The composition and distribution of nodular monazite in the Lower Palaeozoic rocks of Great Britain

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Abstract

Millimetric, ellipsoidal monazite nodules found within Lower Palaeozoic sedimentary rocks in Wales, south-west England and Brittany are characterised by a pronounced zonation of light and heavy *REE*, an inclusion fabric of low-grade metamorphic minerals indistinguishable from the host rock and a low Th content. They are interpreted as the product of *in situ* recrystallization of detrital monazites derived from pegmatitic or granitic source rocks and are potentially useful as indicators of Lower Palaeozoic sedimentary rock provenance.

KEYWORDS: monazite, nodules, Lower Palaeozoic rocks, rare earth elements, Great Britain.

Introduction

GEOCHEMICAL drainage surveys carried out in several parts of Britain have identified areas characterised by anomalously high levels of rare earth elements (*REE*) in panned stream sediment concentrates (e.g. Cameron *et al.*, 1984; Cooper *et al.*, 1984, 1985; R. C. Jones, pers. comm.). These are caused by the presence of a very distinctive form of nodular monazite, similar to that recorded in the Palaeozoic rocks of Brittany (Donnot *et al.*, 1973).

In this paper we detail the composition of this unusual form of monazite, compare it with other monazites, discuss its origin and show how its distribution is related to the palaeogeography of the Lower Palaeozoic.

Occurrence

The distribution of nodular monazite in Britain can be related on a regional scale to the background geology (Fig. 1). Very high levels of *REE* (> 1% Ce), all due to the presence of monazite, have been recorded only from panned stream sediments collected in catchments draining Ordovician and Silurian sedimentary rocks of the Welsh Basin (Table 1). The monazite enters the streams directly from weathering rock exposures, glacial till and soils. Detailed work in the Afon Gwesyn catchment, central Wales (Fig. 1), has shown that the nodules, grain size 0.05 mm to 2 mm with a maximum frequency at 0.5–0.7 mm, are dispersed throughout the sedimentary sequence at a concentration of 25–40 grains per kg (Read, 1983). At this level they do not exert a major control over either *REE* or phosphate abundances which are generally lower than expected for sedimentary rocks of this type (Read, 1983; Gromet *et al.*, 1984).

In the Berwyn Dome and central Wales there is no apparent stratigraphic control on the occurence of *REE* anomalies in panned concentrates (Ball and Nutt, 1976; Cooper *et al.*, 1984) and nodules have been extracted from rocks of Caradoc to Upper

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Mineralogical Magazine, June 1987, Vol. 51, pp. 271–80

