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THE ^{87}Rb-^{86}Sr ISOTOPE GEOCHEMISTRY OF THE BLUESCHIST AND GREENSCHIST METAVOLCANICS OF THE RÝCHORY MTS CRYSTALLINE COMPLEX, WEST SUDETES, BOHEMIAN MASSIF[3]

Abstract. The blueschists and greenschists of the Radčice Group (the Rýchory Mts complex, West Sudetes) were analysed for Rb-Sr isotopes. The $^{87}Sr/^{86}Sr$ values of the metabasites, recalculated to Early Cambrian–Early Ordovician ages presumed for their magmatic origin, are mostly scattered between values of mantle-derived igneous rocks and Early Paleozoic oceanic waters. Either an introduction of seawater Sr into protolith or secondary alteration of Rb-Sr system during regional metamorphism can be a reason of this feature. Two extremely high Sr isotope values possibly indicate an input of radiogenic Sr leached from rocks of continental crust by post-magmatic hydrothermal alterations and/or metamorphic fluids.

Due to the scatter of the measured values in the Rb-Sr diagram it is impossible to derive an isochron and initial Sr isotope ratio valid for the whole sample set of the metabasites. However, two blueschists, only weakly altered, are giving value 0.7039 as initial $^{87}Sr/^{86}Sr$ ratio. Thus a mantle-derived origin of the primary rocks can be presumed. The "isochron" defined by these samples in the Rb-Sr plot may be an indication of the Late Proterozoic to Early Ordovician magmatic age of the metabasite protolith. The Early Ordovician age may be accepted provided that the Radčice Group metabasite protolith took origin during hypothetic early-stage seafloor spreading, following on the intracontinental rifting dated to the same period by bimodal volcanism of the East Krkonoše Mts. This event would be set into the concept of Early Paleozoic rifting and opening of oceanic basins along the northern periphery of Gondwana.

Key words: Rb-Sr isotope data, oceanic-floor and oceanic-island basalts, blueschist, greenschist, Early Paleozoic, West Sudetes, Bohemian Massif.

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INTRODUCTION

The blueschist facies metamorphics, situated along sutures of contrasting terranes within many orogenic belts, indicate the former existence of subduction zones (e.g. Miyashiro 1961, Ernst 1973, Banno, Nakajima 1991 *etc.*). However, in the Variscan orogenic belt of Europe subduction-related HP-LT metamorphics are exceptional. Tectonic removing and extensive HT-LP recrystallization associated with widespread later granitoid intrusions obliterated the blueschists for the most part (Matte 1986 *etc.*). These rocks have been described only from several areas of the Variscan orogen – in the Iberian, Armorican, and Bohemian Massifs (Triboulet 1974, Cháb, Vrána 1979, Munhá *et al.* 1984, Smulikowski 1995 *etc.*). The corresponding ages of the blueschist metamorphism are very early Variscan (in southern part of Armorican Massif) to Variscan (in northern Portugal) (Maluski 1977, Gil Ibarguchi, Dallmeyer 1991). The protolith rocks – in composition possibly related to oceanic-floor basalts (e.g. Matte 1986) – are dated to Early Paleozoic (Peucat, Cogné 1977, Munhá *et al.* 1984) and Middle Proterozoic (Peucat *et al.* 1982).

GEOLOGICAL SETTING

The West Sudetes – or Lugosudeticum (Narębski 1994) – constituting the north-eastern margin of the Bohemian Massif, represent a hetereogeneous region composed of Proterozoic and Paleozoic sequences affected by Cadomian and Variscan metamorphism and intruded by plutons of Cadomian and Variscan granitoids (e.g. Chlupáč 1993, Narębski 1994). In the scale of the European Variscan orogen the West Sudetes are considered a mosaic complex of accreted terranes which have distinct Cambrian to Carboniferous histories (Narębski l.c.) (Fig. 1).

In the midst of the West Sudetes, in the East Krkonoše Mts, the Rýchory Mts crystalline complex is exposed (e.g. Svoboda and Chaloupský 1966). Towards the west its rock sequences are connected with the Lower Paleozoic in the area of Roprachtice and Železný Brod (e.g. Svoboda, Chaloupský 1966, Chaloupský *et al.* 1989) (Figs 1b and 2). On the nothern side the Rýchory Mts crystalline complex continues in Poland in the Rudawy Janowickie complex (e.g. Teisseyre 1973). Generally, the Rýchory Mts complex was metamorphosed to a higher range of greenschist facies; however, its significant metamorphic feature is the rather frequent occurrence of Na-amphiboles in metabasites (e.g. Hampel 1911, Pelikan 1928, Chaloupský *et al.* 1989), which are interpreted as relics of earlier blueschist facies metamorphic assemblage (Wieser 1978, Patočka *et al.* 1994).

