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Jiří BENDL[1], František PATOČKA[2]

THE Rb-Sr ISOTOPE GEOCHEMISTRY OF THE METAMORPHOSED BIMODAL VOLCANIC ASSOCIATION OF THE RÝCHORY MTS CRYSTALLINE COMPLEX, WEST SUDETES, BOHEMIAN MASSIF[3]

Abstract. The Rb-Sr isotope data on porphyroid and greenschist samples of the Ponikla Group (the Rýchory Mts crystalline complex, West Sudetes) indicate that the protolith of these rocks can be a bimodal volcanic association (dominated by acid components) related to continental rifting. The possible age of the magmatic origin of the protolith, based on the Rb-Sr isochron, is 501 + 8 Ma (Early Ordovician). A large-scale fragmentation of the Gondwana plate northern margin during the Cambrian and Ordovician, deduced from the abundance of mafic-felsic volcanic suites in the Lower Paleozoic of the European Variscides, is supported also by the interpretation of the Rb-Sr isotope data on the Ponikla Group metavolcanics.

The 350 and 365 Ma intersects of the hypothetical evolution curve of Sr isotope composition in the Rýchory Mts marble, and the curve of Sr isotope ratio fluctuations in the Paleozoic marine carbonates, as well as the relics of oolitic texture, often observed in the marbles, may probably point to Famennian to Tournaisian age of the marble sedimentary precursor.

The Rb-Sr isotope data on the Rýchory Mts metavolcanics and marble suggest that the Ponikla Group is a metamorphosed volcano-sedimentary sequence formed between the Early Ordovician and the Late Devonian/Early Carboniferous. As a place of its origin is suggested a rifted off passive continental margin of some of the Gondwana-derived fragments.

Key words: Rb-Sr isotope data, bimodal volcanic association, porphyroid, greenschist, marble, Early Paleozoic, West Sudetes, Bohemian Massif, Gondwana.

1 Analytika Ltd., U Elektry 650, CZ-198 00 Praha 9, Czech Republic.

2 Geological Institute of the Academy of Sciences of the Czech Republic, Rozvojova 135, CZ-165 00 Praha 6, Czech Republic.

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INTRODUCTION

The northeastern margin of the Bohemian Massif, the West Sudetes (Svoboda, Chaloupský 1966), more recently also termed Lugosudeticum (Narębski 1994), is a heterogeneous region composed of Proterozoic and Paleozoic sequences affected by Cadomian and Variscan metamorphism and intruded by plutons of Cadomian and Variscan granitoids. It consists of several major fault-bounded segments – possibly accreted terranes – which have distinct Cambrian to Carboniferous histories. According to Narębski (*l. c.*) these are Lusatian-Jizera-Krkonoše, Góry Sowie Mts, Middle Odra and Orlické hory Mts - Snieżnik Kłodzki units. The most significant effusive, intrusive and tectonometamorphic events took place along their margins (e.g. Narębski *et al.* 1982, 1986; Oliver *et al.* 1993; Furnes *et al.* 1994; Narębski 1994; Winchester *et al.* 1995).

The low- to medium-grade metamorphosed mafic-felsic volcanics are exposed in minor units surrounding the Lusatian-Jizera-Krkonoše unit from the east and south: in the Rudawy Janowickie-Lasocki Grzbiet-Rýchory Mts, Železný Brod and Ještěd complexes (Chaloupský *et al.* 1989) (Fig. 1).

Ages varying widely from Early Cambrian to Early Devonian are presumed for the primary volcanic rocks of the above mentioned units of the western part of Lugosudeticum (e.g. Kodym, Svoboda 1948; Teisseyre 1973; Narębski *et al.* 1986; Chaloupský *et al.* 1989). However, precise data on the protolith ages of metaigneous rocks are needed for reliable reconstructions of the tectonomagmatic development of the West Sudetes. Early Ordovician volcanism in the Rudawy Janowickie seems to be indicated by U-Pb zircon ages of 505 ± 5 Ma for a relict felsic volcanic rock forming boudins within metabasites, and 494 ± 2 Ma for a rock described as hornblende gabbro (Oliver *et al.* 1993).

