Estonian Journal of Earth Sciences, 2015, **64**, 1, 31–35 doi: 10.3176/earth.2015.06

New results for Palaeozoic volcanic phases in the Prague Basin – magnetic and geochemical studies of Lištice, Czech Republic

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Received 30 June 2014, accepted 21 October 2014

Abstract. Palaeo-, rock magnetic and geochemical studies were conducted on volcanic samples from the Lištice area to improve the knowledge of Palaeozoic volcanic evolution in the Prague Basin. The magnetic data display no significant differences between two studied localities, indicating one magnetizing event for both localities. Geochemical data suggest that Lištice basalt could have originated from deep melting of the garnet peridotite mantle source during the attenuation and rifting of the continental lithosphere connected with asthenospheric mantle upwelling. The dataset furthermore supports the evidence of syn- or post-intrusive fluid interactions and low-temperature stages of alteration. The Ti-magnetite within amygdales of the samples was found to be carrying the characteristic remanent magnetization and reflects probably the Permo-Carboniferous remagnetization of volcanic phases.

Key words: Teplá–Barrandian Unit, Prague Basin, palaeomagnetism, rock magnetism, geochemistry.

INTRODUCTION

The Prague Basin, Teplá–Barrandian Unit, Czech Republic, is a large Ordovician to Devonian basin which was tilted during Variscan Orogeny. Similarly to the other peri-Gondwanan terrains, it preserves evidence of intense basic volcanic activity during the Silurian (Stampfli et al. 2002). The Prague Basin, and especially its sedimentary sequence, has been extensively studied (e.g., Fiala 1970; Krs & Pruner 1995; Melichar 2004). However, the information about Palaeozoic volcanic evolution, and especially its palaeosetting and development, are still scarce due to lack of magnetic and geochemical data on Prague Basin volcanites, as well as due to large scatter in the existing palaeomagnetic directions (e.g., Krs et al. 2001; Aïfa et al. 2007; see also Global Paleomagnetic Database, http://www.ngu.no/geodynamics/gpmdb/).

For the purpose of this research 50 samples were collected from Lištice quarry (SI08) and roadside (SI07) outcrops during 2010–2014. Lištice volcanites were subjected to palaeomagnetic, rock magnetic and geochemical studies to gain new insights into Palaeozoic evolution and its volcanic phases.

GEOLOGICAL SETTING

Volcanism in the Prague Basin was restricted to the Llandovery–Ludlow series and was controlled by deep-seated faults, both parallel and perpendicular to the longitudinal axis of the basin, providing ascent paths for mantle-derived magmas (Štorch 1998). Major volcanic accumulations (e.g., Svatý Jan Volcanic Centre) are concentrated in the vicinity of syn-sedimentary Tachlovice Fault, which was further reactivated during Variscan Orogeny (Kříž 1991). An onset of volcanic activity in the Svatý Jan Volcanic Centre is represented by intrusion of the Lištice basalt into Telychian shales (*Stomatograptus grandis* Subzone) of the Motol Formation in the northern tectonic segment of the Prague Basin. Lištice basalts are exposed in an abandoned quarry and along the roadside close to Lištice village (Fig. 1). Basalt is medium-grained, with ophitic texture formed by plagioclase and clinopyroxene and matrix consisting of chlorite, zeolite, Ti-magnetite, titanite, ilmenite, apatite and pyrite.

METHODS

Palaeo- and rock magnetic measurements were carried out in the Laboratory of Paleomagnetism, Institute of Geology AS CR, v. v. i. Palaeomagnetic directions were obtained from drilled cores (ø = 2.5 cm). The core samples were subjected to progressive thermal (TH) or alternating field (AF) demagnetization. Thermal demagnetization (80 °C–560 °C) was carried out using the MAVACS (Magnetic Vacuum Control System; Příhoda et al. 1989) apparatus. The remanence (e.g.,

