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The Orthogneiss and Schist Complex of the Karkonosze–Izera Massif (Sudetes, SW Poland): U-Pb SHRIMP zircon ages, Nd-isotope systematics and protoliths

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Abstract Many basement units of the Variscan orogen that are exposed in the Sudetes, SW Poland, comprise widespread ~500 Ma orthogneisses and associated mica schists, the latter often of unknown age and derivation. Our new U-Pb sensitive high resolution ion microprobe (SHRIMP) zircon ages from two samples of the Izera metagranites, both around 503 Ma, are in a good agreement with the well established late Cambrian–early Ordovician magmatism in the West Sudetes. An Archean inherited zircon age of ~ 3.4 Ga is one of the oldest zircon ages reported so far from the Bohemian Massif. The orthogneisses of the Karkonosze–Izera Massif (KIM) have calculated T_{DM} ages of between 1.50 and 1.93 Ga, but these ages are not necessarily evidence for a Mid-Proterozoic crustal derivation: more probably, they reflect the average of several detrital components mixed into the granitoid magma sources. In spite of likely age differences, the Lusatian greywackes, which outcrop to the west, and the mica schists of the KIM display similar geochemical characteristics, suggesting that both could have been derived from similar sources. However, the presence of lower Ordovician products of within-plate volcanism – intercalations of quartzofeldspathic rocks and amphibolites within the mica schists – supports an idea that the mica schist protoliths, derived mainly from crustal rocks, could have also contained an admixture of contemporaneous volcanic materials. The age spectra of inherited zircons from the KIM orthogneisses and their Nd-isotopic signatures are comparable to the Lusatian greywackes: this suggests that the Lusatian greywackes, or very similar rocks, could have been the source material for the granitic protoliths of the KIM orthogneisses.

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INTRODUCTION

The Karkonosze–Izera Massif (KIM), as defined by Mazur (1995) but previously termed the Izera–Karkonosze Block (Mierzejewski & Oberc-Dziedzic, 1990), is the largest geological unit in the West Sudetes (SW Poland). This massif lies at the eastern end of the Lusatian–Izera Massif, as defined by Żelaźniewicz & Aleksandrowski (2008), and at the NE edge of the Bohemian Massif. The KIM consists of a number of structural units that have been interpreted as a nappe complex (Mazur, 1995; Mazur & Kryza, 1996; Mazur & Aleksandrowski, 2001, and references therein). One of these units is the Izera–Kowary Unit, and this comprises the largest and, structurally, most internal metamorphic unit of the KIM. Together with the western part of the Lusatian–Izera Massif, which lies adjacent to the NW, the Izera–Kowary Unit represents the pre-Variscan continental basement of the Saxothuringian Basin (Mazur & Aleksandrowski, 2001). The Izera–Kowary Unit was later intruded by the Variscan Karkonosze granite, which acts to separate the Izera Complex in northern part of the KIM from the metamorphic complexes of the eastern and southern parts of the massif.

The Izera–Kowary Unit is composed predominantly of metagranites and gneisses that have been dated, using a variety of methods, at 515–480 Ma (Borkowska *et al.*, 1980; Korytowski *et al.*, 1993; Kröner *et al.*, 2001; Oliver *et al.*, 1993; Żelaźniewicz, 1994). The gneisses of the Izera–Kowary Unit are themselves known under several different regional names: either the Izera gneisses or the undeformed Rumburk/Izera granites in the Izera Complex (Oberc-Dziedzic, 1988); the Karkonosze gneisses in the southern part of the KIM in the Czech territory (Chaloupský *et al.*, 1989); and the Kowary gneisses on the eastern/southeastern side of the Karkonosze granite (Teisseyre, 1973).

Petrographic, geochemical and isotopic evidence all support a crustal derivation of the gneiss protoliths (Oberc-Dziedzic *et al.*, 2005; Pin *et al.*, 2007). Some information about the age of the source materials for these protoliths has come from zircon ages that were obtained mainly by the multigrain- and zircon-evaporation techniques (Kröner *et al.*, 2001; Oliver *et al.*, 1993) and, occasionally, by the SHRIMP method (Oberc-Dziedzic *et al.*, 2010).

The orthogneisses of the Izera–Kowary Unit are associated with mica schists. These mica schists have been interpreted as a metamorphic envelope intruded by the gneiss protoliths (e.g. Oberc-Dziedzic, 2003). However, new data by Oberc-Dziedzic *et al.* (2010) suggest that the protoliths of the gneisses and quartzofeldspathic rocks, which are embedded in the mica schists in the southern part of the KIM (likely as volcaniclastic intercalations), have broadly the same age of ~ 500–490 Ma. Both the protoliths of the gneisses and the quartzofeldspathic rocks have been interpreted as products of bimodal magmatism connected with late Cambrian and early Ordovician rifting at the margin of the future Saxothuringian "terrane" (Kryza & Pin, 1997; Oberc-Dziedzic *et al.*, 2005; Pin *et al.*, 2007, Oberc-Dziedzic *et al.*, 2010). Having a similar age as the gneisses, the mica schists are probably not the original country rocks to the ~ 500 Ma granite intrusions. The close structural proximity of the gneisses and the schists is probably the result of tectonic juxtaposition (Oberc-Dziedzic *et al.*, 2010). Whether this interpretation is also valid for the other mica schists associated with the orthogneisses in other parts of the KIM is a subject for further geochronological investigations.

In this paper, we present new U-Pb SHRIMP zircon ages from two samples of the Izera granites and compare them with previously published SHRIMP data for the Kowary gneisses and quartzofeldspathic rocks of the Izera–Kowary Unit (Oberc-Dziedzic *et al.*, 2010). Furthermore, using both previously published Nd-isotopic systematics (Kröner *et al.*, 2001; Crowley *et al.*, 2002; Linnemann *et al.*, 2004; Oberc-Dziedzic *et al.*, 2005) and our new Nd-isotopic data, we attempt to better constrain the provenance and evolution of the protolith source materials for the gneisses and mica schists.

GEOLOGICAL SETTING

The Karkonosze–Izera Massif (KIM) (Fig. 1) is composed of Neoproterozoic?–Palaeozoic metasedimentary rocks and lower Palaeozoic metagranitoids, interpreted as a pile of four thrust units showing different lithostratigraphy and metamorphic histories. These four units have been named, from bottom to top, as follows: (l) the Izera–Kowary Unit, (2) the Ještěd Unit, (3) the South Karkonosze Unit, and (4) the Leszczyniec Unit (Mazur, 1995; Mazur & Kryza, 1996; Mazur & Aleksandrowski, 2001; but see also other interpretations by Kodym & Svoboda, 1948; Oberc, 1972; Seston *et al.*, 2000; Kozdrój *et al.*, 2001 and Kozdrój, 2003). The Variscan Karkonosze pluton has been dated at between 304 Ma and 328 Ma (Pin *et al.*, 1987; Duthou *et al.*, 1991; Kröner *et al.*, 1994; Marheine *et al.*, 2002; Machowiak & Armstrong, 2007; Kusiak *et al.*, 2008a, b), but comes into direct, intrusive contact only with the Izera–Kowary Unit.

The lowest and apparently autochthonous Izera–Kowary Unit is composed of orthogneisses and mica schists. The gneisses themselves have been regionally subdivided into the Izera, Kowary and Karkonosze orthogneiss variants, all separated by the Karkonosze pluton. The Izera orthogneisses have been dated at 515–480 Ma using a range of methods: whole rock Rb–Sr (Borkowska *et al.*, 1980); U-Pb multigrain zircon age (Korytowski *et al.*, 1993; Oliver *et al.*, 1993; Żelaźniewicz, 1994); and the zircon evaporation method and $^{207}Pb/^{206}Pb$ mean ages (Kröner *et al.*, 2001). The Kowary orthogneiss has been dated at ~ 492–481 Ma using a U-Pb multigrain zircon age (Oliver *et al.*. 1993) and at 487 ± 8 Ma using the SHRIMP method (Oberc-Dziedzic *et al.*, 2010). The Karkonosze orthogneiss has a similar age of 501 ± 1 Ma and 503 ± 1 Ma, as determined using the zircon evaporation method and $^{207}Pb/^{206}Pb$ mean ages (Kröner *et al.*, 2001). The similar petrographic, geochemical and textural features, as well as nearly identical ages of the Izera, Kowary and Karkonosze orthogneisses, strongly suggest that they derived from one magmatic body.

The Izera, Karkonosze and Kowary gneisses are accompanied by mica schists. As with the orthogneisses, these schists have different names in different parts of the KIM: to the north of the Karkonosze granite there are the Złotniki Lubańskie schists, the Stara Kamienica schists and the Szklarska Poręba schists; to the south of this granite are the Velká Úpa Group schists; and to the eastern side of the granite is the Czarnów Schist Formation. Nevertheless, the available data does not rule out that all these schists could belong to one and the same series, i.e., the Velká Úpa Group (Oberc-Dziedzic *et al.*, 2010). The Velká Úpa Group was originally named by Chaloupský (1965) for a schist "series" in the southern part of the KIM that comprises an ~ 1,000 m thick, monotonous mica schist

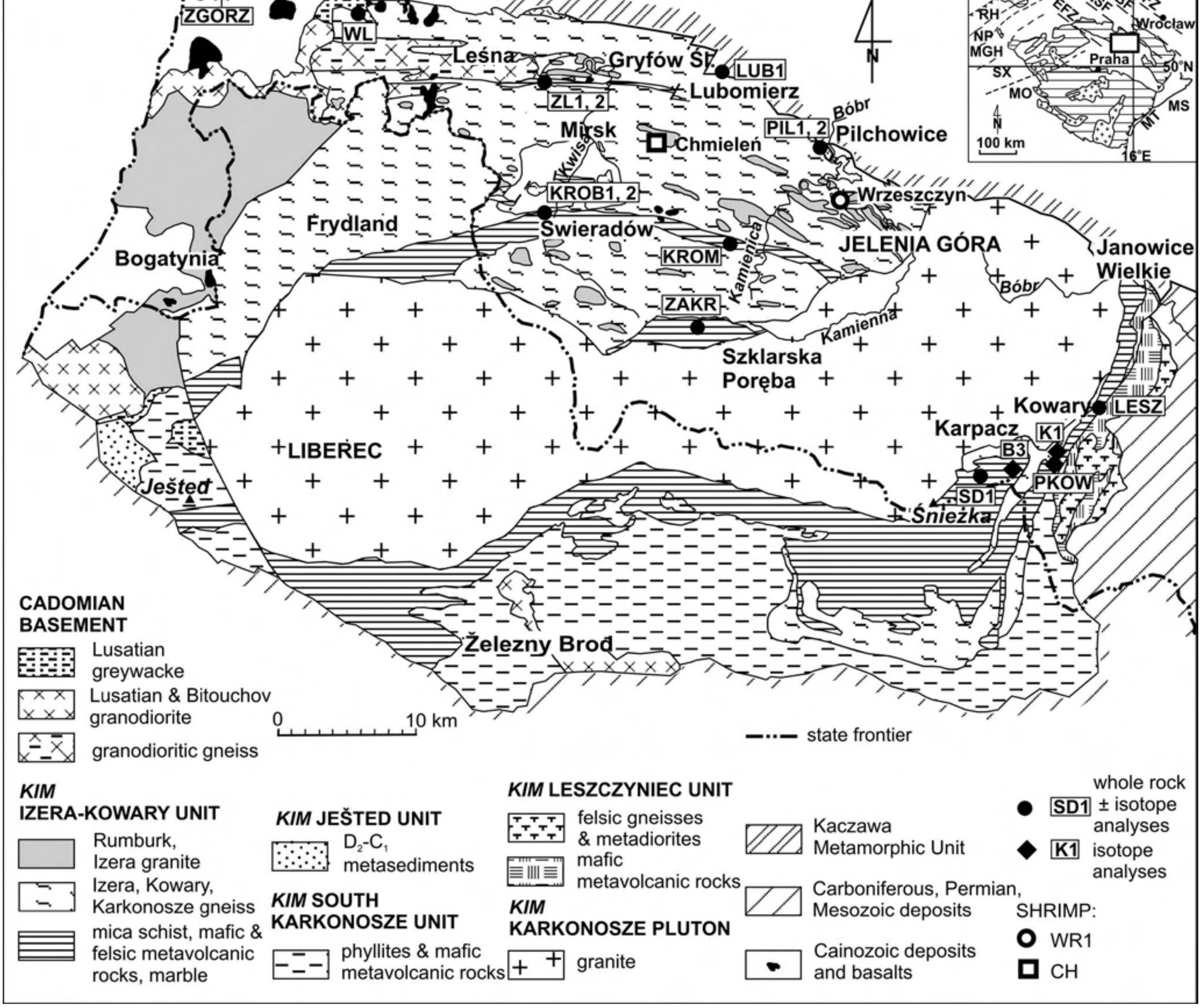

Fig. 1. Geological sketch map of the Karkonosze–Izera Massif (based on Chaloupský *et al.*, 1989; Mazur, 1995; Mazur & Aleksandrowski, 2001; Oberc-Dziedzic, 2003). Abbreviations are as follows: Main map: KIM (Karkonosze–Izera Massif); Inset map: EFZ (Elbe Fault Zone), ISF (Intra-Sudetic Fault), MGH (Mid-German High), MO (Moldanubian Zone), MS (Moravo-Silesian Zone), NP (Northern Phyllite Zone), OFZ (Odra Fault Zone), RH (Rhenohercynian Zone), SBF (Sudetic Boundary Fault), SX (Saxothuringian Zone), TB (Teplá–Barrandian Zone). Rectangle shows the position of the KIM within the Bohemian Massif. Sample locations: *Lusatian greywackes* (Table 1, Table 2): ZGORZ = N50°9'12'', E15°1'12''; WL = N51°5'10'', E15°8'31''; *mica schists* (Table 1, Table 2): ZL1, ZL2 = N51°1'2'', E15°20'4''; KROB1, KROB2 = N50°55'44'', E15°20'41''; KROM = N50°54'21'', E15°33'44''; ZAKR = N50°50'59'', E15°31'39''; SD1 = N50°45'17'', E15°46'20''; LUB1 = N51°1'21'', E15°31'50''; PIL1, PIL2 = N50°57'54'', E15°38'24''; LESZ = N50°47'21'', E15°53'56''; *quartzofeldspathic rock* (Table 2): B3 = N50°45'41'', E15°17'50''; *Kowary orthogneisses* (Table 2): K1 = N50°47'12'', E15°51'56''; PKOW = N50°46'2'', E15°51'42''; *Izera granites* (SHRIMP, Table 3): CH = N50°59'1'', E15°27'20''; WR1 = N50°56'5'', E15°39'59''; GPS coordinates are given in WGS 84.

