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Identification of a buried Late Cenozoic maar-diatreme structure (North Moravia, Czech Republic)

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Abstract: The maar-diatreme volcanic structure in the vicinity of the village of Lomnice near the town of Bruntál (North Moravia, Czech Republic) has been investigated using a set of geophysical methods including ground magnetometry, gravimetry and electrical resistivity tomography. The structure was detected by an aerial magnetic survey in the second half of the 20th century. Since its discovery only limited information about this buried structure has been available. The coherence of the magnetic anomaly of 190 nT and Bouguer anomaly of −4.7 mGal indicates a volcanic origin of the structure. The funnel-shaped maar-diatreme structure is filled with lacustrine clay and colluvium of Carboniferous greywacke, which forms the country rock. The surface diameter of the structure is about 600 m, the depth is more than 400 m. The spatial association with other volcanic centers in the surroundings of the town of Bruntál infers the relative dating of the Lomnice maar. The phreatic eruption and maar-diatreme formation could be an indirect consequence of effusive activity of the nearby Velký Roudný volcano. The Lomnice structure is the first Plio-Pleistocene maar-diatreme ever described in North Moravia and Silesia.

Key words: applied geophysics, ground magnetometry, gravimetry, electrical resistivity tomography, maar-diatreme, Plio-Pleistocene, Central European Volcanic Province, Bohemian Massif.

Introduction

The Late Cenozoic volcanic activity in the eastern part of the Bohemian Massif (North Moravia) belongs to the Central European Volcanic Province (CEPV), which includes the Rhenish Massif and Eifel area, Germany and the Eger (Ohře) Rift in the Bohemian Massif, Czech Republic (Kopecký 1964; Schreiber & Rotsch 1998; Ulrych et al. 2011) (Fig. 1). The anorogenic volcanism (Ulrych et al. 2011) in the province is linked to the development of a major intracontinental rift system and to domal uplift of the Variscan basement. Mantle processes such as the diapiric upwelling of small-

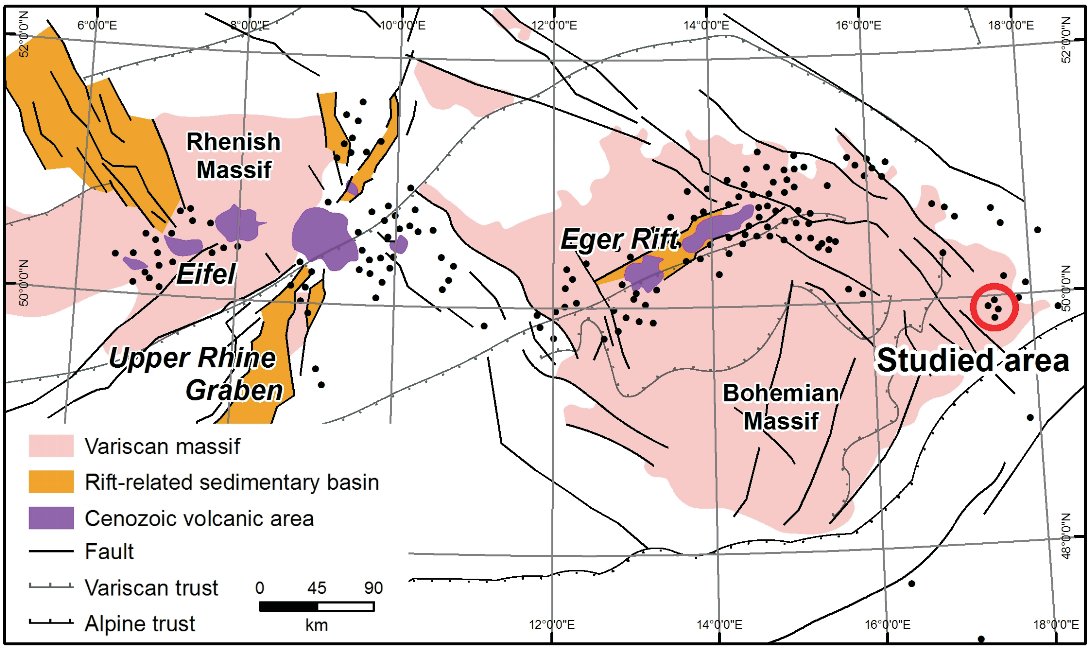

Fig. 1. Simplified tectonic map showing the position of the studied area in the CEVP (based on Ulrych et al. 2011).

scale convective instabilities from the base of the upper mantle (Wilson & Downes 2006) or episodic rising of mantle plumes (Wedepohl & Baumann 1999) are considered as the driving mechanisms for the volcanic activity.

While the time constraints and tectonic models for the development of the Eger Rift and its volcanism are frequently discussed in the literature (Babuška & Plomerová 2008; Ulrych et al. 2011), little is known about the easternmost part of the volcanic province in North Moravia and Silesia (Fediuk & Fediuková 1985; Birkenmajer et al. 2007; Lustrino & Wilson 2007). The Plio-Pleistocene (5.5 to 0.8 Ma) anorogenic volcanic activity in North Moravia is aligned with the Sudetic fault system and it is spatially and temporally associated with increased CO_2 fluxes, development of geomorphic faults, present-day seismic activity and active graben-like sedimentary basins (Grygar & Jelínek 2003; Špaček et al. 2009).