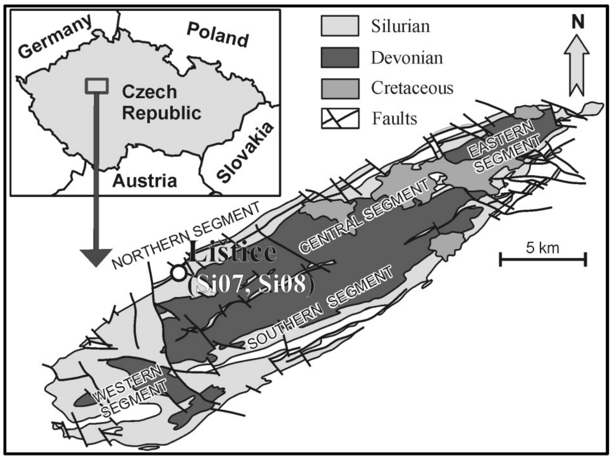

Fig. 1. Geological map of the Prague Basin (after Kříž 1998). Lištice is marked by a white circle.

natural remanent magnetization (NRM)) was measured using either the AGICO JR-6A spinner magnetometer or 2G Superconducting Rock Magnetometer 755 (SQUID), and the magnetic susceptibility (χ) was checked with the AGICO KLF-4A Automatic Magnetic Susceptibility Meter. Alternating field demagnetization (≤100 mT) was carried out using either JR-6A in conjunction with AGICO LDA-3 apparatus, or SQUID. The results of palaeomagnetic measurements were analysed with Remasoft software (Chadima & Hrouda 2006).

Rock magnetic measurements were carried out on selected samples to obtain magneto-mineralogical data and support the palaeomagnetic results. Temperature dependence of magnetic susceptibility (χ–T) in an argon atmosphere over a temperature range of –192 °C to 700 °C using an AGICO MFK1 kappabridge in conjunction with a CS4/CSL furnace was determined to identify the ferromagnetic fraction. To further verify the identity of magnetic minerals, three samples were subjected to the 3-axes Lowrie method (Lowrie 1990), where each sample was first saturated in three perpendicular directions: 1–2 T in the x-axis, 300 mT in the y-axis and 100 mT in the z-axis, and then thermally demagnetized as described before. A few samples were also, after AF-demagnetization, progressively magnetized up to 900 mT or 2 T using the Magnetic Measurements pulse magnetizer (MMPM10) and then stepwise demagnetized (≤100 mT) using LDA-3 to obtain information about saturation remanent magnetization (M_{RS}). Furthermore, standard geological thin sections were obtained from six samples for magnetic scanning to localize the magnetic minerals and anomalies within samples. Thin sections were demagnetized with the 100 mT field and then subjected to progressive acquisition of isothermal remanent magnetization up to 900 mT (using Weiss coils) and scanned using the Youngwood Science and Engineering magnetic scanner (youngwoodscience@gmail.com). The resulting 2D image shows the values of magnetization detected over the 17 mm × 17 mm surface of the sample.

A representative sample of Lištice basalt for geochemical analyses was crushed, homogenized and ground in an agate mill. Major-element analyses were carried out at the Central Laboratories of the Czech Geological Survey, Prague (wet silicate analyses: FAAS, ICP-OES, PMT, IR spectrometry). The trace-element data came from Activation Laboratories, Vancouver (ICP-MS package 4B2 Research, sample dissolution by a lithium metaborate/tetraborate fusion followed by rapid digestion in a weak nitric acid solution). Whole-rock data were processed by the GCDkit package (Janoušek et al. 2006).

RESULTS

The results show that χ and NRM are on average higher in SI07 than in SI08 samples (Table 1). The Q-ratio remained the same for both localities (only two SI07 samples had $Q > 1$).

The acquisition of saturation remanence (Fig. 2A) indicates that over 50% of magnetization is gained already by 100 mT in both localities. This is supported also by the Lowrie method (Fig. 2B), which shows that low coercivity fraction (magnetite) dominates the magnetic properties. However, contrary to acquisition curves which show saturation by 200–300 mT for most of the samples, the Lowrie method demonstrates the presence of higher coercive fraction, while medium coercivity minerals (100–300 mT) are mostly absent or do not contribute much to total magnetization.

The χ–T (Fig. 2C) of samples shows, in addition to magnetite (Curie temperature $T_C = 550$ °C and Verwey transition $T_{Ver} = -158$ °C), three other distinct transitions: around 120, 340 and 620 °C. The first transition corresponds to goethite while the second (340 °C) could be T_C of iron sulphides, such as pyrrhotite, or transition from goethite to hematite. Traces of hematite can be seen at Néel temperature $T_N = 620$ °C. In most cases the cooling curve of χ–T shows dissolution of the low-Ti magnetite and generation of a newly formed fraction with T_C between 400 and 500 °C (most possibly magnetite with a higher Ti content).

