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Middle/Late Cambrian intracontinental rifting in the central West Sudetes, NE Bohemian Massif (Czech Republic): geochemistry and petrogenesis of the bimodal metavolcanic rocks

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The Early Palaeozoic East Krkonoše Complex (EKC) situated in the central West Sudetes, NE Bohemian Massif, is a volcano-sedimentary suite containing abundant mafic and felsic volcanics metamorphosed to greenschist facies.

The trace element distribution patterns and Nd isotope signatures ($\varepsilon_{Nd500} = -3.1$ to $+6.6$) of the metabasites (metabasalts) indicate that they may be related to a rising mantle diapir associated with intracontinental rifting. At the early stage, limited melting of an upwelling asthenosphere produced alkali basalts and enriched tholeiites which compositionally resemble oceanic island basalts. A later stage of rifting with larger degrees of melting at shallower depths generated tholeiitic basalts with E-MORB to N-MORB characteristics.

The values of $(^{87}Sr/^{86}Sr)_i = 0.706$ and $\varepsilon_{Nd500} = -5 + 1$ of the porphyroids (metarhyolites) as well as the lack of rocks with intermediate compositions suggest that the felsic rocks were formed by a partial melting event of continental crust triggered by mantle melts.

The geochemistry of the EKC bimodal metavolcanics and their association with abundant terrigenous metasediments suggest that the felsic–mafic volcanic suite was generated during intracontinental rifting. This process, widespread in Western and Central Europe during the Early Palaeozoic, is evidence of large-scale fragmentation of the northern margin of the Gondwana supercontinent. Copyright © 2001 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Bimodal magmatic suites, ubiquitous in the European Variscan Belt, extend from northwestern Iberia (e.g. Sanchez Carretero *et al.* 1990), through the southern Massif Central (Pin and Marini 1993; Briand *et al.* 1995) and Armorican Massif (Bernard-Griffiths *et al.* 1986) to the West Sudetes of the Bohemian Massif (e.g. Narębski *et al.* 1986; Furnes *et al.* 1994; Narębski 1994; Winchester *et al.* 1995; Floyd *et al.* 1996). They are probably related to an Early Palaeozoic large-scale ensialic rifting (Pin 1990), and fragmentation of the northern Gondwana supercontinent (Ziegler 1989).

Early Palaeozoic volcanic suites which can shed light on the pre-Variscan evolution of the northern margin of Gondwana are abundant in the West Sudetes. The West Sudetes (NE Bohemian Massif) are composed of Late Proterozoic to Early Carboniferous metamorphosed supracrustal sequences that were intruded by Late Proterozoic

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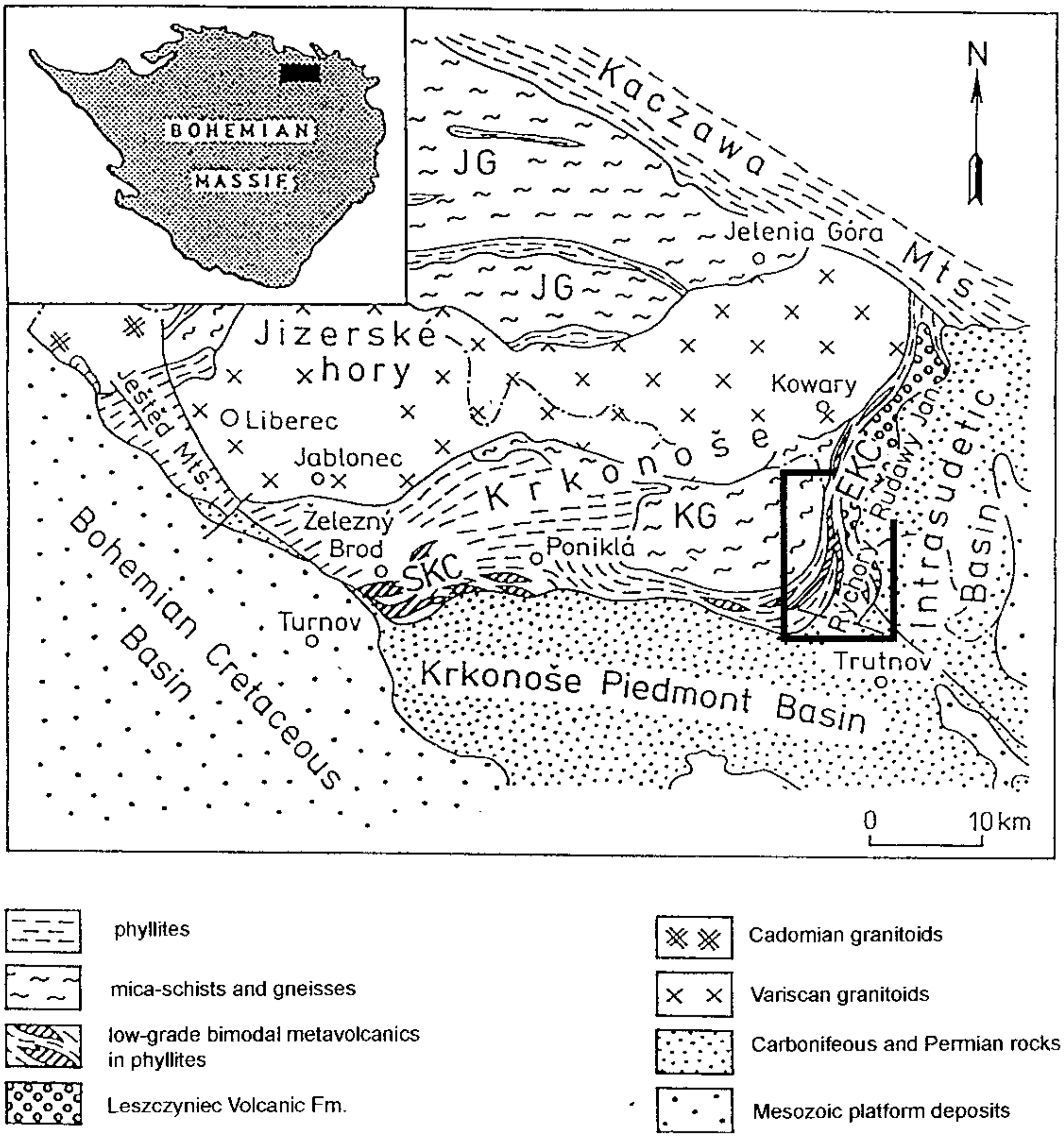

Figure 1. Simplified geological map of the West Sudetes-Krkonoše, Jizerské hory and Ještěd Mts. Based on Chlupáč (1993). JG, Jizera Gneiss; KG, Krkonoše Gneiss and associated rocks; EKC, East Krkonoše Complex; SKC, South Krkonoše Complex. The inset shows the studied region within the Bohemian Massif. The rectangle in the lower right of the figure corresponds to the area shown in Figure 2.

and Palaeozoic granitoids (Svoboda and Chaloupský 1966; Teisseyre 1973; Żelaźniewicz 1997). The West Sudetes are inferred to be a collage of terranes amalgamated during the Variscan orogeny (e.g. Narębski 1994).

The Early Palaeozoic metavolcanics of the central West Sudetes show considerable diversity both in the metamorphic grade and the nature of the protolith. They occur as minor units distributed along the eastern and southern margins of the Krkonoše-Jizera terrane of Narębski (1994), namely in the East and South Krkonoše Complexes (Figure 1). The geochronological data (Oliver *et al.* 1993; Bendl and Patočka 1995) put the onset of the volcanism to the Middle to Late Cambrian. According to fossil evidence (e.g. Chlupáč 1993) the volcanic activity was protracted, lasting until the Silurian (and possibly Devonian) and, in the westernmost parts of the terrane (in the Ještěd Mts), until the Early Carboniferous. The long magmatic period is comparable to that of time-equivalent analogous suites of the Saxothuringian zone (e.g. Tischendorf *et al.* 1995) and of the Polish West Sudetes (Narębski *et al.* 1986; Furnes *et al.* 1994; Winchester *et al.* 1995, 1998).

The purpose of this paper is to present geochemical data (major and trace elements and Sm-Nd isotopes) on the bimodal metavolcanic suite of the East Krkonoše Complex of the central West Sudetes, and in evaluating their petrogenesis to constrain their tectonic setting as well as their significance for the Early Palaeozoic evolution of the northern margin of the Gondwana supercontinent.

2. GEOLOGICAL SETTING

The East Krkonoše Complex (EKC) is situated in the central part of the West Sudetes where it forms an almost continuous mountain range: the Rýchory Mts (in the Czech Republic) and the Lasocki Ridge and Rudawy Janowickie Mts (in Poland). The eastern margin of the EKC is formed by the Leszczyniec Volcanic Fm. (LVF) (e.g. Svoboda and Chaloupský 1966; Teisseyre 1973) (Figure 1). The complex is composed of rock bodies that display steeply dipping NNW–SSE foliation related to the N–S oriented Leszczyniec shear zone of late Variscan age (e.g. Mazur and Kryza 1996; Żelaźniewicz 1997).