A new set of the Rb-Sr isotope data on metavolcanic rocks of a bimodal association from the Rýchory Mts (porphyroids and greenschists) is presented in this paper.

GEOLOGIC SETTING

In the midst of the West Sudetes (forming the eastern rim of the Krkonoše Mts - Jizera unit), the Rýchory Mts crystalline complex is exposed. Towards the west this rock sequence is connected with the Lower Paleozoic in the area of Poniklá and Železný Brod by a narrow belt (e.g. Svoboda, Chaloupský 1966; Chaloupský *et al.* 1989). The northern continuation of the Rýchory Mts crystalline complex in Poland are Lasocki Grzbiet and Rudawy Janowickie (e.g. Teisseyre 1973) (Fig. 1b).

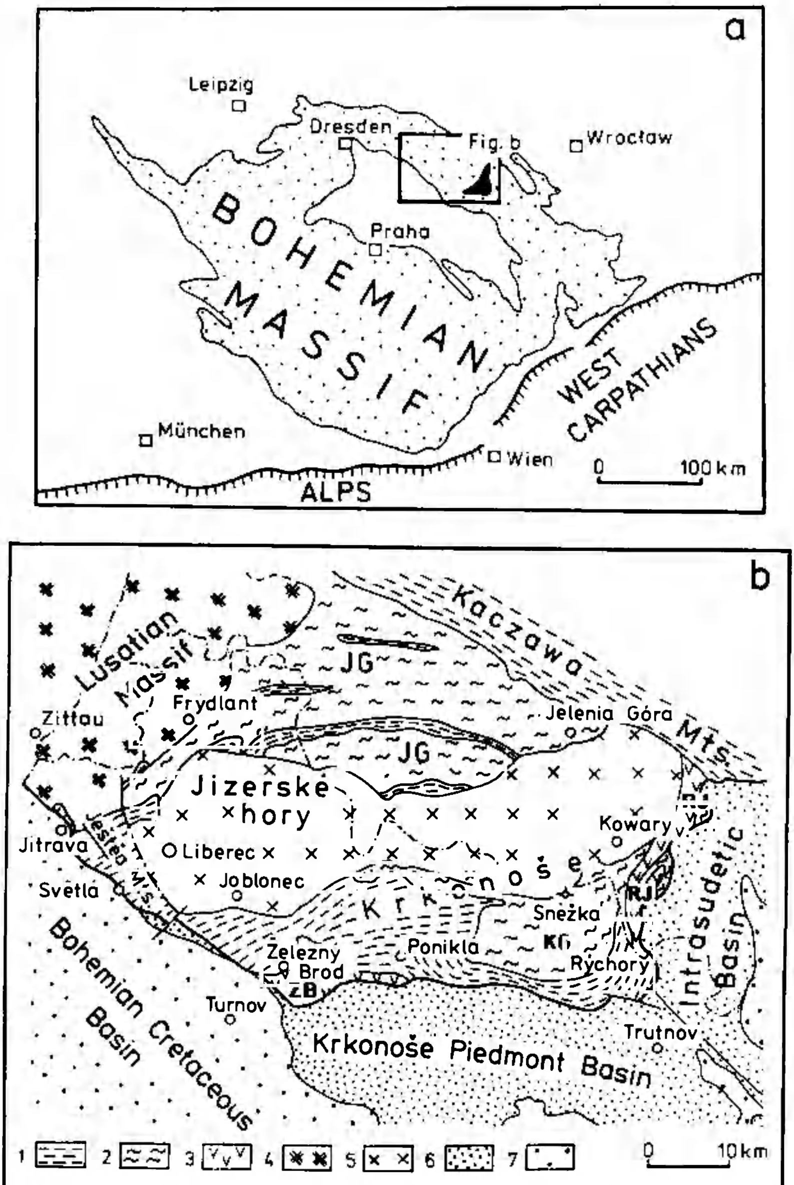

Fig. 1. **(a)** Location of the studied region - area in the frame corresponds to Fig. 1b, the black area in the frame corresponds to Fig. 2. **(b)** Geological sketch map of the western part of the Western Sudetes - Krkonoše, Jizerske hory and Jested Mts – after Chlupač (1993). *1* – low-grade metamorphic units; *2* – medium- to high-grade metamorphic units (mica-schists, gneisses); *3* – metamorphosed volcanic 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 Železny Brod complex; RJ – the Rudawy Janowickie and Lasocki Grzbiet complexes. *Dashed line* – state borders

