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Geochemical constraints on the origin of the mid-Palaeozoic diabases from the Holy Cross Mts. and Upper Silesia, southeastern Poland

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A geochemical study of Palaeozoic diabase dykes and sills from the Holy Cross Mts. and Upper Silesian Block (southeastern Poland) has revealed that these diabases are most probably derived from fractional crystallization of three distinct primary melts. All diabases are relatively evolved subalkaline tholeiites with low *mg*-numbers that vary between 50.7 and 60.5. Their mantle normalised incompatible element patterns are intermediate between that of enriched mid-ocean ridge basalt (E-MORB) and ocean island basalt (OIB). The compositional differences within the diabases are interpreted in terms of slightly variable degrees of partial melting of their mantle sources combined with variable degrees of subsequent gabbro fractionation in highly-level magma chambers. Some incompatible element ratios (e.g. Zr/Nb, Y/Nb) in the diabases and Nd isotope data from the cogenetic diorites seem to be consistent with mixing of partial melts from both enriched lithospheric and depleted asthenospheric mantle sources. Both Upper Silesian and Holy Cross diabases show strong chemical similarity to the continental flood basalts (CFB), which are associated with extensional tectonics. The Bardo diabase, located in the northern part of the Małopolska Block, can be hypothetically linked to the detachment of this unit from the Baltica margin and subsequent displacement to its final position between the late Ludlovian and Emsian, whereas the Milejowice-Janowice diabase (Łysogóry Unit) possibly relates to the extension of the Baltica passive margin during the Late Silurian, in the final stage of its collision with East Avalonia.

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Key words: Holy Cross Mountains, Upper Silesia, diabase, geochemistry, partial melting, magma fractionation.

INTRODUCTION

Three tectonostratigraphic units can be identified within the Palaeozoic Platform in the foreland of the East European Craton in southeastern Poland: the Upper Silesia Block (USB), the Małopolska Block (MB) and the Łysogóry Unit (ŁU) (Fig. 1). Palaeozoic sedimentary successions of the two latter crustal blocks are exposed in the south of the Holy Cross Mts. (northern part of the Małopolska Block; Pożaryski and Tomczyk, 1968) and in the north of the HCM (Łysogóry Unit). The Holy Cross Fault separates these two regions. Palaeozoic deposits of these three units were affected by sporadic basaltic magmatism represented by diabase dykes and sills (e.g. Czarnocki, 1919; Tokarski, 1921; Morozewicz, 1925; Ryka, 1957; Kardymowicz, 1967; Kowalczewski, 1974, 2004; Cebulak and Kotas, 1982; Buła, 2000). Views have been commonly expressed in the literature about the close genetic affinity among Holy Cross diabases (e.g. Ryka, 1959; Szczepanowski, 1963; Kardymowicz, 1967) and their relations to similar rocks from Upper Silesia (Małkowski, 1954; Kardymowicz, 1967; Ryka, 1974). This paper aims to test these views using new geochemical data.

GEOLOGICAL POSITION OF DIABASES

The northeastern boundary of the Upper Silesia Block, along which it is joined to the Małopolska Block, is the well-defined Kraków-Lubliniec Fault Zone (see Żaba, 1999). Plutonic rocks of the USB Precambrian basement were consolidated during the Cadomian epoch (e.g. Dudek, 1980; Bukowy, 1984; Żelaźniewicz *et al.*, 1997) and their chemical characteristics indicate outer arc or island arc tectonic settings (Jelinek and Dudek, 1993). This magmatism probably occurred at the active margin of the Gondwana continent as a result of Late Proterozoic subduction of the Tornquist Sea (e.g. Finger and Steyrer, 1995).

In the Goczałkowice IG 1 borehole, drilled in the south of the USB (Fig. 1), a diabase intrusion (~ 41 m thick) occurs at a

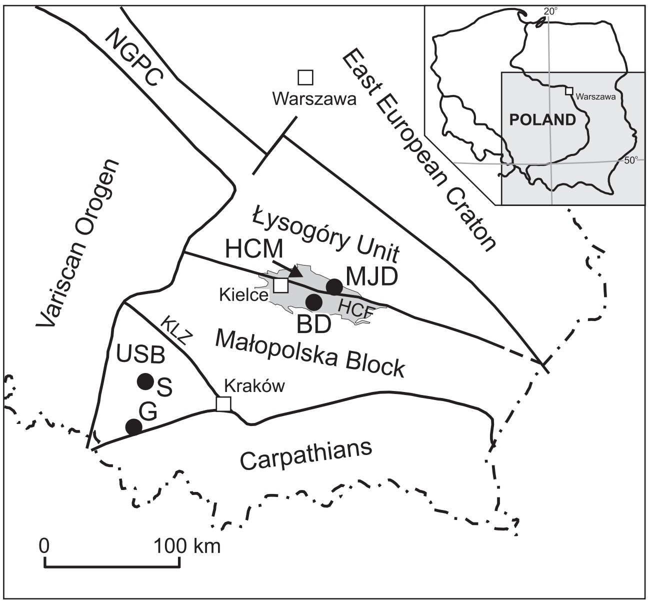

Fig. 1. Location of diabases studied within the context of the main structural units in Poland

BD — Bardo diabase; G — Goczałkowice IG 1 borehole; HCF — Holy Cross Fault; HCM — Holy Cross Mountains; KLZ — Kraków-Lubliniec Fault Zone; MJD — Milejowice-Janowice diabase; NGPC — North German-Polish Caledonides; S — Sosnowiec IG 1 borehole; USB — Upper Silesian Block

discordant contact between weakly metamorphosed Precambrian rocks of the crystalline basement and Lower Cambrian deposits (Cebulak and Kotas, 1982). A diabase-diorite intrusion (~ 92 m thick), penetrated by the Sosnowiec IG 1 borehole in the central part of the USB, cuts Middle Cambrian marine clastics (Buła, 2000).

In the Bardo Syncline, located in the centre of the Kielce region, a diabase intrusion 20–30 m thick occurs at the contact between lower Ludlow graptolitic shales and upper Ludlow shale-greywackes. The Bardo diabases (BD) were folded together with the Ludlow rocks and were discordantly overlain by Emsian deposits (Kowalczewski and Lisik, 1974). Analysing tectonic data, these authors suggested a late Ludlow-Siegenian age of this intrusion, although Nawrocki (2000) places the age of the intrusion in the late Ludlow–early Gedinnian. An attempt to date the diabases by K–Ar and Ar–Ar methods gave inconsistent results (Migaszewski, 2002).

The Milejowice-Janowice diabases (MJD) from the Łysogóry region form a narrow zone (max. 20 m) of 3.5 km-long dykes cutting folded Late Ordovician (Caradoc) to latest Silurian (Pridoli) shales and greywackes. Kowalczewski (2004) is of the opinion that these diabases were probably intruded during the late Gedinnian–early Siegenian.

SAMPLING AND ANALYTICAL METHODS

Twenty two representative samples of the freshest diabases from the Holy Cross Mts. boreholes: Milejowice 1 and 2, Janowice 1 and 2 (MJD) and Prągowiec 1 and 1a (BD), were collected for petrographic and geochemical investigations. Results of studies of diabase-diorite intrusions from the Goczałkowice IG 1 and Sosnowiec IG 1 boreholes, drilled on the Upper Silesia Block (Nawrocki and Krzemiński, 2001; Krzemiński, unpubl. data), were also taken into consideration for comparative analysis.

Chemical analyses of 15 whole-rock samples were performed at the Central Chemical Laboratory of the Polish Geological Institute. Major element analyses were performed by X-ray fluorescence spectrometry (XRF) on fused glass discs, and the trace elements Rb, Ba, Sr, Co, Ni, Cr, Nb, Zr, Th, Y and La were determined on pressed powder pellets using a *Philips PW2400* instrument. Concentrations of Nd, Sm and Sc were measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES). Ce contents in samples from the Janowice 1 borehole were determined by ICP-AES, but in other samples they were analysed by XRF on pressed powder pellets.

