RARE EARTH ELEMENTS IN MINERALISED GRANITE AUREOLES

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The REE distribution patterns in aureoles surrounding selected small Sn and W specialised granite intrusions are described. In contrast to previous studies of aureoles related to larger plutons no consistent pattern is discernible. This observation also contrasts with the extensive metasomatic haloes for alkalis, Sn and W observed for the same cupolae. It is speculated that the cusps are not sufficiently large to affect the distribution of REE in the aureoles by retaining a temperature gradient long enough for a recognisable pattern to develop.

The granites have a lower REE content than the aureoles. Any possible addition of small amounts of REE with a "granite signature" is not recognisable within the inhomogeneity of the original distribution patterns which are also affected by both enhancement and dilution processes. The variance of the REE increases near to the granites.

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INTRODUCTION

The emplacement of granite magmas into the middle crust causes a variety of effects within their surrounding country rocks. These are amply demonstrated in the South-west peninsula, where contact metamorphic hornfels and spotted slate aureoles are accompanied by pegmatites, skarn and granite-related hydrothermal mineralisation. Contact metamorphism is generally considered to involve reactions that take place isochemically within systems isolated from chemical interaction with the granite magma, heat transfer providing the sole impetus. However, there is a growing amount of evidence that indicates pervasive metasomatism as distinct from the obviously fracture controlled processes such as hydrothermal alteration and mineralisation. We have previously discussed the distributions of alkalis, W and Sn throughout the aureoles included in the present study, and have shown that there is pervasive addition of all of these components into the inner aureole in a zone extending to several hundreds of metres from the contacts (Beer and Ball, 1986; Ball et al, 1998). Mitropolous (1982) for the Lands End Granite aureole, and Stone and Awad (1988) for the Tregonning Granite aureole, have shown that there is an increase in the REE contents close to the contacts. In this paper we discuss the distribution of the Rare Earth Elements (REE) in the contact zones of small cupolae, that are either mineralised or are close to the "emanative centres" for mineralisations (Dines, 1956).

The REE form a coherent group within the periodic table (Hermann, 1970) which is characterised by the so-called Lanthanide Contraction whereby, despite the increase in Atomic Mass and Number from La to Yb, the ionic size diminishes gradually and progressively. In most geological situations the REEs are trivalent but in certain geochemical conditions two of the elements (Eu and Ce) exhibit other valencies; Eu can be bivalent and Ce can be tetravalent. The bivalency of Eu is common in igneous rocks, but the quadrivalent nature of Ce is usually only recognisable as a result of sedimentary and weathering processes that involve intense oxidation. Eu^{2+} is similar in geochemical behaviour to Sr^{2+}, the main host for which in many igneous rocks is plagioclase. As a consequence granites produced by crystal fractionation or by partial melting in which plagioclase is diminished, frequently have Eu also lower in the acidic fraction. This effect produces a relative depletion of Eu. This is represented by a negative anomaly in distribution profiles in which the REEs are normalised against chondrite abundances, and most of the granites from Cornubia show this feature. The Eu change is usually estimated by averaging the normalised concentration of the bracketing Sm and Gd and expressing the depletion (or enhancement) as a factor or a percentage. Although not strictly a REE, Y is often included in studies of REE distributions because of its similar nature.

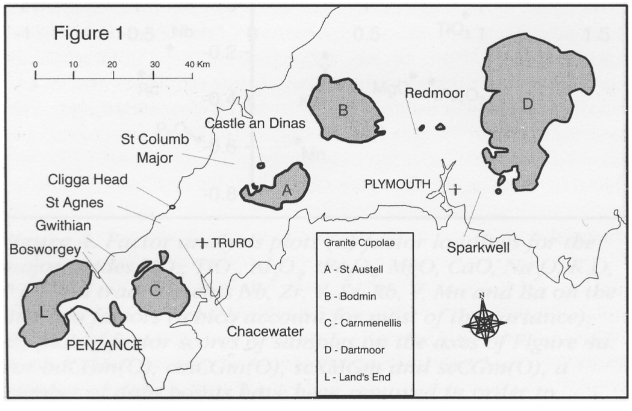


Figure 1. *Location diagram.*

In Cornubian granites and the surrounding sedimentary rocks the main mineral host for the REE is monazite (Bashem *et al*, 1982, Jefferies, 1985). Jefferies (1985) has shown that both monazite and zircons (in the Carnmenellis Granite) have very strong Eu depletion anomalies and that reliance on this feature as an indication of granite differentiation is suspect. In some granites the Y enriched mineral xenotime, has been identified.

It is generally recognised that the feldspars, in most rocks, have a positive Eu anomaly whilst the micas generally show a depletion (Towell *et al.,* 1965, Alderton *et al*, 1980). Alderton *et al.* (1980) have shown that the REEs are potentially mobile during alteration of the granites. In their study they concluded that the trivalent REEs (i.e. all REE with the exception of some Eu) were removed during potassium silicate metasomatism.. Such metasomatism is recognised by the development of K feldspar at the expense of plagioclase and biotite. Accompanying changes are loss of Sr (from plagioclase) and Li from the biotite and a contrasting gain in Rb. They also observed in the Henbarrow area that greisening resulted in a stronger Eu depletion. These authors also studied the distributions of the REE in co-existing mineral phases in the granites and concluded that K feldspar, plagioclase and tourmaline all showed a relative Eu enhancement whilst muscovite, biotite and chlorite exhibited a strong Eu depletion.

In sedimentary rocks REE distribution patterns mirror the average crustal igneous rocks. Any Eu anomaly is inherited from the parent rocks and is unaffected by sedimentary processes or by low-grade regional metamorphism. However Ce is affected by weathering and