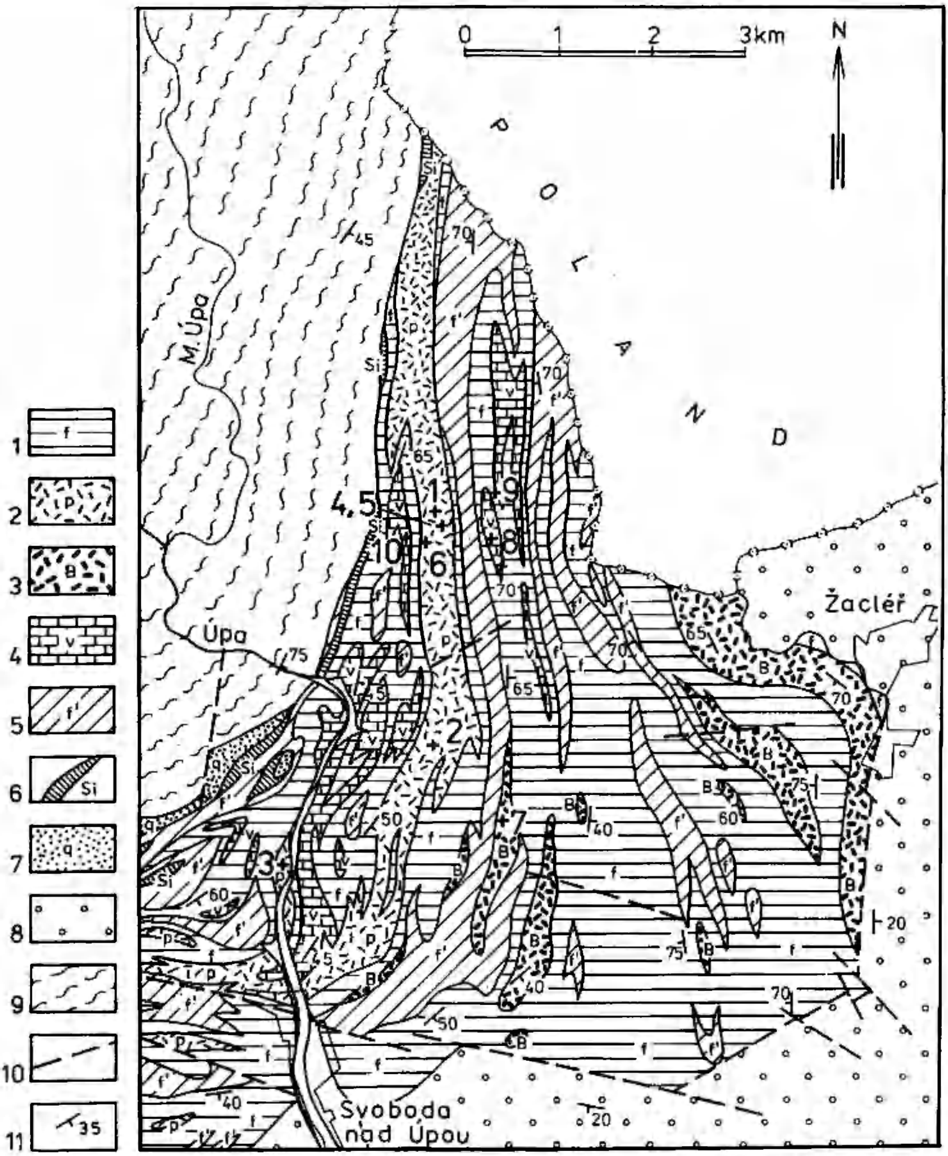

Fig. 2. Geological map of the Rychory Mts crystalline complex – adapted after Chaloupský (1989). The Ponikla Group forms the most of the Rychory Mts area; only the metabasite bodies in the eastern part of the complex represent the Radčice Group defined by Chaloupský *et al.* (1989). The sample sites are presented in the map by using the numbers from Table 1. *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 Quarternary); *9* – Krkonoše gneisses and mica-schists and metabasites of the Velká Úpa Group (undistinguished); *10* – faults; *11* – foliation

The Rýchory Mts complex is generally metamorphosed to higher range of greenschist facies; however, its significant metamorphic feature is the rather frequent occurrence of Na-amphiboles in metabasites, which are interpreted as relics of earlier blueschist facies metamorphic assemblage (e.g. Wieser 1978; Patočka *et al.* 1994).

