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ORIGINAL PAPER

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Early Palaeozoic crustal melting in an extensional setting: petrological and Sm–Nd evidence from the Izera granite-gneisses, Polish Sudetes

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Abstract The Izera Block in the West Sudetes, which is composed of granites, gneisses (and transitional granite-gneisses) and minor mica schists, is one of the largest outcrops of Early Palaeozoic (ca. 500 Ma) metagranitoid rocks in the basement units of the Variscides of Central Europe. The Izera granites show S-type features: magmatic cordierite, relict garnet and sillimanite, lack of mafic enclaves, and absence of coexisting tonalites and diorites. The paucity of pegmatites indicates that the granitic magma was relatively dry. The S-type character of these granites is further supported by their peraluminous character (A/CNK 1.0–1.63), high content of normative corundum (up to 3.5%) and relatively high $^{87}Sr/^{86}Sr$ initial ratio. The chemical variation of these rocks was controlled by the fractional crystallization of plagioclase (CaO, Sr, Eu/Eu*), biotite and cordierite (Al_2O_3, MgO, FeO), zircon (Zr, Hf) and monazite (REE). Initial ϵNd values range from −5.2 to −6.9 (mean: −5.9, SD = 0.6). These largely negative ϵNd values imply that the granitic magmas emplaced ca. 500 Ma were extracted from a source reservoir that was strongly enriched in LREE (i.e., with low Sm/Nd ratio) on a time-integrated basis. The relatively consistent depleted mantle model ages (1,730–2,175 Ma; mean: 1,890 Ma) is in agreement with the earlier reported presence of ca. 2.1 Ga old inherited Pb component in zircon from the closely related Rumburk granite. This points to an old (Early Proterozoic) crustal residence age of the inferred metasedimentary protoliths of the Izera granitoids, with only minor contribution to their protoliths of juvenile components of Late Proterozoic/Early Palaeozoic age. Although the Izera granites show some trace element features reminiscent of syn-collisional or post-collisional granitoids, they more likely belong to the broad anorogenic class. Our data corroborate some previous interpretations that granite generation was connected with the Early Palaeozoic rifting of the passive margin of the Saxothuringian block, well documented in the region by bimodal volcanic suites of similar age (Kaczawa Unit, eastern and southern envelope of the Karkonosze–Izera Block). In this scenario, granite magmatism and bimodal volcanism would represent two broadly concomitant effects of a single major event of lithospheric break-up at the northern edge of Gondwana.

Keywords Granitoids · Gneisses · Geochemistry · Nd isotopes · Tectonic setting · Sudetes

Introduction

The Izera Complex (IC), which is defined here as the rock assemblage forming the Izera Block in the West Sudetes (Fig. 1), composed of granites and gneisses (and transitional textural varieties termed here granite-gneisses), is one of the largest outcrops of the Early Palaeozoic metagranitoid rocks, characteristic and widespread in the basement units of the Variscides of Central Europe. The granites and gneisses are deformed to various degrees and display rather complex interrelationships, which led to various, often controversial interpretations (for a review of earlier concepts, see Oberc-Dziedzic 1988). The most intriguing questions concerning the origin and evolution of these rocks include:

a. Magma sources and primary igneous processes (homogenous vs. heterogeneous sources, metasedimentary vs. (meta)igneous protoliths and their characteristics, relative contribution of mantle and crustal materials, etc.).

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b. Geodynamic significance of granite generation and inferred emplacement settings: continental rift, supra-subduction, syn-collisional or post-collisional environments, etc.
c. The country rocks of the granites and their pre-intrusion structural-metamorphic history.
d. The post-intrusive evolution of the rock complex: deformation and metamorphism of the granites and their country rocks.
e. Timing of the processes: pre-intrusive, syn-intrusive and post-intrusive events, the latter including the major Variscan deformation, metamorphism and magmatism.

Kröner et al. (2001) studied single zircon $^{207}Pb/^{206}Pb$ ages and whole-rock Nd isotopic systematics of the so-called "granitoid gneisses" in several rock complexes in the Czech West Sudetes (Jizerské hory, Krkonoše Mountains, and Orlice-Sněžnik Complex). They interpreted these rocks as having been generated in a volcanic arc setting related to an important and regionally extensive post-Cadomian magmatic event (single zircon ages interpreted to reflect the time of emplacement of the "granitoid gneiss" protolith ranging between 502 Ma and 515 Ma). That magmatic event was thought to have been connected to continental arc magmatism on the active margin of Avalonia during the closure of the Tornquist Ocean. Based on Nd mean crustal residence ages (Arndt and Goldstein 1987; Liew and Hofmann 1988), varying between 1.5 Ga and 1.7 Ga, the same authors suggested that the "granitoid gneisses" were largely generated by melting of predominantly Grenville-age basement that was inferred to be part of the northern margin of Gondwana. Different models, preferring continental rift rather than magmatic arc settings were proposed by several authors (Kryza and Pin 1997; Crowley et al. 2000, 2002).

In this paper, we present Sm–Nd data on granites and gneisses of the large Polish part of the IC, the major outcrop not covered by the Kröner et al. (2001) study. We also use new trace and REE data combined with other field and petrological evidence to better constrain various aspects of the petrogenesis of these rocks, in particular to clear up the problems of magma sources for the granites and palaeotectonic setting of their emplacement.

Geological setting

The IC (Fig. 1) is situated in the northern part of the Karkonosze–Izera Massif. To the south, it is bordered by the Variscan Karkonosze granite, which thermally affects the Izera gneisses and mica schists. To the north and northeast, the IC is separated from the low-grade metamorphic Kaczawa Unit by the Intra-Sudetic Fault Zone. To the west, the IC borders to the Lusatian Massif; the contact between the Lusatian granodiorites of Neoproterozoic (Cadomian) age and the Early Palaeozoic Rumburk–Izera granites (the latter representing undeformed varieties of the Izera gneisses) is intrusive.

The IC is composed mainly of porphyritic—coarse-grained granites and augen gneisses, and fine-grained granites and gneisses, all derived from 515 Ma to 480 Ma intrusives (Borkowska et al. 1980; Korytowski et al. 1993; Oliver et al. 1993; żelaźniewicz 1994). Relatively dark granodioritic gneisses are typical of the western part of the IC. All types of gneisses enclose lenses of coarse-grained, porphyritic granites. Most of these lenses can be considered as undeformed parts of granitic protoliths of the gneisses, but some of them display intrusive contacts, which are evidence of possible two Early Ordovician magmatic episodes separated by a tectonic event. The gneisses and granites locally contain small (up to several meters thick) variously deformed basic dykes.

The granitoid protoliths of the Izera gneisses, the undeformed remnants of which are the so-called Rumburk granites (also known as the Izera granites), intruded the 587–540 Ma (żelaźniewicz et al. 2003) granodiorites of the Lusatian Massif to the west. In addition to this, they also intrude Neoproterozoic metasedimentary and metavolcanic rocks (Berg 1923; Achramowicz and żelaźniewicz 1998) of 640–557 Ma age (żelaźniewicz et al. 2003), which are preserved as the three belts of mica schists, up to several 100 m wide. The presence of enclaves of laminated plagioclase gneisses in the coarse-grained Izera granites and enclaves of mica schist with porphyroblastic biotite in the fine-grained Izera granites (Oberc-Dziedzic 1988) documents that the country rocks of the Izera granite comprised not only mica schists but also older gneisses, deformed and metamorphosed before the granite emplacement, i.e., before the Early Ordovician.

The belts of mica schists divide the IC into three parts, which can be interpreted, based on lithological and structural arguments, as different depths of the original granitoid body. The northern, probably the deepest part of the body, north of the Zotniki Lubańskie Belt (Fig. 1), is composed of coarse-grained granites, flaser gneisses and granodioritic gneisses. The middle part, between the Zotniki Lubańskie Belt and the Stara Kamienica Belt, comprises mainly augen gneisses, coarse-grained granites and thin but long bodies of fine-grained granites and gneisses parallel to the schist belts; it may represent the middle level of the granitic body. In the southern part, the fine-grained gneisses and granites are the most widespread: this part apparently corresponds to the uppermost or outer part of the original intrusion. Characteristically, small bodies of leucogranites occur along the southern side of the schist belts.