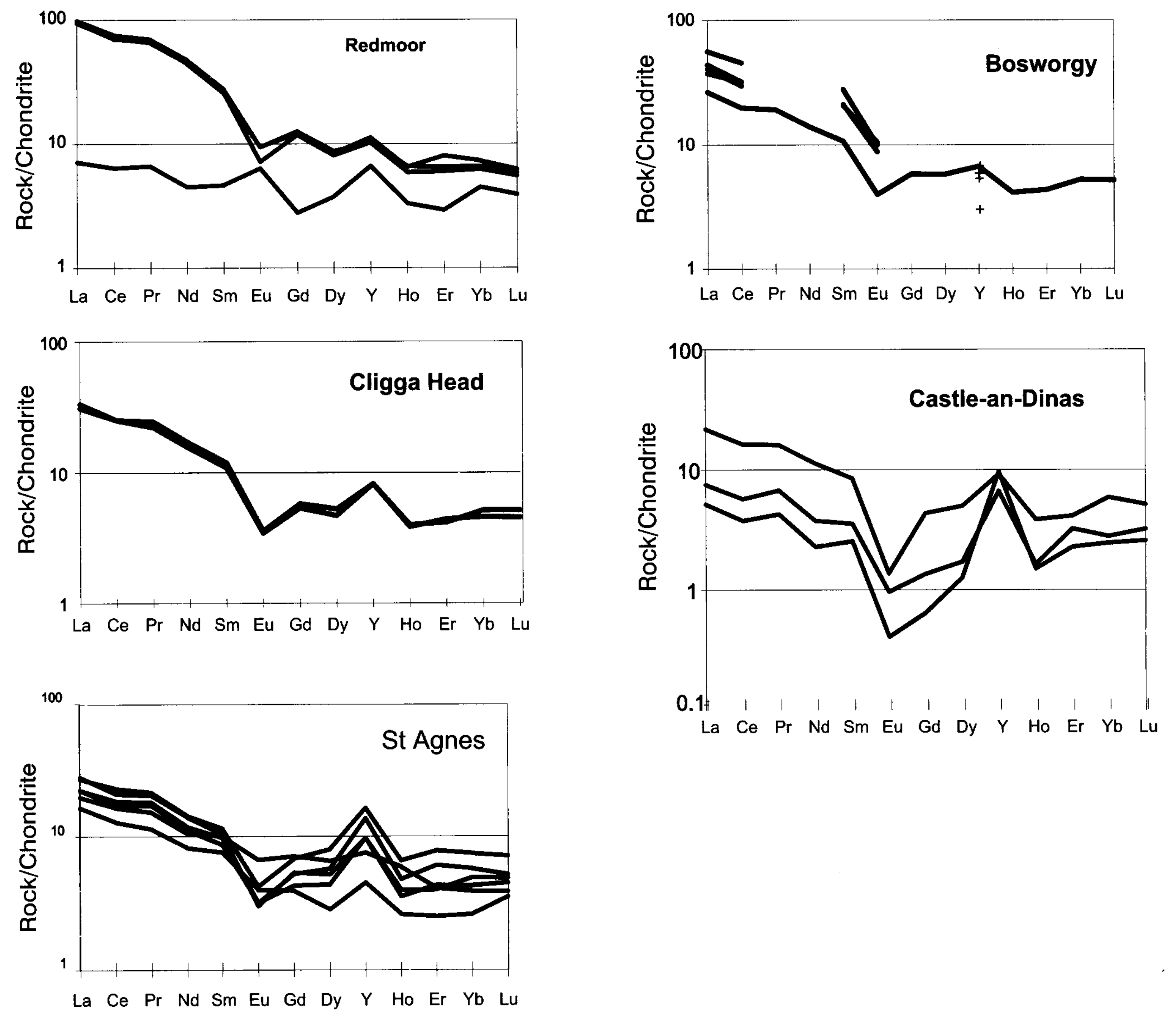


Figure 2. REE spectre (Chondrite Normalised) for the granite cupolae

by some sedimentary processes. Ronov *et al* (1967) showed that oxidation of Ce^{3+} to Ce^{4+} takes place in an alkaline environment under surface conditions. In chemical properties Ce^{4+} is closer to the heavy REE (HREE) than the light REE (LREE).

In this study the analyses have been undertaken using Inductively Coupled Plasma Mass Spectrometry (Dr. J. N Walsh, King's College, London), by Instrumental Neutron Activation Analysis (Herald Reactor Centre, Aldermaston) (Table 1) and for La, Ce and Y by X-ray Fluorescence Spectrometry (Midlands Earth Science Associates, Nottingham) (Table 2).

REE IN THE GRANITES—

The cusps for the present study are located in the roof zone of the Cornubian Batholith and the aureoles have been shown to be enriched in alkalis, Sn and W. (Beer and Ball, 1986; Ball *et al*, 1998). The locations of the cusps are given in Figure 1.

Exley *et al.* (1983) proposed three major granite types (A, B and C) with two further variants derived from these by metasomatic alteration involving Li addition. The A-type granite is a "primitive" almost dioritic rock found as infrequent inclusions within B-type granites. B-type granites represent 90% of the exposed plutons by volume and are represented in this study by the Redmoor and Bosworgey cupolas. The less widespread C- type granites (Castle an Dinas, Cligga Head and St Agnes) are more evolved, have characteristically higher Rb and Cs and, usually, higher Li. The granites all show consistent REE distribution patterns with LREE > HREE and most show an Eu depletion anomaly (Figure 2). In this way they are similar to other Cornubian granite REE patterns (Alderton Pearce and Potts, 1980; Darbyshire and Shepherd, 1985; Jefferies, 1984; 1985; Stone and Awad, 1988). The later C-type and Li enriched granites are all lower than the type "B" granites in total REE and in their LREE/HREE ratios. Although we have no quantitative information we gain the distinct impression that, compared to monazite, the Y rich mineral xenotime is relatively more abundant in the late stage type "C" granites than in the earlier type "B".

REE IN THE COUNTRY ROCKS

Petrography.

Two principal zones of metamorphism were distinguished petrographically in the Redmoor and Bosworgey aureoles, comprising an outer zone of spotted, phyllitic rock, and an inner zone of coarser, banded hornfels. Beyond these, at more than 900 m from the granite contact, textures more typical of low metamorphic grade slates are present. In the outer aureole zone, the politic aureole rocks