On the basis of systematic lithostratigraphic studies, Chaloupský

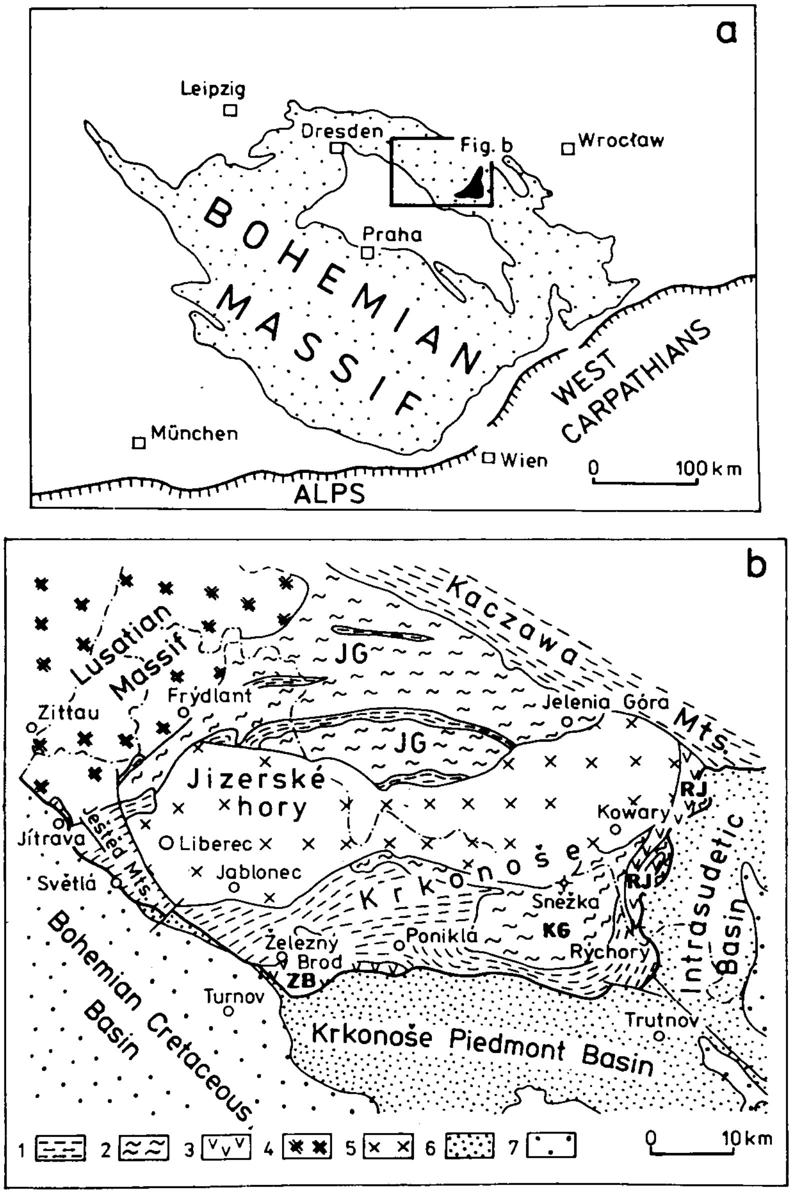

Fig. 1. **(a)** Location of the studied region - area in the frame corresponds to Fig. 1b, the black area in the frame corresponds to Fig. 2. **(b)** Geological sketch map of the western part of the Western Sudetes - Krkonoše, Jizerské hory and Ještěd Mts – after Chlupáč (1993). *1* – low- to medium-grade metamorphic units; *2* – medium- to high-grade metamorphic units (mica-schists, gneisses); *3* – metamorphosed volcanic, in Rudawy Janowickie and Lasocki Grzbiet also sedimentary rocks; *4* – pre-Variscan granitoids; *5* – Variscan granitoids, *6* – Carboniferous and Permian syn- and post-orogenic deposits; *7* – Mesozoic platform deposits. JG – Jizera Gneiss; KG – Krkonoše Gneiss and associated rocks; ZB – the metavolcanic Železný Brod complex; RJ – the Rudawy Janowickie and Lasocki Grzbiet complexes. *Dashed line* – state borders

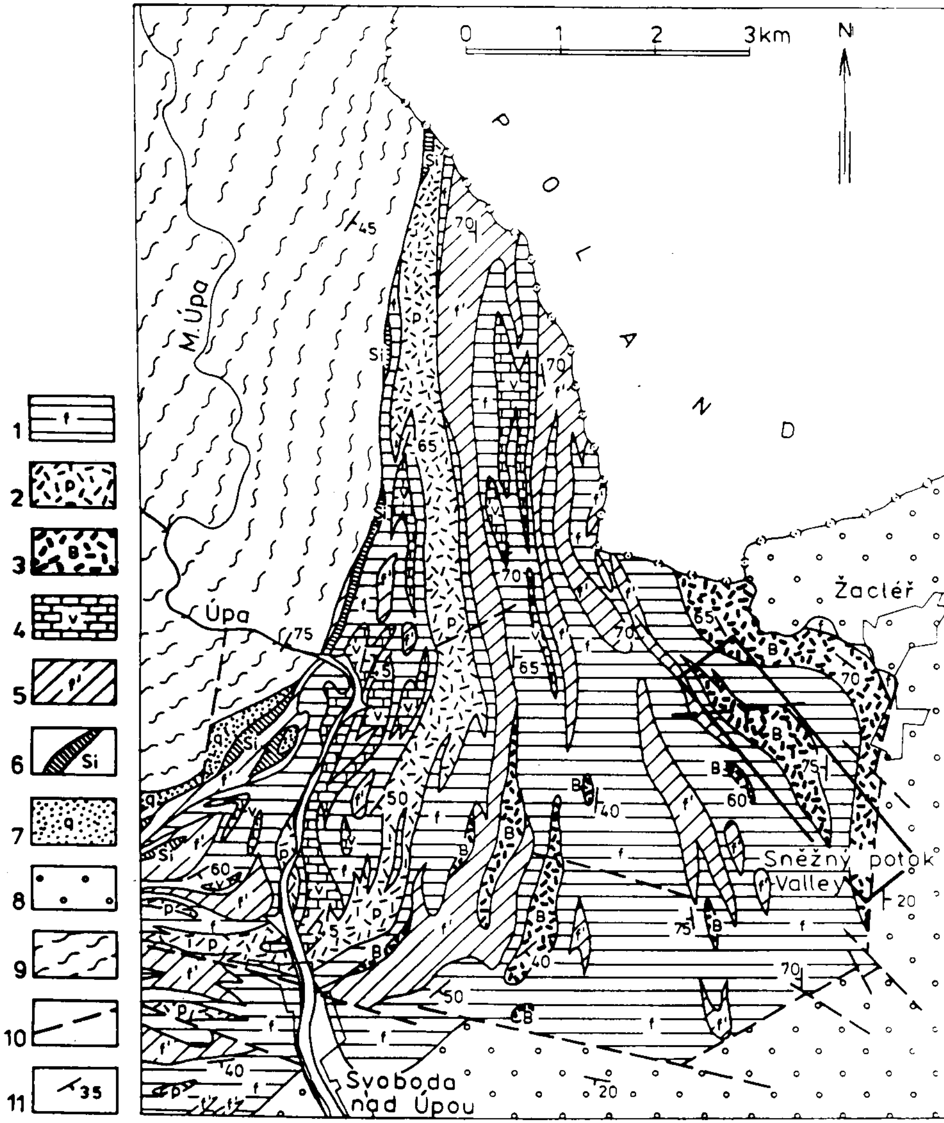

Fig. 2. Geological map of the Rýchory Mts crystalline complex – adapted after Chaloupský (1989). The Poniklá Group forms the most of the Rýchory Mts area; only the metabasite bodies in the eastern part of the complex represent the Radčice Group defined by Chaloupský *et al.* (1989). All samples analysed for Rb-Sr isotopes were taken in the Sněžný potok Creek valley (rectangle on the right side of the figure) *1* – chlorite-sericite phyllites; *2* – porphyroids; *3* – metabasites; *4* – marbles; *5* – graphite-sericite phyllites; *6* – metalydites; *7* – sericite quartzites; *8* – platform cover (Upper Carboniferous to Quaternary); *9* – Krkonoše gneisses and mica-schists and metabasites of the Velká Úpa Group (undistinguished); *10* – faults; *11* – foliation

et al. (1989) recognized two sequences within the Rýchory Mts crystalline complex – the Poniklá and the Radčice Groups – which were originally defined in the region of Roprachtice and Železný Brod (Figs 1b and 2).