On the Czech territory the EKC is for the most part represented by a low-grade metamorphosed volcano-sedimentary suite composed of quartzites, phyllites, marbles, metacherts and bimodal metavolcanic rocks (Figure 2). Felsic metavolcanic rocks (porphyroids) are far more abundant than mafic types (greenschists, greenstones) (Figures 2 and 3). The whole-rock Rb-Sr age of 501 ± 8 Ma (Bendl and Patočka 1995) dates the igneous protolith of the bimodal metavolcanics around the Middle/Late Cambrian boundary (cf. Davidek *et al.* 1998). Mafic blueschists (usually retrogressed into greenschist facies) are enclosed in phyllites in the eastern part of the Rýchory Mts (Figure 2). These metavolcanics show geochemical characteristics of rocks of oceanic crust (Patočka *et al.* 1996; Maluski and Patočka 1997; Dostal *et al.* 2000), and the blueschist bodies are interpreted to be the dismembered southernmost promontory of the LVF (Patočka and Smulikowski 1998) (Figure 1). The U-Pb data on zircons from the mafic blueschists yielded a protolith age of 485 ± 4 Ma (Timmermann *et al.* 1999), compatible with U-Pb zircon ages of 505 ± 5 Ma and 494 ± 2 Ma for the felsic and mafic rocks of the LVF main body (Oliver *et al.* 1993); these ages correspond to the timespan since Middle Cambrian to the earliest Ordovician (cf. Gradstein and Ogg 1996; Davidek *et al.* 1998).

The EKC experienced two main Variscan metamorphic events (Patočka *et al.* 1996). The first was a blueschist facies metamorphism ($T = 300–500°C$ and $P = 0.7–1.0\,GPa$) followed by a greenschist facies event. The ^{40}Ar-^{39}Ar dating of phengites from the mafic blueschists yielded an age of 360–365 Ma for the end of the blueschist facies metamorphism, and an age of 340–345 Ma for the greenschist facies overprint (Maluski and Patočka 1997; Marheine *et al.* 1999).

3. PETROGRAPHY OF METAVOLCANIC ROCKS

In the East Krkonoše Complex, the bodies of mafic and felsic metavolcanic rocks are closely associated and even grade into each other (Teisseyre 1973; Chaloupský *et al.* 1989; Bendl and Patočka 1995).

Felsic metavolcanic rocks are made up of albite, quartz, muscovite, chlorite and clinozoisite. The phenocrysts (c. 1–2 mm in size) are oriented parallel to the rock fabric. Albite phenocrysts are abundant; quartz and/or microcline phenocrysts are rare. The quartz phenocrysts usually show semi-hexagonal shapes typical of magmatic quartz. Some rocks display mylonitic fabric. Only the outcrops of large bodies of felsic metavolcanics with abundance of feldspar (± quartz) phenocrysts were sampled for the purpose of this study (Figure 2). These rocks – termed porphyroids or metarhyolites – are considered to be metamorphosed equivalents of felsic lavas and/or shallow subvolcanic intrusives; the associated sericite phyllites are interpreted as metamorphosed felsic pyroclastic (Bendl and Patočka 1995).

Mafic metavolcanic rocks (metabasites), subordinate in the complex, are composed of actinolite, chlorite, epidote, albite and carbonate. Sodic amphiboles are ubiquitous but rare (Chaloupský *et al.* 1989; Smulikowski 1995,

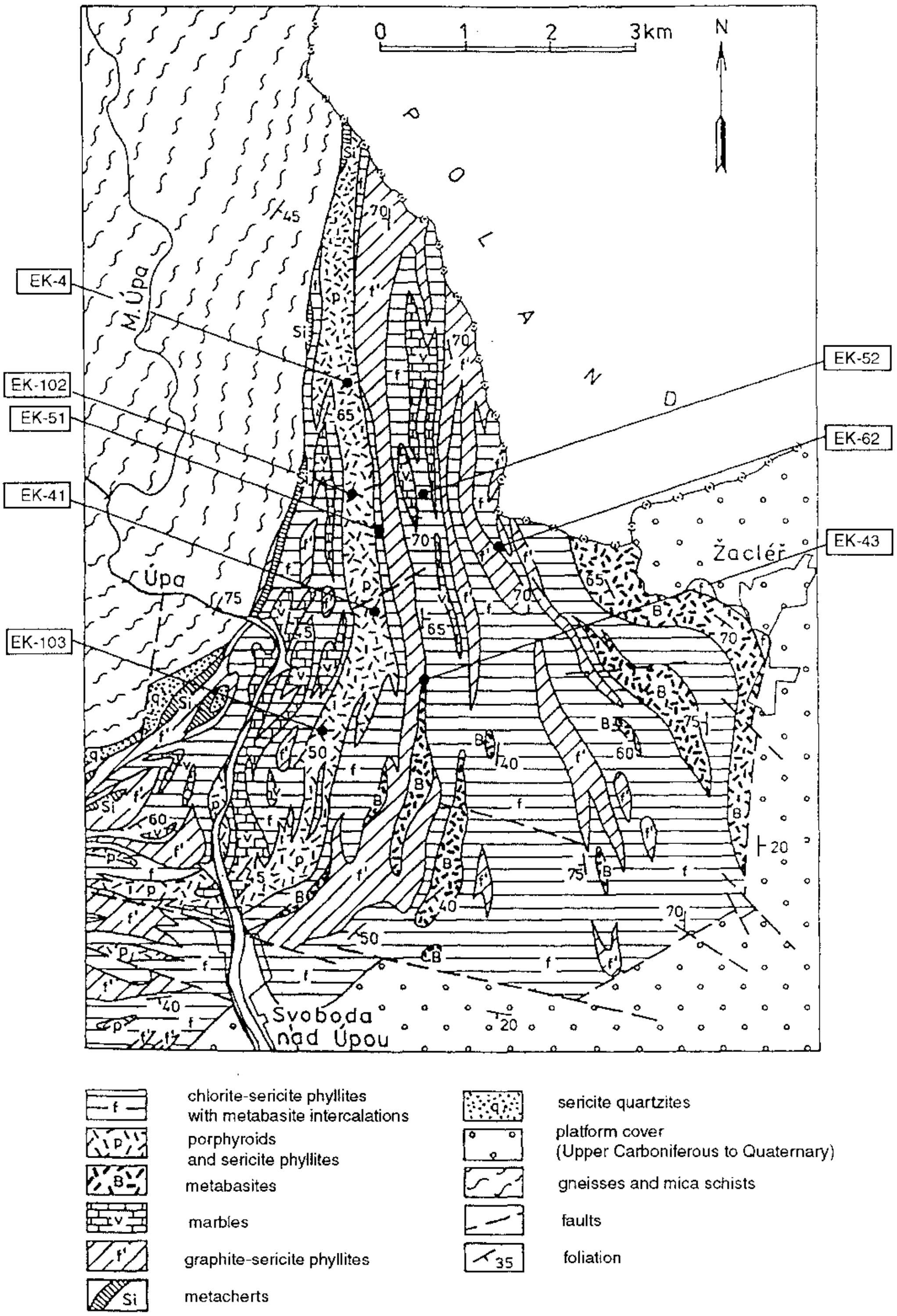

Figure 2. Geological map of the East Krkonoše Complex. Based on Chaloupský (1989).

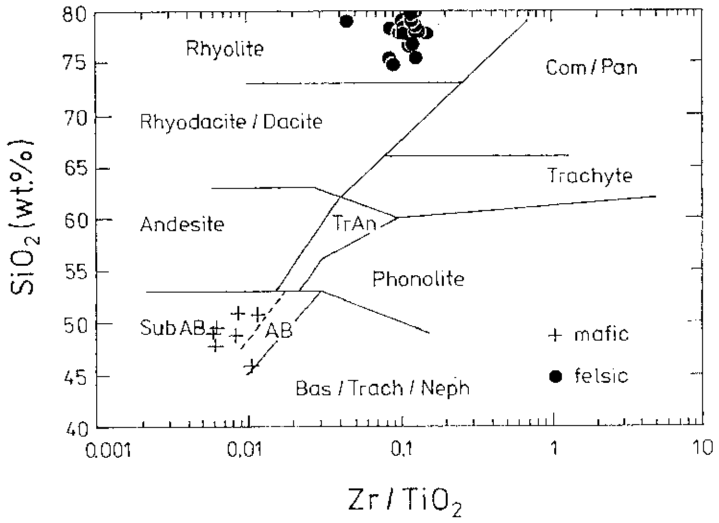

Figure 3. Zr/TiO_2 vs SiO_2 diagram (based on Winchester and Floyd 1977) illustrating the bimodal nature of the metavolcanic rock association of the East Krkonoše Complex and the subalkaline to alkali composition of the basic rocks of the suite.

1999; Patočka and Novák 1997). More massive metabasites (greenstones) – supposed to represent primary basic lavas (Bendl and Patočka 1995; Patočka and Smulikowski 1998) – were sampled by the authors (Figure 2).

4. ANALYTICAL METHODS

Representative samples (21 felsic and eight mafic metavolcanic rocks) were selected from a bimodal suite sample set collected during the mapping of the Rýchory Mts. Major element concentrations were determined in the Institute of Geology of the Czech Academy of Science using wet chemical technique (Table 1). Some trace (Rb, Sr, Ba, Zr, Nb, Y, Cr, Ni, Sc, V, Cu and Zn) elements were analysed by X-ray fluorescence at the Department of Geology, Saint Mary's University, Halifax; eight samples (four mafic and four felsic rocks) were also analysed by inductively coupled plasma-mass spectrometry for the rare earth elements (REE), Hf, Zr, Nb, Y and Th (Table 2). The precision and accuracy are discussed in Dostal *et al.* (1986, 1994). In general, they are less than 5% for major elements and 2–10% for trace elements.