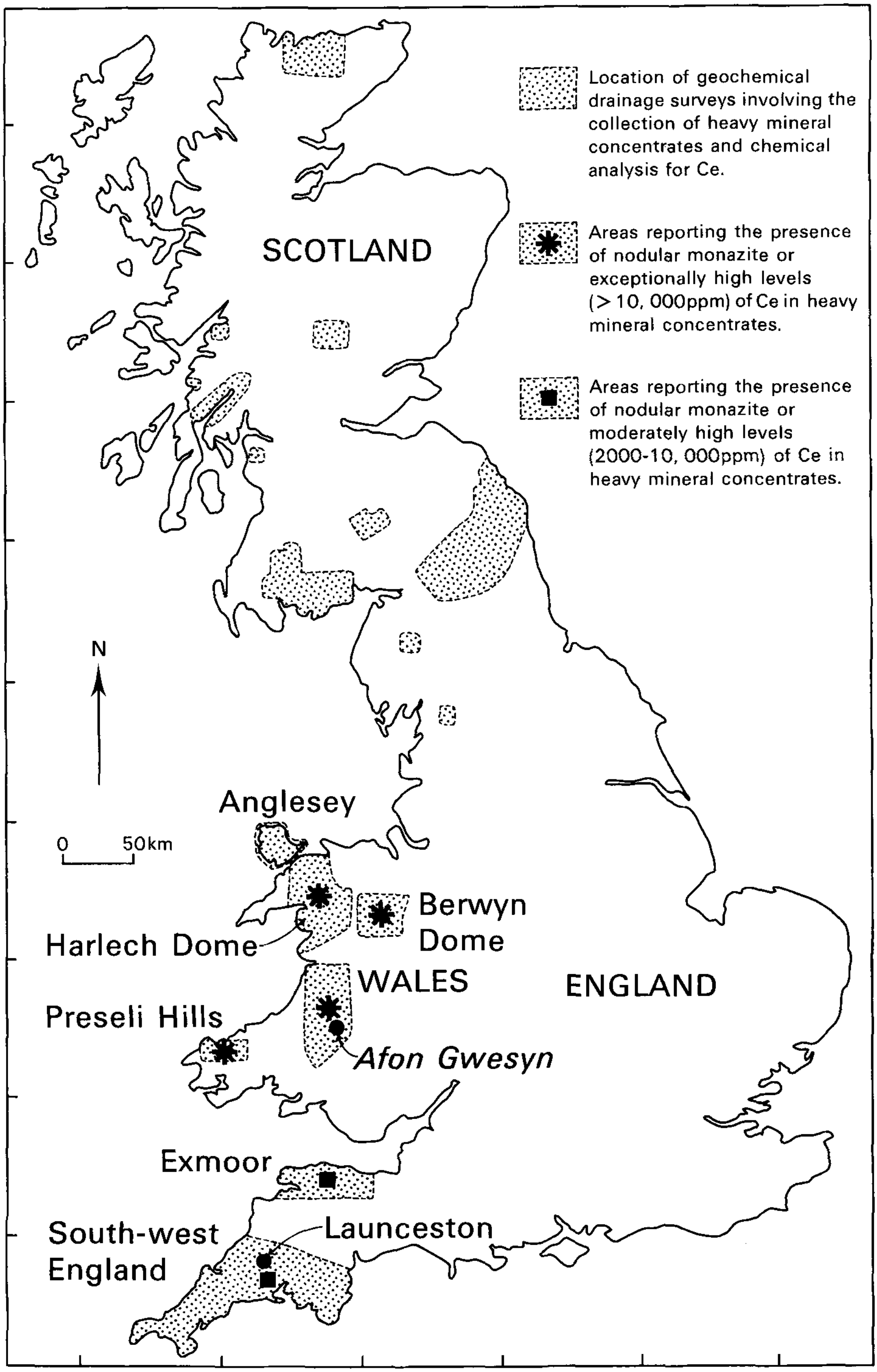

FIG. 1. The distribution of cerium in panned stream sediment concentrates.

Llandovery age (Read, 1983). In the Harlech Dome, however, there is a progressive change from low *REE* levels in panned stream sediment samples collected over the Lower and Middle Cambrian to very high values ($\leqslant$ 14% Ce) in streams draining Caradocian to Silurian sedimentary rocks (Cooper *et al.*, 1985). In the Preseli Hills consistently high *REE* levels in panned concentrates are a feature of the area occupied by rocks of Llandeilo to Ashgill age (Cameron *et al.*, 1984).

TABLE 1

Cerium levels in panned stream sediment concentrates

Area	Cerium content (ppm)			
	Samples	Median	Maximum	Minimum
Lake District Skiddaw Group	5	170	300	130
Anglesey	490	50	660	< 21
Snowdonia	170	140	>10,000	30
Harlech Dome+				
Harlech Grits Group	141	53	490	< 21
Mawddach Group	177	692	8,500	< 21
Caradoc-Ashgill	121	2,990	140,000	44
Berwyn Dome+	399	2,015	>10,000	89
Central Wales+	488	1,600	>10,000	50
Preseli Hills+	358	1,231	84,500	37
Exmoor	809	85	6,100	< 21

+ Data compiled from British Geological Survey Mineral Reconnaissance Programme Reports, referenced in the text.

Monazite nodules are also responsible for some high *REE* levels in panned stream sediments in south-west England (Fig. 1, Table 1). On Exmoor high levels of Ce, reflecting the presence of nodular monazite, occur in an east-west belt between Ilfracombe and Roadwater, south-east of Minehead, suggesting derivation from the Mid to Upper Devonian Ilfracombe Beds. A second group of high Ce values ($\leqslant$ 8200 ppm) is located in the Tavistock-Launceston area, close to the Devonian-Carboniferous boundary, but here it is not certain that nodular monazite is the source (R. C. Jones, pers. comm.).

Nodular monazite has not been found in the Palaeozoic rocks of northern Britain. Panned concentrates collected from catchments draining the Arenig-Llanvirn sedimentary rocks of Anglesey failed to indicate the presence of nodules (Cooper *et al.*, 1982; Table 1). Five concentrates collected from catchments draining representative outcrops of the Tremadoc to Llanvirn age Skiddaw Group in the Lake District all contained low *REE* levels (Table 1). Panned concentrates obtained from catchments draining Lower Palaeozoic rocks in southern Scotland (Leake *et al.*, 1978*a*, *b*) yielded few Ce values in excess of 300 ppm and none greater than 1000 ppm. Correlation of Ce with Y and Ti suggested that most of the higher values were related to the presence of sphene. Heavy-mineral concentrates collected in other parts of northern England and Scotland during the BGS mineral reconnaissance programme and other geochemical surveys (Fig. 1) have also failed to report the presence of high *REE* concentrations related to nodular monazite (e.g. Leake and Aucott, 1973; Coats *et al.*, 1982).