Analyses of olivine and palagonite were carried out using a *Jeol JSM-35* electron microprobe equipped with a *Link energy-dispersive spectrometer* at the Polish Geological Institute. Accelerating voltage was 20 kV with a beam current of 2 nA and 50 s count time. Natural and synthetic mineral standards were used and the raw data were reduced with a ZAF correction procedure.

PETROGRAPHY

The Milejowice-Janowice diabase is characterised largely by a fine-grained subophitic texture (Fig. 2a), with local medium-grained variants with transitions to ophitic texture. The main mineral components are plagioclase and clinopyroxene. One of the diabase samples contains a small amount of fresh olivine in the form of fine anhedral grains, frequently fractured and with an admixture of secondary iron oxides (Fig. 2b). Its chemical composition, characterised by a slightly greater amount of MgO than FeO* or the other way round ($Fo_{71.3–58.1}$; Table 1), is typical of olivines from gabbros and some continental tholeiitic basalts. More frequent are saponite pseudomorphs after olivines, accompanied by secondary quartz, iron oxides and occasionally carbonates. There was also one sample with a weakly resorbed peridotitic mantle xenolith, now totally composed of saponite pseudomorphs after olivine (Fig. 2c) with minute inclusions of a dark brown chrome spinel. Iron and titanium oxides are common. Biotite, apatite and brown amphibole occur in trace amounts. Relics of brown amorphous palagonite were occasionally observed (Fig. 2d). It is rich in Fe, but poor in Mg and alkalis; its normative composition corresponds to quartz tholeiites with a large amount of hypersthene (Table 2). Of secondary minerals, the most common is olive-brown and brown-green saponite replacing olivine and palagonite. It belongs to the saponite — Fe-saponite series, poor in Al. Pale green chlorite occurs in small amounts between plagioclase laths.

The Bardo diabase occurs in two varieties of medium-grained or fine-grained rocks. Both olivine and pseudomorphs after olivine are lacking in each variety. Instead, we can observe very characteristic oval or irregular concentrations of fibrous palagonite several millimetres in diameter (see Stroncik and Schmincke, 2002), an alteration product of basic glass (Fig. 2e). Palagonite is replaced at the rims by secondary sheet silicates and is often accompanied by secondary quartz and, oc-

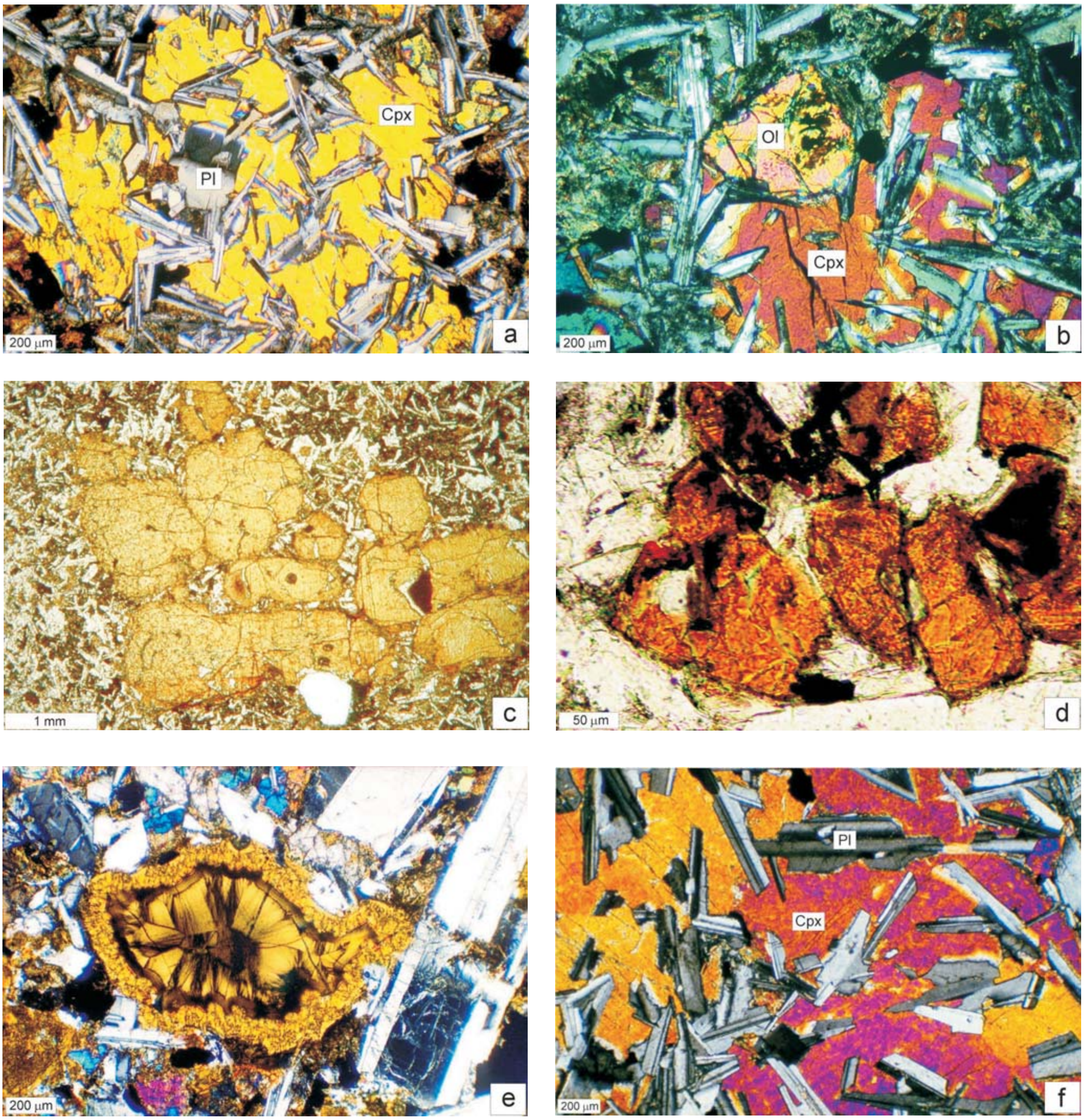

Fig. 2. Photomicrographs of diabase samples

a — typical subophitic texture with fine plagioclase laths (Pl) partially enclosed by large clinopyroxene grains (Cpx), Janowice 1 borehole, depth 75.9 m, crossed polars; **b** — predominant plagioclase and clinopyroxene (Cpx) accompanied by unaltered olivine (Ol), Milejowice 2 borehole, depth 16.2 m, crossed polars; **c** — peridotitic mantle xenolith composed of saponite pseudomorphs after olivine, Janowice 2 borehole, depth 53.2 m, plane-polarized light; **d** — palagonitized amorphous mafic glass in diabase from Milejowice 1 borehole, depth 110.0 m, plane-polarized light; **e** — poorly crystalline fibro-palagonite replaced by spherolites of smectite at the rim, Prągowiec 1a borehole, depth 108.7 m, crossed polars; **f** — diabase from Goczałkowice IG 1 borehole, depth 3133.6 m, showing subophitic texture with clinopyroxene (Cpx)-plagioclase (Pl) assemblage, very similar to that of Milejowice-Janowice diabase, crossed polars

casionally, by carbonates. Brown amorphous palagonite occurs only in a microcrystalline or microlithic mesostasis observed in small amounts in interstices.