The foliation in the gneisses strikes NW–SE, dipping at a steep angle either to the NE or to the SW. The foliation surfaces in the gneisses and locally common basic dykes are usually parallel and concordant with the lithological boundaries of these rocks. The stretching lineation dips mainly to the NW at moderate angles but

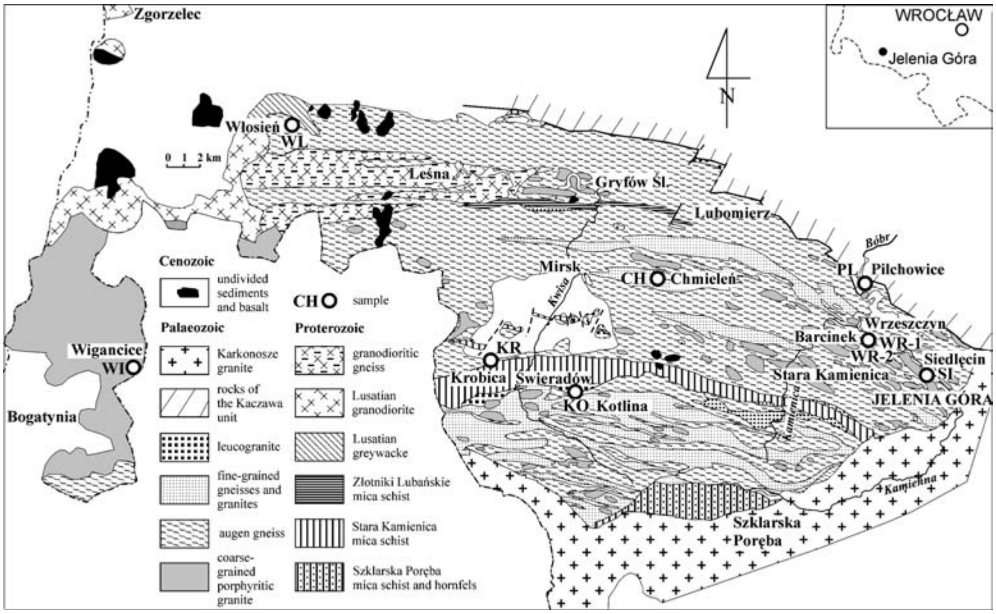

Fig. 1 Geological map of the Izera Block (Oberc-Dziedzic 2003 and references therein)

the NE, SW and SE orientations are also present. Oberc (1967) divided the IC into domains in which the lineation shows uniform orientation, often different in neighbouring domains; this interpretation explains such a distribution as an effect of superimposed folding.

Mazur (1995) proposed a model of two ductile deformation events. The Late Devonian penetrative shearing D_1 event was associated with the northwest-directed thrusting and progressive metamorphism. It produced penetrative foliation S_1 and the NW–SE trending stretching lineation in gneisses and mica schists. The next deformation event D_2 that occurred under mid-grade to low-grade metamorphic conditions (Kryza and Mazur 1995), was expressed by the east–southeast directed extensional collapse. The late stage of D_2 was coeval with the Karkonosze granite emplacement, ca. 328 ± 12 Ma (Pin et al. 1987; Duthou et al. 1991), and regional doming which resulted in the reorientation of D_1 structures on the flanks of the dome.

According to żelaźniewicz et al. (2003) the IC, being a part of the Lusatian–Izera unit, belonged to a passive margin of the Saxothuringian, which rifted off the West Gondwana during the Ordovician. In Early Devonian times, the Lusatian–Izera unit was to be influenced by a mantle plume, which caused extension and rifting accompanied by injections of basic dykes. The injections continued with the progressive extensional deformation of the country rocks. The deformation of the IC, which resulted in the development of steeply dipping shear zones and mylonites, was interpreted to have occurred during three stages: (1) normal slip—to sinistral transtensional stage with an overall transport direction top-to-the NE/N/NW, (2) dextral transpressional stage with the transport top-to-the SE/E, and (3) compressional stage.

In some other models, which are largely based on observations from neighbouring units, the IC with the Lusatian Massif, form the structurally lower elements of a tectonic stack of WNW directed thrust units (Mazur and Kryza 1996; Collins et al. 2000; Seston et al. 2000).

Petrography

The IC comprises of several types of granites, which represent undeformed parts of an Early Palaeozoic batholith. Based on geological and petrographic premises (Oberc-Dziedzic 2003), we suppose that the batholith was composed of granites with poorly expressed foliation and lineation. The most widespread coarse-grained granite forms several varieties, which differ in grain size, the contents of magmatic cordierite (always transformed into pinite), K-feldspar megacrysts and restite minerals. The coarse-grained granite contains enclaves of gneisses and fine- to medium-grained granites. The marginal parts of the batholith were composed of leucogranites and fine-grained, porphyritic cordierite-bearing granites with small xenoliths of mica schist. Very similar fine-grained granites also formed long, narrow bodies, within the coarse-grained, porphyritic granites (Fig. 1). These bodies are aligned parallel to the magmatic foliation of coarse-grained granites, and often contain lenses of coarse-grained granites. The observed complicated relationships between the coarse-grained and fine-grained granites suggest that the former could intrude in at least two stages, which overlapped at the time of the fine-grained granite formation. The porphyritic, coarse-grained granite was cut by thin leucocratic granite veins and by centimetre thick veins of fine-grained to medium-grained, cordierite granites.

The coarse-grained granites (Fig. 1, samples: SI, PL and WI) are porphyritic, rapakivi-like and usually grey-blue rocks due to the colour of quartz and microcline. Microcline megacrysts are 3–5 cm long, locally exceed-ing 10 cm. Occasionally, white plagioclase rims are developed. The coarse-grained matrix is composed of blue or grey quartz, plagioclase, microcline, black biotite clusters and prismatic pinite pseudomorphs after cordierite up to 2 cm in length. Rectangular shape plagioclase grains are frequently zoned with cores more calcic (An_{17}) than rims (An_{10}). The cores are often replaced by epidote-sericite aggregates, whereas the outer zones are myrmekitic. Locally, the outer part of plagioclase crystals, and, less often, also large pinite pseudomorphs, contain small garnet grains. Brown to brown–red pleochroic biotite encloses zircon, epidote and opaque inclusions. Biotite clusters are accompanied by large grains of apatite and ilmenite rimmed by leucoxene. The biotite is occasionally replaced by muscovite and epidote. The microcline of the matrix always occurs as xenomorphic grains, the larger ones being perthitic. Amidst the matrix constituents, fine-grained aggregates of quartz, biotite and plagioclase are found, the latter being strongly altered and myrmekitic at their contact with microcline.

A variety of the coarse-grained granites, the cordierite (pinite)-garnet-bearing granitoid (Fig. 1, sample WR-1) contains only scarce or no microcline. This rock is composed of euhedral, strongly altered plagioclase rimmed by fine myrmekite. Fairly abundant pinite hosts numerous garnet and, locally, sillimanite inclusions. Garnet is also encountered at the outer parts of plagioclase grains and along mica clusters.

The coarse-grained porphyritic granites contain scarce schlieren and enclaves. Dark schlieren are composed of biotite flakes, up to 5 mm in size, tabular plagioclase, quartz, pinite and sparse microcline (Fig. 1, sample WR-2). Light schlieren are very fine-grained and rich in micrographic intergrowths. Enclaves of fine-grained and medium-grained granitoids are several cm up to 1 m large. They are spherical, ellipsoid and "loaf-like" in shape, and they all consist of quartz, plagioclase, microcline, biotite, muscovite and pinite in varying proportions. They can be interpreted as autoliths.

The coarse-grained granites are cut by thin veins of fine-grained to medium-grained granites rich in K-feldspar. The latter differ from the fine-grained granites described below in that they display a coarser-grained texture and uniform distribution of biotite. Their characteristic feature is the presence of pinite and, less frequently, garnet and sillimanite relics.

The fine-grained granites (Fig. 1, sample CH) are grey rocks with random or weakly ordered fabric. They contain megacrysts of quartz, biotite, plagioclase and microcline and, locally, prisms of pinite. The fine-grained groundmass (grain size below 0.5 mm) is composed of plagioclase and microcline, which contain abundant quartz inclusions. Outer parts of some microcline megacrysts show micrographic texture.

Leucogranites (Fig. 1, sample KO) are whitish rocks composed of quartz and either albite alone or albite and K-feldspar and almost completely devoid of biotite (Kozowski 1974). The K-feldspar is mainly perthitic microcline partly replaced by chessboard albite. The primary albite grains show albite twinning. Albite forms also partly chessboard, and partly simply twinned crystals. In some leucogranites, a late generation of microcline with a distinct twin network is found. In some cases, it overgrows an earlier perthitic K-feldspar. Some leucogranites are rich in tourmaline.