Outside Britain, monazite nodules have been found in the Ordovician, principally Llanvirn, and Dinantian shales of Brittany where they are dispersed in the rocks at a concentration of up to 0.2 g/kg (Donnot *et al.*, 1973). They have also been reported from shales and siltstones of Precambrian to Cretaceous age in Alaska, USA, Morocco, Madagascar, southern France, USSR and Gabon; in stanniferous placers from Siberia and Zaire; from monazite placers in Taiwan and uncertain sources in Spain, Niger, Bolivia, Canada, Pakistan, Thailand, Bangladesh and Peru (Overstreet, 1967; Matzko and Overstreet, 1977; Rosenblum and Mosier, 1983). It is probable that nodular monazite is even more widespread than this list suggests, for it is only detected easily by the mineralogical or chemical analysis of heavy-mineral concentrates.

Petrography

Monazite nodules from Wales are petrographically similar to those from south-west England and appear to be indistinguishable from those of Brittany, termed 'monazite grise' by Donnot *et al.*, 1973. Their petrography has been described in detail elsewhere (Donnot *et al.*, 1973; Cooper *et al.*, 1983; Read, 1983). In brief, the nodules are 0.05-2 mm in diameter, grey, ellipsoidal and metamict with an inclusion fabric of low-grade metamorphic minerals, principally quartz, albite feldspar, sericite and ripidolite (chlorite). They are quite distinct in physical and optical properties from igneous monazites (Table 2).

Composition

Monazite nodules from the Harlech Dome, Berwyn Done, central Wales and Exmoor were analysed by wavelength dispersive probe at University College London using synthetic *REE* glass standards for calibration (Read, 1983). Inclusions within nodules from central Wales were analysed

TABLE 2.

Comparison of the Physical and Optical Properties of Monazite Nodules with those of Crystalline Igneous Monazite

	Nodular Monazite	Igneous Monazite
Colour	Grey to green-grey. Brown and opaque in thin section.	Yellow-brown. Yellow to colourless in thin section.
Form	Ellipsoidal, polycrystalline.	Monoclinic, euhedra common.
Cleavage	Very poorly defined.	Prominent {001}, moderate {001}.
Twinning	Radial sector	Twin plane {100} common, rare lamellar on {001}.
Extinction	Undulose.	Sharp, small extinction angle (2^{o}- 10^{o}) on longitudinal sections.
Birefringence	Low, obscured by colour.	High, upper third to lower fourth order.
Orientation	Length slow.	Length slow.
Interference Figure	Biaxial positive.	Biaxial positive.
Hardness	5	5
Density	Variable 4 to 4.6, depending on proportion of inclusions.	4.6 to 5.5.
Radioactivity	Very weak.	Often marked.

for major elements by energy dispersive probe. Analysis was performed by a Cambridge Scientific Instruments Microscan 5 operating at an accelerating potential of 20 kV and probe current 5×10^{-7} A. Counting time was 100 seconds; peak resolution and matrix corrections were made by the standard ZAF 4 program. Bulk analysis of monazite in stream sediments from central Wales was performed by inductively coupled plasma spectrometry at Kings College London (Walsh *et al.*, 1981; Read, 1983).

Comparison of nodular monazite analyses. Published *REE* analyses for monazites for a wide variety of parageneses are given in Table 3. Also listed is the mean *REE* composition of panned stream sediments from the Afon Gwesyn in central Wales estimated to contain approximately 400 000 nodules (Fig. 1; Read, 1983). As no other phase bearing appreciable *REE* is present in the samples, concentrations have been recalculated to $\Sigma REE = 100\%$ and are taken to be representative of monazite from the area.

There are no bulk analyses of monazite from Exmoor but microprobe data of individual grains proved to be compositionally indistinguishable from Welsh samples. Direct comparison with nodular monazites from Brittany and elsewhere is constrained by the extreme zonation recorded within the British monazites and the incompleteness of the analyses from other areas. From Table 3 it can be seen, however, that monazites from Wales and Brittany are broadly similar in bulk composition and that all nodular monazites are characterised by high levels of Eu and low concentrations of Th with respect to monazite from other sources. The highest Th content found in Wales was 1.7% (Read, 1983). Uranium was not detected in Welsh nodules though Rosenblum and Mosier (1983) report 28 ppm and 260 ppm U in monazite from Alaska and Taiwan respectively.