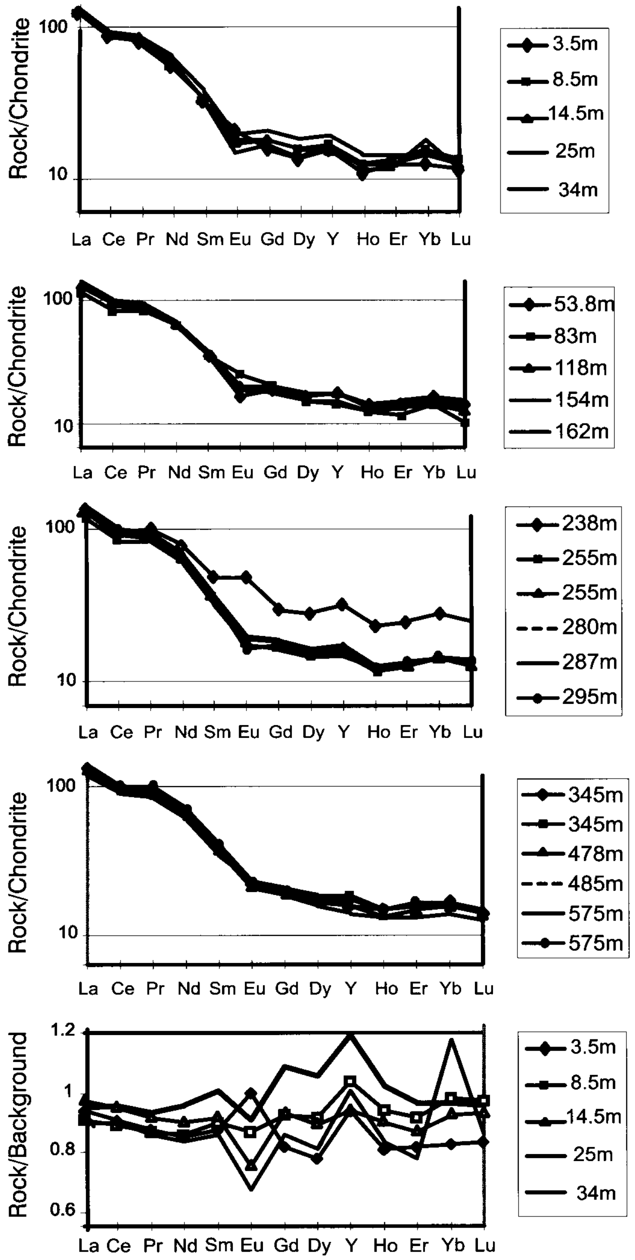


Figure 3. REE spectra (Chondrite Normalised) for the Redmoor aureole (ICPMS). The legend data refer to the distance from the contact. The final spidergram shows the proximal samples normalised against the mean of the most distant samples (background) between 345 m and 575 m from the contact.

display a striking lepidoblastic texture in which muscovite flakes display a very high degree of orientation generally parallel with bedding. In the inner zone, within 400 m, the phyllitic rock gives way to coarser textures in which overgrowth by discordant biotite flakes have partially obscured the muscovite foliation. In addition, K-feldspar replaces the contact metamorphic muscovite and also forms non-orientated porphyroblasts. Thus, an early lepidoblastic muscovitic assemblage preceded formation of the non-orientated, higher grade minerals which represent the peak of contact metamorphism.

At least four styles of subsequent metasomatic alteration can also be identified in the aureole and the granite. These include kaolinisation and sericite-chlorite alteration (which may affect the alkali distributions) as well as formation of tourmaline ± fluorite. In addition, a late (post-biotite) generation of non-orientated white mica, present within granite and out to at least 250 m out from the contact, is interpreted as of metasomatic/ hydrothermal origin.

The petrography of samples from the Castle-an-Dinas, Cligga Head and St Agnes aureoles indicate rocks in which pervasive alteration has obliterated earlier biotite-grade contact metamorphism. The presence of tourmaline suggests that metasomatising fluids were B-enriched, and in addition samples from St Agnes show evidence for fluorine metasomatism (fluorite presence).

Of the aureoles studied, it is likely that only Redmoor and Bosworgeywere sufficiently well sampled to provide a complete traverse through the aureole. Samples were only available from the outer part of the Castle-an-Dinas aureole. Other traverses were affected by lithological inhomogeneity, as at Cligga Head, where there are sandstones and chert rich pelites, and at St Agnes, where sandstones occur at the contact and also about 500 m from the contact..

Petite samples were collected from two background areas (no evidence of contact metamorphism) thought to be representative of the specific geological environment in which the cupolae were emplaced. These were at least 2.5 kilometres from the nearest granite outcrop and, as far as can be judged, a similar distance from a buried cusp or ridge. Samples from west Cornwall (Gwithian, Chacewater and Truro) relate to both the Bosworgey and St Agnes aureoles, whereas those from near St Columb were considered to represent background to the Cligga Head and Castle an Dinas aureoles.

A further group of fresh pelitic borehole samples was available from an area of weak mineralisation at Sparkwell, near Hemerdon. All reported high alkali element concentrations and the rocks were concluded (Beer and Ball, 1986) to have suffered low grade W and Sn mineralisation (Sn, mean 17±12 ppm, maximum 43 ppm, and W, mean 7±6 ppm, range 0-21 ppm).

Redmoor Aureole.

Analyses of three granites and one intrusive potassic microgranite (elvan) are available for this cusp (Figure 2). The granites all plot closely together and show LREE > HREE and with a marked Eu depletion anomaly. In common with Alderton, Pearce and Potts (1980) we note the greater negative Eu anomaly in the most greisened sample. The elvan is characterised both by lower total REE content and lower LREE /HREE. Furthermore the elvan shows a positive Eu anomaly whilst all the other samples show negative anomalies. There is a slight positive Y anomaly in the granites and this is more marked for the elvan.

The distribution patterns for the REE throughout the aureole show the expected LREE > HREE and an Eu depletion (Figure 3). In the outer part the values for the Eu depletion anomaly are about 0.75-0.80. As one approaches the granite so the Eu anomaly values become more scattered and in some samples values as low as 0.58 are found within about 60m of the contact. However the variation is great and there seems no consistent change in this parameter. The other REEs also show no consistent change with proximity to the contact. Both La (Figure 4) and Ce show a slight gradual increase with distance from the contact. However, this is not matched by the pattern exhibited byY or the other HREE. For example the Yb distribution matches the Y distribution closely with the single high value in both graphs for the same sample. This particular sample (at 238m from the contact) also exhibits a positive Eu anomaly of 1.28 and relatively high values for the HREE. This rock is a biotite schist and is the only one of the samples from the aureole to contain epidote, albeit as a minor component. We can find no REE analyses for epidote in the Southwest peninsula. The Ca content of this rock is unexceptional (CaO = 0.71%) and the Sr content (35 ppm) is below the average for the other Redmoor aureole rocks (88, ranging 37-235 ppm).

The final spidergram shows the proximal samples normalised

Table 1.

