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THE COMPOSITION OF ACCESSORY MINERAL PHASES WITH POSSIBLE PETROGENETIC IMPLICATIONS FOR THE HERCYNIAN GRANITES OF NORTH-WEST FINISTÈRE, BRITTANY, FRANCE.

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During the Hercynian orogeny the region of north-west Finistère was intruded by a series of granites. Four of these, the Aber-Ildut, Ploudalmézeau, Kernilis and Landunvez plutons are the subject of this present study. An isotope study (Jennings and Rowbotham, 1993), has been extended to include a study of rare earth elements and their host minerals. This indicates that Sm and Nd do not appear to behave coherently and show evidence of fractionation, which may be significant in the application of Sm-Nd systematics. Also included are detailed analyses of zircon which illustrates trace element partitioning between co-existing phases. Data presented here on the accessory minerals in the granitoids indicates that the behaviour of the light rare earth elements (LREE) is dominated by the presence of monazite and allanite. Application of monazite/melt partition coefficients for the LREE demonstrates that in those granitoids relatively unaffected by hydrothermal fluids, monazite is the principal host for these elements. Use of allanite/melt partition coefficients reveal that allanite is an additional repository for the LREE where hydrothermal activity has taken place. Application of the monazite geothermometer using LREE solubility data give inconsistent temperatures of crystallisation of between 630°C and 929°C whereas zirconium solubility data gives more consistent temperatures of 747°C to 767°C.

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INTRODUCTION

Regional geology

The regional geology of north-west Finistère is not well understood. Chauris (1966) described a probable basement unit, the Gneiss de Tréglonou, as being of early Proterozoic age (Icartian). However, the work of Cabanis *et al.* (1979) and Bale and Brun (1986) put forward alternative views on the geological history of Leon. Cabanis *et al.* (1979) indicate an Rb/Sr age of 385±8Ma for the Gneiss de Tréglonou and suggest that this particular unit is in itself an earlier intrusion. Further, Bale and Brun (1986), in a structural study, showed that, at about 340 Ma, Leon had been subjected to 150 km of north-easterly dextral movement before becoming located in its present position. The Gneiss de Tréglonou is succeeded by a series of pelites and psammites, now at amphibolite facies. All of these units were subjected to deformation during the Cadomian and Hercynian orogenies; during this latter event this Precambrian terrane (Roach, 1977) was intruded by a series of granites, four of which, Aber-Ildut, Ploudalmézeau, Kernilis and Landunvez are the subject of this study. A preliminary report on the petrography of the rocks, the mineralogy of the major phases and their petrochemistry has been presented by Jennings and Rowbotham (1993).

Accessory minerals

The main accessory phases of all the granites are monazite, zircon, apatite and ilmenite, and in addition it is noted that allanite has been observed in the Inner facies of the Aber-Ildut pluton and garnet in the Tremazan facies of the Landunvez pluton. The Aber-Ildut granite comprises two facies, an outer equigranular, coarse-grained, two-mica, frequently tourmalinised granite, and an inner red, porphyritic unit, comprising quartz, megacrysts of K feldspar, plagioclase, biotite, isolated muscovite and titanite. Subsequent hydrothermal activity has produced such alteration products as epidote/clinozoisite and chlorite. This facies also contains an abundance of fine grained mafic inclusions. The Landunvez granite also consists of two facies: the Tremazan facies, a coarse grained, porphyritc rock, comprising quartz, both feldspars, two micas and garnet and the Scoune facies, an equigranular, medium/coarse grained rock, comprising the same mineralogy as the Tremazan but without garnet. Monazite is euhedral and varies from colourless to yellow and possesses a high birerefingence, which may reflect variations in Th content (Frondel, 1958). Pleochroic haloes are in evidence and confirm significant radioactivity.

Zircon is also euhedral in form, colourless, optically zoned and equidimensional, measuring up to 400 microns. Inclusions within particular grains of zircon are, chlorite, quartz and potassium feldspar. High order interference colours can be observed, but radiation effects are less marked than those surrounding monazite. Invariably, both monazite and zircon are located within flakes of biotite and form part of the biotite-apatite assemblage.

Allanite is located within grains of potassium feldspar and apatite. In feldspar grains, allanite is euhedral but where it is located as an inclusion within apatite, it is anhedral, and in both settings it shows an irregular distribution of interference colours. The coexistence of monazite and allanite was noted in early studies of the Idaho Batholith (Anderson, 1942) who observed that, in general terms, monazite existed where allanite did not, and further described how, when they did coexist, allanite had been formed as the result of 'endomorphic alteration' under changing conditions of pressure and temperature, effectively being formed as a precipitation from hydrothermal fluids. Lee and Bastron (1967), on the other hand, showed that high concentrations of Ca in the melt led to the destabilisation of monazite and the formation of allanite. Bearing in mind that CaO content of the inner facies of the Aber-Ildut is some 2.5 wt % compared to less than 1.0 wt % in the other plutons then this is a factor to consider. This chemical feature can be correlated with the observation of allanite in this inner facies of the Aber-Ildut pluton.

