Emplacement dynamics of phonolite magma into maar-diatreme structures — Correlation of field, thermal modeling and AMS analogue modeling data

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A B S T R A C T

Emplacement mode and original shape and dimensions of a well exposed phonolite body in the České středoohoří Mountains (Czech Republic) were reconstructed using combined techniques of structural analysis of magmatic fabrics and columnar jointing together with analogue and thermal mathematical modeling of cooling for different shapes of experimental bodies. Phreatomagmatic rocks in the vicinity of some phonolite stocks in the area of interest suggest that the phonolite bodies were likely emplaced into maar-diatomates. Our modeling revealed that intrusion of magma into phreatomagmatic maar-diatreme craters can result in cryptodomes, erosive domes, lava lakes or branched intrusions. The fabric and columnar jointing pattern of the selected phonolite body reveals best fit with an asymmetric extrusive dome emplaced into the maar crater. The scaling analysis and thermal modeling also suggest that the phonolite extrusion could have formed within 6–66 days and cooled to the background temperature after 10,000 years. Combined analogue and thermal modeling also revealed that the phonolite extrusions into maar-diatreme craters are marked by upper tier (collonade) of vertical columns and lower tier of curved and outward flaring columns. Both tiers in the phonolite extrusions are divided by a subhorizontal suture.

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1. Introduction

Phonolite and trachyte bodies form expressive landmarks in several Tertiary intra-continental volcanic provinces in Europe. These provinces are associated with the rift systems of Rhein graben (Germany), Eger rift in Bohemian Massif (Czech Republic) and Limagne graben (France) that formed due to complex tectonic processes in the foreland of the Alpine orogeny (Fig. 1). Phonolite and trachyte magmas were emplaced during the last evolution stages of these rift systems (Camus, 1975; Kopecký, 1978).

The emplacement mechanism and original shapes of phonolite and trachyte bodies are often poorly constrained, because of unknown paleosurface level and poor exposure of the host rocks in their surroundings, although they likely represent eroded remnants of cryptodomes, lava domes, laccoliths, lava flows or exposed volcanic conduits (Varet, 1971; Camus, 1975; Kopecký, 1978; Ullrich et al., 2000; Lorenz and Haneke, 2004; Závada et al., 2009b). A puzzling evidence in the phonolite bearing volcanic provinces is that both low-aspect ratio (coulées or thin laccoliths) and high-aspect ratio bodies (e.g. cryptodomes) can be found, which reflects either different local environment of the magma/lava emplacement (e.g. flat surface versus volcanic crater) or less likely the large variation in rheological properties of magma controlled by crystal content and melt chemistry (Dingwell et al., 1996; Saar et al., 2001; Giordano et al., 2004). Another unresolved feature of phonolite magma emplacement is that some individual phonolite bodies merge in plan-view with neighboring bodies, while others form solitary monuments. Earlier detailed studies of phonolites and trachytes attempted to define their emplacement mode using flow kinematics deduced from internal fabrics and fractures and considered the phonolite bodies as extrusion domes or “squeeze-up mounds” of highly viscous magma on the paleosurface (Closs and Closs, 1927; Varet, 1971; Jančušková et al., 1992; Arbaret et al., 1993; Závada et al., 2009b). In some cases, slices of basement rocks were reported to be uplifted by viscous drag of the magma along the steep walls of the intrusions (Varet, 1971; Kopecký, 1978).

For a group of phonolite stocks close to Most town in the České středoohoří Mountains in Bohemia (Fig. 1), Kopecký (1985) suggested that these represent teardrop shaped intrusions into maar-diatomates, while Fedik (1985) proposed that these are only remnants of a differentially eroded coulée of phonolite lava. The first explanation is supported by outcrops of maar deposits in the vicinity of the phonolite stocks (Kopecký, 2000). Intrusion of magma into the maar-diatomates (phreatomagmatic volcanoes) is typical for the final stage of the phreatomagmatic volcano evolution, when the influx of water
triggering the phreatomagmatic explosions in the root zone of the volcano is terminated or insufficient (Konečný and Lexa, 2003; Lorenz, 2003; Martin and Németh, 2004, 2005; Auer et al., 2007).

The mechanical interaction between intruding magma and host maar sediments or the tuff ring surrounding the phreatomagmatic volcanoes was documented for basalts by Konečný and Lexa (2003) and Martin and Németh (2005), respectively. However, possible intrusion/extrusion shapes and emplacement dynamics of magma into the weakly consolidated explosive deposits of the maar-diatreme system was not yet systematically evaluated, e.g. by numerical or analogue modeling.

