# In situ growth of monazite in anchizonal to epizonal mudrocks: first record from the Variscan accretionary prism of the Kaczawa Mountains, West Sudetes, SW Poland

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Abstract We report the first occurrence of diagenetic or low grade metamorphic monazite from the Palaeozoic mudrock successions of the Kaczawa Complex of the West Sudetes, Poland. Where observed in relation to the enclosing mudrock, this monazite comprises tiny irregular grains, less than 20 microns in diameter, intergrown with the surrounding matrix minerals. This monazite resembles previously described examples of diagenetic monazite from elsewhere in the world in mostly possessing low contents of Th and U but differs in forming much smaller grains, which show only slight zonation of rare earth elements (REEs). Some of the monazite grains studied also appear to have formed synchronously with the cleavage, perhaps a function of early deformation and fluid release in an accretionary prism environment. Relatively Th-rich cores, and an association with altered detrital biotite in some instances, suggests that at least some of the *in situ* monazite growth might have taken place as overgrowths on primary detrital monazite particles.

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## INTRODUCTION

Monazite, a rare-earth element phosphate, (REE) PO<sub>4</sub>, is a common accessory mineral, and one of the major lanthanide-bearing minerals, often containing considerable amounts of thorium and uranium. Though typically found in small amounts, it is widespread, and best known from acid igneous and high grade metamorphic rocks and as detrital grains in sedimentary rocks; however, it is easily overlooked under the microscope because of its general optical similarity to the more common zircon. Recently, monazite has attracted increasing interest because it is: (a) an important tracer of REE, Th and U behaviour and distribution in rocks; and (b) widely applicable as a geochronometer, both for radiometric dating and for "chemical" dating methods based on analysis of Th, U and Pb isotopic ratios or elemental concentrations in the mineral (e.g. Suzuki & Adachi, 1994; Montel et al., 1996).

Among the most intriguing and newly described aspects of monazite is its presence in sedimentary- to lowgrade metamorphic rocks where the mineral may appear not simply as an older detrital component, but as an authigenic or low-grade metamorphic phase. The formation of authigenic monazites indicates that widespread mobilization and redistribution of REEs in diagenetic and very low-grade metamorphic environments, i.e. in settings where these elements had, until recently, been assumed to be effectively immobile (Milodowski & Zalasiewicz, 1991; Evans & Zalasiewicz, 1996).

In this paper, we report on the first discovery of monazite in low-grade mudrocks in the Palaeozoic successions of the Kaczawa Complex in the West Sudetes. This complex is interpreted to comprise fragments of a Variscan accretionary prism, and it offers a unique research object for the investigation of sedimentary, diagenetic and very lowgrade metamorphic processes and associated deformation, and for their comparison with those described in recent accretionary wedges (Collins *et al.* 2000, and refs. therein). The monazite we recorded differs significantly from the typical low-temperature monazite recorded from elsewhere around the world, and so may be an important "witness" of processes in the distinctive accretionary environment.

# LOW TEMPERATURE MONAZITE: A BRIEF OVERVIEW OF COMPARATIVE MATERIAL FROM WALES AND ELSEWHERE

Monazite is most typically a high-temperature mineral of igneous and high-grade metamorphic origin. However, since the 1970s, there have been persistent accounts of the occurrence of enigmatic, inclusion-rich, "grey monazite". This was most commonly found as placer deposits, and consequently, the context of its geological origin was not preserved.

Large numbers of such grey monazites were recovered from heavy mineral concentrates of stream sediment samples in Wales during regional geochemical mapping by the British Geological Survey. Areas where abundant grey monazite was found coincided with marked regional cerium anomalies. Detailed petrographical investigations showed that they closely resembled the grey monazite reported widely from elsewhere in the world, including from Brittany, Belgium, Spain, Siberia, Taiwan, the USA and several African countries (e.g. Matzko & Overstreet, 1977; Rosenblum & Mosier, 1983); that is, they were around a millimetre in diameter, contained numerous inclusions of quartz, chlorite and illite, showed a marked chemical zonation (with heavy rare earth elements, HREEs, concentrated in the cores, and light rare earth elements, LREEs, in the rims) and were Th-poor by comparison with typical monazites. The Welsh Basin monazites may be taken as exemplary of this widespread but cryptic form of low-temperature monazite and, since they have been studied in the most detail (see below), they were employed for comparison in this study.

The grey monazites from Wales were originally interpreted as altered igneous monazites (Read *et al.*, 1987). However, grey monazites were subsequently discovered hosted in cleaved mudrocks in central Wales (Milodowski & Zalasiewicz, 1991) in the course of regional geological mapping (Davies *et al.*, 1997), and their relationship to the host rock necessitated a revised interpretation. They were found to be markedly concentrated in organic-rich, laminated hemipelagite ("graptolite shale") layers sandwiched in between mud-dominated turbidite depositional units. These hemipelagite units were found to have an up to tenfold enrichment in LREEs compared with average shale, whereas the intervening turbidite mudrock layers were found to be correspondingly depleted in LREEs (Fig. 1).