The AF-demagnetization characteristics (Fig. 3A) of the samples revealed two magnetic components: the low-coercivity (<40 mT) component and the medium-coercivity (<100 mT) characteristic remanence component (ChRM). Similarly, the TH-demagnetization (Fig. 3B) of the majority of samples showed also two components:

Table 1. Rock magnetic and palaeomagnetic data

Locality	χ (10^{-3} SI)	NRM (A/m)	Q	T_C (°C)	Medium magnetizing field (mT)	M_{RS} (mT)
Lištice roadside (SI07)	23.4	0.51	0.6	120; 340; 550; 620	65	270
Lištice quarry (SI08)	1.6	0.03	0.6	120; 340; 550; 620	40	200

Locality	N	D	I	α95	Plat	Plon	dp	dm
Lištice roadside (SI07)	8	17.0	7.4	10.7	41.5°N	171.1°W	6.2	12.4
Lištice quarry (SI08)	33	4.7	5.3	5.1	42.5°N	172.4°W	2.7	5.3
Total								
in situ	41	7.1	5.7	4.7	42.5°N	175.6°W	2.5	4.9
tilt-corrected	41	20.0	45.9	4.8	62.6°N	152.6°E	4.1	6.4

χ, magnetic susceptibility; NRM, natural remanent magnetization; Q, Koenigsberger ratio; T_C, Curie temperature; M_{RS}, saturation magnetization; N, number of samples; D, declination; I, inclination; α95, confidence limit; Plat, pole latitude; Plon, pole longitude; dp, semi-axis of the ellipse of confidence; dm, semi-axis perpendicular to the great circle.

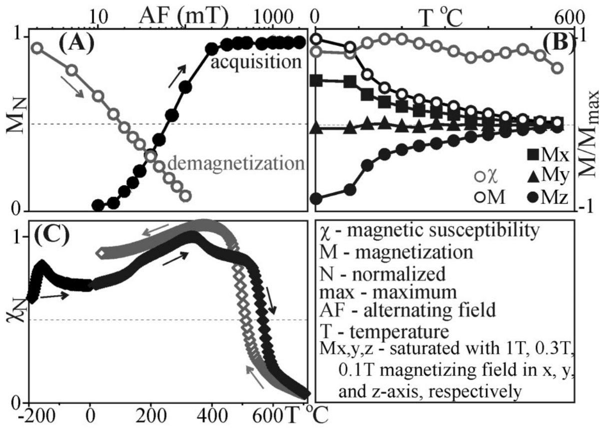

Fig. 2. Examples of (**A**) acquisition and demagnetization of saturation remanence, (**B**) Lowrie method: showing the thermal demagnetization of isothermal remanent magnetization components and (**C**) temperature dependence of magnetic susceptibility.

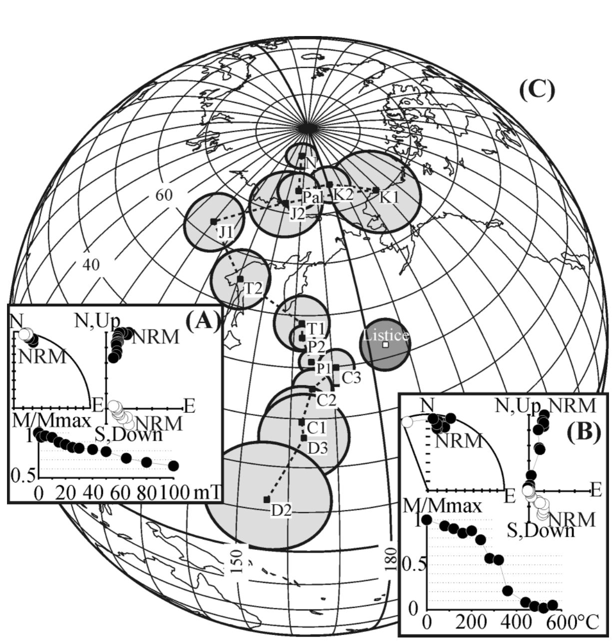

Fig. 3. Examples of (**A**) AF- and (**B**) TH-demagnetization, and the (**C**) apparent polar wander path for a stable Europe based on Besse & Courtillot (1991), Krs & Pruner (1995) including VGP from ChRM of this study in darker grey. NRM marks the natural remanent magnetization; D, C, P, T, J, K and Pal symbolize the Devonian, Carboniferous, Permian, Triassic, Jurassic, Cretaceous and Palaeogene, respectively.