Most of the Rýchory Mts area is formed by the Poniklá Group – the varied sequence of quartzites, phyllites (graphite-sericite types dominate) to mica schists, marbles, metalydites and metavolcanics. Felsic metavolcanics – porphyroids (rhyolites, felsic tuffs) – strongly prevail over mafic ones – greenschists (basic pyroclastics?); the Poniklá Group is considered to be formed during Ordovician to Silurian (e.g. Chaloupský *et al.* 1989). The Early Ordovician volcanism of the Poniklá Group is indicated by Rb-Sr whole rock age 501 ±8 Ma from its bimodal volcanics (Bendl, Patočka 1995). Similar age – 505 ±5 Ma (U-Pb, zircon) – is known from relict felsic volcanic rock, forming boudins within metabasites of the Rudawy Janowickie complex (Oliver *et al.* 1993) (Fig. 1b).

The Radčice Group, exposed in the eastern part of the Rýchory Mts, is supposed to be of Early to Middle Cambrian age according to Chaloupský *et al.* (1989). There the Na-amphibole-bearing metabasites are abundant (Fig. 2). In the metabasite bodies the NNE-SSW trending and almost vertically dipping foliation is often strongly expressed, with a prominent stretching lineation which is approximately N-S oriented; both features are probably related to the NNE-SSW trending East Krkonoše shear zone described e.g. by Cymerman and Piasecki (1994). The metabasites experienced blueschist facies metamorphism; the mineral assemblage shows that the metamorphic conditions of the Rýchory Mts blueschists origin were identical to those of the Sanbagawa rocks (e.g. Hosotani, Banno 1986). The PT range of the blueschist metamorphism was: T = 300°-500°C and P = 7-10 kbar; the blueschist metamorphism was followed by greenschist facies retrogression (Patočka *et al.*, 1994, 1996). Cháb and Vrána (1979), Guiraud and Burg (1984), Narębski *et al.* (1986) and Patočka *et al.* (1994) suggest a possible relationship of the HP-LT metamorphism in the West Sudetes to the Variscan collision of continental crust associated with subduction of a hypothetical oceanic lithosphere.

Cháb and Vrána (1979) considered a Variscan age for the tectonometamorphic development of the West Sudetes. The metamorphic event related to some of the oldest Variscan phases (of Middle to Late Devonian age) was recognized there by Teisseyre (1973); this statement is supported by U-Pb zircon and monazite as well as Rb-Sr biotite ages from non-mylonitized gneisses of the Góry Sowie Mts, ranging between 380 and 360 Ma (van Breemen *et al.* 1988), and by the results of the ^{40}Ar-^{39}Ar geochronology on phengites from the Rýchory Mts mafic blueschists dating the termination of the HP-LT metamorphism to 360 Ma (Maluski, Patočka 1996). However, the prin cipal stage of Variscan orogeny in the Krkonoše-Jizera complex is re lated to the Sudetic phase (late Viséan) (Chlupáč 1993). N stratigraphic evidence supporting any presumed effects of the Lat Caledonian orogenic phase (e.g. Kodym, Svoboda 1948, Chaloupský e *al.* 1989, Oliver *et al.* 1993) was found in the Early Paleozoic to Earl Carboniferous sequence which is well preserved in the western par of the Krkonoše-Jizera crystalline complex (Chlupáč 1993).

PETROGRAPHY OF THE METABASITES OF THE RÝCHORY MTS CRYSTALLINE COMPLEX

In the Rýchory Mts the mafic blueschists are well preserved onl in the eastern part of the complex where the metabasite bodies of th Radčice Group are situated (e.g. Chaloupský *et al.* 1989) (Fig. 2). Va rious types of blueschists seem to dominate in these bodies; the gre enschists are interpreted by Patočka *et al.* (1994, 1996) as retro gressed blueschists.

Blueschists

The Rýchory Mts. mafic blueschists display wide variety of struc tures: well foliated very fine-grained blueschists to medium-graine rocks showing almost massive appearance, were described there b Patočka *et al.* (1994, 1996). These metavolcanics are mostly of grey green colour, they are rarely dark grey with deep blue shade. All mafi blueschists generally comprise Na-amphibole + epidote + albite + ac tinolite + sphene + carbonate ± chlorite; the usual rock fabric is fibronematoblastic texture (Fig. 3).

Sodic amphibole is the most characteristic rock-forming minera of the mafic blueschists. The Na-amphibole often tends to be idiomorp hic; the individuals 2 × 0.5 × 0.25 mm in dimensions are rather usual This mineral displays strong pleochroism; the colours are following: – indigo-blue to violet-blue, β – blue-grey, γ – yellowish-green. Patočk *et al.* (1994) described glaucophane, ferroglaucophane and crossite i the mafic blueschists. In the sphene-rich rock samples the Na-amphi boles have very dark blue to almost opaque black cores. The Na-amp hibole is often accumulated into thin layers associated with albit clusters parallel to foliation planes. In the blueschist specimens, sho wing microscopic isoclinal folds, the Na-amphibole needles are simpl dissected; the individual sections follow the folds in absence of any sig nificant bending.

The Na-amphiboles are usually surrounded by green amphibol and chlorite; however, the green amphibole (Patočka *et al.* 1996) ofter does not correspond to **actinolite** but to Na-amphibole too.

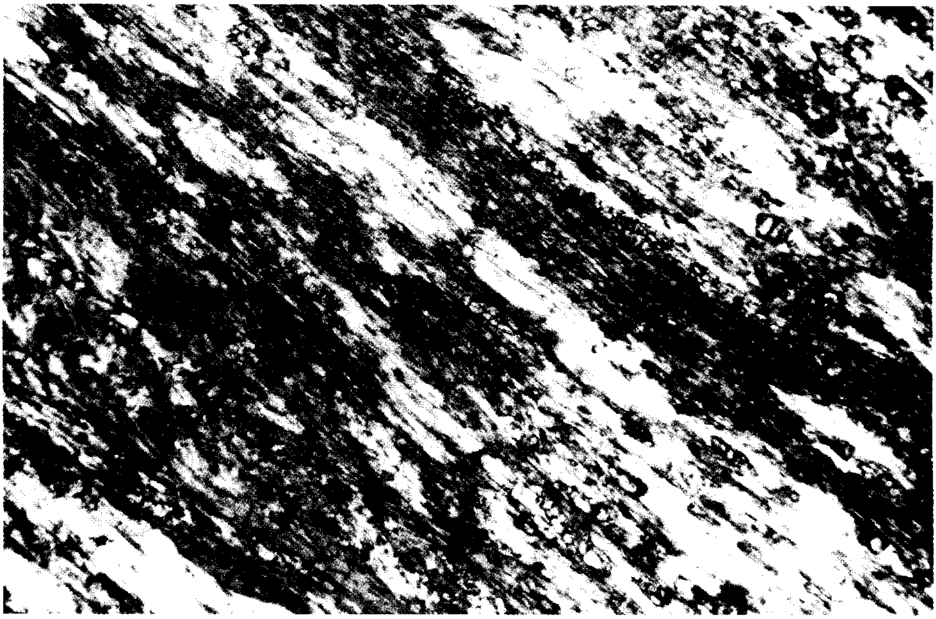

Fig. 3. Epidote blueschist of the Poniklá Group (Rýchory Mts crystalline complex) – sample No. 7. The rock is showing perfect parallel fabric. Crossed polarizers; magnification x36. Photo M. Šťastný

Epidote is an abundant mineral in the studied blueschists. Idiomorphic porphyroblasts are quite frequent. Homogeneous layers of epidote as well as epidote aggregates having up to 5 mm in diameter were found in some samples; these rocks are described as **epidote blueschists**.