Fig. 1. Welsh "grey monazites": distribution of monazite nodules within a turbidite sequence, BSE images of nodules and examples of REE patterns (after Milodowski & Zalasiewicz, 1991) for a turbidite mudstone (LREE depleted) and a laminated hemipelagite (LREE enriched).



Fig. 2. Geological sketch of the Kaczawa Mountains and sample location (based on Kryza & Muszyński, 2003, and Collins *et al.*, 2000). Inset map shows the location of the study area in the Variscan Belt of Europe: AF – Alpine Front, AM – Armorican Massif, BM – Bohemian Massif, MC – Massif Central, VF – Variscan Front.

It was thus clear that the Welsh monazites were authigenic in origin and had grown as a result of REEs being mobilized from their original location in the turbidite muds (where they would have been loosely bound to clay minerals and iron hydroxides), transported, fractionated and redeposited in the organic-rich hemipelagic layers. The precise timing of this growth is poorly constrained texturally, although their formation preceded the maximum burial compaction of the mudrocks and occurred prior to the regional cleavage-forming (Acadian) event, as the nodules preserve a relatively uncompacted fabric of included detrital grains and the cleavage fabric is disrupted around the resistant monazite bodies (Milodowski & Zalasiewicz, 1991).

These Welsh monazites, albeit containing low amounts of thorium and uranium, have been dated radiometrically (Evans & Zalasiewicz, 1996; Evans *et al.*, 2002); the ages obtained are consistent with growth post-sedimentation and pre-cleavage formation, and are similar to whole-rock Rb-Sr dates obtained from the same mudrocks, interpreted to reflect the smectite-illite transition at around 2 km burial depth (Evans, 1996), while the REE distribution might also be linked to hydrocarbon expulsion (Evans *et al.*, 2002).

Such authigenic "grey monazite" is abundant across large parts of the Welsh Basin, but a key remaining problem regarding its origin is its highly irregular distribution temporally and geographically. Rocks of comparable age and generally similar facies and grade occur across, for example, northern England and Scotland, but similar monazites seem to be absent from those rocks (Read *et al.*, 1987) though they are common, for instance, in early Palaeozoic strata in Belgium (Burnotte *et al.*, 1989). Authigenic monazite also seems, to the best of current knowledge, to be rare in strata of post-Palaeozoic age. Thus, these new records of low-temperature monazite in the Sudetes may help provide clues to the factors that encourage or hinder monazite growth in mudrocks at low temperatures.

## MONAZITE FINDINGS IN THE KACZAWA COMPLEX: GEOLOGICAL CONTEXT

The Kaczawa Complex (Fig. 2) is composed of lowgrade metamorphic rocks (up to blueschist and greenschist facies) of sedimentary and volcanic origin, which range in protolith age from possible Cambrian to Early Carboniferous. The age of many parts of the succession remains uncertain due to the scarcity or lack of biostratigraphic or other geochronological evidence (Fig. 3). The primary features (often well-preserved) of the rocks, including their overall lithological characteristics, sedimentary and volcanic textures and structures, geochemical composition, together with available age constraints (e.g. Silurian graptolites, and conodont assemblages of Ordovician, Devonian and Early Carboniferous age) allow a general scenario of crustal evolution to be deciphered. This comprises an early, pre-orogenic (pre-Variscan) interval, starting with initial rifting of continental crust in the Cambrian?-Ordovician. This led to a more mature basin, developed on oceanic crust in the Silurian-Devonian. Ocean closure and accretion occurred in later (including early-orogenic) phases of the development of the Kaczawa Complex. Lithological variations and inter-relationships (e.g. the presence of oceanic trench-type deposits), the character of the lithostra-



**Fig. 3.** Generalized lithostratigraphic log of the Kaczawa Complex (after Kryza & Muszyński, in Furnes *et al.*, 1994, modified). The shell symbol indicates biostratigraphic evidence.

tigraphic units (thrust sheets with fragments of stratigraphic succession and mélange bodies), and the type of and variation in metamorphism (including blueschist facies rocks) all suggest that the Kaczawa Complex comprises fragments of a Variscan accretionary prism (Baranowski *et al.*, 1987, 1990, 1998; Haydukiewicz, 1987; Kryza & Muszyński, 1992; Furnes *et al.*, 1994). This model has been supported by more recent studies and generally adopted in several recent tectonic models, most of which interpret the Kaczawa Complex as a stack of WNWdirected thrust units (Kryza & Muszyński, 2003, and references therein).