Six samples of the metavolcanic rocks (three mafic and three felsic rocks) were selected for Nd isotopic analyses (Table 3). The $^{143}Nd/^{144}Nd$ values and the concentrations of Sm and Nd were determined by isotope dilution and thermal ionization mass spectrometry in CNRS – Université Blaise Pascal, Clermont Ferrand, following the technique outlined by Pin and Marini (1993). The $^{143}Nd/^{144}Nd$ values were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The La Jolla Nd standard analysed at the same time yielded average of $^{143}Nd/^{144}Nd = 0.511854 \pm 0.000013$ ($n = 15$). Initial ratios and E_{Nd} values were calculated assuming the age of 500 Ma for the rocks (Bendl and Patočka 1995). E_{Nd} and T_{CHUR} values were calculated based on modern values of $^{143}Nd/^{144}Nd_{CHUR} = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1966$, and $\lambda^{147}Sm = 6.54 \times 10^{-12}\ a^{-1}$. Depleted mantle model ages (T_{DM}) were calculated according to DePaolo (1981).

5. EFFECTS OF SECONDARY PROCESSES

The use of chemical compositions of metavolcanic rocks to determine the tectonic setting in which they were generated is based upon well defined relations between magma chemistry and tectonic settings (e.g. Pearce 1982;

Table 1. Major and trace element abundances in representative samples of the metavolcanic rocks of the East Krkonoše Complex

	Metabasites				Porphyroids			
Sample	EK-43	EK-51	EK-52	EK-62	EK-4	EK-41	EK-102	EK-103
Major elements (wt%)								
SiO_2	45.97	48.17	42.62	41.89	73.87	74.72	76.32	76.79
TiO_2	1.67	2.50	0.95	3.52	0.18	0.06	0.12	0.08
Al_2O_3	14.43	15.38	16.96	17.91	12.15	13.05	1.59	12.57
Fe_2O_3	3.17	4.41	4.21	3.19	1.81	1.26	1.19	1.29
FeO	7.66	6.56	4.57	8.35	0.33	0.08	0.29	0.33
MnO	0.18	0.14	0.12	0.28	0.01	0.02	0.02	0.02
MgO	8.70	6.06	8.45	5.29	0.25	0.51	0.83	2.33
CaO	8.79	8.21	8.90	6.06	0.06	0.30	0.31	0.78
Na_2O	3.51	2.73	3.50	2.36	1.37	1.35	1.25	1.73
K_2O	0.10	0.79	0.25	2.34	8.79	5.39	6.28	1.04
P_2O_5	0.19	0.41	0.11	1.05	0.06	0.02	0.04	0.01
H_2O	4.96	3.74	5.53	7.27	0.35	1.55	0.99	2.70
CO_2	0.69	0.27	3.99	2.44	0.05	0.01	0.18	–
Total	100.02	99.37	100.16	99.80	99.28	99.32	99.41	99.26
Trace elements (ppm)								
Cr	172	175	253	4	191	70	–	59
Ni	125	62	135	9	52	48	10	8
Co	53	40	45	28	37	31	43	76
V	378	291	179	233	13	6	5	2
Rb	12	10	4	104	164	148	197	45
Ba	154	276	55	419	883	950	1265	682
Sr	217	391	192	267	14	41	47	99
Ta	0.9	0.75	0.19	6.79	1.12	0.85	0.98	–
Nb	–	13.1	3.3	127.9	7.6	4.6	4.1	7
Hf	2.1	4.95	1.67	8.58	2.93	3.39	4.13	–
Zr	90	251	65	414	131	98	153	91
Y	25	32	16	31	17	28	30	52
Th	0.5	1.73	0.39	9.31	10	12.24	13.53	16
La	7.4	17.59	3.43	80.47	12.99	13.65	25.95	22.30
Ce	24.10	42.10	9.40	163.20	53.71	39.99	60.26	56.80
Nd	12.90	24.88	7.36	67.00	10.85	13.65	24.57	41.80
Sm	3.69	5.72	1.99	11.49	2.27	3.80	4.88	9.28
Eu	1.11	1.95	0.88	3.43	0.16	0.37	0.38	0.30
Gd	3.76	6.40	2.93	10.00	2.14	4.12	4.46	3.46
Tb	0.68	1.05	0.42	1.25	0.41	0.77	0.80	0.65
Ho	1.00	1.24	0.59	1.22	0.64	0.97	1.18	0.86
Tm	0.42	0.52	0.27	0.44	0.39	0.45	0.60	0.43
Yb	2.80	3.32	1.64	2.52	2.76	3.07	4.06	2.97
Lu	0.22	0.46	0.25	0.40	0.41	0.41	0.56	0.40

Pearce *et al.* 1984) and an assumption that at least the abundances of the relatively immobile elements were not significantly modified by secondary processes.

The concentrations of the high-field strength elements (HFSE), REE and transition elements in the samples of the EKC mafic and felsic metavolcanics probably reflect the primary magmatic distributions (Figures 3 to 7, Tables 1 and 2). The overall similarities of the abundances of these elements in the metavolcanic rocks of the EKC to those of modern volcanics (e.g. Winchester and Floyd 1977; Pearce 1982; Pearce *et al.* 1984; Wilson 1989) suggest that their distribution was not significantly modified and can be used for petrogenetic and geotectonic interpretations.

Table 2. Geochemical characteristics of the East Krkonoše Complex metavolcanic rocks discussed in the text. The Eu/Eu* and $(La/Yb)_N$ values are related to the chondrite-normalized REE distribution patterns.

sample	K_2O/Na_2O	Mg#	Zr/Nb	Zr/Y	Nb/Y	Th/La	Ti (ppm)	Ti/Zr	Eu/Eu*	$(La/Yb)_N$
Metabasites										
EK-43	0.03	58.86	–	3.6	–	0.10	10,020	23.86	–	18.87
EK-51	0.29	50.43	19.16	7.84	0.41	0.10	15,000	59.76	–	3.15
EK-52	0.07	64.31	19.70	4.06	0.21	0.11	5,700	87.69	–	1.24
EK-62	0.99	45.66	3.24	13.35	4.13	0.12	21,120	51.01	–	18.96
Porphyroids										
EK-4	6.42	–	17.24	7.71	0.45	0.77	10,800	82.44	0.24	2.62
EK-41	3.99	–	21.30	3.50	0.16	0.90	360	3.67	0.31	2.47
EK-102	5.02	–	37.32	5.10	0.14	0.52	720	4.71	0.27	3.55
EK-103	0.60	–	13.00	1.75	0.13	0.71	480	5.27	0.13	4.17

Table 3. Sm-Nd isotope data for the metavolcanic rocks of the East Krkonoše Complex

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd500}	T_{DM} (Ma)	T_{CHUR} (Ma)
Metabasites							
EK-52	2.18	7.18	0.1835	0.512936 (17)	+6.6	600	–
EK-43	3.69	12.9	0.1724	0.512853 (11)	+5.7	740	–
EK-62	12.7	73.6	0.1042	0.512498 (8)	+3.1	770	–
Porphyroids							
EK-41	3.78	14.0	0.1635	0.512248 (6)	−5.5	1800	–
EK-102	5.92	28.2	0.1268	0.512162 (7)	4.9	1550	1040
EK-103	9.28	41.8	0.1343	0.512214 (10)	−4.3	1590	1040

6. WHOLE-ROCK GEOCHEMISTRY

The metavolcanic rocks from the East Krkonoše Complex are distinctly bimodal: the mafic rocks have SiO_2 ranging from 46 to 52 wt% (volatile-free) whereas the felsic rocks have SiO_2 above 72 wt% (Figure 3). The terms 'basalt' and 'rhyolite' are used for metabasites (metabasalts) and porphyroids (metarhyolites), respectively, in the following discussion, although the rocks are composed of secondary minerals, typical of low-grade regional metamorphism.

6.1 Mafic rocks

The mafic rocks include a variety of compositions ranging from alkali to subalkaline basalts as shown in the Zr/TiO_2 vs SiO_2 plot (Figure 3). On the Mg# [$= 100 \times MgO/(MgO + FeO^*)$ in mole %] vs Zr and Mg# vs TiO_2 diagrams (Figure 4), the subalkaline basalts display a tholeiitic fractionation trend, characterized by an increase of Zr and TiO_2 with differentiation. The Mg# value varies between 30 and 65 (Table 2). The tholeiitic basalts are, on average, less differentiated (i.e. with higher Mg#) than the alkali basalts. The major element composition of both basalt types resembles that of oceanic and some continental intraplate basalts. The tholeiitic basalts differ from island-arc tholeiites by higher abundances of Ti and other HFS elements (Figure 5, Tables 1 and 2).

The abundance of incompatible trace elements increases with differentiation (Figure 4) and also with the degree of alkalinity as indicated by the Nb/Y ratio (Winchester and Floyd 1977) (Table 2). Compared to primitive melts derived from upper-mantle peridotites (Maaloe and Aoki 1977), the abundances of compatible elements are lower in the EKC mafic metavolcanics and indicate that the basaltic rocks underwent significant fractional crystallization.