"series" subdivided into two sections by a lithologically variegated succession of mica schists, accompanied by quartzite, graphite schist, marble, calc-silicate rocks and amphibolite (Chaloupský *et al.*, 1989). Mazur (1995) considered the Czarnów Schist Formation as equivalent to the variegated member of the Velká Úpa Group. However, the geological position of the Czarnów Schist Formation is still a matter of debate (see Smulikowski, 1999).

A supposition that all schists of the Izera–Kowary Unit could belong to one and the same series seems to be supported by number of arguments: similar petrographic features of the Stara Kamienica schists and the Velká Úpa schists (Chaloupský *et al.*, 1989); similar ages of the quartzofelspathic rock from the Velká Úpa Group (Oberc-Dziedzic *et al.*, 2010) and the porphyroid (metarhyolite) from the Rychory schist series (Bendl & Patočka, 1995), which is considered by Kozdrój (2003) as the southern continuation of the Czarnów Schist Formation.

In the northern part of the KIM, the Izera–Kowary Unit is represented by the Izera Complex (Fig. 1) composed mainly of two sets of rocks derived from the 515–480 Ma intrusives (Borkowska *et al.*, 1980; Korytowski *et al.*, 1993; Oliver *et al.*, 1993; Żelaźniewicz, 1994). These intrusive-derived rocks are divided into two broad textural varieties: (1) coarse-grained varieties, represented by flat-lensoid gneisses, streaky laminated gneisses, augen-laminated gneisses, augen gneisses grading into granite-gneisses (with a weak gneissic texture) and porphyritic coarse-grained granites; (2) fine-grained varieties, represented by frequently porphyritic fine-grained granites and gneisses. The fine-grained granites form narrow, aligned bodies within the coarse-grained gneisses.

At the NW edge of the KIM, the Izera gneisses are juxtaposed with granodioritic gneisses, dated at 533 ± 9 Ma by the U-Pb method (Żelaźniewicz *et al.*, 2004) and corresponding to the undeformed Lusatian granodiorites intruding the Neoproterozoic Lusatian greywackes (Fig. 1).

All the textural gneiss varieties enclose lenses of coarse-grained, porphyritic granites, the so-called Izera, or Rumburk, granites. These lenses are considered as either remnants of undeformed granitic protoliths of the coarse-grained gneisses, or as intrusions into the Lusatian granodiorite (Ebert, 1943; Domečka, 1970; Żelaźniewicz *et al.*, 2003; Żelaźniewicz *et al.*, 2004). The coarse-grained gneisses and granites locally contain small (up to several meters thick) younger, but variously deformed, mafic dykes.

The mica schists of the Izera Complex form three belts embedded within the Izera gneisses, each up to several hundred meters thick (Fig. 1): The Złotniki Lubańskie Belt is in the northern part of the KIM, the Stara Kamienica Belt is in the central part, and the Szklarska Poręba Belt is in the southern part. The schists of the Złotniki Lubańskie Belt are different in composition from the schists of the two other belts. They are rather similar to the Lausatian greywackes (Berg, 1935; Kozłowski, 1974; Oberc-Dziedzic, 1988; Chaloupský *et al.*, 1989) and probably represent their metamorphic equivalents. This correlation is supported by the zircon ages of 640–620 Ma and 580–557 Ma obtained from metatuffite intercalations in the Złotniki Lubańskie schists (Żelaźniewicz *et al.*, 2003), which correspond to zircon ages from volcanogenic intercalations in the Lausatian greywackes (Gehmlich *et al.*, 1997).

The rocks of the Izera–Kowary Unit experienced progressive medium temperature–medium pressure metamorphism, up to low amphibolite facies conditions, locally overprinted by contact metamorphism caused by the Karkonosze intrusion (Kryza & Mazur, 1995).

ANALYTICAL METHODS

New major-, trace-, and rare earth element data were obtained from 12 whole-rock samples of mica schists and one whole-rock sample of the Lusatian greywacke. The analyses were performed at Actlabs, Canada, using combined x-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (ICP–MS) techniques and applying this laboratory's "LITHORES 4" routine (Fig. 1; Table 1).

Eight samples of mica schist and 2 samples of Lusatian greywacke – one of which had previously been analysed for major-, trace- and rare earth elements (WL sample, Oberc-Dziedzic *et al.*, 2005) – were analysed for Sm-Nd isotopes, following the procedures in Pin & Santos Zaldugui (1997). The analytical data are listed in Table 2, together with initial $^{143}Nd/^{144}Nd$ ratios expressed as εNd_i values, corrected for *in situ* decay of ^{147}Sm, assuming an age of 500 Ma for the mica schists (Oberc-Dziedzic *et al.*, 2010) and 570 Ma for the greywackes (c.f. Linnemann *et al.*, 2004), and with model ages relative to the depleted mantle model of De Paolo (1981a, b).

Two samples of the relatively undeformed Izera granites from Chmieleń (sample CH) and Wrzeszczyn (sample WR1) were selected for geochronological studies (Fig. 1). Petrographic, geochemical and isotopic data on these two samples have already been published (see the CH and WR-1 samples in Oberc-Dziedzic *et al.*, 2005).

The selected samples, each ~ 5 kg in weight, were crushed and the heavy mineral fraction (0.06–0.25 mm) was separated using standard heavy liquid and magnetic separation techniques. Zircons were handpicked under a microscope, mounted in epoxy resin and polished; transmitted and reflected light photomicrographs were taken, as well as cathodoluminescence and back scattered electron images of the zircons in order to select spots on certain grains for *in situ* U-Pb analyses. The sensitive high resolution ion microprobe (SHRIMP II) at the All-Russian Geological Research Institute (VSEGEI) in St. Petersburg was used to determine zircon ages in the samples selected.

SHRIMP analytical details are given in the Appendix. Uncertainties for individual analyses (ratios and ages) are at the one σ level; however, the uncertainties in calculated concordia ages are reported at the 2 σ level. The results of the zircon analyses are shown in Table 3.

PETROGRAPHY OF STUDIED SAMPLES

THE IZERA GRANITES

Sample WR1 (from Wrzeszczyn) represents an almost undeformed coarse-grained variety of the Izera granite, whereas sample CH (from Chmieleń) represents a fine-grained variety of the Izera granite.

The coarse-grained Izera granite. This granite is a porphyritic rock whose often bluish-grey colour is due to the tint of quartz and microcline. Microcline megacrysts are 3–5 cm long, locally exceeding 10 cm, and are occasionally mantled with white plagioclase rims. The coarse-grained matrix is composed of blue or grey quartz, plagioclase, microcline, black biotite clusters and prismatic pinite pseudomorphs after cordierite, which are up to 2 cm in length. Rectangular plagioclase grains are frequently zoned, with cores more calcic (An_{17}) than rims (An_{10}). Plagioclase cores are often replaced by epidote–sericite aggregates; outer zones are often myrmekitic. Locally, the outer parts of a plagioclase may contain small garnets, and similar garnets may also be seen in large pinite pseudomorphs. Reddish-brown biotite encloses zircon, epidote and opaque inclusions. Biotite clusters are accompanied by large grains of apatite and by ilmenite rimmed by leucoxene. The biotite is occasionally replaced by muscovite and epidote. The microcline of the groundmass always occurs as xenomorphic grains; relatively large groundmass microclines are perthitic. The groundmass also contains fine-grained aggregates of quartz, biotite and plagioclase: the latter are strongly altered and there may be myrmekite present where plagioclase is adjacent to microcline.

Sample WR1 (Fig. 1) comes from a cordierite (pinite)-garnet-bearing variety of this coarse-grained granite that contains little to no microcline. This rock is composed of euhedral, strongly altered plagioclase, rimmed by fine myrmekite. Pinite is relatively abundant and hosts numerous garnet, and locally sillimanite, inclusions. Garnet is also encountered in the outer parts of plagioclase grains and along mica clusters.

The fine-grained Izera granite. The fine-grained granite of sample CH (Fig. 1) is a grey rock with a weak or absent preferred orientation. It contains phenocrysts of quartz, biotite, plagioclase and microcline and, locally, prisms of pinite (Oberc-Dziedzic, 1988). The fine-grained groundmass (grain-size below 0.5 mm) is composed of plagioclase and microcline both containing abundant quartz inclusions. The outer parts of some of the microcline phenocrysts show a micrographic texture.

MICA SCHISTS

Representative samples of mica schists from the Izera–Kowary Unit were taken from the larger outcrops of the region for comparative geochemical and isotope analysis (Fig. 1).

All the mica schists examined in this study contain various proportions of quartz and muscovite. However, other petrographic characteristics, such as grain size, additional mineral components or metamorphic grade, vary between outcrops.

Mica schists of the Złotniki Lubańskie Belt. These schists are of a lower metamorphic grade than other schists in the Izera–Kowary Unit. Sample ZL1 contains chlorite, albite and numerous opaque minerals. Sample ZL2 is coarser-grained, contains biotite porphyroblasts and is poor in opaque minerals.

Mica schists of the Stara Kamienica Belt. Schist samples KROB1 and KROB2 are rich in muscovite. They also contain chlorite, biotite, chloritoid, garnet and unevenly dispersed cassiterite and sulfides. Some layers of schists are exceptionally rich in garnet (KROB2). Sample KROM is rich in chlorite. Pinite is present, as are porphyroblasts of younger biotite and andalusite. The opaque minerals are the products of biotite decomposition, and opaques also penetrate the andalusite porphyroblasts.

Hornfelses of the Szklarska Poręba Belt. Hornfels sample ZAKR is a dark grey, massive rock composed of chaotically distributed biotite, quartz, andalusite, cordierite, magnetite and rare, reversely zoned, plagioclase. Andalusite forms intergrowths with K-feldspar and, less frequently, with cordierite, and is often accompanied by large plates of muscovite. These rocks also contain relict garnet.

To verify previously proposed relationships between the Złotniki Lubańskie mica schists and the Lusatian greywackes (Smulikowski, 1972; Kozłowski, 1974), representative greywacke samples were analysed.

The Lusatian greywacke. This greywacke is represented by two samples: sample WL1 from a crag at Włosień (Fig. 1), and sample ZGORZ, taken from the exposure at the Zgorzelec railway station (not on Fig. 1). Sample WL1 was previously analysed for major, trace and REE elements (Oberc-Dziedzic *et al.*, 2005). Both samples are fine-grained, laminated rocks composed of quartz, rare plagioclase and white mica.

Mica schists of the Velká Úpa Group. These schists are exposed south of the Karkonosze granite. The sample SD1 represents mica schists that were thermally metamorphosed at the contact with the granite and which preserve easily visible foliation and lineation. These schists are composed of quartz, muscovite, sillimanite, andalusite and cordierite. The rocks also contain small amount of plagioclase and K-feldspar. Opaque minerals are arranged in streaks parallel to the foliation. An isotopic analysis was performed on sample B3 (Fig. 1), a quartzofeldspathic rock that is embedded in the mica schists and that had previously been analysed for major, trace and REE elements and zircon SHRIMP ages (Oberc-Dziedzic *et al.*, 2010).

Mica schists of the Czarnów Formation. These schists occur in the eastern part of the Izera–Kowary Unit (Fig. 1). Sample LESZ shows a distinct foliation defined by muscovite, quartz and rare olive-green biotite (Oberc-Dziedzic & Oberc, 1972). The most characteristic feature of these schists are albite porphyroblasts that are up to 2 mm in size, contain 6% An (Kryza & Mazur 1995) and are usually untwinned. These porphyroblasts contain numerous inclusions of needle-like rutile, often arranged in sigmoid strips. Garnet forms small, partly chloritized grains.

The mica schists from the Czarnów Formation were petrographically correlated with mica schists that form a narrow belt along the northern border of the KIM, i.e., between the Izera Complex and the Kaczawa Metamorphic Unit (Oberc-Dziedzic, 1966; Oberc-Dziedzic & Oberc, 1972). Samples of these schists from Pilchowice and from Lubomierz (Fig. 1) were taken for a comparative study.

Mica schists from Pilchowice. These schists are represented by sample PIL1, which was taken from the middle part of the sample outcrop, and sample PIL2, which was taken close to the Izera granite. Sample PIL1 is composed of quartz and muscovite ± chlorite and contains albite porphyroblasts which, unlike the albite from the Czarnów Formation schists, do not have rutile inclusions (Oberc-Dziedzic & Oberc, 1972). Sample PIL2 contains

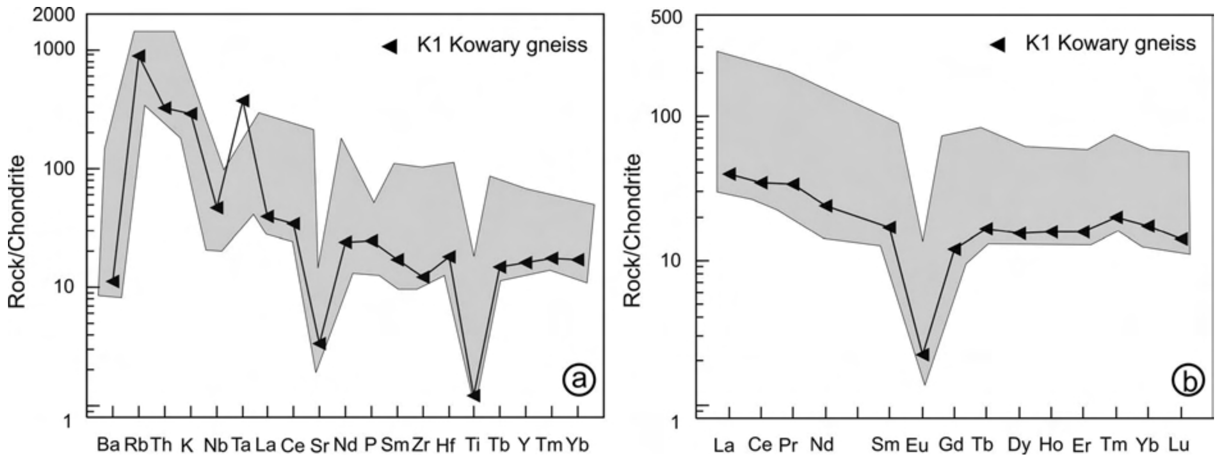

Fig. 2. (**a**) Chondrite-normalized multi-element diagram, using the normalization values of Thompson (1982), and (**b**) chondrite-normalized rare earth element (REE) plot, using normalization values of Nakamura (1974) with additions from Haskin *et al.* (1968), for the Kowary gneiss from the Izera–Kowary Unit (IKU) and from which one can compare the values of the undeformed Izera/Rumburk granites (shaded) from the northern part of the IKU.

less muscovite than PIL1. Foliation is defined by flattened grains of quartz, albite and K-feldspar. This schist also contains calcite.