Within the Kaczawa Complex, there are distinctive mélanges interpreted as products of continuous/overlapping sedimentary and tectonic processes which left sets of structures comparable with those recorded from recent accretionary wedges. These structures suggest tectonic deformation of still poorly-consolidated rocks with high rates of fluid throughput (Collins *et al.* 2000), conditions which may have influenced or controlled the redistribution of REE, together with Th and U, as indicated by the newly discovered monazite mineralization.

Two sites in the southern part of the Kaczawa Mountains were selected for reconnaissance investigations of heavy minerals in alluvial deposits. "Grey monazite" was not detected in any of the samples (superficially similar, regular, ball-shaped opaque nodules resembling such monazites were found, but EDS spectra showed these structures to be composed of metallic Fe or Fe oxides, most probably representing airborne industrial dust: Tyszka, 2003).

Monazite was found, though, in the host rocks, in seven specimens of metapelites: five in the northern part and two in the southern part of the Kaczawa Mountains.

Here, we present preliminary descriptions, analytical results and interpretations. More detailed studies of these phenomena are in progress, aimed at constraining the timing of, and the processes controlling the monazite growth, and establishing their implications for helping to determine the evolution of the Variscan accretionary prism.

## **METHODS**

Monazite was identified and petrographically characterized either in polished thin sections or in polished heavy mineral grain-concentrates. It was detected and observed by back-scattered electron microscopy (BSEM) and its identity was confirmed by energy-dispersive spectra (EDS). This work was carried out in: the Department of Mineralogy and Petrology, Wrocław University, Poland; Department of Geology, University of Leicester, UK; Department of Earth Sciences, Oxford University, U.K; and at the British Geological Survey (BGS), Nottingham, U.K.

Quantitative microprobe analyses of the monazites were performed in Oxford (samples 35/S 582.0, 35/S 703.4 and 35/S 915.2), and in Wrocław (samples ZL1e, JA2, and WO1c). Instrumentation and selected analytical conditions: Oxford – JEOL JXA-8800R, 15 kV, 80 nA, standards: synthetic UO<sub>2</sub>, ThP<sub>2</sub>O<sub>7</sub>, REE phosphates (Smithsonian Institution), natural PbS (galena), peak overlap correction for U and Pb, ZAF correction; Wrocław – CAM-BRIDGE Microscan9, 15 kV, 80 nA, standards: synthetic  $UO_2$ , ThP<sub>2</sub>O<sub>7</sub>, REE phosphates (Smithsonian Institution), natural crocoite PbCrO<sub>4</sub>, peak overlap correction for U and Pb, ZAF correction. BSEM observations at the BGS were carried out using a LEO 435VP Variable Pressure SEM instrument. This enabled observations to be made on uncoated samples, thereby allowing observation of relationships with any possible carbon (organic) components.

## SITE AND SAMPLE DESCRIPTION

## STANISŁAWÓW BOREHOLE CORES

The monazite-bearing specimens come from core samples from borehole 35/S, penetrating the "metamudstonediabase association" (Baranowski *et al.*, 1998) of the Chełmiec Unit in the northern part of the Kaczawa Complex (Fig. 2).

#### Sample 38/S (487.3 m) = 4a

This core sample is of a laminated mudrock, with laminae ranging from < 1 mm to 10 mm thick, and comprising paler, quartz-rich and darker, clay-rich material. The grain size is around 0.02 mm but the illite-chlorite stacks in the clay-rich laminae reach 0.1 mm in diameter. A ThO<sub>2</sub> phase (rutile?), and pyrite and monazite were found as accessories. The rock possesses a distinct, bedding sub-parallel foliation defined by mica and chlorite alignment, and a highangle crenulation cleavage which separates domains of variable thickness (usually 1–5 mm).

Monazite is quite frequent, as small grains 5–20 microns in size. These are irregular, often with small 'amoeboidal' outgrowths (Fig. 4a). Some of the elongated monazite grains are clearly cleavage-parallel (Fig. 4b). The morphology and textural position of the monazite in this sample demonstrates the authigenic to, perhaps, partly tectonically controlled origin of this mineral in the mudrock.

#### Sample 35/S (582.0 m)

This core section consists of laminated green slate. The primary, apparently horizontal bedding is well preserved. Paler laminae, 0.1–5.0 mm thick, are composed of very fine-grained quartz and calcite aggregates (locally with mylonitic texture) and chaotically distributed Fe-Mg and K micas 10–20 microns across (no XRD data on these micas are yet available); accessory minerals are represented by apatite and framboidal pyrite 5–10 microns in diameter. These layers alternate with darker laminae, which mainly contain Fe-Mg and K micas. There is a distinct cleavage at 45 degrees to the lamination, which is more conspicuous within the darker laminae, where it is defined by spaced planes along which mica particles have been reoriented.