On the basis of systematic lithostratigraphic studies, Chaloupský *et al.* (1989) defined two volcano-sedimentary and volcanic sequences within the Rýchory Mts crystalline complex – the Poniklá and the Radčice Groups (however, both of them constitute also the Poniklá-Železný Brod region) (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 (metarhyolites, ignimbrites?) – strongly prevail over mafic ones – greenschists (basic pyroclastics) (e.g. Chaloupský *et al.* 1989). The Poniklá Group is considered to be of Ordovician-Silurian age (Chaloupský *et al. l.c.*); only the upper part of the sequence, comprising graphitic phyllites and phyllitic slates with intercalations of metalydites and bituminous marbles, is paleontologically dated – to Llandovery and Early Wenlock, according to the graptolite fauna (e.g. Chlupáč 1953, 1993).

The earliest possible age for the onset of tectonometamorphic development of the Rýchory Mts crystalline complex can be possibly identified with the oldest Variscan phases presumed in the West Sudetes. Following that, it can be dated to Middle Devonian (Teisseyre 1973; Cháb, Vrána 1979; Chlupáč 1993). 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 preliminary Early Variscan ^{39}Ar-^{40}Ar data measured on blueschist facies metavolcanics from the eastern Krkonoše by H. Maluski (personal communication in Smulikowski 1994). However, the principal stage of Variscan orogeny in the Krkonoše-Jizera and Ještěd units is related to the Sudetic phase (late Visean) (Chlupáč 1993).

PETROGRAPHY OF THE METAVOLCANIC ROCKS OF THE PONIKLÁ GROUP IN THE RÝCHORY MTS CRYSTALLINE COMPLEX

Porphyroids

The most abundant metavolcanic rocks of the Poniklá Group in the Rýchory Mts crystalline complex are various types of porphyroids,

Fig. 3. Porphyroid of the Ponikla Group (Rychory Mts crystalline complex) – sample No. 1. Note well preserved albite phenocryst and clear banding within the rock matrix. Crossed polarization; magnification ×36. Photo M. Šťastný

described also as sericite-quartz-albite schists according to Chaloupský *et al.* (1989) (Fig. 2).

These felsic metavolcanics are usually fine grained and mostly display light grey to light green-grey colour, white or pink-white varieties are less frequent. Pronounced linear and/or planar fabric characterizes all porphyroids.

Mineral composition of the matrix of the studied porphyroids is rather uniform. As their principal constituents, these rocks contain quartz, albite, sericite and clinozoisite. Albite is often intergrown with quartz. Clinozoisite is present in widely varying amounts – in some porphyroid types its content is up to 10%, while other types are almost free of this mineral. In some cases clinozoisite grows across the sericite planes. The ubiquitous accessory minerals in the porphyroids are pyrite, magnetite and limonite.

Distinct banding is a specific feature of almost all porphyroid types. Alternating bands of coarser grained quartz-albite layers and finer grained sericite-quartz-albite layers are observed in these rocks; the layers are several tenths of a mm to several mm thick (Fig. 3). However, in very fine grained types of porphyroids banding is usually imperfect and often is almost missing.

Phenocrysts form ca 5-10 % of the rock volume of the porphyroids. Albite is the most abundant mineral present in the form of phenocrysts; the phenocrysts (of average length of ca 1-2 mm) are hypidiomorphic to xenomorphic in shape and usually twinned. Albite phenocrysts are conformably oriented relative to the rock fabric. Quartz and/or microcline phenocrysts are very rare (phenocrysts of both minerals are always xenomorphic as well as significantly smaller compared with the albite ones). The phenocrysts sometimes accumulate into several mm long lenses and/or bands (the quartz accumulations are rather fine grained).

Texture of the porhyroids is generally blastoporphyric, and the texture of the porphyroid matrix is granoblastic to granolepidoblastic.