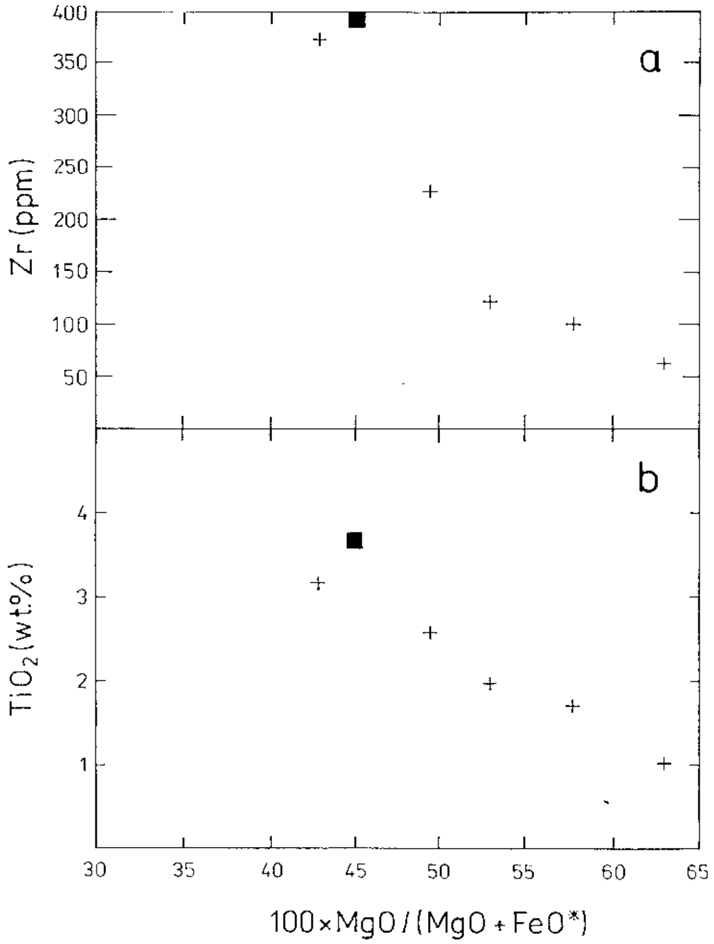

Figure 4. The metabasites of the East Krkonoše Complex in (a) Mg# [= 100×MgO/(MgO+FeO*) in mole %] vs Zr and (b) Mg# vs TiO_2 diagrams. (+, equivalents of tholeiitic basalts; ■, equivalents of alkali basalts).

The chondrite-normalized REE patterns (Figure 6a) of the alkali basalts show a distinct enrichment of light REE (LREE) and fractionated heavy REE (HREE) with a $(La/Yb)_N$ ratio around 20, whereas the tholeiitic types have a significantly flatter pattern with values of this ratio between 1 and 4 (Table 2).

The mantle-normalized abundance patterns of incompatible elements, shown by the EKC alkali basaltic rocks, peak at Nb and smoothly decrease from Nb to more compatible elements such as Y and HREE (Figure 7a). The patterns are similar to ocean island basalts (OIB) (Figure 7b) and to many alkali basaltic lavas from continental environments (Menzies *et al.* 1985; Kempton *et al.* 1987; Fang *et al.* 1992; Pin and Paquette 1997). The tholeiitic basalts have significantly flatter patterns, similar to those of E-type MORB (Figure 7a,b).

The basalts have high positive E_{Nd} values (Table 3). Tholeiitic basalt EK-52 with an almost flat REE pattern also has the most radiogenic Nd isotope signature ($E_{Nd} = +6.6$) implying a mantle source which was strongly depleted in LREE on a time-integrated basis. Alkali basalt EK-62 has a lower E_{Nd} value (+3.1), whereas sample EK-43 is intermediate, both in $(La/Yb)_N$ ratio (Table 2) and Nd isotope composition ($E_{Nd} = +5.7$).

6.2 *Petrogenesis of mafic rocks*

In general, compositional differences among the mafic rocks may reflect differences in the source composition, in the degree of melting and/or fractional crystallization, or in the degree of contamination with coeval felsic lavas or

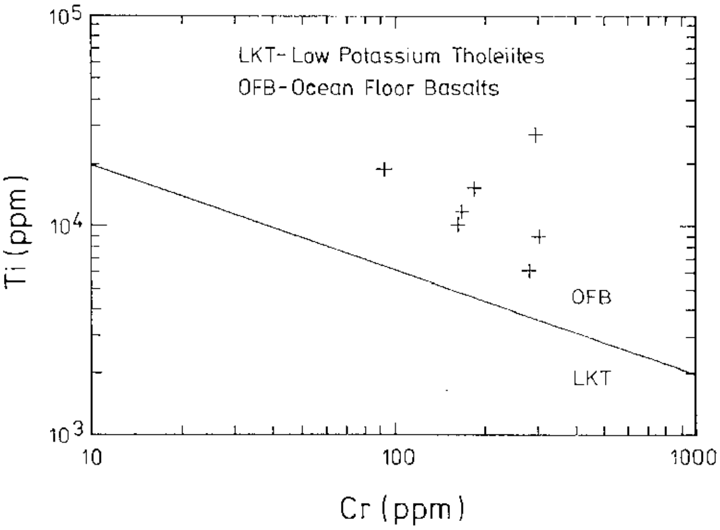

Figure 5. The subalkaline metabasites of the East Krkonoše Complex in Cr vs Ti discrimination diagram. Based on Pearce (1975).

continental crust. However, the geochemical differences between the tholeiitic and alkali basaltic rocks, including the E_{Nd} value and trace element characteristics, cannot be explained by crustal contamination; in fact, their high E_{Nd} values, low Th/La ratios and a lack of Nb depletion (Figure 7a, Tables 1 to 3) suggest that the mafic rocks were not significantly affected by crustal contamination.

Although the basaltic rocks were modified by fractional crystallization, the significant variations in the $(La/Yb)_N$ and Zr/Nb ratios in the basaltic samples of similar Mg# (Figure 7a, Table 2) indicate that the basalts cannot be generated by closed-system fractional crystallization of a single parent magma as also shown by variable E_{Nd} values.

An increase of the $(La/Yb)_N$ ratio from tholeiites to alkali basalts is typical of intraplate basaltic suites (e.g. Shimizu and Arculus 1975; Takahashi and Kushiro 1983; Sun and McDonough 1989) and has been attributed to the decreasing degree of partial melting of the source (Table 2). In addition, the distinct depletion of HREE in the EKC alkali basalts implies the presence of garnet in the melting residue, whereas the flat HREE pattern of the tholeiitic basalts implies that garnet was not involved in their genesis (Figure 6a). Thus, differences in the slope of the REE patterns and in elemental ratios, such as Zr/Y and Ti/Zr (Figures 6a and 7a, Table 2), between the tholeiitic and alkali basaltic rocks can be explained by different degrees of melting of a source in the garnet (for alkali basalts) and in the spinel (for tholeiitic basalts) stability fields. Mantle-normalized incompatible trace element profiles of the EKC basalts do not exhibit a negative Nb anomaly (Figure 7a). In contrast, many continental flood basalts with a significant subcontinental lithospheric or crustal component, such as those of Columbia River and Karoo, exhibit a negative Nb anomaly (Hooper and Hawkesworth 1993). The lack of a subduction signature in the composition of the EKC metabasaltic rocks indicates that they were not generated from subcontinental lithospheric mantle heavily fluxed by subduction components. The basalts were probably derived from a source with an incompatible element composition between that of oceanic island basalts and E-type MORBs.

Radiogenic isotope ratios indicate that the mantle source was heterogeneous. The mantle sources of the EKC metabasalts varied considerably in E_{Nd} values, from $+3.1$ to $+6.6$ (Table 3), suggesting that these mafic rocks are melts of a heterogeneous upper asthenosphere, composed largely of a depleted mantle matrix ($E_{Nd} = +7$) but containing incompatible element-enriched blobs or veins (variable E_{Nd} values $> +1$) (e.g. Cousens *et al.* 1995). Mixing of melts from both blobs and matrix would produce a source composition which has a range of incompatible element patterns and E_{Nd} values. Incompatible element-rich alkali basaltic rocks have the lowest E_{Nd}, a feature consistent with this model (Figure 7a, Table 3). Similar geochemical variations appear to be common in rift-related

