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Chronological implications of the paleomagnetic record of the Late Cenozoic volcanic activity along the Moravia-Silesia border (NE Bohemian Massif)

VLADIMÍR CAJZ[1], PETR SCHNABL[1], ZOLTAN PÉCSKAY[2], ZUZANA SKÁCELOVÁ[3], DANIELA VENHODOVÁ[1], STANISLAV ŠLECHTA[1] and KRISTÝNA ČÍŽKOVÁ[1]

[1]Institute of Geology AS CR, v.v.i., Rozvojová 269, 165 00 Praha 6, Czech Republic;
cajz@gli.cas.cz; schnabl@gli.cas.cz; slechta@gli.cas.cz; cizkova@gli.cas.cz
[2]Institute of Nuclear Research of the Hungarian Academy of Sciences, Bem tér 18/C, H-4001 Debrecen, Hungary; pecskay@namafia.atomki.hu
[3]Czech Geological Survey, Erbenova 348, 790 01 Jeseník, Czech Republic; zuzana.skacelova@geology.cz

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Abstract: This paper presents the results of a paleomagnetic study carried out on Plio-Pleistocene Cenozoic basalts from the NE part of the Bohemian Massif. Paleomagnetic data were supplemented by 27 newly obtained K/Ar age determinations. Lavas and volcaniclastics from 6 volcanoes were sampled. The declination and inclination values of paleomagnetic vectors vary in the ranges of 130 to 174 and –85 to –68° for reversed polarity (Pleistocene); or 345 to 350° and around 62° for normal polarity (Pliocene). Volcanological evaluation and compilation of older geophysical data from field survey served as the basis for the interpretation of these results. The Pleistocene volcanic stage consists of two volcanic phases, fairly closely spaced in time. Four volcanoes constitute the Bruntál Volcanic Field; two others are located 20 km to the E and 65 km to the NW, respectively. The volcanoes are defined as monogenetic ones, producing scoria cones and lavas. Exceptionally, the largest volcano shows a possibility of remobilization during the youngest volcanic phase, suggested by paleomagnetic properties. The oldest one (4.3–3.3 Ma), Břidličná Volcano, was simultaneously active with the Lutynia Volcano (Poland) which produced the Zálesí lava relic (normal polarity). Three other volcanoes of the volcanic field are younger and reversely polarized. The Velký Roudný Volcano was active during the Gelasian (2.6–2.1 Ma) and possibly could have been reactivated during the youngest (Calabrian, 1.8–1.1 Ma) phase which gave birth to the Venušina sopka and Uhlířský vrch volcanoes. The reliability of all available K-Ar data was evaluated using a multidisciplinary approach.

Key words: Plio-Pleistocene basalts, paleomagnetism and magnetostratigraphy, volcanology, K/Ar dating, airborne magnetometry and gravimetry, Moravia and Silesia.

Introduction

Cenozoic volcanism in the NE part of the Bohemian Massif occurs prevalently in Polish Silesia. It stretches into the territory of the Czech Republic to a limited extent only. The volcanic locations of this wider area constitute the Odra Tectono-Volcanic Zone (OTVZ, *sensu* Kopecký 1987) of the WNW–ESE strike, as a part of the so-called Bohemo-Silesian Volcanic Arc. Volcanic rocks are located mostly inside the Fore-Sudetic Block which is limited by the Odra Fault in the NE (outside the studied area in Poland) and the Sudetic Marginal Fault (SMF) in the SW, and elongated parallel to the OTVZ.

The basaltic volcanic products in northern Moravia and southernmost Silesia are among the youngest in the territory of the Bohemian Massif (e.g. Ulrych et al. 2011). Their composition ranges mostly between olivine nephelinite and nepheline basanite (e.g. Barth 1977; Fediuk & Fediuková 1985, 1989; Ulrych et al. 1999; and others). These volcanics represent primitive basaltic magmas (Vokurka & Bendl 1992, 1993), much like most other similar Cenozoic volcanics in the Bohemian Massif. These rocks were studied in their paleomagnetic properties by Marek (1969, 1973, 1974) and Kolofíková (1976), in the Czech Republic and by Birkenmajer et al. (2002) in Poland.

Volcanic occurrences of this wider region concentrate on three smaller areas in the territory of the Czech Republic. The greatest concentration of basalts is in the Bruntál Volcanic Field (BVF) near Bruntál in the Nízký Jeseník Mts. These basalts are not eroded to a very high degree, and their lavas locally overlie river terraces (e.g. Horský et al. 1972). Unpublished data of Bellon from the 1970s (*in* Kopecký 1987) brought the first information that they formed in the Pliocene. The Plio-Pleistocene age was confirmed by Šibrava & Havlíček (1980) using the K/Ar method. The second area of basaltic occurrences lies on the Czech-Polish border near Zálesí. No radiometric datings have been published from this location but geological evidence assigns these rocks to the Lutynia area in Poland. The only other separate occurrence near Opava (third area) was dated to the Miocene (Shrbený & Vokurka 1985). The rock of the nearby location of Štemplovec has been totally excavated and cannot provide data anymore.

Geological setting and volcanology

Magma of the volcanic occurrences was emplaced into Upper Paleozoic rocks. Only the Lutynia area and the Zálesí area are situated in the Králický Sněžník Crystalline Complex;

basalts near Bruntál are hosted/underlain by slightly metamorphosed rocks of the Horní Benešov Formation and unmetamorphosed rocks of the Moravice Formation, both belonging to the Nízký Jeseník Mts regional unit (Fig. 1). The Miocene Hůrka Hill near Opava and the occurrence at Štemplovec of unknown age penetrate through the Moravice Formation sediments only.

The Sudetic Marginal Fault, separating the Žulová granitic massif from the crystalline complexes of the Králický Sněžník Mts and the Hrubý Jeseník Mts in the territory of the Czech Republic, is accompanied by several faults of similar strike in both crystalline complexes. A continuation of one of the closest faults to the SMF, or the continuation of the SMF itself, proceeds to the area of the BVF (see Fig. 1). As the SMF is presently active (Štěpančíková et al. 2010), it could be responsible for some magmatic activity during the Pleistocene or even earlier. A similar scenario of tectonic predisposition was published by Barth (1977).

The volcanic landforms have been described as stratovolcanoes or composite volcanoes. This terminological misunderstanding possibly arose from the first description of Jahn (1907) and an old-fashioned understanding of the presence of both explosive and effusive products. Volcanic activity in the BVF started as somewhat explosive and soon produced scoria cones. At the beginning explosiveness was influenced by contact with water during magma ascent. Partly-palagonitized phreatomagmatic tuffs were formed. This is most visible at the Venušina sopka Volcano. In this point of view, the role of the SMF-parallel faults during the volcano formation is well acceptable — surface water and ascending magma can meet on fault planes. This influence was relatively small and variable. Activity of all the below described volcanoes of the BVF can be described as mostly phreatomagmatic at the beginning. Further volcanic activity was of magmatic type, producing scoriae and plastic bombs (Fig. 2a). Later it associated with effusive activity with smaller or larger lava production (Fig. 2b). This is a typical development of the most common type of a monogenetic volcano. We suppose mostly low-energy magmatic activity of Strombolian type, close to the Hawaiian type.

As Hůrka Hill near Opava represents an old eroded subvolcanic form and Štemplovec site does not provide any data, we focused only on four separate volcanoes and one "rootless" basaltic occurrence.