Greenschists

The greenschists are less frequent in the Ponikla Group in the Rýchory Mts crystalline complex compared with the porphyroids (Fig. 2). They are generally fine grained and well foliated rocks of grey-green colour.

The greenschist mineral association is comprised of actinolite, chlorite, epidote, albite and carbonate. Actinolite is usually invisible to the naked eye; it can be discerned only where it is clustered in abundance into dense aggregates displaying linear fabric. Actinolite needles, arranged parallel to foliation, are almost colourless and show faint pleochroism. Albite forms isometric xenomorphic grains 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 albite. Chlorite, characterized by weak pleochroism, partly substitutes actinolite. Epidote tends to form porphyroblasts, even idioblasts. On the other hand, minute epidote grains are concentrated into either shapeless clusters or parallel bands. Sphene, carbonate, white mica and ore minerals (magnetite and pyrite) are present in subordinate quantities and often are accessories in the studied rocks. Quartz and K-feldspar were identified in several specimens. In some samples abundant lenses (ca 2×1mm) composed of albite and/or carbonate were found. Most of these rocks have fibronematoblastic texture.

An imperfect banding, shown by parallel sets of very thin layers (ca. 2 mm) of alternating dark and light minerals, is a general feature of the greenschists (Fig. 4). In some samples the light components (for the most part albite, carbonate and accessory white mica) dominate; on the other hand, in the chlorite-rich specimens mafic components (chlorite and actinolite) prevail. The latter type of greenschists, showing lepidonematoblastic texture, is very well foliated.

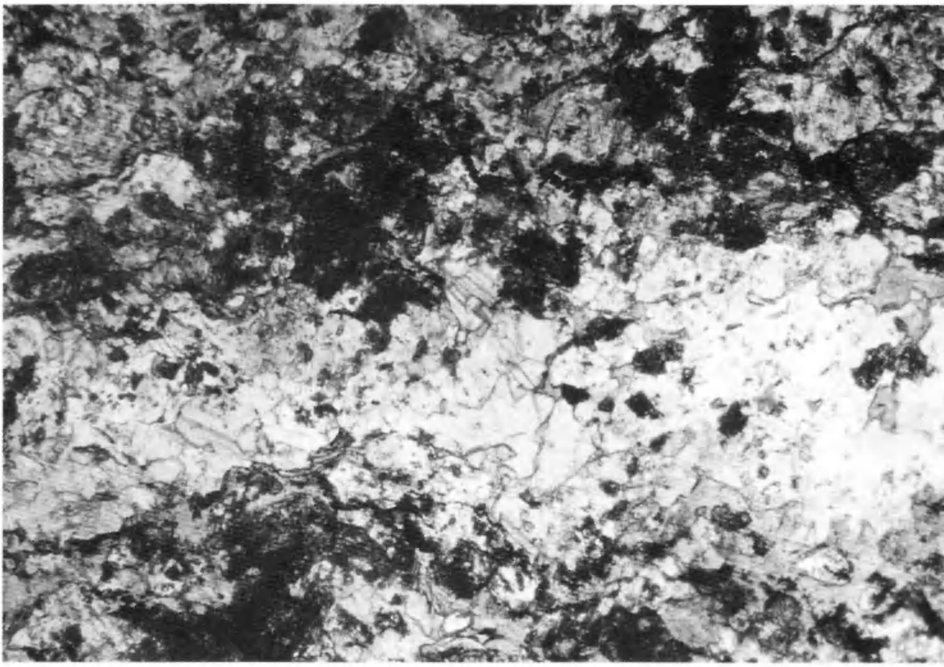

Fig. 4. Greenschist of the Ponikla Group (Rýchory Mts crystalline complex) – sample No. 7. An imperfect banding can be recognized in the sample. Crossed polarization; magnification ×36. Photo M. Šťastny

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 rocks of the Ponikla Group were sampled, and rather voluminous whole-rock specimens (10-35 kg) were taken (Table 1). The samples were carefully crushed and homogenised for Rb-Sr analyses.