Monazite only occurs in the darker laminae, where it is one of the most abundant accessory minerals; it is accompanied by framboidal pyrite, rutile(?) and apatite, and all of these phases form grains 5–10 microns across. Monazite occurs as irregular clusters or as elongated grains parallel to the cleavage.

#### Sample 35/S (703.4 m)

This core section comprises laminated dark grey slate. The overall texture of this rock reflects strong folding and shearing of the primary rock. Paler laminae are 2–5 mm





Fig. 4. BSE images of monazite in laminated metamudrock; (a) amoeboidal authigenic grain; (b) elongated cleavage-parallel monazite grain. Stanisławów, sample 38/S-487.3 m (4a). Mnz – monazite, Chl – chlorite, Mc – mica, Qtz – quartz.

thick and mainly composed of recrystallized quartz and white mica, with some of the laminae containing significant quantities of framboidal pyrite. The darker laminae are 0.2–2.0 mm thick and very fine-grained, with white mica prevailing over quartz. A tectonic cleavage is clearly expressed in the darker layers, by local alignment of the micas into spaced cleavage planes, with strain fringes around some pyrite grains. Two generations of mineral veins, 0.5–3.0 mm thick, occur in the rock, of quartz (older, syn-cleavage) and carbonates (younger, postcleavage); the latter comprise thicker ankerite veins, with some grains of chalcopyrite and zinc sulphides, and thinner, brownish siderite veins.

Monazite mainly occurs within the darker laminae, where it is associated with pyrite, apatite and rutile, and in the ankerite-rich veins. It forms irregular grains up to 10 microns in diameter, or occurs as intergrowths with quartz and white mica. Some of the larger monazite grains are zoned with a core and a rim showing ~1% and ~0.5% ThO<sub>2</sub>, respectively (Table 1).

#### Sample 35/S (915.2 m)

This sample is of a greenish fine- to medium grained, distinctly foliated sandstone, with the foliation appearing as aligned, bedding-parallel, 1–4 mm thick lenses of wellcrystallized quartz aggregates. The greenish matrix is built mainly of white mica, mostly oriented parallel to the foliation. In thin section, planes relating to a second, crenulation cleavage are visible, along which mica flakes have been re-oriented or folded. Carbonate aggregates are randomly distributed throughout this sample.

The monazite in this sample was detected only in a polished thin section of a heavy mineral separate. It is present in very small amounts (less than 1% of total heavy mineral grains) and not as well-formed separate grains but rather as complex intergrowths with other phases such as quartz and mica. Most commonly, monazite appears as tiny inclusions within a dark mica-like phase resembling altered biotite (Fig. 5). One quantitative WDS analysis of this monazite indicates a very low Th content (0.18 wt % ThO2). This chemical feature and the textural context suggest *in situ* growth/recrystallization of the monazite.

#### SURFACE EXPOSURES

Locality ZL1 is an exposure of mélange on the east side of road between Złotoryja and the Wilków basalt quarry (Fig. 2). The mélange (protolith age unknown: Devonian-Carboniferous?) comprises a weakly metamorphosed, variously laminated/bedded grey mudrock, with thin beds and aligned lenses, up to 20 cm thick, of more massive sandstone.

The deposit sampled comes from a strongly aligned sandstone lens c. 5 cm thick. Cut, the rock shows a brecciated texture, with the dominant pale grey, massive, finegrained sandstone being irregularly disrupted into fragments 0.1–3.0 cm across, separated by an irregular network of darker-coloured veinlets up to 5 mm thick.

In thin section, the sandstone is composed of quartz and feldspar grains, 0.1–0.5 mm across, and subordinate, al-

tered, pale to brownish mica, dispersed in a very finegrained (c. 0.01 mm diameter) quartz-rich matrix. Frequent open pores represent the removal of leached primary grains, perhaps of sulphide or carbonate. The irregular veinlets are mostly composed of well-recrystallized quartz, but they pass into veins filled with fine-grained material similar to that in the sandstone matrix. They probably represent mud injection followed by quartz recrystallization within a primary greywacke.

The monazite occurred as a few grains (c. 0.5% of the total number of heavy mineral grains) in heavy concentrates dominated by rutile, apatite, altered biotite and haematite. The monazite grains were rather regular, elongated and oval in shape, and mostly fringed by altered biotite. The grain cores are richer in Th and poorer in LREE compared with their rims (Table 1, analyses JAC-c = core, and JAY-r = rim).

Our observations are from a heavy mineral concentrate only, and so provide little information concerning the textural position of the monazite in this rock. Thus, we cannot provide an unequivocal interpretion of the origin of the monazite; however, the morphology and relatively Th-rich cores suggest a detrital derivation of this mineral, with the Th-poor rims suggesting an *in situ* overgrowth.