A diabase from the intrusion core in the Goczałkowice IG 1 borehole (Upper Silesia) is very similar to the Milejowice-Janowice diabase. It is characterised by a slightly coarser grain size than the MJD and shows subophitic to ophitic textures (Fig. 2f). Some infrequent oval pseudomorphs, composed of olive-green or brownish smectite and iron oxides, probably represent olivine, but no fresh grains were observed. Amorphous palagonite is also absent. A more fine-grained diabase occurs in outer zones of the diorite-diabase intrusion penetrated by the Sosnowiec IG 1 borehole. In the upper part, composed of diabases, the intrusion contains a small amount

Table 1

Representative microprobe analyses of olivine in diabase from Milejowice 2 borehole

Sample:	M-2-96		
SiO_2 (*wt %*)	37.03	37.65	36.47
FeO_{tot}	25.63	26.35	35.06
MnO	0.35	0.38	0.39
MgO	35.8	35.29	27.36
CaO	0.63	0.38	0.34
Total	99.44	100.05	99.62
mg-no.	74.5	73.7	62.1
O =	4	4	4
Si	0.989	1.000	1.015
Fe^{2+}	0.572	0.585	0.816
Mn	0.008	0.009	0.009
Mg	1.425	1.397	1.135
Ca	0.018	0.011	0.010
Sum	3.011	3.000	2.985
Fo	71.3	70.3	58.1
Fa	28.7	29.7	41.9

mg-no. = 100 Mg/(Mg + 0.85 Fe_{tot}); Fo — forsteryt; Fa — fajalit

of an interstitial granophyric phase with fine quartz-orthoclase intergrowths.

GEOCHEMICAL RESULTS

MAJOR ELEMENTS

The Milejowice-Janowice diabase has a very homogeneous chemical composition (Table 3). Contents of major element oxides vary within a narrow range. Its *mg*-number ranges from 54.9 to 59.1, and MgO content is 6.5–7.2 wt.%. The BD shows considerable chemical diversity between the medium-grained (samples P-1-88.9 and P-1a-108.7) and fine-grained varieties (sample P-1a-94.3). Both varieties have higher loss on ignition (up to 6.77 wt.%) than the MJD and USD, which may be due to large concentrations of fibrous palagonite and sheet silicates. The BD is similar to the MJD only in Al_2O_3 and Fe contents. As compared to MJD, the medium-grained diabase is richer in SiO_2 (49.1 and 51.0 wt.%) and poorer in CaO. The fine-grained diabase is enriched in alkalis, showing a lower MgO content (5.6 wt.%) and *mg*-number 50.7. Considering the major element contents, the Upper Silesian diabases (USD) show a very close affinity to the MJD. Most of the oxides occur in almost identical amounts: the MgO content varies from 6.9 to 7.5 wt.%, and the *mg*-number ranges from 57.9 to 60.5 (Krzemiński, unpubl. data).

The geochemical affinity between the MJD and the USD is illustrated on variation diagrams of major and minor elements using the MgO content as a differentiation index (Fig. 3). These diabases are commonly tightly clustered in a single group within which no trends were usually observed. Along with the BD, they only show weak trends characterised by an increase in TiO_2, K_2O and P_2O_5 contents with a decreasing MgO content. Correlation between most of the oxides and MgO, also taking into consideration pyroxene and amphibole diorites from the Sosnowiec IG 1 borehole, is much better: it is negative for SiO_2, TiO_2, K_2O and P_2O_5, and positive for CaO.

Table 2

Microprobe analyses and CIPW norms of palagonite in diabase from Milejowice 1 borehole

Sample:	M-1-91			
SiO_2 (*wt %*)	38.79	37.64	38.93	35.73
TiO_2	0.00	0.10	0.10	0.30
Al_2O_3	5.26	4.57	4.33	5.09
Cr_2O_3	0.00	0.00	0.00	0.13
FeO_{tot}	24.31	24.96	24.11	22.56
MnO	0.03	0.06	0.23	0.22
MgO	4.89	4.40	4.20	4.01
CaO	2.29	2.41	1.91	1.66
Na_2O	0.09	0.72	0.87	0.60
K_2O	0.42	0.32	0.61	0.65
Total	76.08	75.18	75.29	70.95
Q	8.7	8.5	6.8	12.3
or	–	–	–	–
ab	–	–	8.5	–
an	14.9	14.9	9.2	9.9
di	–	–	0.7	–
hy	71.9	73.1	70.9	69.4
ol	–	–	–	–

TRACE ELEMENTS

The chemical homogeneity of the MJD is also reflected in contents of compatible trace elements: Ni and Co contents vary within narrow ranges. The USD are poorer in Cr and Co than the MJD. Ni contents are similar. Higher variations in Cr content were observed within the BD, where the fine-grained diabase is notably poorer in this element (21 ppm) as compared to the medium-grained variety (68–69 ppm). These contents are much lower than in the MJD and USD. Co contents in the BD are similar to those in the USD. Rubidium, representing large ion lithophile elements (LILE), occurs in almost identical amounts in all the diabases analysed. Zirconium is a high field strength element (HFSE), occurring in slightly larger amounts in the MJD (102–108 ppm) than in the USD (78–102 ppm). Higher Zr contents are characteristic of the BD, in particular of the fine-grained variety (195 ppm). Contents of yttrium and light rare earth elements (LREE) are very similar in the MJD and USD. The Bardo diabase shows increased LREE contents, especially in its fine-grained variety. Trace element variation diagrams (Fig. 3) show considerable geochemical affinity between the MJD and USD, regarding in particular incompatible elements. Good correlation between some incompatible elements (Rb, Zr, Ce, Y) + Ni and MgO can be observed within the diabase-diorite series. Within diabases themselves (MJD, BD and USD), the correlation is much less convincing. Nevertheless, the BD, in particular their fine-grained variety, represent a transitional geochemical link from the MJD and the USD to diorites of the Sosnowiec IG 1 borehole.

CLASSIFICATION OF THE DIABASES

On the Zr/TiO_2–Nb/Y classification diagram, all the analysed diabase samples plot within a subalkaline basalt or basaltic andesite field (Fig. 4a). A high Fe/Mg ratio and silica content indicate a tholeiitic affinity for these diabases (Fig. 4b). Their tholeiitic signature is confirmed by the presence of normative

Table 3

Whole-rock major and trace element analyses of Milejowice-Janowice and Bardo diabases (Prągowiec 1 and 1a boreholes)