White mica is common in the blueschists. The studied micas are phengites. White mica (muscovite) aggregates also fill rectangular forms, having ca. 0.4 mm across, surrounded by small epidote and chlorite grains on tiny cracks; these aggregates were interpreted by Patočka *et al.* (1996) as pseudomorphs replacing **lawsonite**. The pseudomorphs were probably reformed by sericitization related to post-metamorphic fluids. The mafic blueschists, characterized by these pseudomorphs are somewhat arbitrarily called **blueschists with lawsonite**.

The mafic blueschists comprising abundant **carbonate** are rare; they were described as **carbonatized blueschists**. Medium to coarse-grained carbonate forms layers parallel to foliation as well as up to 4 mm thick veinlets. Sodic amphibole needles are often enclosed in carbonate grains. The carbonate bearing blueschists often have high content of **plagioclase** (albite – $An_{<2}$, and albite to oligoclase – An_{10} to An_{11}). Usual forms are hypidiomorphic to xenomorphic poikilobla-

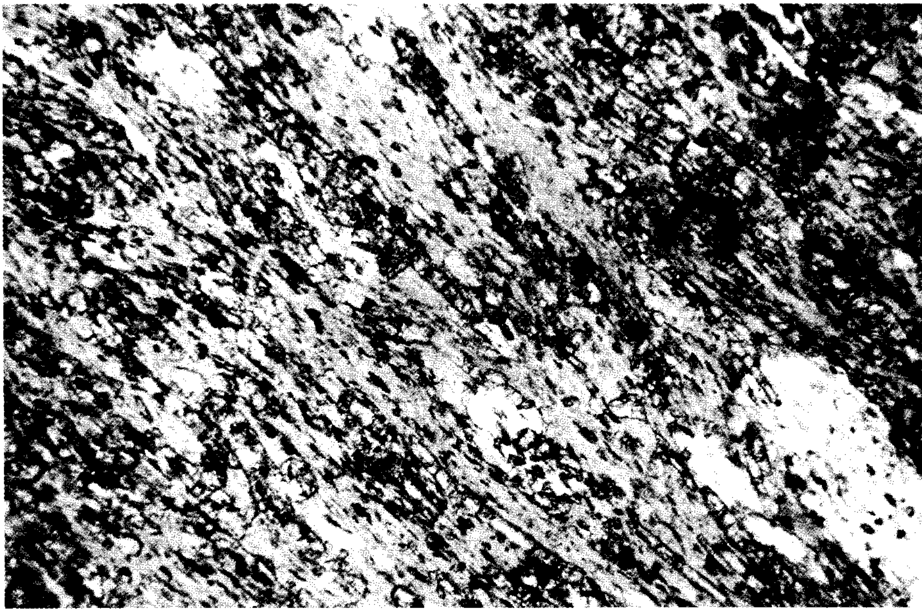

Fig. 4. Actinolite greenschist of the Poniklá Group (Rýchory Mts crystalline complex – sample No. 4. The rock is showing both perfect parallel fabric and banding (given by alternating chlorite+amphibole bands and epidote ones). Albite porphyroblasts are present. Crossed polarizers; magnification x36. Photo M. Šťastný

stic grains up to 0.5 mm in diameter. When albite is dominating over carbonate, the rocks are defined as **albite blueschists**.

Chlorite flakes are usually surrounding and partly substituting amphiboles. Chlorite flakes are often hosts of idiomorphic **magnetite**, which is in some samples haematitized and/or limonitized; its rectangular shapes have up to 1.5 mm in diameter.

Quartz and **K-feldspar** are accessory in the mafic blueschists.

Greenschists

Actinolite greenschists are well foliated rocks of grey-green colour. A well defined banding, given by parallel set of thin layers (ca. 2 mm) where dark and light minerals alternately prevail, is a general feature of these rocks. In some samples the light components (mostly albite and carbonate) dominate; most of the actinolite greenschists have fibronematoblastic texture. On the other hand, in the chlorite-rich rocks mafic components (chlorite and actinolite) prevail. The latter type of greenschists, showing lepidonematoblastic texture, is very well foliated (Fig. 4).

Mineral composition of all studied samples of the actinolite greenschists is identical. **Actinolite** needles, usually arranged parallel to foliation, are almost colourless and show faint pleochroism. **Albite** forms isometric xenoblastic grains having 0.02 to 0.5 mm in diameter. Albite grains rarely show polysynthetic banding according to albite and/or pericline twin law. Anorthite component content is almost negligible in albites of actinolite greenschists. Albite as well as **epidote** tends to form porphyroblasts. On the other hand, minute epidote grains and prisms are concentrated into either shapeless clusters or parallel bands. **Chlorite**, characterized by weak pleochroism, is partly substituting actinolite. **Sphene**, **carbonate**, **white mica** and **ore minerals** (**magnetite** and **pyrite**) are present in subordinate quantity and are often accessory in the actinolite greenschists.

Epidote greenschists, usually showing a lighter shade of green-grey colour and often displaying imperfect parallel fabric, have ample abundance of colourless mineral of epidote group – possibly **zoisite** according to optical characteristics. The studied rocks comprise also **albite**, **white mica** and **chlorite**. **Actinolite** as well as **limonite** are accessoric. **Quartz** and **K-feldspar** were identified in some specimens.

ANALYTICAL METHODS

A complicated tectonometamorphic development of the Rýchory Mts crystalline complex (Teisseyre 1973, Chaloupský *et al.* 1989, Patočka *et al.* 1994, etc.) was taken into account when the metabasites of the Radčice Group were sampled, and rather voluminous whole-rock specimens (10-25 kg) were taken (Table 1). The samples were carefully crushed and homogenized; the quarts of acquired powders were dissolved in 2 : 5 mixture of HNO_3 and HF.

The concentrations of Sr and Rb were determined by XRF-method with Philips PW 1450 spectrometer (Gematest Ltd.) after Verdurmen *et al.* (1979) and Harvey and Atkin (1981). Strontium isotopic ratios were measured on the Finnigan MAT 262 mass spectrometer (Czech Geological Survey, Praha). Strontium was loaded on double filaments using H_3PO_4. During Sr isotopic analyses the NBS SRM 987 standard was repeatedly measured yielding an average ratio of $^{87}Sr/^{86}Sr$ = 0.710255 ± 0.000043.

