Geochemistry of the Late Devonian intermediate to acid metavolcanic rocks from the southern part of the Vrbno Group, the Jeseníky Mts. (Moravo-Silesian Belt, Bohemian Massif, Czech Republic): paleotectonic implications

František PATOČKA[1] *and Jiří VALENTA*[2]

[1] *Geological Institute, Academy of Sciences of Czech Republic, Rozvojová 135, 165 00 Praha 6 — Suchdol, Czech Republic*

[2] *Unigeo Ostrava, Geological Center Rýmařov, nám. Svobody 5, 795 01 Rýmařov, Czech Republic*

ABSTRACT: The alkaline intermediate to acid metavolcanic rocks of the southern part of the Vrbno Group (the Jeseníky Mts., Moravo-Silesian Belt) are interpreted as a within-plate trachyte-rhyolite suite metamorphosed to lower greenschist facies. Primary volcanics of the Late Devonian age were probably generated by the differentiation of basic melts geochemically comparable with tholeiitic to mildly alkaline within-plate basalts. The geochemical characteristics of the rocks studied are considered to indicate lithosphere extension and thinning of the Devonian structure transformed to the Moravo-Silesian Belt by the Variscan orogeny. Nevertheless, the subduction-related chemical features shown by some Devonian rocks of the Jeseníky Mts. presumably indicate an arc and back-arc (the latter initiated like an intracontinental rift) tectonic setting as the most probable for the emplacement of the primary volcanics.

KEY WORDS: trachytes and rhyolites, metavolcanic rocks, geochemistry, tectonic setting, Devonian, Bohemian Massif, Mid-European Variscides

Introduction

A substantial number of studies have been devoted to the geochemistry of the Devonian volcanic rocks of the Jeseníky Mts. during the last three decades, as they were identified as the host-rocks of several strata-bound base-metal massive sulfide deposits (e.g. Fojt 1965; Čabla et al., 1979; Pouba and Ilavský 1986). Early works, limited to major element geochemistry, regarded the Devonian volcanic rocks to be a spilite-keratophyre association (Tomšík 1959; Fojt 1962, 1966; Barth 1963, 1966; Pouba 1971; Fediuk et al. 1974; Scharm and Kühn 1975 etc.). However, subsequent trace element data interpreted the metabasites as equivalents of some modern basalt types — ocean-floor tholeiites, transitional types from ocean-island to continental tholeiites and alkaline within-plate basalts (Souček 1978a, 1981; Přichystal 1985; Jedlička and Pecina 1990) as well as island arc tholeiitic to calc-alkaline basalts (Čabla et al. 1979; Jakeš and Patočka 1982; Patočka 1987); the same authors chemically characterized the acid metavolcanics as calc-alkaline and alkaline igneous rocks. Major and minor element geochemistry of the association comprising alkaline intermediate to acid extrusive rocks, less frequent among the Jeseníky Mts. volcanics, was investigated by Patočka and Valenta (1990).

Geologic setting

The Devonian volcano-sedimentary sequence of the Jeseníky Mts., the Vrbno Group (Svoboda et al. 1966) (Fig. 1), is situated in the northern part of the Moravo-Silesian Belt. The Moravo-Silesian Belt (i.e. the eastern margin of the Bohemian Massif) is considered to be an equivalent of the Rhenohercynian Zone (Stille 1951; Engel et al. 1983; Franke 1989).

The Vrbno Group rocks were intricately folded and regionally metamorphosed to greenschist facies during the Sudetic phase of the Variscan orogeny. In the southern part the Vrbno Group is narrowed to ca. 3 km.

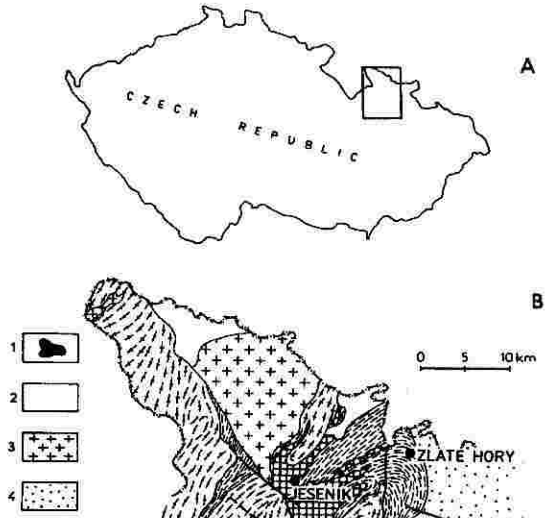

Fig. 1 A: Position of the Jeseníky Mts., Czech Republic. B: Geological map of the Jeseníky Mts.; rectangle marks the southern part of the Vrbno Group, i.e. the Horní Město region. 1 — Cenozoic volcanics, 2 — Cenozoic sediments, 3 — Variscan granites, 4 — Early Carboniferous sediments, 5 — Devonian volcano-sedimentary sequence, 6 — amphibolite bodies of Devonian age, 7 — pre-Devonian metamorphics.

This volcano-sedimentary sequence experienced three deformation phases distinguishing the Variscan orogeny in the whole Jeseníky Mts. region (Orel 1973; Rajlich 1974; Puda and Valenta 1984). The metamorphism of the Devonian rocks is very weak and may correspond to the chlorite zone (Souček 1978b).

In the Horní Město area, various types of muscovite schists are the dominant rocks in the Vrbno Group; graphite schists, quartzites and marbles are less abundant. Metakeratophyres and porphyroids are very frequent, whereas chlorite schists, spilites and other mafic metavolcanics are rare (Barth 1966; Fojt 1962, 1966). All rock types form strongly flattened and elongated bodies. Gradual transitions among metakeratophyres, porphyroids and muscovite schists are usual. The muscovite schists are presumably metamorphosed keratophyre tuffs intercalated with coarser grained pyroclastics, displaying well-preserved primary features of lapilli tuffs and agglomerates (Fojt 1962; Valenta et al. 1988).

The volcano-sedimentary sequence in the southern part of the Vrbno Group (approximately 250 m thick) represents one of the principal centres of the Devonian volcanism in the Moravo-Silesian Belt (Barth 1963). Abundant microfossils found in marble intercalations (Hladil 1986) indicate that a substantial part of the volcano-sedimentary sequence was formed between the end of Givetian and the latest Frasnian (Fig. 2). Barth (1966) suggested a shallow sea-floor environment for the keratophyre effusions although Puda and Valenta (1984) proved that subaerial volcanic activity was dominant over submarine in this area.

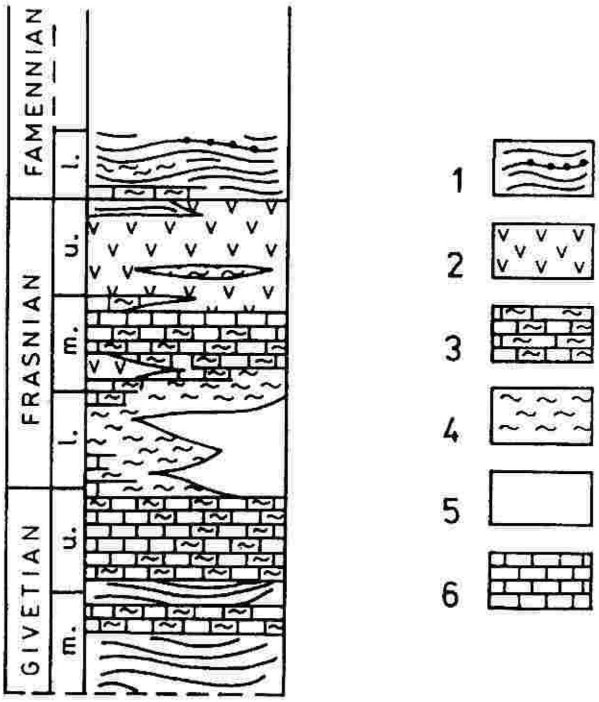

Fig. 2 Stratigraphy of the Vrbno Group Devonian volcano-sedimentary sequence in the Horní Město area (Valenta et al. 1988). 1 — calcareous graphitic schists locally containing chert intercalations, 2 — metabasites, 3 — muscovite-carbonate to carbonate-muscovite schists, 4 — metamorphosed pyroclastics of intermediate and acid volcanics, 5 — intermediate and acid metavolcanics (metatrachytes and metarhyolites), 6 — detrital and organodetrital marbles.

In the vicinity of Horní Město town a small stratabound massive sulfide deposit is situated. The deposit composes of several lens-shaped ore-bodies that conform to the host rocks (for the most part keratophyres and muscovite schists). Principal sulfides are pyrite, sphalerite and galena. A volcano-sedimentary origin of the ores is suggested (e.g. Čabla et al. 1979). The tonnage of the deposit is estimated as 9 kt Pb and 21 kt Zn (Vaněček et al. 1985).

