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Geochemical characteristics and petrogenesis of phonolites and trachytic rocks from the České Středohoří Volcanic Complex, the Ohře Rift, Bohemian Massif

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ABSTRACT

Trachyandesites, trachytes and phonolites represent the most evolved rock types within the České Středohoří Volcanic Complex (CSVC) in the Ohře/Eger Rift. The K–Ar ages of the suite range from ~33.8 to ~25.8 Ma. Major and trace element variation in the basanite – trachybasalt – trachyandesite series can be explained by several stages of modification of parental magmas by assimilation-fractional crystallization (AFC) involving fractionation of olivine, clinopyroxene, apatite, amphibole and Ti-oxide and bulk continental crust (BCC) as an assimilate. Relative to plausible basanitic starting compositions, the trachytes are moderately depleted in Sr, exhibit more pronounced depletions in P and Ti and some of them also show mild MREE depletion. Such composition requires variable amphibole, clinopyroxene, plagioclase ± apatite, titanite and/or Ti-magnetite fractionation and BCC assimilation. Two types of phonolites (type A and B phonolite) can be distinguished on the basis of overall REE patterns, Gd/Gd* ratios and Ba and Sr contents. Type B phonolites are depleted in Ba, Sr and MREE as a result of extensive alkali feldspar, plagioclase and amphibole fractionation. Modelling of trace element distributions implies basanitic magmas as the most likely parental composition of the basanite – trachybasalt – trachyandesite – trachyte – phonolite suite formed through magmatic differentiation. The Sr–Nd isotopic compositions in the samples can be explained with the assimilation of continental crust by such parental magmas. The highly radiogenic $^{87}Sr/^{86}Sr$ found in some phonolites are contrasted by uniform Nd isotopic signature; this feature may be explained by contamination and/or overprint of source magmas by Na–Rb-rich material with radiogenic Sr signature formed due to high-Rb (>200 ppm) character of these melts/fluids. The nature of such contaminant is further evidenced by elevated Li (and Cs in some cases) abundances in type B phonolites although at least two distinct fluids are implicated from the Li–Cs correlations. The derivation of these melts/liquids from sedimentary and/or meta-sedimentary crustal sources is underscored by variable but overall light Li isotopic compositions. Some phonolites exhibit enrichments in high-field-strength elements coupled with increased Zr/Nb ratios. In contrast to previous studies, we show that this feature, apparent in many volcanic rocks from the Bohemian Massif, can be explained with progressive melt fractionation of parental magmas involving amphibole and plagioclase.

1. Introduction

Phonolites and trachytes are volcanic rock types characteristic for intraplate settings at oceanic and continental environments. Classic occurrences of Cenozoic phonolites and trachytes in rift settings can be found in the East-African Rift System (Goles, 1976; Lippard, 1973; Macdonald, 2003; Macdonald and Scaillet, 2006) and Fortaleza district in Brasil (Macciotta et al., 1990) belonging to the South American Rift Province but equally young phonolites and trachytes are also common in ocean island settings, for example Tristan da Cunha and Saint Helena (Le Roex et al., 1990), Canary Islands (Bryan et al., 1998), French Polynesia and Marquesas (Legendre et al., 2005). In the Cenozoic European Volcanic Province (CEVP), abundant felsic volcanic rocks have been reported in the Massif Central (e.g., Briot et al., 1991; Caroff et al., 1997; Downes, 1984, 1987; Wilson et al., 1995), The Upper Rhine Valley (Schreiber et al., 1999; Vieten et al., 1988; Wörner et al., 1983), and the Bohemian Massif (Ulrych et al., 1999). A coeval origin

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of phonolites/trachytes and associated mafic members in the CEVP has been invoked for the Massif Central (Wilson et al., 1995), the Bohemian Massif (Ulrych et al., 1999), Siebengebirge volcanic field (Jung et al., 2012; Kolb et al., 2012) and the Rhön area (Jung, 1995; Jung et al., 2013).