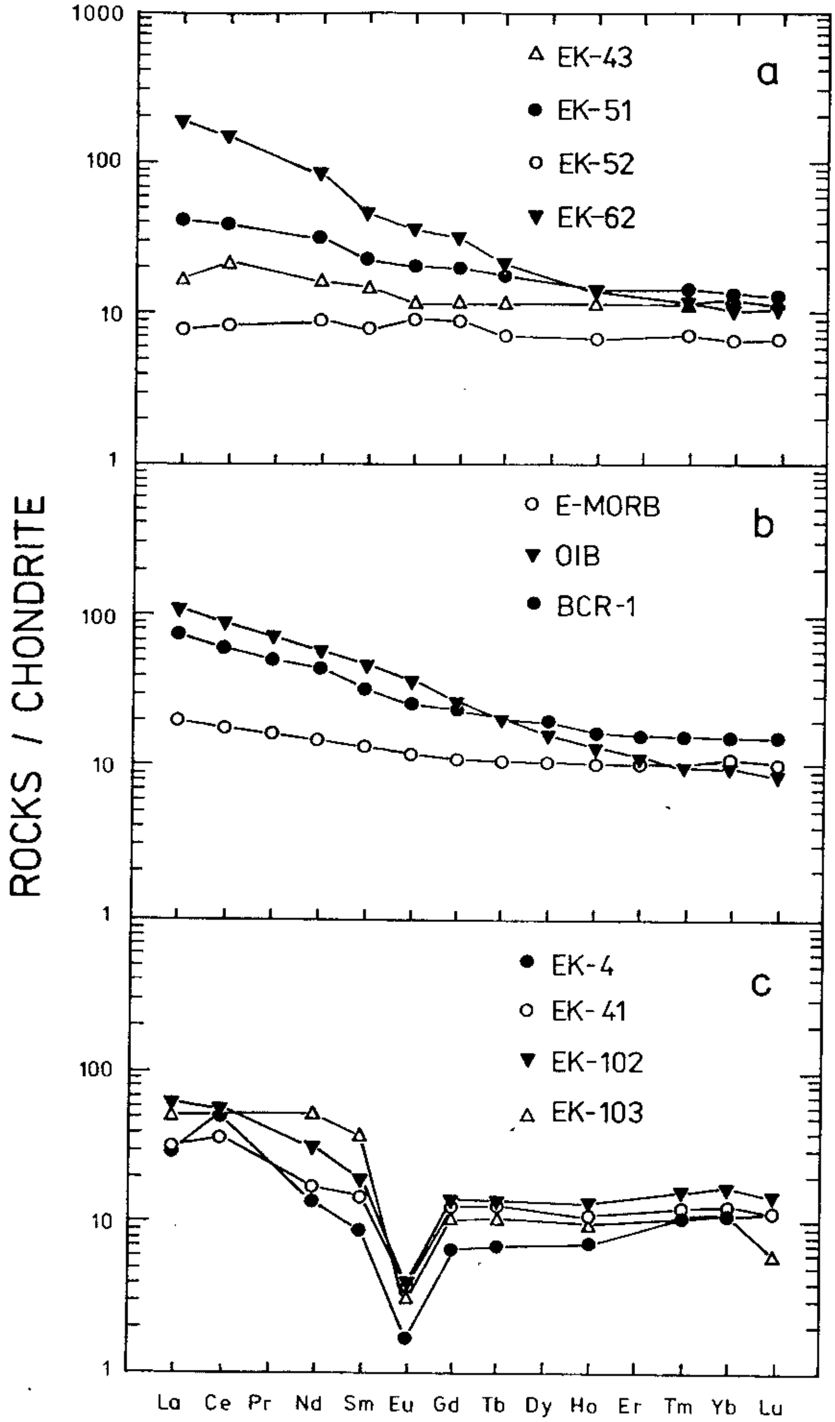

Figure 6. Chondrite-normalized rare earth element abundances in the metavolcanic rocks of the East Krkonoše Complex: (**a**) metabasites; (**b**) average E-type mid-ocean ridge basalt and ocean island basalt (Sun and McDonough 1989) and USGS standard rock BCR-1 (Columbia River Plateau Basalt, representative rock-type of the CFB-provinces) (Govindaraju 1994); (**c**) porphyroids. Normalizing values after Anders and Grevesse (1989).

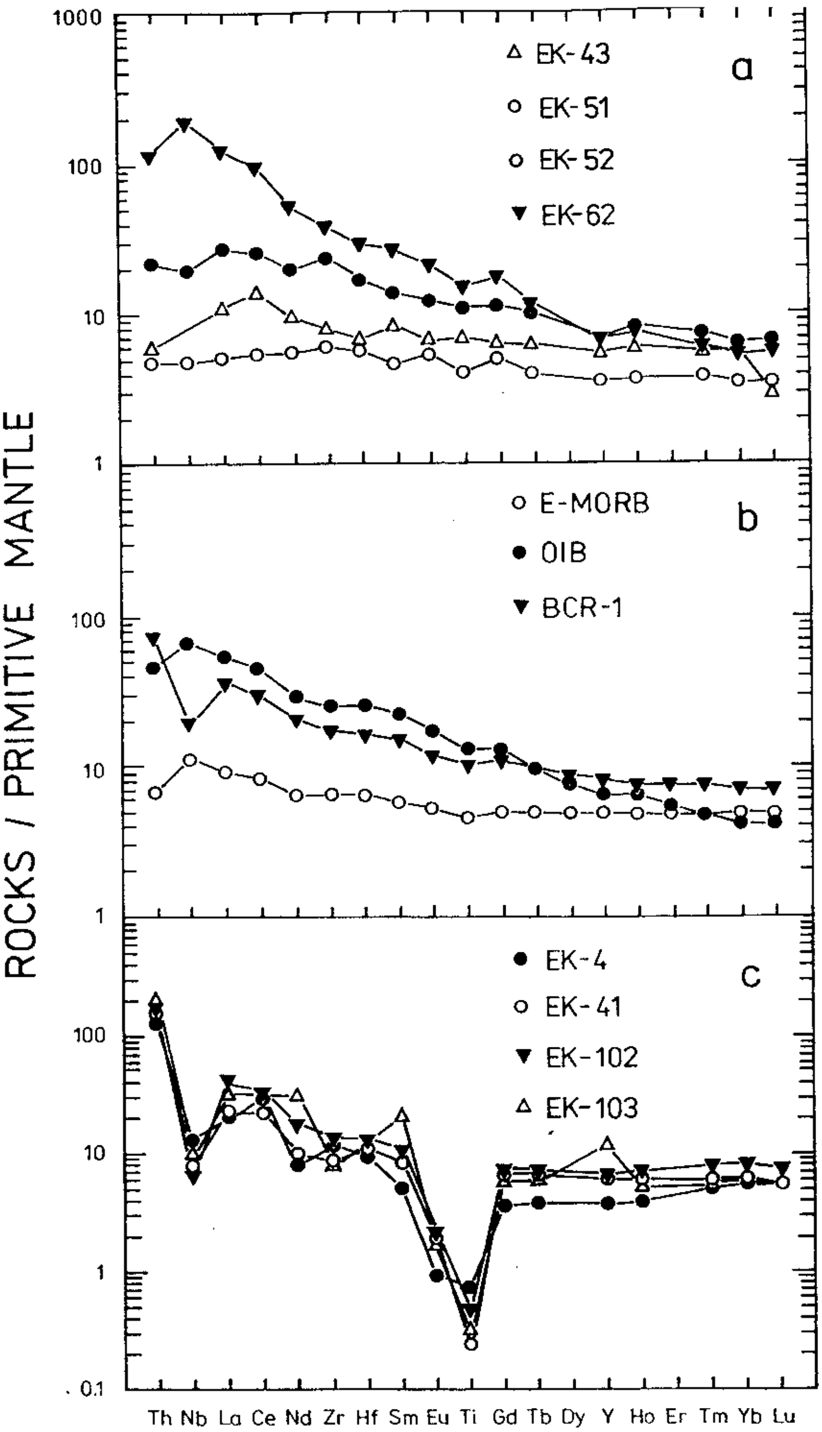

Figure 7. Mantle-normalized incompatible trace element abundances in the metavolcanic rocks of the East Krkonoše Complex: (**a**) metabasites; (**b**) average E-type mid-ocean ridge basalt and ocean island basalt (Sun and McDonough 1989) and USGS standard rock BCR-1 (Columbia River Plateau Basalt, representative rock-type of the CFB-provinces) (Govindaraju 1994); (**c**) porphyroids. Normalizing values after Sun and McDonough (1989).

settings with strong attenuation of continental lithosphere including the broadly coeval rocks of the Massif Central (Pin and Marini 1993; Pin and Paquette 1997).

6.3 *Felsic rocks*

The felsic metavolcanic rocks have mostly rhyolitic composition with SiO_2 above 72 wt% and Al_2O_3 above 11 wt% (volatile-free abundances). They are K-rich mostly with K_2O above 5 wt% and typically with $K_2O > Na_2O$ (Table 1). Most REE patterns of the rhyolites are enriched in LREE and have flat, unfractionated HREE patterns as is shown by sample EK-103 (Figure 6c). The $(La/Yb)_N$ ratios range from 2.4 to 4.2; the patterns also display distinct negative Eu anomalies demonstrated by Eu/Eu^* values as low as 0.13 (Table 2). Their mantle-normalized incompatible element patterns are characterized by negative Nb, Eu and Ti anomalies, and resemble modern rhyolites (Figure 7c).

The initial E_{Nd} values of the rhyolites are significantly unradiogenic and contrast markedly with those of the associated basalts: −4.3 to −5.5 versus + 3.1 to + 6.6, respectively (Table 3).

6.4 *Petrogenesis of felsic rocks*

The felsic rocks in the bimodal suites may have been formed either by fractional crystallization from coeval basaltic magmas, or by crustal anatexis. Compared to the basalts, the REE patterns of the rhyolites have flatter HREE and also have a distinct negative Eu anomaly; they also frequently have a more pronounced enrichment of LREE (Figure 6a,c). In comparison with the associated basalts, the mantle-normalized incompatible trace element patterns of the rhyolites are characterized by negative Nb and Ti anomalies (Figure 7a,c).

The rhyolites also have a more distinct enrichment of strongly incompatible trace elements such as Th (Tables 1 and 2). The rhyolites have unradiogenic Nd isotope compositions, ruling out any close relationship with the associated metabasites. This contrasts with the Leszczyniec Volcanic Fm. (Figure 1) where felsic rocks of the bimodal suite have high E_{Nd} values (between + 6 and + 7) (Kryza *et al.* 1995). The negative values of E_{Nd} ($= -5 \pm 1$) as well as the moderate value of the initial Sr isotope ratio ($= 0.706$) (Bendl and Patočka 1995) of the EKC rhyolites suggest that their protolith contained a major continental crust component, reflecting either crustal melting of reservoirs with low Sm/Nd and moderate Rb/Sr time-integrated ratios, or substantial incorporation of crustal melt during differentiation from mantle magmas (via AFC).

The overall features of the EKC bimodal suite, i.e. the lack of intermediate rocks, the high proportion of felsic to mafic volcanic rocks as well as the differences in the distribution of incompatible trace elements, and the large contrast in E_{Nd} values, favour crustal anatexis (triggered by rising basaltic magma) as the generation process of the rhyolites.