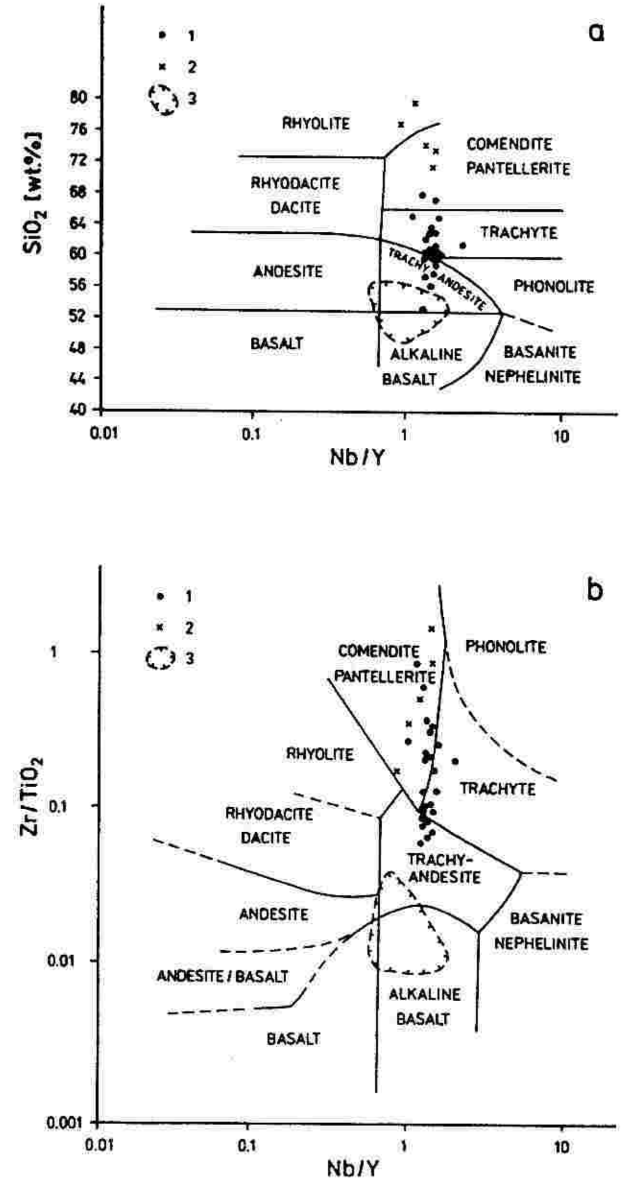

Fig. 3 Metatrachytes (1) and metarhyolites (2) from the southern part of the Vrbno Group in Nb/Y versus SiO_2 (a) and Nb/Y versus Zr/TiO_2 (b) diagrams after Winchester and Floyd (1977); field of nine metabasites from the middle part of the Devonian sequence (underlying the volcano-sedimentary unit comprising the metatrachytes and metarhyolites) is outlined (3).

Petrography

In the metakeratophyres and metakeratophyre tuffs the most abundant mineral components are albite and K-feldspar (in some cases also Na-orthoclase), forming both phenocrysts and rock groundmass. The latter, displaying a trachytic texture, contains also biotite, chlorite, quartz, stilpnomelane, muscovite and carbonate. The porphyroids (the term "metarhyolites" is further used according to SiO_2

content), and also related pyroclastics, comprise alkali feldspars and quartz as principal constituents. These minerals form phenocrysts as well as substantial part of groundmass, involving muscovite, chlorite, biotite and carbonate, too. The fluidal texture of the metakeratophyres and porphyroids often sustained a low-grade metamorphism; in the pyroclastics the primary textures are also preserved (Barth 1966; Fojt 1966). Considering an unique petrographic feature of the metakeratophyres, i.e. well preserved trachytic texture, Cháb (in Valenta et al. 1988) defined these rocks as metatrachytes. Detailed petrography of the metatrachyte and metarhyolite samples, described in this study, was published by Patočka and Valenta (1990).

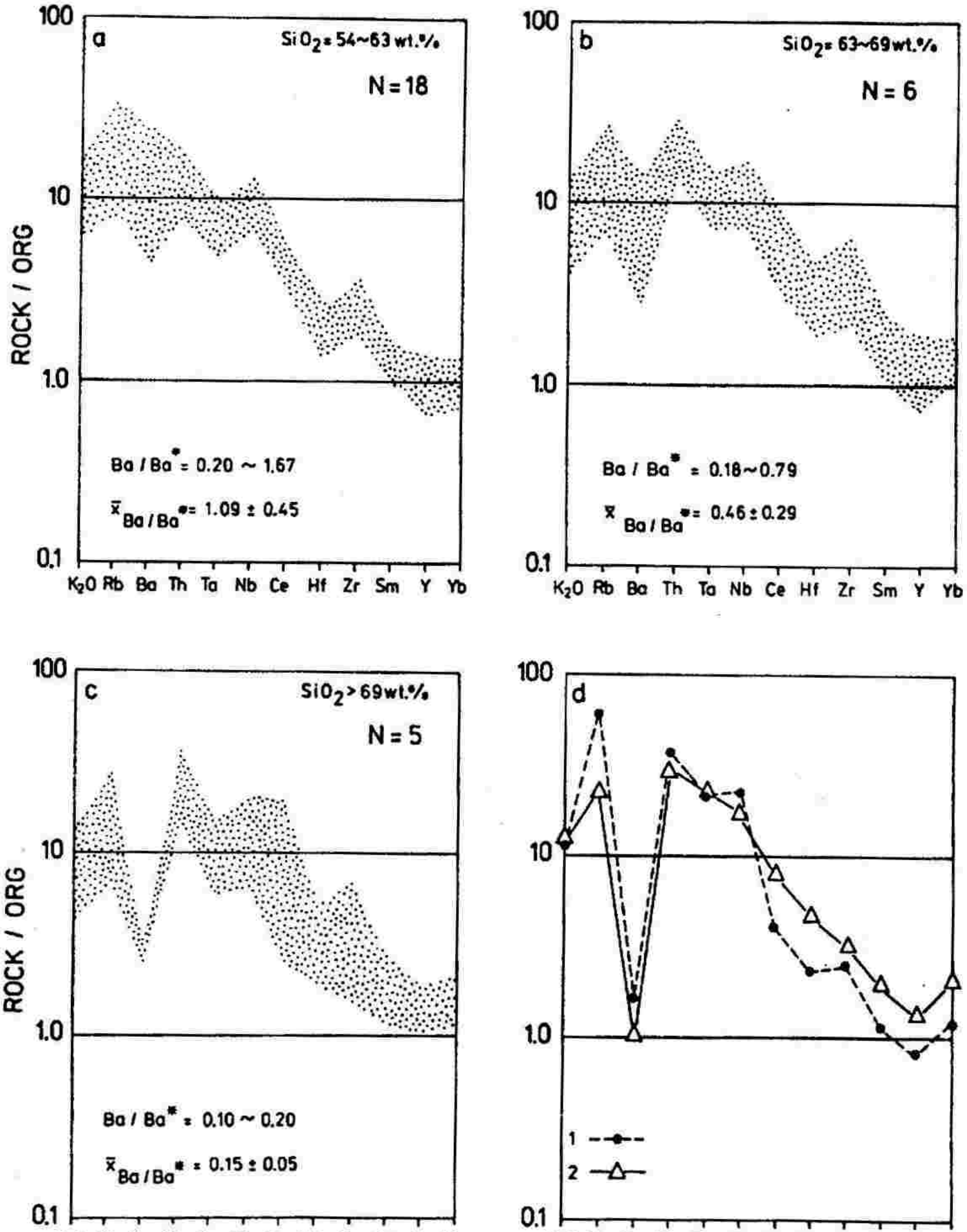

Fig. 4 a, b and c — ocean-ridge granite normalized trace element distributions in the intermediate metatrachytes (a), acid ones (b) and metarhyolites (c) of the Vrbno Group southern part; d — similarly normalized trace element distribution in the representative within-plate granitic rocks. 1 — Oslo Rift, 2 — Ascension Is. (Pearce et al. 1984). ORG-trace element abundances are taken from the same authors. Numbers of samples analysed as well as ranges of Ba/Ba* ratios (showing the rock depletion in Ba relative to other trace elements) and their arithmetic means are given in the figures.