An important issue in studies of bimodal mafic–felsic association are the processes leading to the development of phonolite magmas. Baker and McBirney (1985); Barberi et al. (1975) and Macciotta et al. (1990) have interpreted the origin of phonolite magmas by low-pressure fractional crystallization of mostly clinopyroxene from nephelinitic parental magmas at shallow crustal levels. Enders et al. (1992) suggested that trachytes in the Rhön area resulted from polybaric differentiation of a basaltic magma and Jung et al. (2013) modelled two concurrent processes, fractional crystallization of hornblende-bearing basanitic magmas and coupled crustal assimilation–fractional crystallization of nephelinite/basanite, for generating the observed incompatible element and radiogenic isotope systematics in this area. Collectively, it appears that crustal components were often extensively involved in the petrogenesis of felsic magmas and bimodal rock suites (Davies and Macdonald, 1987; Wilson et al., 1995). On the basis of Sr–O isotopic data, Vieten et al. (1988) suggested two principal paths for the origin of phonolites from the Siebengebirge: (i) fractional crystallization of parental mafic melts and (ii) combined assimilation–fractional crystallization process involving a substantial crustal contamination during the ascent. Wilson et al. (1995) documented a common asthenospheric mantle source for two coexisting strongly alkaline (basanite – tephrite – phonolite) and weakly alkaline (alkali basalt – trachyandesite – trachyte – rhyolite) series in the Cantal, Massif Central, that originated by combined assimilation–fractional crystallization processes.

In order to provide further constraints on the genesis of intra-plate alkaline volcanism in continental settings, new whole-rock geochemical data as well as Sr–Nd–Li isotopic compositions for a trachyandesite – trachyte – phonolite association of the České Středohoří Volcanic Complex (CSVC) within the CEVP is presented, coupled with detailed mineral chemistry. Together with the Lužické hory Mts. and the Cheb–Domažlice Graben, these are typical areas of phonolite and trachyte volcanism in the Bohemian Massif (e.g., Pazdernik, 1997; Ulrych et al., 2000). By considering previously published data for basanites, trachybasalts and basaltic trachyandesites (Ulrych et al., 2002), the volcanic rocks from CSVC represent a continuous basanite–trachyte–phonolite series. Implications for the petrogenesis of alkaline felsic volcanism are outlined.

2. Geological setting

The Cenozoic intraplate alkaline volcanism in Western and Central Europe is associated with a generally NNE–SSW trending rift belt, formed in the early Cenozoic, and comprises rare volcanic occurrences in Spain, voluminous products in France, Germany and Czech Republic, that ceases towards south-western Poland (Lustrino and Wilson, 2007). This large-scale rift system formed in response to the Alpine orogeny caused by the collision of the European and African plates in the early Tertiary. The asthenospheric mantle upwelling, related to the Alpine orogeny, resulted in the generation of large volumes of mantle-derived alkaline magmas by decompression melting of both asthenospheric and lithospheric sources and modification of these parental magmas by variable crustal contamination during their ascent (Goes et al., 1999; Jung et al., 2005, 2011; Pivec et al., 1998; Ulrych et al., 1999; Wedepohl and Baumann, 1999; Wilson and Downes, 1991). In the Bohemian Massif, three main volcanic periods can be distinguished (Ulrych et al., 2011): (i) pre-rift (79–49 Ma), (ii) syn-rift (42–16 Ma) and (iii) late-rift (16–0.3 Ma). Primitive mafic alkaline (nephelinite–basanite/tephrite) accompanied by subordinate tholeiitic magmas prevail in all periods over felsic and intermediate rock types. A detailed review of available major/ trace element and Sr–Nd–Pb isotopic data of the CEVP volcanic rocks, indicates a common sub-lithospheric mantle source of the alkaline volcanism which is referred to as Common Mantle Reservoir (CMR) by Lustrino and Wilson (2007) or the European Asthenospheric Reservoir (EAR) by Cebrià and Wilson (1995).