In this contribution, we constrain the shapes and emplacement dynamics of phonolite bodies emplaced into phreatomagmatic craters using a combined approach of field analysis of magmatic fabrics and cooling fractures together with analogue modeling and thermal modeling of their cooling. At first, we measured the spatial distribution of fabrics and columnar jointing on exceptionally well exposed Bořeň u Bíliny phonolite body, which was probably emplaced into a phreatomagmatic crater. Several analogue models of magma emplacement into phreatomagmatic craters were then created to test the similarity of their relative dimensions and internal fabrics with those on the Bořeň phonolite body. Finally, thermal models based on the geometry of selected analogue models and equipped with thermophysical parameters characterizing the rocks in the field were constructed for comparison of the thermal models and the thermal structure of the Bořeň phonolite body. The shapes of analogue models ranged between teardrop shaped cryptodomes to lava domes with outward flaring thick stems or lava lakes with flat bottom surface depending mainly on the degree of initial overpressure of the analogue material and also on the "thickness" of the intruding material controlled by the mixing ratio of the analogue melt (water) and analogue crystals (plaster of Paris). Our modeling implies that the most probable geometry for the Bořeň body is an asymmetrical extrusion, where the model magma intruded the maar-diatreme structure through the center of the crater, partially pushed aside the filling of the maar and extruded and extended laterally by inflation and diffusence on the crater floor. In some cases, intrusion of the analogue material branched within the model diatreme and resulted in two subsequently emplaced extrusive bodies on the crater periphery. Our results also suggest a new explanation for the geological origin of both Devils Tower and Missouri Buttes phonolite bodies (WY, USA), which will be further elaborated in a special paper.

2. Geological setting

The Tertiary volcanic activity in the region of České středoohoří Mountains is associated with the SW–NE trending continental Eger Rift corresponding to a reactivated first order Variscan tectonic boundary (Plomerová et al., 2003; Hrubcová et al., 2005. The rifting in this area was accompanied with mantle upwelling and several tectonic phases of reactivation of deep seated regional fabrics and faults (Špičák and Horálek, 2001; Uličný, 2001).

The volcanic activity in the region can be divided into three main periods (Cajz et al., 1999): (1) low-differentiated, weakly crustal-contaminated upper mantle magmas — basanitic lavas (carrying lherzolite xenoliths) and volcanoclastics, 36–26 Ma in age, (2) trachybasaltic magmas and volcanoclastics including trachytes and phonolites of bimodal tephrite/basanie–phonolite suite, marked by crustal differentiation and assimilation of the primary mantle magma and by the lack of lherzolite xenoliths, 31–25 Ma in age, and (3) flows of...
basanites, geochemically similar to the first group, dated at 24 Ma. The first group of volcanic products forms subvertical dykes or lava flows along the major faults bounding the rift. The phonolites and trachytes of the second phase intrude the Cretaceous sediments and are emplaced as shallow intrusive laccoliths, extrusive domes or intrusions into maar-diatremes (Kopecký, 1978; Ulrych et al., 2000). These bodies have circular or elliptical form in the map and are aligned along the SW–NE trending faults of the Eger rift system. The volcanic products of the third phase are not present in the studied area and consist of basanite lava flows close to Děčín town.

The best exposed phonolite body in the České středohoří Mountains is the Bořeň u Bíliny forming a prominent landmark in the vicinity of Bílina town (Fig. 1, body no. 1). The Bořeň phonolite is classified as a nephelinitic phonolite, because it contains abundant nepheline (up to 5 vol.%) or simply as phonolite according to the USGS chemical classification (Le Bas et al., 1986; Hrouda et al., 2005). Other phonolite bodies, Želenický Hill and Zlatník, of similar composition and texture are aligned behind the Bořeň Hill at a distance of 2 and 3 km, respectively, in the WSW direction. Other three large phonolite bodies occur further west on the periphery of the Most town. Two of them, Široký Hill and Hněvín, merge in the map on their circumference. Ryzelský Hill is the largest in areal extent and represents a solidified coulée of phonolitic lava (Kavka, 1981). Other three subcircular bodies are present east and northeast from Most town; Špičák (no. 11), Červený Hill (no. 4) and a phonolite plug revealed by coal exploration drilling works under the Quaternary deposits 1 km east from Červený Hill (Fig. 1, body no. 10). Other irregular patches of phonolite bodies in the map probably represent remnants of small intrusions (sills or laccoliths) or lava flows.