Mica schists from Lubomierz. Schist sample LUB1 is a fine-grained rock composed of aligned muscovite plates with subsidiary chlorite, elongated grains of quartz and rare albite. Younger muscovite porphyoblasts are obliquely oriented relative to the foliation.

BULK ROCK CHEMISTRY

THE IZERA GRANITES AND GNEISSES

Chemical analyses of major, trace and rare earth elements of the Izera granites and gneisses have been given in Oberc-Dziedzic *et al.* (2005). Here, we summarize these previous data and reproduce multi-element and REE diagrams for the Izera granites and gneisses and the Kowary gneiss (Oberc-Dziedzic *et al.*, 2010) in order to compare them with the new data for the associated mica schists (Table 1).

Major elements

The Izera granites and gneisses are generally potassium-rich, although medium and low potassic varieties are known. Most of the granites and gneisses are calcic and peraluminous, with A/CNK in the range 1.0–1.63, and with high normative corundum (up to 3.5%). The SiO_2 contents are usually within the range of 70–77% but decrease to 65% in varieties rich in biotite, pinite and garnet; K_2O contents vary from 2% to more than 7%.

The geochemical variations of the Izera granites are reflected in their mineral composition. A decrease in Al_2O_3, MgO, FeO_{tot}, TiO_2, as well as Na_2O and CaO, with increasing SiO_2 and K_2O, mineralogically coincides with a systematic decrease in cordierite (pinite), biotite and plagioclase contents, and an increase in K-feldspar. Such a trend probably reflects the magmatic differentiation and/or removal of restitic phases (Oberc-Dziedzic *et al.*, 2005). The SHRIMP-analysed samples represent granitoids situated at the beginning of this hypothesised differentiation trend (the cordierite/pinite-garnet-bearing granitoid, sample WR1), and at its end (the fine-grained granite, sample CH).

Trace elements

Some trace elements, such as Rb, display no correlation with SiO_2, whereas others, such as Ba and Sr, decrease with increasing SiO_2. This trend suggests some fractionation of the feldspar. Concentrations of Zr, Th and Ce generally decrease with increasing SiO_2, suggesting that these elements were probably removed during the fractionation of accessories like zircon and monazite. The concentrations of U and Pb generally increase with increasing SiO_2, suggesting that these heavy elements concentrated as incompatible elements during magma differentiation or possibly as a result of late-stage fluids.

The multi-element diagram of trace element concentrations normalized to chondrite (Fig. 2a) is characterised by a flat, weakly fractionated sector of less incompatible elements, between Yb and Sm, and considerable increase in most incompatible elements, from Nd to Rb. The parallel distribution of the patterns strongly suggests a genetic link between the granites and the gneisses. The strongly negative Nb, Ta, Sr, P anomalies and the negative Ti anomalies indicate fractionation processes and/or scarcity of these components in the source materials. The Nb and Ta negative anomalies are usually considered as typical of continental crust material (Taylor & McLennan, 1985). The negative Sr, P, Ti anomalies reflect a highly evolved magma and point to plagioclase, apatite, and ilmenite fractionation and removal. All samples show low ratios of

Table 1

Major (wt %) and trace element (ppm) whole-rock analyses of mica schists from the Izera-Kowary Unit and the Lusatian greywackes

	ZL1	ZL2	KROB1	KROB2	KROM	ZAKR	SD1	LUB1	PIL1	PIL2	LESZ	ZGORZ	WL
SiO_2	58.44	60.96	64.37	51.58	58.9	49.04	63.69	61.88	63.61	68.75	66.04	61.81	64.75
TiO_2	0.653	1.003	0.836	0.747	0.538	0.995	0.913	0.657	0.826	0.673	0.671	0.781	0.79
Al_2O_3	19.27	20.69	17.22	22.14	18.89	29.85	18.5	19.03	17.46	14.78	15.49	17.92	15.59
Fe_2O_3	6.89	5.92	8.4	11.97	9.03	8.92	6.04	5.23	5.57	4.68	6.72	6.02	5.59
MnO	0.046	0.043	0.042	0.047	0.078	0.233	0.045	0.019	0.057	0.048	0.152	0.039	0.06
MgO	2.96	1.94	1.38	2.03	1.93	2.51	1.5	2.3	2.3	1.75	1.84	2.35	2.42
CaO	0.35	0.17	0.16	0.76	0.29	0.37	0.26	0.24	0.54	1.03	0.39	0.57	1.07
Na_2O	3.47	0.68	0.2	0.27	0.53	0.94	0.69	1.27	2.73	2.42	2.14	2	2.09
K_2O	3.95	4.89	4.01	5.03	4.67	5	4.99	4.53	3.96	3.12	3.07	3.96	3.63
P_2O_5	0.21	0.15	0.11	0.12	0.32	0.11	0.1	0.2	0.23	0.17	0.19	0.19	0.23
LOI	3.3	3.72	3.02	4.29	3.93	1.85	3,00	3.62	3.04	3.14	3.04	4.06	2.62
Sum	99.54	100.2	99.75	98.99	99.11	99.83	99.73	98.98	100.3	100.6	99.75	99.71	98.84
A/NK	1.9	3.2	3.7	3.8	3.2	4.3	2.8	2.7	2.0	2,0	2.3	2.4	2.1
A/CNK	1.8	3.1	3.5	3,0	2.9	3.9	2.6	2.6	1.8	1.6	2,0	2.1	1.7
Sc	16	17	15	18	9	22	15.8	16	15	12	15	16	13
Be	3	3	3	4	3	6	5	4	3	3	3	3	3
V	108	118	102	136	52	141	95	115	100	80	92	113	71
Co	18	12	13	42	11	23	18	10	12	14	17	9	24
As	2.9	4.1	3.5	20.7	2.9	< 0.5	3.2	26.3	4.1	21.5	< 0.5	4.6	15
Cr	72	87	75	93	26	120	78	84	74	63	59	71	53
Sb	< 0.2	0.2	0.8	0.7	< 0.2	0.3	0.4	1.2	0.4	0.8	0.5	2	1.8
Cu	17	2	2	174	15	7	22	28	22	41	18	40	18
Pb	4	< 3	6	12	20	45	< 3	158	14	12	18	13	34
Ni	46	37	35	53	12	60	47	21	29	29	33	34	
Zn	72	26	20	49	121	133	36	372	70	81	74	69	90
Cd	< 0.5	< 0.5	< 0.5	0.7	< 0.5	< 0.5	0.8	1	< 0.5	< 0.5	< 0.5	< 0.5	
Ga	26	26	26	35	25	38	23	27	22	19	23	26	19
Ge	1.5	2.1	1.9	1.6	1.2	3.3	2.2	1.7	1.3	1.1	2.1	1.7	1.5
Rb	221	223	241	212	285	291	269	180	114	109	156	134	132
Sr	67	33	23	53	33	123	53	71	155	112	80	94	187
Y	23.3	35.4	24.3	42.3	33.8	25.3	34.1	35.7	29.1	25.2	26	33	24.8
Zr	187	229	181	241	255	134	224	163	261	248	150	174	193
Nb	11.4	16	13.8	15.9	11	15.2	19.7	14.8	12.4	10.7	12.3	13.4	13
Mo	< 2	7	< 2	6	< 2	4	< 2	3	3	< 2	5	6	
Ag	< 0.3	0.4	< 0.3	0.4	< 0.3	0.5	< 0.3	0.4	< 0.3	< 0.3	< 0.3	< 0.3	
In	0.2	0.1	0.3	0.6	0.6	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	
Sn	8	7	41	107	8	5	7	3	3	3	4	4	3
Cs	4.5	3.9	10.3	6.6	5.8	22.7	17.6	5.1	3.8	2.6	12.4	6.7	4.7
Ba	929	791	514	723	491	917	438	975	1011	1019	623	1107	987
Hf	5	6.2	5.2	6.7	7	3.9	6.6	4.7	6.7	6.4	4.1	5	6
Ta	1.17	2.13	1.84	3.14	1.9	3.25	2.28	1.8	1.7	1.63	1.93	1.32	1.01
W	16.1	23.9	31.7	60	30.4	78.7	48.3	24.4	30.6	43.3	52.1	16.3	
Tl	1.2	0.89	1.12	0.68	1.34	1.48	1.5	1.16	0.55	0.52	0.69	0.71	0.86
Bi	0.9	0.3	5.2	36.7	0.2	0.2	0.5	0.2	0.2	0.4	0.8	1.1	0.2
Th	10.5	13.9	12.6	15.3	12.8	21.7	15.9	11.1	10.6	10.1	11.6	12.2	11.4
U	2.76	3.42	3.63	4.23	6.02	3.62	3.85	4.01	2.8	2.44	2.14	3.7	3.02
La	18.2	42.4	40	59	14.5	71.2	47,00	44	40.9	38.5	39.8	36.2	35
Ce	61.9	83.4	85.1	127	35.6	137	91.4	94.1	86.5	78.7	81.9	81.6	74.7
Pr	4.38	10.1	9.07	13.9	4.15	13.2	11.2	10.1	9.06	8.36	8.58	8.88	7.35
Nd	15.9	38.7	34.3	52.6	15.9	46.2	40.8	38	35	32.2	32.3	34.7	30.4
Sm	3.31	7.14	6.38	10.2	3.66	7.04	7.88	7.49	6.67	5.96	6.08	6.88	6.21
Eu	0.823	1.53	1.44	2.84	0.795	1.68	1.68	1.45	1.54	1.46	1.36	1.38	1.35
Gd	3.27	5.77	4.81	8.1	3.6	5.28	6.53	6.05	5.34	4.97	4.99	5.78	5.6
Tb	0.6	1.04	0.8	1.36	0.87	0.86	1.03	1.1	0.94	0.82	0.86	1.03	0.86
Dy	3.79	6.23	4.44	7.76	5.74	4.9	6.04	6.08	5.34	4.7	4.9	5.84	4.87
Ho	0.77	1.24	0.88	1.44	1.12	0.92	1.2	1.15	1.03	0.89	0.93	1.12	0.9
Er	2.33	3.76	2.69	4.05	3.44	2.74	3.65	3.51	2.98	2.67	2.64	3.31	2.72
Tm	0.371	0.573	0.396	0.581	0.559	0.423	0.561	0.53	0.44	0.4	0.378	0.513	0.417
Yb	2.41	3.73	2.55	3.64	3.56	2.89	3.42	3.37	2.82	2.57	2.4	3.29	2.62
Lu	0.363	0.575	0.392	0.504	0.523	0.448	0.476	0.489	0.403	0.39	0.363	0.488	0.424
Σ REE	118.417	206.188	193.248	292.975	94.017	294.781	222.867	217.419	198.963	182.59	187.481	191.011	173.4
LaN/YbN	5.05	7.6	10.49	10.84	2.72	16.47	9.19	8.73	9.7	10.02	11.09	7.36	8.93
Eu/Eu*	0.77	0.73	0.8	0.96	0.67	0.85	0.72	0.66	0.79	0.82	0.76	0.67	0.7

Table 2

Nd and Sm isotopic data for mica schists, quartzofeldspathic rocks, granites and orthogneisses from the Izera-Kowary Unit and the Lusatian greywackes

	Rock	Sample	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd_0	$\varepsilon Nd_{500\ Ma}$	$\varepsilon Nd_{570\ Ma}$	T_{DM} (Ga)	Analyst/References	Sm/Nd
1	Lusatian greywacke (Pl)	ZGORZ	7.11	36.6	0.1173	0.511967 (3)	-13.1	-7.1	-7.4	1.70	C. Pin, this study	0.19
2		WL	6.31	33.2	0.1149	0.511953(4)	-13.4	-8.2	-7.5	1.68		0.19
3	greywacke Lausitz Anticl.	Teu 01	6.4	32.8		0.512021(4)			-6.3		Linnemann & Romer (2002)	0.2
4		Vog 01	5.01	27.6		0.511863(5)			-8.8			0.18
5	mica schist	ZL1	3.35	17.1	0.1186	0.511971 (4)	- 13.1		-7.4	1.72	C. Pin, this study	0.2
6		ZL2	4.66	24.1	0.1168	0.512039 (4)	- 11.7		-5.9	1.58		0.19
7		KROB1	4.69	25.4	0.1117	0.511979 (8)	- 12.9	-7.5		1.59		0.18
8		ZAKR	7.11	48	0.0896	0.511874 (3)	- 14.9	-8.1		1.44		0.15
9		SD1	7.79	41.7	0.1130	0.511961 (6)	- 13.2	-7.9		1.64		0.19
10		LUB1	8.11	41.9	0.1169	0.511968 (4)	- 13.1	-8		1.69		0.19
11		PIL1	6.28	33.7	0.1127	0.511941 (5)	- 13.6	-8.3		1.66		0.19
12		LESZ	7.1	38.9	0.1104	0.511912 (7)	- 14.2	-8.7		1.67		0.18
13	mica schist	98-18	6.24	33.81	0.1115	0.511981(6)	-12.8	-7.4		1.80	Crowley *et al.* (2002)	0.18
14		98-20	3.62	19.54	0.1121	0.511937(8)	-13.7	-8.3		1.86		0.19
15		98-21	4.5	22.49	0.1210	0.511991(6)	-12.6	-7.8		1.78		0.2
16	quartzfelds	B3	0.667	1.94	0.2077	0.512259(2)	-7.4	-8.2		—	C. Pin, this study	0.34
17	Izera granites and ortho -gneisses	SI	6.46	29.3	0.1332	0.512095(8)	-10.6	-6.6		1.80	Oberc-Dziedzic *et al.* (2005)	0.22
18		WR1	8.86	36.3	0.1475	0.512179(14)	-9.0	-5.9		1.99		0.24
19		WR2	15.1	68	0.1345	0.512143(10)	-9.7	-5.7		1.73		0.22
20		PL	6.15	27.2	0.1367	0.512160(7)	-9.4	-5.5		1.75		0.23
21		CH	3.7	15.1	0.1481	0.512205(8)	-8.5	-5.4		1.95		0.25
22		KO	1.09	2.97	0.2219	0.512372(7)	-5.2	-6.9		-		0.37
23		KR	2.8	11	0.1537	0.512191(10)	-8.8	-6.0		2.18		0.25
24		WI	2.58	10.9	0.1428	0.512196(7)	-8.7	-5.2		1.82		0.24
25	Rumburk gran-ite	CS3	1.44	5.01	0.1734	0.512290	-6.8	-5.4		2.9	Kröner *et al.* (2001)	0.29
26		CS4	2.23	9.25	0.1458	0.512290	-6.8	-3.6		1.7		0.24
27		CS5	5.06	27.02	0.1132	0.512151	-9.5	-4.2		1.4		0.19
28	Karkonosze ortho-gneisses	CS6	8.58	42.81	0.1211	0.512151		-4.7		1.5	Kröner *et al.* (2001)	0.2
29		CS7	4.45	22.82	0.1179	0.512125		-5		1.5		0.2
30		CS8	2.38	8.229	0.1751	0.512307		-5.1		3.0		0.29
31	Kowary orthogneisses	K1	2.73	11.1	0.1492	0.512226 (4)	-8.1	-5.1		1.93	C. Pin, this study	0.25
32		PKOW	1.34	5.07	0.1598	0.512251 (4)	-7.6	-5.2		2.25 (Tchur: 1.61)		0.26

Zr/Nb (18.5–4.5) and Nb/Th (0.58–1.44) and most samples also show low ratios of Ce/Pb (1.6–3.30, though Pb is considered as potentially mobile during metamorphism), which is also a characteristic of continental crust (Hofmann, 1988; Wedepohl *et al.*, 1991; Nutman *et al.*, 1999).