The Cenozoic volcanic rocks in North Moravia have been known and mapped since the end of the 19th century (Makowsky 1882; Klvaňa 1893), but information about their age and geochemistry is scarce (Marek 1973; Šmejkal 1980; Šibrava & Havlíček 1980; Birkenmajer et al. 2002a,b, 2004, 2007; Pécskay et al. 2009). The existing geophysical research was focused mainly on the regional magnetic surveys (Gruntorád & Lhotská 1973; Šalanský & Gnojek 2002; Šalanský 2004) and only a few shallow geophysical data are available for specific volcanic features such as diatremes (Šalanský & Gnojek 2002).

Shallow geophysical imaging, including magnetometry, gravimetry and electric conductivity (resistivity) surveys proved to be a useful approach in the mapping of diatreme volcanoes (Macnae 1995; Schulz et al. 2005; Matthes et al. 2010). Recently, Cenozoic maars and diatremes were geophysically imaged in the western and northern parts of the Bohemian Massif (Schulz et al. 2005; Lindner et al. 2006; Mrlina et al. 2009; Skácelová et al. 2010).

The aim of this paper is to provide information on the shape and subsurface structure of a maar-diatreme volcano near Lomnice, North Moravia based on detailed magnetometric and gravimetric mapping combined with electrical resistivity tomography. The geophysical image of the maar-diatreme can be useful for subsequent dating and tectonic interpretation of the Plio-Pleistocene volcanic activity in the easternmost part of the CEVP.

Geological setting

The North Moravian Cenozoic volcanism represents the easternmost part of the Odra tectono-volcanic zone (Kopecký 1978; Ulrych et al. 1999). It is traditionally subdivided into two groups, which differ in location and age (Pacák 1928). The outer group (in the concept of a Variscan orogene zonation) is of Tertiary age and is related to the Sudetic Marginal Fault. Major volcanic structures are hosted in the Fore-

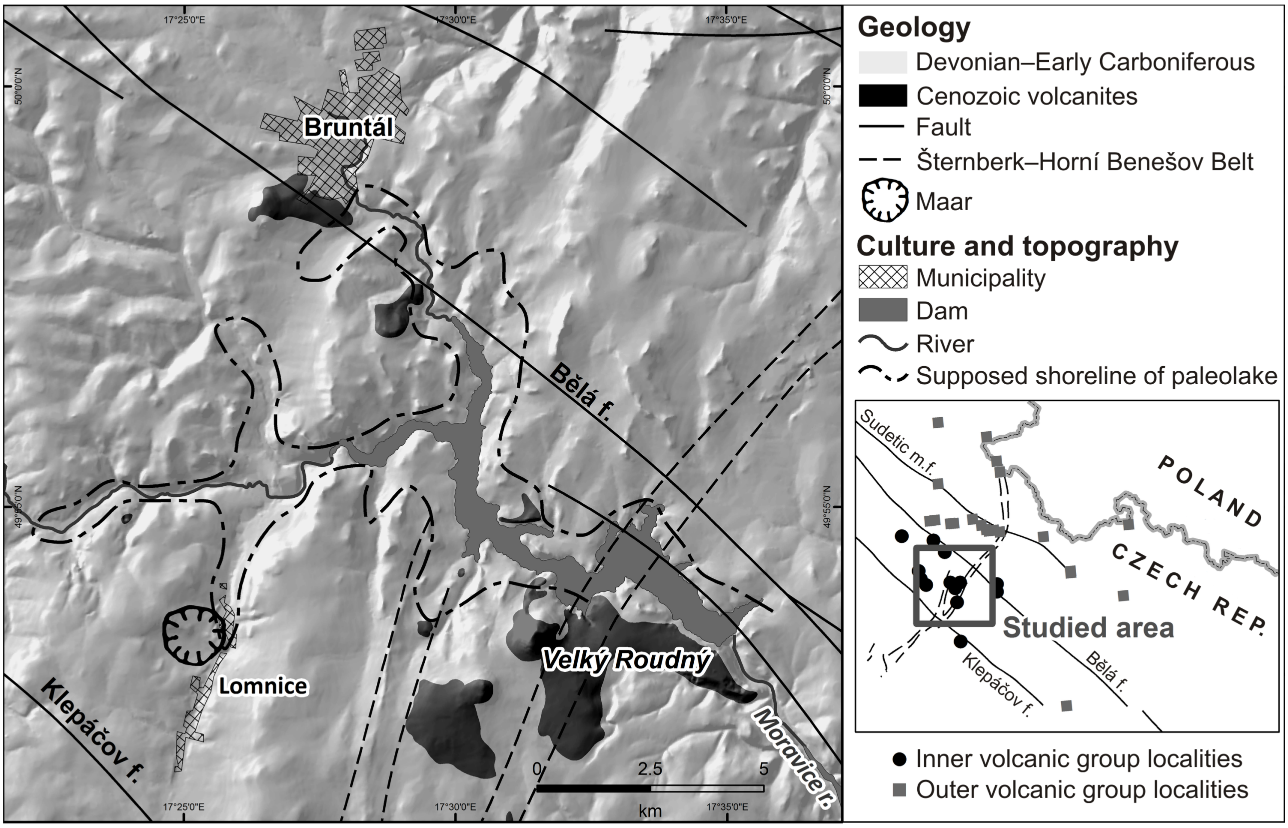

Fig. 2. Geological and tectonic sketch of the Cenozoic volcanic field in the surroundings of the town of Bruntál with a possible shoreline of the paleolake according to the present-day topography.