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

Table 1

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

Sample No.	Weight [kg]	Rb [ppm]	Sr [ppm]	$^{87}Rb/^{86}Sr$	1σ	$^{87}Sr/^{86}Sr$	1σ	$(^{87}Sr/^{86}Sr)$ 501 Ma
1	35	187	54.4	10.0	0.2	0.775788	0.000048	0.704392
2	26	48.5	119	1.18	0.024	0.714442	0.000046	0.706017
3	20	102	97.5	3.03	0.03	0.727443	0.000057	0.705810
4	19	153	70.7	6.29	0.12	0.750588	0.000054	0.705680
5	18	181	62.6	8.41	0.08	0.765552	0.000043	0.705508
6	20	131	92.7	4.1	0.08	0.735163	0.000050	0.705891
7	10	18.2	277	0.19	0.022	0.706925	0.000055	0.705568
8	20	6.9	112	0.178	0.019	0.709024	0.000064	0.707753
9	15	52.2	275	0.549	0.0074	0.709491	0.000078	0.705571
10	15	50	99.9	1.45	0.029	0.717446	0.000046	0.707094

1-6 - porphyroids, 7 - greenschist, 8 - marble, 9 and 10 - carbonate phyllites. Analyst J. Bendl (Analytika Ltd., Praha)

Rb-Sr ISOTOPE DATA

For application of Rb-Sr isotope analysis, six porphyroid samples and a single greenschist specimen were taken in the Rýchory Mts crystalline complex. All samples were taken from the Ponikla Group as it was regionally defined there by Chaloupský *et al.* (1989) (Fig. 2). The nearby carbonate-rich metasediments – marble and carbonate phyllites, i.e. rocks presumably also rich in Sr (e.g. Bowen 1979) – were sampled for comparison with regard to sensitivity of the Rb-Sr whole-rock system to secondary processes (hydrothermal alterations, weathering etc.) (e.g. Compston *et al.* 1982; Schleicher *et al.* 1983). The whole-rock data for the samples are listed in Table 1. Measured $^{87}Sr/^{86}Sr$ ratios were corrected for fractionation effects to the value $^{86}Sr/^{88}Sr = 0.1194$ (Steiger, Jager 1977).

According to the sufficient scatter of $^{87}Rb/^{86}Sr$ values measured on the studied samples of metavolcanic rocks of the Ponikla Group, an isochron can be constructed in the diagram of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ isotope ratios, respecting the requirement of having at least four samples with Rb/Sr ratios that are as far apart as possible (e.g. Geyh, Schleicher 1990). In the $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ plot (Fig. 5a), whe-

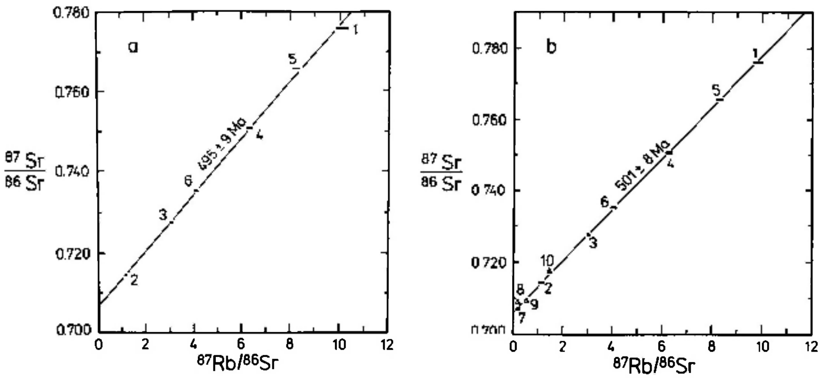

Fig. 5. Plots of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ isotope ratios of the rock samples of the Ponikla Group (Rýchory Mts crystalline complex). The error boxes are 1σ for the samples of metavolcanics. Sample numbers are as in Table 1. (**a**) Plot showing only the porphyroid samples and corresponding isochron. (**b**) Plot including the porphyroid and greenschist samples as well as the samples of metasediments – marble and carbonate phyllites (marked as triangles). The isochron is based on the samples of metavolcanic rocks

re only porphyroid samples are shown, the slope of the isochron defines an age 495 ± 9 Ma with an initial strontium isotopic ratio 0.70611 + 0.00041. In the next diagram (Fig. 5b) the greenschist sample is also considered. There the age of the isochron is 501 ± 8 Ma, and an initial Sr isotopic ratio is 0.70578 ± 0.00026. Isochrons calculations follow Ludwig (1992). For the calculation the decay constant $1.42.10^{-11}.y^{-1}$ of the isotope ^{87}Rb was used (e.g. Steiger, Jäger 1977).