Inclusions in monazite grains. Inclusions are ubiquitous within the British monazite nodules but are mostly microlitic and inseparable from the main grain mass. Electron microprobe analyses were performed, however, on larger chlorite inclusions within nodules from the Afon Gwesyn catchment in central Wales (Fig. 1) and compared with analyses of chlorite in the host rocks. A summary of eleven inclusion analyses, corresponding to an Fe-rich ripidolite composition (Deer *et al.*, 1962), is given in Table 4 from which it can be seen that major elements show very limited variation (< 12% relative standard deviation) about their mean. The results cannot be distinguished from analyses of chlorite laths in the enclosing rocks (Table 4).

Zonation of REE *within individual nodules.* Monazite nodules from both Wales and Exmoor

TABLE 3

The REE composition of nodular monazites and monazites from igneous rocks (ΣREE recalculated to 100%)

%	Nodules			Igneous rocks (Fleischer & Altschuler, 1969)					
	Central Wales[1]	Brittany (Donnot et al., 1973)	Average 'dark' monazite[3]	Granitic pegmatites		Granitic rocks		Alkalic rocks and Carbonatites	
				Mean	Range	Mean	Range	Mean	Range
La	20.9	15.60	19.03	20.5	8.6-31.7	23.9	11.9-34.7	31.3	19.3-40.8
Ce	45.8	43.39	45.03	44.1	34.0-55.3	46.5	35.1-53.9	51.2	43.9-58.2
Pr	6.2	5.80	5.44	5.7	1.8-8.4	5.4	1.4-11.5	4.3	2.0-6.8
Nd	20.8	24.84	23.87	20.0	12.7-33.2	18.2	9.0-31.3	11.2	6.6-18.6
Sm	3.30	5.37	3.92	5.1	0-16.3	3.1	0-6.6	0.7	0-3.0
Eu	0.66	0.93	0.61	0.1	0-0.5	< 0.1	0-0.5	<0.1	0-0.2
Gd	1.59	4.07	2.10	3.8	0-8.5	1.9	0-5.1	0.3	0-2.2
Tb	N.A.	N.A.	N.A.	0.1	0-0.4	< 0.1	0-0.7	-	-
Dy	0.49	N.A.	N.A.	0.2	0-3.5	0.7	0-2.7	0.4	0-5.4
Ho	0.07	N.A.	N.A.	< 0.1	0-0.9	< 0.1	0-0.7	< 0.1	0-0.9
Er	0.12	N.A.	N.A.	0.1	0-2.4	0.1	0-1.3	0.4	0-3.7
Tm	N.A.	N.A.	N.A.	< 0.1	0-0.3	< 0.1	0-0.6	<0.1	0-1.6
Yb	0.03	N.A.	N.A.	0.1	0-3.0	< 0.1	0-1.1	0.2	0-1.7
Lu	<0.01	N.A.	N.A.	< 0.1	0-0.1	< 0.1	0-0.1	-	-
Th	≤1.0	< 0.05	0.81	≥5.5[2]		-	-	-	-

N.A.: Not analysed

- : No data available

[1]REE by ICP, Th by wavelength dispersive probe

[2]Matzko and Overstreet (1977)

[3]Weighted average of 31 analyses of 'dark' (nodular) monazite from eight countries (Rosenblum and Mosier, 1983).

TABLE 4.

The composition of chlorite inclusions in monazite nodules and of chlorite grains in rocks from the Afon Gwesyn catchment

	Chlorite inclusions (n=11)				Chlorite grains in rock (n=11)			
Oxide	Mean	Median	Maximum	Minimum	Mean	Median	Maximum	Minimum
SiO_2	23.9	23.9	25.2	22.8	23.3	23.2	23.8	23.0
Al_2O_3	23.7	23.8	24.4	23.1	23.8	23.6	24.3	23.2
Fe_2O_3	31.1	31.2	32.7	28.6	32.7	32.5	33.8	31.5
MgO	6.9	6.5	9.1	6.0	7.6	7.7	8.2	7.0
CaO	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Na_2O	0.1	<0.1	0.4	<0.1	0.1	0.1	0.6	<0.1
K_2O	0.3	0.3	0.9	<0.1	0.1	<0.1	0.1	<0.1
TiO_2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
MnO	0.4	0.2	0.8	0.1	0.3	0.3	0.4	0.2
Total	86.6	86.6	87.8	85.5	88.0	88.1	89.4	86.9

display a pronounced zonation of light, intermediate and heavy *REE* and a strong differentiation between core and rim across single grains (Fig. 2). In the core, ratios normalised to shale (Piper, 1974) increase from La to a maximum at Sm before decreasing sharply to Dy. In contrast, the rims exhibit a monotonic decrease in normalised concentrations, except for Eu, from La to Dy. Both core and rim have shale-normalised negative Eu anomalies, though zonation between core and rim is still evident (Table 5). Element scans across a nodule (Fig. 3) give a symmetrical pattern from rim to rim with high La concentrations, approximately 20%, restricted to a narrow band (maximum 60 μm) around the perimeter of the grains. Ce concentrations show less variation than La but also decrease towards the core whereas Pr shows little differentiation. Nd and the heavier *REE* increase in concentration towards the core of the nodules (Fig. 3). Th levels show no consistent trend across grains (Table 5) and do not correlate with variations in the content of any rare earth element.