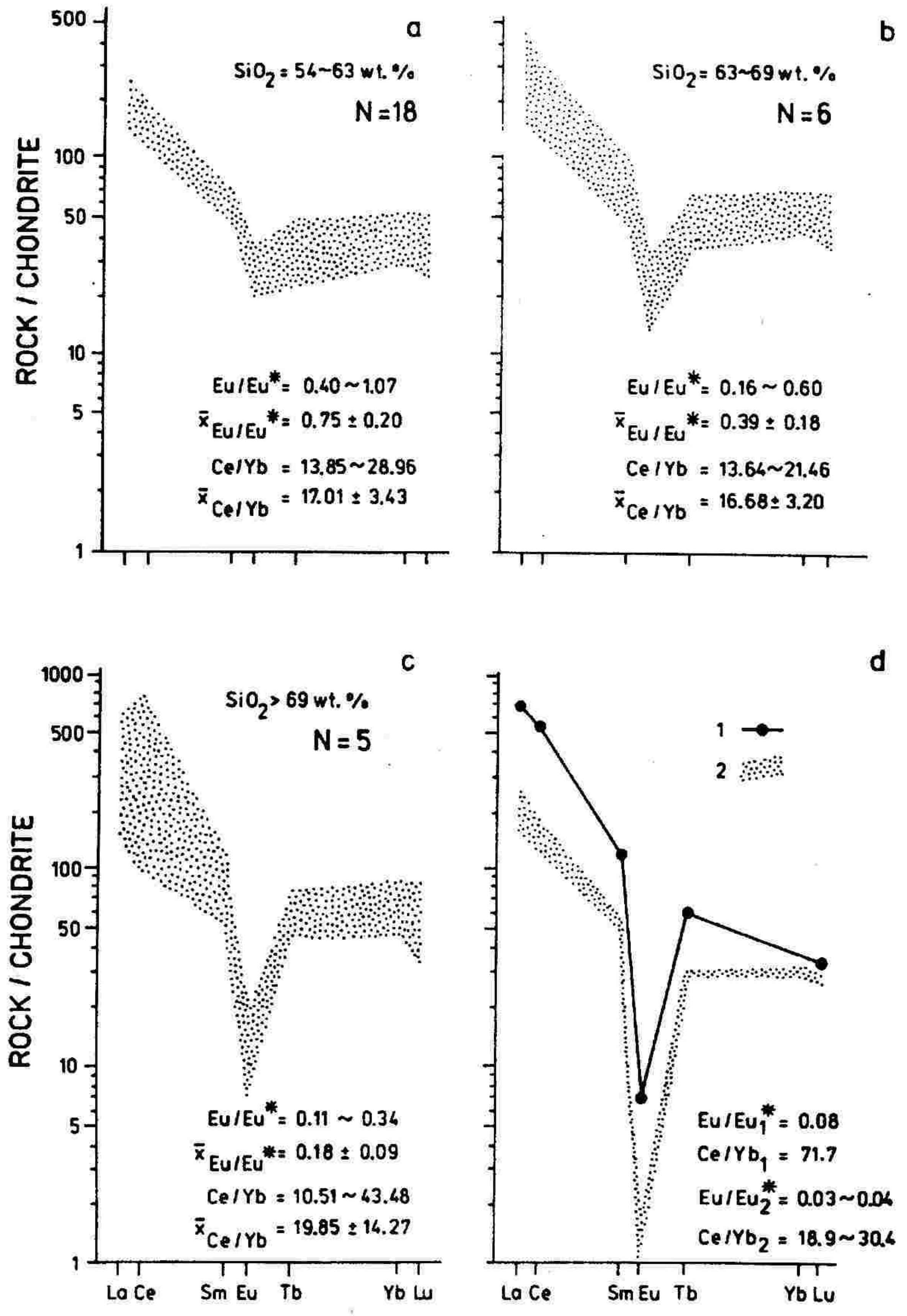

Fig. 5 a, b and c — chondrite normalized REE distributions in the intermediate metatrachytes (a), acid ones (b) and metarhyolites (c) of the Vrbno Group southern part; d — chondrite normalized lanthanide distributions in trachyte of the Gough Is. (1) (Zubatareva et al. 1979) and in rhyolites of the Sierra la Primavera, Mexico (2) (Mahood 1981). The Eu/Eu* ratio and Ce/Yb one ranges and arithmetic means as well as numbers of samples analysed are given in the figures. Chondrite REE values are taken from Herrmann (1970).

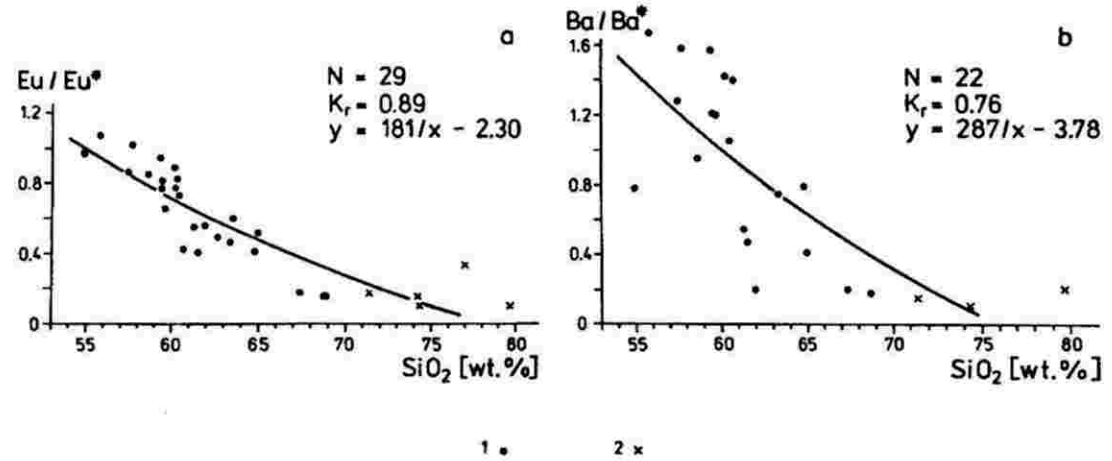

Fig. 6 Relationships of the SiO_2 content versus negative Eu-anomaly (a) and Ba-depletion (b) (cf. Figs 4 and 5) in the intermediate to acid metavolcanics of the Vrbno Group southern part. Correlation coefficients and corresponding regression curve equations are presented in the figures. 1 — metatrachytes, 2 — metarhyolites.

Analytical methods

The samples of the Devonian metatrachytes and metarhyolites were taken from the single deep borehole, situated ca. 4 km to NE from Horní Město town. All samples were analyzed for major and trace element abundances (Table 1). Major element concentrations were determined in the laboratories of the Unigeo, Ostrava (analysts Ing. S. Holubová, J. Mrlíková and J. Koutná) using wet chemical analysis. Trace element abundances were established by X-ray fluorescence analysis in the same laboratories (analysts L. Janáčková and co-workers). Analyses of rare earth elements were prepared by neutron activation in the Central laboratories of the Geoindustria, Praha (analysts Ing. J. Moučka and co-workers).

Geochemistry

Major elements

The studied metavolcanics display a wide variation of the SiO_2 abundances (54 to 80 wt.%). The majority of the samples can be classified as intermediate to moderately acid rocks; the boundary between petrographically defined metatrachytes and metarhyolites is 69 wt.% SiO_2. The whole sample set is divided into intermediate metatrachytes (54 to 63 wt.% SiO_2), acidic metatrachytes (63 to 69 wt.% SiO_2) and metarhyolites (SiO_2 over 69 wt.%) (Table 1, Fig. 3a). Analogous variability characterize alkali abundances as well as K_2O/Na_2O ratios. In the most of the samples alkali ratios vary from 0.25 to 2.00; two metarhyolite samples show extremely high values — 15.33 and 16.00 (Table 1).

As it is demonstrated by Nb/Y vs SiO_2 diagram by Winchester and Floyd (1977) (Fig. 3a) the alkaline types dominate among the metatrachytes and metarhyolites. Most of the rocks investigated are specified there as equivalents of trachyandesites and trachytes; types corresponding to pantellerites, comendites and rhyolites are less frequent. However, in a Nb/Y vs Zr/TiO_2 plot (Fig. 3b) after the same authors all samples studied are situated in fields of alkaline volcanics. Alkaline nature of the Horní Město metavolcanics was described by Fojt (1962, 1966).

Trace elements

The trace element concentrations in the intermediate and acid metatrachytes, and in the metarhyolites — normalized to ocean-ridge granite composition (Pearce et al. 1984) — are shown in Figs 4a, b and c. A close mutual similarity of these three types of metavolcanics in the relative abundances of the trace elements, employed in the spidergram (with the single exception of Ba), is evident.

The metavolcanic rocks are characterized by high contents of REE (of LREE especially) (Figs 5a, b and c). Both intermediate and acid metatrachytes display approximately the same degree of LREE fractionation, as expressed by close average values of the Ce/Yb ratio (Figs. 5a and b, Table 1). On the other hand, the acidic metatrachytes are distinguished by a prominent negative Eu-anomaly (Fig. 5b, Table 1). A wider variation of LREE contents is the specific feature of the metarhyolites as well as striking negative anomaly of Eu (Fig. 5c). A negative correlation between the SiO_2 concentrations and Eu-anomaly values is evident in the sample set investigated (Fig. 6a). In these rocks the same relation exists also between the silica content and the depletion of Ba, when expressed as the Ba/Ba* ratio (Fig. 6b).

Discussion

Secondary changes in the rock composition

The chemical composition of the metavolcanics studied was presumably not fundamentally changed by secondary processes — either hydrothermal activity (during the Horní Město massive sulfide deposit origin) or subsequent low-grade regional metamorphism of the Sudetic phase; low abundances of CO_2 and H_2O in the rocks seem to support this suggestion (Table 1). Also, although scattered, the metatrachytes and metarhyolites mostly occupy the low temperature troughs in the triangular CIPW-norm diagrams Q-Ab-Or and An-Ab-Or (Fig. 7a, b); this can be interpreted as possible indicator of generally preserved primary magmatic composition.

Nevertheless, in several samples the alkali contents were altered. The values $K_2O/Na_2O > 1.0$ point to either Na-depletion or K-enrichment in some rocks; in samples showing substantially reduced Na_2O abundance the Na-loss compensated by increment of K can be presumed (Table 1).

The presumed primary pantellerite-comendite composition of some metarhyolite samples was probably transformed to rhyolitic one by silicification — as their positions in Nb/Y vs SiO_2 and Nb/Y vs Zr/TiO_2 diagrams suggest (Figs. 3a and b). This process seems to be evidenced by the metarhyolite sample shift towards the Q-apex in the Q-Ab-Or diagram (Fig. 7a).