Břidličná Volcano (BV)

This is the oldest preserved basaltic rock of the BVF. The volcano is eroded down to the near-surface level of the magmatic vent, or just to the pre-volcanic superficial position. The inner-crater facies passing to the vent-breccia is exposed in an old quarry. Semi-plastic bombs are preserved, documenting a position very close to the vent. The majority of clastic material is represented by somewhat altered scoriae

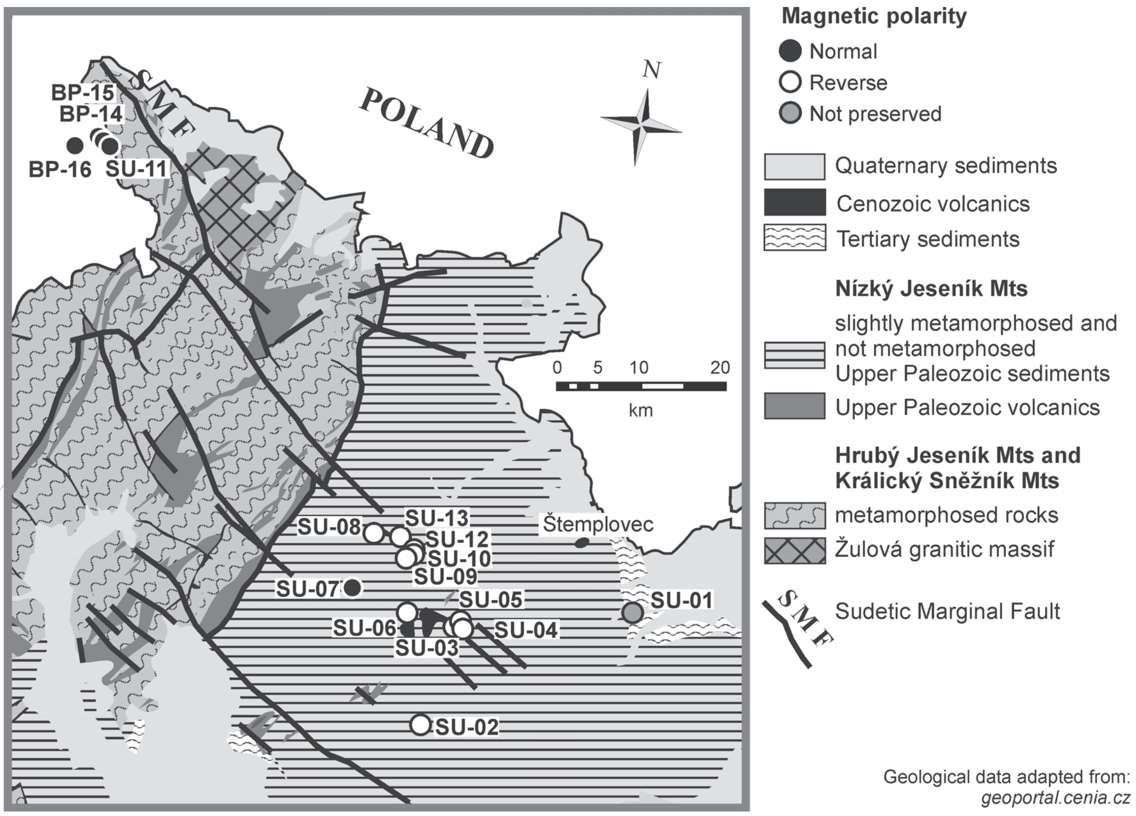

Fig. 1. A simplified geological map showing sampling sites and primary magnetic polarities of the studied rocks. Bruntál Volcanic Field (BVF) is shown by samples SU-02 to 10 and SU-12+13 in the central part of the frame. Zálesí (SU-11) and samples BP (14 to 16; taken from Birkenmajer et al. 2002) locate the Lutynia area in the NW.

Fig. 2. Selected volcanological features visible in outcrops: **a** — a ballistic-transported plastic bomb from the Uhlířský vrch Hill Volcano (UV) cinder cone; **b** — a thick columnar-jointed lava flow of the Venušina sopka Volcano (Mezina, sampling site SU-10), the change in jointing corresponds to facies development.

and the finest material is possibly primarily reduced in volume. The alteration visible on the outcrop can be caused by syngenetic process (phreatic influence) and by weathering, too. The massive basalt of the plug has been excavated for commercial use. The volcano very probably produced lava(s) but no outcrops are preserved now. Nevertheless, a small relic of lava was observed before exploitation (Jahn 1909). The size of the vent cut suggests a relatively large scoria cone of the Břidličná Volcano at the time of its origin.

Uhlířský vrch Hill Volcano (UV)

This volcano is situated closest to Bruntál. It represents a remnant of a scoria cone with a single thin lava flow extending to the east. Now, two walls of an old quarry expose scoriae, while the central more solid rock has been excavated. The exposed, mostly centroclinally stratified layers (the inner facies) mostly consist of scoriaceous lapilli and bombs. Centripetal layers are developed as well, further from the feeder. The stratification is visible in grading and in colour: an alternation of more and less palagonitized pyroclastics is visible. This may be a result of a pulsation caused by interaction with water in the vent in the early stages of volcanic activity. Palagonitization decreases upwards while the frequency of semiplastic bombs increases in the same direction. Red- to brown-coloured baked clasts of country rock (accidental pyroclasts) are present. A relatively great number of large ballistic-transported bombs, occur and have been deposited in plastic form. Spindle- to cow dung-shaped forms were observed, sometimes an indication of a bread crust-type bomb is visible. These bombs contain primary paleomagnetic field vector — their temperature was above the Curie point at the time of deposition. A small outcrop of slightly vesiculated and sonnenbrand-altered lava is hardly detectable in a railway cut 1 km to the E from the vent. The idea of Barth (1977) on the collapse of the cinder cone in its eastern part and production of a single small lava flow in this direction seems to be very realistic.

Venušina sopka Volcano (VS) near Mezina

This is another small volcano of the BVF but with higher effusive activity. The cinder cone in the central part of the hill is the most phreatic-influenced one among the volcanoes of the BVF. Accidental pyroclasts of Paleozoic country rocks are relatively frequent in altered scoriae. Basaltic vesiculated pyroclasts with chilled margins were observed. Spindle-shaped bombs are also present and about 1 m large bomb with a bomb-sag is exposed in an old quarry at the summit. A lava flow over 20 m thick was exploited in two abandoned quarries down on the slope, near the Černý potok Creek (see Fig. 2b). The older quarry described by Jahn (1907) really shows an unconformity dipping 40° to the E, but this does not represent the boundary between "two lava flows": no typical lower and upper facies of flows are developed. The rock is the same on both sides of this boundary; only a small difference in jointing is visible, representing a facies change inside the flow. Most probably, the unconformity originated subparallel to the dip of the lava body during cooling. A younger quarry in the same lava body exposes several facies of the same unit. Lava breccias are developed at the base, and the facies are represented by levels with different intensity of vesiculation and different intensity of sonnenbrand disintegration. Columnar jointing runs across all the facies. We suppose that the thickness is not caused by a stacking of several (up to 4!) lava flows. The enormous thickness resulted from a decrease in flow velocity and its stopping by a body of hyaloclastic breccia at the lava front, now mostly eroded. This body was produced by thermal shock at the contact of the lava with an active water flow.

Velký Roudný Hill Volcano (VR)

This is the largest volcano of the BVF. It also displays the largest preserved effusive production. Our description of this volcano slightly differs from that of previous authors (e.g. Barth 1977). The two summits lying closely apart — Velký ("large") Roudný and Malý ("small") Roudný Hills — were sometimes believed to represent two separate volcanoes. We suppose that Malý Roudný Hill is not an independent volcano. Now, it represents only a part of the same volcano (its cinder cone), separated and modelled by erosion from another summit. This is supported by the presence of a single vent based on the evaluation of geophysical survey (see the part "Gravity and airborne magnetometry..." below). The same idea of a large volcano is suggested from small basaltic occurrences like Volárenský vrch Hill, Křišťanovice and possibly Zlatá Lípa near Červený vrch Hill. All these may represent erosional relics of other flows from the same volcano. No signs of separate vents were found. All the exposed basalts of this position show only signs of lavas. Unfortunately, the outcrops in pyroclastics are poor for comparison. Variation in the chemistry of lava in one flow mentioned by previous authors is a usual phenomenon and cannot be used for the flow determination. Moreover, the compact facies has been altered. We suppose a location of the feeder between the future Velký Roudný and Malý Roudný Hills, building of a large cinder cone with possible (but not proved) parasitic vents and production of several lava flows (3?). The largest preserved flow fills the valley of the paleo-Moravice River (Slezská Harta, Bílčice-Leskovec). Volárna relic represents the second flow. The southern flow can be traced as far as the proximity of Křišťanovice (4 km) now forming a small erosional relic. The connection of the Zlatá Lípa site to this flow is more problematic because of the large distance (ca. 12–13 km). Although it is far from the supposed vent, this connection cannot be excluded. Lava production in several flows can be deduced from the spatial distribution of the relics, not from superposition as no superimposed lavas are exposed now. The largest flow filling the paleovalley of the river shows only several facies, and the unconformity still visible in the active quarry of Bílčice does not represent a boundary between two units. The enormous thickness of ca. 50 m can be explained by flow deceleration by hyaloclastite breccia which formed at the lava/stream interface at the front and on the surface of the flow. Sediments of fluvial terraces are known to underlie this flow (Horský et al. 1972). Kolofíková (1976) employed anisotropy of magnetic susceptibility to the study of the flow orientation. Her results correspond to the supposed directions of the flow and its facies development (see also Tarling & Hrouda 1993). The lens-like layer of porcelanite-rich material in the old quarry (near the lava front) mentioned in Barth & Zapletal (1978) and interpreted as a boundary between two flows may also represent a hyaloclastite breccia (not preserved now).