Pegmatites are scarce in the IC. They form small nests-like or irregular bodies within the pinite-bearing porphyritic granites. Their inner parts contain large crystals of K-feldspar, quartz, muscovite and tourmaline. The marginal parts of the pegmatites are rich in feldspar + blue quartz intergrowths.

Gneisses form several varieties: flat-lensoid gneisses, streaky-laminated gneisses, augen-laminated gneisses, augen gneisses and granite-gneisses (with a weak gneissic texture). Apart from the various textures, they differ in mineral and chemical composition and degree of deformation. The augen gneisses (Fig. 1, sample KR) represent the most common variety often grading into granite-gneisses. The augen gneisses often occur in association with augen-laminated gneisses. The foliation of the augen gneisses is mainly defined by matrix domains composed of plagioclase, quartz and biotite. The matrix domains surround microcline phenocrysts, usually 1.5–3 cm (maximum 10 cm) long.

A greywacke of the Lusatian Block was included in our set of samples for comparative purposes (Fig. 1, sample WL). This is a grey or grey-greenish massive rock, composed of angular grains of quartz and albite of 0.3–0.8 mm in size. It also contains small flakes of sericite, detrital apatite and zircon, and newly formed tourmaline.

Mineralogical and petrological evidence of magma origin and emplacement conditions

In all the varieties of the Izera granites, including those in enclaves and veins, variable mineral assemblages of cordierite + garnet + sillimanite, sillimanite + garnet, or garnet alone are present (Oberc-Dziedzic 1988). The cordierite is always replaced by pinite partly recrystallised into muscovite. In the coarse-grained granites, the pinite pseudomorphs form large, 1–2 cm-long grains rather than inclusions in other minerals, indicating that the original cordierite was an important rock-forming mineral. The veins of medium- to fine-grained granites, however, frequently contain quartz grains with pinite inclusions. Both the euhedral shape of cordierite crystals as well as their size, which varies concordantly with the grain size of the host rock, point to their cotectic magmatic origin (Clarke 1995) and growth during the crystallization of a melt (Oberc-Dziedzic 1991). This process took place at various emplacement levels (Wall et al. 1987), but at pressures less than 5 kbar (Johannes and Holtz 1996).

Garnet forms two types. The first one, containing 18.5–29.5% of grossular component, overgrows biotite.

The same type of garnet, accompanied by sillimanite, occurs as inclusions in magmatic cordierite. The second type of garnet, having 32–44% of grossular component, forms inclusions in plagioclase (Oberc-Dziedzic 1991).

It is likely that the first type of garnet, sillimanite, and part of biotite, as well as scarce corroded cores of plagioclase represent relics derived from the granite protolith. The chemical composition of the first type of garnet, resembling that of garnets from granulites and mica schists, suggests a crustal affinity of the protolith, which was subjected to high-grade metamorphism (Achramowicz and żelaźniewicz 1998). The origin of the second type of garnet is not clear (restitic phase?).

The presence of magmatic cordierite and relict Al-rich minerals, such as garnet and sillimanite, points to the S-type character of the Izera granites, which is also evidenced by the conspicuous lack of mafic enclaves and any associated tonalites/diorites.

The paucity of pegmatites further suggests that the parental magma of the Izera granites was relatively dry. Although the formation of pegmatites does not require elevated water contents (London 1996), the scarcity of pegmatites and aplites in the Izera granitoids is symptomatic and unlike what is commonly observed in typical leucogranites.

Whole-rock geochemistry

The assessment of major element characteristics is based on the 62 published analyses of the Izera granites and gneisses collected from Polish and Czech publications (Oberc-Dziedzic 1988 and references therein). Whole-rock major and trace element data, including REE elements were also obtained from nine new samples in Actlabs, Canada using combined XRF and ICP-MS techniques (routine "LITHORES 4"). The latter set includes: seven samples of granites, one sample of gneiss and one sample of the Lusatian greywacke (Fig. 1; Table 1).

The same new specimens, excluding the greywacke sample, have been analysed for Sm–Nd isotope systematics, following procedures described by Pin and Santos Zalduegui (1997). The analytical data are listed in Table 2 together with initial $^{143}Sm/^{144}Sm$ ratios expressed as ϵNd_i values corrected for in situ decay of ^{147}Sm assuming an igneous emplacement age of 500 Ma (cf. Oliver et al. 1993) and model ages relative to the depleted mantle model of De Paolo (1981a, 1981b).

Major elements

The Izera granites and gneisses are generally potassium-rich (Fig. 2), but medium and low potassic varieties are also found. Most of the granites and gneisses are calcic (Fig. 3) and mostly peraluminous rocks with A/CNK as high as 1.0–1.63 (Fig. 4) and high, up to 3.5%, content of normative corundum. Only the youngest leucocratic granite veins show peralkaline/metaluminous character, possibly due to metasomatic changes.

The Izera granites show two kinds of chemical trends, which are reflected in their mineral composition. The first trend displays a decrease in Al_2O_3, MgO, FeO_{tot}, and TiO_2, as well as Na_2O and CaO, with increasing SiO_2 (Fig. 5a–c, e–h), which, mineralogically coincides with a systematic decrease in cordierite (pinite), biotite and plagioclase contents. Projection points of coarse-grained granites on these diagrams (Fig. 5) are scattered along the whole trend, probably reflecting the magmatic differentiation (Oberc-Dziedzic 2003). The projection points of fine-grained granites also follow the trend, but they are concentrated at high values of SiO_2.

The second kind of chemical diversity in the Izera granites is the observed wide range of their K_2O contents, mostly from 2% to more than 7% (exceptionally up to 9.4%). Following this variation, the granites can be arranged into a sequence which on the basis of increasing K_2O/Na_2O is: (I) coarse-grained granites rich in cordierite and garnet and devoid of K-feldspar (K_2O/Na_2O = 0.58–0.95); (II) enclaves of medium-grained granites with K_2O/Na_2O ratio about 1.4; (III) coarse-grained granites (1.2–1.8); (IV) fine-grained granites (1.6–1.9); (V) veins of fine- to medium-grained granites (2.64–2.77); (VI) veins of leucocratic granites (2.48–3.12; Oberc-Dziedzic 1988). The increase of K_2O/Na_2O ratio in the sequences I–V can be interpreted as a result of magmatic differentiation and/or removing of restitic phases. The lack of distinct correlation between (K_2O + Na_2O) and SiO_2 (Fig. 3), and between K_2O and SiO_2 (Figs. 2, 5d) may point to late-stage metasomatic alteration of the solid rocks (Kozowska-Koch 1965) and/or to chemical changes connected with deformation and fluid infiltration. However, the high contents of K_2O in veins of leucocratic granites VI can be, in part (?) connected with metasomatic processes.

The augen gneisses are chemically and mineralogically less diversified than the granites. They display higher average contents of alkalis and more variable K_2O/Na_2O ratio than the granites (Oberc-Dziedzic 1988) probably due to selective element mobility during deformation.

The major elements characteristics of the Izera granites and their mineral composition are typical of the cordierite-bearing peraluminous granitoids (CPGs) according to Barbarin classification (1996, 1999). On the A–B diagram (Barbarin 1996), they show a trend roughly similar to the Australian S-type granites (Fig. 6). Such a trend is characterised by a decrease of peraluminosity with differentiation, which is reflected by decreasing cordierite contents. The peraluminous character of the Izera granites is also well highlighted by the CaO/Na_2O versus Al_2O_3/TiO_2 diagram of Sylvester (1998, Fig. 7). In this diagram, the Izera granites overlap

Table 1 Major (wt%) and trace element (ppm) whole-rock analyses of the Izera granites, gneiss and the Lusatian greywacke