Evidence for post-magmatic hydrothermal activity in these granites manifests itself by the perturbation of Rb-Sr systematics, together with the formation of mineral alteration products (Jennings and Rowbotham, 1993) and it is pertinent to note that Corey and Chatterjee (1990) have demonstrated the mobility of the REE under metasomatic conditions. It is necessary, therefore, to be able to appreciate whether allanite acts as a substitute for monazite in its role as an alternative repository for the REE and Th and whether this is facilitated by conditions of lower temperature and pressure. It is considered on this occasion that the nature and distribution of allanite is reminiscent of a secondary rather than primary phase and in certain cases is suggestive of precipitation from late-stage REE bearing hydrothermal fluids.

Major and trace element whole rock chemistry

Major and trace element petrochemistry has been outlined by Jennings and Rowbotham (1993), who demonstrate the peraluminous nature of all these Hercynian granitoids. Both major and trace element distributions show linear trends which Jennings and Rowbotham ascribe to either fractional crystallisation from a more basic parent or simple dilution effects of increasing SiO_2 with reduced proportions of other oxides.

In addition to the previously reported petrochemistry, six samples from the Aber-Ildut pluton, two from Ploudalmézeau, two from the Kernilis and five from the Landunvez plutons were analysed by ICP-MS techniques to determine whole rock concentrations of the REE. (See Table 1 and Figure 2 from Jennings and Rowbotham (1993) for sample locations). In Table 1 the concentrations are chondrite-normalised using the values of Nakamura (1974). Profiles of this REE data from the granitoids are depicted in Figure 2. The Aber-Ildut and Landunvez spectra can be separated into those which pertain to the more evolved and those which relate to more basic compositions. The Aber-Ildut data shows a reduction in bulk REE concentrations across the pluton, the lowest concentration (AI9I) representing that found in the more evolved outer facies. This is an indication that the REE are progressively taken up by the REE minerals i.e. monazite and allanite, rather than behaving as incompatible elements and increasing in concentration as chemical evolution proceeds. It is noted that the LREE/HREE ratio as highlighted by La/Yb_N decreases as fractionation proceeds, which illustrates the preferential removal of the LREE in the mineral phase. Variation in the Eu anomaly has been probably the result of a corresponding variation in plagioclase removal as the magma crystallises.

The Landunvez spectra again reveal a reduction in bulk REE concentration across the pluton and it is thought that similar processes to those in the Aber-Ildut were responsible for the final profiles. The presence of a combination of negative and positive Eu anomalies is significant. It is noted that the concentration of Eu remains essentially constant, such that changes in oxidation state from its normal +3 to +2 states, where Eu becomes soluble, can be ignored as a possible reason for this phenomenon, as can variations in plagioclase removal. It is thought that the change in anomaly probably represents a depletion of the light and heavy REE by a combination of the preferential removal of the LREE into monazite and the HREE into garnet.