Rare earth elements (REE)

In the Izera granites, the absolute abundances of total REE are 101–159 ppm in both the coarse-grained and fine-grained granites (Oberc-Dziedzic *et al.*, 2005). Rare earth element values are higher in the garnet–cordierite and biotite-rich granitoids; they are considerably lower in the gneisses and very low in the biotite-poor or absent granites. Chondrite-normalized REE patterns (Fig. 2b) are very similar in all samples. Typically, they display flat heavy rare earth element (HREE) patterns and a distinct enrichment in light rare earth elements (LREE): $(La/Yb)_N$ 1.93–5.51. In all samples, except those of biotite schlieren, the $(La/Yb)_N$ ratio decreases with decreasing Ce_N, as expected when monazite fractionation occurs. In contrast, the HREE fractionation with changing REE content is very limited. This suggests that zircon fractionation did not play a significant role in producing the final REE values for these rocks. All specimens show a distinct negative Eu/Eu* anomaly (0.11–0.43).

Sm-Nd isotopes

The Izera granites and gneisses display a large range of $^{147}Sm/^{144}Nd$ ratios (0.13–0.22; Table 2), which is tentatively interpreted as the fractionation of a LREE-rich accessory phase (probably monazite), leading to a progressive increase of Sm/Nd ratio in the residual liquid. Initial εNd values (Table 2; Fig. 3) show a limited scatter, from –5.2 to –6.9 (mean: –5.9, SD = 0.6). The lowest εNd value (–6.9) was observed in metasomatically altered leucogranite. Izera granite T_{DM} model ages fall within a fairly narrow range (1.73–2.175 Ga; mean: 1.89 Ga; Table 2; Fig. 3).

MICA SCHISTS AND THE LUSATIAN GREYWACKES

Chemical analyses of schists and greywacke are shown in Table 1. The table includes the previously published analyses of sample WL1 (Oberc-Dziedzic *et al.*, 2005).

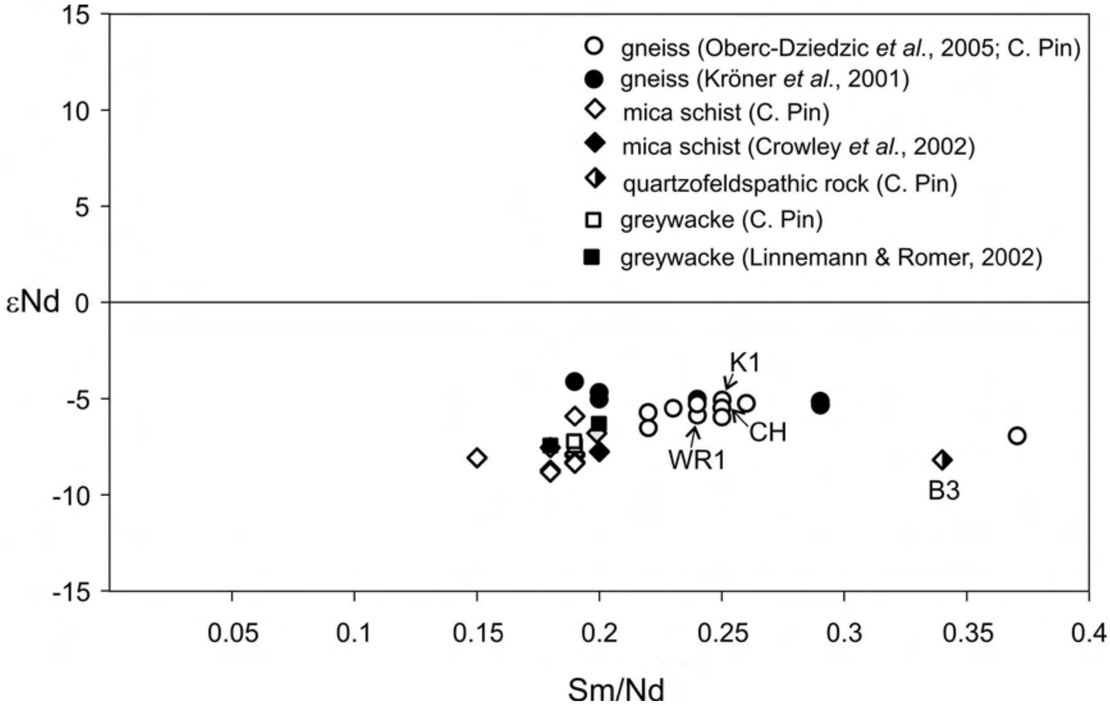

Fig. 3. εNd versus Sm/Nd data compiled for gneisses, mica schists and quartzofeldspathic rock from the Izera–Kowary Unit and for the Lusatian greywackes.

Major elements

The SiO_2 contents in the schists vary between ~ 49% (sample ZAKR) to 68% (PIL1), whereas in the greywackes the range is far more restricted, 61.8–64.8%. The wide range of Al_2O_3 (15–30%) in the mica schists corresponds to variable mica concentrations in these rocks. The Al_2O_3 contents in the greywackes are 15.6–18.0%. The Na_2O values (0.2–3.47) reflect the amount of albite in the mode. There are roughly equal concentrations of Mg in all these schists, but it is noteworthy that there is a considerably higher amount of Fe in the mica schists of the Stara Kamienica and Szklarska Poręba belts compared to the other mica schists and greywackes. Thus, the elevated amount of Fe may reflect the presence of non-silicate Fe minerals, e.g., magnetite (sample ZAKR) or sulphides (KROB2).

Chemical compositions of the mica schists from the Izera–Kowary Unit and the Lusatian greywackes were compared with those of typical sedimentary rocks. In the scheme of Pettijohn *et al.* (1972), the Lusatian greywackes (ZGORZ, WL), the mica schists from the northern part of the KIM (PIL1, PIL2, LUB1), the mica schists from the eastern part of the KIM (LESZ), and one sample of the Złotniki Lubańskie schists, all plot within the greywacke field (Fig. 4a). The remaining samples (KROB1, KROB2) are rich in muscovite and fall beyond this field or even beyond the diagram. In the SandClass system of Herron (1988), all the samples fall into the shale field, except for sample PIL2 which lies in the wacke field (Fig. 4b).

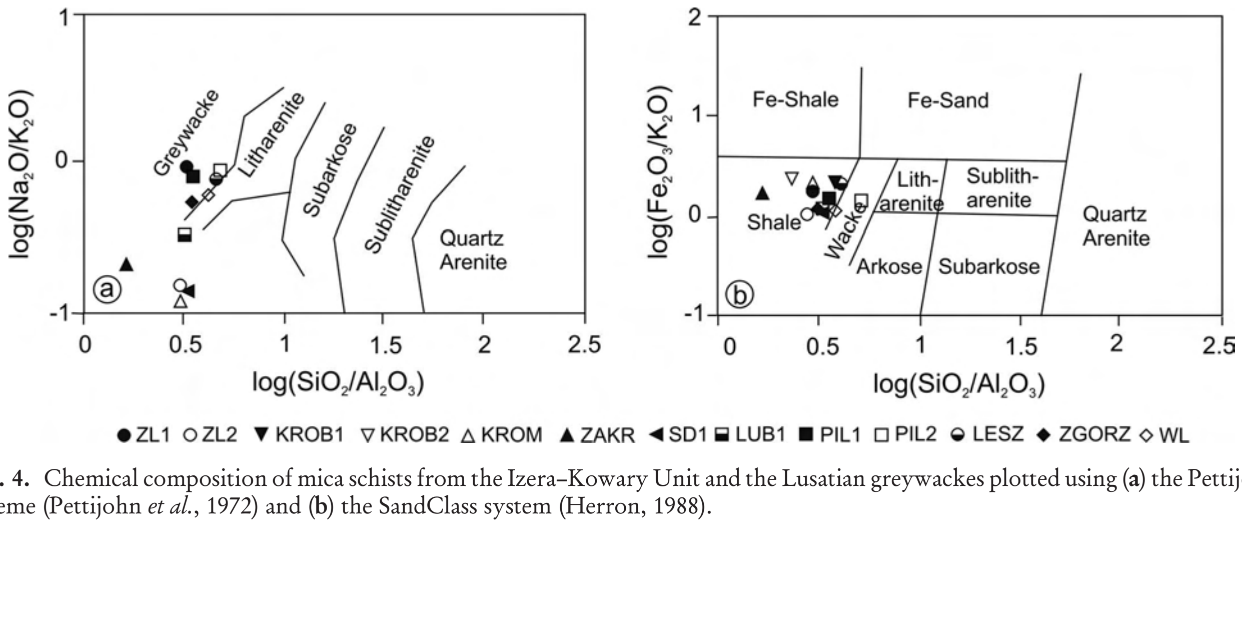

Fig. 4. Chemical composition of mica schists from the Izera–Kowary Unit and the Lusatian greywackes plotted using (**a**) the Pettijohn scheme (Pettijohn *et al.*, 1972) and (**b**) the SandClass system (Herron, 1988).

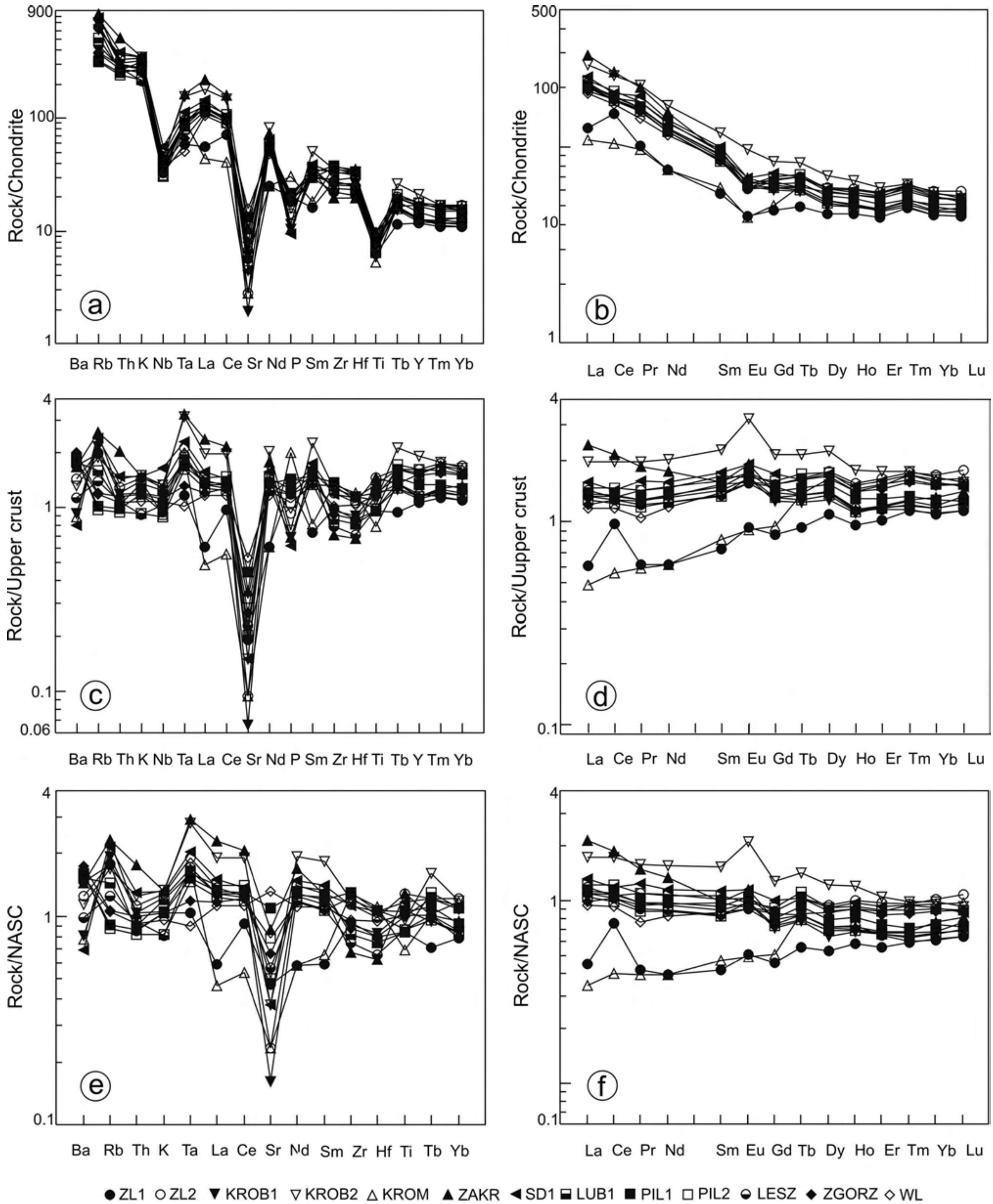

Fig. 5. Multielement diagrams for mica schists from the Izera-Kowary Unit and the Lusatian greywackes. (**a**) Chondrite-normalized multi-element diagram; normalization values of Thompson (1982). (**b**) Chondrite-normalized rare earth element (REE) plot; normalization values of Nakamura (1974) with addition from Haskin *et al.* (1968). (**c**) Upper crust-normalized multi-element diagram; normalization values of McLennan *et al*. (2006). (**d**) Upper crust-normalized REE plot; normalization values of Taylor & McLennan (1985). (**e**) North American Shale Composite (NASC)-normalized multi-element diagram; normalization values of Gromet *et al.* (1984). (**f**) NASC-normalized REE plot; normalization values of Gromet *et al.* (1984) with additions from Haskin *et al.* (1968).