Sample	SI	WR-1	WR-2	PL	CH	KO	KR	WI	WL
SiO_2	72.3	64.23	65.19	70.46	74.76	78.6	77.00	73.01	64.75
TiO_2	0.41	0.35	1.28	0.34	0.19	0.09	0.16	0.29	0.79
Al_2O_3	13.36	18.7	14.18	14.74	13.66	12.88	12.01	13.9	15.59
Fe_2O_3	2.87	3.49	7.84	2.48	1.61	0.14	1.66	2.37	5.59
MnO	0.04	0.05	0.06	0.03	0.03	0.01	0.02	0.03	0.06
MgO	0.78	0.86	2.03	0.65	0.29	0.04	0.29	0.47	2.42
CaO	1.5	3.13	1.37	1.58	0.93	0.47	0.54	0.93	1.07
Na_2O	2.64	4.63	2.21	3.21	3.02	7.36	2.86	2.9	2.09
K_2O	4.05	2.5	4.04	4.96	5.09	0.00	4.57	5.05	3.63
P_2O_5	0.19	0.4	0.37	0.16	0.18	0.25	0.18	0.2	0.23
LOI	1.12	1.46	1.69	1.72	0.65	0.22	0.86	0.8	2.62
Total	99.26	99.8	100.26	100.33	100.41	100.06	100.15	99.95	98.84
A/NK	1.5	1.8	1.8	1.4	1.3	1.1	1.2	1.4	2.1
A/CNK	1.2	1.2	1.3	1.1	1.1	1.0	1.1	1.2	1.7
Cr			48						53
Ni			52						
Co	42	28	41	29	34	32	45	42	24
Sc	6	6	20	7	4	2	5	5	13
V	33	30	97	24	8			15	71
Cu	12	12	31				27	24	18
Pb	19	12	10	26	22		16	15	34
Zn	34		100				54		90
Sn	5	4	2	3	3	2	7	4	3
Ge	1.4	1.7	1.7	1.3	1.7	2.5	3.2	1.6	1.5
Mo							5		
W	286	191	244	206	272	244	378	354	115
Sb				0.2	0.2		0.2	0.4	1.8
As	6	53			10				15
Bi		0.3					0.1		0.2
Rb	156	168	261	176	259	6	246	259	132
Cs	2	11.9	7	2.4	11	0.1	2.9	12.7	4.7
Ba	578	117	296	678	373		77	369	987
Sr	115	116	66	92	54	39	37	58	187
Be	3	11	5	3	3	1	2	3	3
Tl	0.98	1.08	1.64	1.01	1.97		1.55	1.58	0.86
Ga	18	27	25	18	17	17	17	19	19
Ta	0.96	1.03	2.03	0.9	1.19	2.58	1.69	1.5	1.01
Nb	9.6	11.1	29.4	10	8.6	14.3	10.6	11.1	13
Hf	5.8	6.9	16.5	4.9	3.3	2.9	3.7	4.3	6
Zr	178	195	508	140	86	64	92	111	193
Y	48	52	104	42	32.6	13.3	32.6	36.3	24.8
Th	14.5	18.4	46.4	17.1	12.1	10.5	12.3	14.4	11.4
U	4.17	5.33	5.24	4.88	8.37	6.49	10.8	7.57	3.02
La	29	37	72.9	29.9	18.3	1.51	10.9	21.6	35
Ce	62.7	82.7	166	64.5	40	4.56	25.6	47.7	74.7
Pr	6.12	8.22	16.4	6.17	3.83	0.56	2.46	4.61	7.35
Nd	25.1	33.4	70.9	25.2	15.1	2.83	9.61	18.6	30.4
Sm	5.84	8.38	15.9	6	3.81	1.12	2.64	4.56	6.21
Eu	0.835	0.876	0.569	0.855	0.473	0.064	0.137	0.521	1.35
Gd	6.54	8.74	16.3	6.27	4.13	1.42	2.89	4.97	5.6
Tb	1.3	1.7	3.1	1.22	0.9	0.34	0.73	1.02	0.86
Dy	7.98	10.1	18.7	7.52	5.75	2.14	5.18	6.36	4.87
Ho	1.63	1.8	3.63	1.49	1.12	0.42	1.07	1.27	0.9
Er	5.1	5.29	11.3	4.56	3.52	1.34	3.61	3.96	2.72
Tm	0.797	0.771	1.77	0.704	0.578	0.239	0.663	0.63	0.417
Yb	4.52	4.49	10.1	3.99	3.36	1.56	3.99	3.69	2.62
Lu	0.678	0.63	1.54	0.584	0.498	0.235	0.573	0.528	0.424
Σ REE	158.1	204.1	409.1	159.0	101.4	18.3	70.1	120.0	173.4
La_N/Yb_N	4.29	5.51	4.83	5.01	3.64	0.65	1.83	3.91	8.93
Eu/Eu*	0.42	0.31	0.11	0.43	0.37	0.16	0.15	0.34	0.7

the strongly peraluminous Hercynian granites, which suggests their similar origin. The Hercynian granites were considered to have derived from both mature and immature sources, and generated at high temperatures of 875–1,000°C (Sylvester 1998).

Trace elements

The variation of selected trace elements in the new Izera samples is shown in Fig. 5 i–p. Rb varies from 261 ppm

Table 2 Nd and Sm isotopic data for the Izera granites and gneiss

Sample	Sm	Nd	$^{147}Sm/^{146}Nd$	$^{143}Nd/^{144}Nd$	ϵNd_{500}	T_{DM}
SI	6.46	29.3	0.1332	0.512095 (8)]	−6.6	1,795
WR-1	8.86	36.3	0.1475	0.512179 (14)	−5.9	1,995
WR-2	15.1	68.0	0.1345	0.512143 (10)	−5.7	1,730
PL	6.15	27.2	0.1367	0.512160 (7)	−5.5	1,750
CH	3.70	15.1	0.1481	0.512205 (8)	−5.4	1,950
KO	1.09	2.97	0.2219	0.512372 (7)	−6.9	–
KR	2.80	11.0	0.1537	0.512191 (10)	−6.0	2,175
WI	2.58	10.9	0.1428	0.512196 (7)	−5.2	1,820

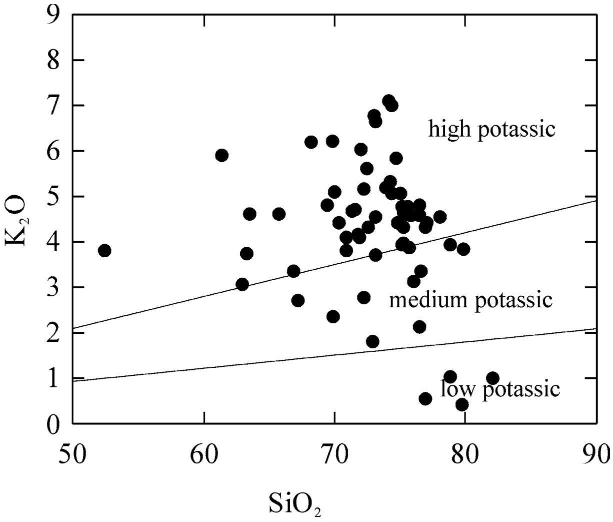

Fig. 2 The Izera granites and gneisses ploted on K_2O/SiO_2 diagram (Gill 1981). 62 published analyses compiled by Oberc-Dziedzic (1988 and references therein)

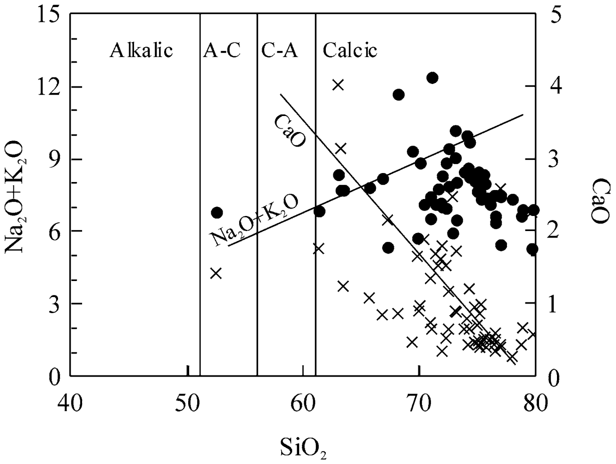

Fig. 3 Calc-alkalinity of the Izera granites and gneisses (division lines after Peacock 1931). 62 published analyses (see Fig. 2). *Dots*, Na_2O+K_2O, *x*, CaO