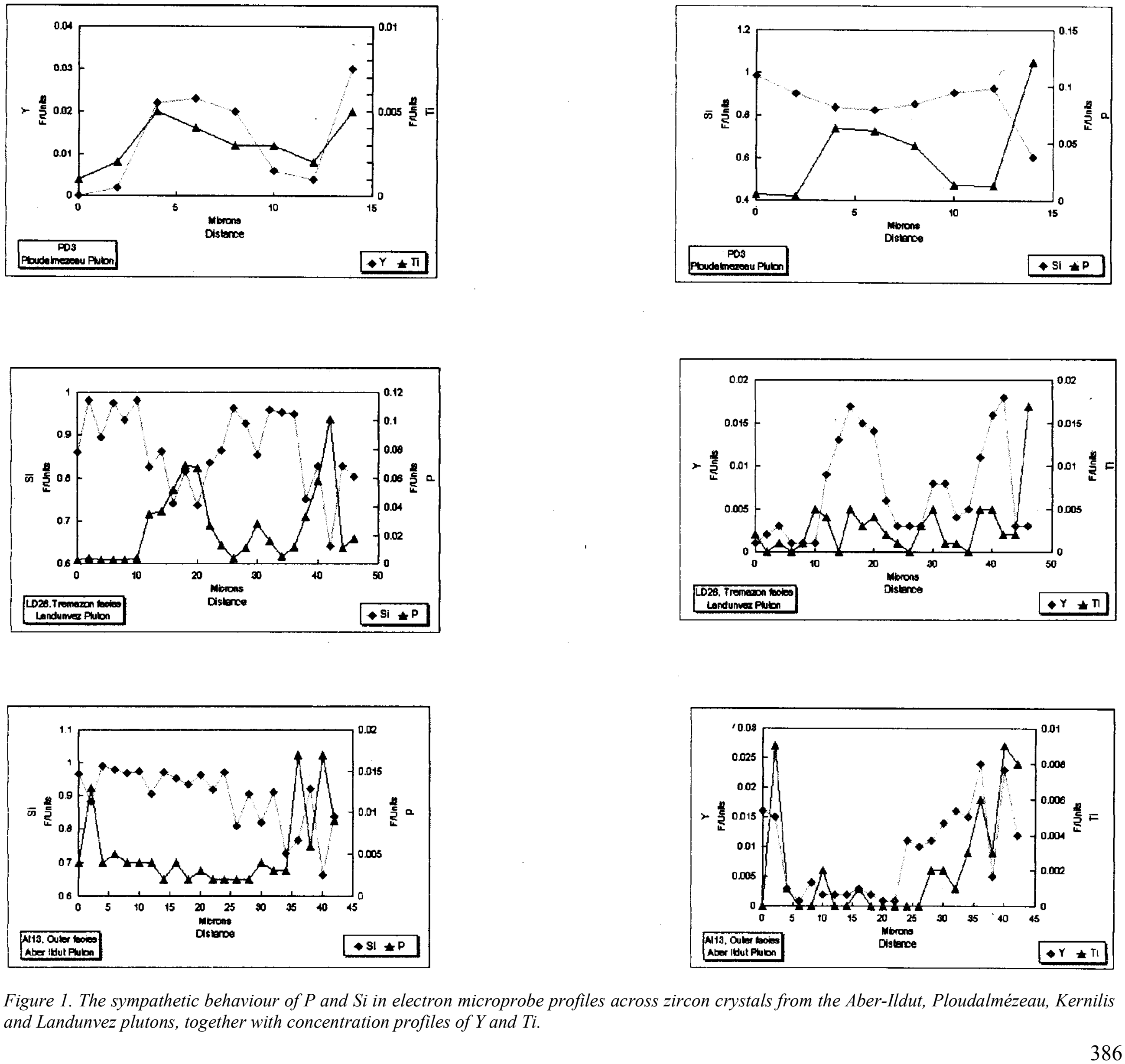

Figure 1. The sympathetic behaviour of P and Si in electron microprobe profiles across zircon crystals from the Aber-Ildut, Ploudalmézeau, Kernilis and Landunvez plutons, together with concentration profiles of Y and Ti.

	AI7	AI9	AI13	AI18	AI18.2	AI26	PD5	PD11A	PD14	PD36	LD27	LD29	LD30A	LD31	LD32	Norm Values
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
La	61.80	2.40	81.90	93.00	56.00	37.90	12.10	20.40	8.70	10.20	35.90	3.60	86.60	6.80	44.40	0.33
Ce	119.86	5.28	173.11	179.95	106.54	76.21	26.24	41.24	17.35	21.25	69.58	5.04	181.78	8.37	89.03	0.86
Pr	12.95	0.51	20.31	19.56	12.50	8.45	3.10	4.50	1.90	2.45	7.61	0.44	18.64	1.04	9.90	0.13
Nd	46.20	2.30	75.20	68.80	46.60	30.20	11.80	16.10	7.00	9.20	27.50	1.60	63.90	4.60	35.40	0.63
Sm	7.01	0.87	12.79	10.24	8.12	5.61	2.53	3.26	1.78	2.52	5.18	0.37	10.00	0.55	5.69	0.2
Eu	1.24	0.04	1.40	1.55	1.57	0.65	0.27	0.31	0.27	0.34	0.83	0.58	1.02	1.17	0.76	0.08
Gd	4.76	0.86	8.39	6.88	6.52	4.18	1.93	2.56	1.66	2.59	4.30	0.42	5.35	0.62	3.55	0.28
Dy	4.10	1.29	5.73	5.26	6.43	3.96	1.81	2.45	1.97	2.70	4.41	1.17	2.67	0.35	2.39	0.34
Ho	0.69	0.16	0.88	0.86	1.12	0.63	0.26	0.40	0.30	0.34	0.79	0.26	0.39	0.07	0.38	0.08
Er	1.85	0.50	2.03	2.12	3.23	1.74	0.67	1.08	0.79	0.75	2.38	1.02	0.68	0.22	0.87	0.22
Yb	1.86	0.73	1.70	1.90	3.03	1.66	0.63	1.03	0.77	0.50	2.40	1.37	0.61	0.14	0.79	0.22
Lu	0.29	0.09	0.26	0.29	0.48	0.24	0.09	0.15	0.11	0.06	0.37	0.23	0.09	0.03	0.13	0.03
La/Yb_N	22.03	2.210	32.23	32.77	12.30	15.31	12.65	13.15	7.54	13.43	9.98	1.76	93.71	34.33	37.36	
Eu/Eu_N	-0.62	-0.13	-0.39	-0.53	-0.64	-0.39	-0.36	-0.31	-0.48	-0.40	-0.52	4.54	-0.38	6.08	-0.48	
Sm/Nd_N	0.47	1.16	0.52	0.46	0.54	0.58	0.67	0.63	0.79	0.85	0.58	0.72	0.49	0.37	0.50	

Table 1. Whole rock REE contents and chondrite-normalised values used for the Aber-Ildut, Ploudalmézeau, Kernilis and Landunvez granites.