the low-temperature (<200 °C) component and medium- to high-temperature (400–560 °C for SI07 and 300–440 °C for SI08) ChRM. The palaeomagnetic data suggest that the low-temperature component is carried by goethite, while the ChRM carrier is most possibly Ti-magnetite. This is in accordance with the rock magnetic experiments where the magnetite was dominating the magnetic properties. The ChRM (Table 1) carries a shallow normal (D = 7.1°, I = 5.7°, α95 = 4.7°), occasionally also reverse inclination of magnetization. The value of the virtual geomagnetic pole (VGP) calculated as in situ is Plat = 42.49°N, Plon = 175.63°W, dp = 2.47°, dm = 4.93°. Tilt-corrected data are presented in Table 1 and are briefly discussed below.

Geochemical analyses show that Lištice basalt is enriched in incompatible elements (Th_N = 13.25; Zr_N = 1.88) compared to normal mid-ocean ridge basalts (NMORB; Fig. 4A; Sun & McDonough 1989) with a low Zr/Nb ratio (~8.3). Furthermore, NMORB-normalized patterns show positive anomalies of Cs, Ba, Sr, K and Ti.

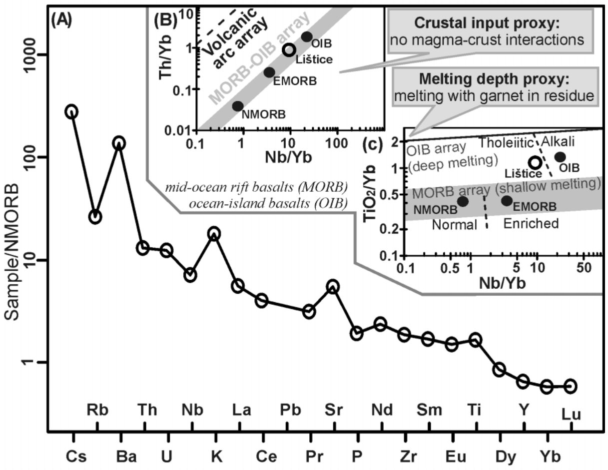

Fig. 4. Trace-element composition of Lištice quarry basalt. (**A**) spiderplot normalized by average NMORB composition (Sun & McDonough 1989); (**B**) Th/Yb versus Nb/Yb plot and (**C**) TiO_2/Yb versus Nb/Yb (after Pearce 2008).

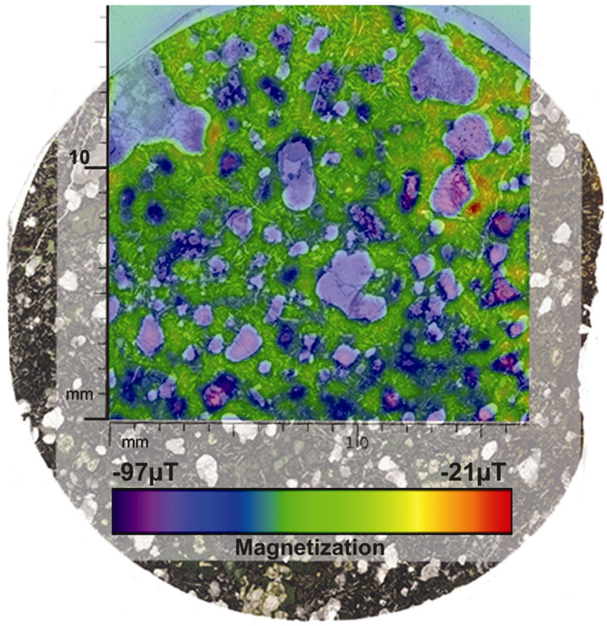

Fig. 5. Example of the optical image of the thin section with the magnetic scan displaying magnetization over the surface of the sample.