Sudetic block and the North Sudetic Depression (Birkenmajer et al. 2004, 2007) in Lower Silesia, Poland. A number of volcanic outcrops (e.g. volcanic plugs, lava flows and cinder cones) have been described and dated by the K-Ar method. The age range of the volcanic activity is since Late Oligocene until Miocene (Birkenmajer et al. 2002a,b, 2004, 2007). The inner Plio-Pleistocene volcanic rocks are concentrated around a crossing of the Bělá and Klepáčov deep fault systems (Sudetic fault system of the Bohemian Massif — Buday et al. 1995) and the Šternberk–Horní Benešov Belt (a tectonic zone with Devonian submarine volcanic belt). Nevertheless this conventional subdivision is not well constrained. The spatial and time correlation is not verifiable as suggested by recent studies at the site Pohoř (Šešulka et al. 2012; Ulrych et al. 2013).

The inner volcanic group in the surroundings of the town of Bruntál comprises several types of volcanic structures, including the Velký Roudný scoria cone with associated lava flows (Cajz et al. 2012), the feeder vent in Břidličná or the Razová subaquatic tuffs (Barth 1977; Cajz et al. 2012). The effusive rocks are mostly represented by olivine basalt, nephelinite basanite and olivine nephelinite (Barth 1977).

The surveyed locality is situated between the village of Lomnice and its subdivision of Tylov (Bruntál district, North Moravia) in a side valley of the Lomnice Brook (Fig. 2). The slopes of the valley are carved in Lower Carboniferous (Visean) greywacke with shale interbeds (Horní Benešov Formation, Nízký Jeseník Culm Basin), which provide the country rock for the diatreme structure. The central part of the valley is filled with Quaternary colluvial and alluvial sediments with underlying lacustrine clays and colluvium. Although the shape of the valley might suggest the presence of the maar, geological mapping fails to detect any evidence of the volcanic structure. No outcrop or piece of volcanic rock has been found at the site. The Lomnice maar as well as the other buried volcanic structures in the vicinity of the town of Bruntál (e.q. Tylov structure) were identified only by airborne magnetic surveys (Gruntorád & Lhotská 1973; Šalanský 2004).

During the 1970s, three shallow boreholes were drilled by geologists of the Czech Geological Survey in the area of airborne magnetic structure at Lomnice (drill holes Lomnice MV-1 — depth 94.5 m, Lomnice MV-2 — depth 86.2 m and Lomnice-Tylov B-1 — depth 52 m). According to the field description of cores (Fig. 3) by J. Dvořák & M. Růžička (unpublished reports), the rock record between ~11 and ~83 m depth consists of an alternation of light green or grey siltstones with emerald green clays, in places with small charcoals, vivianite coatings (Lomnice MV-1 — 43.7 m), a big piece of wood (70.2 m) and possibly volcanoclastic admixture (89.20 m). The clays and silts are typically finely laminated, with individual laminae 2 to 3 mm thick. That is why they can be interpreted as deposits of a maar lake. Unfortunately, no rock samples are retained, as all samples were lost during the moving of the Czech Geological Survey in 1993. The location of the collars is also unclear. The approximate position of the B-1 drill hole is shown in Růžička's detailed but unpublished geological map. The coordinates of the other two holes are unknown.