The enriched HREE of sample LD29I is almost certainly due to the presence of garnet which is usually enriched in HREE and whose presence was noted in Jennings and Rowbotham (1993)

MINERAL CHEMISTRY OF THE MINERAL PHASES

Monazite

Eight samples of monazite, analysed by electron microprobe are presented together with one of allanite (Table 2). In addition, traverses across five grains of zircon are shown in Figure 1, and averages for all the analyses in each traverse are given in Table 3.

Core and rim analyses from the inner facies of the Aber-Ildut pluton (AI26A) and the Tremazan facies of the Landunvez pluton (LD28) are given in Table 2 and are significant in that they illustrate variations in the concentration of Th, with increases occurring as the rim is approached. This is accompanied by a corresponding decrease in the La/Nd ratio and may be the result of either cooling taking place under non-equilibrium conditions or diffusion initiated by radioactive decay. An increase in Th concentration around a crystallising phase in a highly viscous granitic melt needs time to achieve equilibrium between melt and crystal, and if there is rapid cooling, then Th will be unable to equilibrate. Alternatively, it should be recognised that the increase in Th content at the edge of the crystal corresponds with a reduction in the concentration in U. Both elements are radiogenic and decay occurs by the emission of alpha particles from the parent nucleus. The recoil energy from such emissions is substantial (Faure, 1986) and may result in Th and U being moved into non- lattice, crystallographic sites, which will facilitate subsequent migration. Fick's Law of Diffusion states that rates of diffusion are proportional to concentration and, as the U/Th ratio is of the order of 0.2, then it is suggested that Th ions may preferentially accumulate at the rim of the crystal, in other words, the zoning may be the result of post-crystallisation processes.

It should be noted that Y, a stable and immobile element, is also located in the monazite lattice with contents varying from 0.7 to 2.9 wt% in mineral grains from different granites. However there is little difference in concentration of Y_2O_3 from core to rim, illustrating its relative stability. The coexistence of monazite and allanite is noted (AI25) with Ce, Nd and Gd being less abundant in the allanite phase.

Influence of REE in monazite on the whole-rock REE

The whole-rock REE concentrations of the respective plutons are shown as chondrite-normalised spectra (Figure 2), together with similarly normalised monazite and allanite concentrations. It can be noted that both minerals exert a significant influence on the LREE fraction of the bulk rock profiles.

An application of published monazite/melt partition coefficients for the REE (Hinton, R.W., written communication, 1994), whereby monazite concentrations are divided by the K_D or partition coefficient to allow comparison with whole rock concentrations, shows that the whole of the LREE in the Ploudalmézeau and Kernilis plutons and the Tremazan facies of the Landunvez pluton are contained in the monazite phase, whereas 20 % of the LREE in the Aber-Ildut and 33 % in the Scoune facies of the Landunvez pluton can be explained in this way. This approach differs from mass balance calculations which rely on the validity of modal abundances in the whole rock, as compared with the validity of particular partition coefficients as in this case. By an additional application of allanite/melt partition coefficients (Rollinson, 1994) it can be demonstrated that the repository for the remainder of the LREE in the inner facies of the Aber-Ildut pluton is allanite; it follows, therefore, that the modal abundance of allanite must be greater to account for the fact that 80 % of the LREE is found in that phase. Clearly further work is required to clarify this position particularly with regard to the Scoune facies of the Landunvez pluton.

Sm-Nd systematics

It should be observed that the Sm/Nd ratios in monazite within particular plutons show variation, see Tables 1 and 2, which indicate that these elements have undergone fractionation, both in the mineral phase and the whole rock. In the mineral phase Nd is incorporated into the monazite lattice in preference to Sm and variation in core and rim analyses illustrates fractionation during the crystallisation of single rock specimens. This means that Sm-Nd systematics which rely on the coherent behaviour of Sm and Nd during mobilisation may be suspect. The fractionation of Sm and Nd