2.1. The České Středohoří Volcanic Complex (CSVC)

A predominant part of the Cenozoic intraplate volcanism in the Bohemian Massif is related to the Ohře/Eger Rift with two dominant volcanic centers, the CSVC and the Doupovské hory Volcanic Complex (DHVC). The CSVC in NW Bohemia represents a relic of the second largest and lithologically the most complicated polyphase volcano-sedimentary edifice. It forms a 20–25 km wide and 80–90 km long range formed by almost continuous occurrences of effusive and volcanosedimentary rocks. Numerous solitary volcanic occurrences in the Lužické hory Mts. are considered to be the NE continuation of the CSVC inside the Ohře Rift. The major volcanic activity culminated in the middle Oligocene to late Miocene (~32 to 24 Ma), the prominent subsidence occurred during crustal extension in the early Oligocene to late Miocene (e.g., Ulrych et al., 2011; Ziegler, 1994). Shrbený (1995) estimated the areal extent of the CSVC to 472 km^2 and the volume of preserved volcanic products to 52 km^3. About 40% of all volcanic rocks are volcanoclastites. Cajz et al. (1999, 2009) divided the sequence of basanitic to trachybasaltic lavas and its volcanoclastic equivalents, spanning in age from 36.1 Ma to 9.0 Ma, into four volcanostratigraphic units. The first, third and fourth unit, respectively, are built by predominant basanites, whereas the second unit (30.8–24.7 Ma) is trachybasaltic.

The phonolitic and trachytic rocks of the CSVC are spatially and genetically associated with basaltic rocks but the volcano-stratigraphic position of the phonolites and trachytes relative to effusive lavas is mostly difficult to constrain due to the scarce field evidence.

2.2. Areal distribution of phonolites and trachytes and sampled localities

Phonolitic and trachytic rocks are irregularly distributed in the CSVC, making up ~6 vol. % (ca. 5% phonolites and 1% trachytes) of all volcanic rocks in CSVC (Hibsch, 1930). Trachytic rocks form about 10 vol. % of all Cenozoic volcanic rocks in the Bohemian Massif (Shrbený, 1995).

Phonolites and alkali trachytes (Afs> > Pl ± Sdl) are exposed in the SW part of the CSVC with phonolites mainly in the vicinity of the towns of Most and Bílina, and alkali trachytes in the Teplice–Bílina–Lovosice triangle. Sodalite and/or analcime trachytes (Afs ± Sdl, Anl) and trachytes (Afs> > Pl) mostly occur in the NE part of the CSVC. The locations of all studied rocks in the CSVC together with position of the basanitic (Ústí Formation) and trachybasaltic series (Děčín Formation) are shown in Fig. 1.

3. Analytical methods

Major element concentrations were determined by XRF using a Philips PW 1404 X-ray fluorescence spectrometer at the Gematest Company, Prague. The precision of the analyses was better than 5% and the accuracy of the data was better than 5% for most elements, inferred from the analysis of the USGS reference material AGV-1 (andesite).

Instrumental neutron and photon activation analyses (INAA and IPAA, respectively) were used for determination of the trace element concentrations using procedures outlined in Řanda et al. (2007). For INAA, the irradiation was carried out in vertical channels located at the periphery of a reactor core of the LVR-15 nuclear reactor housed at the Nuclear Research Institute Řež. Two modes of INAA were employed, the short-time (1 min) and long-time (2 hours) irradiation. For IPAA, the microtron (cyclic electron accelerator) MT-25, housed at the Nuclear Physics Institute of the Czech Academy of Sciences, was operated at 22 MeV electron beam energy and 15 μA mean current. Elements determined by the INAA and IPAA methods have combined uncertainties (1σ) between 1 and 15 % determined by analyzing the AGV-1 reference material (USGS, see Supplementary Table 1).