The alkali abundance changes in the Horní Město metavolcanics were probably associated with rock- hydrothermal solution interaction, involving feldspar decomposition to K-retaining sericite and clay minerals. Silicification of these rocks seems to be linked to the same process. Both silicification and alkali content alterations are well known in volcanic rocks from the surroundings of massive sulfide deposits (Tatsumi and Clark 1972; Ijima 1974; Gibson et al. 1983 etc.). In the Jeseníky Mts., the alterations of Devonian intermediate to acid metavolcanics have been described by Fojt (1962, 1966), Fediuk et al. (1974), Barth (1963, 1966, 1977) and Valenta et al. (1988).

The alterations mentioned above also refer to LIL-element concentrations — especially Rb and Ba (Ludden et al. 1982 etc.). Most of the Horní Město metavolcanics also display almost the same extent of K and Rb abundance variations (Figs 4a, b and c). Nevertheless, in these rocks the concentrations of Ba presumably resemble the primary ones, as the correlation between the progressive Ba-depletion and the growing silica content indicates (Figs. 4a-c and 6b).

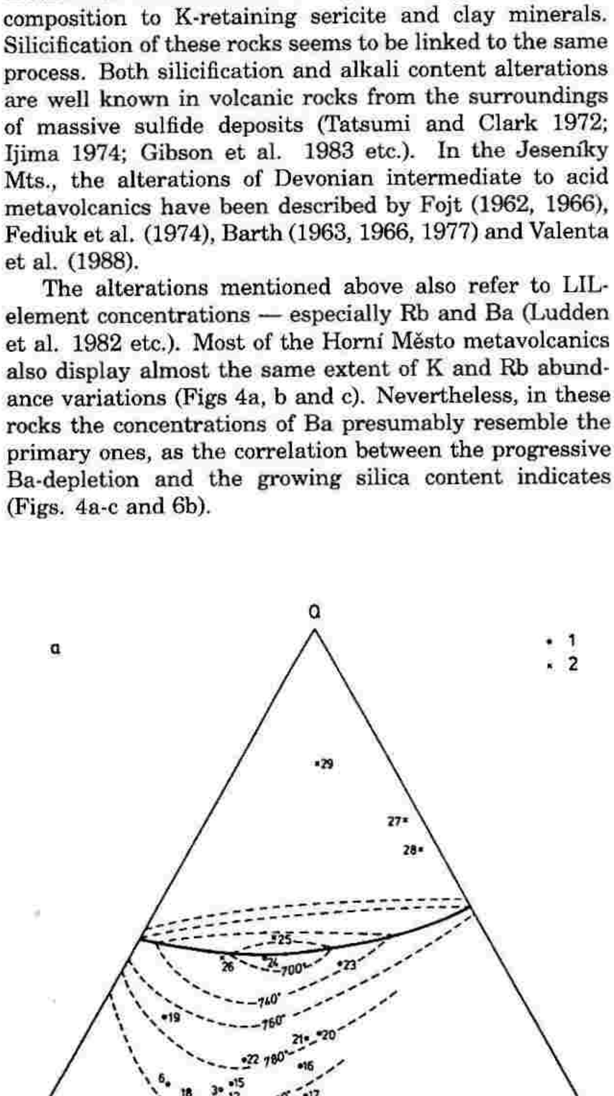

Fig. 7 The intermediate to acid metavolcanic rocks from the Vrbno Group in the C.I.P.W. normative triangular diagrams Q-Ab-Or (a) and An-Ab-Or (b). Cotectic lines and isotherms for 2 Kb (a) and 5 Kb (b) after Tuttle and Bowen (1958). 1 — metatrachytes, 2 — metarhyolites.

Magmatic development

The common features of the ORG-normalized trace element distribution patterns, shown by the studied metavolcanics, i.e. approximately equal Rb, Th, Ta and Nb values, general increment of Yb to Rb values (substantial from Yb to Nb and moderate from Nb to Rb) and sizable Ba-depletion in the acid rocks, are the signature of alkaline within-plate granites (Pearce et al. 1984) (Fig. 4). The affinity of the metavolcanics to alkaline igneous rocks, shown by Nb/Y vs SiO_2 and Nb/Y vs Zr/TiO_2 diagrams (Fig. 3), is also documented by the chondrite-normalized REE distribution patterns (Fig. 5).

The co-magmatic origin of the primary effusives is suggested by almost identical variation ranges of the Ce/Yb ratios of the three types distinguished among the studied metavolcanics (with exception of the single metarhyolite sample) (Figs 5a, b and c and Table 1). This assumption is supported by good negative correlations between the SiO_2 contents and the values of Eu-anomaly and Ba-depletion respectively (Fig. 6), since both features indicate an effect of Ca-plagioclase and K-feldspar fractional crystallization from a common parental melt (e.g. Hanson 1978).

In Fig. 8a the minor element compositions of the Horní Město metavolcanics are displayed as the double-normalized values after Thompson (1982). The most conspicuous characteristics of the distribution patterns presented are prominent "negative anomalies" of Ba, Sr, P and Ti and less pronounced depletion in K and Sm. Good negative correlations between the SiO_2 abundances and Sr- and Ti-depletion, expressed as Sr/Sr^* and Ti/Ti^* ratios in the sample set studied, were demonstrated by Patočka and Valenta (1990). Following that, it can be assumed that beside Ca-plagioclase and K-feldspar also apatite and Fe-Ti-oxide were involved in the residual mineral assemblage formed during the fractional crystallization of the metavolcanics protolith primary melt.

The same fractional crystallization process probably participated in the petrogenesis of intermediate to acid rock suites occurring in Continental Flood Basalt provinces (e.g. Bellieni et al. 1984; Mantovani et al. 1985; Lightfoot et al. 1987). The Deccan Trap trachytes and rhyolites show almost identical geochemical features to the Horní Město metatrachytes and metarhyolites. According to the last named authors the chemical composition of the intermediate to acid Deccan Trap volcanics is different to that of typical crustal melts; the origin by low-volume partial melting of basalt followed by variable amounts of fractional crystallization is proposed for these rocks. The role of partial melting is supported by the presence of a wide silica gap dividing the Deccan Trap basalts from the local trachytes and rhyolites (Lightfoot et al. l.c.).

An analogous mechanism could be postulated for the origin of the Horní Město metavolcanics protolith, but, since there does not exist any significant gap in SiO_2 content between the metabasites and intermediate metavolcanic rocks (e.g. Barth 1977), only fractional crystallization from the basaltic melt can be presumed.

The above mentioned double-normalization (Fig. 8) virtually eliminates the scattering effect of fractional crystallization of varying amounts of olivine, plagioclase and clinopyroxene from the parental basic magma (Thompson 1982). That is, the parental melt type of a differentiate can be estimated from the resulting spidergram. For this purpose the normalized averages of the metatrachyte and metarhyolite trace element compositions are plotted in Fig 8a (values of the "negative anomalies"-forming elements are extrapolated in both average distribution patterns).

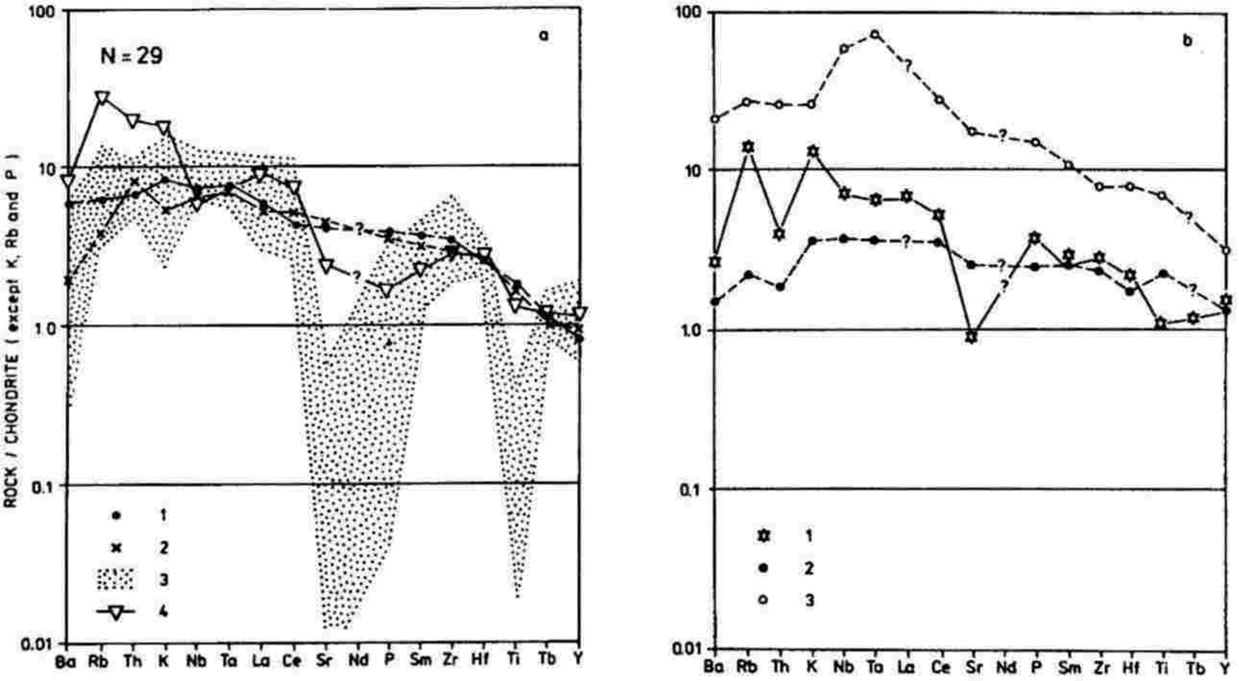

Fig. 8 a: composition of the intermediate to acid metavolcanics from the Vrbno Group southern part, normalized to chondrite composition (except Rb, K and P, normalized to primitive mantle values) and to Yb_N after Thompson (1982); 1 — metatrachyte average, 2 — metarhyolite average (Ba, Sr, P, Sm and Ti values are extrapolated in both average patterns), 3 — envelope common to both metatrachytes and metarhyolites, 4 — similarly normalized compositions of the upper continental crust (Taylor and McLennan 1985); b: 1 — average of nine metabasites of the Devonian sequence middle part (underlying the volcano-sedimentary unit comprising the metatrachytes and metarhyolites studied), 2 — tholeiitic within-plate basalt, 3 — alkaline within-plate basalt (Pearce 1982).