7. GEODYNAMIC MODELS

7.1 *Melt generation*

The Early Palaeozoic basaltic rocks of the East Krkonoše Complex were emplaced in a 'within-plate' setting. The lack of a subduction signature in the mantle-derived basalts suggests that their source was not in the lithospheric subduction-modified mantle, but in the asthenospheric mantle. Several tectonic models for the basalts can be considered. They include: (a) CFB-like mantle plume-related origin; (b) back-arc spreading; and (c) mantle upwelling and/or crustal extension and attenuation.

(a) The eruption of the basalts can be tentatively attributed to the initiation of a mantle plume and continental break-up such as occurred in the development of continental flood basalts (CFB) provinces (e.g. Cox *et al.* 1984; Peccerillo *et al.* 1988). However, compared to typical CFB sequences, the EKC basalts are significantly smaller in volume; this is true both in terms of the total volumes erupted and, more significantly, in terms of the rate of extrusion and the volumes of many individual eruptions. The small eruption rate accompanied by protracted extrusions, argues against this model for the studied basalts.

(b) Unlike typical back-arc basalts, the mafic rocks do not show any geochemical subduction imprints, implying that the rocks are not related to back-arc spreading; more N-MORB-like basalts would also be expected in the back-arc spreading tectonic setting.

(c) The geochemical data demonstrate that the basalts are chemically similar to OIB (Figures 6 and 7, Table 3) suggesting that they are related to asthenospheric mantle (cf. Floyd *et al.* 2000). The basalts probably resulted from the impingement of asthenospheric mantle upwelling on lithosphere thinned by extension. The asthenospheric upwelling and melting may not only have caused the OIB-like basalt genesis but also, by softening the lithosphere, triggered further extension and melting in the overlying continental crust.

The contrast between alkali and tholeiitic magmatism may reflect differences in the depth and degree of partial melting: relatively high degrees of partial melting at lower pressures (spinel stability field) for the tholeiites, and lower degrees of partial melting at higher pressures (garnet stability field) for the alkali basalts. The data are consistent with progressive upwelling of the asthenospheric mantle. During the ascent, melting of the asthenospheric mantle in the garnet stability field generated the alkali basalts, while subsequently a larger degree of melting of the mantle upwelling at a shallower depth produced the tholeiitic basalts. As the spinel–garnet transition occurs at a depth of around 60–80 km (Watson and McKenzie 1991), the initial depth of origin for the alkali basalts is nominally this deep or deeper. Although the data from the EKC do not indicate the time relation between tholeiitic and alkali basalts, a comparison with a similar sequence in the Kaczawa Mts suggests that the alkali basalts are older than the tholeiitic basalts (Furnes *et al.* 1994; Winchester *et al.* 1998).

The thermal energy, provided by the ascent of mantle-derived basic magmas related to asthenospheric upwelling, was responsible for partial melting at lower or medium crustal levels (e.g. Fang *et al.* 1992; Dostal *et al.* 1993; Pin and Paquette 1997) which yielded felsic magmas of the EKC rhyolites.

The great volume of the felsic rocks as well as the association of the metavolcanic rocks with abundant terrigenous metasediments – quartzites, phyllites (e.g. Teisseyre 1973; Chaloupský *et al.* 1989) – seems to point to an origin during the development of the intracontinental rift. This tectonic setting is also evidenced by the crustal contamination features in some of the volcanics (Patočka and Smulikowski 1998) and by the c. 2.0 Ga old zircon xenocrysts found in the relict felsic rocks of the EKC Polish part (Oliver *et al.* 1993). The presence of continental crust at depth may also be confirmed by the occurrence of the Paczyn Gneisses there (Smulikowski and Patočka 1998).

7.2 Relationship to other bimodal suites

The Early Palaeozoic East and South Krkonoše Complexes – the latter situated on the southwestern margin of the Krkonoše-Jizera terrane (Figure 1) – are characterized by abundant intracontinental rift-related bimodal metavolcanics (Bendl and Patočka 1995; Winchester *et al.* 1995; Fajst *et al.* 1998; Floyd *et al.* 2000). The complexes are considered to be essentially equivalent (e.g. Svoboda and Chaloupský 1966; Teisseyre 1973; Żelaźniewicz 1997), and the protolith history of the EKC metavolcanics is in its principal features comparable with the evolution of the South Krkonoše Complex (SKC) rocks (Fajst *et al.* 1998). The age of the EKC is also comparable to the SKC, i.e. the Cambrian to Silurian (Chlupáč 1993, 1997, 1998).

However, the EKC volcano-sedimentary suite is both spatially and temporally (Oliver *et al.* 1993; Bendl and Patočka 1995; Timmermann *et al.* 1999) intimately associated with the Leszczyniec Volcanic Fm. (LVF) (Figure 1) which is dominated by N- to E-MORB-like mafic rocks (Kryza *et al.* 1995; Winchester *et al.* 1995; Maluski and Patočka 1997; Dostal *et al.* 2000). The LVF suite is presumed to be generated during the protracting Early Palaeozoic extension of the EKC intracontinental rift leading to a narrow oceanic basin opening (e.g. Winchester *et al.* 1995; Patočka and Smulikowski 1998; Dostal *et al.* 2000).

The absence of a voluminous mafic suite of the LVF type, either in the SKC or in its close vicinity, indicates that the tectonic setting and magmatic development of the latter complex did not involve the generation of early oceanic lithosphere which is presumed in the EKC-LVF history; the comparison of the major geochemical features of the EKC-LVF and SKC metavolcanics, respectively, is interpreted by Fajst *et al.* (1998) as the record of magmatic development of the (a) laterally expanding and (b) linearly propagating (from E to W) intracontinental rift arm.

The intracontinental rift development in the central West Sudetes was also associated with emplacement of granitoid bodies which are exposed both as the large core antiform of the Krkonoše-Jizera terrane and as rather small bodies scattered in the surrounding volcano-sedimentary sequences (Borkowska *et al.* 1980; Kryza and Pin 1997; Biaelk 1998; Kachlík and Patočka 1998). The granitoids were intruded between 515 and 480 Ma (Borkowska *et al.* 1980; Kröner *et al.* 1994), and are coeval with the EKC and SKC volcanic acitivity.

The structural and metamorphic features indicate that the Krkonoše-Jizera terrane is a stack of para-autochthonous to allochthonous slices (Kachlík 1997) thrust to the NW on the Saxothuringian foreland during the Variscan collision of the Teplá-Barrandian terrane with Saxothuringian terrane (Franke *et al.* 1995; Mazur and Kryza 1996; Kachlík and Patočka 1998). In such a setting, the Krkonoše-Jizera terrane rift arm may be presumed to be a prolongation of the Vesser Rift composed of c. 500 Ma old volcano-sedimentary complexes of bimodal suites occurring along the northern border of the Saxothuringian plate (Bankwitz and Bankwitz 1998).

The metavolcanic rocks of the Krkonoše-Jizera terrane show distinct similarities with the metavolcanics of the NW Bohemian Massif (Mariánské Lazně Complex, Kladská Unit) both in geochemistry and emplacement ages (Kachlík 1997; Winchester *et al.* 1998; Crowley *et al.* 2000). Even though Variscan tectono-metamorphic histories of these units differ in degree and scale, their Early Palaeozoic magmatic developments may be correlated. Existing geochemical and structural information indicate that the ultramafic/mafic parts of the Mariánské Lazně Complex, the Zone of Erbendorf-Vohenstrauss and Münchberg klippe may represent the western continuation of an ophiolite-bearing suture zone between Saxothuringian and Teplá-Barrandian terranes (e.g. Winchester *et al.* 1998; Crowley *et al.* 2000).

The EKC-LVF and SKC volcanism and sedimentation commenced prior to the subduction-related blueschist facies metamorphism which is almost ubiquitous in the Krkonoše-Jizera terrane (Smulikowski 1995; Patočka *et al.* 1996). Taking into account modern active plate margin geometry and convergence rates (e.g. Windley 1977), the onset of subduction of the above-mentioned narrow oceanic basin lithosphere might be contemporaneous with the Early Givetian Variscan tectonism (375 to 380 Ma) which terminated Early Palaeozoic sedimentation and volcanism in the Teplá-Barrandian terrane (Chlupáč *et al.* 1992; Patočka *et al.* 1993). Provided that the Early Palaeozoic lithospheric extension of the Barrandian may have been related to the development of the intracontinental rift in the Krkonoše-Jizera terrane, the Barrandian basin could be interpreted as the farthest promontory of a failed lateral rift arm. Late Variscan horizontal movements along the Elbe fault obliterated this originally continuous structure (Patočka and Kachlík 1998).

The large-scale extensional tectonic setting recorded by the Krkonoše-Jizera terrane metavolcanic suites was related to the Early Palaeozoic lithospheric attenuation and rifting of Cadomian basement; these processes were widespread in the Western and Central European realms (Pin 1990), and heralded the northern Gondwana fragmentation and origin of the pre-Variscan peri-Gondwanan microplates (e.g. Ziegler 1989).

8. CONCLUSION

The geochemical data on the Early Palaeozoic East Krkonoše Complex (EKC) metavolcanic rocks and their association with large volumes of terrigeneous metasedimentary rocks suggest that the volcanic rocks were formed during intracontinental rifting related to incipient break-up of Cadomian basement of the West Sudetes. Together with a number of volcanic and volcano-sedimentary suites occurring in Western and Central Europe which are similar in age and original tectonic setting, they may be interpreted to be evidence of large-scale fragmentation of the northern margin of the Gondwana supercontinent. The mafic rocks were probably formed by the melting of asthenospheric mantle upwelling. At greater depth in the garnet stability field, a low degree of melting produced alkali basalt melts. As the mantle rose, a larger degree of melting at a shallower depth (in a spinel stability field) generated magma parental to the tholeiitic basalts. Rising basaltic magma probably triggered melting in the lower or middle continental crust leading to the generation of abundant felsic volcanic rocks.