Locality	Milejowice 1			Milejowice 2			Janowice 1			Janowice 2			Prągowiec 1	Prągowiec 1a	
Sample	M-1-65	M-1-67	M-1-91	M-2-69	M-2-75	M-2-96	J-1-63	J-1-66	J-1-71	J-2-45	J-2-54	J-2-55	P-1-88.9	P-1a-94.3	P-1a-108.7
Depth [m]	80.6	83.5	110.0	84.7	92.0	116.2	66.7	70.3	75.9	53.2	76.7	81.0	88.9	94.3	108.7
SiO_2 (*wt %*)	47.51	47.58	47.38	47.09	47.10	47.00	47.17	47.30	47.89	47.10	47.41	47.90	49.11	46.86	50.97
TiO_2	1.84	1.72	1.84	1.90	1.77	1.76	1.77	1.81	1.77	1.83	1.81	1.81	1.93	2.55	1.90
Al_2O_3	17.46	18.19	17.32	17.71	17.10	16.96	17.13	17.06	17.14	17.49	17.28	17.43	17.95	17.70	17.87
$Fe_2O_{3\,tot}$	12.01	11.33	12.05	12.54	12.58	12.68	12.39	12.15	11.91	12.48	11.88	11.31	12.53	12.74	11.21
MnO	0.23	0.20	0.22	0.28	0.21	0.21	0.27	0.26	0.23	0.30	0.24	0.24	0.14	0.23	0.16
MgO	7.23	7.02	6.90	7.05	6.80	6.76	6.47	6.52	6.49	7.25	7.21	6.86	7.15	5.61	6.18
CaO	10.37	10.57	10.88	10.11	11.10	11.43	11.51	11.84	11.61	10.46	10.95	11.26	7.85	10.20	8.36
Na_2O	2.68	2.71	2.69	2.60	2.64	2.59	2.68	2.59	2.53	2.64	2.79	2.78	2.57	3.12	2.62
K_2O	0.51	0.53	0.57	0.56	0.54	0.47	0.46	0.32	0.29	0.29	0.28	0.27	0.58	0.73	0.54
P_2O_5	0.16	0.14	0.16	0.17	0.15	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.20	0.25	0.19
LOI	2.89	3.53	2.07	2.86	1.87	1.65	2.26	2.04	1.97	2.38	2.27	2.16	5.65	6.77	3.99
mg-no.	58.4	59.1	57.2	56.7	55.7	55.4	54.9	55.5	55.9	57.5	58.6	58.5	57.1	50.7	56.2
Cr (*ppm*)	279	292	242	240	230	254	259	242	255	248	243	247	68	21	69
Co	57	56	54	53	53	57	57	54	54	52	53	46	40	37	39
Ni	104	104	100	96	105	102	98	100	104	98	103	99	42	29	42
Ba	1337	974	1300	826	603	437	150	135	123	114	195	198	194	244	176
Rb	18	19	21	21	22	20	20	16	15	16	14	14	15	20	16
Sr	346	364	316	329	285	284	272	255	256	263	273	272	293	284	297
Nb	9	9	10	9	9	9	9	8	9	9	9	9	11	13	11
Zr	106	102	105	108	104	102	104	106	102	103	102	103	152	195	151
Sc	34.1	32.2	33.7	34.3	33.7	34.0	33.9	34.7	35.2	34.8	34.7	35.4	32.6	35.5	33.9
Y	21	20	21	25	23	22	23	23	22	22	22	22	28	39	27
La	12	14	7	12	11	11	15	7	8	11	6	16	21	23	19
Ce	25	17	22	35	32	26	16	17	16	25	27	36	36	67	47
Nd	11	11	12	13	12	12	12	12	12	11	12	12	16	29	17
Sm	4	4	4	4	4	4	4	4	4	4	4	4	5	7	5
Zr/Nb	11.8	11.3	10.5	12.0	11.6	11.3	11.6	13.3	11.3	11.4	11.3	11.4	13.8	15.0	13.7
$(La/Nb)_{PM}$	1.38	1.61	0.73	1.38	1.27	1.27	1.73	0.91	0.92	1.27	0.69	1.85	1.98	1.84	1.79
Q	–	–	–	–	–	–	–	–	–	–	–	–	1.1	–	4.5
or	3.1	3.2	3.4	3.4	3.2	2.8	2.8	1.9	1.7	1.7	1.7	1.6	3.5	4.4	3.2
ab	24.4	24.6	24.5	23.7	24.1	23.7	24.5	23.7	23.1	24.1	25.4	25.3	23.5	28.6	23.9
an	34.6	36.3	34.0	35.6	33.8	33.9	33.9	34.6	35.2	35.5	34.2	34.7	36.3	32.8	36.0
di	13.2	12.6	15.8	11.4	17.0	18.3	18.5	19.4	18.0	12.9	15.8	16.7	1.6	13.7	3.9
hy	9.5	7.9	6.0	10.1	4.5	4.1	3.6	6.2	11.7	10.2	6.7	8.6	27.2	2.9	21.6
ol	8.8	9.3	9.9	9.2	11.1	10.9	10.4	7.9	4.0	9.1	9.8	6.8	–	9.2	–

mg-no. = 100 Mg/(Mg + 0,85 Fe_{tot}); LOI — loss on ignition; PM — primitive mantle-normalised ratio (normalising values are from Sun and McDonough, 1989); oxides contents are normalised to 100% volatile free

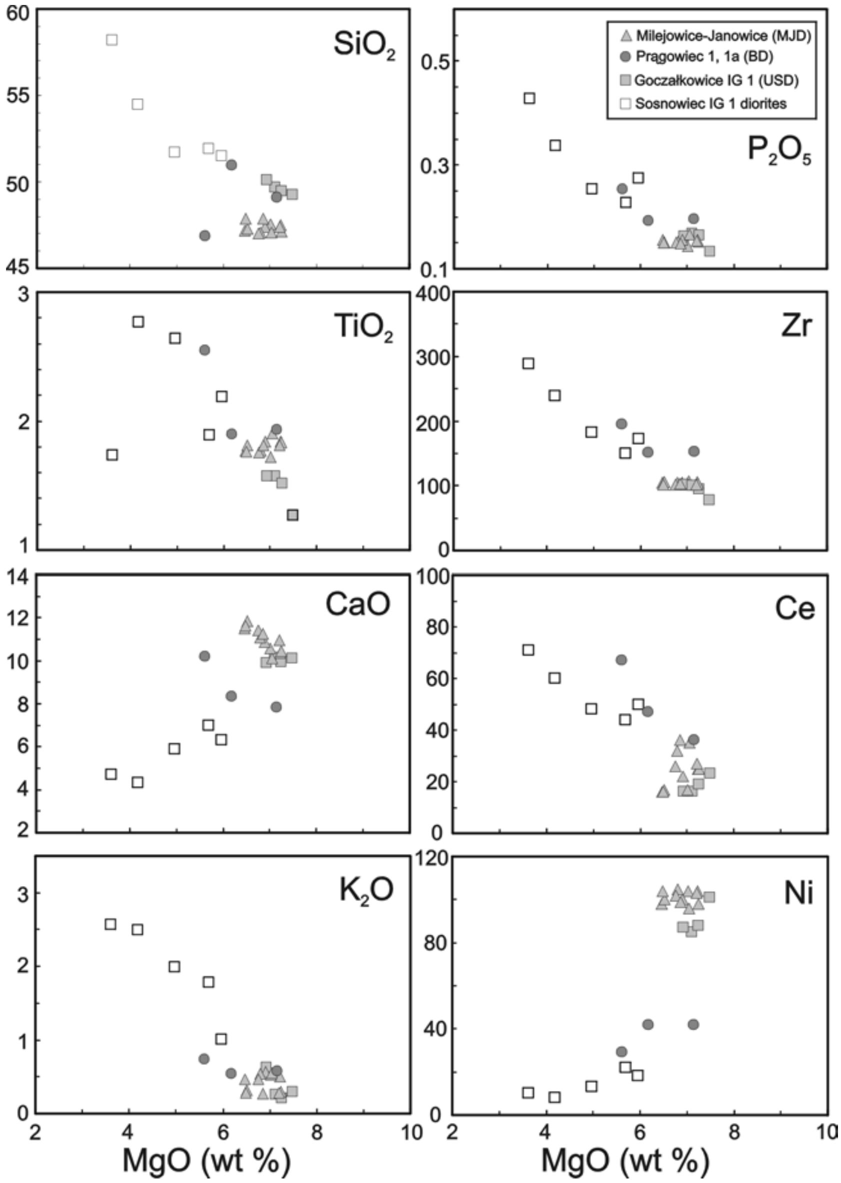

Fig. 3. Selected major and trace element variation against MgO content in the Holy Cross Mts. diabases and Upper Silesian diabases and diorites; data for Upper Silesia samples are taken from Krzemiński (unpubl. data)

hypersthene. Its content in the MJD varies from 3.6–11.7% (Table 3), and in the USD from 16.9 to 20.6% (Krzemiński, unpubl. data). An especially large amount of normative hypersthene and a small amount of normative diopside is observed in the medium-grained Bardo diabase. The CIPW normative composition classifies the MJD, the fine-grained BD, and partly the USD as olivine tholeiites. The latter are characterised by the smallest amount of normative olivine (1.1–3.7%), and one sample has a small amount of normative quartz. The medium-grained Bardo diabase has a normative composition corresponding to quartz tholeiites of low quartz content.