It is not known whether monazite nodules from elsewhere are zoned, though it appears probable as Matzko and Overstreet (1977) found a change in Ce/La ratio from core to margin in black, nodular monazite from Taiwan. The mean of five analyses of 'monazite grise' from Brittany (Donnot *et al.*, 1973), recalculated to $\Sigma REE = 100\%$ (Table 3), gives a regular, convex shale-normalised curve reaching a maximum at Sm (Fig. 2). The pattern is similar to that of the core in nodules from Wales and Exmoor.

Comparison with igneous monazites. Compilations of monazite analyses from a number of igneous rock types (Fleischer and Altschuler, 1969) are given in Table 3. Light *REE* concentrations in the nodules resemble monazite from granite pegmatites most closely, whereas intermediate and heavy *REE* values are closer to the mean of granitic rocks. Although showing negative anomalies on shale-normalised plots, the Eu content of nodules from both Wales and Brittany is higher than the upper limit of igneous monazite (0.5%) given by Fleischer and Altschuler (1969). *REE* concentrations in the Welsh and Breton nodules are dissimilar to monazite obtained from 23 alkalic rocks and carbonatites (Table 3). La and Ce are only 2% higher than the lower limit of the composition range whereas Nd, Sm and Eu are above the upper limit. According to Overstreet (1967), however, the low Th content shown by the nodules is typical of monazites from carbonatites and, in addition, to those from low-temperature veins and the lower grades of metamorphism. These features are discussed in the following section, concerned with the origin of nodular monazite.

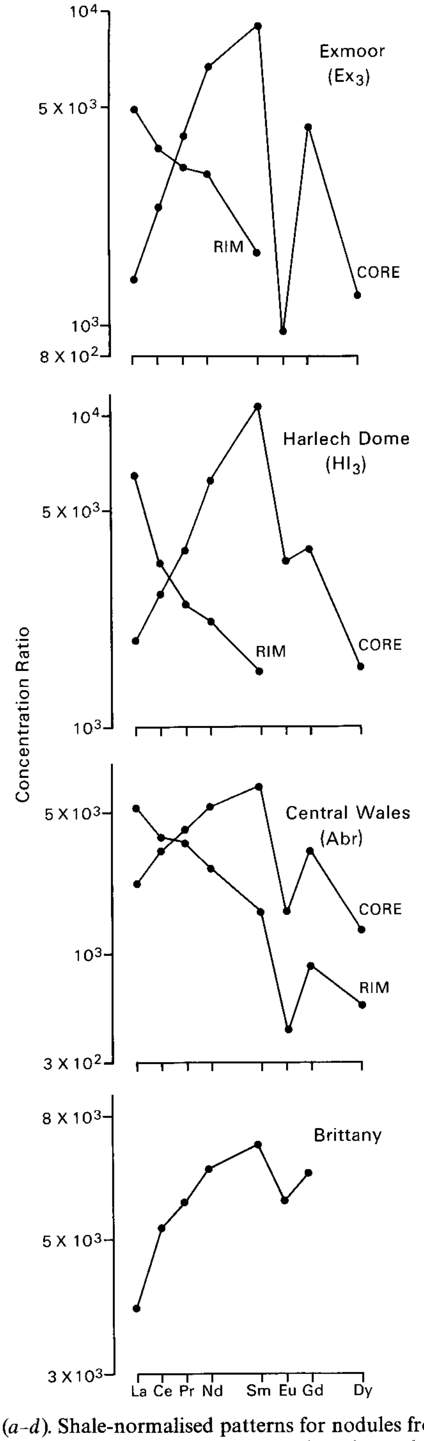

FIG. 2 (*a–d*). Shale-normalised patterns for nodules from Exmoor, the Harlech Dome and central Wales and for mean *REE* concentrations in monazite from Brittany (Donnot *et al.*, 1973).

TABLE 5. Microprobe analyses of Monazite Nodules from Central Wales (Ab), Harlech Dome (Hl) and Exmoor (Ex).