Trace elements

The mica schists and greywackes display, in most cases, strikingly similar concentrations and ratios of trace and rare earth elements (Table 1, Fig. 5), independent of lithostratigraphic unit. The greatest deviations from the general geochemical trend occur for mica schists within a given unit (e.g. KROB1, KROB2 and KROM) or even within the same exposure (KROB1, KROB2 and ZL1, ZL2). On diagrams of trace element concentrations normalized to chondrite (Fig. 5a), all the schist samples show a negative Nb anomaly, considered as typical of the continental crust (Taylor & McLennan, 1985). The distinct Sr anomaly (Figs. 5a, 5c, 5e) reflects the low concentration of this element in the schists (23–155 ppm) and greywackes (94 and 187 ppm), compared with chondrite values (11,800 ppm; Thompson, 1982), upper crustal values (350 ppm; McLennan *et al.*, 2006) and North American Shale Composite (NASC) values (142 ppm; Gromet *et al.*, 1984). The diagrams of trace element concentrations (Fig. 5c), normalized to upper continental crust (McLennan *et al.*, 2006) and to NASC (Gromet *et al.*, 1984), show nearly the same patterns.

The plot of REE normalized to chondrite (Fig. 5b) is characterized by enrichment in LREE, the presence of a small negative Eu anomaly and a flat, nearly horizontal HREE section. The patterns of REE plots normalized to upper crust (Fig. 5d) and NASC (Fig. 5f) are nearly identical: they are very similar for nine of the 13 samples and show flat LREE and HREE patterns and a small positive Eu anomaly. The REE concentration plots for samples KROB2, ZAKR, ZL1 and KROM have not only more complex patterns, reflecting different proportions of particular elements, but also higher (KROB2 and ZAKR) and lower (ZL1 and KROM) bulk concentrations compared with the average REE contents. Samples KROB2 and ZAKR contain significant amounts of opaque minerals, whereas samples ZL1 and KROM, which are depleted in LREE, have considerable contents of chlorite.

The REE distribution pattern in an "average" metasedimentary schist is parallel to the REE pattern of the continental crust (Taylor & McLennan, 1985; McLennan *et al.*, 2006). Mica schists in general display a considerable homogeneity in their REE patterns, with only slight differences for schists of different ages. Our geochemical data from the Izera–Kowary Unit mica schists seem to support this general observation: there are no significant differences in the REE patterns for schists representing different tectonostratigraphic units, in spite of their possibly different ages. The general similarity of the REE plots for the Neoproterozoic, unmetamorphosed Lusatian greywackes and for the mica schists suggests that metamorphic processes do not disturb REE proportions (Mayer *et al.*, 1996, 1997). However, these proportions can be modified by fluids, which may cause chloritization or sericitization (e.g. in sample KROM), or by the crystallization of opaque minerals (KROB2 and ZAKR). The specific REE pattern for sample ZL1 may reflect an admixture of mafic volcaniclastic material in the protolith.

The trace and rare element concentrations and proportions may provide information on the origin of the metamorphic rocks. On the Eu/Eu* vs Gd_N/Yb_N diagram (Taylor & McLennan, 1995; Fig. 6), all the samples of the Izera–Kowary Unit and of the Lusatian greywackes fall within the field of active margin sediments. This field overlaps with the field of cratonic sediments into which fall the Lusatian greywacke samples ZGORZ and WL and the schist samples LUB1, SD1, and ZL2.

In the La/Th versus Hf diagram (Fig. 7), which aims to show sources and compositional discrimination between turbiditic sandstones (Floyd & Leveridge, 1987), the mica schists of the Izera–Kowary Unit and the Lusatian greywackes plot in the acid arc source. The dis-

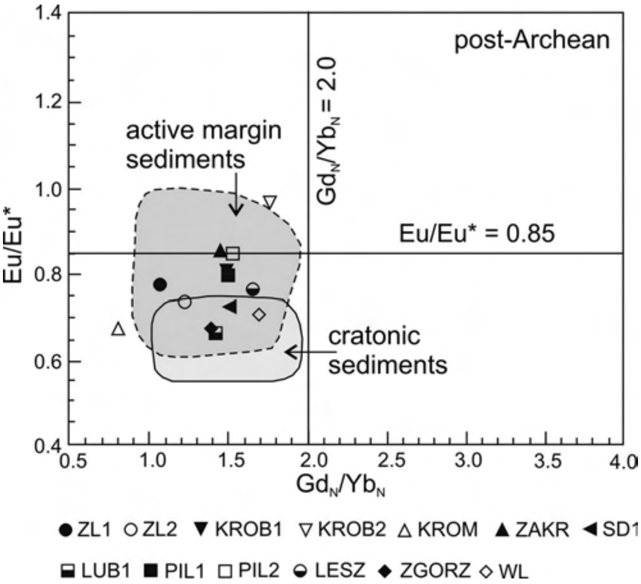

Fig. 6. Plot Eu/Eu* versus Gd_N/Yb_N for mica schists of the Izera–Kowary Unit and the Lusatian greywackes. The grey field corresponds to the "cratonic" sedimentary rocks of various ages (Taylor & McLennan, 1995; McLennan *et al.*, 2006).

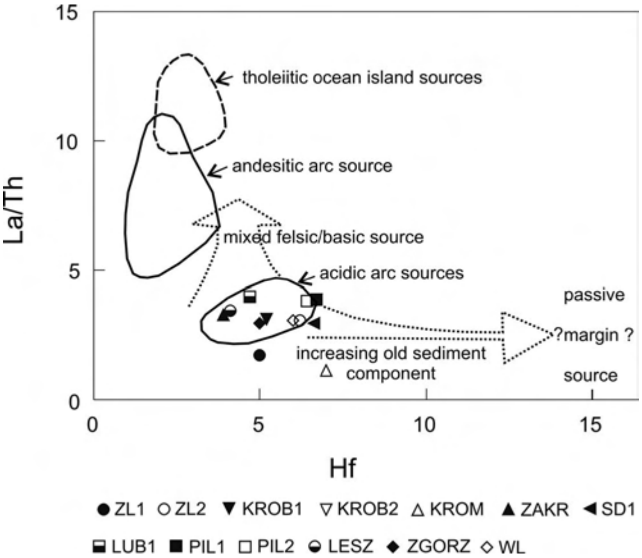

Fig. 7. Izera–Kowary Unit mica schists and Lusatian greywackes plotted on the La/Th versus Hf diagram for source and compositional discrimination of turbiditic sandstones (Floyd & Leveridge, 1987).

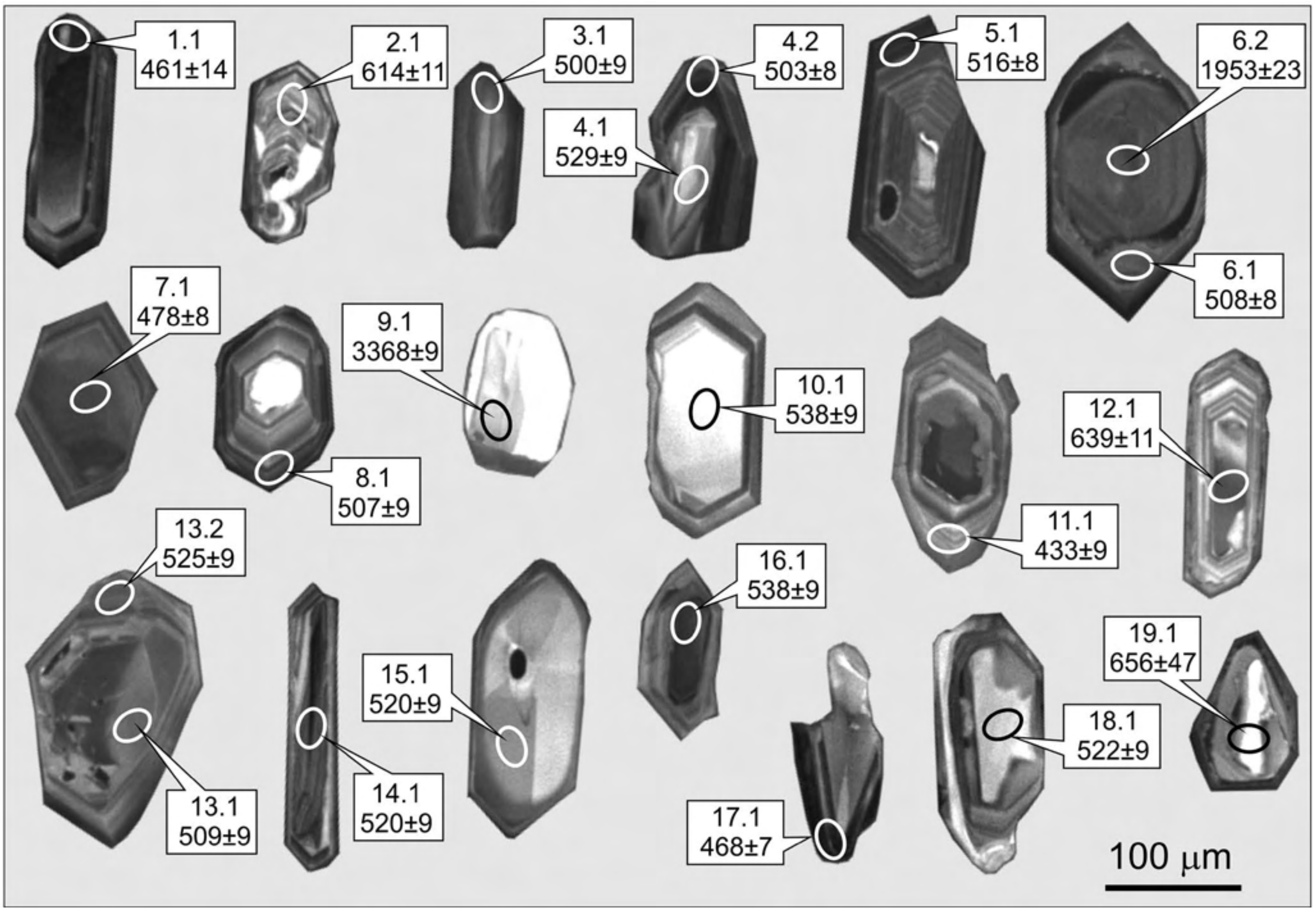

Fig. 8. Cathodoluminescence images of zircons analyzed from the orthogneiss of Chmieleń (sample CH). Various morphological types and various internal structures are represented (see text for further explanation). Analytical points indicated by ellipses (note that magnification is slightly different from grain to grain; an approximate scale bar is given); the identifying spot numbers correspond to those in Table 3; $^{206}Pb/^{238}U$ ages and one σ errors are given.

crimination diagrams for the Izera–Kowary Unit schists and the Lusatian greywackes (Figs. 6 and 7) suggest that the protoliths for these rocks came from active margin, or geochemically similar, settings.

Sm-Nd isotopes

The mica schists from the Izera–Kowary Unit display a very narrow range of $^{147}Sm/^{144}Nd$ ratios (0.111–0.118), an exception being sample ZAKR which shows an even lower value (0.089). Initial εNd_{500} values display a limited scatter, from –7.4 to –8.7 (mean: –7.9, SD = 0.7). The highest value (–5.9) was observed in sample ZL1, which is probably derived from a protolith containing a volcanogenic component (Table 2).

T_{DM} model ages of the schists are very similar (1.44–1.72 Ga; mean of 1.62 Ga) (Table 2). They correspond exactly to the apparent crustal residence ages of 1.4 to 1.7 Ga as defined by Liew & Hofmann (1988) for metamorphic rocks, sediments and granitoids of the Hercynian Fold Belt of Europe.

The Lusatian greywackes have similar $^{147}Sm/^{144}Nd$ ratios (0.115 and 0.117, Table 2) as the mica schists. The εNd_{570} values of –7.4 and –7.5 for the Lusatian greywackes are similar to the mica schists and greywackes from the Lusatian Anticline (Linnemann & Romer, 2002). T_{DM} values of 1.7 and 1.68 are close to the higher values obtained for the mica schists (Table 2).

SHRIMP ZIRCON STUDY

The rock types sampled for SHRIMP analysis were the Izera fine-grained porphyritic granite from Chmieleń (CH, Fig. 1) and the coarse-grained cordierite/pinite-garnet-bearing granite from Wrzeszczyn (WR1, Fig.1). All the ages for both rock types are quoted with errors at the 95% confidence level (2 σ). The $^{207}Pb/^{206}Pb$ ages are, in most cases, very imprecise, therefore the $^{206}Pb/^{238}U$ ages are preferred. These latter ages are more precise when the degree of discordance is small.

SAMPLE CH: IZERA FINE-GRAINED PORPHYRITIC GRANITE FROM CHMIELEŃ

General zircon characteristics

Euhedral, normal- to long-prismatic zircon crystals predominate. They are transparent and colourless, with rather simple (grains 1, 7, 14) or strong (grains 5, 12) zonation (Fig. 8). Some otherwise morphologically similar zircon grains may display indistinct or irregularly structured interiors (grains 2, 11, 16), while others contain rounded or irregular cores (grains 6, 8, 18). Parts of some crystals (grains 17, 18) display a specific, barrel-shape morphology, with two well-developed pyramids, {101} and {211}. Around 10% of the grains are cathodoluminescent bright (grains 2, 9, 10, 15), and a similar proportion are broken, perhaps due in part to the separation procedure.

Age groupings of the CH zircons

The ages that were determined for the Izera zircons from sample CH, based on a total of 22 analyzed points, fall into four groups.

Group 1: 1.95–3.4 Ga

The oldest analysed zircon yielded a slightly reversely discordant data point with a $^{206}Pb/^{238}U$ age of 3442 ± 94 Ma (2 σ) and a $^{207}Pb/^{206}Pb$ age of 3368 ± 18 Ma, which gives a more robust minimum estimate of the initial zircon age. This very old grain is subhedral and is very bright under cathodoluminescence (CL) (Table 3; Fig. 9a). The second oldest age is from an oval-shape core (grain 6.2), which gave a significantly reversely discordant data point (D = –11%) (Table 3). The $^{207}Pb/^{206}Pb$ age of 1953 ± 46 Ma is interpreted as the most realistic minimum age of that grain, which has a euhedral overgrowth with a $^{206}Pb/^{238}U$ age of 508 ± 8 Ma.