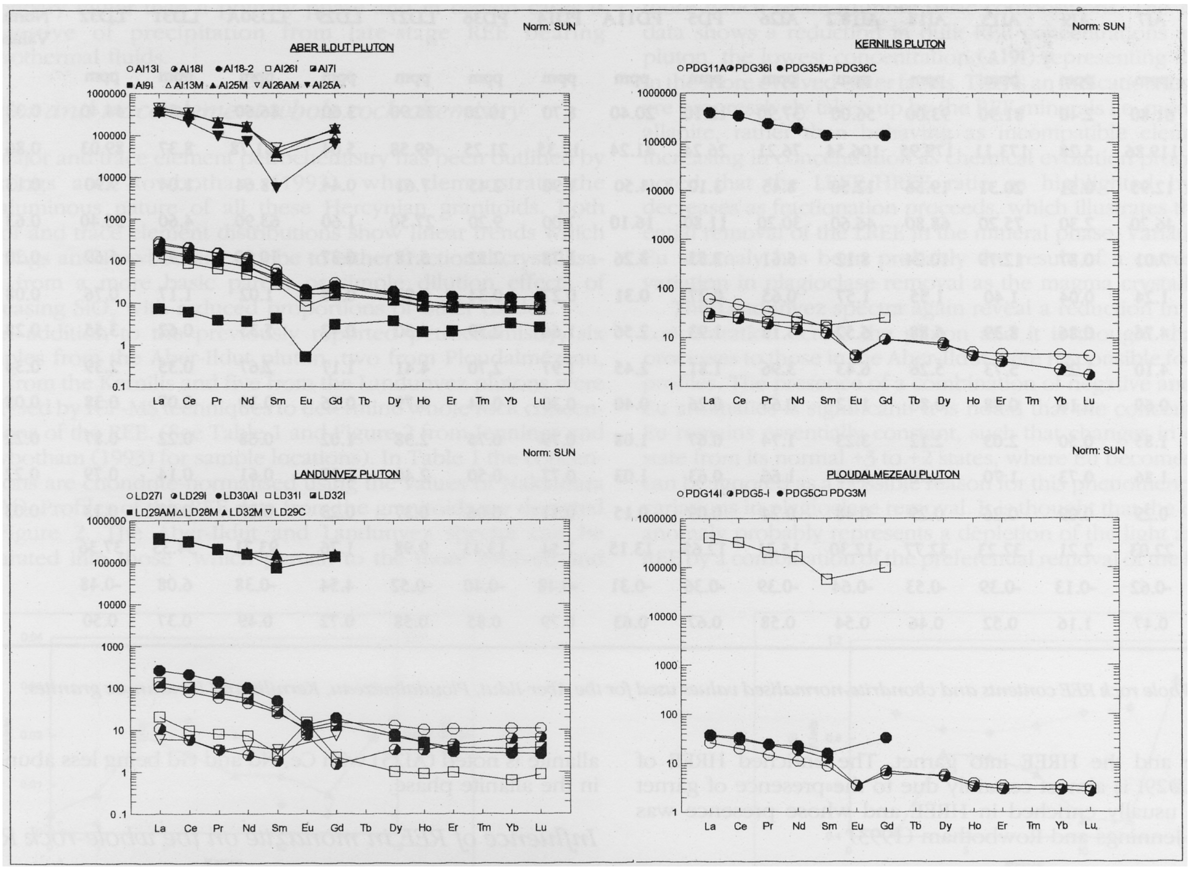

Figure 2. Comparison of chondrite normalised REE abundances in monazites with whole rock concentrations, together with calculated profiles of the LREE contents of the Aber Ildut, Ploudalmézeau, Kernilis and Landunvez plutons.

in evolving peraluminous granites has also been observed by Turpin *et al.* (1990). Experimental work by Montel (1993) and Rapp and Watson (1986) has shown that the presence of monazite leads to fractionation of the LREE as the result of non-ideal behaviour in phosphate solution. This brings into question the validity of, for example, model age determinations which assume that Sm/Nd ratios remain unaltered during evolution of the magma.

The work of Montel (1993) and Rapp and Watson (1986) further led to the derivation of equations which permit temperature determinations of crystallisation and the modelling of whole-rock profiles of the LREE based on microprobe analyses of monazite. The acknowledged limitations of the equations which follow are:

(1) that they are only applicable to melt compositions with a low mafic content;

(2) that the effects of the presence of volatiles are unknown;

(3) that the whole of the LREE must be taken up in monazite;

(4) that equilibrium between melt and mineral must be maintained.

The temperature values based on equation 1 in Montel (1993) are given below:-

$$\text{In}\,(REE_t) = 9.5 + 2.34D + 0.3879 - \sqrt{H_2O} - \frac{13318}{T}\ .$$

$$\text{where } REE_t = \sum \frac{REE_t\,(ppm)}{at.weight\,(g.mol^{-1})} \quad \text{and } D = \frac{(Na+K+Li+2Ca)}{Al} \times \frac{1}{(Al+Si)}$$

H_2O is in Wt %

T in kelvin

Na, K, Li, Ca and Si are in at .%

Aber-Ildut pluton	- outer facies	929°C
	- inner facies	857°C
Ploudalmézeau pluton		829°C
Kernilis pluton		739°C
Landunvez pluton	- Tremazan facies	630°C
	- Scoune facies	847°C

For comparative purposes Montel (1993) obtained temperatures for the following granites:

Huelgoat pluton (Hercynian granite N.Brittany)	715°C-802°C;
Carnmenellis pluton, Cornwall	768°C-813°C;
Cornubian batholith S.W. England	584°C.

