
ThO_2	3.31	0.17	9.93	7.99	1.39	0.33	1.53	2.60
UO_2	u.d.l.	u.d.l.	2.26	0.46	2.26	3.39	94.37	91.73
Y_2O_3	0.36	0.74	2.12	0.89	38.54	39.75	0.18	0.34
La_2O_3	13.51	14.86	10.16	12.60	u.d.l.	0.08	u.d.l.	u.d.l.
Ce_2O_3	31.20	32.86	24.25	27.82	0.07	0.08	u.d.l.	0.11
Pr_2O_3	3.52	3.49	2.65	3.00	u.d.l.	u.d.l.	0.16	0.00
Nd_2O_3	12.68	11.51	9.60	10.72	0.40	0.43	u.d.l.	u.d.l.
Sm_2O_3	2.41	2.35	2.35	2.10	0.86	0.90	u.d.l.	u.d.l.
Gd_2O_3	3.58	3.66	3.22	3.29	2.36	3.02	u.d.l.	u.d.l.
Dy_2O_3	0.18	0.26	0.64	0.31	4.83	5.68	u.d.l.	0.16
Er_2O_3	0.01	0.01	0.16	0.08	3.97	3.17	u.d.l.	u.d.l.
Yb_2O_3	0.00	0.00	0.02	0.02	4.47	2.85	u.d.l.	u.d.l.
Sc_2O_3	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.06	u.d.l.	u.d.l.
Bi_2O_3	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.22	0.21
MnO	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.05	u.d.l.	u.d.l.	u.d.l.