Zircon grains 12.1 and 17.1 show a positive discordance (D = +10 and +50, respectively), and their $^{207}Pb/^{206}Pb$ ages (704 and 983 Ma) should be treated as minimum ages. Zircon grain 2.1 has a negative discordance (D = –12) due to its very imprecise $^{207}Pb/^{206}Pb$ ratio (Table 3). For this reason, the $^{206}Pb/^{238}U$ age of 614 ± 22 Ma for grain 2.1 provides a minimum estimate of the crystallization age.

Group 2: Minimum ages between 509 and 538 Ma

This group comprises five points with only small degrees of normal discordance and, consequently, their $^{206}Pb/^{238}Pb$ ages are treated as minimum estimates of the crystallization event: grain 14.1 = 520 ± 17 Ma (D = +7); grain 13.2 = 525 ± 17 Ma (D = +8); grain 4.1 = 529 ± 18 (D = +9); grain 13.1 = 509 ± 18 (D = +14); grain 10.1 = 538 ± 18 (D = +13) (Fig. 9b). Four of these points are located in internal, indistinctly structured and CL moderately bright parts of crystals; one (13.2) is in a rim. They all display moderate $^{232}Th/^{238}U$ ratios, between 0.16 and 0.42, and low common Pb concentrations.

Three grains have nearly concordant data points, with the following $^{206}Pb/^{238}U$ ages: grain 5.1 = 517 ± 16 Ma

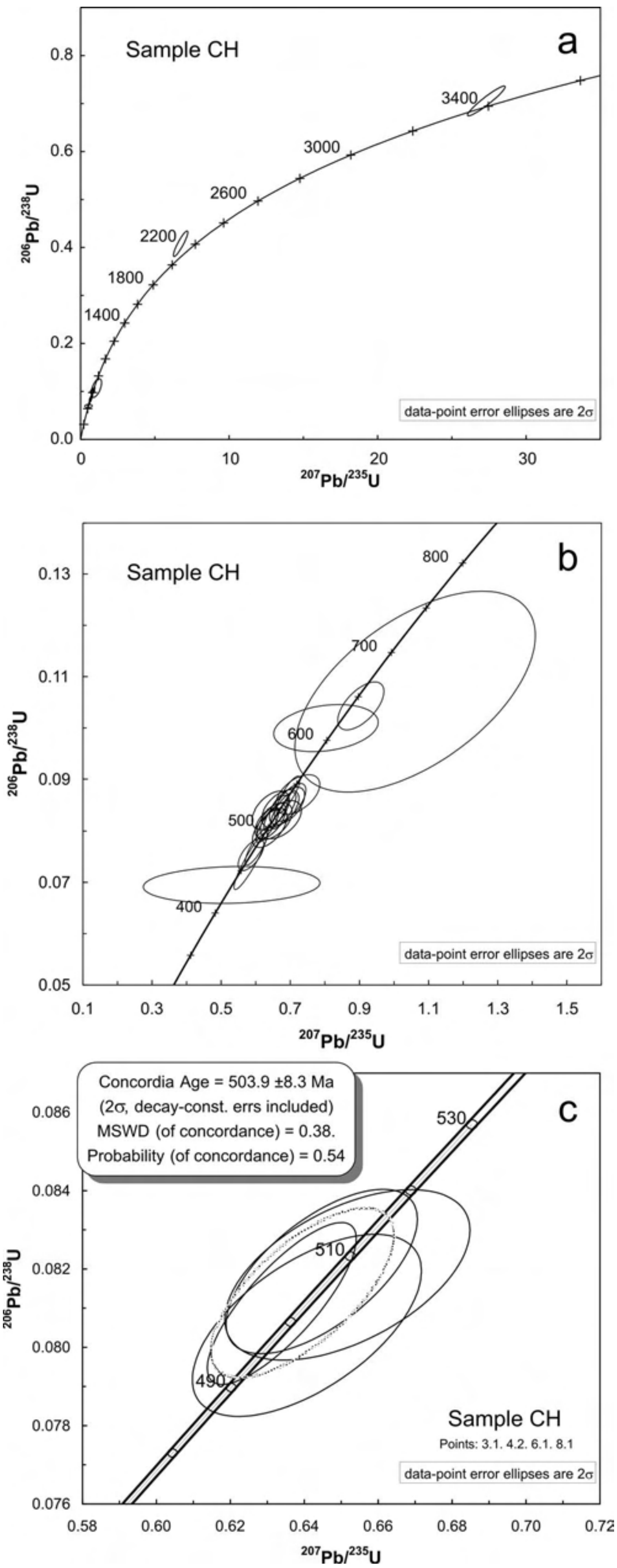

Fig. 9. (**a**) Concordia diagram showing results of SHRIMP II zircon analyses from the orthogneiss of Chmieleń, sample CH; (**b**) mean $^{206}Pb/^{238}U$ age calculated for four nearly concordant points around 500 Ma.

Table 3

SHRIMP data for the granite from Chmieleń, sample CH, and granite from Wrzeszczyn, sample WR1

Spot Name	$^{206}Pb_c$ %	U ppm	Th ppm	$^{232}Th/^{238}U$	$^{206}Pb^*$ ppm	(1)Age $^{206}Pb/^{238}U$ Ma	±	(1) Age $^{207}Pb/^{206}Pb$ Ma	±	D %	(1)$^{207}Pb^*/^{206}Pb^*$	±. %	(1)$^{207}Pb^*/^{235}U$	±. %	(1)$^{206}Pb^*/^{238}U$	± %	err corr
CH 1.1	-	644	43	0.07	41.0	461.2	13.7	499	29	8	0.0572	1.3	0.58	3.3	0.0742	3.1	0.920
CH 11.1	7.37	459	207	0.46	29.6	433.2	8.9	426	437	-2	0.0553	19.6	0.53	19.7	0.0695	2.1	0.107
CH 17.1	0.35	1009	784	0.80	65.6	468.4	7.5	469	44	0	0.0564	2.0	0.59	2.6	0.0754	1.7	0.639
CH 7.1	-	535	37	0.07	35.3	477.5	8.5	485	27	2	0.0568	1.2	0.60	2.2	0.0769	1.8	0.830
CH 3.1	0.13	252	30	0.12	17.5	499.5	9.2	518	56	4	0.0577	2.6	0.64	3.2	0.0806	1.9	0.597
CH 4.2	0.04	676	61	0.09	47.1	502.8	8.1	479	28	-5	0.0567	1.3	0.63	2.1	0.0811	1.7	0.802
CH 8.1	0.31	210	36	0.18	14.8	507.1	8.6	520	63	3	0.0577	2.9	0.65	3.4	0.0818	1.8	0.523
CH 6.1	0.11	377	29	0.08	26.6	507.7	8.3	494	45	-3	0.0571	2.0	0.64	2.6	0.0819	1.7	0.638
CH 13.1	0.26	282	113	0.42	20.0	509.0	8.9	581	68	14	0.0594	3.1	0.67	3.6	0.0822	1.8	0.504
CH 5.1	0.01	401	33	0.09	28.7	516.5	8.3	501	30	-3	0.0572	1.4	0.66	2.2	0.0834	1.7	0.776
CH 14.1	0.02	446	91	0.21	32.1	519.6	8.5	556	32	7	0.0587	1.4	0.68	2.2	0.0839	1.7	0.762
CH 15.1	0.20	199	74	0.38	14.4	519.8	9.0	434	65	-17	0.0555	2.9	0.64	3.4	0.0840	1.8	0.525
CH 18.1	0.15	179	41	0.24	13.0	521.9	8.8	519	61	-1	0.0577	2.8	0.67	3.3	0.0843	1.7	0.532
CH 13.2	0.31	346	56	0.17	25.3	525.0	8.7	568	54	8	0.0590	2.5	0.69	3.0	0.0849	1.7	0.573
CH 4.1	0.08	280	67	0.25	20.6	529.1	8.8	579	44	9	0.0593	2.0	0.70	2.7	0.0855	1.7	0.651
CH 16.1	0.01	550	108	0.20	41.1	537.8	8.7	524	24	-3	0.0579	1.1	0.69	2.0	0.0870	1.7	0.835
CH 10.1	0.18	175	27	0.16	13.1	538.2	9.2	609	67	13	0.0601	3.1	0.72	3.6	0.0871	1.8	0.498
CH 2.1	0.89	182	183	1.04	15.8	614.2	11.0	540	163	-12	0.0583	7.5	0.80	7.7	0.1000	1.9	0.244
CH 12.1	0.13	192	35	0.19	17.2	639.5	11.1	704	51	10	0.0629	2.4	0.90	3.0	0.1043	1.8	0.606
CH 17.1	0.88	149	16	0.11	13.8	655.7	46.6	983	226	50	0.0719	11.1	1.06	13.4	0.1071	7.5	0.558
CH 6.2	0.06	368	154	0.43	129.1	2204.8	50.1	1953	23	-11	0.1198	1.3	6.73	3.0	0.4078	2.7	0.905
CH 9.1	0.02	72	35	0.50	43.4	3441.6	48.0	3368	9	-2	0.2809	0.6	27.32	1.9	0.7055	1.8	0.948
WR1 14.1	0.50	716	36	0.05	45.1	453.7	11.9	497	65	10	0.0571	2.9	0.57	4.0	0.0729	2.7	0.680
WR1 11.1		525	158	0.31	34.8	480.3	7.6	516	27	7	0.0576	1.2	0.61	2.1	0.0774	1.7	0.798
WR1 8.1	0.47	235	55	0.24	15.8	484.3	8.4	496	73	2	0.0571	3.3	0.61	3.8	0.0780	1.8	0.474
WR1 5.1	0.10	446	82	0.19	30.1	486.8	7.8	467	32	-4	0.0564	1.5	0.65	2.5	0.0822	1.7	0.657
WR1 7.1	0.34	127	34	0.27	8.6	488.1	8.5	535	72	10	0.0582	3.3	0.63	3.7	0.0787	1.8	0.485
WR1 16.1	0.54	244	36	0.15	16.6	489.2	8.1	441	72	-10	0.0557	3.2	0.61	3.7	0.0788	1.7	0.471
WR1 16.2	0.02	1753	26	0.02	118.9	489.9	8.0	482	14	-2	0.0567	0.6	0.62	1.8	0.0790	1.7	0.936
WR1 6.2	0.17	207	31	0.16	14.1	490.8	8.4	497	58	1	0.0571	2.6	0.62	3.2	0.0791	1.8	0.561
WR1 6.1	0.25	238	62	0.27	16.2	491.9	8.3	532	57	8	0.0581	2.6	0.63	3.1	0.0793	1.8	0.558
WR1 10.1	0.20	235	78	0.34	16.2	495.5	8.4	486	47	-2	0.0568	2.2	0.63	2.8	0.0799	1.8	0.633
WR1 2.2	0.26	235	31	0.14	16.2	497.1	8.2	565	65	14	0.0589	3.0	0.65	3.4	0.0802	1.7	0.502
WR1 13.1	0.27	337	66	0.20	23.3	498.4	9.1	560	37	12	0.0588	1.7	0.65	2.6	0.0804	1.9	0.744
WR1 17.1	0.00	407	28	0.07	28.4	503.6	8.0	506	27	0	0.0574	1.2	0.64	2.1	0.0812	1.7	0.802
WR1 17.2	-	204	55	0.28	14.2	504.3	8.4	561	65	11	0.0588	3.0	0.66	3.5	0.0814	1.7	0.499
WR1 8.2	0.04	904	54	0.06	63.5	506.4	8.1	498	65	-2	0.0572	3.0	0.64	3.4	0.0817	1.7	0.490
WR1 4.1	0.06	361	32	0.09	25.5	509.0	8.2	522	42	3	0.0578	1.9	0.65	2.5	0.0822	1.7	0.657
WR1 12.1	0.14	339	34	0.10	24.0	509.9	9.0	550	36	8	0.0585	1.7	0.66	2.5	0.0823	1.8	0.742
WR1 1.1	0.04	609	67	0.11	43.5	514.5	8.3	525	26	2	0.0579	1.2	0.66	2.0	0.0831	1.7	0.817
WR1 2.1	0.25	384	26	0.07	27.6	516.8	8.3	514	51	0	0.0576	2.3	0.66	2.9	0.0835	1.7	0.587
WR1 15.1	0.10	502	188	0.39	39.3	562.6	8.9	585	30	4	0.0595	1.4	0.75	2.2	0.0912	1.7	0.764
WR1 9.1	0.48	316	151	0.49	25.3	572.5	9.4	477	94	-17	0.0566	4.3	0.73	4.6	0.0929	1.7	0.373
WR1 3.1	0.84	42	81	2.00	10.7	1669.2	71.7	1766	72	6	0.1080	4.0	4.40	6.3	0.2955	4.9	0.777

Errors are 1 σ; Pb_c and Pb* indicate common and radiogenic portions. respectively. Error in Standard calibration was 0.47% (not included in above errors but required when comparing data from different mounts).
(1) Common Pb corrected using measured ^{204}Pb.

(D = –3); grain 18.1 = 522 ± 18 Ma (D = –1); grain 16.1 = 538 ± 17 (D = –3). These points represent different parts of the analysed zircon crystals: the first (grain 5.1) is in a CL dark margin, whereas the two others are in a CL bright core (grain 18.1) and a CL dark core (16.1). There is also a contrast between these grains in their $^{232}Th/^{238}U$ ratios: grain 5.1 = 0.09; grain 18.1 = 0.24; grain 16.1 = 0.20.

Group 3: ~ 500–508 Ma, average concordia age 503.9 ± 8.3 Ma (2σ)

This group comprises four analytical points (Fig. 9c) with slightly discordant ages: grain 3.1 = 500 ± 18 Ma (D = + 4); grain 4.2 = 503 ± 16 Ma (D = –5); grain 8.1 = 507 ± 17 Ma (D = +3); grain 6.1 = 508 ± 16 (D = –3). All these points are located in marginal parts of crystals and all have low $^{232}Th/^{238}U$ ratios between 0.08 and 0.18. These features indicate a possible late-stage magmatic or metamorphic origin for these zircon margins.