Sample Number	Location			Rock Type	Distance	La	Ce	Pr	Nd	Sm	Eu	Gd	Dy	Y	Ho	Er	Yb	Lu
Redmoor Area																		
BH KB-1A COLLAR AT SX 36022 71488						BH RM-11 COLLAR AT SX 3435 7070												
BH RM-2 COLLAR AT SX 3487 7096						BH RM-14 COLLAR AT SX 37650 69256												
BH RM-10 COLLAR AT SX 3490 7100						BH RM-29 COLLAR AT SX 3450 7155												
		Bore Hole	Depth															
KB2208		KB1A	418.5m	Granite		2.28	5.93	0.78	2.69	0.93	46	0.86	1.16	13	0.24	0.6	0.85	0.12
KB2214		KB-1A	4406m	Granite		31.76	70.6	8.35	28.65	5.49	0.68	3.89	2.69	20	0.48	1.4	1.24	0.18
KB2215		KB-1A	448.2m	Granite		30.41	65.87	8.03	26.62	5.17	0.69	3.76	2.58	22	0.47	1.7	1.38	0.19
KB2217		RM29	523.6m	Granite		30.29	66.6	7.84	26.81	5.21	0.52	3.67	2.49	20	0.43	1.3	1.18	0.17
KB2221		KB-1A	418m*	Slate	3.5m	39.89	82.36	9.79	33.96	6.53	1.58	4.96	4.14	31	0.83	2.6	249	0.36
KB2222		KB-1A	402m*	Slate	8.5m	38.8	80.99	9.77	34.39	6.67	1.38	5.56	4.9	34	0.96	2.9	2.95	0.42
KB2223		KB-1A	388m*	Slate	14.5m	41.39	86.06	10.25	36.15	6.8	1.2	5.62	4.74	31	0.92	2.8	2.79	0.4
K62224		KB-1A	362m*	Slate	25m	38.45	81.59	9.62	33.52	6.39	1.07	5.18	4.31	33	0.85	2.5	3.54	7
KB2225		KB-1A	345m'	Slate	34m	40.54	86.6	10.46	38.17	7.5	1.45	6.57	5.63	39	1.04	3.1	2.9	0.41
KB2226		KB-1A	313.6m	Slate	53.8m	41.34	86.21	10.52	37.81	7.06	1.16	5.92	5.21	34	1.01	3	3.01	0.44
KB2227		KB-1A	273.4m	Slate	83m	37.8	78.72	9.79	35.98	7.03	1.85	6.06	4.86	27	0.88	2.5	2.72	0.31
KB2228		KB-1A	231.0m	Slate	118m	44.02	92.82	11.25	40.33	7.35	1.44	5.87	4.96	34	0.94	2.8	2.76	0.39
KB2229		KB-1A	190m*	Slate	154m	43.63	92.62	11.13	39.47	7.4	1.51	6.12	5.28	35	1.02	3.1	3.17	0.46
KB2234		RM-11	272m•	Slate	162m	42.12	87.78	10.54	37.2	6.83	1.39	5.47	4.84	29	0.93	2.8	2.8	0.4
KB2230		KB-IA	100.5m	Slate	238m	40.32	88.62	11.37	44.15	942	3.54	8.96	8.74	64	1.7	5.2	5.16	0.76
KB2235		RMII	170m*	Slate	255m	36.8	77.68	9.67	34.13	6.35	1.3	5.11	4.39	30	0.83	2.7	2.62	0.38
KB2231		KB-IA	81.9m	Slate	255m	40.41	83.88	10.18	35.78	6.5	1.31	5.2	4.54	34	0.87	20	2.62	0.38
KB2232		KB-1A	49.7m	Slate	287m	43.9	89.2	11.06	39.85	7.17	1.41	5.6	4.9	34	0.93	2.8	2.64	0.39
KB2240		RM14	155m*	Slate	295m	4123	87.09	10.63	37.49	6.93	1.2	5.38	4.66	32	0.89	2.8	2.7	0.4
KB2233		RM14	45m*	Slate	345m	42.93	91.07	11.15	39.75	7.45	1.61	6.12	5.49	37	1.05	3.2	3.14	0.44
KB2236		RMII	68m*	Slate	345m	44.9	95.15	11.67	41.45	7.66	1.53	6.23	5.56	37	1.05	3.3	3.12	0.43
KB2238		RMIO	157m*	Slate	478m	43.06	90.2	11.16	39.4	7.09	1.47	5.65	5.12	31	0.97	3.1	2.92	0.43
KB2237		RMIO	330m*	Slate	485m	39.75	84.1	10.37	37.21	6.95	1.7	5.7	4.85	27	0.95	2.8	2.65	0.38
KB2239		RM4	204m*	Slate	575m	40.79	88.55	11.1	39.46	7.53	1.57	6.22	5.58	31	1.05	3.3	3.13	0.46
KB2241		RM2	165m*	Slate	575m	44.11	95.31	11.89	42.72	7.95	1.65	6.34	5.38	34	1.05	3.4	3.09	0.45
Castle-an -Dinas Area																		
KB2026	SW	9460	6205	Granite	Dump	1.66	3.54	0.51	1.37	0.51	0.03	0.2	0.39	19	0.11	0.5	0.47	0.08
KB2025	SW	9460	6205	Granite	Dump	2.42	54	0.81	2.27	0.71	0.07	0.42	0.53	13	0.12	0.7	0.53	0.1
KB2088		Mine No/ level		Granite	15m	6.93	15.24	1.93	6.76	1.7	0.1	1.35	1.55	18	28	0.9	1.12	0.16
Cligga Head																		
KB2044	SW	7381	5366	Granite	2m	9.85	23.52	2.65	9.14	2.18	0.25	1.66	1.45	16	0.28	0.9	0.87	0.14
KB2042	SW	7393	5372	Slate	10m	24.31	54.77	05-Apr	20.65	4.07	0.77	3.51	3.23	25	6	2	1.84	0.3
KB2043	SW	7393	5362	Hornfels	30m	47.47	106.3	11.39	41.15	7.91	1.53	6.47	5.36	39	1.07	32	2.85	0.45
KB2041	SW	7403	5373	Slate	120m	43.67	101.5	11.1	41.36	8.36	1.84	7.22	6.39	45	1.28	3.7	3.39	0.51
KB2040	SW	7430	5376	Slate	400m	40.7	92	10.13	36.71	6.99	17	5.26	4.53	30	93	2.9	2.9	0.47
St Agnes Area																		
KB2028	SW	7036	5061	Granite	Quarry	8.61	21.36	2.55	8.58	2.31	0.31	2.12	201	32	0.48	1.7	1.42	0.22
KB2027	SW	7036	5061	Granite	Quarry	7.21	17.27	2.16	7.09	1.94	0.23	103	1.77	27	0.35	1.3	1.09	0.16
KB2029	SW	7036	5061	Granite	Quarry	7.08	16.28	2.05	672	1.74	0.23	1.32	1.36	19	0.26	0.9	0.81	0.14
KB2033	SW	7019	5026	Granite	Dump	6.35	15.3	1.83	6.35	1.99	0.49	2.19	2.02	15	0.43	0.9	0.74	0.12
KB2034	SW	7019	5026	Granite	Dump	5.23	12.11	1.36	4.99	1.54	0.29	1.21	0.87	9	0.19	0.5	0.5	0.11
KB2092	SW	7015	5087	Granite	Dump	8.94	19.53	245	8.29	2.08	0.22	1.66	1.61	19	0.29	0.8	0.94	0.15
Bsworgey Area																		
		Bosworgey BH COLLAR AT SW 5806 3367																
BXD15		Bosworgey BH		Granite	3.3m	12	30	nd		3.8	<1			10				
BXD16		Bosworgey BH		Granite	22.2m	13	28	nd		4.2	0.64			11				
BXD17		Bosworgey BH		Granite	30m	14	30	nd		4.1	0.76			6				
BXD18		Bosworgey BH		Granite	33.7m	18	43	nd		5.6	0.72			13				
BXD19		Bosworgey BH		Granite	38m	8.51	18.58	2.3	8.31	2.13	0.29	1.8	1.78	13	0.3	0.9	0.99	0.16
BXD20		Bosworgey BH		Hornfels	2m	55	90		39	9.1	12			32				
BXD21		Bosworgey BH		Hornfels	20m	93	150		50	19	3.7			71				
BXD22		Bosworgey BH		Hornfels	20m	57	110		42	9.4	2.6			34				
BXD25		Bosworgey BH		Hornfels	27.6m	67	86		5	8.9	2.2							
BXD27		Bosworgey BH		Hornfels	40m	48	73		19	7.2	0.2							
BXD13	SW	5933	3454	Slate	91m	73	125		67	10	3.2			42				
BXD14	SW	5928	3454	Slate	95m	110	175		69	16	4.3			39				
BXD23		Bosworgey BH		Slate	96m	57	100		47	8.1	0.45			26				
BXD3	SW	5801	3362	Slate	100m	52	81		53	7.4	2.2			21				
BXD4	SW	5798	3365	Slate	100m	64	100		3.1	9.1	2.9			26				
BXD1	SW	5806	3356	Slate	105m	67	110		34	9.1	4.1			26				
BXD2	SW	5803	3359	Slate	105m	83	120		51	13	4.4			42				
BXD12	SW	5950	3450	Slate	110m	74	120		47	11	3.7			41				
BXD26		Bosworgey BH		Slate	129m	67	105		39	9.9	0.72							
BXD11	SW	5959	3453	Slate	136m	54	97		36	8.2	3			31				
BXD24		Bosworgey BH		Slate	150m	87	160		73	12	3			39				
BXD10	SW	5968	3452	Slate	176m	55	100		37	80	2.8			28				
BXD9	SW	5773	3391	Slate	195m	56	96		45	8.1	2.9			32				
BXD5	SW	5790	3373	Slate	250m	75	120		10	11	4			36				
BXD8	SW	5776	3390	Slate	250m	55	87		51	8.4	2.8			34				
BXD6	SW	5787	3377	Slate	270m	58	94		60	8.4	2.7			26				
BXD7	SW	5780	3384	Slate	270m	65	110		57	9.2	3.8			35				
BXD28	SW	5864	3493	Slate	1000m	46	112		43	8.7	2.8	1.1	5.9	34	3	0.5		
BXD29	SW	5861	3495	Slate	1000m	40	118		43	7.6	2.4	1.1	1	30	3	0.5		
Background																		
KB2249	SW	582	381	Slate		46.67	93.37	12.28	43.41	7.84	1.53	5.82	5.13	28	0.97	3.1	2.88	43
KB2252	SW	788	408	Slate		53.85	113.2	15.35	58.6	12	2.5	11	9.35	53	1.76	5.2	4.42	0.63