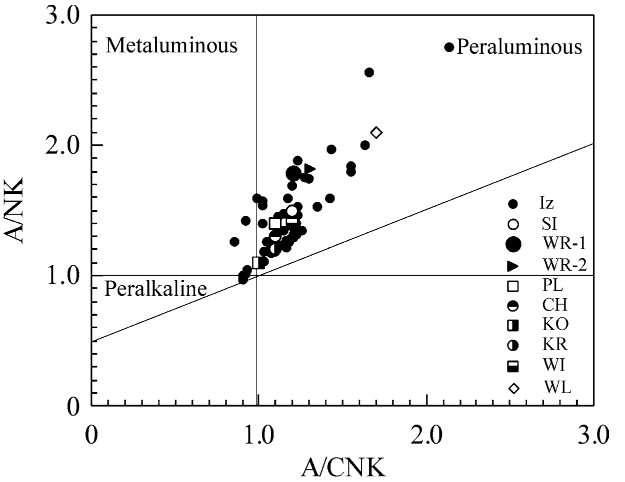

Fig. 4 Aluminousity of the Izera granites and gneisses. 62 published analyses (Iz, *solid circle*) and nine new analyses. Divisions after Maniar and Piccoli (1989)

in biotite schlieren (WR-2) to 6 ppm in the leucogranite (KO), and displays no clear correlation with SiO_2 (Fig. 5i). Ba also shows considerable scatter (987 ppm in greywacke WL and 77 ppm in gneiss KR) and is negligible in the leucogranite. There is no evident correlation between Ba and K_2O contents. In most specimens, Ba and Sr decrease with increasing SiO_2 suggesting, if we assume that LIL elements were rather immobile, feldspar fractionation processes (Fig. 5j, k). Zr (195–64 ppm), Th (18.4–11.4 ppm) and Ce (82.7–4.56 ppm) concentrations generally decrease with increasing SiO_2 (Fig. 5 l, n, p). These elements are largely removed during the fractionation of both zircon and monazite. In biotite schlieren (WR-2), concentrations of Zr (508 ppm), Th (46.4 ppm) and Ce (166 ppm) are considerably higher than in other samples (Table 1). On several diagrams (Fig. 5l, n, p), this specimen departs considerably from the trend. The contents of U and Pb generally increase with increasing SiO_2 (Fig. 5 m, o), suggesting that they were concentrated as incompatible elements during magma differentiation or by late-stage fluids.

The variation diagrams show that the schlieren (WR-2), in many cases also the greywacke (WL) and the cordierite-garnet rich granitoid (WR-1), are situated far from general trends. The chemical distinction of the greywacke compared with granites is obvious, considering their different origin. However, for a range of components, including Al_2O_3, FeO_{tot}, TiO_2, Ba, Zr, U (Fig. 5a, e, g, k–m), the greywacke follows the main granite trend, which indicates that rocks similar to the Lusatian greywackes could have been precursors of the

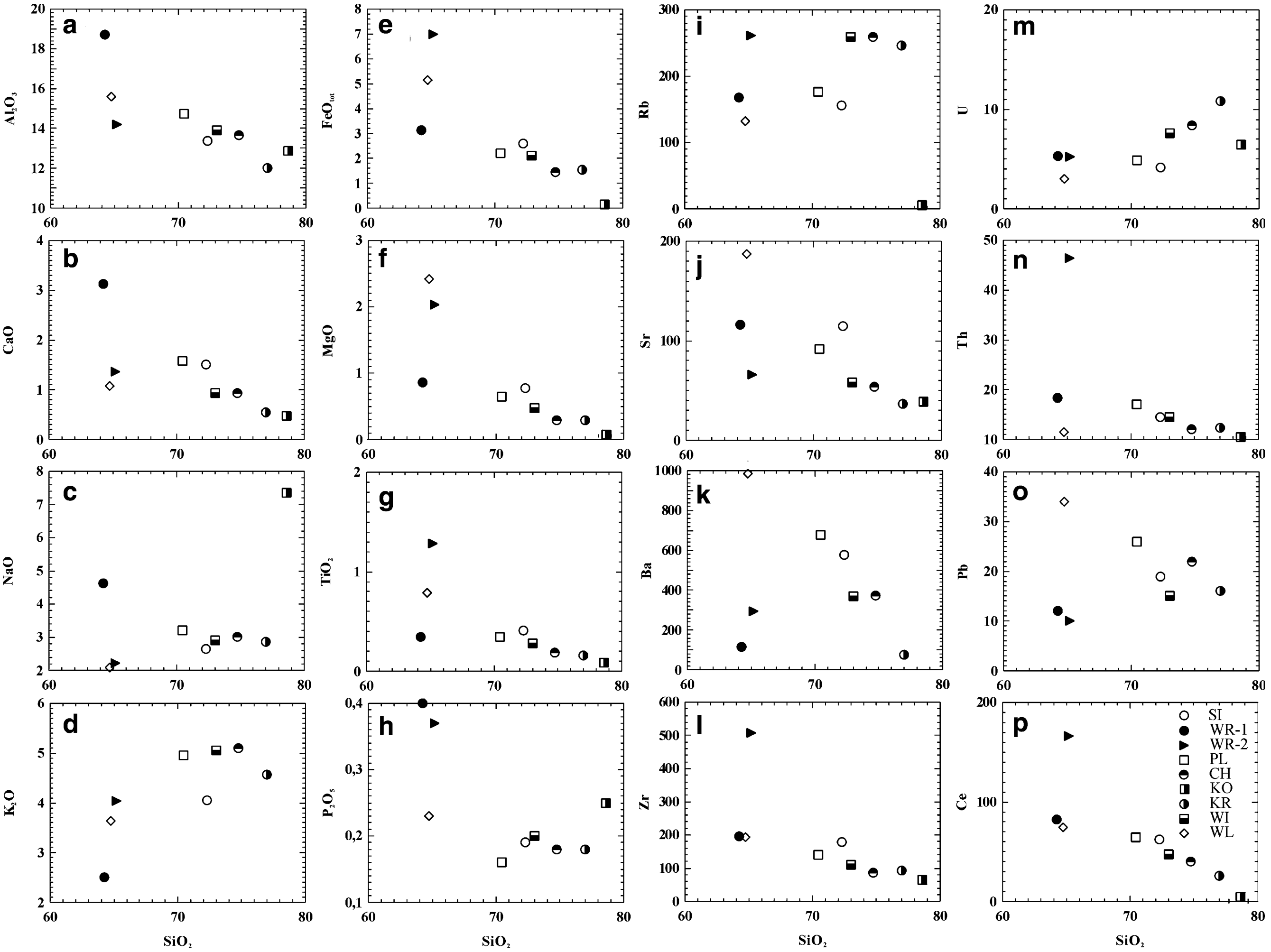

Fig. 5 Harker and trace element variation diagrams for the Izera granites. Major elements in wt%, trace elements in ppm

Izera granites. The chemical and mineralogical distinction of the cordierite-garnet rich granitoid (WR-1) points to its different, probably restitic origin or restite-enriched characteristics. In the case of the biotite schlieren (WR-2), it is not easy to decide whether it is a cumulate or restite. However, its field proximity to the cordierite-garnet rich granitoid (WR-1) suggests its restitic rather than cumulative origin.

The multi-element diagram of the trace element concentrations normalized to chondrites (Fig. 8) is characterised by a generally 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 genetic links between most of the analysed rocks. Nearly, all the samples display strong Nb, Ta, Sr, P and Ti negative anomalies that suggest fractionation processes and/or scarcity of these components in the source materials. Only the leucogranite (KO), having very low values of all trace elements, shows a positive P anomaly, although the absolute concentration of this element is similar as in

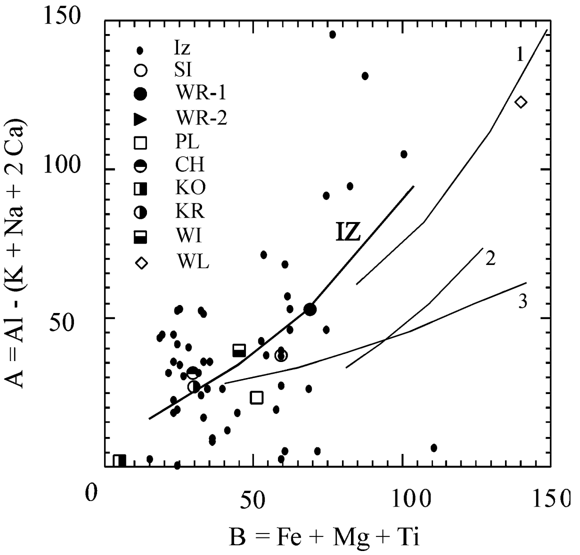

Fig. 6 Position of the Izera granites and gneisses (trend IZ) in A–B diagram, modified from Debon and Le Fort (1983) by Barbarin (1996). 62 published analyses (Iz, *small solid circle*) and nine new analyses. Trends for Australian S-type cordierite rich granitoids: [1] Layos granite, Toledo complex, Spain; [2] Carolles–Vire pluton, Mancellia batholith, northern Brittany, France; [3] Kosciusko batholith, southeastern Australia, according to Barbarin (1996)