When compared with the upper continental crust average (Taylor and McLennan 1985) the metavolcanics differ substantially — in lower contents of Ba, Rb, Th, K, La and Ce as well as in lack of both Nb-depletion and high Th/La ratio, generally characterizing the upper crust of continents (Dupuy and Dostal 1984). The metatrachyte and metarhyolite trace element patterns resemble these of the within-plate basalts after Pearce (1982) (Fig. 8b) in the slightly upward curved shape peaking where K, Nb, Ta and La are plotted. As the overall flat shape of the patterns and low normalized trace element values indicate, the studied metavolcanics can be compared with tholeiitic and/or mildly alkaline within-plate basalts with regard to relative abundances of trace element contents (provided that the depletions in Ba, K, Sr, P, Sm and Ti are neglected) (Fig. 8a). Also the most conspicuous feature of both metatrachyte and metarhyolite ORG-normalized trace element patterns — the proximity of the normalized abundances of Rb, Th, Ta and Nb (Figs 4a, b and c) — is the signature of within-plate basalt differentiate (Pearce et al. 1984).

The metabasites, analogous in geochemistry to within-plate basalts, are well known from the Vrbno Group Devonian (e.g. Patočka 1987; Jedlička and Pecina 1990). Metamorphosed basic rocks were found also in the Horní Město area, in the midst of the Devonian sequence underlying the studied volcano-sedimentary unit (Puda and Valenta 1984). These mafic rocks show double-normalized element distribution (Thompson 1982) resembling that of tholeiitic within plate basalt, provided that the most mobile element (Rb, K and Sr) values are neglected (Fig. 8b) (Valenta et al. 1988). In the Nb/Y vs SiO_2 and Nb/Y vs Zr/TiO_2 diagrams (Fig. 3) the metabasites occupy the position of alkaline basalts to trachyandesites and seem to be associated with differentiation trends of the studied metatrachyte-metarhyolite suite. It is suggested that the primary melt of the metabasite protolith could be considered also as the parental magma of the protolith of the metatrachytes and metarhyolites.

Paleotectonic implications

Within-plate magmatism is regarded as a prominent indicator of lithosphere extension and thinning (McKenzie 1978; Houseman and England 1986; Kusznir and Ziegler 1992 etc.). It is widely accepted that continental lithosphere extension provides a suitable regime for the generation of both basic and acid within-plate magmas (e.g. Keen 1987; Lightfoot et al. 1987; McKenzie and Bickle 1988).

As suggested above, the Horní Město metatrachyte and metarhyolite protolith melt probably evolved from the basaltic magma in composition resembling tholeiitic to mildly alkaline WPB. The upper mantle derived magmas cannot be formed below the thick continental lithosphere since they are seggregated and equilibrated at depths around 35 km (Ringwood 1975; Lavecchia and Stoppa 1990; Liu and Chase 1991 etc.). During the generation of the basaltic melts below the modern rift zones the overlying lithosphere is virtually thinned to the crust (e.g. Zorin and Lepina 1985); the upper astenosphere extracted melts rise diapirically to underplate the base of the continental crust (Kusznir and Ziegler 1992). Barth (1977) presumed "thinning of the Jeseníky Mts. block crust" in Devonian; his hypothesis was based on the prevalence of the silica-undersaturated Devonian volcanics in this region. The extensional tectonics and development of rift valleys are assumed as the principal events of the Devonian history of the Moravo-Silesian Belt northern part by Cháb et al. (1980) and Přichystal (1985, 1993).

The Moravo-Silesian Belt is the eastern representative of the Rhenohercynian Zone (e.g. Engel et al. 1983) where the Devonian lithospheric extension is indicated — in Cornwall, in the Rheinisches Schiefergebirge Mts. and in the Harz Mts. In these areas as well as in the nearby Polish Sudetes the extension might proceeded locally into opening of limited ocean basins (e.g. Pin et al. 1988; Neugebauer 1989; Narebski 1994). Paleontologically defined sedimentation time-span of carbonate interacalations within the studied volcano-sedimentary sequence, ranging from the end of Givetian to the latest Frasnian (Hladil 1986), corresponds very well to the Sm-Nd age of 375±34 Ma determined for formation of the Lizard Complex ophiolitic rocks by Davies (1984). The MORB-like basalts from the southern Rheinisches Schiefergebirge Mts. are probably of the late Middle Devonian age (Grösser and Dörr 1986). At least some of the Sudetic ophiolites were formed during the extensional regime that existed there between the Middle Devonian (ca. 385 Ma) and Early Namurian (Wajsprych 1986; Narebski et al. 1988; Pin et al. 1988; Narebski 1994).

The geochemistry of the Horní Město intermediate to acid metavolcanics indicates that the tectonic setting of the substantially thinned continental lithosphere probably existed at least in some parts of the Moravo-Silesian Belt between the latest Middle Devonian and middle Late Devonian (e.g. Přichystal 1993).

Nevertheless, some of the Jeseníky Mts. Devonian rocks provide evidence for an origin at an active plate-margin; the geochemical features of island-arc tholeiitic to low-K calc-alkaline basalts was identified in the metabasites of the Vrbno Group northern part (Fišera et al. 1973; Čabla et al. 1979; Jakeš and Patočka 1982; Patočka 1987). Minor element geochemistry of the pelitic schists exposed in this area also appears to indicate similarity between the source region of the sedimentary precursors and an ensialic island-arc (Patočka 1992).

These tectonic setting indicators suggest that for some time the northern part of the Moravo-Silesian Belt was a convergent plate-boundary, as supposed earlier — e.g. by Čabla et al. (1979). Further evidences of the compressional tectonic environment are an ophiolite geochemistry of both of the Devonian basic-ultrabasic bodies of the Jeseníky Mts. (Jelínek and Souček 1981) and Alaskan type intrusions distributed along the boundary of the Moravo-Silesian Belt and the West Sudetes (Narebski 1994). Sawkins and Burke (1980) postulated an island-arc type complex at the southern margin of the mid-European zone of crustal extension, which developed later into the Rhenohercynian Zone. The geochemistry of some Rhenohercynian basalts, largely Middle to Late Devonian in age (Cabanis et al. 1982; Wedepohl et al. 1983; Floyd 1984 etc.), as well as that of metabasites from the Polish Sudetes (e.g. Dzedzicowa 1979; Narebski et al. 1988; Pin et al. 1988), are very similar to MORB composition, points to that the extension was not limited to mere intracontinental rifts (Pin 1990; Narebski 1994). A Devonian back-arc basin linked to hypothetical southeastward subduction of the Sudetic ocean is presumed in the NE part of the Bohemian Massif (Wajsprych 1986; Pin et al. 1988).

It is probable that the Horní Město metatrachyte to metarhyolite protolith was emplaced in a complex Devonian structure, in a tectonic setting comparable to modern arc and back-arc (the latter evolved from ensialic rift), which was transformed to the Moravo-Silesian Belt during the Variscan orogeny. This structure was characterized — beside the above mentioned features of the destructive plate-margin — both by extensional tectonics (cf. Pin 1990) and by within-plate magmatism (cf. Richards et al. 1990 etc.).

Conclusion

The Late Devonian metatrachytes and metarhyolites, abundant in the volcano-sedimentary sequence of the southern part of the Vrbno Group, were possibly not substantially altered in chemical composition during the origin of the associated massive sulfide deposit (Horní Město) and/or low-grade Sudetic phase regional metamorphism. The geochemistry indicate that the trachyte-rhyolite association was co-magmatic and evolved through the fractional crystallization of Ca-plagioclase, K-feldspar, apatite and Fe-Ti-oxide from a common basic parental melt. The protolith magmas are different to typical upper crustal melts (lower contents of Ba, Rb, Th, K, La and Ce, lack of both Ta- and Nb-depletion, and high Th/La ratio) and strongly resemble within-plate granites. These melts were presumably derived from parental basic magma comparable with tholeiitic to mildly alkaline within-plate basalts.