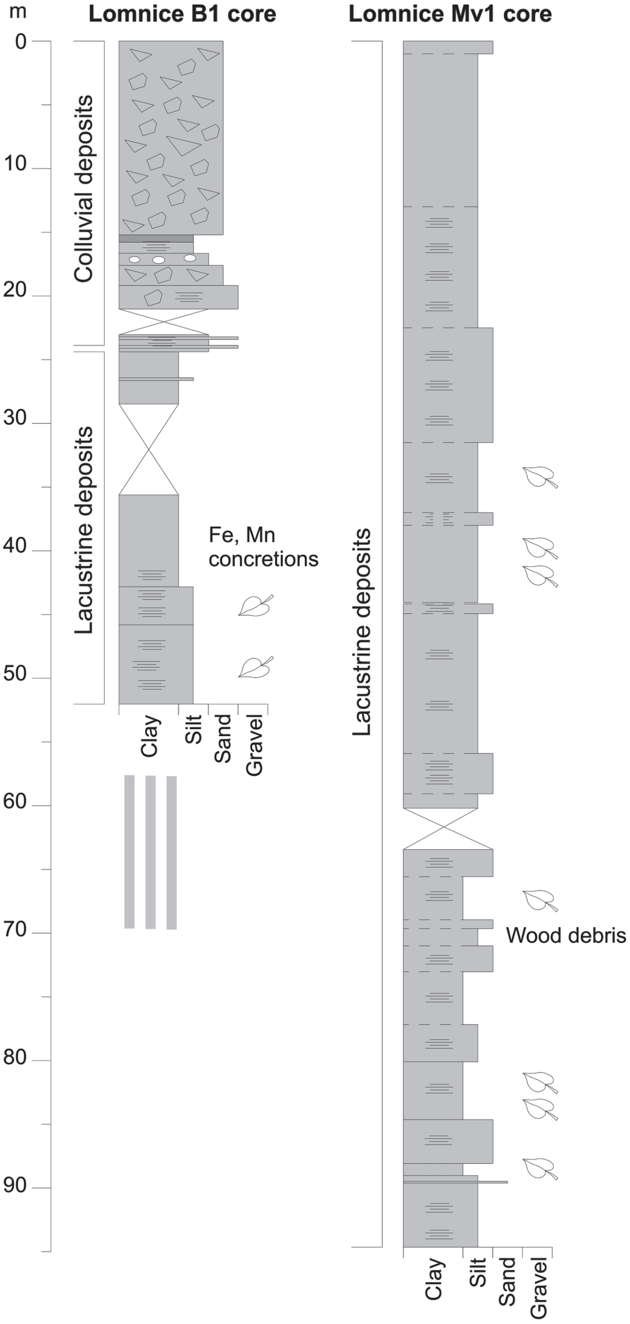

Fig. 3. Lithological log of the historic drill holes B1 and MV1 (modified from Dvořák & Růžička, unpublished data).

Methodology

The combination of several geophysical methods was applied in the survey of the Lomnice maar structure.

The ground magnetic survey was carried out using the cesium magnetometer SM-5 NAVMAG (Scintrex, Canada). The instrument enables a continuous measuring of total magnetic field and records data with frequency of two points per second. The position is measured by built-in GPS antenna with a precision of about 5 meters. The accuracy of position was checked by hand-held GPS Trimble Juno ST. Fifteen profiles were measured, each 0.5 km long, running in NE-SW direction. Based on this data we have interpolated a contour map of magnetic anomalies, which covers an area of 0.73 km^2.

The gravimetric survey was done along 2.8 km long NNE-SSW profile, with 100 m station spacing. The profile crosses the center of the Bouguer gravity anomaly found formerly by Váca & Šutor (1968) during the older areal gravity survey of 4.4 points per sq km (the distance between points of this older measurement was ~500 m, accuracy 0.04 mGal, reduction density 2.67 g.cm^{-3}). For the new gravimetric survey we used a SODIN 410 (Sodin W Gravity Ltd, Canada). Terrain elevations were gauged by levelling and the positions of points were checked up with a hand-held GPS. The accuracy of the gravity measurements was 0.02 mGal.

Preliminary shape and depth assessment of the extent of the diatreme body was done in PotentQ software, the final modelling was carried out using the GM-SYS (Oasis Montaj, Canada). The parameters of the magnetic field (total intensity 48982 nT, declination 3.67°, inclination 66°) were taken from the World Magnetic Model 2010 Calculator of the British Geological Survey (http://www.geomag.bgs.ac.uk/data_service/models_compass/wmm_calc.html).

Due to lack of geological information from the historic drill holes, three general bodies were considered in the model: country rock (Lower Carboniferous greywacke), maar filling (lacustrine sediments) and volcanic rocks of the diatreme in the deeper part of the modelled structure. The Quaternary deposits in the uppermost part of the maar are inconsequential. The magnetic susceptibility of basalts from surface samples at other North Moravian localities is $15–40\times10^{-3}$ SI (Foltýnová 2003) and depends on the weathering state of the rock (Müllerová & Müller 1972). For the model purposes we have used the value 33×10^{-3} SI for the basalt breccia. The susceptibility of greywacke (0.15×10^{-3}) was measured by hand-held kappameter KT-6 (Satisgeo, Czech republic). The susceptibility of the lacustrine sediments (mostly clays) usually tends to zero (Schulz et al. 2005; Mrlina et al. 2009). Remanent magnetization was not considered in the magnetic data processing.

The density of the surrounding upper Paleozoic rocks is 2.71 g.cm^{-3} (Čejchanová 1981). For maar sedimentary filling (sheet washes of greywackes and Plio-Pleistocene sediments) we used a density of ~2 g.cm^{-3}. Volcanic breccias and relicts of basalt volcanism are expected to have the highest density with up to 3 g.cm^{-3}. The input parameters of magnetic susceptibility and density are shown in Table 1.