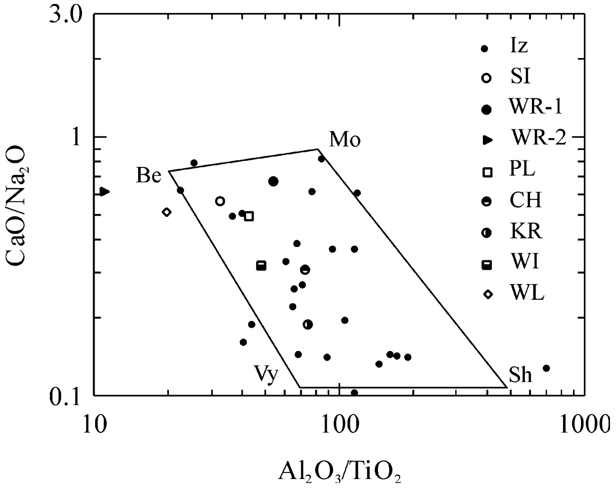

Fig. 7 The Izera undeformed granites on the CaO/Na$_2$O versus Al$_2$O$_3$/TiO$_2$ diagram of Sylvester (1998) for collision-related granites. The field is defined by four end-member intrusions: Bethanga (Be), Moschumandi (Mo), Vysoky-Kamen (Vy) and Shisha Pangma (Sh). 25 published analyses (Iz, *solid circle*) and nine new analyses

the other granite samples (Table 1, Fig. 5h). The Nb and Ta negative anomalies are usually considered as typical of a middle crust material (Wilson 1989), but they are also well developed in upper crustal materials (Taylor and McLennan 1985). The Sr, P and Ti negative anomalies reflect highly evolved magma and point to plagioclase, apatite, and ilmenite fractionation and removal. All samples show low Zr/Nb (18.5–4.5), Nb/Th (0.58–1.44) and most of them also low Ce/Pb (1.6–3.30) ratios characteristic of continental crust (Hofmann 1988, Wedepohl et al. 1991; Nutman et al. 1999). The very high Ce/Pb ratio (6.9 and 16.6) of the cordierite-garnet-rich granite (WR-1) and biotite schlieren (WR-2) mainly reflects the high concentration of Ce and suggests a restitic origin for the schlieren.

Rare earth elements (REE)

The absolute abundances of total REE are 101–159 ppm in the coarse-grained granite (SI, PL and WI) and fine-grained granite (CH). They are slightly higher (204 ppm) in the garnet-cordierite rich granitoid (WR-1) and over twice as high in the biotite schlieren (WR-2), but they are considerably lower in the gneiss (KR, 70 ppm) and very low in the leucogranite (KO, 18 ppm). The total REE in the greywacke (WL) is similar to those in the granites. Chondrite-normalized REE patterns (Fig. 9) are very similar in all samples except for the leucogranite (KO) and greywacke (WL). Typically, they display flat HREE patterns and distinct LREE enrichment: $(La/Yb)_N$ 1.93–5.51. In all samples, except the biotite schlieren and greywacke, the $(La/Yb)_N$ ratio decreases with decreasing Ce_N (Fig. 10a) as expected when monazite fractionation occurs. In contrast, the fractionation of heavy REE elements with changing REE content is very limited (Fig. 10b). This suggests that zircon fractionation did not play a significant role for REE. The degree of light REE fractionation $(La/Sm)_N$ versus Sm_N is high, but the projection points of the schlieren, cordierite-garnet rich granite and leucogranite are placed beyond the trend (Fig. 10c). Finally, there is no distinct fractionation of heavy REE $(Gd/Yb)_N$ versus Yb_N ; Fig. 10d). All the rocks (Table 1) show distinct negative anomaly of Eu/Eu* which is between 0.11 in the biotite schlieren (WR-2), 0.43 in granite (PL), up to 0.70 in greywacke (WL).

From the evidence above, the major and trace element variation in the Izera granites appears to be controlled primarily by fractional crystallization of plagioclase (CaO, Sr and Eu/Eu*), biotite and cordierite (Al_2O_3, MgO and FeO), zircon (Zr and Hf) and monazite (LREEs and Th). Also the granites may have been affected by late metasomatic alterations as indicated by the strongly different K_2O/Na_2O ratios and, partly (?), by LREEs contents in the deformed granite (KR) and leucogranite (KO).

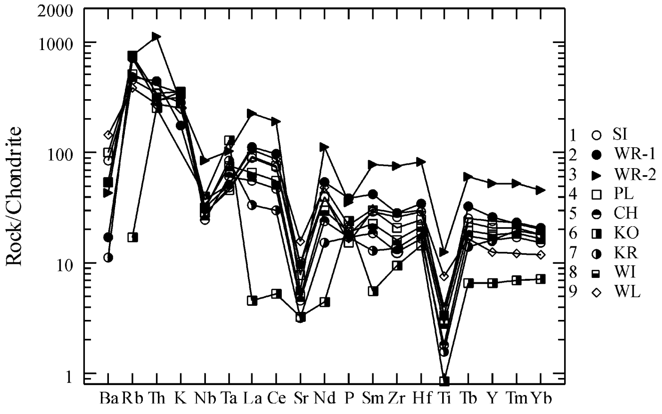

Fig. 8 Chondrite normalized multi-element diagram for the Izera granites, gneiss and greywacke samples. Normalization values of Thompson (1982)

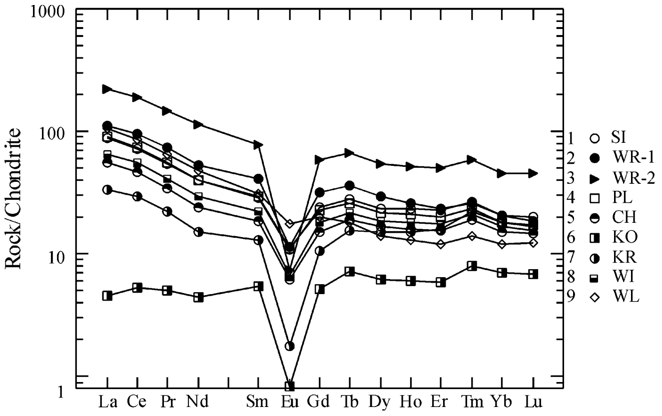

Fig. 9 Chondrite-normalized REE plot for the Izera granites, gneiss and greywacke samples. Normalizing values of Nakamura (1974), with additions from Haskin et al. (1968)

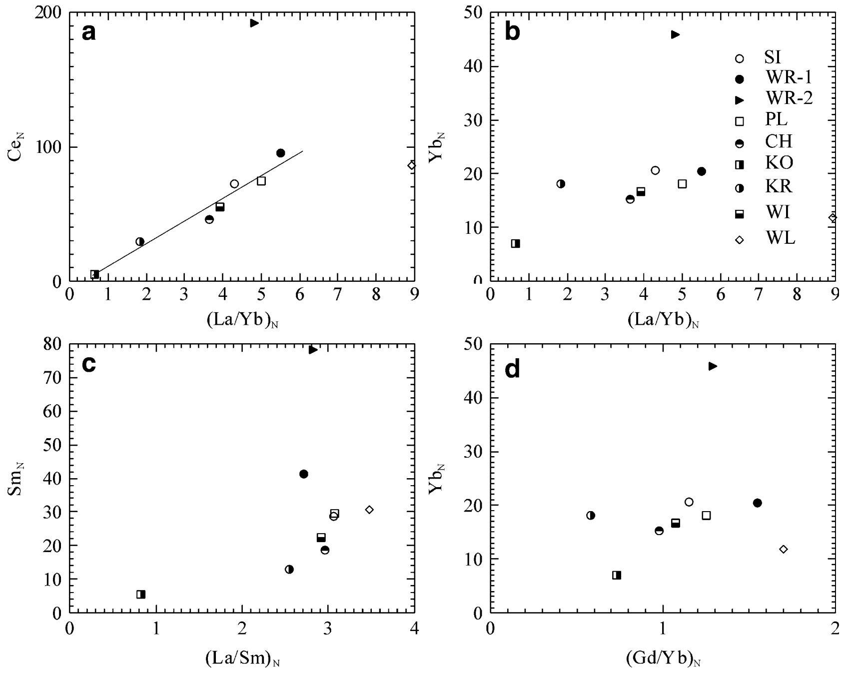

Fig. 10 Bivariate graphs of chondrite normalized REE elements. Normalizing values of Nakamura (1974), with additions from Haskin et al. (1968)

Sm–Nd isotope results

The analysed samples (Table 2) display a large range of ^{147}Sm/^{144}Nd, from 0.13 to 0.22, interpreted to reflect, at least in part, 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 at 500 Ma show a limited scatter, from -5.2 to -6.9 (mean: -5.9, SD = 0.6), irrespective of the rock types. The lowest value (-6.9) is observed in the sample KO corresponding to the most evolved (leucogranitic) rock studied, with only 3 ppm Nd, which might have suffered (through assimilation–crystal fractionation processes, ACF) some assimilation of metasedimentary material or/and metasomatic changes.