The geochemical features of the rocks studied seem to provide evidence for lithosphere extension and thinning in the Devonian structure transformed later on (during the Variscan orogeny) to the Moravo-Silesian Belt. Consideration of paleotologically determined age of the marble intercalations (the end of Givetian to the latest Frasnian) within the volcano-sedimentary complex indicate that these processes were contemporaneous with the extensional tectonics in the Rhenohercynian Zone and Polish Sudetes.

However, the subduction-related geochemistry of some Jeseníky Mts. Devonian metabasites and sediments as well as the ophiolite affinity, shown by basic-ultrabasic bodies, and presence of the Alaskan type intrusions, point to more complex tectonic setting of the metatrachyte-metarhyolite protolith emplacement. With regard to the characteristics of all rock types mentioned, the arc and back-arc (developed from intracontinental rift) geodynamic setting is suggested.

Acknowledgements

The authors are indebted to Dr. Peter A. Floyd, University of Keele, Keele, Staffordshire, United Kingdom, and Dr. Jan Cháb, Czech Geological Survey, Prague, Czech Republic, for their criticizm. We thank also to to Ms. Jana Rajlichová, Mr. Josef Brožek and Mr. Josef Forman, Geological Institute, Academy of Sciences of Czech Republic, for preparation of drawings.

References

BARTH V. 1963. Variscan geosynclinal volcanism in the Hrubý and Nízký Jeseník Mts. and its relation to tectonics (in Czech). *Sborník Prací University Palackého, Geografie — Geologie*, 10, 5-117.

BARTH V. 1966. The initial volcanism in the Devonian of Moravia. *In: Paleovolcanites of the Bohemian Massif*. Geological Survey, Prague, 115-125.

BARTH V. 1977. On the chemical development of Variscan magmatism in the Bohemian Massif northeastern part (in Czech). *Acta Universitas Palackienae Olomucensis, Geographica — Geologica*, 16, 31-52.

BELLIENI G., BROTZU P., COMIN-CHIARMONTI P., ERNESTO M., PACCA I.G. and PICCIRILLO E.M. 1984. Flood Basalt to Rhyolite Suites in the Southern Paraná Plateau (Brazil): Palaeomagnetism, Petrogenesis and Geodynamic Implications. *Journal of Petrology*, 25, 579-618.

CABANIS B., CHANTRAINE J., HERROUIN Y. and TREUIL M. 1982. Etude géochimique (majeurs et traces) des spilites et dolérites de Bolazec. Mise en évidence d'un domaine en distension crustale au Dévonien inférieur en Bretagne centre-ouest. *Bulletin du BRGM*, 2, (I), 47-61.

ČABLA V., HETTLER J. and TOMŠÍK J. 1979. Ore deposits of the Zlaté Hory ore district from viewpoint of the plate tectonics theory (in Czech). *Sborník GPO*, 20, 12, 5-69.

CHÁB J., FIŠERA M. and SKÁCELOVÁ D. 1980. The Moravian Paleozoic — a rift model (in Czech). *In: Proceedings of the 2nd International Scientific Conference, Sect. 11 — Basic and Applied Geophysics*. School of Mining, Ostrava, 9.

DAVIES G.R. 1984. Isotopic evolution of the Lizard complex. *Journal of the Geologal Society, London*, 141, 3-14.

DUPUY C. and DOSTAL J. 1984. Trace element geochemistry of some continental tholeiites. *Earth Planetary Science Letters*, 67, 61-69.

DZIEDZICOWA H. 1979. Problem of origin of basaltic magmas nad their connection with Niemcza zone ultrabasites: proposed model of geotectonic regime. *In* GUNIA, A. (ed.): *The selected problems of stratigraphy, petrography and tectonics of the region E of Sowie Góry*. Wroclaw University, 107-120.

ENGEL W., FRANKE W. and LANGENSTRASSEN F. 1983. Paleozoic sedimentation in the northern branch of the Mid-European Variscides — essay of an interpretation. *In*: MARTIN, K.H. and EDER, F.W. (eds) *Intracontinental Fold Belts*. Springer, Berlin — Heidelberg — New York. 9-41.

FEDIUK F., POUBA Z. and RENÉ M. 1974. The origin of siliceous rocks of the Hrubý Jeseník Mts (in Czech). *Acta Universitatis Carolinae, Geologica*, 3, 203-230.

FIŠERA M., JAKEŠ P., POUBOVÁ M. and ŠVENEK M. 1973. Petrographic-geologic study on the basic volcanics of the Zlaté Hory ore district, Jeseníky Mts. (in Czech). — *Unpublished report of the National Museum*, Praha.

FLOYD P.A. 1984. Geochemical characteristics and comparison of the basic rocks of the Lizard complex and the basic lavas within the Hercynian troughs of SW England. *Journal of the Geological Society, London*, 141, 61-70.

FOJT B. 1962. Petrographic characteristics of the kies and base metal ore deposits at Horní Město region (in Czech). *Práce Brněnské Základny Československé Akademie Věd*, 34, 385-444.

FOJT B. 1965. Über einige genetische Probleme der Kieslagerstätten am östlichen Rand des Silesiums in ČSSR. *Freiberger Forschriften der H.R.C.*, 186, 105-113.

FOJT B. 1966. Keratophyre rocks of the kies deposits in the Jeseníky Mts. area. *In: Paleovolcanites of the Bohemian Massif*. Geological Survey, Prague, 107-114.

FRANKE W. 1989. Variscan plate tectonics in Central Europe — current ideas and open questions. *Tectonophysics*, 169, 221-228.

GIBSON H.L., WATKINSON D.H. and COMBA C.D.A. 1983. Silicification: hydrothermal alteration in an Archean goethermal system within the Amulet Rhyolite formation, Noranda, Quebec. *Economic Geology*, 78, 954-971.

GRÖSSER J. and DÖRR W. 1986. MOR-Typ-Basalte im östlichen Rheinischen Schiefergebirge. *Neues Jahrbuch der Geologie Paläontologie, Monatshefte*, 12, 705-722.

HANSON G.N. 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planetary Science Letters*, 38, 26-43.

HERRMANN A.G. 1970. Yttrium and lanthanides: abundances in cosmos, meteorites, tektites and lunar specimens. *In*: WEDEPOHL, K.H. (ed.) *Handbook of geochemistry*, — 39, 57-71-C-1-10. Springer. Berlin — Heidelberg — New York.

HLADIL J. 1986. Preliminary report on microfacies and age of carbonate intercalations in the Janovice-Ruda borehole (the Vrbno Group, Nízký Jeseník Mts.) (in Czech). *Zprávy o geologických výzkumech v r. 1984*, 76-77.

HOUSEMAN G. and ENGLAND P. 1986. A dynamic model of continental extension and sedimentary basin formation. *Journal of Geophysical Research*, 91, B1719-B1729.

IJIMA A. 1974. Clay and zeolite alteration zones surrounding Kuroko deposits in the Hokuroku district, northern Akita, as submarine hydrothermal diagenetic products. *In*: ISHIHARA, S. (ed.) *Geology of Kuroko Deposits*. Society of Mineralogy and Geology of Japan Special Issue, Tokyo, 267-290. 6.

JAKEŠ P. and PATOČKA F. 1982. Compositional variations of the Devonian volcanic rocks of the Jeseníky Mts. *Věstník Ústředního ústavu geologického*, 57, 4, 193-204.

JEDLIČKA J. and PECINA V. 1990. Chemism of the metabasites from Suchá Rudná, Vrbno Group, Hrubý Jeseník Mts. (in Czech). *Věstník Ústředního ústavu geologického*, 65, 5, 301-313.

JELÍNEK E. and SOUČEK J. 1981. Geochemistry of the Jeseník and Sobotín amphibolite bodies. *Acta Universitatis Carolina, Geologica*, Hejtman Vol., 4, 379-411.

KEEN C.E. 1987. Some important consequences of lithospheric extension. *Tectonics*, 73, 28-57.

LAVECCHIA G. and STOPPA F. 1990. The Tyrrhenian zone: a case of lithosphere extension control of intracontinental magmatism. *Earth Planetary Science Letters*, 99, 336-350.

LIGHTFOOT P.C., HAWKESWORTH C.J. and SETHNA S.T. 1987. Petrogenesis of rhyolites and trachytes from the Deccan Trap: Sr, Nd isotope and trace element evidence. *Contributions to Mineralogy and Petrology*, 95, 44-54.

LIU M. and CHASE C.G. 1991. Evolution of Hawaiian basalts: a hotspot melting model. *Earth Planetary Science Letters*, 104, 151-165.

LUDDEN J.M., GÉLINAS L. and TRUDEL P. 1982. Archean metavolcanics from the Rouyn-Noranda district, Abitibi Greenstone Belt, Quebec. 2. Mobility of trace elements and petrogenetic constraints. *Canadian Journal of Earth Sciences*, 19, 2276-2287.

MAHOOD G.A. 1981. Chemical evolution of a Pleistocene rhyolitic center: Sierra la Primavera, Jalisco, Mexico. *Contributions to Mineralogy and Petrology*, 77, 129-171.

MANTOVANI M.S.M., MARQUES L.S., De SOUSA M.A., CIVETTA L., ATALIA L. and INNOCENTI F. 1985. Trace element and strontium isotope constraints on the origin and evolution of Paraná continental flood basalts of Santa Catarina State (Southern Brazil). *Journal of Petrology*, 26, 187-209.

McKENZIE D.P. 1978. Some remarks on the development of sedimentary basins. *Earth Planetary Science Letters*, 40. 25-32.