The volcanological results briefly described above were tested using the orientation of the paleomagnetic field vector and evaluation of magnetic and gravimetric regional fields. K/Ar dating was used as well.

The paleogeographic reconstruction of this volcano (Cajz et al. 2010) also incorporated two other sites of tuffites near the villages of Karlovec and Razová (Barth & Zapletal 1978). Our opinion on their origin is again only slightly different from previous authors. The source area for most of the scoriaceous material in tuffites can be placed in an old cone of the Břidličná Volcano, destroyed and transported by the paleo-Moravice River. The country rock surrounding this volcano (low-grade metamorphosed slates) was removed together with the scoriaceous material. Sedimentary clasts of the tuffites are low-grade metamorphosed rocks which do not correspond to the country rock of the tuffites. During effusive activity of the younger Velký Roudný Hill Volcano, a lava dam-lake was formed, the stream gradient of the river got changed, and the mixed pyroclastic-sedimentary material was deposited in the lake. Afterwards, the river used the contact between the lava and the former valley side to cut the present Moravice River channel. Some of the scoriae in tuffites may also have been produced during the activity of the Velký Roudný Volcano. This can be documented by the volume of redeposited pyroclasts in the sedimentary record at Razová, which shows a very slow increase in the upwards direction.

Zálesí lava flow

This erosional remnant is situated on the Czech-Polish border near Zálesí and has no vent in the territory of the Czech Republic. We suppose the production of this lava from the Lutynia area (Poland) where the vent is located, 1–2 km from the sampled location. The idea of this relation was tested using a comparison of magnetic properties of basalts on both sides of the border, comparing data of the Zálesí lava flow and previously published data from Lutynia (Birkenmajer et al. 2002).

Methods of study

Paleomagnetic and basic rock-magnetic studies

The previous studies by Krs (1968) and Marek (1969, 1973) first discovered reversed polarity in the BVF, with the exception of the Břidličná Volcano which is normally polarized. The latter author (Marek 1974) measured normal polarity at the Zálesí lava flow, which is the closest Czech location to the Polish sites, and discovered normal polarity of the basaltic occurrence from Ladek Zdrój. We have confirmed the older data obtained on an astatic magnetometer using a greater number of samples and different measurement techniques (see below). Normal polarity was recently detected by Birkenmajer et al. (2002) in the Lutynia area of Poland.

Thirteen sites in the territory of the Czech Republic were newly sampled and processed. Hand-operated drilling on outcrops provided 216 laboratory samples. The natural remanent magnetization was measured using the JR5a and JR6 spinner magnetometers and 755R superconducting rock magnetometer made by AGICO and 2G Enterprises, respectively. The samples for measuring were predominantly chosen according to the Koenigsberger ratio the (Q-parameter) which should be lower than 10; however data from the Břidličná volcano proved that Q-parameter can primarily reach over 40. The samples were demagnetized by alternating field in LDA-3a demagnetizer and 2G600 automatic sample degaussing system in 8 to 9 successive fields between 2 and 80 mT, and thermally demagnetized in MAVACS apparatus at temperatures between 80 and 600 °C with a 40° step. On most of the samples two Curie temperatures T_{c1} = 160–200 (300) °C and T_{c2} = 500–580 °C (Table 1) were recorded.

Table 1: Paleomagnetic and radiometric data for the sampling sites, data of Birkenmajer et al. (2002) are added for comparison. Curie temperature A and B is adequate to T_{c1} and T_{c2}, respectively. **Abbreviations of volcanoes:** VR — Velký Roudný Hill, BV — Břidličná, VS — Venušina sopka Hill, UV — Uhlířský vrch Hill. For more information on age see Tables 2 and 3 and the text.

Code	Site	Area	Volcano	Landform	N	E	Curie temp. A(°C)	Curie temp. B(°C)	Q-ratio	pol.	Declin. (°)	Inclin. (°)	α 95 (°)	n/N	Age *prev. studies*	Age ATOMKI
SU-01	Kamenná hora u Otic	Opava	Otice	vent eroded	49°54.828´	17°51.541´	200		2.8	???	*206*	*–13.8*	5.4	12/12	20 ± 3 SV	
SU-02	Zlatá Lípa (Červená h.)	BVF	VR?	lava relic	49°46.455´	17°31.727´		580	0.9	R	173.9	–83.5	4.2	9/9	1.24 LW	1.79 ± 0.15
SU-03	Bílčice quarry	BVF	VR	lava-S. margin	49°53.032´	17°34.385´	200	520	1.2	R	165.3	–75.8	3.7	25/25	2.7 ± 0.5 SH	2.33 ± 0.14
SU-04	Slezská Harta 1	BVF	VR	lava-N. margin	49°53.230´	17°34.690´	200	560	1.6	R	166.1	–76	4.8	19/20	1.46 ± 0.15 SH	2.21 ± 0.16
SU-05	Slezská Harta 2	BVF	VR	lava-surface	49°52.824´	17°34.991´	160	520	2.0	R	157.4	–81.5	5.0	15/22	1.28 ± 0.4 SH	2.37 ± 0.29
SU-06	Volárna	BVF	VR	lava relic	49°53.534´	17°29.352´	200	580	1.2	R	130.8	–75.5	5.1	16/16		2.48 ± 0.31
SU-07	Břidličná	BVF	BV	vent	49°54.726´	17°23.789´	180		30.0	N	349.9	61.5	5.2	6/7		3.74 ± 0.56
SU-08	Bruntál-trať	BVF	UV	lava relic	49°58.302´	17°27.923´	200	560	1.1	R	140.5	–68.5	4.2	10/10	2.4 ± 0.5 SH	1.54 ± 0.15
SU-09	Mezina 1	BVF	VS	lava	49°57.597´	17°29.358´	200	560	4.6	R	145.1	–79.6	5.2	16/16	1.94 ± 0.22 SH	1.26 ± 0.16
SU-10	Mezina 2	BVF	VS	lava	49°57.475´	17°29.226´	200	560	0.5	R	172.1	–84.8	3.6	17/17		0.83 ± 0.12
SU-11	Zálesí u Javorníka	Lutynia	Lutynia	lava relic	50°21.300´	16°55.369´	300	500	17.5	N	345	62.8	3.6	20/20		
SU-12	Venušina sopka	BVF	VS	bomb-cinder c.	49°57.007´	17°28.733´		580	4.6	R	134	–78.4	3.9	17/17	1.11 LW	2.14 ± 0.08
SU-13	Uhlířský vrch	BVF	UV	bomb-cinder c.	49°58.366´	17°25.339´		580	8.7	R	138.7	–83.8	3.1	16/25	1.47 LW	
BP-14	Lutynia-active quarry	Lutynia	Lutynia	plug	50°21.574´	16°54.671´				N	345*	67*	3.7*			4.56 ± 0.20*
BP-15	Lutynia-old quarry	Lutynia	Lutynia	lava	50°21.827´	16°54.091´				N	348*	62*	4.4*			3.83 ± 0.17*
BP-16	Ladek Zdrój	Lutynia	?	lava	50°21.121´	16°51.849´				N	359*	61*	3.6*			5.46 ± 0.23*

Explanations:
BVF = Bruntál Volcanic Field
* = paleomagnetic and radiomagnetic data from Birkenmajer et al. 2002
R — reversed polarity, N — normal polarity.
n — number of samples used for statistics
N — number of measured samples
n ? N — reasons described in text
SH = Šibrava & Havlíček 1980
SV = Shrbený & Vokurka 1985
LW = Lustrino & Wilson 2007

A principal component analysis by Kirschvink (1980) was performed for all measured samples and group statistics including mean direction (Fisher 1953) was computed on the distinguished primary components for all sites. The primary components were recorded in the temperature range 320–560 °C or field range 15–80 mT.