Two electrical resistivity tomography (ERT) sections were made using the ARES automatic geoelectrical system (GF Instruments, Czech Republic) with the Wenner-Schlumberger array and 5 m electrode spacing. The first section with a total length of 890 m, running in a NE-SW direction across the diatreme was measured using the roll-along method of a 32-electrode (155 m) array. Based on the results from the first survey, another section overlapping the first one, with a total length of 1155 m was gauged in a NE-SW direction using the roll-along method of 104 electrodes (515 m) in a single array. In order to reduce total measurement time with multiple (eight) repetitions of the roll-along method, we used the Wenner-Schlumberger array. Although it is not the best method for imaging of vertical structures, we chose it as a relatively rapid and simple compromise, which is suitable for imaging of layered structure of the maar-diatreme sedimentary fill.

Table 1: Input values of magnetic susceptibility and density for the geophysical model. Fig. 5 — Gravity model of the maar-diatreme structure.

Rock	**Magnetic susceptibility (SI)**	**Density (g.cm^{-3})**
Lower Carboniferous greywacke	0.15 × 10–3	2.71
Lacustrine sediments	0 × 10–3	2
Basalt, basalt breccia	33 × 10–3	2.8

Two 2D inverse models of resistivity were generated from the measured apparent resistivity data using least-square inversion method by RES2DINV software (Geotomo Software, Malaysia). The first section (Fig. 6 — top) encompassed 2172 data points in 15 data levels. The inverse model has 1522 blocks in 9 layers with the maximum pseudodepth of 31.3 m below the surface. The block uncertainty of the inverse model ranges from <1 % (near surface) to ~10 % (maximum depth) of the model resistivity values. The root mean square (RMS) error of model iteration 5 is 1.8 %, which indicates high-quality data. The second section (Fig. 6 — bottom) was measured along the same line but it was extended further to the NW and SE in order to detect the wall and the deeper structure of the diatreme. The inverse model has 8,360 blocks in 20 layers with the maximum pseudodepth 67.4 m below the surface. However, probably due to large variations in surface resistivities the iteration process became relatively unstable after three iterations, with the resulting large RMS error of 23.7 %. Low-quality data as indicated by low sensitivities of the model blocks are distributed especially in the lower half of the section between 50 and 500 m along the section (Fig. 6). In order to enhance the vertical structure of the diatreme walls, we applied three different weights (1, 1.5 and 2) of vertical-to-horizontal flatness filter in the RES2DINV software. However, the inversion models were almost identical for any of the three values. The inversion model on Fig. 6 was generated with the vertical-to-horizontal flatness filter weight of 1.0.

Results

New magnetic and gravity measurement detected a deep funnel-shaped structure, which is interpreted as a maar-diatreme. Joint gravity and magnetic modelling of the structure was done along a 2.8 km long gravity profile. There is an obvious ~250 m shift between the tops of the main positive magnetic anomaly and negative gravity anomaly (Fig. 4). Most likely it reflects the different distribution of sources of the magnetic and gravity anomalies. The maar filling base should not be at the same level. In the NW part the thickness of the filling may be larger, and this would cause the gravity minimum. At the place of the magnetic maximum, the surface of the diatreme filling seems to be shallower.

The magnetic survey revealed a ring structure with a positive magnetic anomaly >100 nT (local peaks even up to