DISCUSSION

The majority of the Ponikla Group porphyroids of the Rýchory Mts show much higher $^{87}Rb/^{86}Sr$ ratios compared with the samples of marble and carbonate phyllites (Table 1). That suggests that significant exchange between the Rb-Sr isotope systems of these metaigneous and metasedimentary rocks during any secondary processes does not seem probable. On the other hand, regarding the greenschist sample, such an exchange cannot be excluded considering its low $^{87}Rb/^{86}Sr$ ratio, comparable with the marble value. Nevertheless, only negligible disturbance of the Rb-Sr system in the felsic-mafic metavolcanic samples of the Ponikla Group can be inferred from the low scatter of $^{87}Sr/^{86}Sr$ values corrected to the age of 501 Ma (Table 1).

The Rb-Sr age of 495 ± 9 Ma, indicating the age of the Rb-Sr system closure, can be interpreted as the time of magmatic origin of protolith rocks of the Ponikla Group porphyroids, since whole-rock isochrons for volcanic rocks subjected to metamorphism usually give the time of effusion (e.g. Geyh, Schleicher 1990) (Fig. 5a).

The initial Sr isotope ratio of 0.70611 for the porphyroids indicates that the protolith magma could not be derived directly from the Earth's mantle. Provided that the magma was of crustal provenance, melting of low-degree differentiated igneous rocks (distinguished by low Rb/Sr ratio) and/or those having generally short crustal residence histories, can be a possible mechanism of the protolith magma origin. Initial strontium isotope values of about 0.706 are specific feature of basic granulites (Peucat *et al.* 1990; Volbracht *et al.* 1994 etc.) which are considered to be characteristic rocks of the lower crust of the Variscan Europe (e.g. Downes 1990) as well as of the lower crust in general (e.g. Yanagi *et al.* 1988). However, not only partial melting of basic granulites, but also considerable contamination of magma rising from the mantle by these melts can produce the above mentioned initial $^{87}Sr/^{86}Sr$ values, since the lower crust at high temperatures is the first material for the ascending magma to encounter.

It has to be pointed out that the isochron based only on the felsic rocks is almost identical to that involving the porphyroid samples as well as the greenschist specimen. The latter indicates both an age of the Rb-Sr system closure and an initial Sr isotope ratio very close to those shown by the former (Fig. 5). Moderate $(^{87}Sr/^{86}Sr)_{501\ Ma}$ values (ca. 0.706), displayed by all samples of the Poniklá Group metavolcanics (Table 1), suggest their close genetic relationship. The felsic melts of the porphyroid protolith could have a possible precursor in mantle-derived transitional to alkaline basic magmas, as is often observed in anorogenic settings (e.g. Pin, Marini 1993). This assumption seems to be supported by the affinity of the chemical composition of the Poniklá Group greenschists to ocean-island transitional and alkaline basalts (Patočka, unpublished data).

Following that, felsic and mafic metavolcanics of the Poniklá Group in the Rýchory Mts crystalline complex can be interpreted as cogenetic members of a bimodal volcanic association of Early Ordovician age. A bimodal suite of rift-related metavolcanic rocks (with less abundant felsic components), dated to the Ordovician by Oliver *et al.* (1993), is described from the neighbouring Rudawy Janowickie complex by e.g. Narębski *et al.* (1986), Kryza *et al.* (1994) and Winchester *et al.* (1995). Bimodal magmatic associations of similar age are interpreted as an indication of tectonic settings of ensialic rifting throughout the European Variscides (Pin 1990) – e.g., in northwestern Iberia (Gil-Ibarguchi, Ortega-Girones 1985), in southern Massif Central and in Brittany in France (Bernard-Griffiths *et al.* 1986; Pin, Marini 1993 etc.) and also in West Sudetes of the Bohemian Massif (Furnes *et al.* 1994; Narębski 1994 etc.).