Representative alternating field and thermal demagnetization curves of four samples are shown in Fig. 3. Magnetic susceptibility was measured by KLY-4S. In order to identify the main magnetic carriers, temperature dependence of magnetic susceptibility was also measured in argon atmosphere from the room temperature up to 600 °C, and field-dependent magnetic susceptibility in the field range of 2–450 A/m. The Curie temperature of 180 °C and the steep field-dependent susceptibility curve (Fig. 4) obtained from the SU-7 site can be explained by the presence of titanomagnetite and other spinelid-group minerals. A similar situation was detected for the volcanics from the Krušné hory Mts (Schnabl et al. 2010) and corresponds with the findings of Vahle & Kontny (2005).

Conventional K/Ar age determination

Several authors published radiometric ages of basalts from the BVF (e.g. Šibrava & Havlíček 1980; Kopecký 1987; Lustrino & Wilson 2007). Some data remained unpublished but are accessible in a report (Shrbený & Vokurka 1985). Results from a ten year-old set were recently published by Pécskay et al. (2009) as an abstract during a regional conference in Olomouc. Birkenmajer et al. (2002) published data from sites in Polish Silesia close to Zálesí.

K/Ar dating of two data sets of samples was performed in the K/Ar Laboratory of the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary. The new K/Ar data set of the BVF was obtained from the same sites as the set for paleomagnetic research. About 200 g of each rock sample were crushed and sieved to 300 mm. Adhering fine particles were removed by rinsing in distilled water. Approximately 0.8 g of sieved sample were weighed for the whole rock. The amount of radiogenic ^{40}Ar was determined by means of the isotope dilution method using ^{38}Ar as a spike. Mass discrimination of argon isotopes was corrected by measuring air Ar. Previously preheated whole rock samples were degassed by RF fusion in Mo crucibles, and the usual getter materials (titanium sponge, getter pills of SAES St707 type and cold traps) were used for cleaning and transporting argon. The purified argon was directly introduced into the mass spectrometer (90° magnetic sector type of 150 mm radius and operated in the static regime). For the determination of the potassium content, about 1 g of the identical sample that was used for Ar measurement was ground in an agate mortar to the grain size finer than 50 mm. About 100 mg of this powdered sample was dissolved in hydrofluoric acid and nitric acid using a teflon bomb. Potassium content was determined by flame photometry with Lithium internal standard (CORNING M 480 flame photometer, digitized). The decay constants of Steiger & Jäger (1977) were used in the age calculation. All analytical errors repre-

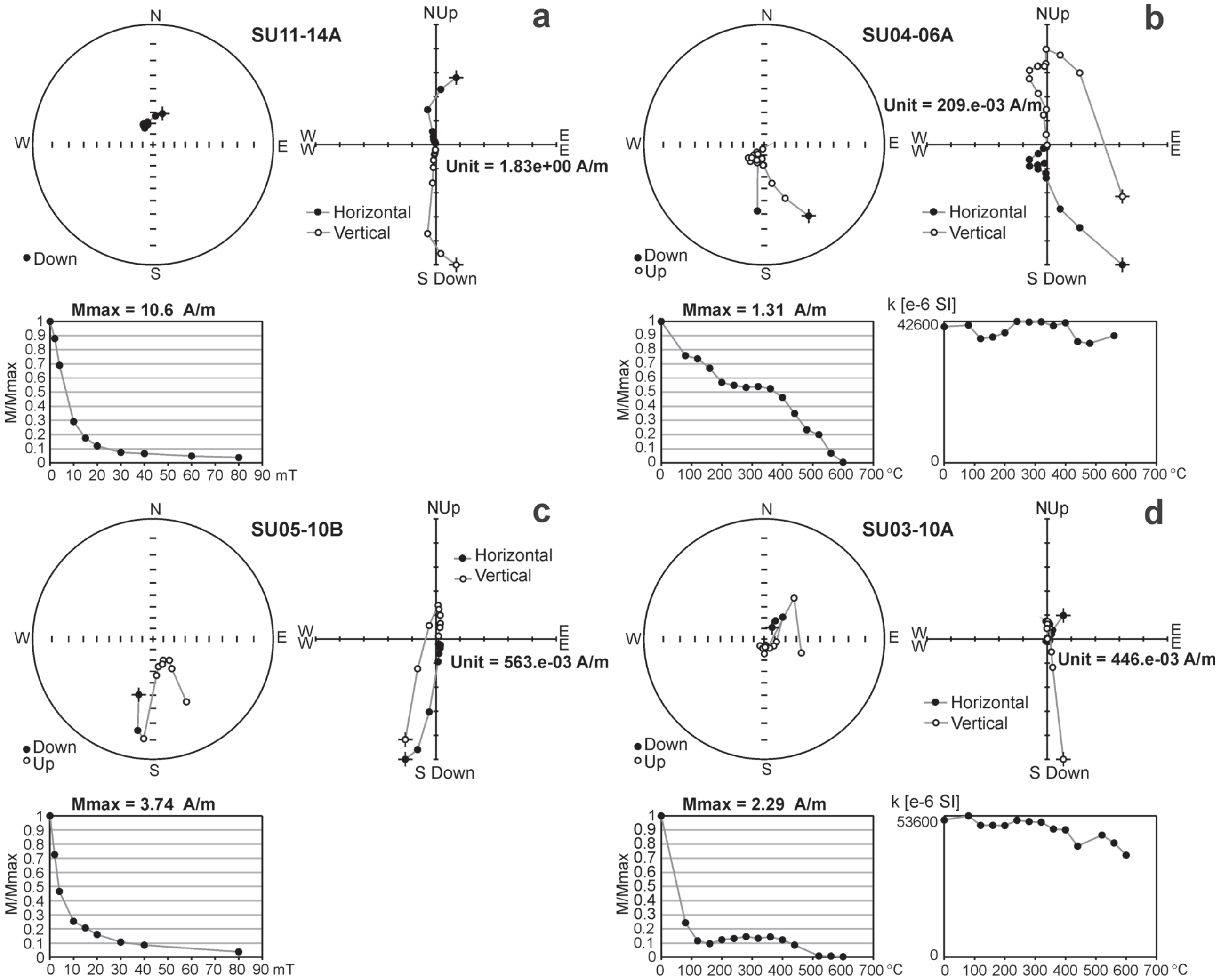

Fig. 3. Demagnetization curves and Zijderveld diagrams of four representative samples: **a, c** — AC field demagnetization curves of samples show a low-coercivity mineral (magnetite). The reversely polarized sample has a relatively strong viscous component; **b, d** — a thermal demagnetization curve showing the presence of magnetite with T_{c1} of 160–200 °C and T_{c2} of 560–600 °C and no change in magnetic susceptibility after individual demagnetization steps.

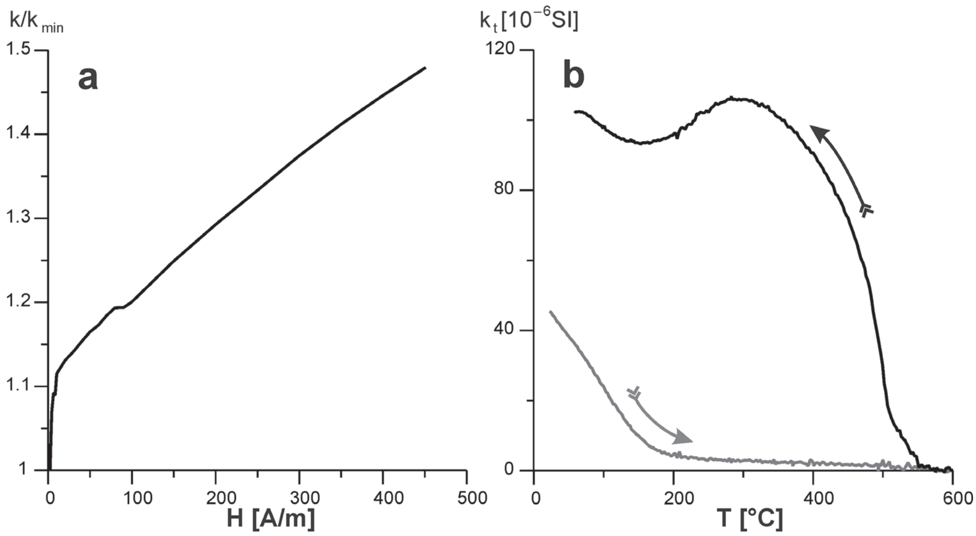

Fig. 4. Basic rock-magnetic measurements at the Břidličná Volcano (SU-07) prove the presence of minerals from the spinelid group (titanomagnetite, etc.): **a** — field-dependent magnetic susceptibility; **b** — temperature-dependent magnetic susceptibility shows phase change during laboratory heating. It is caused by newly formed magnetite in the altered rock during the procedure.

sent one standard deviation (68 % confidence level). Multiple runs of the inter-laboratory standards (Asia 1/65, LP-6, HD-B1 and GL-0) were used for checking the measurements. Details of the instruments, the applied methods and results of the calibration have been described elsewhere (e.g. Balogh 1985).