Table 1. *Locational and analytical data. The Bosworgey analyses were mostly by INAA whereas the remaining samples were analysed by ICPMS. Y analyses are by XRFS. Some of the Bosworgey samples were taken from shallow boreholes at a depth of about 30-35 m., apart from those from the cored borehole. The Redmoor samples were from cored boreholes. "Distance" gives a precise indication of the distance to the granite contact where intersected in cored boreholes. Other distances are based upon interpretation of gravity data controlled by the cored boreholes, or are measured from outcrop.*

Table 2.

Sample Number	Location			Rock Type	Distance		La	Ce	Y
Redmoor Area									
KB2212		KBIA	440.8m	Granite			19	29	20
KB2213		KB-1A	443.6m	Granite			18	34	19
KB2216		KB-1A	451.8m	Granite			25	60	20
KB2218		RM29	t530.3m	Granite			22	62	22
KB2219		RM29	t547.1m	Granite			25	51	22
KB2054	SX	3579	7215	Slate	280m		32	76	27
KB2021	SX	3610	707	Homfels	1km		37	95	36
KB2022	SX	3610	707	Slate	1km		37	69	34
KB2023	SX	3454	6983	Slate	2km		33	73	29
KB2024	SX	3403	6899	Slate	3km		25	43	29
Castle-an Dinas Area									
KB2086		Mine No.4 level		Granite			10	0	26
KB2087		Mine No.7 level		Granite	5m		16	26	31
KB2089		Mine No.7 level		Granite	65m		5	0	22
KB2090	SW	9453	624	Granite	Pit		5	0	19
KB2091	SW	9453	624	Granite	Pit		5	0	24
KB2053	SW	9453	624	Granite	Pit		9	0	18
KB2267	SW	9432	6159	Slate	460m		44	80	49
KB2261	SW	9479	6308	Slate	600m		49	122	58
KB2269	SW	9438	6127	Slate	680m		53	103	43
KB2263	SW	9454	6167	Slate	420m		29	92	32
K82264	SW	9457	6166	Slate	420m		34	72	63
KB2265	SW	9488	6374	Slate	1.3Km		42	90	37
KB2266	SW	9499	6373	Slate	1.3km		32	85	37
KB2262	SW	9487	6305	Slate	600m		52	89	42
KB2268	SW	9433	6127	Slate	680m		40	94	37
Cligga Head									
	Adit	SW 737	537						
KB2061	Adit	300 ft level		Granite	12 m		4	21	18
KB2060	Adit	300 ft level		Hornfels	1.5m		44	110	36
KB2059	Adit	300 ft level		Hornfels	3m		28	57	37
KB2058	SW	7433	5375	Slate	420m		49	93	43
KB2057	SW	7436	5376	Slate	450m		36	88	27
KB2056	SW	7447	5381	Slate	600m		51	83	30
KB2055	SW	7470	5400	Slate	800m		29	62	26
St Agnes Area									
KB2030	SW	7036	5061	Hornfels	1m		31	57	26
KB2031	SW	7036	5061	Hornfels	5m		36	56	28
KB2032	SW	7019	5026	Hornfels	120m		25	64	29
KB2035	SW	6998	4997	Slate	150m		40	98	32
KB2036	SW	6993	4997	Slate	150m		109	176	56
KB2039	SW	7077	5064	Slate	300m		45	105	42
K62038	SW	7082	5051	Slate	500m		34	67	35
KB2245	SW	7082	5051	Slate	500m		43	81	46
KB2037	SW	7099	5034	Slate	800m		50	113	40
Background Samples									
Sparkwell									
KB2272	SX	5905	5784	Slate		55	92	43	
KB2273	SX	5902	5794	Slate		39	71	32	
KB2274	SX	5902	5796	Slate		32	84	33	
KB2275	SX	5902	5802	Slate		34	86	31	
KB2276	SX	5897	5807	Slate		28	49	27	
KB2277	SX	5897	5812	Slate		46	86	33	
KB2278	SX	5908	5820	Slate		48	99	36	
KB2279	SX	5908	5821	Slate		47	107	36	
KB2280	SX	5899	5815	Slate		38	73	40	
St Columb									
KB2202	SW	914	64	Slate	>3Km	41	81	43	
KB2203	SW	914	64	Slate	>3Km	54	99	47	
KB2204	SW	914	64	Slate	>3Km	42	62	28	
KB2201	SW	929	653	Slate	3Km	41	88	46	
KB2207	SW	918	641	Slate	>3km	36	69	36	
KB2206	SW	928	647	Slate	2.5 km	31	48	26	
KB2205	SW	931	647	Slate	2.5 km	38	59	34	
West Cornwall									
KB2247	SW	598	409	Slate		41	43	44	
KB2248	SW	592	415	Slate		29	52	38	
KB2246	SW	722	4840	Slate	2.5Km	90	107	36	
KB2250	SW	747	45	Slate		84	148	54	
KB2251	SW	816	421	Slate		46	105	31	
KB2253	SW	794	462	Slate		42	82	31	
KB2254	SW	818	47	Slate		46	87	41	
KB2253	SW	834	498	Slate		21	42	22	
KB2256	SW	846	462	Slate		29	62	27	