These largely negative ϵNd values imply that the granitic magmas emplaced ca. 500 Ma (Borkowska et al. 1980; Korytowski et al. 1993; Oliver et al. 1993; żelaźniewicz 1994; Kröner et al. 2001) were extracted from a source reservoir that was strongly enriched in LREE (i.e., with low Sm/Nd ratio) on a time-integrated basis. Therefore, the Nd isotope data emphasize the typical crustal derivation of the Early Ordovician Izera granitoids, in agreement with the ubiquitous occurrence of peraluminous minerals (cordierite, garnet, sillimanite) and the radiogenic Sr isotope signature (^{87}Sr/^{86}Sr$_i$ = 0.7090 ± 0.0013) measured by Borkowska et al. (1980).

Nd model ages might have been somewhat biased towards higher values by the late-stage fractionation of LREE-rich accessory minerals, as possibly exemplified by sample KR with $\mathrm{T_{DM}}$ = 2,175 Ma. However, the relatively consistent depleted mantle model ages measured in this work (1,730–2,175 Ma; mean: 1,890 Ma) are in agreement with the presence of ca. 2.1 Ga old inherited Pb component in zircons of the neighbouring Rumburk granite (Oliver et al. 1993). Therefore, it is suggested that the model ages point to an old (Early Proterozoic) crustal residence age of the inferred metasedimentary protoliths of the Izera granitoids, with only minor contribution of juvenile components of Late Proterozoic/Early Palaeozoic age to their protoliths.

Our results are somewhat different from those obtained by Kröner et al. (2001) for the Izera gneisses exposed on the Czech side near the town Frydland which show initial ϵNd values -4.2, -5.0, and -5.3 and $\mathrm{T_{DM}}$ = 1.5–1.6 Ga calculated for an emplacement age of ~515, 506, and 505 Ma, respectively. Nevertheless, the $\mathrm{T_{DM}}$ = 1.5–1.7 Ga calculated by these authors for the Izera, Karkonosze, and Śnieżnik gneisses are much too old for substantiating the Grenville event claimed by them (Kröner et al. 2001). Based on xenocrystic zircon data (which give merely minimum ages) up to 1,707 Ma (Krøner et al. 2001, sample CS 3, Rumburk granite), it is clear that the $\mathrm{T_{DM}}$ does not refer simply to any crust-forming event. It is much more likely that a range of sources were mixed, probably as detrital sediments from possibly many sources, including a major component from ca. 2.1 to 2.0 Ga sources (Birrimian/Eburnean, major event in West Africa), and for this reason these data alone do not provide conclusive information on the crust below the Sudetes Mountains.

Discussion

The Izera granites show clear S-type affinities. This statement is based on the mineralogical, petrographic and field criteria, such as the presence of magmatic cordierite, and other strongly aluminous minerals: garnet and sillimanite, the lack of mafic enclaves (which should not be mistaken with younger mafic dykes) in the granites, and the lack of coexisting tonalites and diorites. The S-type character of these granites is also evidenced by their peraluminous character and high ^{87}Sr /^{86}Sr initial ratio (0.7090 ± 0.0013, Borkowska et al. 1980). Their low Nb/Th and Ce/Pb ratios are characteristic of the continental crust (Hofmann 1988). The model ages point to an old (Early Proterozoic) crustal residence age of the metasedimentary protoliths of the Izera granitoids.

The formation of peraluminous granites is usually, but not exclusively (peraluminous magmas can also be produced in rift-related settings; cf. discussion below) interpreted as related either to crustal thickening connected with collision or to the period of extension, which follows the collision (Sylvester 1998). Barbarin (1996) proposed a petrogenetic model which assumes the production of two groups of peraluminous granites: (1) two-mica monzogranites to leucogranites [Muscovite-bearing Peraluminous Granitoids (MPGs)], often rooted in ductile shear zones and showing evidence of deformation, and (2) biotite-rich, cordierite-bearing tonalites to monzogranites CPGs forming intrusive plutons. According to the model, crustal thickening during collision brings metasedimentary and other crustal rocks close to their melting temperature. If partial melting is triggered by the addition of water, the resulting "wet" anatexis produces leucogranitic to monzonitic magmas in which muscovite crystallises (MPGs). However, if heat is provided by mantle-derived magmas underplating the crust or injected into it, the "dry" anatexis produces peraluminous tonalitic to monzogranitic magmas in which cordierite crystallises. This scenario should not be restricted to post-collision settings, but may equally well be valid in rifting environments, provided that suitable source rocks occur in a favourable thermal regime (compare discussion in Crowley et al. 2000).

According to Sylvester (1998), the post-collisional exhumation of overthickened crust (> 50 km) heated by radiogenic decay of K, U and Th during syncollisional thickening, produces small- to moderate-volume of cool granitic melts with high Al_2O_3/TiO_2 ratios. Such melts are typical of the "high-pressure" Himalayas and European Alps collisions. However, if a syncollisional crustal thickening did not exceed 50 km, as in the case of "high temperature" collision typical of the Variscides or Lachlan Fold Belt, crustal anatexis may have occurred as a result of post-collisional lithospheric delamination and upwelling of hot asthenosphere, forming large volume of hot peraluminous melts with low Al_2O_3/TiO_2 ratios. The first group of granitoids corresponds to MPGs granites, the second group to the CPGs granites. On the CaO/Na_2O versus Al_2O_3/TiO_2 diagram (Fig. 7) of Sylvester (1998), the Izera granites take the same position as the Variscan and Lachlan Fold Belt granites and, on the A–B diagram (Fig. 6) of Barbarin (1996), roughly follow the trend of the Australian S-type granites.

The Early Palaeozoic Izera granites are products of Cambro–Ordovician magmatic activity, which resulted in numerous plutons in the West Sudetes (Oliver et al. 1993; Turniak et al. 2000) and in extensive parts of the Variscan Belt of Europe. The emplacement of these plutons was alternatively interpreted to have been linked to an extensional, e.g., continental-rift setting of the northern margin of Gondwana (e.g., Pin and Marini 1993, Kryza and Pin 1997), or to supra-subduction volcanic arc setting (Oliver et al. 1993; Kröner and Hegner 1998; Kröner et al. 1994, 2001).

The concept of a continental rift-related setting for Cambro-Ordovician plutonism in the West Sudetes is supported by the coeval, so-called bimodal magmatism, with typical within-plate mafic rocks and alkali rhyolites, known from e.g., the Kaczawa Unit (511 ± 39 Ma, Pin, in Kryza 1993) and the Staré Město Belt (~500–505 Ma, Kröner et al. 2000). However, the genetic relationships between the Early Palaeozoic volcanic suites and the widespread, roughly coeval granitoid plutons do not seem very straightforward. The granitoids, including the Izera (Rumburk) granites, do not display mineralogical and geochemical features characteristic of rift-related A-type alkali granitoids (Whalen et al. 1987; Eby 1992 and references therein). Particularly, Ga/Al ratio in the Izera granites (2.31–2.58) is lower than in typical A-type granites (3.75, Whalen et al. 1987). Moreover, the Izera granites and A-type granites plot in different fields in Pearce et al. (1984) diagram: the Izera granites in the VAG field (Fig. 11) and the A-type granites (Eby 1992) in the within-plate granite field.