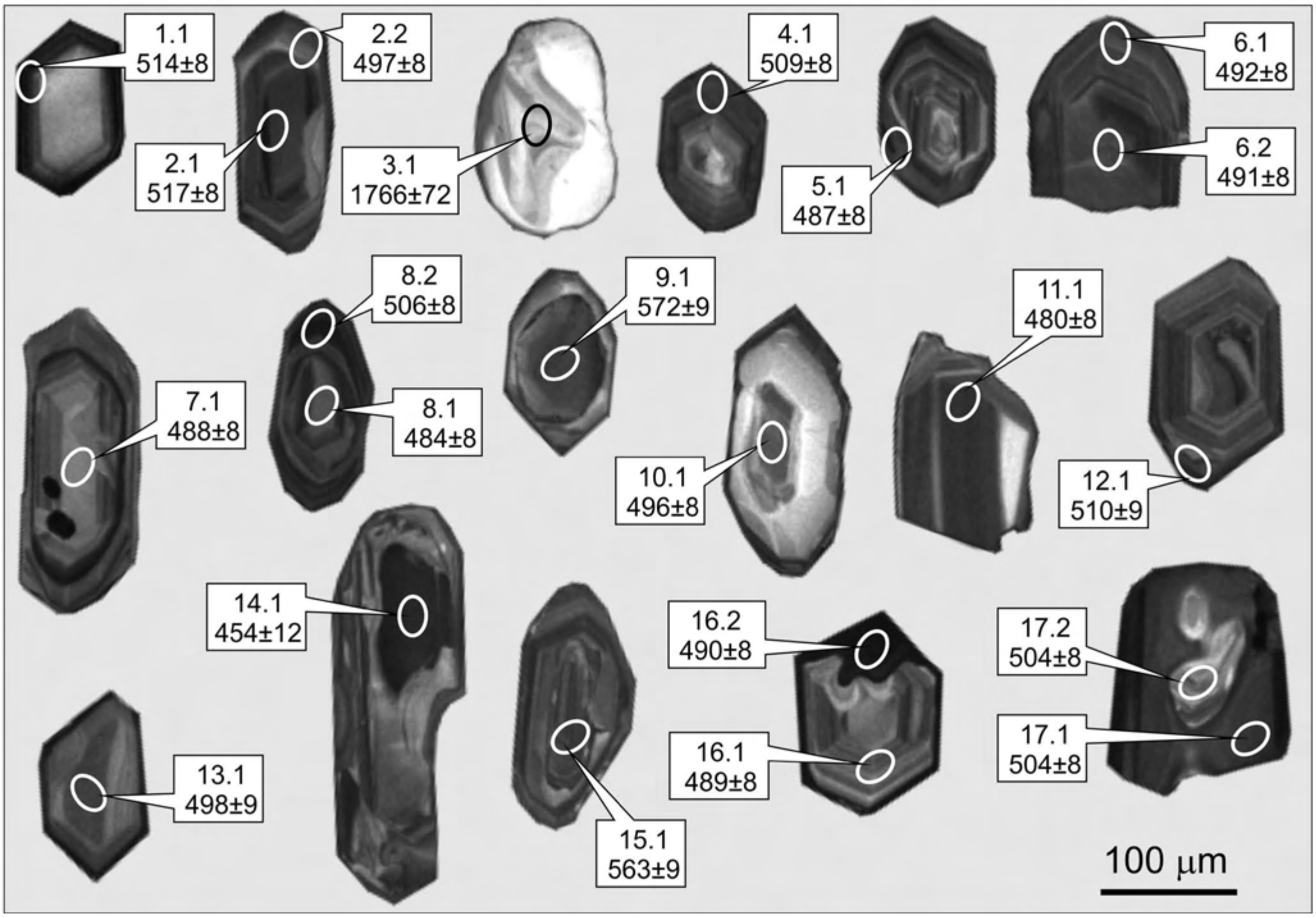

Fig. 10. Cathodoluminescence images of zircons analyzed from the orthogneiss of Wrzeszczyn (sample WR1). Analytical points indicated by ellipses (approximate scale bar is given); the identifying spot numbers correspond to those in Table 3; $^{206}Pb/^{238}U$ ages and one σ errors are given.

Group 4: ~ 461–478 Ma

These youngest grains (excluding point 11.1, which has an extremely large error and high Pb_c content of 7.37%) are all reasonably concordant (D between 0 and +8%) with the following $^{206}Pb/^{238}U$ ages: grain 1.1 = 461 ± 27 Ma (D = +8); grain 17.1 = 468 ± 15 Ma (D = 0); grain 7.1 = 478 ± 17 Ma (D = +2). The oldest point in this group was measured in the core of a euhedral and rather structureless crystal, whereas the remaining three were found in the rims of zoned euhedral crystals. The chemical and isotopic characteristics of these three points are diverse: $^{232}Th/^{238}U$ varies from 0.07 to 0.80. The oldest point is close, within analytical error, to Group 3. The simplest interpretation is that the points comprising Group 4 reflect grains belonging to the older groups, but which suffered variable degrees of radiogenic lead loss.

Conclusions for the CH zircons

1. The Izera fine-grained porphyritic granite from Chmieleń (sample CH) contains one inherited zircon of Archean age (3.4 Ga), which is also one of the oldest zircons found in the Bohemian Massif; one of Palaeoproterozoic age (~ 2.0 Ga); and two of Neoproterozoic age, but with rather imprecise minimum ages of ~ 600–700 Ma. The latter two points are relatively discordant.

2. Sample CH contains a distinct population of zircons that are 500–508 Ma old. Their features suggest that they are late-stage magmatic (or even metamorphic) zircons. A few $^{206}Pb/^{238}U$ ages are older, ~ 517–538 Ma, and these may represent either inheritance of zircons of that age or result from analytical overlapping of the main population of ~ 500 Ma with older zircons.

3. The youngest zircon ages for sample CH are rather widely dispersed between 461 and 478 Ma, with two points at ~ 465 Ma. These youngest ages are mostly found in the very rims of grains, probably reflecting variable degrees of radiogenic lead loss from ~ 500 Ma or older zircons.

SAMPLE WR1: THE COARSE-GRAINED CORDIERITE/PINITE-GARNET-BEARING GRANITE FROM WRZESZCZYN

General zircon characteristics

The zircons are normal-prismatic, euhedral, rarely subhedral or broken, and mostly colourless and transparent (Fig. 10). Grains 2.4, 2.5, 2.6, 2.8 and 2.9., among others, have a specific "rounded" barrel shape, indicating the presence of two pyramids, {101} and {211}. Many grains

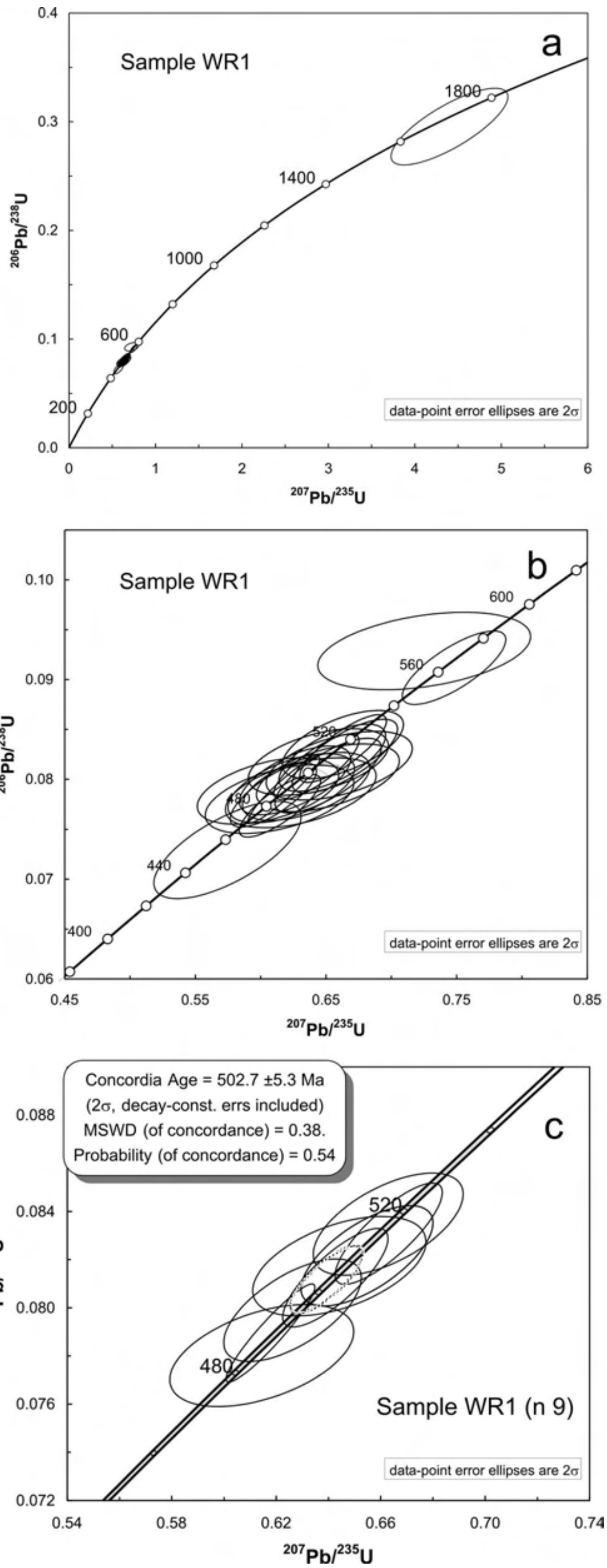

Fig. 11. Concordia diagram showing results of SHRIMP II zircon analyses from the orthogneiss of Wrzeszczyn, WR1.

display regular recurrent zonation (grains 2.12, 2.4, 2.5, 2.6, 2.7, 2.8). In a few crystals, a core-type structure is present either as a rounded body (grains 2.7 and 2.9), or a CL dark, more irregular field (grains 2.14 and 2.2). Grains 2.10 and 2.3 are exceptionally CL bright; grain 2.3 has a distinctive oval habit.

Age groupings of the WR1 zircons

The ages that were determined for the Izera zircons from sample WR1, based on a total of 22 analyzed points, fall into three groups.

Group 1: Minimum age of ~ 1.8 Ga

One grain, 3.1, yielded a moderately discordant data point with a Palaeoproterozoic minimum $^{207}Pb/^{206}Pb$ age of 1766 ± 144 Ma (Table 3, Fig. 11a). This grain is exceptional: rounded in shape, very CL bright and with a thin dark overgrowth. It is relatively U-poor (42 ppm) and has a very high $^{232}Th/^{238}U$ ratio of 2.0.

Group 2: Minimum ages of ~ 560–580 Ma

A single grain, 15.1, gives a slightly discordant point with a $^{206}Pb/^{238}U$ age of 563 ± 18 Ma, identical within analytical uncertainty to its $^{207}Pb/^{206}Pb$ age of 585 ± 60. This suggests a late Neoproterozoic crystallization age. Another grain, 9.1, with a similar $^{206}Pb/^{238}U$ age of 572 ± 18 Ma, shows a reverse discordance of –17, which is interpreted to reflect the imprecise determination of ^{207}Pb ($^{207}Pb/^{206}Pb$ age of 477 ± 184 Ma). Both 15.1 and 9.1 points are within weakly structured and moderately CL bright cores. Both are relatively high in Th (188 and 155 ppm), with moderate $^{232}Th/^{238}U$ ratios of 0.39 and 0.49, respectively.

Group 3: Concordant ages of ~ 484–517 Ma

Six analytical points (grains 12.1, 17.2, 13.1, 2.2, 6.1 and 7.1) have $^{206}Pb/^{238}U$ ages dispersed between ~ 488 and 510 Ma (Table 3, Fig. 11b).Their normal degree of discordance, between +8 and +10, is probably insignificant, taking into account the large analytical uncertainty of $^{207}Pb/^{206}Pb$ ages (typically ± 60 to 130 Ma, at the 95% confidence level). The same interpretation might hold for the discordant grain 11.1, which has a minimum $^{206}Pb/^{238}U$ age of 480 ± 16 Ma and a $^{207}Pb/^{206}Pb$ age of 516 ± 54 Ma (D = +7): some radiogenic lead loss cannot be precluded. The 7 points of this group are located both in cores and rims of zircon crystals, and they all have rather constant and not too high $^{232}Th/^{238}U$ ratios of 0.10 to 0.31.

A cluster of 10 analytical points (grains 2.1, 1.1, 4.1, 8.2, 17.1, 10.1, 6.2, 16.2, 5.1, and 8.1) have nearly concordant ages and are widely scattered between 484 and 517 Ma; discordance varies between –4 and +3. The average concordia age for this group is 503 ± 5 Ma (2 σ) (Fig. 11c). However, the oldest ages could be "contaminated" by overlap with inherited portions of crystals as well as with their younger parts; thus, grains with slight normal discordance may, in fact, be a little older. The analytical overlap question cannot be resolved without analysing a larger set of grains and/or increasing the degree of age resolution permitted by the SHRIMP technique. The 10 points are located both in internal and marginal parts of zircon grains, with various CL brightness and structural patterns. They have rather low $^{232}Th/^{238}U$ ratios (0.07–0.34) with the minimum value of 0.02 in point 16.2, which is also relatively high in U and may signify late-magmatic or metamorphic zircon overgrowth.

Finally, grain 14.1 has a CL dark core and gives a younger $^{206}Pb/^{238}U$ age of 454 ± 24 Ma. It has a relatively high Pb_c of 0.50% and very low $^{232}Th/^{238}U$ ratio of 0.05. This grain also has a high positive discordance, indicating that the true age is probably approximated by the minimum $^{207}Pb/^{206}Pb$ age of ~ 500 Ma.

Conclusions for the WR zircons

1. Inherited components in the coarse-grained cordierite/pinite-garnet-bearing granite from Wrzeszczyn (sample WR1) comprise three ages: one at 1.8 Ga, and two at ~ 563 Ma. The latter two come from two similar grains, with similar chemical and isotopic features, suggesting that these zircons grew during the Cadomian orogeny.

2. The major groups of zircons in sample WR1 yielded an average concordia age of 503 ± 5 Ma. Their rather wide dispersion of ages, from 484 to 517 Ma, may reflect a prolonged magmatic/metamorphic crystallization. Secondary disturbances could have been caused by, for example, deformation and metamorphism, or simply analytical overlap with zircon domains containing a small inherited component.

3. The single younger $^{206}Pb/^{238}U$ age of 454 ± 24 Ma found in the core of grain 14.1 probably reflects radiogenic lead loss from a ~ 500 Ma old zircon.