FeO	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.87	u.d.l.	0.27	u.d.l.
CaO	0.09	0.05	2.52	1.56	0.10	0.36	u.d.l.	0.03
PbO	u.d.l.	u.d.l.	0.24	0.15	0.08	0.10	3.74	3.65
F	u.d.l.	u.d.l.	u.d.l.	u.d.l.	0.11	0.05	u.d.l.	u.d.l.
Total	99.83	98.78	99.67	100.63	92.44	93.17	100.88	99.25
P	0.960	0.980	0.985	0.980	0.965	0.962	0.000	0.000
Si	0.025	0.000	0.004	0.009	0.032	0.021	0.000	0.000
Ti	0.000	0.000	0.000	0.000	0.000	0.011	0.000	0.000
Zr	0.000	0.000	0.000	0.000	0.000	0.008	0.000	0.000
Th	0.030	0.002	0.089	0.072	0.012	0.003	0.016	0.027
U	0.000	0.000	0.020	0.004	0.018	0.027	0.943	0.931
Y	0.008	0.016	0.045	0.019	0.752	0.767	0.004	0.008
La	0.201	0.222	0.148	0.183	0.000	0.001	0.000	0.000
Ce	0.460	0.487	0.351	0.402	0.001	0.001	0.000	0.002
Pr	0.052	0.051	0.038	0.043	0.000	0.000	0.003	0.000
Nd	0.182	0.166	0.136	0.151	0.005	0.006	0.000	0.000
Sm	0.034	0.033	0.032	0.029	0.011	0.011	0.000	0.000