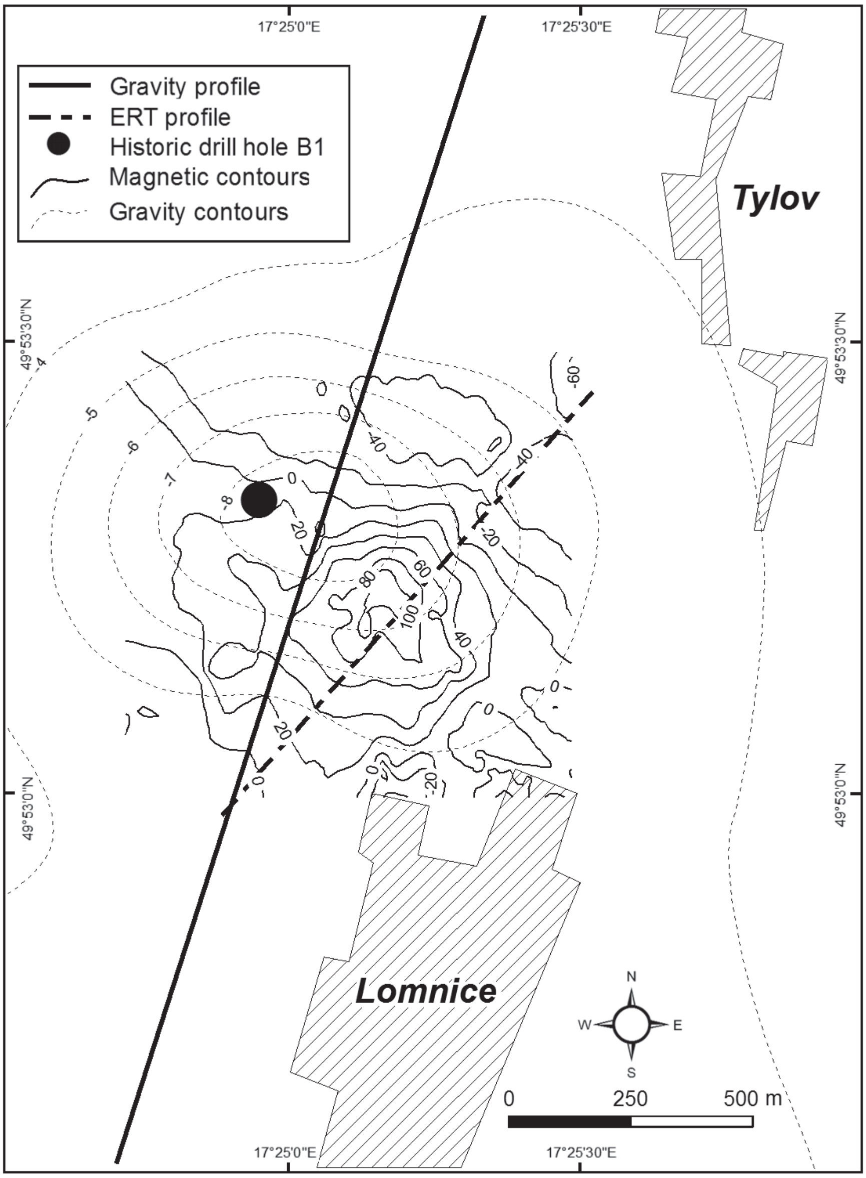

Fig. 4. Gravity (from Váca & Šutor 1968) and magnetic anomalies with location of gravity and ERT profile.

190 nT). The vertical magnetic model on Fig. 5 shows a more than 500 m deep funnel-shaped structure, which is interpreted as a maar-diatreme. The maar is filled with lacustrine clay and colluvial sediments and in the lower part of the maar-diatreme structure, we assume a highly magnetic body, probably a lava intrusion (whole diatreme is a volcanic vent). The top surface of the highly magnetic rock (basalt breccia, basalt) is at the depth of more than 200 m.

The Bouguer anomaly of the Lomnice maar structure shows a value of −4.7 mGal. The regional trend of 0.19 mGal/km was subtracted from the Bouguer gravity along the profile and residual gravity values represented input into the modelling process. Furthermore, with the horizontal dimension of the maar structure of about 600 m in diameter (according to magnetic survey), it was necessary to restrict the gravity model in the vertical direction. Thereby the 2.5D model was created. The outcome of the gravity modelling is a maar structure more than 500 m in diameter and with a depth of 400 m. The SSW side dips gently, while the northeast slope is steeper (Fig. 4).

According to magnetic and gravity data, colluvial sediments and sheet washes of Lower Carboniferous rocks are present in the uppermost part of the maar structure. Beneath them Plio-Pleistocene lacustrine sediments and volcanic breccias with relicts of the basalt volcanism are expected. This is consistent with results of ERT measurement.

Two zones of high resistivity values (~200 to a maximum of 14,003 Ω.m) are visible at both margins of the two inverse model sections (0 to ~70 m; ~980 to 1155 m distance on surface). They are interpreted as country rock comprising the Lower Carboniferous succession of greywackes alternating with siltstones. The boundaries of these high-resistivity zones are sharp and delineate a concave, bowl-shaped body of low resistivity values (<20 to ~130 Ω.m) located in between, and interpreted as the diatreme fill. The resistivity