INCOMPATIBLE ELEMENT PATTERNS

Incompatible element patterns for the MJD, BD, USD and diorites from the Sosnowiec IG 1 borehole are shown on a multielement diagram normalised to the primitive mantle (Fig. 5). The BD are markedly more enriched in LREE and HFSE than the MJD. A moderate negative Nb anomaly was observed in the BD and in four samples of the MJD. For the Nb–Zr range, characteristics of the MJD are slightly inclined towards Zr, whereas characteristics of the BD are nearly flat. Compared to the average N-MORB (depleted mid-ocean ridge basalts), the MJD and BD are markedly enriched in incompatible elements, and the degree of enrichment increases towards the LREE and LILE. The degree of enrichment increases in the BD, reaching a level between enriched mid-ocean ridge basalts (E-MORB) and ocean island basalts (OIB), which are, however, lacking in a negative Nb anomaly. The MJD show very similar patterns and degree of enrichment as the USD, except for Nb. Thus the MJD either have no negative Nb anomaly or the anomaly is weaker than in the USD. Moreover, as a result of

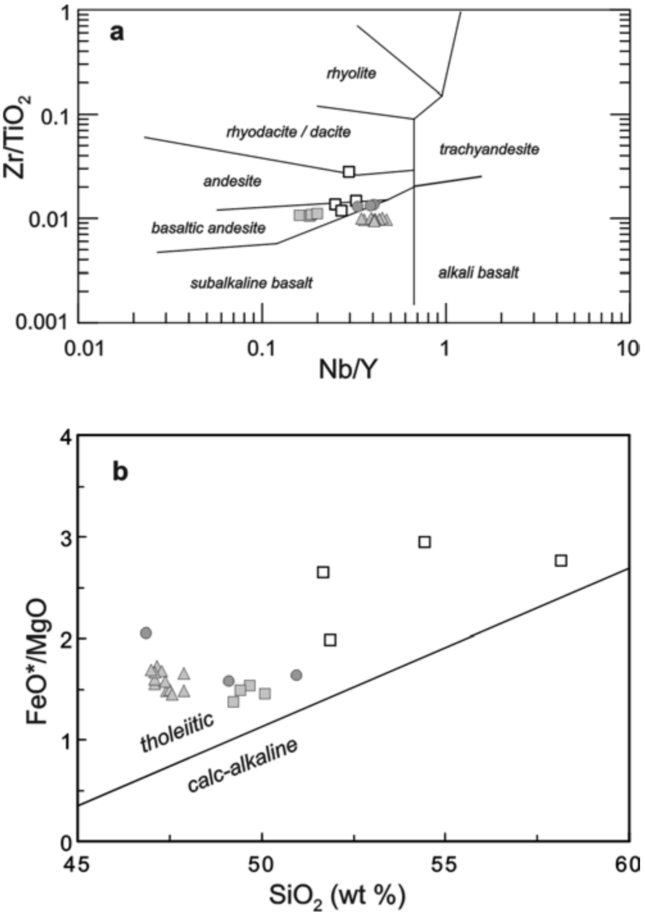

Fig. 4. a — Zr/TiO$_2$ vs. Nb/Y classification diagram (after Winchester and Floyd, 1977); b — FeO*/MgO vs. SiO$_2$ plot for samples from the Holy Cross Mts. and Upper Silesia

The boundary line between tholeiitic and calc-alkaline series was defined by Miyashiro (1974); symbols as in Figure 3

the low Nb contents of the USD, their characteristics in the Nb–Zr range are slightly inclined towards Nb, i.e. the opposite of MJD characteristics. The Bardo diabases, in particular their fine-grained variety, have characteristics resembling diorites from the Sosnowiec IG 1 borehole, or intermediate characteristics between the diorites and the MJD and USD.

DISCUSSION

COMPARISON WITH SOME CONTINENTAL FLOOD BASALTS

Figure 6a and b shows a comparison between the MJD and BD, and representative characteristics of continental flood basalts (CFB) of the Deccan, with the maximum volcanic activity in the Late Cretaceous (Melluso *et al*., 1995), and the Siberian Province with extrusions in the Early Triassic (Wooden *et al*., 1993). Rocks comparably evolved to the Holy Cross Mts. diabases, i.e. with similar average values of *mg*-number, were selected for consideration. Both Deccan and Siberian basalts show similar patterns and enrichment in incompatible elements as do the MJD. They are conspicuous by a weak negative Nb anomaly (Deccan), or a lack of it (Siberia), and — for the Nb–Zr range — a similar inclination of characteristics towards Zr: Deccan — average Zr/Nb ratio = 13.8, Siberia = 11.7 (see also Table 3). The medium-grained Bardo diabase has characteristics similar to the more enriched Deccan diabases. This variety also shows close geochemical affinity to lavas and dykes of the Jurassic Vestfjella basaltic andesites from the Ferrar Province (Antarctica), considered as a continuation of the South African Karoo Province (e.g. Luttinen and Furnes, 2000) (Fig. 6c). The fine-grained BD shows even higher K, LREE, P, Zr and Ti contents than Deccan diabases and correlates well with Miocene CFB of the Columbia River Province (USA) (Fig. 6d). In all these CFB provinces, volcanic extrusions took place in an extensional tectonic setting. Stretching of the Gondwana crust during the Mesozoic resulted in breakup of the continent and in opening of the South Atlantic and Indian oceans (e.g. Gallagher and Hawkesworth, 1994; Kirstein *et al*., 2000). The volcanic activity in the Karoo-Ferrar Province (e.g. Vestfjella basalts) probably occurred prior to the separation of Antarctica from Africa, whereas numerous volcanic extrusions across the Indian Peninsula took place after the Gondwana breakup. These extrusions may have been associated with a drift of the Indian plate over an extremely active mantle plume (Courtillot *et al*., 1986; Wilson, 1989). Basalts of the Columbia River Province developed during moderate crustal extension, which did not result in breakup of the North American continent (Prestvik and Goles, 1985; Hooper and Hawkesworth, 1993). The Siberian Province of CFB is also an example of post-orogenic extension caused by a rising mantle diapir beneath the margin of the Siberian craton after its collision with Baltica at the Permian/Triassic boundary (Wooden *et al*., 1993).

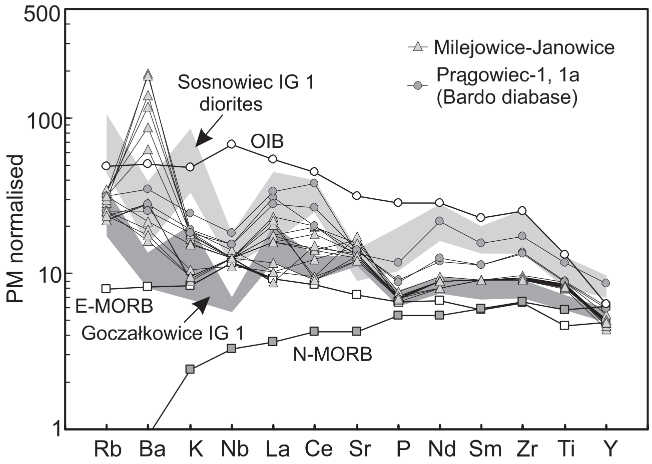

Fig. 5. Primitive mantle (PM) normalised incompatible element patterns for samples from the Holy Cross Mts. and Upper Silesia

N-MORB — data for mid-ocean ridge basalts (“normal”), E-MORB — data for mid-ocean ridge basalts (enriched), OIB — ocean island basalts and normalising values from Sun and McDonough (1989); data for Goczałkowice IG 1 and Sosnowiec IG 1 samples are from Krzemiński (unpubl. data)