Gd	0.048	0.049	0.042	0.043	0.029	0.036	0.000	0.000
Dy	0.002	0.003	0.008	0.004	0.057	0.066	0.000	0.002
Er	0.000	0.000	0.002	0.001	0.046	0.036	0.000	0.000
Yb	0.000	0.000	0.000	0.000	0.050	0.031	0.000	0.000
Al	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sc	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.000
Bi	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.002
Mn	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Fe	0.000	0.000	0.000	0.000	0.027	0.000	0.010	0.000
Ca	0.004	0.002	0.106	0.066	0.004	0.014	0.000	0.002

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Pb	0.000	0.000	0.003	0.002	0.001	0.001	0.045	0.045
F	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.000

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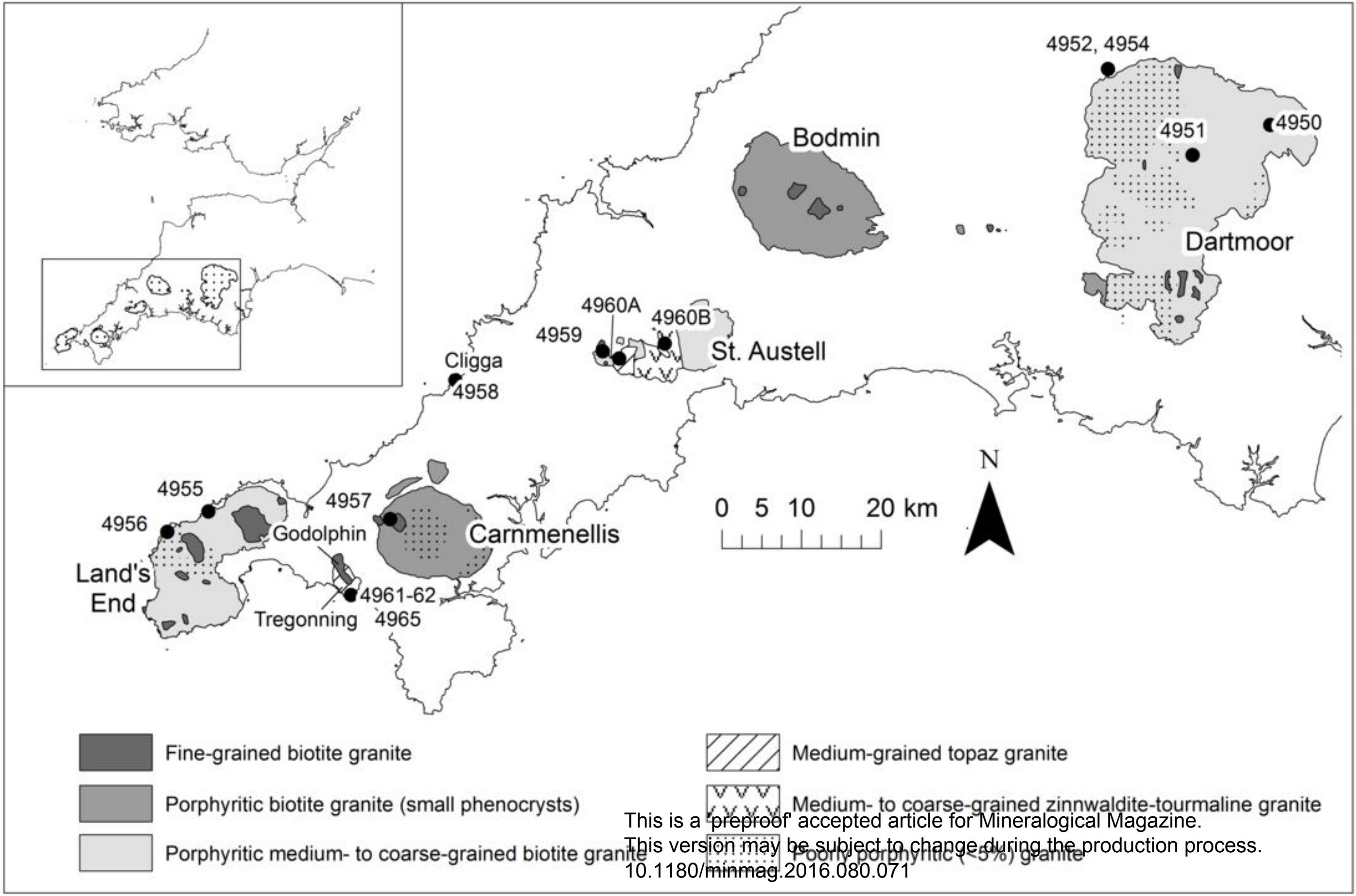

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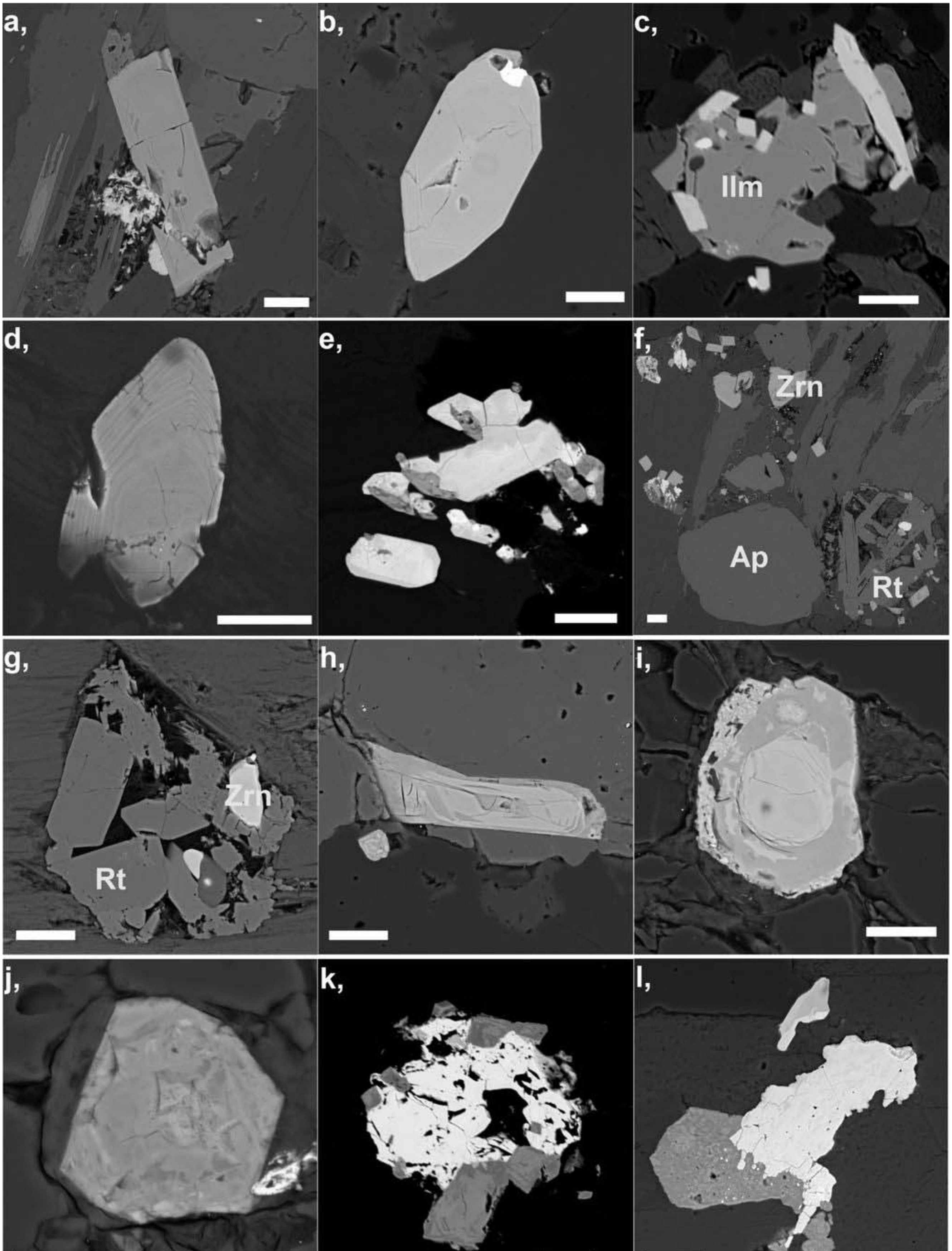