Locality JA is in Janówek, in an abandoned quarry on the north side of road, c. 600 m west of the major crossroads in the village, located within the outcrop of the Janówek mélange (Devonian–Carboniferous?; Haydukiewicz, 1987). In the quarry, the rocks are mostly homogeneous dark bluish-grey slates, with the lamination expressed as 0.5–5 cm-scale alternations of more and less massive layers, with strongly aligned lensoid bands. A distinct lineation appears as elongated wrinkles on the foliation surfaces. Cut sections show the rock to be strongly sheared, with disrupted and strongly foliated thin laminae of pale to dark grey muddy material and lensoid quartz segregations. Brecciated domains and S-C structures are common.

In thin section, the rock shows a chaotic texture reflecting intense shearing and brecciation of a probably inhomogeneous, primary, mud-dominated deposit. The darker laminae comprise very fine-grained and strongly foliated aggregates of white mica interpenetrated by a dark substance. Paler laminae and chaotic domains are greatly variegated as regards grain size, ranging from 0.001 mm to c. 2 mm in diameter within strongly recrystallized quartz lenses. The very dark (carbonaceous?) material is very irregularly distributed, in accordance with the chaotic appearance of the rock.

Monazite was found as a major constituent of the heavy mineral fraction obtained from this sample, reaching a content of c. 10% of the heavy mineral grain content. It is mainly associated with altered biotite, rutile and apatite. The monazite forms weakly rounded grains c. 10–20 microns in diameter, locally fringed by altered dark mica.

The monazite grain cores are relatively Th-rich (up to c.  $3 \text{ wt. }\% \text{ ThO}_2$ ); whereas the Th content in the rims is significantly lower, possibly indicating authigenic overgrowths on inherited monazite cores (Fig. 6 and Table 1).

Locality WO1 in Wojcieszów Dolny, is an exposure in a stream bed, c. 250 m east of the church. The exposure is

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Fig. 5. Textural and chemical features of monazite-mica-quartz intergrowth from fine-grained foliated sandstone: (a) BSE image, (b) EDS spectrum of mica, (c) EDS spectrum of monazite, (d-h) X-ray distribution maps of Al, K, Si, P and total REE. Stanisławów, sample 35/S-915.2 m.

located in the central part of a large outcrop of (Ordovician?) "grey metamudstones" intruded by small diabase sills.

The dark grey to black slates are generally homogeneous, very fine-grained, strongly foliated rocks, with a lineation expressed as delicate wrinkles on the foliation surface. Cut, the rock shows subtle laminae, 0.5–3.0 mm thick, of paler and darker material, some with pyrite crystals.

In thin section, the laminae show different proportions of relatively coarser and relatively finer (quartz- and mica-rich) material. The grain size as a whole is mostly below 0.02 mm. The white mica streaks are locally rustcoloured and associated with dispersed blackish (carbonrich?) material. The original rock was, most probably, a fine-grained cherty mudrock that underwent strong deformation to produce a mylonite-like texture.

Monazite was found only in the heavy mineral fraction obtained from this rock, in which it reaches a content of c. 5% of the heavy mineral grain content. Apart from monazite, the heavy fraction is dominated by pyrite, altered biotite, apatite and haematite. The monazite grains have a mostly irregular, xenomorphic shape, and quite often are intergrown with altered mica.

The chemical features are similar to those described in the previous sample. Some analyses display low but significant amounts of uranium (up to  $0.14 \text{ wt. }\% \text{ UO}_2$ ; Table 1),



Fig. 6. EDS spectra of monazite from the Janówek mélange: (a) grain core, (b) grain rim. Sample JA1.

but the EDS spectra often show very low Th, thus suggesting low-temperature recrystallization of the mineral.

## CHEMICAL COMPOSITION OF MONAZITES

Representative microprobe analyses are given in Table 1 and selected chemical characteristics are shown in Figures 7–9. The ThO<sub>2</sub> concentrations vary between 0 and 3.5 wt. %, and the UO<sub>2</sub> contents are mostly below 0.1 wt. %. Consequently, PbO, as a radiogenic product, is also very low, not exceeding 0.06 wt. % (Fig. 8). As expected, the PbO concentrations are clearly positively correlated with ThO<sub>2</sub> and, less evidently, with UO<sub>2</sub> (Fig. 7).