Rb-Sr ISOTOPE DATA

In the Rýchory Mts. crystalline complex seven blueschist samples and two greenschist specimens were collected for application of Rb-Sr isotope analysis. The whole set of samples was taken from the Radčice Group, as it was lithostratigraphically identified and regionally defined in the eastern part of the Rýchory Mts complex by Chaloupský *et al.* (1989) (the Sněžný potok Creek valley – Fig. 2). The corresponding whole-rock Rb-Sr data for these samples are listed in Table 1; one lo-

Table 1

Rb-Sr isotope data of the whole-rock samples of mafic metavolcanics from the Radčice Group in the Rýchory Mts crystalline complex

Sample No.	Weight [kg]	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	Iσ	$^{87}Sr/^{86}Sr$	Iσ	$(^{87}Sr/^{86}Sr)$ 525-570 Ma	$(^{87}Sr/^{86}Sr)$ 500 Ma
1	16	9.51	223.3	0.1244	0.0100	0.7057	0.000039	0.7048-47	0.7048
2	14	7.26	515.4	0.0408	0.0089	0.7144	0.000038	0.7141	0.7141
3	10	11.43	102.2	0.3277	0.0035	0.7081	0.000057	0.7057-54	0.7058
4	12	3.59	301.9	0.0329	0.0007	0.7053	0.000053	0.7051-50	0.7051
5	24	11.63	136.4	0.2491	0.0026	0.7088	0.000053	0.7069-68	0.7070
6	17	7.37	501.1	0.0426	0.0028	0.7148	0.000049	0.7145-44	0.7145
7	18	57.9	367.1	0.4606	0.0050	0.7078	0.000050	0.7044-41	0.7045
8	22	5.05	101.3	0.1455	0.0030	0.7073	0.000055	0.7062-61	0.7063
9	19	15.66	76.4	0.5990	0.0121	0.7090	0.000060	0.7045-41	0.7047

The samples Nos 1 and 4 are greenschists, the other specimen are blueschists. Analyst J. Bendl (Analytika Ltd., Praha). The $^{87}Sr/^{86}Sr$ values of the metabasites recalculated to Early to Middle Cambrian and Early Ordovician ages presumed for their magmatic origin (see the text) are presented in last two columns.

cality of blueschists, the abandoned quarry, was sampled twice (Nos 8 and 9). Measured $^{87}Sr/^{86}Sr$ ratios were corrected for mass fractionation effect to the value $^{86}Sr/^{88}Sr = 0.1194$ (Steiger, Jäger 1977).

In the diagram of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ isotope ratios (Fig. 5a) the samples are widely scattered and do not yield one linear array. Consequently, an isochron, corresponding to the whole presented set of data, cannot be constructed in this diagram; it is also impossible to

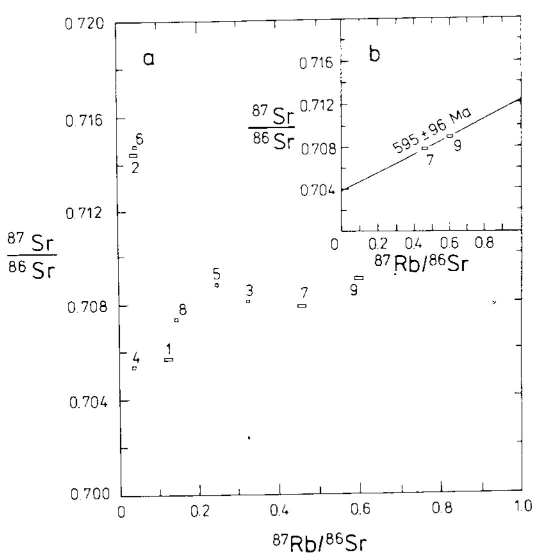

Fig. 5. a – diagram of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ isotope ratios of the whole-rock samples of mafic metavolcanics from the Radčice Group in the Rýchory Mts crystalline complex. The samples Nos 1 and 4 are greenschists, the other specimen are blueschists. Dimensions of rectangles correspond to σ errors; **b** – the tentative "two-point isochron" defined by two blueschists samples, Nos 7 and 9 (Table 1), showing the Rb-Sr whole-rock age 595 ± 96 Ma and the initial ratio $^{87}Sr/^{86}Sr = 0.7039 \pm 0.0007$. Isochron calculation follows York (1969) and the constants used are those from Steiger and Jäger (1977).

derive an initial Sr isotope ratio value valid for all measured metabasite samples.

DISCUSSION

The recent chemical composition of the Radčice Group metabasites has to be regarded as a product of the protolith composition deeply altered by primeval volcanic rock-seawater interaction prior to regional metamorphism, Variscan blueschist metamorphism followed by retrogression into greenschist facies, and post-metamorphic secondary changes (e.g. hydrothermal mineralization, weathering). Investigation of the whole rock geochemistry (Patočka *et al.* 1994, 1996, Maluski, Patočka 1996) proved that the Radčice Group mafic blueschists and greenschists were for the most part substantially depleted in K and Rb either during regional metamorphism (Floyd, Winchester 1978, Gale, Pearce 1982, Beard *et al.* 1995 *etc.*) or before it when their protolith possibly experienced hydrothermal seawater alteration at a volcanic center (e.g. de la Roche 1974, Humphris, Thompson 1978); the rock-seawater interaction is indicated by remarkable negative anomaly of Ce (e.g. Masuda, Nagasawa 1975, Patočka 1987) shown by some metabasite samples. Any significant post-metamorphic alterations were not proved in the studied rocks.

The chemical composition of majority of the Radčice Group metabasite samples, measured for Rb-Sr isotope data, was changed as described above (Patočka, unpublished data). The petrological investigation on the Rudawy Janowickie mafic metavolcanics also yielded evidence of identical sea-floor type alterations of primary rocks, possibly contemporaneous with volcanic activity (Teisseyre, 1973, Wieser, 1978).

The $^{87}Sr/^{86}Sr$ values of Radčice Group metabasites recalculated to ages 525 to 570 Ma – i.e. corresponding to Early to Middle Cambrian time interval of protolith origin, postulated by Chaloupský *et al.* (1989) on the basis of lithostratigraphic correlations – are mostly scattered between values 0.704 and 0.707, i.e. between values characterizing mantle-derived igneous rocks and oceanic waters in the Early Paleozoic, respectively (e.g. Faure 1986) (Table 1). Almost the same scatter is shown by the sample set $(^{87}Sr/^{86}Sr)_{500\ Ma}$ values when the protolith origin is related to hypothetic sea-floor spreading which may evolve from the intracontinental rifting dated by bimodal volcanism of the East Krkonoše Mts crystalline complex to Early Ordovician; the felsic-mafic metavolcanics of the Rýchory Mts (the Poniklá Group) show Rb-Sr whole-rock age 501 ± 8 Ma (Bendl, Patočka 1995), the Rudawy Janowickie felsic rocks are dated to 505 ± 5 Ma by U-Pb method on zircons (Oliver *et al.* 1993). The Radčice Group blueschists and greenschists appear to show geochemical affinity to oceanic-floor and oc- anic-island basalts (Patočka *et al.* 1994, 1996); in the central part the West Sudetes an Ordovician formation of oceanic-type crust is al recorded by metavolcanic rock sequences of the Rudawy Janowick (Winchester *et al.* 1995) and the Kaczawa Mts (Furnes *et al.* 1994 The Radčice Group rocks also display rather rough negative correl tion between possibly seawater-induced negative Ce-anomaly valu and Sr isotope ratios (Fig. 6). That is, the strontium isotope compos tion in the studied metabasite samples may be regarded as a produ of varying input of seawater Sr due to lava-seawater and/or rock-s awater hydrothermal alterations at a volcanic center during initi formation of the Radčice Group metabasite protolith (e.g. McCulloc *et al.* 1980).