PARTIAL MELTING AND MAGMA FRACTIONATION

Like most CFB tholeiites, the Holy Cross Mts. and Upper Silesia diabases have relatively evolved compositions. Low values of MgO, Ni and Cr contents, and *mg*-number, with high SiO$_2$ con-

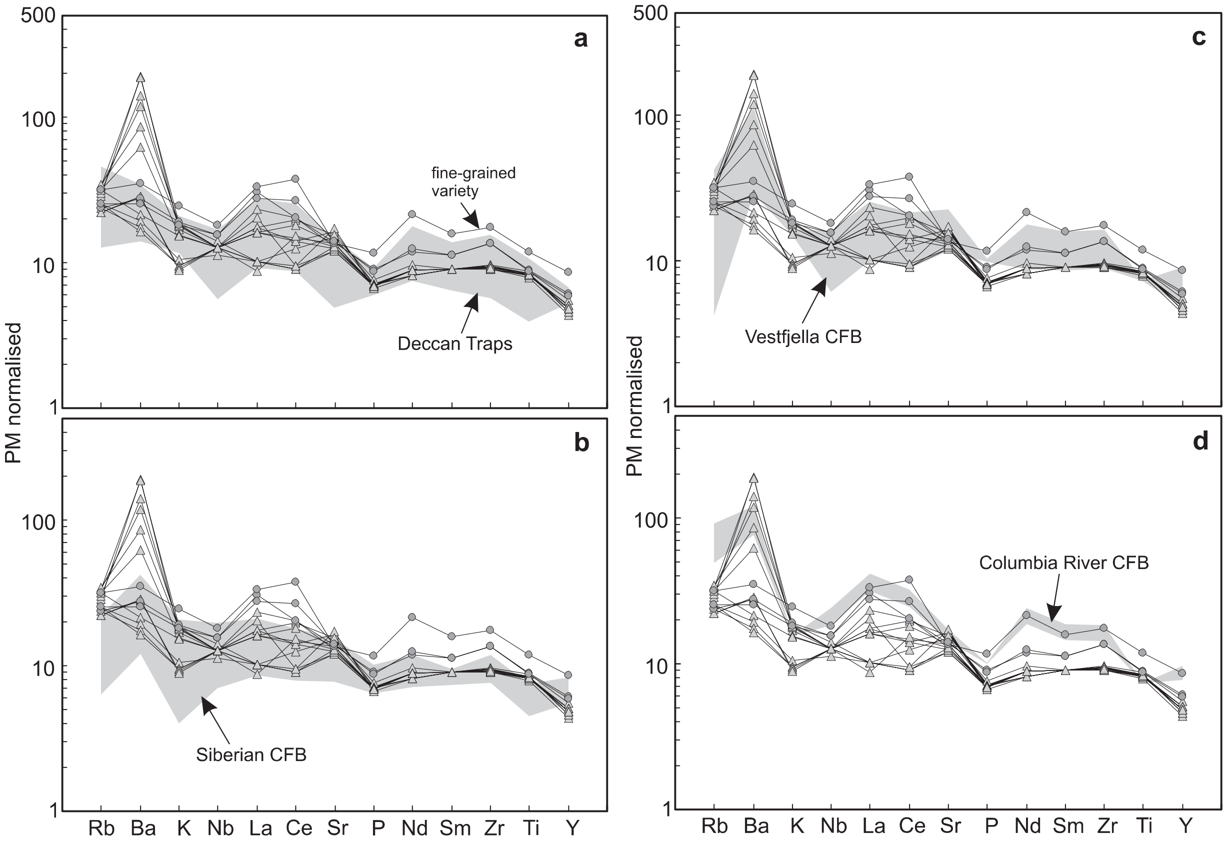

Fig. 6. Primitive mantle normalised incompatible element patterns for diabases from the Holy Cross Mts. compared with continental flood basalts (CFB) from four provinces

The shaded areas show ranges of samples from the Deccan region (Melluso *et al*., 1995), Siberia (Wooden *et al*., 1993), Vestfjella (Luttinen and Furnes, 2000) and Columbia River (Hooper and Hawkesworth, 1993); see text for discussion; normalising values from Sun and McDonough (1989); symbols as in Figure 5

tents, make them considerably different from primary melts, which could be in equilibrium with mantle peridotites (see Cox, 1980). The plagioclase + clinopyroxene ± olivine phenocrysts association, characteristic of most CFB, suggests that they were subject to extensive low-pressure crystal fractionation, which was the main mechanism of their composition evolution from MgO-rich primary picritic magma to rather highly evolved magmas (*op. cit.*).

Some of the variation in chemical composition of the analysed diabases can be explained by crystal fractionation in their parental melts. A good positive correlation between (Cr + Ni) and *mg*-number in the diabase-diorite series from the Upper Silesian Block is consistent with fractionation of olivine, clinopyroxene and chrome spinel, and indicates that dioritic magma was formed as a result of a crystal fractionation of a parental basaltic magma (Fig. 7a). The Bardo diabases plot along the trend line of Upper Silesian diabase-diorite. Thus they could occupy a transitional position between these two members of the differentiation series. However, in the (Cr + Ni) vs. Zr plot, Bardo diabases plot beyond the correlation line of Upper Silesia diabases and diorites (Fig. 7b). The opposite relationship occurs between the BD and MJD: a very poor correlation (R^2 = 0.41) in the (Cr + Ni) vs. *mg*-number plot, and a nearly maximum correlation (R^2 = 0.99) in the (Cr + Ni) vs. Zr plot. There is no correlation on both these plots between the MJD and USD. The above relationships show that compositional variability in diabases was also influenced by another factor that could be a degree of partial melting of the mantle source. The degree of partial melting in the least evolved primary magma is measured by the Zr/Nb ratio, mainly due to a greater incompatibility of Nb than Zr, and therefore due to a greater tendency for Nb to be concentrated in the partial melt (see Yurtmen *et al*., 2002). Thus, a decrease in the degree of partial melting results in a decrease in the Zr/Nb ratio, as does an increase in the degree of fractionation of mafic phases. An increase in the degree of fractionation also results in a decrease in Cr and Ni contents, and therefore a positive correlation on the (Cr + Ni) vs. Zr/Nb plot in the comagmatic series should be expected. No such correlations between the MJD and BD or between the MJD and USD can be observed in Figure 7c, however there is a positive correlation within the diabase-diorite series of the Upper Silesia Block. These three groups of diabases are most probably products of fractionation of different primary melts, formed due to different degrees of partial melting of mantle sources. The primary melt of the MJD was generated by the lowest degree of melting, whereas the primary magma of the USD represented a higher degree of partial melt. Increased contents of incompatible elements in the BD, in particular in the fine-grained variety, are not caused by a considerably lower degree of partial melting because, in the case of the MJD, the degree of source melting was even slightly lower, and its enrichment in incompatible elements is lower than in the BD. Such a composition of the BD results mainly from a higher degree of fractionation. This interpretation is confirmed by a higher content of normative hypersthene in USD than in the MJD (see Table 3), since the increase in the degree of partial melting enhances the amount of this component in the melt generated (DePaolo and Daley, 2000).