Gravity and airborne magnetometry used for interpretation

Geomagnetic data were acquired by a detailed airborne survey of the Nízký Jeseník Mts on the scale 1:25,000 in the late 1970s (Dědáček & Gnojek 1980). The anomalies were interpreted by Šalanský & Gnojek (2002) and Šalanský (2004). A detailed gravity survey was realized during the early 1970s (with measurement density of 3 points per 1 km^2) and the gravity data were compiled to the Bouguer, regional and residual gravity maps (Kadlec et al. 1972).

The generally monotonous positive regional magnetic field in the study area (except for the distinct positive magnetic Šternberk–Horní Benešov Zone with iron mineralization) is modified by several local anomalies in the Bruntál area induced by Cenozoic volcanics. Reversely polarized volcanic bodies with Q-parameter above 1 cause negative anomalies. Lavas and pyroclastic rocks of the VR Volcano near Leskovec nad Moravicí represent the source of the three distinctive negative anomalies (Fig. 5). Each negative anomaly in the original maps is accompanied by a small positive anomaly on the N. It points to the tabular shape of bodies more than the steep anisometric one. But only detailed field measurements could specify their geometry. An anomaly of about −10 nT situated to the NE along the Moravice River reflects the largest preserved volcanic flow. The anomaly of −50 nT to the SW corresponds to Malý Roudný Hill. A central, very distinctive negative magnetic anomaly of about −60 nT coincides with a small local positive gravity anomaly of more that 15 μms^{-2} in the regional gravity survey. Such a type of coincidence is typical for a volcanic vent (e.g. Lidner et al. 2006; Cassidy et al. 2007). The close-up gravity field map places this small positive gravity anomaly close to Velký Roudný Hill. As the magnetic anomalies correspond to the tops of both hills and no solid basalts are known on their summits, the anomalies are supposed to reflect only volcaniclastics. On the other hand, their intensity is higher than that of an anomaly induced by a relatively thick lava flow. The existence of parasitic feeders of a large volcano is one of the possible explanations. Volcanological interpretation of such data is problematic because the results of the geophysical survey are not unambiguous. A more detailed field geophysical survey is needed for correct specification of the geometry and exact location of the vent.

The Uhlířský vrch Hill (UV) and the Venušina sopka (VS) volcanoes, closer to Bruntál, are characterized by weak negative magnetic anomalies (about −10 nT relative to background). The individual vents cannot be precisely determined from geophysical fields, they are monotonous. The Břidličná Volcano vent is indicated by an elongated local positive magnetic anomaly (normal magnetization). Similar positive magnetic anomaly about 3 km to the S, accompanied by a negative gravity anomaly (−25 μms^{-2}), indicates the supposed buried volcanic maar near Lomnice. This unique phenomenon is visible only in the gravity and magnetic data.

Results

A new volcanological evaluation of the volcano remnants was made. The older volcanological evaluation was generally confirmed (Horský et al. 1972; Barth 1977). Only in the case of the largest volcano, Velký Roudný Hill and the neigh-

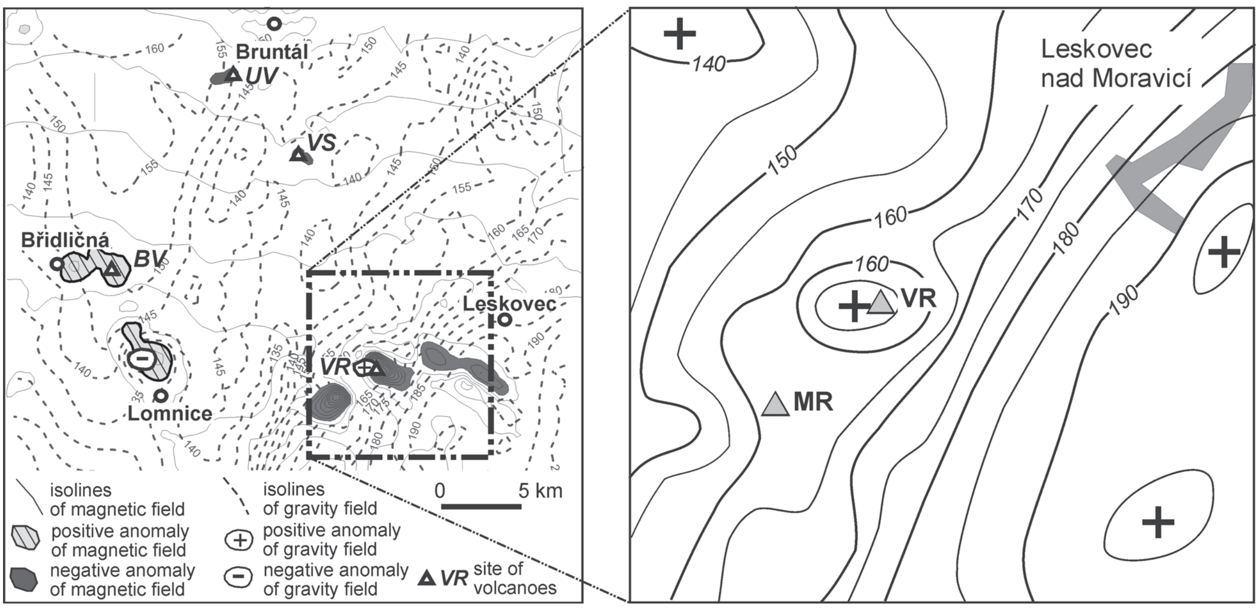

Fig. 5. Summarized regional magnetic [nT] and gravity [μms^{-2}] fields of the Bruntál Volcanic Field (BVF) and a close-up map of the gravity field at Velký and Malý Roudný Hills (VR)–(10 μms^{-2} = 1 mGal). Adapted from Šalanský & Gnojek (2002) and Kadlec et al. (1972).

bouring hill of Malý Roudný, our results are slightly different. Basalts of this area were studied in their paleomagnetic properties and several of them were processed to obtain their K/Ar ages. Paleomagnetic results were compared with existing reliable radiometric data. This, together with the analysis of magnetic and gravity fields, allowed us to reconstruct volcanic activity in time and space and supported the volcanological evidence. A combination of different approaches resulted in evaluation of the whole set of K-Ar data.

Paleomagnetism

Lavas and bombs from cinder cones on both smaller volcanoes of the BVF (UV and VS) were sampled. The sampled bombs were chosen based on volcanological observation — the plastic type ones (e.g. cow-dung and spindle-shaped) were preferred. Only lavas were accessible at VR. Paleomagnetic results proved that larger bombs were transported above the Curie temperature (560 °C for VS and 400–560 °C for UV). The primary field of explosive and effusive products of Uhlířský vrch Hill is visible in Fig. 6a. The primary field of both lavas and pyroclastics of VS is documented in Fig. 6b. Differences in the paleofields between UV and VS are only 1.3°. Secular variation of all volcanoes is not centred because of the supposed short duration of volcanic activity, complying with the relatively short lives of monogenetic volcanoes. From this, we can conclude a nearly identical time of origin of the two volcanoes, moreover, when the K/Ar ages are very close.

Paleomagnetic data from the Velký Roudný Volcano (Fig. 6c) were obtained from lava of its largest flow; pyroclastics are not available for sampling. The samples chosen for paleomagnetic evaluation come from the compact facies of the lava flow. Data from site SU-03 (Bílčice quarry) were systematically rotated 13° to the N compared to the others from the same lava flow. Horský et al. (1972) have discovered tilting of large basaltic blocks during the investigation for the dam construction. This finding is in agreement with the geological position of the sampling site and the mechanism of disintegration of the lava body. This was the reason for the apparent heterogeneity of data from one location.