Two samples of the studied mafic metavolcanics show extremel high Sr isotope ratios (between 0.714 and 0.715), more radiogenic tha those of seawater 500 to 570 Ma ago, as well as very low $^{87}Rb/^{86}Sr$ v lues (ca 0.04) (Nos 2 and 6 in Fig. 5a and Table 1). This feature ma indicate either an admixture of terrigenous clastic material (derive from mature rocks of continental crust), enhancing $^{87}Sr/^{86}Sr$ ratio the primary mafic rocks provided that basic pyroclastics (hyaloclast tes, granulates?) were a protolith of the metabasites, or an enrichmen of primary volcanics in radiogenic Sr leached from mature continent rocks during post-magmatic hydrothermal alterations (e.g. Gey Schleicher 1990). Both processes can be taken into account when th above mentioned origin of the Radčice Group metabasite protolith, r lated to hypothetic early-stage seafloor spreading, is considered. N vertheless, the first process would have to heighten not only th

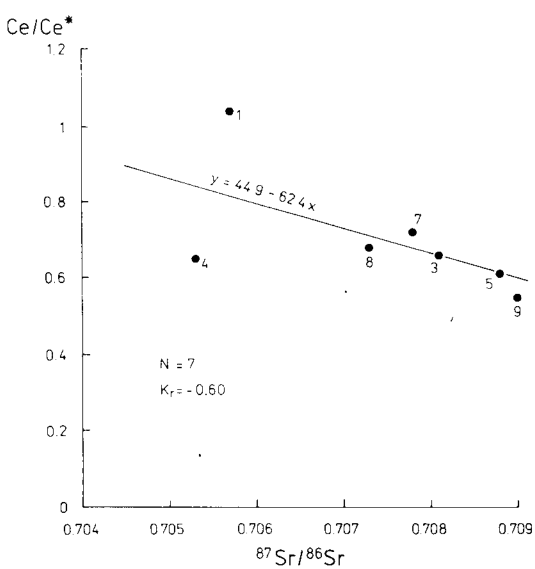

Fig. 6. Relationship of the Ce/Ce ratio (i.e. negative Ce-anomaly value to $^{87}Sr/^{86}Sr$ ratio in the Radčice Grou mafic metavoclanics; rocks showing ex- tremely radiogenic Sr isotope composi tion (where the origin by rock-seawate interaction cannot be presumed) ar not included. Correlation coefficien and corresponding regression line equ ation are presented.

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It has to be pointed out that
samples can be also disturbed d
grade regional metamorphism.
are rather speculative.

content of Sr in the metabasites but very probably also these of K and Rb. On the contrary, both samples show contents of K_2O as low as 0.06 wt.%, and almost negligible concentrations of Rb – ca 7 ppm (Maluski, Patočka 1996). As mentioned above, a rock-seawater hydrothermal alteration (reducing alkali concentrations) either accompanied or followed the origin of metabasite protolith. That is why, the latter mechanism – i.e. introduction of ^{87}Sr by means of hydrothermal leaching from continental rocks – is considered here as more probable.

It has been well established that Rb-Sr whole rock system is sensitive to secondary processes, especially when fluid phase is present during low-grade regional metamorphism (e.g. Hickman, Glassley 1984, Asmerom *et al.* 1991, Evans 1991) and during uplift and unloading subsequent to metamorphism (Bottrell *et al.* 1990). Following that, the scatter of the Rb-Sr data displayed by the Radčice Group metabasites can be also explained as a result of uplift related greenschist facies retrogression of the mafic blueschists after the subduction-related metamorphism (Patočka *et al.* 1994, 1996) which was possibly associated with increased permeability of rocks and water-rock interactions facilitating changes of the Rb-Sr system (e.g. Evans *et al.* 1995).

The Radčice Group volcanic rocks, probably genetically related to oceanic lithosphere, were tectonically emplaced into continental crust during Variscan orogeny (Patočka *et al.* 1994, 1996); then, the extremely radiogenic Sr isotope composition, characterizing two metabasite samples (Fig. 5a and Table 1), can also indicate an introduction of considerable amounts of Sr leached from evolved continental crust rocks by metamorphic fluids (Wasserburg *et al.* 1964) and retained in Ca-rich metamorphic minerals (such as epidote which is abundant in both samples) (e.g. Geyh, Schleicher 1990). The significant depletion of alkalis during regional metamorphism (e.g. Beard *et al.* 1995) could diminish $^{87}Rb/^{86}Sr$ ratios in these metabasites (as well as in the sample No. 4 – Fig. 5a and Table 1).

Two blueschist specimens, Nos 7 and 9 (Fig. 5a and Table 1), show the chemical composition almost unaltered (by rock-seawater interaction and/or metamorphism) in comparison with the rest of sample set (Patočka, unpublished data). If the straight line defined by these two points in the $^{87}Rb/^{86}Sr$ vs $^{87}Sr/^{86}Sr$ plot was an isochron (Fig. 5b), the values of Rb-Sr whole-rock age (595 ± 96 Ma) and the initial Sr isotope ratio ($^{87}Sr/^{86}Sr$ = 0.7039) could be derived.

It has to be pointed out that the Rb-Sr systems of both metabasite samples can be also disturbed due to hydrothermal alteration and low-grade regional metamorphism. Therefore, the above derived values are rather speculative.

CONCLUSIONS

The mafic metavolcanics (blueschists and greenschists) of the Radčice Group (the Rýchory Mts crystalline complex, West Sudetes) were measured for Rb-Sr isotope composition. The $^{87}Sr/^{86}Sr$ data on the metabasites were corrected firstly to Early to Middle Cambrian age of primary rocks, based on lithostratigraphic correlations, and secondly to age of protolith related to hypothetic sea-floor spreading subsequent to the intracontinental rifting dated by felsic-mafic volcanism of the East Krkonoše complex to Early Ordovician. The corrected data are mostly scattered between Sr isotope values characterizing mantle-derived igneous rocks and oceanic waters in the Early Paleozoic, respectively (Table 1). This specific feature of the metabasite geochemistry was made by either input of seawater Sr into protolith rocks, or secondary changes in Rb-Sr system during regional metamorphism (enhancing rock permeability and water-rock interaction). Two extremely high Sr isotope values possibly indicate an introduction of radiogenic Sr leached from rocks of continental crust during post-magmatic hydrothermal alterations and/or by metamorphic fluids and substituted in Ca-rich minerals (e.g. epidote).