It should be noted that all the plutons contain the volatile bearing phase tourmaline, and therefore the calculated temperatures should be considered suspect, particularly those between 847°C and 929°C, which are likely to be in excess of the total solubility of monazite (Montel, 1993).The temperatures obtained for the Kernilis, Ploudalmézeau and Tremazan facies of the Landunvez pluton appear to be more realistic and were used to model whole rock LREE concentrations using equations 1, 2 and 3 from Montel (1993). The calculated profiles are shown in Figure 2 where it is apparent that they

TABLE 2

	Al25(A)	AI13	Al26A	AI26A(C)	Al26A(R)	AI25	LD29A	LD28(C)	LD28(R)	LD32	PD3	PD35
	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt%	Wt %	Wt %
	n=1	n=1	n=1	n=1	n=1	n=1	n=1	n=1	n=1	n=2	n=2	n=2
P_2O_5	0.00	28.43	29.83	29.76	29.62	28.70	30.31	30.11	29.48	30.26	28.87	29.20
CaO	4.20	0.99	1.35	0.62	1.05	1.40	1.59	1.66	1.75	1.8	1.n	1.54
FeO	2.60	0.04	0.17	0.00	0.41	0.50	0.00	0.04	0.26	0.44	0.07	0.23
La_2O_3	11.40	15.01	14.67	17.07	15.57	12.50	13.10	11.99	11.31	12.29	13.53	12.99
PrO_2	1.30	2.66	2.61	2.71	2.65	2.70	2.71	2.67	2.45	2.73	2.71	3.07
Sm_2O_3	0.10	0.67	1.02	0.96	106.00	0.8	1.37	2.14	2.15	3.18	1.76	2.79
CeO_2	18.20	29.34	29.99	32.25	29.94	27.80	28.26	27.07	26.41	27.72	28.28	29.57
Nd_2O_3	4.50	10.26	9.74	10.48	10.20	10.60	9.64	10.84	10.66	10.55	10.18	12.02
Gd_2O_3	1.70	2.48	3.75	3.78	3.64	4.10	3.65	4.22	4.73	4.11	3.84	3.79
MgO	3.00	0.00	0.08	0.00	0.00	0.00	0.09	0.02	0.13	0.02	0.00	0.00
Al_2O_3	11.20	0.06	0.33	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.01
SiO_2	33.8	0.88	0.07	0.33	0.54	0.60	0.00	0.00	0.28	0.01	0.36	0.16
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ThO_2	0.00	8.04	7.54	3.83	6.72	8.30	8.78	7.91	9.85	6.02	8.74	7.66
Y_2O_3	-	0.77	-	-	-	1.10	-	2.89	2.81	2.12	1.11	0.70
UO_2	-	0.61	-	-	-	0.40	-	1.54	1.37	2.68	1.14	0.46
Total	92.10	100.23	99.98	101.79	101.38	99.60	99.51	103.09	103.62	102.83	102.87	103.52
	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units	F/Units
P	0.00	0.92	0.95	0.93	0.93	0.93	0.98	0.94	0.92	0.94	0.91	0.92
Ca	0..46	0.04	0.05	0.03	0.04	0.06	0.07	0.07	0.07	0.07	0.07	6.00
Fe	0..22	0.00	0.01	0.00	0.01	0..02	0.00	0.00	0.01	0.01	0.02	0.01
La	0..43	21.00	0.20	0.23	0.21	0.18	0.18	0.16	0.15	0.17	0.19	0.18
Pr	0.05	0.04	0.04	0.04	0.03	0.04	0.04	0.03	0.03	0.04	0.04	0.04
Sm	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.03	0.03	0.02	0.03
Ce	0.65	0.39	0.38	0.42	0.39	0.37	0.38	0.35	0.34	0.36	0.37	0.38
Nd	0.17	0.14	0.13	0.14	0.14	0.14	0.13	0.14	0.14	0.14	0.14	0.16
Gd	0.06	0.03	0.15	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05
Mg	0.46	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Al	1.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Si	3.47	0.03	0.01	0.01	0.02	0.02	0.00	0.00	0.01	0.00	0.01	0.06
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Th	0.00	0.07	0.06	0.03	0.06	0.07	0.08	0.07	0.08	0.05	0.07	0.07
Y	-	0.02	0.00	0.00	0.00	0.02	0.00	0.06	0.06	0.04	0.02	0.01
U	-	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.00
O	12.5	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Total	8.3	1.91	1.98	1.89	1.87	1.91	1.92	1.91	1.92	1.91	1.92	1.91
La/Nd		1.51	1.53	1.68	1.57	1.22	1.39	1.14	1.09	1.20	1.37	1.11
Sm/Nd_N	0.08	0.20	0.34	0.28	0.32	0.23	0.44	0.61	0.63	0.93	0.54	0.72

Table 2. Electron microprobe analyses of monazites and allanite from the Aber-Ildut granite, together with analyses of monazite from the Ploudalmézeau, Kernilis and Landunvez granites, all with recalculated structural formulae using 12.5 oxygens for the allanite and 4 oxygens for the monazite.

do not match the measured ones. In addition, calculations using different temperatures did not give a good correlation, which means that one or more of the assumptions mentioned earlier has been contravened, with the presence of allanite in the Inner facies of the Aber-Ildut pluton and an implied presence in the Scoune facies of the Landunvez pluton being crucial. Probable disequilibrium between melt and mineral and the existence of volatiles may also be significant.