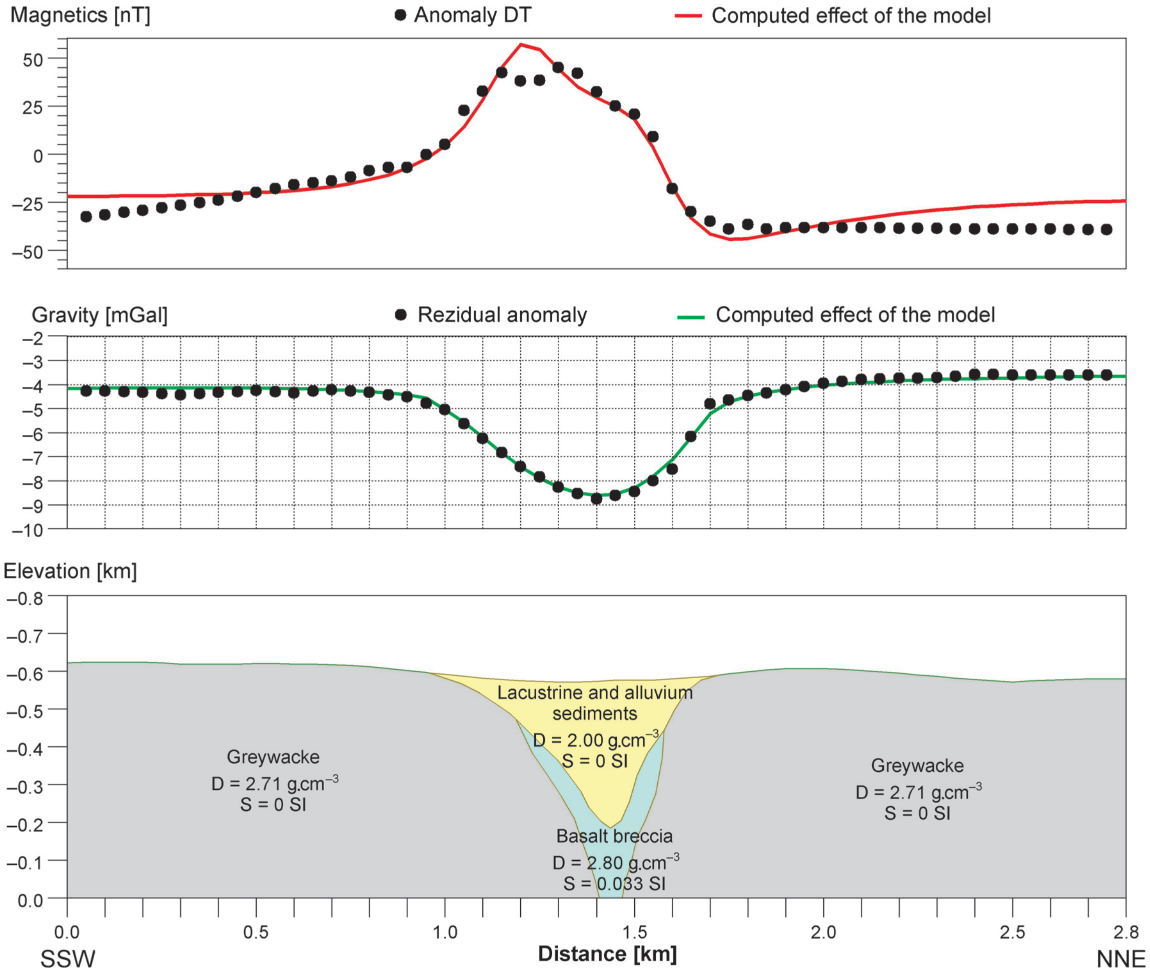

Fig. 5. Gravity and magnetic profile across the maar-diatreme structure near Lomnice.

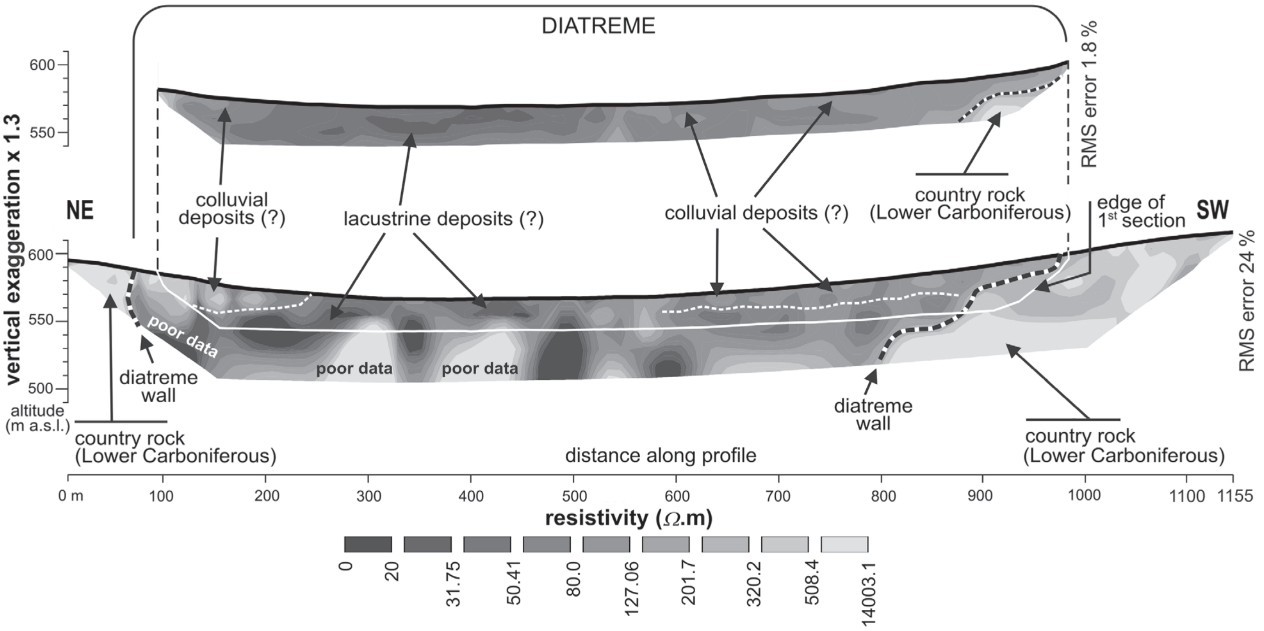

Fig. 6. Two overlapping ERT sections showing inverse models of resistivity and their interpretation. Note the prominent low-resistivity zone interpreted as lacustrine mudstones between ~200 and ~500 m distance along the profile as well as the maar-diatreme walls at ~70 and ~980 m.

Table 2: Summary of K-Ar dating at the Velký Roudný volcano.