Oliver et al. (1993) and Kröner et al. (2001) suggest that magmatic precursors of the ~ 500 Ma West Sudetes granitoid gneisses, including the Izera, Karkonosze and

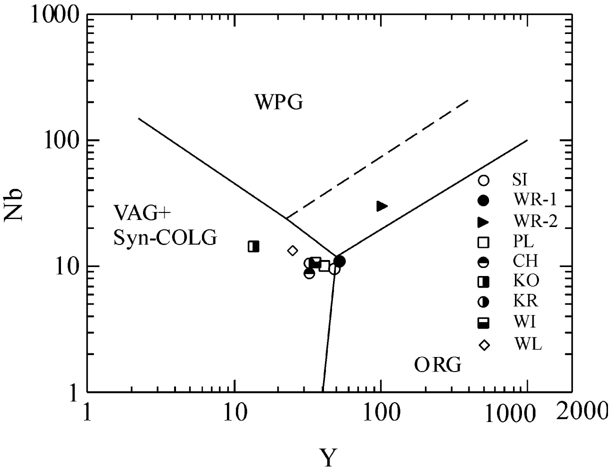

Fig. 11 Position of the Izera (Rumburk) granites on the Nb versus Y trace element diagram (after Pearce et al. 1984). VAG: volcanic arc granites, Syn-COLG: syn-collisional granites, ORG: ocean ridge granites, WPG: within plate granites

Orlica-Śnieżnik gneisses were generated in a volcanic arc setting which constituted part of magmatic arc of Eastern Avalonia developed in Cambrian times. Kröner et al. (2001) based their statement on the chemical composition of granitoid gneisses, which they interpreted as showing calc-alkaline character and confined to the volcanic arc (VAG) field on the Nb versus Y trace element discrimination diagram of Pearce et al. (1984).

In our opinion, the Izera granitoids do not show any feature typical of the VAG granites. First of all, they do not bear evidence for having any significant mafic juvenile components. Furthermore, more basic, tonalitic and dioritic, members of calc-alkaline trend, typical of VAG setting, are lacking among the Early Palaeozoic granitoid gneisses, in contrast to subduction-related magmatism. Moreover, the calc-alkaline trend alone does not define the VAG environment because high-K, calc-alkaline granites may also be generated in a post-collisional environment and plot in the VAG field (Pearce et al. 1984; Förster et al. 1997; Kryza and Pin 1997, and Crowley et al. 2002).

Consequently, in spite of the fact that our samples of the Izera granites also plot in the VAG field, close to the boundary with the WPG field on the Y versus Nb diagram (Fig. 11), we do not share Kröner's et al. (2001) conclusion of the VAG affinity of the Early Palaeozoic granitoid gneisses, for the following general and specific reasons.

First, a note of caution should be given on the use of diagrams aiming to infer geotectonic setting from the selected trace element contents and/or ratios measured in igneous rocks, particularly when this approach is applied to granitoids. Basically, the trace element signature of igneous rocks does not reflect in any simple way geodynamic environments, but rather arises from the combination of the chemical composition of their source material(s) and of the effects of a sequence of petrogenetic processes from partial melting to final solidification through, among others, fractional crystallization, magma mixing and assimilation. Albeit far from being free of pitfalls, discrimination diagrams designed for basaltic rocks (see Rollinson 1993 for a review) have been successfully used in many cases because there exists a broad, but systematic relationship between a few major mantle reservoirs (or end-members of a more continuous upper mantle) and major plate tectonic settings. By using concentrations, and/or ratios, of selected incompatible trace elements (that is, elements with small bulk solid/liquid partition coefficients), showing similar (or slightly different) behaviour during partial melting of mantle rocks, or crystallization of basaltic magmas, it is possible to circumvent (or assess) the effects of variable degree of partial melting and the extent of fractional crystallization. Thereby, reasonable inferences (particularly the degree of depletion) can be drawn on the mantle source of a given basalt, or metabasalt, provided that elements believed to be immobile during alteration and metamorphism are used. Then, the tectonic setting, which prevailed at the site of magma generation is deduced in a relatively straightforward way, from the generally well-established (albeit potentially hazardous in some cases) connection between the inferred magma source reservoir (for example, strongly depleted mantle) and the commonly associated plate tectonic context (e.g., mid-ocean ridge).

The situation is markedly different when dealing with granitoids, which are mostly restricted to, and produced within the continental crust. The chemistry of granitoid magmas is, in this case as well, a reflection of the nature of the source materials, which suffered partial melting and subsequent evolution of the melt. However, it does not bear any simple relationship with the geodynamic setting prevailing at the time of magma generation, because (in contrast with mantle reservoirs) there is no systematic link between possible crustal source reservoirs and any specific tectonic context. In other words, similar fertile crustal protoliths (e.g., metapelites, metagreywackes, metatonalites, and amphibolites) may cross their solidus curve in a variety of tectonic settings, extensional or compressional, in so far as a suitable temperature increase occurs. Therefore, it may be anticipated safely that chemically similar granitic magmas could be produced by broadly similar degrees of partial melting of similar source materials, irrespective of the local geodynamic setting, provided that the relevant solidus can be crossed. For these reasons, it is claimed that trying to fingerprint palaeogeodynamic contexts on the basis of trace element discrimination diagrams alone may give very misleading results when dealing with granitic rocks.

Specifically, typical metaluminous, alkaline to peralkaline A-type granitoids are only an end-member among the vast class of anorogenic granitoids, defined on both tectonic and chemical grounds. Indeed, it has long been recognized (e.g., Hanson and Al-Shaieb 1980; Anderson and Thomas 1985) that subalkaline or even peraluminous silicic igneous rocks are not restricted to volcanic arcs formed at convergent plate boundaries, but also occur in rifting environments and form a distinct group of anorogenic granitoids. Alkaline A-type granitoids could be generated by the partial melting of lower crustal lithologies (felsic granulites), which suffered depletion through earlier melt extraction (Collins et al. 1982; Clemens et al. 1986), or merely H_2O loss during a metamorphic event (Skjerlie and Johnson 1992). In other cases, A-type magmas belonging to bimodal associations can be interpreted in terms of evolved liquids from basaltic precursors, or partial melts from underplated mafic bodies (e.g., Poitrasson et al. 1995). In either case, unusually high temperatures are required to trigger partial melting of relatively refractory source rocks, implying the involvement of thermal ± mass input from underlying mantle, as it occurs commonly during lithospheric extension. This is the reason why such HT melts are typically associated with rift-related settings. However, if the rifted continental crust is relatively immature and contains fertile rock types at depth, partial melting of such lithologies is even more likely to occur, and capable of generating anorogenic granitoids, including peraluminous varieties, depending on the specific nature of the source rocks.

In this scheme, two different, and possibly successive styles of anorogenic granitoids are anticipated, depending on the fertility of the rifted crustal segment: first, relatively large volumes of peraluminous to metaluminous granitoids would be produced from the most fertile lithologies (metapelites, metagreywackes, etc.; e.g., Clemens and Vielzeuf 1987; Thompson 1996 and references therein) present in the melting domain; second, alkaline to peralkaline types could be produced from the more refractory lower crustal lithologies only when a sufficient input of heat allows these rocks to melt. The second, most typical (per-) alkaline A-type granitoids could occur either alone, in cratonic segments characterized by an ancient restitic lower crust, or in association with meta- or peraluminous granites, when less differentiated crustal segments are stretched. In the latter case, the alkaline varieties would preferentially occur at a late stage of the igneous event, following the early production of more voluminous melts from fertile reservoirs. It is suggested that the Izera rocks belong to the first group of anorogenic granitoids, generated from fertile protoliths such as those forming (volcano-) sedimentary wedges peripheral to continental blocks. In this scenario, the lack of subsequent (per-) alkaline granitoids in the Izera region might simply result from a thermal input that was insufficient to cause further partial melting of the refractory assemblages left behind after the extraction of early-formed peraluminous melts.

All the mentioned arguments suggest that although the Izera granites show features typical of granitoids intruded during collision (Barbarin 1996, 1999) or a post-collisional extension sensu Sylvester (1998), they might equally well have no relationship with any collision, and be purely anorogenic.

The Izera granites seem to follow magmatic events that produced the ca. 540 Ma Lusatian granodiorites interpreted either as magmatic arc related (żelaźniewicz et al. 2003) or post-collisional granitoids (Biaek 2003), closing the Cadomian orogeny. The extension might have accompanied the Early Palaeozoic rifting of the passive margin of the Saxothuringian block that was subsequently detached from the West Gondwana (żelaźniewicz et al. 2003). The rifting produced bimodal volcanic suites documented in the Kaczawa unit (Furnes et al. 1994) and in the eastern and southern envelope of the Karkonosze–Izera Block (Kryza et al. 1995, Winchester et al. 1995, Dostal et al. 2001; see also discussion in Crowley et al. 2000, 2002). The magmatic activity represented by the granites and roughly coeval or subsequent bimodal volcanic suites could therefore be two broadly concomitant effects of a single major event of lithospheric break-up at the northern edge of Gondwana.

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