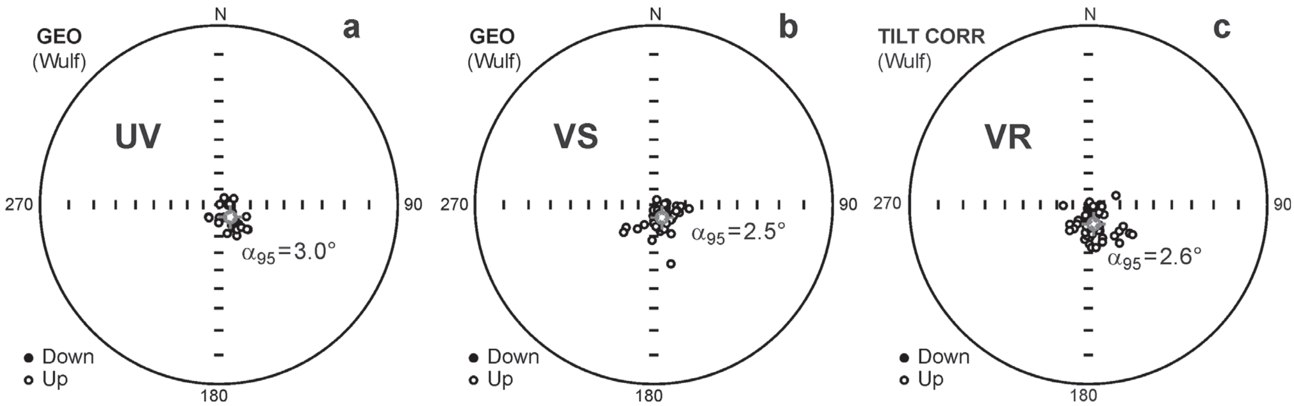

Fig. 6. Summarized paleomagnetic vector projections of the youngest volcanoes: **a** — Uhlířský vrch Hill (UV), pyroclastics and lava. The most components are computed between 400 and 600 °C or 20–100 mT. **b** — Venušina sopka Volcano (VS), pyroclastics and lava. The most components are computed between 280 and 560 °C or 15–80 mT. **c** — Velký Roudný Hill (VR), lava. The most components are computed between 320 and 560 °C or 15–80 mT.

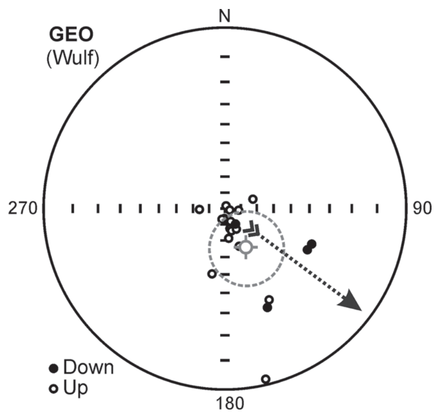

Fig. 7. Paleomagnetic vector projection of the complex data with a–a lava breccia clasts (Slezská Harta lava flow — VR) and the lava flow direction. The most components are computed between 280 and 600 °C or 15–80 mT.

One interesting effect was observed on a-a brecciated surface of the largest lava flow of VR. Figure 7 shows the extraordinary distribution of samples taken from breccia clasts, which resulted in α95 value of 23.2° for the whole location. This is caused by a special type of sample — the rotation of clasts from destroyed already cooled surface incorporated into fluidal lava is responsible for this phenomenon. Grouping of these samples shows direction of axis similar to the direction of the flow and very close to the interpreted AMS data of Kolofíková (1976). This phenomenon can be derived from the style of rotation of a-a clasts at the surface in the central part of the flow. Data from only one location cannot be statistically significant; anyway, combination of AMS and direction of remanent magnetization offers a theme for methodological study on behaviour of a-a lava flows.

Grouping of all reliable data of the VR lava flow (see Fig. 6c) enabled comparison of the paleofield of the largest lava flow from VR with that of smaller volcanoes (UV and VS). The angle between the mean directions of their vectors is 4.5 and 5.0°, respectively. Unfortunately, this small difference does not provide a conclusive basis for magnetostratigraphic interpretation itself. Anyway, it agrees with new radiometric data which divide the reversely polarized volcanic bodies into two separate phases.

A wider difference of 6.4 and 8.0° is obtained if we compare the sites of the isolated lava relics of Zlatá Lípa and Volárna, most possibly belonging to the VR volcano, too. From this, we conclude the possibility of the production of other flows from the same volcano (VR). The Volárna relic seems to be produced close in time to the main flow, while the Zlatá Lípa relic may represent a younger flow.

Two of our sampling sites are normal polarized. The Břidličná Volcano has an extremely high Q-parameter (average around 30, but often exceeding 40). Usually, these high values are explained by a secondary influence, such as lightning. But in this case, the sampling site is situated in the depth of the old quarry, so the influence by lightning is not realistic. A more probable reason can be seen in the titanomagnetite composition (see Fig. 4).

Another normal-polarized occurrence is the lava relic near Zálesí on the Czech-Polish border. Its paleomagnetic characteristics are comparable with those of the basaltic occurrences in Polish territory (Marek 1974; Birkenmajer et al. 2002), close to the sampling site. Volcanological evaluation proves the relation of this lava relic at Zálesí to the plug of Lutynia. Figure 8 shows very close vector orientations for all normal-polarized volcanics in the Lutynia vicinity, including the Břidličná Volcano. This situation can be explained by volcanic activity in a very close time span. The conclusion offers two results: the Zálesí lava flow was produced from the Lutynia Volcano as supposed from geology; and the Břidličná and Lutynia volcanoes were active nearly simultaneously.

The Kamenná hora Volcano near Otice is one of the oldest in the region. The site displays a deeply eroded vent whose volcanic rock was strongly altered. The main magnetic carrier is titanomagnetite (Curie temperature around 200 °C). The mean paleomagnetic directions are D = 206° and I = –14°, similar to those measured by Marek (1974). The inclination is extremely low compared to other Cenozoic rocks. Both values show rather "Paleozoic-like" directions, similar to data from Barrandian volcanics (Kletetschka et al., in print). Given the known age of 20 Ma for the Otice volcano (Shrbený & Vokurka 1985), the acceptable explanation can be seen in a possible rotation of the only preserved block in an old quarry, most probably due to quarrying activities. This is the reason why we suppose that the primary polarity is impossible to reconstruct (see Fig. 1), and this location is not suitable for paleomagnetic studies.

K/Ar datings

Table 1 compares new data from the laboratory in Debrecen and older data of previous authors from other laboratories. Older data from several sites differ significantly from new ones (Table 2), moreover, the localization of several previous sampling sites is very poor (see e.g. Lustrino & Wilson 2007). The latter data were published without analytical errors, so their informative value is not fully comparable with the others.

Conventional K/Ar dating of 12 representative whole-rock samples was carried out in two sets (Table 3). The first set of 6 samples was collected and analysed 10 years ago. These preliminary data remained unpublished for a long time but were accessible. In the meantime, a new flame photometer (CORNING M 480) has been set up in Debrecen, therefore the potassium analyses made on the first set of samples were repeated. Considering that consistent results were achieved, the mean K contents were used for the recalculation of the previous K/Ar ages. At the same time, 6 additional samples were collected from the same sites for paleomagnetic studies, hoping to get confirmation of the meaningful ages obtained on the previous samples.

On the basis of the preliminary results, we concluded that the BVF basaltic rocks are generally younger than the alkaline basaltic rocks exposed at Lutynia and Ladek Zdrój. On the other hand, the analytical data suggested that the volcanic activity was episodic: older than 3.4 Ma, around 2.3 Ma and younger than 1.5 Ma. However, such an estimation does not consider possible geologically induced disturbances of the argon isotope system, such as Ar loss by alteration or excess Ar by incorporation of xenocrysts/xenoliths. Because of these uncertainties, we use all the available and reliable radiometric data in this study, determined in different laboratories (see Table 2). The paleomagnetic data are also taken into account for the final model of the volcanic evolution.