Table 2. *Locational and analytical data. Analyses by XRFS for Ce, La and Y.*

against the mean of the five samples between 575 and 345 m. This follows the procedure described by Wolff and Storey (1984) and provides an indication of the differences between the distant samples, taken as background, and those close to the contact. The diagram confirms the lower levels close to the contact of about 5 to 10 %, and the increased variability.

Bosworgey Aureole.

Only partial analyses were available for the Bosworgey granite rocks (Figure 2), however the normal pattern of REE distributions is observed with a marked LREE> HREE, an Eu depletion anomaly and a positive Y anomaly.

A similar range of REEs is observed for the aureole rocks. There is a pronounced scatter for the T (total) REE as shown by the La data (Figure 4) with lower values at the contact and at a great distance. Unfortunately data for Gd were not available so that the conventional Eu depletion anomaly could not be assessed. Recourse therefore had to be made to the Sm/Eu ratio as a measure of the Eu depletion. The Sm/Eu ratio decreases with distance (Figure 5), reflecting the lower Eu and higher Sm values observed in some of the samples in inner part of the aureole. However the data are scattered and there is no obvious clear pattern. The La/Y ratios show a broad swell of high values between 300 and 50m from the contact but much lower values at the contact and for the background.

St Agnes Aureole.

The granite is characterised, as most Type "C" granites, by low TREE, and by a well developed negative Eu anomaly and positive Y anomaly (Figure 2).

Data were only available for Ce, La and Y for the rocks of the aureole. The La distribution is similar to the Bosworgey aureole with a pronounced scatter and low values at the contact and for the "background". There is some slight evidence for an increase in Ce and La in the proximal zone as shown by a slight increase in the La/Y (Figure 5) and Ce/Y ratios, especially in one sample at 150m from the contact but there seems no other evidence of a marked change in REE contents. The anomalous sample is not otherwise geochemically remarkable.

Cligga Head Aureole.

The granite, like other type "C" granites, exhibits low TREE concentrations with a marked Eu depletion and positive Y anomalies (Figure 2).

The aureole rocks again show marked scatter within a few hundred metres of the contact but with a suggestion of a decline towards the contact (Figure 4). Only four samples were analysed for the broad spread of REE. These show a general increase of the LREE relative to the HREE (La/Y) with distance, and a decrease in the Eu anomaly (Figure 5).

Castle an Dinas Aureole.

This Li rich granite exhibits low to very low levels of total REE, a strong Eu depletion and a positive Y anomaly (Figure 2).

Unfortunately no aureole sample was obtainable closer than 420m from the contact. It is therefore not surprising that there is no discernible pattern of consistent change within this part of the aureole. (Figures 4 and 5)

Background.

Apart from those samples in the outer portions of the aureoles. there are only a few analyses for REE in background areas. In common with the outer aureole samples the REE show higher levels than the granites, a marked LREE > HREE and a slight Eu depletion anomaly (0.72). Floyd and Leveridge (1987) noted a similar Eu depletion (0.7) in their study of the Gramscatho sedimentary rocks.

The analyses from lightly mineralised Sparkwell samples show no significant difference compared with the background for La, Ce, or Y and the ratios of these elements.

ASSESSMENT OF DATA

There appears to be no convincing evidence for a change in the Eu depletion anomaly through the aureole for Redmoor and, although there is a suggestion of rather scattered low values in the Eu anomaly close to the contact, this is not statistically significant. This is shown in both the Eu/Eu* and in the Sm/Eu plot (Figure 5). However there does seem to be some evidence for an increase in the extent of Eu depletion for the Bosworgey and Cligga Head granites, although the data are sparse (Figure 5).

Despite the pronounced scatter there does seem to be an increase in La/Y ratios with proximity to the granite for the Redmoor and Bosworgey aureoles, but the data are inconclusive for the St Agnes and Castle an Dinas aureoles whilst the reverse is the case for the Cligga Head aureole.

The total REE as exemplified by the La distributions show rather conflicting patterns (Figure 4). The type "B" granites, typified by the Redmoor and Bosworgey cusps, show either no change or only a slight decline with distance. In contrast the Cligga Head and St Agnes aureoles show a slight increase although part of this may be explained by the presence of quartz-rich rocks close to the contact, whilst for the Castle an Dinas aureole the sampling is inadequate to show any pattern.

The La/Y ratios (Figure 5) indicate a rather clearer relationship with distance for the Redmoor, Bosworgey and possibly the St Agnes aureoles, although again the data shows pronounced scatter. and only some of the proximal samples have a higher La/Y ratio than those at a distance. The reverse is true of the Cligga Head aureole and again sampling is inadequate for the Castle-an Dinas aureole.