Zircon

Discussion on element fluctuations across zircon grains assumes that zircon is magmatic, as indicated by the presence of concentric zoning patterns, and has crystallised as part of the whole granitic cooling process. U, Th and Y concentrations are substantially lower in zircon (Tables 2 and 3) than in coexisting monazite. Figure 1 depicts oscillatory patterns in concentrations of P and Si within the zircon lattice, which appear to show sympathetic behaviour with P substituting for Si. Examination of Figure 1 shows a positive correlation between Y and P. In zircon the concentration of Y fluctuates, unlike in the monazite phase where its concentration appears not to vary. This probably reflects or can be explained by the steric constraints affecting Y and Ti, both of similar ionic radius, which compete for the same lattice site within zircon, such that any increase in Y should correspond to a decrease in Ti. The traverse across LD28 from the Tremazan facies of the Landunvez pluton provides a good illustration of this, but the traverses across PD3 from the Ploudalmézeau pluton and AI13 from the outer facies of the Aber-Ildut pluton show that other factors affect the distribution of these elements.

Table 3

	LD32	Al25	A113	LD28	PD3
	n=8	n=21	n=21	n=24	n=8
	Wt %	Wt %	Wt %	Wt %	Wt %
SiO2	32.56	31.68	29.05	30	29.48
Al2O3	0.02	0	0.96	0.15	0.43
MgO	0	0.02	0.09	0.06	0.01
CaO	0.02	0.01	0.73	0.13	0.11
Nb2O5	0.12	0	0	0	0
ZrO2	64.93	67.72	67.65	68.53	67.63
P2O5	0.19	0.15	0.44	0.43	0.48
Y2O3	0.1	0.14	0.82	0.16	0.25
FeO	0.46	0.14	1.64	0.79	0.42
MnO	0.08	0	0	0	0.05
ThO2	0	0	0.32	0	0
TiO2	0	0	0.33	0.12	0.09
UO2	0	0	0.25	0.17	0.12
Total	98.48	99.85	100.28	100.54	99.06
	F/Units	F/Units	F/Units	F/Units	F/Units
Si	1.01	0.98	0.88	0.93	0.92
Al	0	0	0.04	0.01	0.02
Mg	0	0	0	0	0
Ca	0	0	0.03	0	0
Nb	0	0	0	0	0
Zr	0.98	1.02	1.01	1.03	1.03
P	0.01	0	0.01	0.01	0.01
Y	0	0	0.02	0	0
Fe	0.01	0	0.05	0.02	0.01
Mn	0	0	0	0	0
Th	0	0	0	0	0
Ti	0	0	0.01	0	0
U	0	0	0	0	0
O	4	4	4	4	4
Total	2.01	2	2.05	2.01	2.01

Table 3. Electron microprobe analyses of zircon crystals from the Aber-Ildut, Ploudalmézeau and Landunvez granites together with recalculated structural formulae based on 4 oxygens.

In a series of zircon solubility experiments, Watson and Harrison (1983) were able to derive the following expression:

$$\text{In } D \frac{\textit{zircon/melt}}{\textit{zirconium}} = \{ - 3.8 - [0.85\ (M-1)]\} + \frac{12900}{T}$$

where $D \frac{\textit{zircon/melt}}{\textit{zirconium}}$ is the concentration ratio of Zr in the

stoichiometric zircon to that in the melt.

T is the absolute temperature in kelvin.

SAMPLE REFERENCE	REMARKS
AI7, AI18, AI26A, AI25	Inner facies, Aber-Ildut pluton
AI9, AI13, AI126	Outer facies, Aber-Ildut pluton
AI18.2	Inclusion, Inner facies, Aber-Ildut pluton
PD3, PD5, PD14	Ploudalmezeau pluton
PD11A, PD35, PD36	Kernilis pluton
LD30A	Admellite de St. Marguerite (Landunvez
pluton)	
LD27, LD28, LD29, LD29A	Tremazon facies, Landunvez pluton
(A)	Allanite
(C)	Core of crystal
(R)	Rim of crystal

Table 4. Details of samples in Figures 1 and 2 and Tables 1 to 3.

M is the cation ratio and for peraluminous granites is usually around 1.3.