Four new K/Ar ages of whole-rock samples (SU-03, 04, 05 and 06) are identical within the analytical error. On the basis of the concordant age, we consider these ages to be statistically significant for the geological setting. Therefore, one can assume that

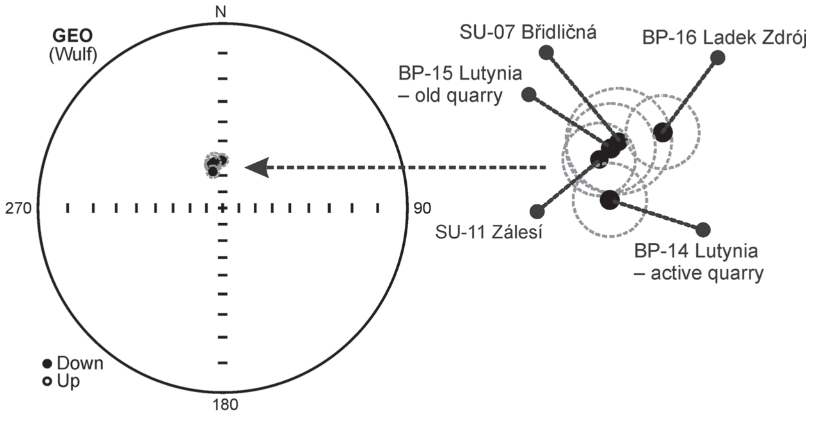

Fig. 8. Paleomagnetic vector projection of the Zálesí lava relic and the Břidličná Volcano vent, compared with products from the Lutynia area. The most components are computed between 200 and 500 °C or 10–80 mT.

Table 2: All available primary K/Ar age data from the region in the territory of the Czech Republic. For abbreviations of authors see Table 1; and P 2009 = Pécskay et al. 2009.

Volcano	Landform	Original site name	Adequate to	K/Ar age (Ma)	Sampling year	Authors
Otice	vent (eroded)	Kamenná hora Hill	SU-01	20 ± 3	?	SV 1985
BV	vent (surface)	Břidličná	SU-07	3.69 ± 0.56	2000	P 2009
VR 1	lava-S. margin	Velký Roudný (Bílčice)	SU-03	3.31 ± 0.24	2000	P 2009
VR 1	lava-S. margin	Bílčice-Leskovec	SU-03	2.7 ± 0.5	?	SH 1980
VR 1	lava-S. margin	Bílčice-Leskovec	SU-03	3.4 ± 0.9	?	SH 1980
VR 1	lava-S. margin	Bílčice	SU-03	2.33 ± 0.14	2010	this paper
VR 1	lava-N. margin	Slezská Harta 1	SU-04	2.21 ± 0.16	2010	this paper
VR 1	lava-surface	Slezská Harta 2	SU-05	2.37 ± 0.29	2010	this paper
VR 1	lava-front	Slezská Harta	*no sample*	1.28 ± 0.4	?	SH 1980
VR 1	lava-front	Slezská Harta	*no sample*	1.46 ± 0.15	?	SH 1980
VR 1	lava-front	Slezská Harta	*no sample*	1.6 ± 0.6	?	SH 1980
VR 1	lava-front	Slezská Harta	*no sample*	2.2 ± 0.9	?	SH 1980
VR 2	lava relic	Volárna	SU-06	2.48 ± 0.31	2010	this paper
VR 2	lava relic	Volárenský vrch	SU-06	2.41 ± 0.14	2000	P 2009
VR?	lava relic	Zlatá Lípa	SU-02	1.75 ± 0.15	2000	P 2009
VR?	lava relic	Zlatá Lípa	SU-02	1.24	1992	LW 2007
VS	lava	Venušina sopka	SU-09, SU-10	0.80 ± 0.11	2000	P 2009
VS	lava	Mezina	SU-09	1.26 ± 0.16	2010	this paper
VS	lava	Mezina	SU-09, SU-10	1.94 ± 0.22	?	SH 1980
VS	bomb-cinder c.	Venušina sopka	SU-12	2.14 ± 0.08	2010	this paper
VS	?	Venušina sopka	?	1.11	1992	LW 2007
UV	?	Uhlířský vrch	SU-08 ?	2.4 ± 0.5	?	SH 1980
UV	lava relic	Bruntál-trať	SU-08	1.54 ± 0.15	2000	P 2009
UV	bomb-cinder c.	Uhlířský vrch	SU-13	1.47	1992	LW 2007
?	?	91/1 — no location	?	0.91	1992	LW 2007
?	?	91/2 — no location	?	1.22	1992	LW 2007
?	?	91/4a — no location	?	4.58	1992	LW 2007

VR1 = Velký Roudný Hill Volcano, its largest lava flow; VR2 = Velký Roudný Hill Volcano, relic of another flow; VR? = relic of possible next younger flow from the Velký Roudný Hill; VS = Venušina sopka Volcano; UV = Uhlířský vrch Hill Volcano.

Table 3: Results of radiometric analyses used for this study (ATOMKI Debrecen, Hungary); sets 2000 (CZB samples) and 2010 (SU samples). Data of the set from 2000 (Pécskay et al. 2009) are recalculated with new results on potassium content.

K/Ar code	Sample code	Site	K (%)	$^{40}Ar_{rad}$ (ccSTP/g)	$^{40}Ar_{rad}$ (%)	K/Ar age (Ma)
5373/A	CZB-4A	Velký Roudný (Bílčice)	0.886	1.155×10^{-7}	20.2	3.35 ± 0.23
5375/B	CZB-6B	Zlatá Lípa	1.078	7.526×10^{-8}	16.4	1.79 ± 0.15
5370/B	CZB-1B	Břidličná	1.31	1.909×10^{-7}	9.1	3.74 ± 0.56
5371/A	CZB-2A	Uhlířský vrch	0.663	3.973×10^{-8}	14.1	1.54 ± 0.15
5372/A	CZB-3A	Venušina sopka	1.136	3.652×10^{-8}	9.6	0.83 ± 0.12
5374	CZB-5	Volárenský vrch (Volárna)	1.118	1.066×10^{-7}	27.2	2.45 ± 0.13
8012	SU-03	Bílčice	0.975	8.845×10^{-8}	23.4	2.33 ± 0.14
8013	SU-04	Slezská Harta	0.95	8.169×10^{-8}	19.3	2.21 ± 0.16
8014	SU-05	Slezská Harta	0.751	6.945×10^{-8}	10.9	2.37 ± 0.29
8015	SU-06	Volárenský vrch (Volárna)	0.985	9.519×10^{-8}	11.1	2.48 ± 0.31
8016	SU-09	Mezina	1.446	7.096×10^{-8}	11.1	1.26 ± 0.16
8017	SU-12	Venušina sopka	1.188	9.872×10^{-8}	27.3	2.14 ± 0.08

these whole rocks contain negligible rock or mineral components with insufficient Ar retentivity or with excess Ar. This assumption is confirmed by the analytical data obtained for a sample from the previous set (CZB-5, sampling site identical with SU-06) — see Table 3. In contrast, the radiometric ages from the VS (CZB-3A and SU-12) appear to be affected by excess Ar (0.83 ± 0.12 and 2.14 ± 0.08 Ma), assuming that the age disturbances are mainly caused by the presence of some very fine-grained xenocrystic material, which is impossible to eliminate from the samples. Consequently, the younger age is closer to the real geological age than the older one. However, it cannot be completely excluded that sample CZB-3A was affected by a slight alteration which resulted in Ar loss. As a consequence, the analytical age determined for this sample should be considered, as a "minimum age".