DISCUSSION AND CONCLUSIONS

The main goal of our study was to show petrological and age relationships between orthogneisses from different parts of the Karkonosze–Izera Massif based on new SHRIMP data and the results of previous geochronology (Oliver *et al.*, 1993; Kröner *et al.*, 2001; Oberc-Dziedzic *et al.*, 2010). We also wanted to shed light on an important problem in the KIM region, that of correlating the geographically different mica schists that often surround the orthogneisses, as well as determining the relationship between these mica schists and the Neoproterozoic Lusatian greywackes (Fig. 1). We have addressed these problems, at least in part, by integrating geochemical data and Nd-isotopic characteristics of the orthogneisses, schists and greywackes. Combining all published data (Kröner *et al.*, 2001; Crowley *et al.*, 2002; Linnemann *et al.*, 2004; Oberc-Dziedzic *et al.*, 2005) and our new Nd isotopic results (Table 2), we try to answer the question of whether the protoliths of the Lusatian greywackes and the mica schists (or, more realistically, rocks similar to them occurring at deeper crustal levels) could have been the source materials for the Izera–Kowary Unit granites (orthogneisses).

Current opinion is that the Izera and Kowary gneiss (Fig. 1; K1) protolith has an igneous character (Żelaźniewicz *et al.*, 2003; Oberc-Dziedzic *et al.*, 2003). Both the gneisses and their undeformed granite varieties show similar mineral composition and may grade into similar structural and textural features. However, igneous cordierite (pinite) and garnet, which are fairly common in the Izera granites, have not yet been reported from the undeformed varieties of the Kowary gneiss. The Izera and Kowary gneisses are calc-alkaline and peraluminous rocks, with features typical of S-type granites (Oberc-Dziedzic *et al.*, 2005; Pin *et al.*, 2007; Oberc-Dziedzic *et al.*, 2010). The S-type character of the Izera and Kowary gneisses is supported by their peraluminosity (A/CNK = 1.0–1.63 for the Izera gneisses/granites; 1.1 for the Kowary gneiss), their high normative corundum (up to 3.5% in the Izera gneisses/granites, and 1.8% in the Kowary gneiss), and their high $^{87}Sr/^{86}Sr$ initial ratios (Borkowska *et al.*, 1980). The Kowary gneiss and Izera gneisses/granites are relatively rich in potassium. Ratios of K_2O/Na_2O are comparable for both the Kowary gneiss (1.26, see Oberc-Dziedzic *et al.*, 2010) and the coarse-grained Izera granites (1.2–1.8, see Oberc-Dziedzic *et al.*, 2005). The Izera gneisses/granites and Kowary gneisses also show similar trace element and REE characteristics. In chondrite-normalized diagrams for selected trace elements and REEs, the Ko- wary gneiss plots within the range of the Izera gneisses/ granites (Fig. 2a, 2b), its lower part corresponding to the strongly deformed Izera gneisses (Oberc-Dziedzic *et al.*, 2005).

The εNd_{500} values of –5.2 to –6.9, and T_{DM}-model ages of 1.73–2.175 Ga obtained for the Izera granites and gneisses (Oberc-Dziedzic *et al.*, 2005; Table 2) are similar to values for the Kowary gneisses (–5.1 and –5.2, T_{DM} = 1.93). The εNd_{500} values given by Kröner *et al.* (2001) for other equivalents of the Izera gneisses, such as the Rumburk granite (–4.2 to –5.4) and the Karkonosze gneisses (–4.7 to –5.1) approach to lower values of the Izera granites, but the T_{DM}-model ages of 1.4–3.0 Ga (Kröner *et al.*, 2001) for these equivalents are more dispersed.

The T_{DM} ages between 1.50 and 1.93 Ga calculated for the granites and gneisses of the Izera–Kowary Unit should not be taken as evidence for their derivation from Mid-Proterozoic crust. They more likely reflect the average of several detrital components mixed into the granitoid sources, although no significant mantle material was added at the time of magma generation (Pin *et al.*, 2007).

The SHRIMP data presented in this study are in a good agreement with previous sets of observations and data: the well established late Cambrian–early Ordovician magmatism that took place in the West Sudetes; the dating of the Izera gneisses at 515–480 Ma (Borkowska *et al.*, 1980; Korytowski *et al.*, 1993; Oliver *et al.*, 1993; Żelaźniewicz, 1994; Kröner *et al.*, 2001); the single-zircon ages of the Karkonosze gneiss obtained by the evaporation and vapor transfer methods (Kröner *et al.* 2001); and the SHRIMP zircon dating of the Kowary gneiss (Oberc-Dziedzic *et al.*, 2010).

The best defined population of zircons in the samples from both Chmieleń (CH) and Wrzeszczyn (WR1) in the

Izera gneisses is ~ 500 Ma old. Zircon characteristics suggest that they are late-stage magmatic (or even metamorphic) crystals. The wide dispersion of ages in sample WR1 may reflect a prolonged magmatic/metamorphic crystallization, secondary disturbances caused by, for example, deformation and metamorphism or, partly, analytical overlap with inherited zircons. A few zircon ages in sample CH are older, ~ 517–538 Ma, and these represent either inheritance of that age or they result from analytical overlapping of the main population of ~ 503 Ma with older domains. However, the 535 Ma Izera gneiss reported by Korytowski *et al.* (1993) was interpreted as the youngest rock measured of the Lusatian granitoids.

The inherited zircons fall into three Precambrian periods: Palaeoarchean (up to 3.4 Ga, and representing one of the oldest zircons found in the Bohemian Massif – sample CH); Palaeoproterozoic (1.8 Ga – sample WR1) and Neoproterozoic (~ 556–609 Ma in sample CH, and 563 Ma in sample WR1). The latter indicate a Cadomian (Panafrican) age of zircon growth.

A previous zircon SHRIMP age of 487 ± 8 Ma has been interpreted as the intrusion age of the protolith of the Kowary gneisses (Oberc-Dziedzic *et al.*, 2010). This age is comparable, within error, to the new ages for the Izera gneisses presented in this paper and is similar to the U-Pb multigrain-zircon ages of ~ 492–481 Ma reported by Oliver *et al.* (1993). The inherited components in the Kowary gneiss are represented by one zircon core of Palaeoproterozoic age (2.0 Ga). Two zircons that fall within the "Cadomian range" (587–653 Ma) are similar to those documented from the Izera gneisses.

The Izera and Kowary gneisses are products of deformation of the same group of mid Cambrian–lower Ordovician granites. However, their average ages differ by about 15 Ma, which may reflect the duration of early Palaeozoic granitic magmatism.

The complex age spectra of inherited zircons that occur in the Izera–Kowary Unit gneisses support the conclusion that their T_{DM} ages of between 1.50 and 1.93 Ga (Table 2) do not give the "real" age of their source but, instead, reflect the average of several detrital components mixed into the granitoid sources (Pin *et al.*, 2007). The inherited zircons that occur in these rocks (3.4 Ga, 1.95 Ga, 1.8 Ga, 0.65–0.54 Ga, see Oberc-Dziedzic *et al.*, 2010 and this study) point to the presence of old, most likely multiply recycled, crustal components in the source of the ~ 500 Ma granitoid magma (Pin *et al.*, 2007). Inherited igneous zircons of ~ 540 Ma suggest a young depositional age for any volcaniclastic sediments and/or the intrusion age of any S-type granitoids that themselves formed the source materials of the 500 Ma granitic magma (Pin *et al.*, 2007). However, this would be the case only if these ~ 540 Ma zircons are interpreted in terms of inheritance from the deep-seated magma sources. Alternatively, these older grains might be xenocrysts caught by the ascending melt en route through the crust to its shallow emplacement level.

The age of deposition of the Lusatian greywackes has been estimated to be between 570 and 540 Ma (Linnemann *et al.*, 2004). The spectrum of SHRIMP zircon ages in the greywacke from Oßling (Linnemann *et al.*, 2004) comprises Archean and Palaeoproterozoic ages ranging from 2.4 to 1.9 Ga, and Neoproterozoic ("Cadomian") ages of ~ 730–540 Ma. Similar zircon ages of 640–620 Ma and of 580–557 Ma have been reported from a metatuffite intercalation in the Złotniki Lubańskie mica schists (Żelaźniewicz *et al.*, 2003). The similarity of zircon ages from both complexes supports the hypothesis that the Złotniki Lubańskie schists are metamorphic equivalents of the Lusatian greywackes that have been embedded within the Izera gneisses (Berg, 1935; Kozłowski, 1974; Oberc-Dziedzic, 1988; Chaloupský *et al.*, 1989).

The age of mica schists from other outcrops in the Izera–Kowary Unit is unknown. However, the new geochronological data obtained for the felsic metavolcanogenic quartzofeldspathic rock embedded into the mica schists of the Velká Úpa Group in the eastern part of the KIM indicate that they are late Cambrian/early Ordovician rather than Neoproterozoic (Oberc-Dziedzic *et al.*, 2010). The zircon age spectra are distributed mainly between ~ 500 and 660 Ma (with a few Proterozoic inherited minimum ages of ~ 970 and 1825 Ma). Younger zircon dates, dispersed between ~ 412 and 464 Ma, are interpreted as a result of Pb-loss likely caused by subsequent, but as yet undefined, metamorphism. Consequently, the felsic metavolcanic rocks and their enclosing mica schists appear to be roughly contemporaneous with, or possibly younger than, the intrusion of ~ 500 Ma orthogneiss protoliths. The age of the mica schists exposed along the border of the KIM and the Kaczawa Unit is still uncertain.

Nevertheless, and despite of the age differences, the Lusatian greywackes and the mica schists of the Izera–Kowary Unit display similar geochemical characteristics. In the major element greywacke classification schemes of Pettijohn *et al.* (1972; Fig. 4a) and Herron (1988; Fig. 4b), most Lusatian greywackes fall into the field of greywacke and shale. The Lusatian greywackes and the mica schists also show similar trace element and REE characteristics. The patterns in the chondrite-, upper crust-, and NASC-normalized multielement and REE diagrams are nearly the same for most samples (Fig. 5).

In the binary plots Eu/Eu* *vs.* Gd_N/Yb_N (Taylor & McLennan, 1995; Fig. 6) and La/Th against Hf (Floyd & Leveridge, 1987; Fig. 7), all samples of greywacke and schist fall in the field of active margin sediments (Fig. 6) and acid arc sources (Fig. 7). This broadly agrees with previous assessments for the origin of the Lusatian greywackes whereby they were thought to be deposited in a convergent-margin basin off northern peri-Gondwana (Kemnitz, 2007). However, the younger sediments that were transformed into mica schists may represent reworked older greywackes, with some admixture of younger materials. Their active margin signature is, therefore, likely to be mostly inherited. It might also come from intercalations of tuffaceous greywackes derived from reworked, older basic volcanic material (Kemnitz, 2007).

The geochemical similarity of the Lusatian greywackes and mica schists suggests that both could have been derived from the same source. However, the presence of Cambrian–lower Ordovician products of within-plate volcanism, represented by intercalations of quartzo-feldspathic rocks and amphibolites in the mica schists, supports the idea that the protoliths of the mica schists derived mainly from crustal rocks containing an admixture of contemporaneous volcanic materials.

The Nd-isotopic records in the Lusatian greywackes and in the gneisses of the Izera–Kowary Unit are very homogeneous. The T_{DM} range for the upper Neoproterozoic greywackes is the same as for the upper Cambrian/lower Ordovician granitic protoliths of the gneisses. It may point to similar source materials of both rock types. In contrast, the εNd_{500} values of the gneisses, –5.2 to –6.9, are distinctly higher than the εNd_{570} values of –6.8 to –8.8 and the εNd_{500} values of –7.1 to –8.2 for the greywackes (Table 2). Given the lack of evidence for any significant input of direct mantle material at the time of granitic magma generation, the shift of εNd values in the gneisses may be caused by the addition of volcaniclastic materials to the source rocks of the granites. Such volcaniclastic materials are present as intercalations in the Lusatian greywackes. Consequently, the Lusatian greywackes, or sediments of similar characteristics, could have been the source rocks for the granitic protoliths of the Izera–Kowary Unit gneisses. This interpretation is supported by the complex age spectra of the inherited zircons that are typically observed in these rocks.

In conclusion, the data in this paper reveal a close geochemical similarity between all the mica schists in the Izera–Kowary Unit and the Lusatian greywackes, which could help in making regional correlations and palaeo- tectonic reconstructions. The age spectra of inherited zircons from the Izera gneisses and these zircon's Nd-isotopic signatures, when compared with the Lusatian greywackes, suggest that the Lusatian (or similar) rocks could have been the source material for the granitic protoliths of the Izera–Kowary Unit orthogneisses.

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Appendix: SHRIMP analytical procedure

In situ U-Pb analyses were performed on a SHRIMP-II at the Centre of Isotopic Research (CIR) at the All-Russian Geological Research Institute (VSEGEI); a secondary electron multiplier in peak-jumping mode was applied, following the procedure described in Williams (1998) and Larionov *et al.* (2004). A primary beam of molecular oxygen was employed to ablate the zircon and so sputter secondary ions. The elliptical analytical spots had a size of $\sim 27 \times 20\ \mu m$; the corresponding ion current was $\sim$ 4 nA. The sputtered secondary ions were extracted at 10 kV. The 80 μm–wide slit of the secondary ion source, in combination with a 100 μm multiplier slit, allowed a mass-resolution of $M/\Delta M > 5000$ (1% valley), thereby resolving all possible isobaric interference. One-minute rastering over a rectangular area of $\sim 60 \times 50\ \mu m$ was employed before each analysis in order to remove the gold coating and possible surface common-Pb contamination.

The following ion species were measured in sequence: $^{196}(Zr_2O)$–^{204}Pb–background Pb (~204 a.m.u)–^{206}Pb–^{207}Pb–^{208}Pb–^{238}U–^{248}ThO–^{254}UO, with integration times ranging from 2 to 20 seconds. Each spot underwent four analytical cycles. Every fifth analysis was carried out on the zircon Pb/U standard TEMORA 1 (Black *et al.*, 2003) that has an accepted $^{206}Pb/^{238}U$ age of 416.75 ± 0.24 Ma. The 91500 zircon standard with a U concentration of 81.2 ppm and a $^{206}Pb/^{238}U$ age of 1062.4 ± 0.4 Ma (Wiedenbeck *et al.*, 1995) was applied as a "U-concentration" standard. The collected results were then processed using the SQUID v1.12 (Ludwig 2005a) and ISOPLOT/Ex 3.22 (Ludwig, 2005b) software and decay constants of Steiger and Jäger (1977). The common lead correction was done using measured ^{204}Pb according to the model of Stacey and Kramers (1975).

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