MANTLE SOURCES

The relative contribution of potential mantle sources to the origin of the diabases analysed is shown on the Zr/Nb vs. Y/Nb diagram (Fig. 8). The diabases plot along the mixing line of OIB and N-MORB, in the area of E-MORB segments, enriched due to the influence of a mantle plume. Considerably lower Zr/Nb and Y/Nb ratios were observed in the MJD and BD plotted near the average composition of OIB, the average composition of enriched subcontinental lithospheric mantle (CLM), and enriched peridotitic xenoliths of the European mantle (Sardinia — Beccaluva *et al*., 2001; southern Italy — Downes *et al*., 2002). Upper Silesian diabases with higher HFSE ratios plot relatively closer to strongly depleted mid-ocean ridge basalts (N-MORB) and weakly depleted xenoliths of the continental lithosphere (Scotland — Downes *et al*., 2001). This suggests a higher contribution of depleted mantle sources in generating the primary magma of the upper Silesian diabases. Thus, we can suppose that two mantle sources contributed to the formation of primary magmas of the diabases analysed: subcontinental lithosphere and asthenosphere. The relative contribution of both these components differed between the Holy Cross Mts. and Upper Silesia.

Neodymium isotopic data are essential for the discussion of primary magma sources. We have such data only for two diorite samples and one diabase sample from the Sosnowiec IG 1 borehole (Nawrocki and Krzemiński, 2001). Values of the ε_{Nd} parameter, calculated for the Early Palaeozoic, vary from +0.4 to –0.4 (Fig. 9). These are intermediate values between typical isotopic characteristics of strongly depleted asthenospheric sources (including a PREMA-type reservoir; see Zindler and Hart, 1986) and enriched lithospheric sources commonly postulated for continental basalts, e.g. associated with regional crustal extension in the Basin and Range Province (DePaolo and Daley, 2000). These two types of mantle sources also show very different geochemical characteristics as defined by La/Nb and Ba/Nb ratios. Rocks from the Sosnowiec IG 1 borehole are also located between these extremes, probably suggesting that both of the sources contributed to the generation of primary magma. On the other hand, isotopic characteristics of the Sosnowiec IG 1 intrusion resemble both the weakly depleted subcontinental lithospheric mantle of Scotland (Downes *et al*., 2001) and average CLM with ε_{Nd} ranging from +2 to –3 (McDonough, 1990). However, CLM has an average La/Nb ratio < 1 (positive Nb anomaly). McDonough (*op. cit.*) considered that it probably excludes CLM as the main source of continental flood basalts. The negative Nb anomaly, observed in some diabase and diorite samples, indicates either magma contamination by the continental crust or a contribution of a "subduction component" in the source. Assimilation of crustal material did not occur on a large scale, as evidenced by low LILE contents and relatively low SiO_2 contents, even in the most fractionated fine-grained Bardo diabases. There-

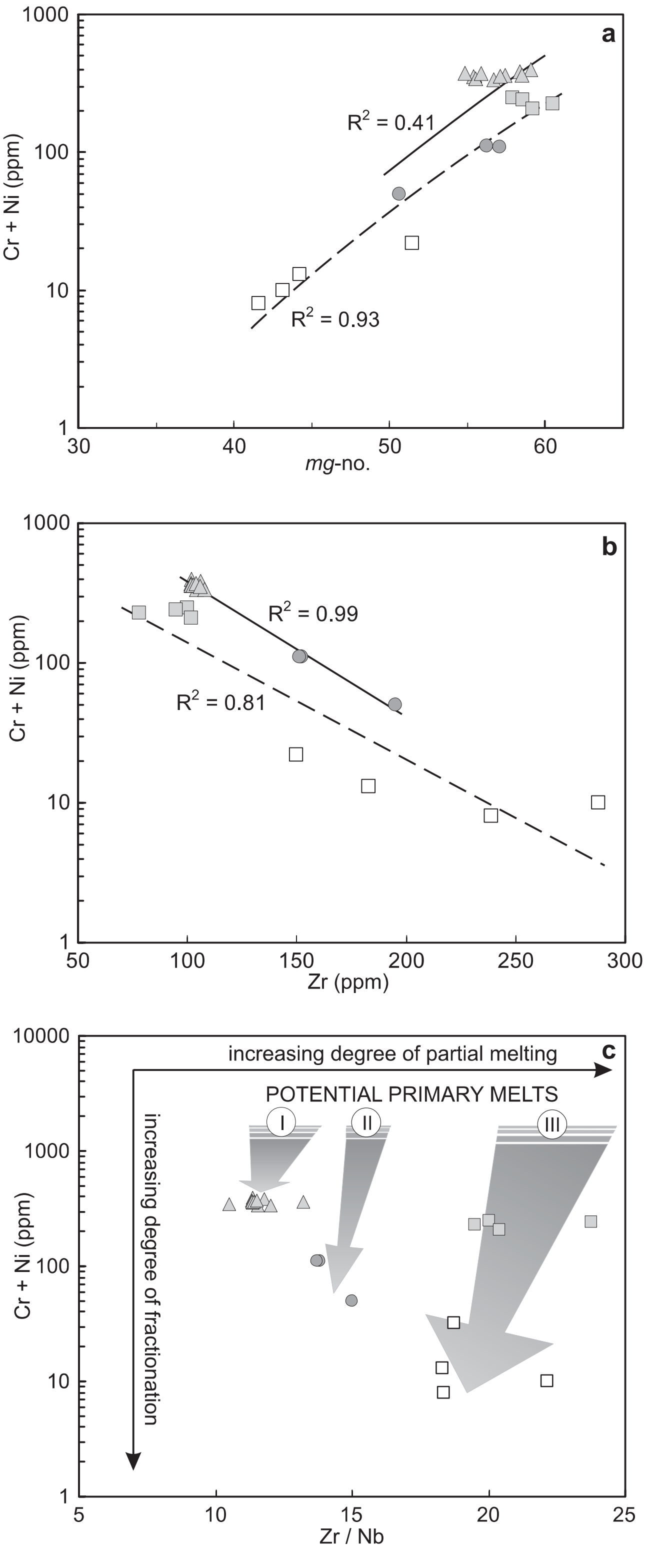

Fig. 7. **a**, **b** — (Cr + Ni) vs. *mg*-number and (Cr + Ni) vs. Zr correlation plots for samples from the Holy Cross Mountains and Upper Silesia; solid and dashed correlation lines represent the Holy Cross Mts. diabases and Upper Silesia rocks, respectively; R^2 is the square of Pearson`s correlation coefficient; **c** — (Cr + Ni) vs. Zr/Nb plot schematically illustrating the effect of the degree of partial melting of mantle sources and fractionation of primary melts on the composition of the rocks studied

Symbols as in Figure 3

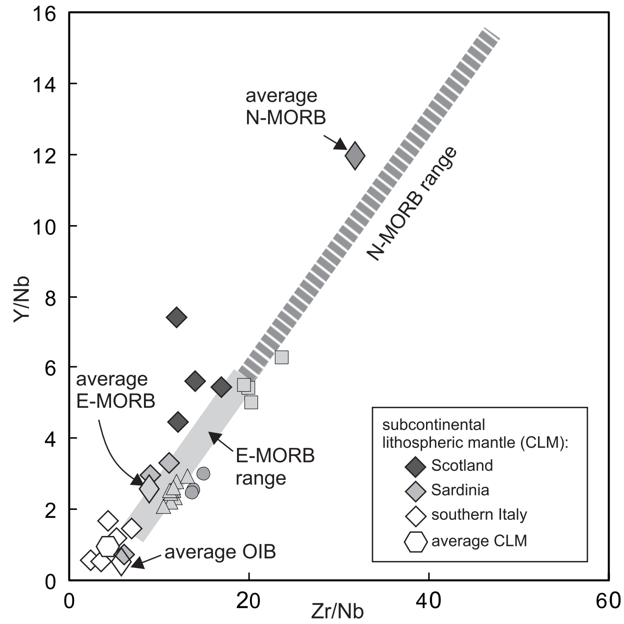

Fig. 8. Y/Nb vs. Zr/Nb for Holy Cross Mts. and Upper Silesia diabases

OIB average values and N-MORB and E-MORB average values and ranges are also shown (data from Sun and McDonough, 1989; Le Roex *et al.*, 1983, 1985); subcontinental lithospheric mantle data are from McDonough (1990), Downes *et al.* (2001, 2002) and Beccaluva *et al.* (2001); symbols as in Figure 3