Discussion

Reversed-polarized young volcanoes of the BVP must be older than 0.781 Ma (Gradstein et al. eds. 2004) — the Matuyama polarity chron. Based on polarity and group statistics results, supported by volcanological evidence, we can discuss the reliability of the K/Ar dating done during the last nearly 40 years in different laboratories. On the example of the products from Velký Roudný Hill (see Fig. 1 for location, samples SU-03 to SU-06) we can explain the result of the evaluation which is documented in Fig. 9. The data obtained in the early 1980s for the largest lava flow (Slezká Harta and Bílčice-Leskovec) have relatively large analytical errors — over 30 %. As a result, a part of the time period belongs to the normal polarity event. One rock body measured several times and in several sampling-places shows different ages. The possible period is therefore so wide that it looses validity. Moreover, the evaluation of volcanological phenomena, which is proved by group statistics of paleomagnetic results, now summarizes 9 ages for the same lava body (VR1 — see Table 2). The time span counted from all these data is 4.3–0.88 Ma, if we give the same weight to each result. The high age of the two above mentioned reversed samples from VR is comparable to the normal polarized activity of BV and Lutynia only by chance; the measured polarity does not allow this possibility. Therefore, such an age is not realistic for the VR activity. So, we have chosen data which were grouped in a time period closest to the reversed polarity subchron. It is important to notice

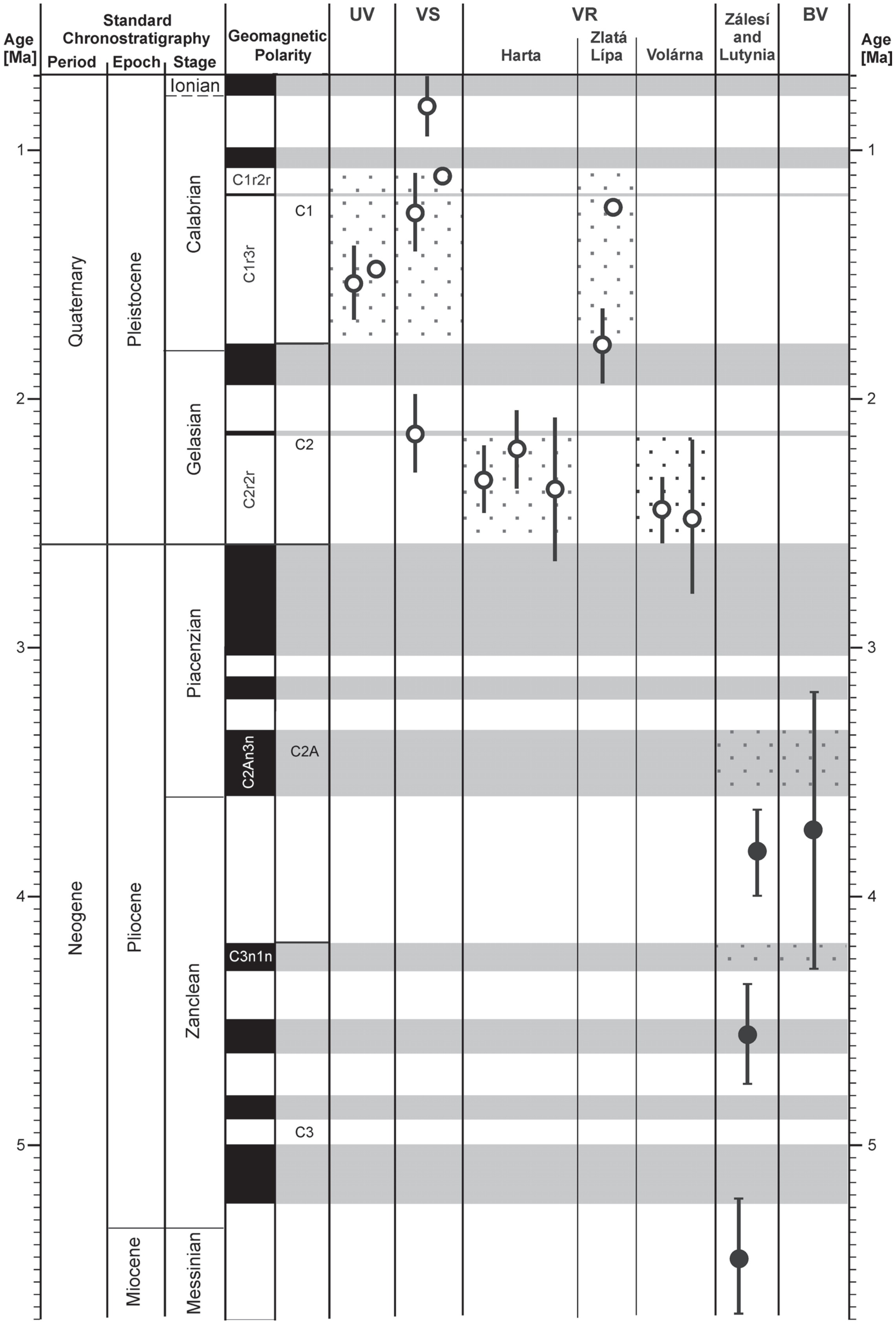

Fig. 9. The highest probability age (dotted time spans) of Pleistocene (reverse-polarized — open circles) volcanoes of the BVF compared to Pliocene (normal-polarized — black dots) volcanic activity. If open circle only — no analytical error was given by previous authors (Lustrino & Wilson 2007). Stratigraphic chart after Gradstein et al. (2004).

that only newly obtained data with smaller analytical errors were the result. Thus, the most possible chron of the lava flow origin is C2r2r (2.581–2.148 Ma). The Volárna lava relic with a slightly different vector orientation is very close in time, belonging to the same chron. Only the Zlatá Lípa lava relic is younger (1.24 Ma in Lustrino & Wilson 2007 or 1.79±0.15 in Pécskay et al. 2009) with a possible origin during the C1r3r Chron. Its vector orientation is slightly different as well.

Based on this, we can conclude that two lava flows were produced from the VR vent, close in time or simultaneously — to the SE (Slezská Harta) and to the W (Volárna). As has been mentioned above, another lava flow oriented to the S (Křišťanovice–Zlatá Lípa) could have been produced later, during a possible remobilization connected with UV and VS formation. This model corresponds to the new volcanological evaluation.

The orientation of the paleofield vector in the products of both smaller volcanoes is nearly identical. Therefore, we suggest that these youngest volcanoes (Uhlířský vrch Hill and Venušina sopka Volcano) were constituted most probably during the C1r3r or C1r2r Chrons (1.778–1.072 Ma), although one K/Ar age from VS (0.80±0.11 Ma in Pécskay et al. 2009) is younger, situated within C1r1r — see above. The only older age (2.14±0.08 Ma), newly obtained from the bomb of the cinder cone (VS), might have been easily influenced by contamination during vesiculation or alteration during the phreatomagmatic event.

As the K/Ar age of the normal-polarized older Břidličná Volcano meets three normal subchrons (C2An2n — 3.207–3.116 Ma; C2An3n — 3.596–3.330 Ma; C3n1n — 4.300–4.187 Ma), only the two older ones represent the most probable time of origin. This is substantiated by the results of group statistics, where the vectors of BV and the Lutynia Volcano are similar. In a similar way, we can evaluate the age of the plug in Poland (Lutynia I) as slightly shifted to a higher age.

Another interesting conclusion can be seen from the point of view of tectonic development. All the studied area is influenced by the tectonics of the Sudetic Marginal Fault. For the ascent of basaltic magmas, we assume the tectonic activity in the form of relative extension, at least. It allows us to suppose close interrelationship of volcanism and tectonics (changes in paleostress field) in time. At the time of the older volcanic activity (Břidličná and Lutynia), tectonic disquiet is mentioned in the mountain ranges of Veľká and Malá Fatra (Kováč et al. 2011), some 150 km to the SE. On the contrary, the time of two younger volcanic phases (Velký Roudný, Venušina sopka and Uhlířský vrch) is supposed to represent a period of tectonic quiescence in the Fatra region. Unfortunately, this study is not able to explain this disparity.

Conclusions

Newly obtained data on spatial and time distribution of volcanic activity do not confirm the idea of its shifting in time from the N to the S (sensu Birkenmajer et al. 2004) in the Czech part of Silesia. We can only state that three different Late Cenozoic volcanic phases exist, with the following most probable timing:

i) Pliocene (Late Zanclean or Early Piacenzian) phase of normal polarity in the span of 4.3–4.2 Ma (C3n1n) or 3.6–3.3 Ma (C2An3n) constituting the Břidličná and Lutynia Volcanoes;

ii) Gelasian phase (2.6–2.1 Ma, C2r2r) which formed the Velký Roudný Volcano with its large lava production; and

iii) Early Calabrian phase (1.8–1.1 Ma, C1r1r+C1r2r) of the Venušina sopka and Uhlířský vrch Hills, with possible remobilization of the Velký Roudný Volcano (southern flow of Zlatá Lípa).

These results represent a strong basis for the Upper Cenozoic volcanostratigraphy of this region. They can also contribute to the ideas on the younger history and development of tectonic activity, connected to the Sudetic Marginal Fault system. The Otice Volcano rock is not appropriate for paleomagnetic studies.

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