Locality	Age	Source
Velký Roudný — Bílčice quarry	3.31 ± 0.24 Ma	Pécskay et al. (2009)
Velký Roudný — Bílčice (nepheline basanite lava)	2.4 ± 0.12 Ma	Ulrych et al. (2013)
Bílčice — Leskovec (Velký Roudný lava flow)	3.4 ± 0.9 Ma	Šibrava & Havlíček (1980)
Chřibský les lava flow (nephelinite basanite)	1.46 ± 0.15 Ma (USGS)	
Chřibský les lava flow (nephelinite basanite)	2.2 ± 0.9 Ma (TI)	
Chřibský les lava flow (alkaline olivine basalt)	1.28 ± 0.4 Ma (USGS)	
Chřibský les lava flow (alkaline olivine basalt)	1.6 ± 0.6 Ma (TI)	

boundaries interpreted as the maar-diatreme walls are dipping steeply in the NW but much more gently in the SE, which very well correlates with the magnetic and gravity survey data (Figs. 4, 5, 6). The zone of very low resistivity values (<20 to ~50 Ω.m), confined to the central part of the maar body (Fig. 6, top part), may represent the maar lake fill (presumably mudstones). This low resistivity zone reaches up to the surface between ~200 and ~500 m distance, giving some thickness constraints to the lacustrine sediments (between ~20 and ~45 m). However, the lower limit of this zone is uncertain due to the low block sensitivity of the inverse model (see above). The low-resistivity zone is in places overlain by near-surface zones of medium resistivity values (~80 to ~160, rarely up to ~400 Ω.m), which thicken towards the walls of the diatreme. Their shape and resistivity ranges may indicate the presence of colluvial sediments deposited at the margins of the former maar (Fig. 6).

Discussion

The coherence of magnetic and gravity anomalies indicates a volcanic origin of the structure. The magnitude of the Lomnice gravity and magnetic anomalies are comparable to some of the West Bohemia and Western Saxony maar-diatreme structures (Mrlina et al. 2009; Matthes et al. 2010). Magnetic and gravity surveys proved to be suitable methods for detection of maars elsewhere (Macnae 1995; Schulz et al. 2005; Lindner et al. 2006; Cassidy et al. 2007). The filling of the maar near the Lomnice village (based on the geophysical survey and historic drill holes in the western part of the maar structure) is also very similar to other known maars of the CEVP. The upper part (lacustrine clays and colluvium) corresponds to the D lithozone of maar crater sediments (laminated silt and clay, sandy and gravel layers) described in the Eifel area by Pirrung et al. (2003). The lower parts are comparable to the C (pyroclasts and wallrock fragments), B (debris of wallrocks and pyroclasts) and A (diatreme breccia) lithozones. However no tephra ring is present at the Lomnice locality.

According to a study of lacustrine tuffites of the Razová pyroclastic complex (altitude 530 m a.s.l.), very significant changes of hydrological regime in the area occurred in the late Pliocene to early Pleistocene (Barth & Zapletal 1978). Lava flows from the Velký Roudný volcano dammed the paleo-Moravice River valley, while the water level rose to at least 550 m a.s.l. creating a large lake. A part of the lake very probably extended up to the maar area (present-day altitude ~570 m a.s.l. — Fig. 1). This might have caused a substantial bedrock water saturation followed by phreatic eruption and birth of the Lomnice maar structure. The initiation of the eruption, which created the maar-diatreme structure, can thereby be related to the activity of the nearby-located Velký Roudný volcano. Several effusive phases were documented based on radiometric dating (Table 2), with at least two main episodes (Cajz et al. 2012).

The assumed Plio-Pleistocene age of the Lomnice maar contrasts with similar maar structures of the Eger Rift (West Bohemia) or the Guttau Volcano Group (Upper Lusatia), which are of the Oligocene-Miocene age (Suhr et al. 2006; Skácelová et al. 2010). On the other hand, the Ar-Ar age of the Mýtina maar in the Cheb Basin (western part of the Eger Rift) is only 288 ± 17 ka (Mrlina et al. 2009).

Conclusion

The combination of detailed magnetic and gravity survey with electrical resistivity tomography (ERT) proved to be very suitable to describe the shape and origin of the previously detected geophysical anomaly near the village of Lomnice. The combination of magnetic and gravity anomalies as well as topographical data points to the presence of a ring structure of volcanic origin, which can be explained best as a maar-diatreme structure. The detailed geophysical survey data and their inversion modelling enabled the definition of the lateral distribution and vertical structure of the diatreme.

The maar-diatreme structure is funnel-shape and about 600 m in diameter near the surface. It extends to a depth of at least 500 m below the present-day surface and it is filled predominantly with lacustrine clays and colluvium. This filling causes the negative gravity anomaly. On the basis of a positive magnetic anomaly, the presence of volcanic rock in the lower part of the diatreme is assumed.

According to other volcanic centers in the surroundings of the town of Bruntál, the Lomnice maar-diatreme is assumed to be of Plio-Pleistocene age (3.4 to 1.5 Ma). The formation of the structure could be related to the water regime variations caused by effusive activity of the Velký Roudný volcano.

The Lomnice structure is the first maar-diatreme ever described in the Moravian-Silesian part of the CEVP.

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