McKENZIE D.P. and BICKLE M.J. 1988. The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology*, 29, 625-679.

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

NAREBSKI W., WOJCIECHOWSKA I. and DOSTAL J. 1988. Initial rifting volcanics in the Klodzko Metamorphic Complex (Polish Middle Sudetes), evidenced by geochemical data. *Bulletin of Polish Academy of Sciences, Earth Sciences*, 36, 261-269.

NEUGEBAUER J. 1989. The Iapetus model: a plate tectonic concept for the Variscan belt of Europe. *Tectonophysics*, 169, 229-256.

OREL P. 1973. Tectonic and structural problems related to mineralization processes in the Paleozoic of the Jeseníky Mts. block (Bohemian Massif) (in Czech). *Unpublished Ph.D. Thesis*, Faculty of Natural Sciences, Charles University, Prague.

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

PATOČKA F. 1992. Minor element geochemistry of of pelitic schists of the Zlaté Hory ore district, the Jeseníky Mts.: Devonian tectonic setting of the primary sediment provenance. *In*: KUKAL, Z. (ed.) *Proceedings of the 1st International Conference on the Bohemian Massif, 1988*. Geological Survey, Prague, 218-221.

PATOČKA F. and VALENTA J. 1990. Geochemistry of metatrachytes and metarhyolites from the southern part of the Devonian Vrbno Group in the Horní Město area and tectonic setting of the origin of the metavolcanics protolith (in Czech). *Časopis pro Mineralogii a Geologii*, 35, 41-64.

PEARCE J.A. 1982. Trace element characteristics of lavas from destructive plate boundaries. *In*: THORPE, R.S. (ed.) *Andesites: Orogenic Andesites and Related Rocks*. Wiley and Sons, Chichester — New York — Toronto, 526-548.

PEARCE J.A., HARRIS N.B.W. and TINDLE A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25, 956-983.

PIN CH. 1990. Variscan oceans: Ages, origins and geodynamic implications inferred from geochemical and radiometric data. *Tectonophysics*, 177, 215-227.

PIN CH., MAJEROWICZ A. and WOJCIECHOWSKA I. 1988. Upper Paleozoic oceanic crust in the Polish Sudetes: Nd-Sr isotopic and trace element evidence. *Lithos*, 21, 195-209.

POUBA Z. 1971. Relation between iron and copper-lead-zinc mineralization in submarine volcanic ore deposits in the Jeseníky Mts., Czechoslovakia. *In: Proceeding of the IMA-IAGOD Meetings 1970. Special Issue of The Society of Mining Geology of Japan*, No. 3, 186-192.

POUBA Z. and ILAVSKÝ J. 1986. Mineral deposits of the Bohemian Massif. *In*: DUNNING, F.M. and EVANS, A.M. (eds) *Mineral Deposits of Europe. Vol. 3: Central Europe. Czechoslovakia.* The Institute of Mining and Metallurgy and The Mineralogical Society, London, 117-146.

PŘICHYSTAL A. 1985. The spilite-keratophyre volcanism of the Šternberk-Horní Benešov Belt in the Nízký Jeseník Mts. (in Czech). *Unpublished Ph.D. Thesis*, Faculty of Natural Sciences, Charles University, Prague.

PŘICHYSTAL A. 1993. Paleozoic to Quarternary volcanism in geological history of Moravia and Silesia. *In*: PŘICHYSTAL, A., OBSTOVÁ, V. and SUK, M. (eds), *Geology of Moravia and Silesia, Volume devoted to 90th anniversary of birth of Prof. K. Zapletal*, Moravian Museum and Faculty of Natural Sciences of the Masaryk Univ., 59-70.

PUDA S. and VALENTA J. 1984. Janovice-Ruda — preliminary prospection (in Czech). *In: Sborník referátů z jednání KRB pro rozvoj rudního geofyzikálního průzkumu v Jeseníkách.* Geofyzika st. p., Brno, 85-90.

RAJLICH P. 1974. Variscan polyphase folding and metamorphism in the Hrubý and Nízký Jeseník Mts. (in Czech). *Práce odboru přírodních věd, Vlastivědný ústav*, 28, 3-46.

RICHARDS J.P., CHAPPEL B.W. and McCULLOCH M.C. 1990. Intraplate-type magmatism in a continent-island-arc collision zone: Porgera intrusive complex, Papua New Guinea. *Geology*, 18, 958-961.

RINGWOOD A.E. 1975. *Composition and petrology of the Earth's mantle.* McGraw-Hill, New York.

SAWKINS F.J. and BURKE K. 1980. Extensional tectonics and mid-Paleozoic sulfide occurrences in Europe. *Geologische Rundschau*, 69, 349-360.

SCHARM B. and KÜHN P. 1975. Siliceous rocks from the kies-polymetallic deposit at Horní Benešov. *In*: POUBA, Z. (ed.) *Correlation of Proterozoic and Paleozoic stratiform deposits (3).* Institute of Geological Sciences, Faculty of Natural Sciences, Charles University, Prague. 91-96.

SOUČEK J. 1978a. Metabasites of the Vrbno and Rejvíz series, Hrubý Jeseník Mts. (in Czech). *Acta Universitatis Carolinae, Geologica, Kratochvíl Vol.*, 323-349.

SOUČEK J. 1978b. Metamorphic zones of the Vrbno and Rejvíz series, the Hrubý Jeseník Mts., Czechoslovakia. *Tschermaks mineralogische und petrographische Mittailungen*, 25, 195-217.

SOUČEK J. 1981. The geochemistry of the Devonian metabasites of the Hrubý and Nízký Jeseník Mts. (in Czech). *Časopis pro Mineralogii a Geologii*, 25, 126-142.

STILLE H. 1951. Das miteleuropäische variszіche Grundgebirge im Bilde des gesamteuropäischen. *Geologische Jahrbuch, Beihefte*, 2.

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. and ŽEBERA K. 1966. *Regional geology of Czechoslovakia*, I. Geological Survey, Prague.

TATSUMI T. and CLARK L.A. 1972. Chemical composition of acid volcanic rocks genetically related to formation of Kuroko deposits. *Journal of the Geological Society of Japan*, 78, 191-201.

TAYLOR S.R. and McLENNAN S.M. 1985. *The continental crust: its composition and evolution.* Blackwell, Oxford.

THOMPSON R.N. 1982. Magmatism of the British Tertiary Volcanic Province. *Scottish Journal of Geology*, 18, 49-107.

TOMŠÍK J. 1959. The base metal ore deposit at Horní Benešov (in Czech). *Časopis Slezského Muzea, Série A*, 8, 73-90.

TUTTLE O.F. and BOWEN N.L.: Origin of granite in the light of experimental studies in the system $NaAlS_3O_8$ — $KALSi_3O_8$ — SiO_2 — H_2O. *Geological Society of America Memoirs*, 74, 65, New York 1958.

WAJSPRYCH B. 1986. Sedimentary record of the tectonic activity on the Devonian-Carboniferous continental margin, Sudetes. *In: Excursion Guidebook, 7th European Regional Meeting of the International Association of Sedimentologists*, Kraków. 141-164.

VALENTA J., DANKO J., FOJT B., HLADIL J., CHÁB J., CHLUPÁČOVÁ M., MÁTL M., NOVÁK J., PÍCHOVÁ E. and REJL L. 1988. Janovice-Ruda — preliminary prospection for Pb-Zn-Ag ores (in Czech). — *Unpublished report*, Unigeo, Ostrava.

VANĚČEK M., PATOČKA F., POŠMOURNÝ K. and RAJLICH P. 1985. The use of isotopic composition of ore lead in metallogenic analysis of the Bohemian Massif. *Rozpravy ČSAV, ř. mat.-přír. věd*, 95, 5, 1-114.

WEDEPOHL K.H., MEYER K. and MUECKE G.K. 1983. Chemical composition and genetic relations of metavolcanic rocks from the Rhenohercynian belt of northwest Germany. *In*: MARTIN, K.H. and EDER, F.W. (eds) *Intracontinental Fold Belts*. Springer, Berlin — Heidelberg — New York. 245-256.

WINCHESTER, J.A. and FLOYD, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20, 325-343.

ZORIN YU.A. and LEPINA S.V. 1985. Geothermal aspects of development of asthenospheric upwelling beneath continental rift zones. *Earth Planetary Science Letters*, 93, 113-122.

ZUBATAREVA L.I., KABANOVA E.S. and MEDVEDEVA I.E. 1979. Magmatism (magmatic rocks) of oceanic islands (in Russian). *Itogi nauki i techniky, Seria Geochimia, Mineralogia, Petrografia*. 10-128.