Due to the wide scatter of the measured values in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram it is impossible to derive an isochron and corresponding initial Sr isotope ratio valid for the whole sample set. However, two blueschists, displaying only faintly altered chemical composition relative to the rest of samples, are giving value 0.7039 as an initial ratio of Sr isotopes. Provided that this value is regarded to represent a hypothetical initial strontium isotope ratio of the Radčice Group mafic metavolcanics, a mantle-derived origin of the primary rocks can be presumed. The "two-point isochron" defined by these samples in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ plot may be interpreted as reference on the age of magmatic origin of the metabasite protolith in the Late Proterozoic to Early Ordovician interval. The Early Ordovician age can be considered provided that the above mentioned origin of the Radčice Group metabasite protolith, related to hypothetic early-stage seafloor spreading, is taken into account. Then, it would fit not only with the evidences of oceanic-type crust generation preserved in the West Sudetes (e.g. Furnes *et al.*, 1994, Winchester *et al.* 1995) but also with Early Paleozoic large-scale rifting and opening of oceanic basins along the northern periphery of Gondwana (e.g. Pin 1990, Furnes *et al.*, 1994, Beard *et al.* 1995).

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REFERENCES

ASMEROM Y., DAMON P., SHAFIQUILLAH M., DICKINSON W.R., ZARTMAN R.E., 1991. Resetting of Rb-Sr ages of volcanic rocks by low grade burial metamorphism. *Chem. Geol.* (Isot. Geosci. Sect.), 87, 167–173.

BANNO S., NAKAJIMA T., 1991. Metamorphic belts of Japan. *Episodes*, 14, 280–285.

BEARD B.L., MEDARIS L.G., JOHNSON C.M., JELÍNEK E., TONIKA J., RICIPUTI L.R., 1995. Geochronology and geochemistry of eclogites from the Mariánské Lázně Complex, Czech Republic: Implications for Variscan orogenesis. *Geol. Rundschau*, 84, 552–567.

BENDL J., PATOČKA F., 1995. The Rb-Sr isotope geochemistry of the metamorphosed bimodal volcanic association of the Rýchory Mts. crystalline complex, West Sudetes, Bohemian Massif. *Geol. Sudetica*, 29, 3–18.

BOTTRELL S.H., GREENWOOD P.B., YARDLEY B.W.H., SHEPHERD T.J., SPIRO B., 1990. Metamorphic and post-metamorphic fluid flow in low grade rock of the Harlech dome, North Wales. *J. Metamorphic Geol.*, 8, 131–148.

CHÁB J., VRÁNA S., 1979. Crossite-actinolite amphiboles from the Krkonoše-Jizera crystalline complex and their geological significance. *Věst. Ústř. Úst. geol.*, 54, 143–150.

CHALOUPSKÝ J. (*ed.*), 1989. Geological map of the Krkonoše and Jizerské hory Mts. 1 : 100,000. 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, Engl. summary). Geological Survey. Praha.

CHLUPÁČ I., 1993. Stratigraphic evaluation of some metamorphic units in the N part of the Bohemian Massif. *N. Jb. Geol. Paläont., Abh.*, 188, 363–388.

CYMERMAN Z., PIASECKI M.A.J., 1994. The terrane concept in the Sudetes, Bohemian Massif. *Geol. Quarterly*, 38, 191–210.

de la ROCHE H., ROCCI G., JUTEAU Th., 1974. Essai de caractérisation chimique des associations spilitiques. *In:* AMSTUTZ G.C. (*ed.*), Spilites and Spilitic Rocks Springer-Verlag Berlin - Heidelberg - New York, 39–58.

ERNST W.G., 1973. Blueschist metamorphism and PT regimes in active subduction zones. *Tectonophysics*, 26: 229–246.

EVANS J.A., 1991. Resetting of Rb-Sr whole-rock ages during Acadian low-grade metamorphism in North Wales. *J. Geol. Soc.*, London, 148, 703–710.

EVANS J.A., MILLAR I.L., NOBLE S.R., 1995. Hydration during uplift is recorded by reset Rb-Sr whole-rock age. *J. Geol. Soc.*, London, 152, 209–212.

FAURE G., 1986. Principles of Isotope Geology, 2nd ed. J. Wiley and Sons. New York.

FLOYD P.A., WINCHESTER J.A., 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chem. Geol.*, 21, 291–306.

FURNES H., KRYZA R., MUSZYŃSKI A., PIN Ch., GARMANN L.B., 1994. Geochemical evidence for progressive, rift-related Early Palaeozoic volcanism in the Western Sudetes. *J. Geol. Soc.*, London, 151, 91–109.

GALE G.H., PEARCE J.A., 1982. Geochemical patterns in Norwegian greenstones. *Canad. J. Earth Sci.*, 19, 385–397.

GEYH M.A., SCHLEICHER H., 1990. Absolute Age Determination. Rubidium/Strontium ($^{87}Rb/^{87}Sr$) Method. Springer-Verlag. Berlin.

GIL IBARGUCHI J.I., DALLMEYER R.D., 1991. Hercynian blueschist metamorphism in North Portugal: tectonothermal implications. *J. Metamorphic Geol.*, 9, 539–549.

GUIRAUD M., BURG J.P., 1984. Mineralogical and petrological study of a blueschist metatuff from the Železný Brod Crystalline Complex, Czechoslovakia. *N. Jb. Miner. Abh.*, 149, 1–12.

HAMPEL J., 1911. Die krystallinen Schiefer der Südabdachung des Riesengebirges zwischen Freiheit und Schneekoppe. *Lotos*, 59, 169–127.

HARVEY P.K., ATKIN B.P., 1981. The rapid determination of Rb, Sr and their ratios in geological materials by X-ray fluorescence spectrometry using a rhodium X-ray tube. *Chem. Geol.*, 32, 155–165.

HICKMAN M.H., GLASSLEY W.E., 1984. The role of metamorphic fluid transport in the Rb-Sr isotopic resetting of shear zones: evidence from Nordre Stromfjord, West Greenland. *Contrib. Miner. Petrol.*, 87, 265–281.

HOSOTANI H., BANNO S., 1986. Amphibole composition as an indicator of subtle variations in epidote-glaucophane system. *J. Metamorphic Geol.*, 4, 123–135.

HUMPHRIS S.E., THOMPSON G., 1978. Hydrothermal alteration of oceanic basalt by seawater. *Geochim. Cosmochim. Acta*, 42, 107–125.

KODYM O., SVOBODA J., 1948. The Caledonian nappe tectonics of the Krkonoše and Jizerské Hory Mts (in Czech). *Sb. St. geol. Úst.*, 15, 109–160.