Application of this expression has resulted in the following temperature determinations; the temperature from the monazite geothermometer are shown thus

Aber-Ildut pluton	- outer facies	743°C {929°C}
	- inner facies	829°C {857°C}
Ploudalmézeau pluton		746°C {829°C}
Landunvez pluton	- Tremazan facies	761°C {630°C}
	- Scoune facies	765°C {847°C}

For comparative purposes, temperatures for the following granites were obtained by zircon geothermometry (Montel, 1993):

Huelgoat granite (N.Brittany)	700°C -793°C
Carnmanellis pluton, Cornwall.	728°C -769°C
Cornubian batholith (S.W. England)	631°C

Differences in the temperature determinations derived horn the two methods are disappointing and may be due to either the existence of a volatile phase referred to earlier, the effects of which have not been modelled, or possibly that D and M values are different from those at the time of original crystallisation. The value determined for the Aber-Ildut pluton from the monazite data is anomalously high at 1.64 which accounts for the very high temperature of 857°C. It is also pertinent to note that the melting experiments of Watson and Harrison (1983) concentrated in the temperature range 860-1020°C. Experiments with temperatures in the proximity of 727°C relied on extrapolation. Generally, however, the temperatures determined using the zircon data are more consistent and appear more realistic, possibly indicating that zirconium partitioning is more resistant to the presence of volatiles and post-magmatic effects and that zirconium is exclusively in one crystallizing phase.

CONCLUSIONS

Limited conclusions can be derived from the analysis of LREE-bearing accessory phases in the Hercynian granitoids of northwest Finistère:

(a) in these granitoids, monazite is the preferred host a the time of crystallisation for the radiogenic elements U and Th in comparison to zircon;

(b) that temperatures of crystallisation derived from the experimental data of Montel(1993) on monazites are inconsistent with those derived using zircon solubility experiments (Watson and Harrison, 1983). The zircon data is in line with temperature determinations for other granites.

(c) use of modelling coefficients of monazite to calculate whole-rock profiles is not a complete explanation.

Work is proceeding in attempt to resolve these inconsistences by the determination of complete REE analyses using alternative techniques.

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REFERENCES

ANDERSON, A.L. 1942. Endomorphism of the Idaho batholith: *Bulletin of the Geological Society of America* **53,** 1099 - 1126.

BALE, P. and BRUN, J-P. 1986. Les complexes metamorphiques du Leon (N-W Bretagne): un segment du domaine eo-Hercynien sud amoricain translate au Devonien. *Bulletin de la Societe Geologique de France,* **8,** t II, 471 - 477.

CABANIS, B., PEUCAT, J.J., MICHOT, J., DEUTSCH, S. 1979b. Remise en cause de l'existence d'un socle orthogneissique ante-cambrien dans le pays de Leon (domaine nord-amoricain); etude geochronologiques par les methodes Rb/Sr et U/Pb des orthogneiss de Tréglonou et de Plounevez-Lochrist. *Bulletin du BRGM (deuxieme serie), section 1,* **4 ,** 357 - 364.

CHAURIS, L. 1966 . *Bulletin de la Carte geologique de la France, LXI,* 9 - 30.

COREY, M.C. and CHATTERJEE, A. K. 1990. Characteristics of REE and other trace elements in response to successive and super-imposed metasomatism within a portion of the South Mountain Batholith, Nova Scotia, Canada. *Chemical Geology.* **85,** 265 - 285.

FAURE, G. 1986. *Principles of Isotope Geology.* Wiley, New York. 589 pp.

FRONDEL, C. 1958. Systematic mineralogy of Uranium and Thorium. *Bulletin of the United States Geological Survey.* **1064,** 1 - 400 .

JENNINGS, J. A. and ROWBOTHAM, G. 1993. A petrogenetic study of granitoids in north-west Finistère, Brittany, France - a preliminary study. *Proceedings of the Ussher Society,* **8,** 160-166.

LEE, D.E. and BASTRON, H. 1967. Fractionation of rare earth elements in allanite and monazite as related to geology of the Mount Wheeler mine area, Nevada. *Geochimica et Cosmochimica Acta,* **31,** 339 - 356.

MONTEL, J-M. 1993 A model for monazite/melt equilibrium and application to the generation of granitic magmas. *Chemical Geology,* **110**, 127 - 146.

NAKAMURA, N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica et Cosmochimica Acta,* **38,** 757- 775.

RAPP, R.P. and WATSON, E.B. 1986. Monazite solubility and dissolution kinetics: implications for the thorium and light rare earth chemistry of felsic magmas. *Contributions to Mineralogy and Petrology.* **94,** 304 - 316.

ROACH, R.A. 1977. A review of the Pre-Cambrian rocks of the British Variscides and their relationship with the Pre-Cambrian of NW France. In: *Le chain varisque d'Europe moyenne et occidentale.* Colloque internationale du centre National de la recherche Scientific. **243,** 66 - 79.

ROLLINSON, H.R. 1993. *Using geochemical data: evaluation, presentation, interpretation.* John Wiley and Sons, New York. 352pp.

TURPIN, L., CUNEY, M., FRIEDRICH, M., BOUCHEZ, J-L. and AUBERTIN, M. 1990. Meta-igneous origin of Hercynian peraluminous granites in N.W. French Massif Central: Implications for crustal history reconstructions. Contributions *to Mineralogy and Petrology,* **104,** 163 - 172.

WATSON, E.B. and HARRISON, T.M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. Earth *and Planetary Science Letters,* **64,** 295 - 304.