In the Early Palaeozoic history of the EKC an intracontinental rift tectonic setting rapidly evolved to incipient oceanic basin regime as indicated by the geochemical features of the Leszczyniec Volcanic Fm. (LVF) mafic rocks in the Polish part of the EKC. The Early Palaeozoic low-grade metamorphosed volcano-sedimentary sequence of the nearby South Krkonoše Complex – considered to be the EKC equivalent – is missing a voluminous mafic suite of the LVF type and never reached such an advanced stage of the lithospheric extension and related magmatic development. The principal geochemical traits of the South and East Krkonoše Complexes as well as the above-mentioned dominance of the N-MORB-like metabasites in the latter may be interpreted as the features of magmatic development of (a) laterally extending and (b) linearly (in the recent geographical situation from E to W) propagating rift arm.

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REFERENCES

Anders E, Grevesse N. 1989. Abundances of the elements: Meteoritic and solar. *Geochimica et Cosmochimica Acta* **53**: 197–214.

Bankwitz P, Bankwitz E. 1998. Terrane fragment belt along the northern margin of the Saxothuringian microplate. In *Pre-Variscan Terrane Analysis of "Gondwanan Europe"*, Linnemann U *et al.* (eds). Schriften des Staatlichen Museums für Mineralogie und Geologie zu Dresden **9-1998**: 97–99.

Bendl J, Patočka F. 1995. The ^{87}Rb-^{86}Sr isotope geochemistry of the metamorphosed bimodal volcanic association of the Rýchory Mts. crystalline complex, West Sudetes, Bohemian Massif. *Geologia Sudetica* **29**: 3–18.

Bernard-Griffiths J, Carpenter MSN, Peucat J.-J, Jahn BM. 1986. Geochemical and isotopic characteristics of blueschist facies rocks from the Île de Groix, Armorican Massif (northwest France). *Lithos* **19**: 235–253.

Białek D. 1998. Aspects of geochemistry of Zawidow granodiorite and Izera granite – arc to rift transition? *Geolines* **6**: 11.

Borkowska M, Hameurt J, Vidal P. 1980. Origin and age of Izera gneisses and Rumburk granites in the Western Sudetes. *Acta Geologica Polonica* **30**: 121–145.

Briand B, Bouchardon JL, Houssa O, Piboule M, Capiez P. 1995. Geochemistry of bimodal amphibolite-felsic gneiss complexes from eastern Massif Central, France. *Geological Magazine* **132**: 321–337.

Chaloupský J. (ed.). 1989. *Geological map of the Krkonoše and Jizerské hory Mts. 1:100000.* Geological Survey: Praha.

Chaloupský J, Červenka J, Jetel J, Králík F, Líbalová J, Píchová E, Pokorný J, Pošmourný K, Sekyra J, Shrbený O, Šalanský J, Šrámek J, Václ J. 1989. *Geology of the Krkonoše and Jizerské hory Mts.* (in Czech, English summary). Geological Survey: Praha.

Chlupáč I. 1993. Stratigraphic evaluation of some metamorphic units in the N part of the Bohemian Massif. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **188**: 363–388.

Chlupáč I. 1997. Palaeozoic ichnofossils in phyllites near Železný Brod, northern Bohemia. *Journal of the Czech Geological Society* **42**: 75–94.

Chlupác I. 1998. New paleontological finds in the western part of the Krkonoše – Jizerské hory Mts. metamorphics and their impact on stratigraphic and tectonic concept. *Geolines* **6**: 29–30.

Chlupác I, Havlíček V, Kříž J, Kukal Z, Štorch P. 1992. *Paleozoic of the Barrandian (Cambrian - Devonian)*. Geological Survey: Praha.

Cousens BL, Allan JF, Leybourne MI, Chase RL, Van Wagoner N. 1995. Mixing of magmas from enriched and depleted mantle sources in the northeast Pacific: West Valley segment, Juan de Fuca Ridge. *Contributions to Mineralogy and Petrology* **120**: 337–357.

Cox KG, Duncan AR, Bristow JW, Taylor SR, Erlank AJ. 1984. *Petrogenesis of the basic rocks of the Lebombo.* Geological Society of South Africa Special Publication, 13: 139–149.

Crowley QG, Floyd PA, Winchester JA. 2000. Early Palaeozoic magmatism in the European Variscides: evidence for plume-related continental break-up. *Geoscience 2000 abstracts.* Geological Society, London; 46.

Davidek K, Landing E, Bowring SA, Westrop SR, Rushton AWA, Fortey RA, Adrain JM. 1998. New uppermost Cambrian U-Pb date from Avalonian Wales and age of the Cambrian-Ordovician boundary. *Geological Magazine* **135**: 305–309.

DePaolo DJ. 1981. Neodymium isotopes in the Colorado Front Range, and crust-mantle evolution in the Proterozoic. *Nature* **291**: 193–196.

Dostal J, Baragar WRA, Dupuy C. 1986. Petrogenesis of the Nutkusiak continental basalts, Victoria Island, N.W.T. *Canadian Journal of Earth Sciences* **23**: 622–632.

Dostal J, Laurent R, Keppie JD. 1993. Late Silurian – Early Devonian rifting during dextral transpression in the southern Gaspé Peninsula (Quebec): petrogenesis of volcanic rocks. *Canadian Journal of Earth Sciences* **30**: 2283–2294.

Dostal J, Dupuy C, Caby R. 1994. Geochemistry of the Neoproterozoic Tilemsi Belt of Iforas (Mali, Sahara): a crustal section of an oceanic island arc. *Precambrian Research* **65**: 55–69.

Dostal J, Patočka F, Pin Ch. 2000. Early Palaeozoic intracontinental rifting and early sea-floor spreading in the central West Sudetes (Bohemian Massif): geochemical and Nd-Sr isotopic study on metavolcanic rocks of the East Krkonoše Complex. *Geolines* **10**: 19–20.

Fajst M, Kachlík V, Patočka F. 1998. Geochemistry and petrology of the Early Palaeozoic Železný Brod Volcanic Complex (W Sudetes, Bohemian Massif): geodynamic interpretations. *Geolines* **6**: 14–15.

Fang Z, Zhao JX, McCulloch MT. 1992. Geochemical and Nd isotopic study of Paleozoic bimodal volcanics in Hainan Island, South China – Implications for rifting tectonics and mantle reservoirs. *Lithos* **29**: 127–139.

Floyd PA, Winchester JA, Ciesielczuk J, Lewandowska A, Szczepanski J, Turniak K. 1996. Geochemistry of early Palaeozoic amphibolites from the Orlica-Snieznik dome (Bohemian Massif): petrogenesis and palaeotectonic aspects. *Geologische Rundschau* **85**: 225–238.

Floyd PA, Winchester JA, Seston R, Kryza R, Crowley QG. 2000. Review of geochemical variation in Lower Palaeozoic metabasites from the NE Bohemian Massif: intracratonic rifting and plume-ridge interaction. In *Orogenic Processes: Quantification and Modelling in the Variscan Belt of Central Europe*, Franke W, Altherr R, Haak Q, Oncken O, Janner D (eds). Geological Society, London, Special Publications **179**: 155–174.

Franke W, Kreuzer H, Okrusch M, Schüssler U, Seidel E. 1995. Stratigraphy, structure and igneous activity. In: *Pre-Permian Geology of Central and Eastern Europe*, Dallmeyer RD, Franke W, Weber K (eds). Springer Verlag: Berlin; 277–293.

Furnes H, Kryza R, Muszynski A, Pin Ch, Garmann LB. 1994. Geochemical evidence for progressive, rift-related early Palaeozoic volcanism in the western Sudetes. *Journal of the Geological Society, London* **151**: 91–109.

Govindaraju 1994. Compilation of working values and sample descriptions for 383 geostandards. *Geostandards Newsletter* **18**: 1 –158.

Gradstein F, Ogg J. 1996. A Phanerozoic time-scale. *Episodes* **19**: 1–2.

Hooper PR, Hawkesworth CJ. 1993. Isotopic and geochemical constraints on the origin and evolution of the Columbia River basalt. *Journal of Petrology* **34**: 1203–1246.

Kachlík V. 1997. Lithostratigraphy and architecture of the Železný Brod Crystalline Unit: the result of Variscan tectonodeformation (in Czech). *Zprávy o geologických výzkumech v roce 1996*: 30–31.

Kachlík V, Patočka F. 1998. Cambrian/Ordovician intracontinental rifting and Devonian closure of the rifting generated basins in the Bohemian Massif realms. *Acta Universitatis Carolinae, Geologica* **42**: 57–66.

Kempton PD, Dungan MA, Blanchard DP. 1987. Petrology and geochemistry of xenolith-bearing alkalic basalts from the Geronimo volcanic field, southeast Arizona: evidence for polybaric fractionation and implications for mantle heterogeneity. In *Mantle Metasomatism and Alkaline Magmatism*, Morris EM, Pasteris JD (eds). Geological Society of America Special Paper, **215**: 347–370.