DISCUSSION

The palaeomagnetic data show the same direction of the ChRM component (and thus also same age) for both SI07 and SI08 localities (Table 1). To define the age of the Lištice ChRM component, its VGP was plotted on the apparent polar wander path (Fig. 3C) for a stable Europe (Besse & Courtillot 1991; Krs & Pruner 1995). The comparison of in situ ChRM with previously known poles (e.g., Krs et al. 2001) indicated the late Carboniferous–early Permian age for Lištice volcanites. A similar pole was previously obtained also by Aïfa et al. (2007), whose low-to-intermediate field and medium-to-high temperature component (C2), reflecting probably magnetite, corresponded to the Middle or Late Carboniferous direction for the Bohemian Massif (with no significant rotation). Our tilt-corrected data, however, suggested a late Jurassic magnetizing event and therefore pinpoint towards successive (Alpine) orogeny. Since Alpine orogeny was not active in the studied area, the tilt-corrected results are not considered any further.

The optical microscopy of thin sections revealed the presence of a multitude of vesicles with amygdales, which are primarily associated with Silurian late magmatic fluid and seawater. Magnetic scanning (Fig. 5) of these thin sections showed that magnetic anomalies match with locations of amygdales (similarly to Kletetschka et al. 2013) or with their outer zones and, thus, the recorded palaeomagnetic signal reflects the age of amygdales. The obtained remanence direction may correspond therefore to either the primary (Silurian) magnetization with non-centred secular variations, which are known to cause major dispersal of palaeomagnetic directions (e.g., Dominguez et al. 2011 and references therein), or indicate the Permo-Carboniferous remagnetization of volcanic phases. As the studied rocks are highly permeable for fluids (Saar & Manga 1999), the amygdales were most possibly subject to further hydrothermal alteration and recrystallization during Variscan orogeny in the late Carboniferous–early Permian. And, thus, primary magnetization of Lištice volcanites was probably overprinted by the Permo-Carboniferous remagnetization hydrothermal event (our ChRM; Fig. 3C).

Although Lištice basalt shows a pristine basaltic whole-rock geochemical signature (Fig. 4A), the distinct anomalies, with an exception of Ti, in the NMORB-normalized pattern could be related to low-temperature stages of alteration and weathering (Hart et al. 1974; Seyfried 1979). Enrichment of Cs, Ba, Sr and K suggests syn- or post-intrusional subsolidus open-system processes, most probably due to an interaction with fluids, rather than to an equilibration of crustal material with basaltic magma. The rest of the whole-rock geochemical signature points to a within-plate setting with character transitional between enriched mid-ocean ridge basalts (EMORB) and ocean-island basalts (OIB) and no prominent crustal contamination (Fig. 4B). Furthermore, Lištice basalt belongs to tholeiitic suite and could have originated by a low degree of partial melting of a garnet peridotite source (Fig. 4C). The geotectonic setting during the onset of volcanism in the Svatý Jan Volcanic Centre could be characterized on the basis of geochemistry and well-documented existence of the Neoproterozoic crust

(Dörr et al. 2002) as attenuation and rifting of the continental lithosphere connected with asthenospheric mantle upwelling.

SUMMARY

The results of our studies indicate the same direction and age for the Ti-magnetite carried ChRM component for both SI07 and SI08 localities. Palaeomagnetic data display the Permo-Carboniferous remagnetization of volcanic phases but could also indicate the Silurian magnetization with non-centred secular variations. The whole-rock geochemical signature suggests low-temperature stages of alteration and syn- or post-intrusional hydrothermal processes. Based on geochemistry, the geotectonic setting during the onset of volcanism could be characterized as attenuation and rifting of the continental lithosphere connected with asthenospheric mantle upwelling.

Acknowledgements. We would like to express our gratitude to Jiří Petráček, Jana Drahotová, Stanislav Šlechta, Jindřich Hladil, Jaroslava Jabůrková, Ladislav Nábělek, Šimon Kdýr, Martin Mazanec and Radka Haislová for their help with sampling, sample preparation and measurements. We would also like to thank Gunther Kletetschka for providing us with the magnetic scanner, and Vojtěch Janoušek and Rostislav Melichar for constructive discussions. We are grateful to Jacek Grabowski and Igor Tunyi for their helpful reviews. This research is supported by Grant Agency of the Czech Republic – P210/10/2351, by Research Plans of the Institute of Geology AS CR Nos RVO67985831 and by Strategic Research Plan of the Czech Geological Survey. The paper is a contribution to IGCP Project 591.

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