MALUSKI H., 1977. Intérêt de la méthode 40Ar/39Ar pour la datation des glaucophanes de l' Ile de Groix (France). *C. R. Sci. Acad. Paris*, 283, 223–226.

MALUSKI H., PATOČKA F., 1996. Geochemistry and ^{40}Ar-^{39}Ar geochronology of the blueschist and greenschist metavolcanics from the Rýchory Mts. complex (West Sudetes, Bohemian Massif): paleotectonic significance. In: Abstracts of the Transeuropean Suture Zone Workshop, Książ, 11-17 April 1996. Państwowy Instytut Geologiczny, Instytut Nauk Geologicznych PAN, Instytut Geofizyki, Wrocław.

MASUDA A., NAGASAWA S., 1975. Rocks with negative cerium anomalies dredged from the Shatsky Rise. *Geochem. J.*, 9, 227–233.

MATTE Ph., 1986. Tectonics and plate tectonics model for the Variscan belt of Europe. *Tectonophysics*, 126, 329–374.

McCULLOCH M.T., GREGORY R.T., WASSERBURG G.J., TAYLOR H.P., 1980. A neodymium, strontium, and oxygen isotopic study of the Cretacous Semail ophiolite and implication for the petrogenesis and sewater-hydrothermal alteration of oceanic crust. *Earth Planet. Sci. Lett.*, 46, 201–211.

MIYASHIRO A., 1961. Evolution of metamorphic belts. *J. Petrol.*, 2. 277–311.

MUNHÁ J., RIBEIRO A., RIBEIRO M.L., 1984. Blueschists in the Iberian Variscan Chain (Trás-os-Montes: NE Portugal). *Comun. Serv. Geol. Port.*, 70, 31–53.

NARĘBSKI W., 1994. Lower to Upper Paleozoic tectonomagmatic evolution of NE part of the Bohemian Massif. *Zbl. Geol. Paläont.*, 9/10 (1994), 961–972.

NARĘBSKI W., DOSTAL J., DUPUY C., 1986. Geochemical characteristics of Lower Paleozoic spilite-keratophyre series in the Western Sudetes (Poland): petrogenetic and tectonic implications. *N. Jb. Miner. Abh.*, 155, 243–258.

OLIVER G.J.H., CORFU F., KROGH T.E., 1993. U-Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *J. Geol. Soc.*, London., 150, 355–369.

PATOČKA F., 1987. The geochemistry of mafic metavolcanics: implications for the origin of the Devonian massive sulfide deposits at Zlaté Hory, Czechoslovakia. *Mineralium Deposita*, 22, 144–150.

PATOČKA F., PIVEC E., OLIVERIOVÁ D., 1994. The mafic blueschists from the Rýchory Mts. crystalline complex (Western Sudetes, Bohemian Massif): metamorphic development and possible protolith composition. *In:* KRYZA R. (*ed.*): Abstracts of the International Conference "Igneous Activity and Metamorphic Evolution of the Sudetes Area, 1994". Inst. Geol. Sci., Wrocław University, 87–90. Wrocław.

PATOČKA F., PIVEC E., OLIVERIOVÁ D., 1996. Mineralogy and petrology of mafic blueschists from the Rýchory Mts. crystalline complex (Western Sudetes, Bohemian Massif). *N. Jb. Mineral., Abh.*, 170, 313–320.

PELIKAN A., 1928. Glaukophan aus dem Riesengebirge. *Lotos*, 76, 335–344.

PEUCAT J.-J., COGNÉ J., 1977. Geochronology of some blueschists from the Ile de Groix (France). *Nature*, 268, 131–132.

PEUCAT J.-J., VIDAL P., GODDARD G., POSTAIRE B., 1982. Precambrian U-Pb zircon ages in eclogites and garnet pyroxenites from South Brittany (France): an old oceanic crust in the West European Hecynian belt? *Earth Planet. Sci. Lett.*, 60, 70–78.

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

SMULIKOWSKI W., 1994. Metamorphic evolution of the East Karkonosze polymetamorphic complex in Lasocki Range, West Sudetes. *In:* KRYZA R. (*ed.*): Abstracts of the International Conference "Igneous Activity and Metamorphic Evolution of the Sudetes Area, 1994". Inst. Geol. Sci., Wrocław University, 93–97. Wrocław.

SMULIKOWSKI W., 1995. Evidence of glaucophane-schist facies metamorphism in the East Karkonosze complex, West Sudetes, Poland. *Geol. Rundsch.*, 720–737.

STEIGER R.H., JÄGER E., 1977. Subcommission on geochronology: convention on the use of decay constant in geo- and cosmochronology. *Earth Planet. Sci. Lett.*, 36, 359–362.

SVOBODA J., CHALOUPSKÝ J., 1966. The West Sudeten Crystalline. *In:* SVOBODA J., DVOŘÁK J., HAVLENA V., HAVLÍČEK V., HORNÝ R., CHLUPÁČ I., KLEIN V., KOPECKÝ L., MALECHA A., MALKOVSKÝ M., SOUKUP J., TÁSLER R., VÁCL J., ŽEBERA K., 1966. Regional Geology of Czechoslovakia, I. Geological Survey. Praha.

TEISSEYRE J.H., 1973. Metamorphic rocks of Rudawy Janowickie and Lasocki Grzbiet ranges. *Geol. Sudetica*, 8, 7–118. Warszawa.

van BREEMEN O., BOWES D.R., AFTALION M., ŻELAŹNIEWICZ A., 1988. Devonian tectonothermal activity in the Sowie Góry gneissic block, Sudetes, SW Poland: evidence from Rb-Sr and U-Pb isotopic studies. *Ann. Soc. Geol. Polon.*, 58, 2–19.

VERDURMEN E.A.T., 1979. Accuracy of X-ray fluorescence spectrometric determination of Rb and Sr concentrations in rock samples. *X-ray Spectrometry*, 6, 3, 117–122.

TRIBOULET C., 1974. Les glaucophanites et roches associées de l' Ile de Groix, Morbihan, France: étude mineralogique et petrogénétique. *Contrib. Mineral. Petrol.*, 45, 65–90.

WASSERBURG G.J., ALBEE A.L., LANPHERE M.A., 1964. Migration of radiogenic strontium during metamorphism. *J. Geophys. Res.*, 64, 20, 4395–4401.

WIESER T., 1978. Glaucophane schists and associated rocks of Kopina Mt. (Lasocki Range, Sudeten). *Mineralogia Polon.*, 9, 17–38.

WINCHESTER J.A., FLOYD P.A., CHOCYK M., HORBOWY K., KOZDROJ W., 1995.

Geochemistry and tectonic environment of Ordovician meta-igneous rocks in the Rudawy Janowickie Complex, SW Poland. *J. Geol. Soc.*, London, 152, 105–115.
YORK D., 1969. Least-squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett.*, 5, 320–324.