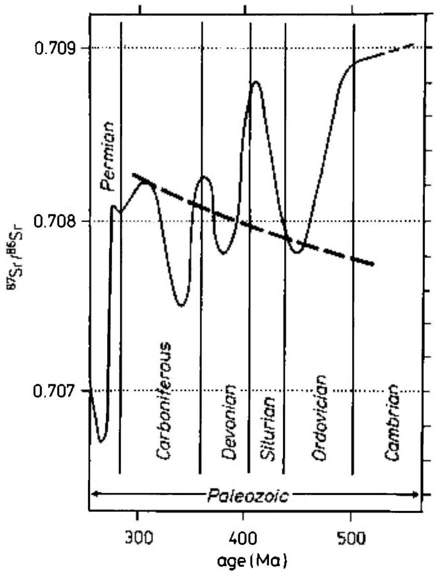

Fig. 6. A hypothetical single-stage evolution curve of the $^{87}Sr/^{86}Sr$ ratio calculated for the sample of the Ponikla Group marble (No. 8 in Table 1) *(dashed line)* shown together with the curve of fluctuations in the Sr isotope ratios in marine carbonates during the Paleozoic from Faure (1986) *(full line)*

The Ponikla Group marble specimen (fine grained homogeneous massive rock) shows quite different $^{87}Sr/^{86}Sr$ ratio relative to the porphyroid Sr values (Table 1). A hypothetical single-stage evolution curve of the Sr isotope composition in the marble was constructed and – provided that the marble precursor was sedimentary carbonate of marine origin – related to the curve of fluctuations in the Sr isotope ratios in marine carbonates during the Paleozoic after Faure (1986) (Fig. 6); here has to be pointed out that the evolution curve is based on merely single sample and that possible secondary disturbances and resettings of the marble Sr-isotope system are neglected in the following consideration. There are six intersects of both curves apparent in this diagram during the Cambrian-Carboniferous interval. The Rýchory Mts marble displays abundant relics of oolitic texture (Hladil, personal communication), which is – in the area of Central Europe – considered to be a specific feature of the Famennian to Tournaisian shallow-water limestones (e.g. Dvořák *et al.* 1986; Hladil *et al.* 1991, 1993). According to that, the intersects pointing to ages of 365 Ma ($^{87}Sr/^{86}Sr$ = 0.708099) and 350 Ma ($^{87}Sr/^{86}Sr$ = 0.708137) may be interpreted as the possible ages of sedimentation of the marble precursor.

CONCLUSIONS

The interpretation of the Rb-Sr isotope data on felsic and mafic metavolcanics (six samples of porphyroids and one greenschist specimen) of the Ponikla Group from the Rýchory Mts crystalline complex shows that magmatic precursors of these rocks can be members of bimodal volcanic association genetically related to continental lithosphere rifting. The resulting isochron slope indicates an age of the Rb-Sr system closure at 501 ± 8 Ma, i.e. the magmatic origin of the protolith can be dated to Early Ordovician.

The Rýchory Mts marbles often show relics of oolitic texture which is probably a specific feature of the Famennian to Tournaisian shallow-water limestones (e.g. Dvořák *et al.* 1986; Hladil *et al.* 1991; 1993). That is, two of the intersects of the hypothetical single-stage evolution curve of the Sr isotope composition in the marble specimen and the curve of fluctuations in the Sr isotope ratios in marine carbonates during the Paleozoic (Faure 1986), corresponding to ages 365 Ma and 350 Ma respectively, may indicate the possible ages of the marble sedimentary precursor.

As rift-related bimodal volcanic suites, dated to the earliest Paleozoic, are described from the whole Variscan Europe, the interpretation of the Rb-Sr isotope data on the Poniklá Group metavolcanics seem to support a large-scale fragmentation of the Gondwana supercontinent plate northern margin during Cambrian and Ordovician time (Ziegler 1989).

A tentative conclusion based on the Rb-Sr isotope data on both felsic-mafic metaigneous rocks and metamorphosed oolitic limestone of the Rýchory Mts is that the Poniklá Group is a metamorphosed volcano-sedimentary sequence formed in the time-span from the Early Ordovician to the Late Devonian/Early Carboniferous on a passive continental margin of some of the Gondwana plate rifted off fragments.

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