Kröner A, Jaeckel P, Opletal M. 1994. Pb-Pb and U-Pb zircon ages for orthogneisses from eastern Bohemia: further evidence for a major Cambro-Ordovician magmatic event. *Journal of the Czech Geological Society* **39**: 61.

Kryza R, Pin Ch. 1997. Cambrian/Ordovician magmatism in the Polish Sudetes: no evidence for subduction-related setting. *Terra Nova* **7**: 144.

Kryza R, Mazur S, Pin Ch. 1995. The Leszczyniec meta-igneous complex in the eastern part of the Karkonosze-Izera Block, Western Sudetes: trace element and Nd isotope study. *Neues Jahrbuch für Mineralogie, Abhandlungen* **170**: 59–74.

Maaloe S, Aoki K. 1977. The major element composition of the upper mantle estimated from the composition of lherzolites. *Contributions to Mineralogy and Petrology* **63**: 161–173.

Maluski H, Patočka F. 1997. Geochemistry and ^{40}Ar-^{39}Ar geochronology of the mafic metavolcanics from the Rýchory Mts. complex (W Sudetes, Bohemian Massif): paleotectonic significance. *Geological Magazine* **133**: 703–716.

Marheine D, Kachlík V, Patočka F, Maluski H. 1999. The Variscan polyphase tectonothermal development in the South Krkonoše Complex (W-Sudetes, Czech Republic). *Journal of the Conference Abstracts* **4**: 95.

Mazur S, Kryza R. 1996. Superimposed compressional and extensional tectonics in the Karkonosze-Izera block, NE Bohemian Massif. In: *Basement Tectonics II*, Oncken O, Janssen C (eds). Kluwer Academic Publishers: Amsterdam; 51–66.

Menzies MA, Kempton PD, Dungan MA. 1985. Interaction of continental lithosphere and asthenospheric melts below the Geronimo volcanic field, Arizona, USA. *Journal of Petrology* **26**: 663 -693.

Narębski W. 1994. Lower to Upper Paleozoic tectonomagmatic evolution of NE part of the Bohemian Massif. *Zentralblatt für Geologie und Paläontologie* **9/10:** 961 -972.

Narębski W, Dostal J, Dupuy C. 1986. Geochemical characteristics of Lower Palaeozoic spilite-keratophyre series in the Western Sudetes (Poland): petrogenetic and tectonic implications. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **155**: 243–258.

Oliver GJH, Corfu F, Krogh TE. 1993. U-Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *Journal of the Geological Society, London* **150**: 355–369.

Patočka F, Kachlík V. 1998. Early Palaeozoic intracontinental rifting in the Bohemian terrane: correlation of volcanic rocks of the central West Sudetes and Barrandian. In *Pre-Variscan Terrane Analysis of 'Gondwanan Europe'*, Linnemann U *et al*. (eds). Schriften des Staatlichen Museums für Mineralogie und Geologie zu Dresden **9-1998**: 175 -176.

Patočka F, Novák JK. 1997. The Na-amphibole bearing metabasites of the W Sudetes: dismembered Variscan suture zone in the Bohemian Massif? In Challenges to Chemical Geology, Novák M *et al* (eds). Abstracts of MAGES 10, *Journal of the Czech Geological Society*, **42**: 67.

Patočka F, Smulikowski W. 1998. The geochemical correlation of the East Krkonoše Complex metabasites (West Sudetes, Czech Republic and Poland) – relation to the Cambrian–Ordovician northern Gondwana breakup: A review. *Acta Universitatis Carolinae, Geologica* **42**: 105–108.

Patočka F, Vlašímský P, Blechová K. 1993. Geochemistry of Early Paleozoic volcanics of the Barrandian Basin (Bohemian Massif, Czech Republic): implications for paleotectonic reconstructions. *Jahrbuch der Geologischen Bundesanstalt* **136**: 871–894.

Patočka F, Pivec E, Oliveriová D. 1996. Mineralogy and petrology of mafic blueschists from the Rýchory Mts. crystalline complex (Western Sudetes, Bohemian Massif). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **170**: 313–330.

Pearce JA. 1975. Basalt geochemistry used to investigate past tectonic settings on Cyprus. *Tectonophysics* **25**: 41–67.

Pearce JA. 1982. Trace element characteristics of lavas from destructive plate boundaries. In *Andesites: Orogenic Andesites and Related Rocks*, Thorpe RS (ed.). Wiley: Chichester: 526–548.

Pearce JA, Harris NBW, Tindle AG. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* **25**: 956–983.

Peccerillo EM, Melfi AJ, Comin-Chiaramonti P, Bellieni G, Ernesto M, Marques LS, Nardy AJR, Pacca LG, Roisenberg A, Stolfa D. 1988. Continental flood volcanism from the Paraná Basin (Brazil). In *Continental Flood Basalts*, MacDougall JD (ed.). Kluwer Academic Publishers: Dordrecht; 195–238.

Pin Ch. 1990. Variscan oceans: ages, origins and geodynamic implications inferred from geochemical and radiometric data. *Tectonophysics* **177**: 215–227.

Pin Ch, Marini F. 1993. Early Ordovician continental break-up in Variscan Europe: Nd-Sr isotope and trace element evidence from bimodal igneous associations of the southern Massif Central, France. *Lithos* **29**: 177–196.

Pin Ch, Paquette JL. 1997. A mantle-derived bimodal suite in the Hercynian Belt: Nd isotope and trace element evidence for a subduction-related rift origin of the Late Devonian Brévenne metavolcanics, Massif Central (France). *Contributions to Mineralogy and Petrology* **129**: 222–238.

Sanchez Carretero R, Eguiluz Pascual E, Carracedo M. 1990. Igneous rocks. Ossa-Morena Zone. In *Pre-Mesozoic Geology of Iberia*, Dallmeyer RD, and Martinez Garcia E (eds). Springer: Berlin; 292–313.

Shimizu N, Arculus JR. 1975. Rare earth element concentrations in a suite of basanitoids and alkali olivine basalts from Grenada, Lesser Antilles. *Contributions to Mineralogy and Petrology* **50**: 231–240.

Smulikowski W. 1995. Evidence of glaucophane-schist facies metamorphism in the East Karkonosze complex, West Sudetes, Poland. *Geologische Rundschau* **84**: 720–737.

Smulikowski W. 1999. Metabasic rocks of the Rudawy Janowickie and Lasocki Range – their significance in the study of metamorphic evolution of the East Karkonosze Complex (West Sudetes, NE Bohemian Massif). *Archiwum Mineralogiczne* **52**: 211–274.

Smulikowski W, Patočka F. 1998. The most important petrological problems of East Karkonosze Complex (in Polish, English summary). *Polskie Towarzystwo Mineralogiczne - Prace specjalne* **11**: 42–47.

Sun SS, McDonough WF. 1989. Chemical and isotopic systematics of ocean basalts: implications for mantle composition and processes. In *Magmatism in the Ocean Basins*, Saunders AD, Orry MJ (eds). Geological Society, London, Special Publication **42**: 313–345.

Svoboda J, Chaloupský J. 1966. The West Sudeten Crystalline. In *Regional Geology of Czechoslovakia, I-1*, Svoboda J *et al.* (eds). Geological Survey: Praha; 215–256.

Takahashi E, Kushiro I. 1983. Melting of a dry peridotite at high pressures and basalt genesis. *American Mineralogist* **68**: 859–869.

Teisseyre JH. 1973. Metamorphic complex of Rudawy Janowickie and Lasocki Grzbiet ridge. *Geologia Sudetica* **8**: **7–129.**

Timmermann H, Parrish RH, Noble SR, Kryza R, Patočka F. 1999. Single cycle Variscan orogeny inferred from new U-(Th-)Pb data from the Sudetes mountains in Poland and the Czech Republic. *Abstracts of the PACE mid-term review and 4th PACE network meeting*. Geological Institute, University of Copenhagen: Denmark; 24.

Tischendorf G, Förster HJ, Frischbutter A, Kramer W, Schmidt W, Werner CD. 1995. Saxothuringian basin. Igneous activity. In *Pre-Permian Geology of Central and Eastern Europe*, Dallmeyer RD, Franke W, Weber K (eds). Springer: Berlin; 249–258.

Watson S, McKenzie D. 1991. Melt generation by plumes: a study of Hawaiian volcanism. *Journal of Petrology* **32**: 501–537.

Wilson M. 1989. *Igneous Petrogenesis. A Global Tectonic Approach*. Chapman and Hall: London.

Winchester JA, Floyd PA. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology* **20**: 325–343.

Winchester JA, Floyd PA, Chocyk M, Horbowy K, Kozdroj W. 1995. Geochemistry and tectonic environment of Ordovician meta-igneous rocks in the Rudawy Janowickie Complex, SW Poland. *Journal of the Geological Society, London* **152**: 105–115.

Winchester JA, Floyd PA, Franke W, Żelaźniewicz A, Patočka F, Kryza R, Cymerman Z, Piasecki MAJ, Seston R, Crowley QG, Kachlík V, Štědrá V, Holland JG. 1998. A review of recent geochemical and structural evidence for major Paleozoic rifting and re-assembly within the Bohemian Massif. *Acta Universitatis Carolinae, Geologica* **42**: 359–360.

Windley BF. 1977. *The Evolving Continents*. Wiley: Chichester.

Żelaźniewicz A. 1997. The Sudetes as a Palaeozoic orogen in central Europe. *Geological Magazine* **133**: 691–702.

Ziegler PA. 1989. *Evolution of Laurussia. A Study in Late Palaeozoic Plate Tectonics*. Kluwer Academic Publishers: Amsterdam.

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