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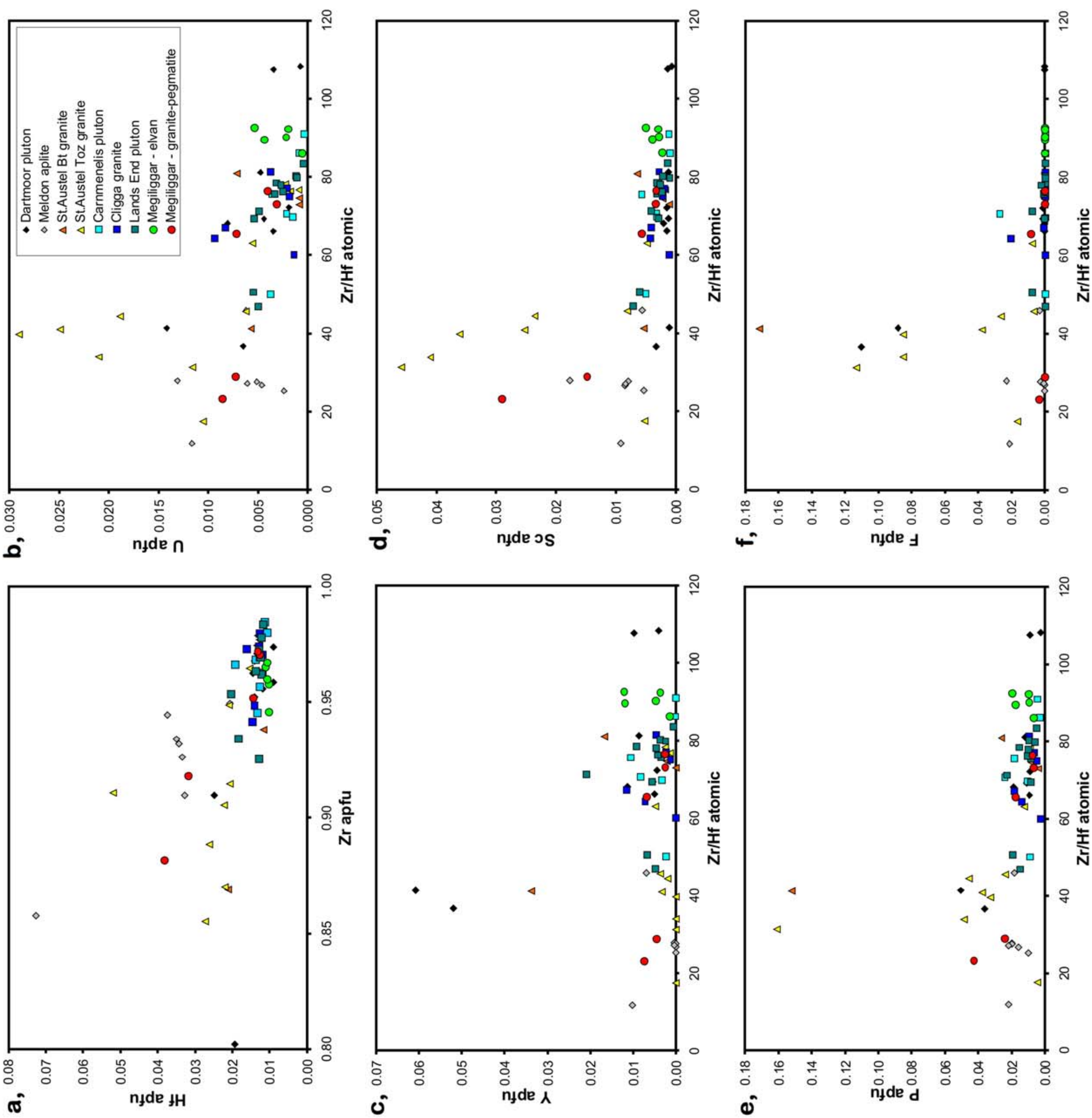

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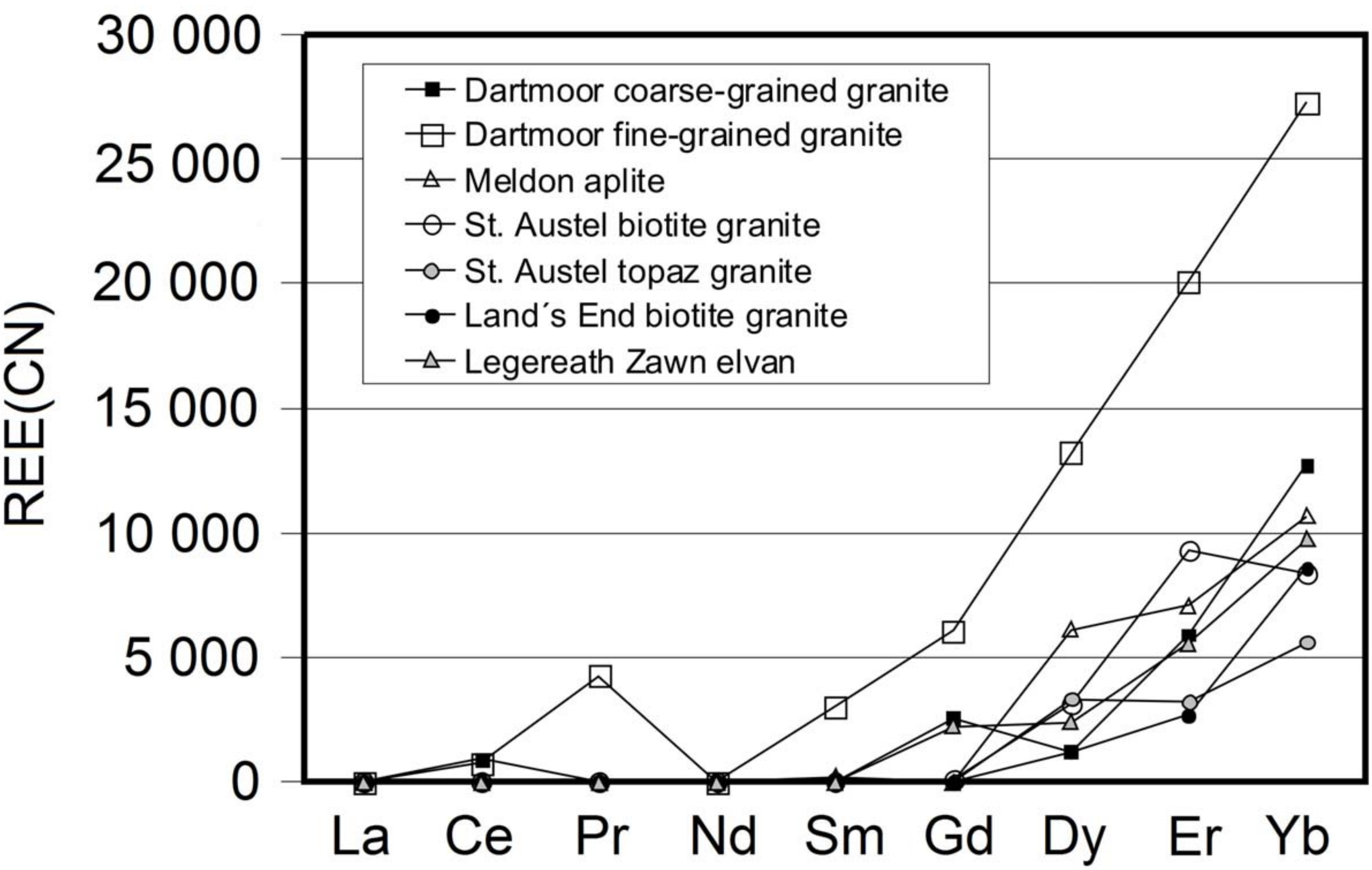

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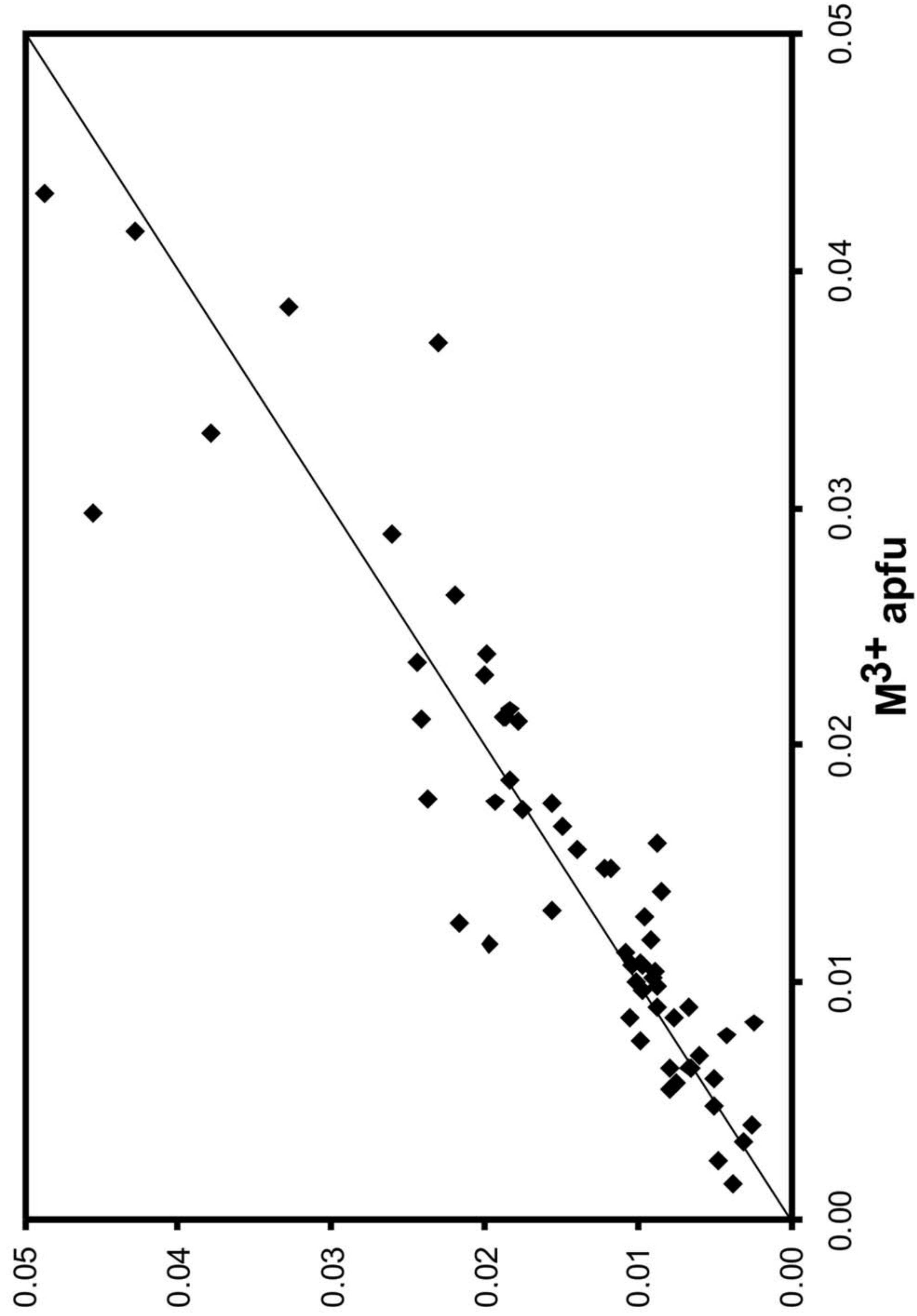

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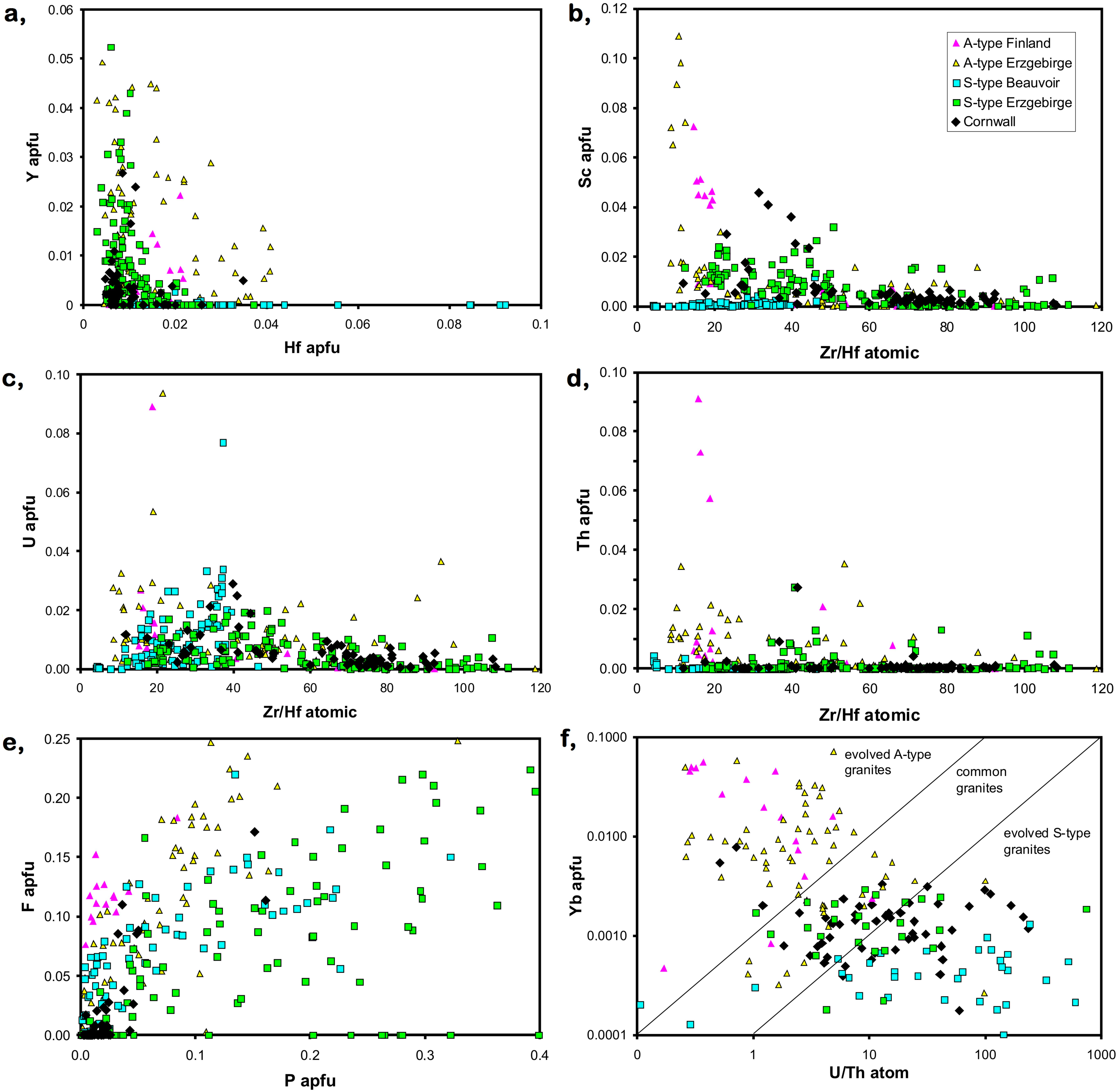

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