fore, buffering of SiO_2 during gabbro fractionation and decreases in MgO content were not obliterated by assimilation of silica-rich crustal material (*cf.* Cox, 1980). Instead, there is a possible interpretation referring to the "subduction component" in the mantle source. The negative Nb anomaly arises under the influence of fluids and melts liberated during subduction. They enhance LREE contents in the overlying subcontinental mantle wedge, simultaneously resulting in relatively small changes in most of the HFSE contents (e.g. Pearce *et al.*, 1995). A similar value of *mg*-number in the MJD and USD, with slightly higher SiO_2 contents in the USD, indicates that the latter originates from a source characterised by a greater contribution of the "subduction component". It also corresponds to the larger negative Nb anomaly in the USD. Such an interpretation is consistent with the incompatible element patterns of the MJD and USD (Fig. 5). A lower degree of partial melting of the mantle source is accompanied by a higher enrichment in incompatible elements. This is not the case with the MJD, considering the LREE and some LILE, but it is observed in some HFSE, particularly Nb, and also Zr and Ti. It follows that a selective increase in LREE contents reflects a higher contribution of the "subduction component" in the mantle source in the case of the USD, than it does in the case of the MJD and BD.

REGIONAL IMPLICATIONS

Some authors consider the Łysogóry Unit, the Małopolska Block (also including south Holy Cross Mts.) and the Upper Silesia Block as terranes detached from the margin of Gondwana (e.g. Unrug *et al.*, 1999; Belka *et al.*, 2000; *cf.* Berthelsen, 1992; Moczydłowska, 1997).

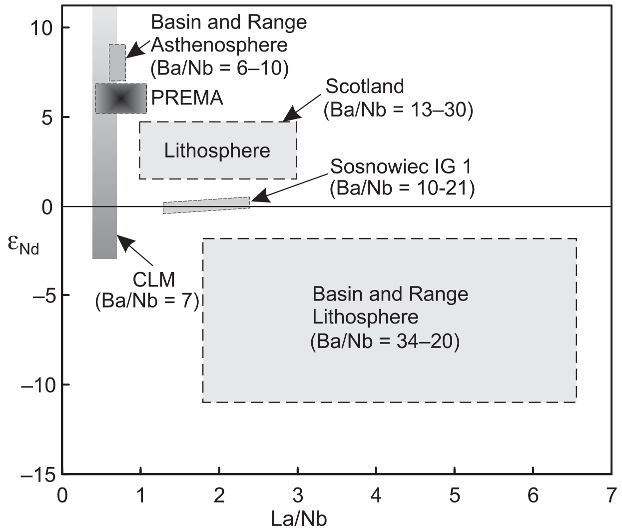

Fig. 9. ε_{Nd} vs. La/Nb for diorite and diabase samples from the Sosnowiec IG 1 borehole (Upper Silesia) (Nawrocki and Krzemiński, 2001; Krzemiński, unpubl. data); inferred compositions of lithospheric and asthenospheric magma sources for Miocene basaltic volcanism related to intracontinental extension in the southwestern Basin and Range Province (USA) are shown for comparison (DePaolo and Daley, 2000); the composition of the PREMA-type asthenospheric reservoir (Zindler and Hart, 1986), average composition of the subcontinental lithospheric mantle (CLM) (McDonough, 1990) and weakly depleted subcontinental lithospheric mantle values in Scotland (Downes *et al.*, 2001) are also plotted; see text for discussion

Assuming this, it can be supposed that the negative Nb anomaly ("subduction component") arose in the lithospheric mantle of these crustal fragments as a result of Late Proterozoic subduction of the Tornquist Sea under the Gondwanan active margin (*cf.* Nance *et al.*, 1991; Jelinek and Dudek, 1993; Finger and Steyrer, 1995). An alternative concept assumes that the Łysogóry Unit is not a terrane, but was part of the southwestern passive margin of Baltica during Ordovician and Silurian times (Dadlez *et al.*, 1994), upon which a Late Silurian foredeep developed during the final stage of collision between Baltica and East Avalonia (Narkiewicz, 2002). At the same time, the Małopolska Block was a stable element of the Baltica margin, originally located probably to the south-east of its present-day position, and subsequently detached and moved along the craton margin and docked as a proximal terrane close to the Łysogóry Unit, not later than in the Early Devonian (Dadlez *et al.*, 1994). On the basis of Ordovician and Silurian subsidence analysis, Narkiewicz (2002) considered that this translation of the Małopolska Block occurred between the late Ludlow and Emsian, which corresponds to the timing of the Bardo diabase intrusion (Kowalczewski and Lisik, 1974). In such a scenario of accretion history of crustal blocks in this area, the Bardo diabase intrusion could represent a record of the detachment and translation of the Małopolska terrane, while the MJD could be considered a response to a magmatic event related to postorogenic extension along the passive hinterland of the Avalonia/Baltica collisional belt. A different provenance of the Łysogóry and Małopolska Blocks (Baltica) and the Upper Silesia Block (Gondwana) better explains the less distinct "subduction signature" of the MJD and BD. In this concept, the "subduction signature" can reflect some undetermined episode of the earlier geodynamic evolution of Baltica.

The Holy Cross and Upper Silesian diabases can be interpreted as fractionation products of more mafic primary magmas generated through partial melting at the base of the continental lithosphere, probably as a result of the thermal activity of a rising mantle plume. The Upper Silesia diabases are a record of a magmatic event associated with stronger decompression in the source area, during the greatest extension and at the thinnest lithosphere due to the rising plume. The MJD of the Łysogóry Unit and the BD of the Kielce region were produced as a result of a weaker mantle-plume influence on the relatively thicker continental lithosphere. Magmatic processes could be related to decreasing activity of the mantle plume in the peripheries of a large magmatic province. The highest mantle-plume influence occurred in the present area of the Central European Variscides with abundant Early Palaeozoic volcanism related to rifting in an extensional setting, and to subsequent fragmentation of the northern margin of Proto-Gondwana (Crowley *et al.*, 1999; Floyd *et al.*, 2000).

CONCLUSIONS

1. The Holy Cross and Upper Silesian diabases have a distinct signature of anorogenic magmatites, typical of continental extensional settings. They also show a very remarkable geochemical affinity to continental flood basalts (CFB), associated with the breakup of Gondwana and the opening of ocean basins in the Mesozoic (Deccan, Karoo-Ferrar), or related to moderate crustal extension (Siberia, Columbia River).

2. All of the diabases analysed represent tholeiitic melts generated probably as a result of the thermal effect of a mantle plume on the base of subcontinental lithosphere. The contribution of each mantle sources was different in the Holy Cross Mts. and Upper Silesia. The distinct "subduction signature" of the Upper Silesia diabases can be hypothetically correlated to Late Proterozoic subduction of the Tornquist Sea under the active margin of Gondwana.

3. Relatively small variations in the chemical compositions of diabases from the three different areas cannot be explained by the fact that they originate from the same primary magma. Primary magmas of the Milejowice-Janowice (MJD), Bardo (BD) and Upper Silesian diabases (USD), probably of picritic composition, were produced under slightly different conditions of mantle source melting, and they were subject to various degrees of gabbro fractionation at shallower crustal levels.

4. The Bardo diabase intrusion may record the detachment of the Małopolska Block from Baltica, and its translation along the craton margin during late Ludlow–Emsian times up to the present-day position. The Milejowice-Janowice diabases can be considered to represent a post-tectonic magmatic event associated with extension of the Baltica passive margin at the final, Late Silurian stage of its collision with East Avalonia.

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