% Oxide	Abs_2 Core	Abs_2 Rim	Abs_3 Core	Abs_3 Rim	Abr $(105)_1$ Core	Abr $(105)_1$ Rim	Hl_3 Core	Hl_3 Rim	Hl_5 Core	Hl_5 Rim	Ex_3 Core	Ex_3 Rim	Ex_1 Core	Ex_1 Rim
La_2O_3	4.2	15.3	3.8	19.3	9.0	21.8	7.7	26.5	5.0	22.2	5.6	20.2	7.4	24.4
Ce_2O_3	19.6	36.5	20.5	30.7	26.8	30.7	22.0	28.1	18.4	30.8	19.6	30.5	24.6	28.4
Pr_2O_3	3.6	3.0	2.7	3.3	4.0	3.6	3.7	2.5	2.9	3.1	4.1	3.2	4.1	2.5
Nd_2O_3	28.5	13.1	27.8	10.7	20.0	9.8	23.8	8.2	24.0	10.9	25.4	11.3	22.8	8.4
Sm_2O_3	9.3	1.2	8.0	1.5	4.8	1.2	8.0	1.1	7.2	1.5	6.8	1.3	5.8	0.9
Eu_2O_3	1.40	0.20	0.98	<0.05	0.26	0.07	0.54	<0.05	<0.05	0.05	0.15	<0.05	<0.05	<0.05
Gd_2O_3	4.33	0.78	3.19	0.19	2.00	0.56	2.36	<0.05	1.94	0.64	2.8	0.07	1.87	<0.05
Dy_2O_3	0.56	0.27	0.3	<0.05	0.70	0.31	0.83	<0.05	0.95	0.34	0.67	<0.05	N.A	N.A
Er_2O_3	N.A	N.A	0.13	<0.10	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
ThO_2	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.21	1.30	0.35	1.22	0.60	0.21	0.72
P_2O_5	27.5	26.5	29.1	28.9	29.3	28.7	29.9	29.4	28.3	29.6	29.8	29.8	29.6	28.4
SiO_2	0.8	0.9	2.1	3.2	0.4	2.0	0.6	2.9	8.2	1.3	1.6	1.0	1.9	6.7
TOTAL	99.79	97.75	98.60	97.79	97.26	98.74	99.43	98.95	98.19	100.78	97.74	97.97	98.28	100.46

N.A. : Not analysed

Note : The identifiers 'r' and 's' refer to monazite separated from rock and stream sediment samples respectively. Subscripts refer to sample numbers of individual monazite grains (Read, 1983).

Origin of the nodules

Mechanism of nodule formation. Various models have been proposed for the formation of nodular monazite, including contact metamorphic processes (Overstreet, 1971; Rosenblum and Mosier, 1983), *REE* precipitation followed by sedimentary-metamorphic authigenesis (Donnot *et al.*, 1973) and weathering of detrital monazite combined with diagenetic nucleation of the derived *REE* into nodules (Matzko and Overstreet, 1977).

Occurrences of nodular monazite in Britain are most unlikely to be related to contact metamorphism. No contact metamorphic aureole or other evidence of plutonic intrusion is known in the vicinity of the Welsh Basin or Exmoor monazite deposits, whereas nodules are not recorded from areas containing similar Lower Palaeozoic sedimentary sequences, such as the Lake District and southern Scotland, which are baked by Caledonian intrusions.

Donnot *et al.* (1973) suggested that the nodules in Brittany were formed from a gelatinous phosphate precipitate via a hydrated light-*REE* enriched precursor, rhabdophane, during early diagenesis. This mechanism fails to explain several features of the nodules described here, notably (i) bulk chemical composition, the extent of *REE* enrichment and preferential light-*REE* fractionation required to produce monazite from sedimentary detritus; (ii) their occurrence in fine-grained sedimentary rocks containing 'average' levels of P and *REE* (Turekian and Wedepohl, 1961; Gromet *et al.*, 1984); (iii) *REE* zonation; (iv) the absence of any anomalous Ce behaviour, to be expected if the nodules are marine precipitates; (v) the limited grain size distribution; (vi) their wide stratigraphic distribution.

We believe the nodules to have formed by the *in situ* recrystallization and authigenic growth of detrital monazite, derived from the erosion and weathering of granitic rocks, during diagenesis and low-grade metamorphism. This would adequately explain most aspects of the *REE* concentration, light-*REE* fractionation, zonation and stratigraphic-geographic distribution. The monazite deriving from coarse-grained acid igneous rocks represents part of the light-*REE*-rich, heavy-*REE*-depleted residuum following crystallization of primary rock-forming silicates. The bulk *REE* composition of the monazite nodules (Table 3) corresponds closely to analyses of 104 pegmatitic monazites and 122 granitic monazites (Fleischer and Altschuler, 1969). Zonation may be attributed to one or more of the following: (i) inherited features; (ii) selective interaction with pore waters and precipitation during recrystallization and authigenic growth; (iii) post-recrystallization alteration. Which of these processes dominated is uncertain. There is no published account of *REE* zonation in monazite and little extant data on