As mentioned above, larger monazite grains are

wt. % ThO<sub>2</sub>, Table 1). However, most of the grains have very low Th contents, often below 1 wt. % ThO<sub>2</sub>. Light REE are strongly fractionated (Fig. 9), from La

to Gd (c. 0.2–0.7 x "North American Shale Composite, NASC, value of Gromet *et al.*, 1984), compared with heavy REE. By contrast, heavy REE, from Tb to Lu, display a stronger variation, oscillating broadly around 0.01–0.2 x NASC value.

zoned, with higher  $ThO_2$  contents in the cores (up to c. 3.5

## DISCUSSION AND CONCLUSIONS

The shape and textural relationships of the tiny monazite grains in the Kaczawa Complex mudrocks and their generally very low contents of U and Th indicate a substantial component of *in situ* growth, in part, seemingly, as overgrowths on cores of detrital monazite. In most samples, the monazite was found in heavy-mineral separates; thus, its exact contextual (fabric) relationships within the host rock is unknown. However, in specimen 38/S, some of the monazite shows a highly irregular outline typical of *in situ* growth, while other grains are evidently controlled by a first-generation cleavage defined by remobilized clay/mica and a dark substance which is either iron oxides or organic matter (Fig. 4). This strongly suggests that the processes of early deformation and cleavage formation could have induced REE, Th and U mobilization and reprecipitation. These elements were probably originally sourced largely from clay minerals, iron-manganese oxyhydroxides and unstable volcanogenic minerals (cf. Milodowski & Zalasiewicz, 1991, p. 119 and references therein), with mobilization during fluid transport associated with diagenesis and deformation.

The microprobe results confirm that the monazite grains in all the Kaczawa samples are Th-poor, with very low U and Pb contents. By contrast, typical igneous and high grade metamorphic monazites have Th and U contents of more than 3 and 0.5 wt. % oxide, respectively (e.g. Suzuki & Adachi, 1994; Montel *et al.*, 1996). The grains are mostly chemically homogeneous, though usually with cores slightly richer in Th (Fig. 6a & b). These features support a model of predominantly *in situ* growth of monazite Selected microprobe analyses of monazites from low-grade metamorphic mudrocks of the Kaczawa Complex