In all of our examples in which there are enough analyses, the REE pattern for the aureole rocks do not become progressively similar to that of the granite as the contact is approached. Such a relationship was reported by Mitropoulos (1982) from around the Lands End Granite, where some of the REE ratios consistently approach the granitic value. This was especially true for La/Y and Ce/Y. Mitropoulos (1982) based his sampling upon a detailed study of the petrography of the contact altered rocks carried out by Khan (1972). In this Khan had subdivided the aureole into the following zones:

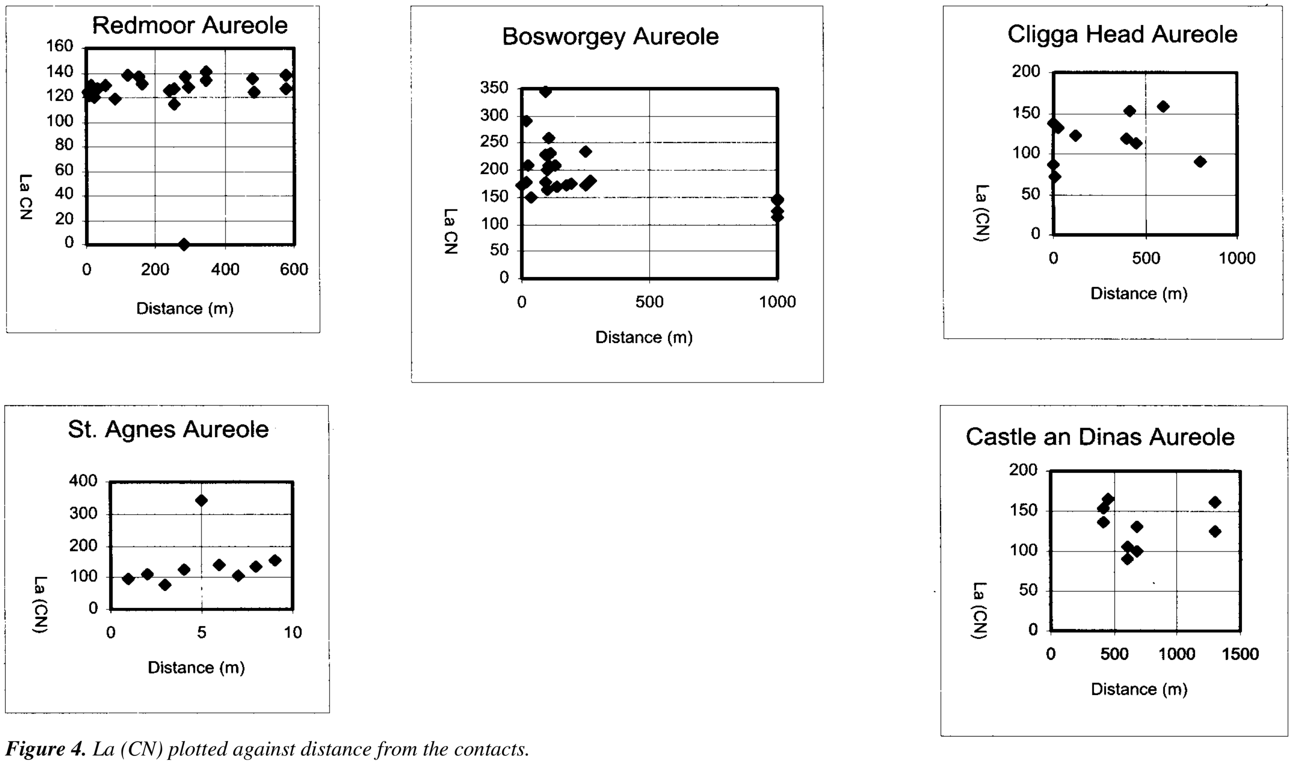
1. 0<8 m - comprising a high grade hornfels of biotite +/- andalusite +/- Kspar.
2. 8-21m - an intermediate zone in which the predominant metamorphic mineral is biotite.
3. 21-360 m - zone of moderate metamorphism in which the main minerals are biotite and feldspar.
4. > 360 m - silicified "sediments"

Mitropoulos concluded that the REE had been added to the sedimentary envelope from the granite by hydrothermal solutions. The TREE contents of the inner aureole are higher than both the country rocks and the granite but the patterns of REE distributions (LREE/HREE and Eu anomalies) become more like the granite as the contact is approached. It is probable that the introduced REE are additional to those fixed in the sedimentary envelope at the time of deposition and hence a complete replacement is unlikely.

Stone and Awad (1988) studied the REEs in the contact zone of the Tregonning granite, a Li rich granite, which typically has low REE contents. Two samples within centimetres of the contact showed elevated levels of all REEs compared with background slate at 2 km. There were however substantially more X-ray Fluorescence Spectrometric data for Ce, La and Y. The authors concluded that although there had been an overall increase in total REE towards the granite, since there was almost a constant Ce/Y and La/Y, the LREE/HREE ratios were maintained. Statistical analysis of the XRFS data show a significant difference between proximal (i.e. < 10m from the contact) and more distant samples for Ce, La and Y.

CONCLUSIONS:

There is little consistent or easily recognisable pattern in the REE distributions that can be unequivocally related to the granite cusps in the present study. This conclusion is at variance with the conclusions of Mitropolous (1985) and Stone and Awad (1988). In both cases these authors noted strong and easily identifiable changes with proximity to the granites. There are however distinct differences in the location and provenance of our samples and the following are suggested as explanations for the differences:


Redmoor Aureole

Bosworgey Aureole

Cligga Head Aureole

St. Agnes Aureole

Castle an Dinas Aureole

Figure 4. *La (CN) plotted against distance from the contacts.*

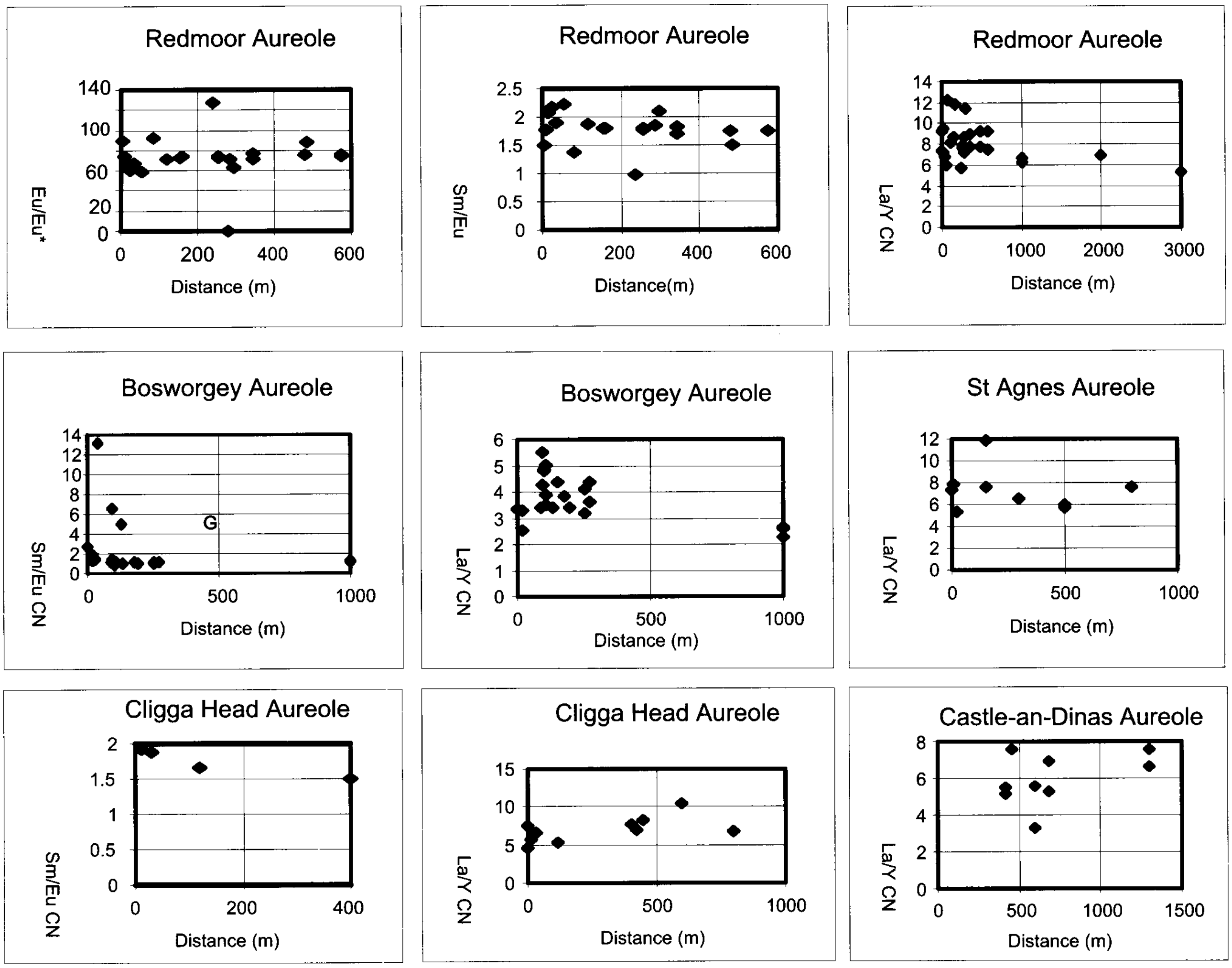


Figure 5. *Various REE (Chondrite Normalised) ratios plotted against distance from the contacts.*

1 The granites discussed here are small and possibly do not retain their temperature or temperature gradients long enough for a recognisable pattern to develop. This contrasts with the situations described by Mitropoulos (1092) and Stone and Awad (1988) in which their sampling locations were on the flanks of much larger plutons.

2 The granites have a lower REE content than the aureole rocks. The aureole rocks originally have a high and on the whole variable content of the REE. A small change resulting from the addition of small amounts of REE with a "granite signature" is not recognisable within the variability of the original distribution patterns.

3. The inhomogeneity in the rocks in the present study precludes the recognition of a real causal variation by the granites. The inhomogeneity arises from a number of causes. As well as an original sedimentary variability the introduction of new chemical elements, especially K, and the growth of minerals resulting from the introduction, can simply dilute the concentration of the original REE. Although the alkali metasomatism is pervasive it is not uniform and the result can be an increase in the variance of the REE close to the aureole. The increased variability of REE in proximity to the contacts is discernible in Figures 3 to 5. Similarly the irregular introduction of potential REE carrying minerals (e.g. possibly fluorite) may have the opposite effect but would certainly increase the variance.

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REFERENCES

ALDERTON, D. H. M., PEARCE, J. A. and POTTS, P. J.1980. Rare Earth Element mobility during granite alteration, evidence from Southwest England. *Earth and Planetary Science Letters,* **49**, 149-165.

BALL, T. K. and BASHAM, I. R. 1984. Petrogenesis of the Bosworgey granitic cusp in the SW England Tin Province and its implications for ore mineral genesis. *Mineralium Deposita,* **19**, 70-77.

BALL, T.K., FORTEY, N.J. and BEER, K.E. 1998. Alkali metasomatism from Cornubian granite cupolae. *Proceedings of the Ussher Society.* **9**, 212-219.

BASHAM, I.R., BALL. T.K., BEDDOE-STEPHENS, B. and MICHIEU. McL. 1982. Uranium-bearing accessory minerals and granite fertility: II Studies in granites from the British Isles. In: *Symposium on uranium exploration Methods*: Paris, International Atomic Energy Agency, Vienna.

BEER, K E. and BALL, T. K. 1986. Tin and tungsten in pelitic rocks from S.W. England and their behaviour in contact zones of granites and in mineralised *areas.Proceedings of the Ussher Society.* **6**. 330-337.

DARBYSHIRE, D.P.F and SHEPHERD, T.J. 1985. Chronology of granite magmatism and associated mineralization, *SW England. Journal Geological Society of London.* **142**, 1159-1177.

DINES H.G 1956. The metalliferous mining region of southwest *England. Memoirs of the Geological Survey of Great Britain.* London. HMSO.

EXLEY, C.S., STONE, M and FLOYD, P.A. 1983. Composition and petrogenesis of the Cornubian granite batholith and post-orogenic volcanic rocks in Southwest England. In: *The Variscan Fold Belt in the British Isles* (Hancock P.L. ed.) 153-177. Bristol, Adam Hilger

FLOYD, P. A. and LEVERIDGE, B. E. 1987. Tectonic environment of the Devonian Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic *sandstones. Journal of the Geological Society, London.* **144**, 531-542.

HERMANN, A. G. 1970. Yttrium and Lanthanides. In: *Handbook of Geochemistry.* Executive Ed. WEDEPOHL, K W. **39**, 57-71. Springer, Berlin.

JEFFERIES, N.L. 1985. The distribution of the rare earth elements withinthe Carnmenellis pluton, Cornwall. *Mineralogical Magazine,* **49**, 495-504.

KHAN, I. H. 1972 . Geochemistry of the aureole of the Land's End Granite. PhD Thesis University of Birmingham, Birmingham. (unpublished).

MITROPOULOS, P. 1982. REE patterns of the metasedimentary rocks of the Land's End aureole, Cornwall. *Chemical Geology,* **23**, 265-280.

RONOVA,B., BALASHOVY,A and MIGDISOVA,A. 1967. Geochemistry of the rare earths in the sedimentary cycle. *Geochemistry International.* **4**, 1-17.

STONE, M. andAWAD, N. T. I. 1988. Behaviour of trace-alkali and other elements at the Tregonning granite - pelite contacts. *Proceedings of the Ussher Society,* **7**, 47-51.

TOWELLD, G., WINCHESTER, J.W. and VOLKOVSKY, S.R.V. 1965. Rare Earth distribution in some rocks and associated minerals of the batholith of Southern California, *Journal of Geophysical Research* **70**, 3485-3496.

WOLFF, J.A. and STOREY, M. 1984. Zoning in highly alkaline magma bodies. *Geological Magazine,* **121**, 563-575.