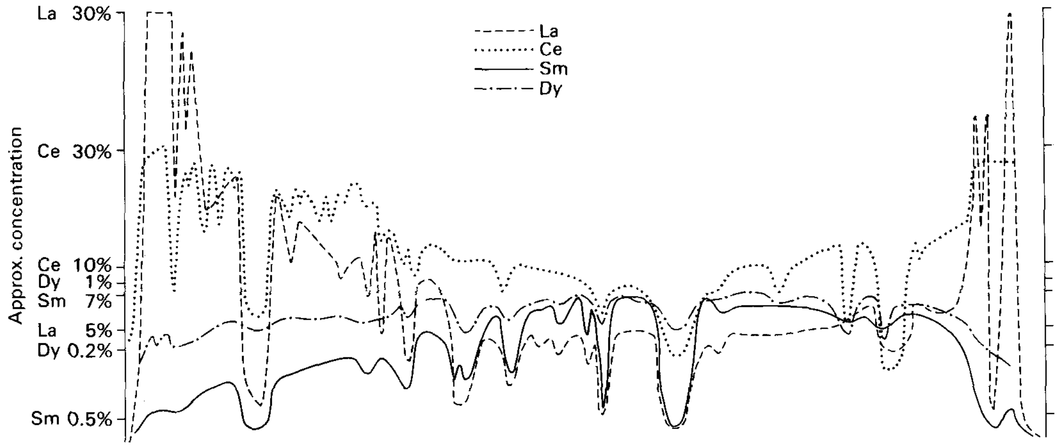

FIG. 3. *REE* zonation across a single monazite nodule (width 0.5 mm).

the solubility of *REE* phosphates. According to Kolthoff *et al.* (1969), $LaPO_4$ ($K_{sp} = 10^{-22.4}$) is slightly more soluble than $CePO_4$ ($K_{sp} = 10^{-22.8}$) and if this trend applies to the remaining elements the zonation pattern shown by the nodules could represent fractional recrystallization; the less-soluble heavy *REE* phosphates precipitating first in the core and Ce, followed by La crystallizing last at the margin.

This model does not readily account for: (i) the low Th content of the nodules with respect to igneous monazites; (ii) their high Eu content in comparison to monazite from granite pegmatite and granitic parageneses. A high Eu and low Th content appears to be a characteristic of nodular monazite. According to Matzko and Overstreet (1977) the Th content of monazite is temperature dependent. Grains crystallized in high-temperature veins, granites and, particularly, granite pegmatites contain Th levels in the region of 5% and on weathering Th is selectively removed from the monazites. We therefore suggest that either Th was lost from the British nodules during weathering and sedimentation processes or interchange of Th between the nodules and enclosing sediments accompanied recrystallization. Little is known of Eu behaviour in this context but it is suggested that the relatively high Eu content is also a product of the same process. Many nodules have pervasive boundaries with the rock matrix and high Eu and low Th concentrations in the monazite could be a low temperature phenomenon.

The absence of grains finer than 0.05 mm supports the contention that the nodules are of detrital origin. The presence of larger nodules may be explained by growth around a nucleus of detrital monazite during low-grade metamorphism provided sufficient phosphate was available. Evidence that this condition is satisfied, at least locally, is provided by the presence of a phosphatic bed of Caradocian age in the Berwyn Hills (Cave, 1965) and the occurrence of phosphatic concretions in the basinal facies mudstone and greywacke sandstone succession of central Wales (Cave, 1979). Such a mechanism would not require an additional source of *REE* and would account for the inclusion of metamorphic constituents within the nodule form. Significantly perhaps, some of the highest Ce levels in heavy-mineral concentrates from Wales are found in catchments containing rocks of Upper Ordovician age.

The metamorphic grade required to induce recrystallization of monazite may be estimated from experimental studies on monazite synthesis (Anthony, 1957; Carron *et al.*, 1958; Donnot *et al.*, 1973). Carron *et al.* (1958) obtained anhydrous phosphates of the *REE* at temperatures of 105 °C and 90 atmospheres pressure whereas Donnot *et al.* (1973) report the synthesis of hydrated $CePO_4$ at temperatures below 100 °C and atmospheric pressure. From a study of carbon graphitization Donnot *et al.* (1973) proposed a maximum temperature of 250 to 300 °C for the Llanvirn shales of Brittany. More recent work based on illite crystallinity and metabasite mineral assemblages suggests at least prehnite–pumpellyite and that, in parts, greenschist facies conditions of burial metamorphism were attained in the rocks of the Central Welsh Basin (Bevins and Rowbotham, 1983; R. E. Bevins, pers. comm.). The temperature and pressure at the onset of greenschist facies, in the range 320–360 °C, depending upon pressure (Liou *et al.*, 1985), are quite sufficient, on the basis of the experimental evidence above, to promote recrystallization of monazite.