Sample	25 (2 (702 4)												
Analysis	1	2	(703.4)	9	15	17	19	22	30	31	38	39	42
P.O.	28.78	28.97	27.40	28.70	23.70	27.96	28.58	27.63	27.64	28.52	27.67	28.05	28.51
$\Gamma_2O_5$	1.03	0.79	0.99	1 16	1 44	1.87	1 31	1 22	0.95	0.72	1 74	1 09	1 16
SiO <sub>2</sub>	0.24	0.19	1.16	0.25	1.46	0.89	0.19	1.26	0.43	0.40	2.06	0.20	0.28
Al <sub>2</sub> O <sub>3</sub>	0.03	0.07	0.76	0.09	0.98	0.11	0.11	0.86	0.03	0.20	0.05	0.01	0.13
MnO	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	0.52	1.46	0.14	0.11	0.90	0.20	0.19	0.27	1.19	0.39	0.34	0.40	0.67
Y <sub>2</sub> O <sub>3</sub>	0.68	0.61	0.32	0.33	0.38	0.30	0.34	0.36	0.19	0.26	0.32	0.34	0.38
La <sub>2</sub> O <sub>3</sub>	15.03	15.10	17.19	15.78	14.10	16.48	15.77	16.73	16.85	16.35	16.02	16.85	17.29
Ce <sub>2</sub> O <sub>3</sub>	29.20	30.18	28.70	31.39	28.72	31.24	31.29	31.50	33.41	31.65	30.55	32.57	31.80
Pr <sub>2</sub> O <sub>3</sub>	3.40	3.19	2.72	3.25	2.97	3.09	3.42	3.30	3.22	3.34	3.23	3.27	3.02
Nd <sub>2</sub> O <sub>3</sub>	13.42	13.49	10.23	11.76	11.48	11.25	13.14	11.45	10.95	12.01	11.16	11.73	11.68
Sm <sub>2</sub> O <sub>3</sub>	2.04	1.72	1.04	1.21	1.30	0.97	1.67	1.00	0.76	1.09	1.09	0.93	1.20
Eu <sub>2</sub> O <sub>3</sub>	0.70	0.75	0.40	0.37	0.45	0.30	0.36	0.33	0.28	0.33	0.28	0.29	0.40
$Gd_2O_3$	1.78	1.60	1.19	1.17	0.97	0.98	1.07	0.92	0.60	1.00	1.09	1.05	1.20
Tb <sub>2</sub> O <sub>3</sub>	0.13	0.04	0.11	0.09	0.19	0.08	0.05	0.04	0.00	0.07	0.15	0.00	0.06
Dy <sub>2</sub> O <sub>3</sub>	0.53	0.30	0.24	0.12	0.26	0.07	0.27	0.20	0.00	0.06	0.07	0.19	0.32
Ho <sub>2</sub> O <sub>3</sub>	0.00	0.08	0.00	0.06	0.08	0.22	0.12	0.04	0.09	0.00	0.00	0.01	0.01
Er <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.01	0.09	0.06	0.02	0.07	0.04	0.00	0.02	0.00	0.00
Tm <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.05	0.09	0.03	0.07	0.02	0.02	0.06	0.04	0.00
Yb <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.00	0.00	0.02	0.06	0.04	0.00	0.00	0.02	0.00	0.04	0.06
Lu <sub>2</sub> O <sub>3</sub>	0.12	0.09	0.05	0.00	0.15	0.00	0.10	0.04	0.00	0.14	0.14	0.10	0.00
PbO	0.01	0.00	0.05	0.03	0.04	0.03	0.01	0.01	0.04	0.00	0.04	0.02	0.00
ThO <sub>2</sub>	1.00	0.61	2.66	1.86	3.48	1.24	0.85	0.47	1.59	0.97	2.97	1.88	0.67
UO <sub>2</sub>	0.05	0.02	0.08	0.06	0.06	0.03	0.03	0.05	0.04	0.01	0.07	0.03	0.03
Total	98.69	99.25	95.41	97.78	93.25	97.51	98.94	97.81	98.32	97.54	99.10	99.09	98.87
Sample		ZL1e						JA2		WO1c			
Analysis	J	CX-c	JCY-r	LBY	-c	LBW-r	LBU-c	:	LBX-r	MBZ-r	MKU	J-c	MKZ-r
P <sub>2</sub> O <sub>5</sub>		29.21	29.02	28.73		29.29	29.30		28.60	28.56	28.	28	28.95
CaO		0.23	0.11	0.	0.29		0.31		0.29	0.27	0.	23	0.33
SiO <sub>2</sub>		0.39	0.32	0.56		0.15	0.44	<u>ا</u>	0.61	3.72	2.	06	3.20
Al <sub>2</sub> O <sub>3</sub>		n.d.	n.d.	n.d		n.d.	n.d.		n.d.	n.d.	n.c	l	n.d.
MnO		n.d.	n.d.	n.d.		n.d.	n.d.		n.d.	n.d.	n.c	l	n.d.
FeO		n.d.	n.d.	n.c		n.d.	n.d.		n.d.	n.d.	n.c	l	n.d.
$Y_2O_3$	0.59		0.48	0.68		0.69	0.66	<u>,</u>	0.50	0.52	0.	55	0.55
$La_2O_3$	/.97		9.06	5.88		9.85	8.52	2	8.03	10.35	10.	11	8.47
$Ce_2O_3$	30.44		31.90	4.02		32.08	30.96	> \	30.02	28.69		/4	27.18
Pr <sub>2</sub> O <sub>3</sub>	4.01		4.02	4.03		3.83	3./0	,	4.0/	4.08	4.	50	4.15
Sm.O	3 56		2 10	5.09		247	<u>13.71</u> <u>15.9/</u> 2.67 <u>3.20</u>		3.5/	15.65	15.	95	3 00
$\operatorname{Sin}_2 \operatorname{O}_3$			5.10 nd	5.	09	2.6/	5.5C	,	5.54 n.d	<u> </u>	2.	75 1	5.99
Gd <sub>2</sub> O <sub>3</sub>		n.d.	n d	n.d	 	n d	n d		n.u.	n d	11.0	1	n d
$Gu_2O_3$ TheOe	n.d.		n d	n d		n d	n.d.		n.d.	n.d. n		1	n.d.
$Dv_2O_2$	n.d.		n d	nd		n d	n d		n d	n.d. n		1	n d
$H_{0}O_{1}$		n d	n d	n.d	l <b>.</b>	n d	n d		n d	n d	n.c	1	n d
$Er_2O_2$	n.d.		n.d	n.d.		n.d.	n.d. n.d.		n.d	n.d	n c		n.d.
$Tm_2O_3$		n.d.	n.d.	n.d.		n.d.	n.d.		n.d.	n.d. n.d.		1.	n.d.
Yb <sub>2</sub> O <sub>2</sub>		n.d.	n.d.	n.d.		n.d.	n.d.		n.d.	n.d.	n	1.	n.d.
Lu <sub>2</sub> O <sub>3</sub>	n.d.		n.d.	n.d.		n.d.	n.d.		n.d.	n.d.	n.c	1.	n.d.
PbO		0.04	0.01	0.	04	0.01	0.05	;	0.00	0.00	0.	00	0.03
ThO <sub>2</sub>		2.23	0.32	2.	69	0.75	3.03	3	2.31	1.23	0.	86	1.69
UO <sub>2</sub>		0.00	0.00	0.	00	0.00	0.01		0.03	0.13	0.	08	0.07
Total		95.83	94.98	95.	04	94.89	96.26	, ,	94.57	96.40	93.	42	95.64

c – core, r – rim

Table 1



Fig. 7. Selected X-Y geochemical plots of monazites from six samples of metamudrocks of the Kaczawa Complex.

in these rocks. The Th enrichment of the cores may be an indication of *in situ* monazite growth around a detrital monazite "seed". Alternatively, it may reflect more Thrich fluids in the early stages of monazite growth; comparable Th-enriched zones are present in, for example, the large authigenic monazites of central Wales (Evans *et al.*, 2002). The preliminary data also suggests an association of

the monazites with the darker, more fine-grained layers in the rock, which are richer in clay minerals and organic matter. In the authigenic monazites of central Wales, the link with organic matter is well established (Milodowski & Zalasiewicz, 1991) and may relate to both the transport and precipitation of the REEs (Evans *et al.*, 2002).