Table 1
Major and trace element composition of the Late Devonian metatrachytes (1–24) and metarhyolites (25–29) from the southern part of the Vrbno Group, the Jeseníky Mts.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Si_2	54.93	55.89	57.50	57.71	58.68	59.31	59.37	59.50	59.65	60.23	60.24	60.36	60.46	60.70	61.36
TiO_2	0.84	0.90	0.69	0.87	0.87	1.04	0.63	0.75	0.51	0.61	0.73	0.65	0.63	0.30	0.44
Al_2O_3	18.28	17.10	17.04	17.82	17.81	17.28	17.42	17.07	17.44	17.07	16.84	16.83	17.58	16.85	16.44
Fe_2O_3	1.78	1.11	1.79	1.48	0.83	1.18	1.97	1.10	1.78	1.18	0.22	0.70	1.78	0.14	0.99
FeO	5.12	4.41	4.91	4.12	4.84	5.61	4.97	3.70	4.63	5.14	6.04	5.62	4.62	2.33	5.09
MnO	0.13	0.15	0.15	0.13	0.11	0.06	0.15	0.09	0.10	0.16	0.11	0.09	0.11	0.09	0.07
MgO	2.26	2.02	1.66	2.06	2.18	1.76	1.33	1.19	1.98	1.47	1.56	1.99	1.27	0.81	1.51
CaO	3.25	3.98	2.92	2.15	1.54	0.92	1.68	2.32	1.10	1.43	1.03	1.12	1.38	3.89	1.83
Na_2O	6.19	5.98	5.43	7.36	6.72	6.30	6.70	6.72	5.45	6.00	5.59	5.56	6.72	6.20	5.38
K_2O	4.67	3.71	3.75	2.88	4.52	2.52	3.43	3.84	5.57	5.12	4.62	4.45	4.24	4.52	4.00
P_2O_5	0.26	0.95	0.23	0.25	0.25	0.26	0.13	0.17	0.16	0.63	0.15	0.12	0.19	0.05	0.07
CO_2	1.25	1.74	2.20	0.99	0.21	0.49	0.79	1.32	0.44	0.52	0.55	0.77	0.34	2.72	0.77
H_2O^+	1.71	1.79	1.70	2.49	1.76	1.75	1.08	1.66	1.98	1.25	1.40	1.72	1.26	0.95	1.20
H_2O^-	0.27	0.19	0.26	0.18	0.18	0.69	0.26	0.24	0.17	0.18	0.77	0.52	0.19	0.06	0.12
total	100.94	99.92	100.23	100.49	100.51	99.17	99.90	99.67	100.96	100.50	99.85	100.50	100.77	99.61	99.27
K_2O/Na_2O	0.75	0.62	0.69	0.39	0.67	0.40	0.51	0.57	1.02	0.85	0.83	0.80	0.63	0.73	0.74
Sr	127	191	108	131	66	78	94	130	54	88	63	68	84	99	45
Rb	101.0	108.0	50.2	37.4	59.8	32.0	53.1	98.8	95.3	85.1	64.0	81.0	92.5	79.6	104.0
Ba	1032	1200	690	690	633	–	917	862	967	924	–	–	830	1160	408
Th	6.60	6.40	7.88	6.71	9.97	7.63	8.72	7.23	9.81	7.06	8.34	10.30	9.73	11.90	7.88
Ta	3.85	3.59	4.15	3.55	4.42	4.34	4.34	4,23	5.16	3.72	4.33	5.34	5.06	6.14	5.38
Nb	70	68	72	69	87	68	85	69	93	72	69	76	87	105	96
Zr	648	592	692	606	856	637	834	641	902	642	632	677	821	1030	950
Hf	13.6	12.5	13.8	14.0	18.4	16.9	17.0	14.3	17.9	13.0	16.2	18.8	18.0	21.0	19.4
La	53.1	45.7	47.1	47.0	58.7	59.2	52.3	49.9	66.4	49.8	59.7	73.7	55.2	63.5	60.5
Ce	109	115	115	112	127	116	128	115	139	108	111	127	128	142	109
Sm	9.55	9.52	9.74	9.82	10.70	10.30	10.70	9.57	11.20	9.40	9.17	10.80	11.1	11.9	11.4
Eu	3.11	3.07	2.72	3.18	2.95	3.14	2.73	2.43	2.32	2.37	2.83	2.94	2.71	1.70	2.04
Tb	1.80	1.16	1.60	1.48	1.82	1.69	1.89	1.38	1.76	1.62	1.95	1.94	2.06	2.33	1.93
Yb	7.39	6.77	6.20	5.74	8.51	8.17	8.43	7.10	8.41	6.39	5.90	8.53	9.00	8.97	7.87
Lu	0.89	0.99	1.02	1.00	1.23	0.97	1.14	0.92	1.23	0.95	1.04	1.26	1.40	1.36	1.27
Y	52	48	53	46	56	52	53	48	60	48	50	53	63	69	64
Ce/Yb	14.75	16.99	18.53	19.51	14.92	14.20	15.18	16.20	16.53	16.90	18.81	14.89	18.55	15.83	13.85
Eu/Eu*	0.97	1.07	0.86	1.02	0.85	0.94	0.77	0.81	0.65	0.77	0.89	0.82	0.73	0.42	0.55

Table 1 — continued

	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Si_2	61.53	61.97	62.72	63.39	63.57	64.81	65.02	67.37	68.71	71.39	74.18	74.34	77.02	79.69
TiO_2	0.51	0.32	0.40	0.30	0.31	0.36	0.37	0.33	0.21	0.15	0.23	0.13	0.30	0.17
Al_2O_3	15.94	16.25	16.96	17.08	15.03	16.31	15.75	14.51	13.63	12.92	12.88	11.06	9.85	9.41
Fe_2O_3	5.01	4.14	0.65	0.59	0.10	0.83	3.59	1.80	1.60	1.40	1.11	1.40	0.79	0.80
FeO	2.48	1.05	4.68	2.65	3.77	3.43	1.46	3.61	3.02	2.17	1.68	1.43	1.80	1.62
MnO	0.01	0.05	0.06	0.07	0.05	0.04	0.02	0.10	0.08	0.02	0.01	0.02	0.05	0.06
MgO	0.98	1.36	1.38	0.48	1.07	1.86	0.25	0.52	1.04	0.80	0.51	1.97	0.60	1.00
CaO	0.81	0.80	0.59	3.09	2.35	0.77	1.23	0.89	1.61	0.78	0.21	0.69	0.70	1.33
Na_2O	4.56	4.89	6.55	6.14	3.75	4.00	5.77	2.77	4.06	3.83	5.35	0.30	0.39	1.40
K_2O	5.99	6.71	3.58	1.67	9.68	5.44	4.58	5.34	3.28	3.51	2.59	4.80	5.98	1.80
P_2O_5	0.05	0.81	0.03	0.04	0.04	0.04	0.07	0.03	tr.	tr.	0.04	tr.	0.07	tr.
CO_2	0.70	0.14	0.26	2.04	1.74	0.21	0.42	0.37	0.94	0.29	0.14	0.27	0.59	0.69
H_2O^+	0.64	0.64	1.16	0.93	1.57	1.57	0.31	1.24	1.28	1.47	0.61	2.58	1.72	1.31
H_2O^-	0.10	0.12	0.22	tr.	0.64	0.10	0.10	0.32	0.20	0.15	0.34	0.18	0.28	0.15
total	99.31	99.25	99.24	99.47	99.67	99.77	99.14	99.20	99.66	98.88	99.88	99.17	100.14	99.43
K_2O/Na_2O	1.31	1.37	0.55	0.27	1.51	1.36	0.79	1.93	0.81	0.92	0.48	16.00	15.33	1.29
Sr	45	40	38	102	67	41	29	40	32	11		19	45	39
Rb	78.8	133.0	89.0	45.2	54.0	106.0	67.6	27.3		45.0	28.0	107.0	92.0	52.7
Ba	432	233	–	462	–	717	338	136	169	145	–	124	–	145
Th	14.30	14.00	11.70	11.7	10.9	11.3	12.9	22.1	19.8	27.5	26.6	17.7	11.8	14.1
Ta	6.21	6.50	5.31	5.55	5.10	5.87	5.44	10.20	8.59	11.20	11.00	7.36	4.47	5.33
Nb	115	128	92	81	74	97	87	164	163	199	189	130	66	105
Zr	1053	1209	916	1003	733	970	1024	2050	1860	2200	2008	680	523	614
Hf	23.7	22.9	21.8	21.0	19.2	21.0	19.4	43.1	34.2	47.6	46.8	22.9	18.2	19.4
La	85.4	83.6	77.8	50.2	78.5	60.7	87.7	150.0	139.0	192.0	199.0	52.9	50.8	47.7
Ce	180	181	132	118	123	132	181	294	269	389	687	124	91	113
Sm	14.1	13.9	–	9.37	10.10	10.10	14.70	20.90	18.70	24.4	20.9	14.9	10.3	14.1
Eu	1.85	2.46	1.74	1.45	2.00	1.39	2.45	1.20	1.01	1.36	1.08	0.55	1.19	0.51
Tb	2.53	2.15	2.19	1.84	1.77	1.89	2.37	3.33	3.58	3.72	3.60	3.21	2.09	2.92
Yb	10.70	6.25	8.94	8.38	8.68	9.68	10.10	13.70	14.30	16.70	15.80	11.80	8.54	9.97
Lu	1.69	0.88	1.22	1.34	1.14	1.41	1.65	2.23	2.22	2.59	2.02	1.65	1.01	1.42
Y	52	97	65	54	53	60	81	121	133	132	120	98	72	93
Ce/Yb	16.82	28.96	14.77	14.08	14.17	13.64	17.92	21.46	18.81	23.29	43.48	10.51	10.64	11.33
Eu/Eu*	0.40	0.56	0.49	0.46	0.60	0.64	0.52	0.18	0.16	0.18	0.16	0.11	0.34	0.11