Source of the monazite-bearing sediments. The apparent restriction of monazite nodules in Britain to Lower Palaeozoic sedimentary rocks of the Welsh Basin and a few horizons within the Variscan sedimentary succession of south-west England suggests that the source rocks exerted an influence on nodule formation or that peculiar physico-chemical conditions existed in the Welsh Basin for long periods during the Lower Palaeozoic. If, as we have suggested, the host rocks exerted control, the occurrence of nodular monazite might be a useful palaeogeographic indicator and comparison with other lines of evidence suggests that this is so.

Although in Cambrian to early Ordovician times land may have existed between Cornubia and south-west France (Renouf, 1974) and the coarse clastic sequences of the Welsh Basin are believed to have come in part from a landmass in what is now the South Wales–Bristol Channel area (Woollands, 1970; Holroyd, 1978), palaeontological evidence is suggestive of a common province between the Welsh Basin and Armorica (e.g. Whittington and Hughes, 1972). The presence of 'monazite grise' in both areas lends support to this, indicating that both the Welsh and Armorican sediments had access to the same source and were deposited under similar conditions.

The pattern of Ce distribution in heavy mineral concentrates from the Harlech Dome and Berwyn Hills indicates either a change of sediment source, or progressive denudation exposing monazite-bearing source rocks during Upper Cambrian to Lower Ordovician times. These conditions then persisted, at least intermittently, through the remainder of the Ordovician and much of the Silurian. According to Crimes (1970), much of the Lower to Middle Cambrian material had a north-westerly source whereas the Upper Cambrian sediments of North Wales were derived from a southerly direction in common with those of Ordovician and Silurian age (e.g. Cummins, 1969).

The occurrence of monazite nodules in streams draining the Ilfracombe Beds of north Devon may be explained if the latter are derived from the weathering of Lower Palaeozoic sedimentary rocks of Wales (Freshney and Taylor, 1980). The apparent lack of nodules in other north Devon rocks suggests that the Ilfracombe Beds formed under distinct palaeogeographic conditions and that no Bristol Channel landmass existed at the time of their deposition. In Brittany, Donnot *et al.* (1973) report the presence of monazite nodules in Dinantian rocks and the possibility exists that these may also be polycyclic.

The presence of monazite-bearing rocks in Snowdonia and their absence on Anglesey supports the contention of Nutt and Smith (1981) that the depositional environment of Ordovician sediments on Anglesey was quite distinct from that of the Anglo-French province. This implies that either Anglesey was not in its present position with respect to mainland Wales in Ordovician times (Nutt and Smith, 1981) or that a topographical high separated the Anglo-French province from the area in which the Ordovician sediments of Anglesey were deposited (e.g. Reedman *et al.*, 1984; Woodcock, 1984).

Conclusions

Monazite nodules from the Palaeozoic sedimentary rocks of central Wales, North Wales and Exmoor are petrographically and compositionally indistinguishable. They exhibit several characteristic features, principally strong zonation of light and heavy *REE*, a low concentration of Th and high concentration of Eu compared with igneous monazite, a uniform grain size and a low-grade metamorphic inclusion fabric indicative of *in situ* formation. As far as can be judged from published information, nodules from Brittany show the same features. *REE* compositions are similar to those quoted for monazites from granite pegmatites and granites but differ substantially from monazites of alkalic rocks and carbonatites. These similarities strongly suggest that the nodules from Wales, Brittany and south-west England have a common or similar origin and that the original *REE* source was igneous monazite from granitic rocks. The inclusion fabric, low Th content and zonation pattern are products of recrystallization and authigenic growth in response to low-grade burial metamorphism. The Upper Palaeozoic nodules are believed to be polycyclic.

Acknowledgements

I. C. Young is thanked for his help with the electron microprobe analyses and J. N. Walsh and J. Barker for providing access to the ICP facilities at King's College London. I. Basham, D. Bernard, J. Bowles, D. Briggs and D. Morgan aided mineralogical aspects of the work. R. C. Jones kindly provided details of Ce concentrations in panned stream sediments from south-west England and D. Bland analysed the samples collected in the Lake District. Other panned concentrates were analysed by T. K. Smith. We would like to thank R. Bevins of the National Museum of Wales for his help and advice. Some of this work was undertaken during the tenure of a NERC CASE studentship award held by D. Read. This paper is published by permission of the Director, British Geological Survey (NERC).

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[*Manuscript received 22 November 1985; revised 3 June 1986*]