Fig. 8. UO<sub>2</sub>-ThO<sub>2</sub>-PbO diagram for monazites from six samples of metamudrocks of the Kaczawa Complex.

In general, the observed strong fractionation of LREE in the Kaczawa monazites corresponds to the similar fractionation ascertained in the whole-rock samples of turbidite mudrocks (depleted in LREE) and associated hemipelagites (enriched in LREE) in Wales (see Fig. 1: cf. Milodowski & Zalasiewicz, 1991), and indicates evident mobility of LREE during diagenesis and low-grade metamorphism.

These Kaczawa monazites differ, though, from the typical "grey monazite" of the literature, as exemplified by the well-studied Welsh examples. They are much smaller, and show much weaker chemical zonation (Fig. 10). The timing of their origin may also be different, as the limited evidence collected to date suggests that their growth was at least partly synchronous with the tectonic foliation, while the Welsh examples are essentially pre-cleavage in origin. Thus, some of the more elongated Kaczawa examples lie within, and generally parallel to, cleavage planes in the rock (Fig. 4b). This suggests that the growth of the monazite was synchronous with cleavage formation, though it cannot be excluded that at least some of these grains formed earlier and were subsequently rotated into the cleavage. On balance, the Kaczawa monazites appear to be one of the relatively few published examples of lowtemperature monazites which seem substantially cleavagerelated, rather than being essentially diagenetic in origin (cf. Rasmusson et al., 2001).

Part of the differences between the Welsh and Kaczawa monazites may be related to their different geotectonic settings. The Welsh examples grew within thick turbidite mudrock successions in a marginal basin (Davies *et al.*, 1997), there being a long interval between the compactional fluid movement that transported the REEs, and the formation of the cleavage. By contrast, the Kaczawa examples formed in an accretionary prism, where there was a continuum between compaction-related and tectonically-



Fig. 9. REE concentrations normalized to "North America Shale Composite", NASC (Gromet *et al.*, 1984) in selected analytical points in sample 35/S (582.0) from Stanisławów.

driven fluid release, and the tectonic deformation affected deposits which were at least in part still "soft" (Collins *et al.*, 2000).

Although the precise controls on the formation of the Kaczawa monazites need further study, some of their potential significance is clear. Firstly, such monazites are potentially dateable (Evans & Zalasiewicz, 1996; Evans et al., 2002), especially given current advances in radiometric dating techniques. Even imprecise dates would provide valuable constraints on the timing of deposition, diagenesis or tectonism of these very poorly biostratigraphically-dated rocks. Secondly, the monazite growth may act as a useful "tracer" of fluid expulsion/movement within an accretionary prism setting. Thirdly, the indication given here of REE mobility has significance for provenance studies based on either REE patterns or on Nd isotopes (cf. Bock et al., 2004). Fourthly, given the "immature" state of these low-temperature monazites by comparison with previously described examples, they may help shed light on the particular micro-environments in which these minerals arise.

In this respect, the association with a dark brownish mica-like phase, with EDS spectra resembling those of "altered biotite", as noted above (Fig. 5), may be significant, with this mineral typically forming an overgrowth or intergrowth with the monazite. More information on this mineral association could illuminate the question of monazite origin. "True" biotite is unlikely to occur as an authigenic mineral in these low-grade metamorphic rocks, seemingly implying an exotic, detrital derivation of the monazite grains. However, there is undoubted evidence that the cleavage-formation processes controlled the redistribution of monazite in the rock during the early stages of tectonic deformation. A possible compromise interpretation is that the detrital biotite contained primary monazite inclusions which served as "embryos" for re-crystallization of secondary monazite during diagenesis and early metamorphism.

Further studies of this mineral are in progress. Its occurrence highlights the complexity of the processes occurring within mudrocks, particularly those with a protracted



Fig. 10. Comparison of textural positions and distinctive features of monazites from mudrocks of the Welsh Basin and the Kaczawa Mountains.

and diverse diagenetic and metamorphic history. We predict that detailed examination of the Sudetic mudrock successions will show monazite, and probably other unusual minerals, to be widespread, and we suggest that close study

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