On the eastern foothill of Hněvín (Kopecký, 2000) and at the northern foothills of Zlatník and Červený Hill, phreatomagmatic deposits are found (Kopecký, 2000). These indicate that the adjacent phonolite plugs were emplaced into phreatomagmatic volcanoes. Extensive mantle of phreatomagmatic deposits was also revealed by drill holes around the plug no. 10 (Fig. 1). Sample of phreatomagmatic lapilli tuff at Zlatník Hill consists of angular fragments of phonolite, basement orthogneiss and angular sideromelane shards with vesicles. The sideromelane fragments indicate that the phreatomagmatic volcanism in the area was active since the first volcanic phase (Fig. 2A, C). Phreatomagmatic agglomerate at Hněvín reveals rounded phonolite clasts with dark chilled margins encased in quartz-rich tuffaceous matrix (Fig. 2B). Some of the phonolite blocks are up to 50 cm in diameter and some are cross-cut by fractures filled with fine grained tuff (Fig. 2B). The only lithic fragments in the phreatomagmatic breccia samples are orthogneisses from the basement. Some parts of the Hněvín outcrop reveal fine-grained phonolitic tuff layers showing abundant fossiliferous relics of plant roots that represent the surficial facies of the maar-diatreme system (Kopecký, 2000; Lorenz and Kurszlaukis, 2007). Phreatomagmatic tephra at Červený Hill is formed by unconsolidated white sand to gravel sized material with local rounded clasts of orthogneisses.

The presence of phreatomagmatic breccias in mantles of several phonolite bodies and also a basanitic maar that was mapped 2 km SSW from the Bořeň phonolite body (Fig. 1; Kopecký, 1991) suggest that the area of interest was subjected to vigorous phreatomagmatic activity during the first two volcanic phases in the Tertiary (Cajz et al.,

Fig. 2. Samples of phreatomagmatic lapilli tuff (A) found on N side of Zlatník Hill and phreatomagmatic agglomerate (B) found on E foothill of Hněvín. Note the chilled black margins of rounded, fractured and altered phonolite fragments in (B). Modal analysis of traced clasts in a thin-section of the Zlatník phreatomagmatic lapilli tuff reveals predominance of the volcanic material (C). Smallest fragment traced in the fine-grained matrix has a diameter of 0.2 cm. Scale bar in (A) is 10 cm.
Abundance of orthogneiss basement fragments encased in the breccias also reflects that the phreatomagmatic activity was established in hard-rock environment (Lorenz, 2003). Occurrence of phreatomagmatic tephra in the vicinity of Zlatník Hill, conspicuous alignment trend of Zlatník, Želenický Hill and Bořeň phonolites following the major fault system active in the area during Tertiary (Kopecký, 1978, 1991) and circular plan-form of these bodies in plan-view suggest that all these bodies were emplaced into phreatomagmatic volcanoes that formed on a zone of structural weakness with a joint aquifer (Auer et al., 2007; Lorenz, 2003). This is also supported by their high-aspect ratio together with exposure of orthogneiss basement rocks on the western foothill of Bořeň. The mantles of phreatomagmatic tephra around these bodies can be buried under the talus of Holocene phonolite block accumulations.

3. Structural and fabric data of the Bořeň phonolite body

The Bořeň phonolite is a circular body in the map with an average diameter of ca. 500 m. On western side of the body, it is in contact with basement orthogneisses. Eastern side of the body is surrounded by thick Quaternary accumulations of blocky phonolite talus and outcrops of Cretaceous sediments covered by basanite lavas of the Zlatník Hill and Bořeň phonolites (see inset of profile in Fig. 1). In the central-SE part of Bořeň, steep walls confined by columnar joints encircle an elevated plateau (Fig. 3A), which forms a natural fortress. NW side of the body is shielded by a steep wall rising from the lowest exposure level of the body up to the toe of the fortress, where it forms a small plateau.

The magmatic fabric in the massive and homogeneous green to grey (altered) phonolite is discernible only locally from the alignment of tiny (0.5–1 cm) sanidine crystals. No macroscopic fold or shear structures can be observed on the outcrops. Orthogneiss xenoliths up to 8 cm in diameter are sparsely distributed in the phonolite. The body is affected by two jointing systems. Orientation of the first set of joints is subparallel to the magmatic fabric and defines an asymmetric onion like internal structure of the cupola (Fig. 3C) well known from other phonolitic or trachytic bodies (Cloos and Cloos, 1927; Varet, 1971; Závada et al., 2009b). This system is analogous to flat lying joints (F-joints) known from high structural levels of plutons (Cloos, 1922). Second system is represented by columnar joints that define steep vertical columns up to 3 m wide in the central-SE part of the body (Fig. 3B, D). Vertical columns are about 30–50 m high and their dip directions diverge as their dip angle decreases on the periphery of the body, where the columns are only 0.5–1 m wide (Fig. 3B, D). Individual joint growth increments typical with transverse bands on the columns well known from solidified basalt lava flows (DeGraff and Aydin, 1987) were detectable only in the NW margin of the body. In this location, joints confining horizontal, 1 m wide and few meters long columns terminate in the vertical wall of massive phonolite. Looking on the Bořeň body from the SE on bright day one can see that the wide and vertical columns encircling the elevated part of the body are underlain by a set of narrower columns about 20 m below the top of the vertical walls and 50 m below the summit of Bořeň (Fig. 4). This discontinuity is interpreted as a suture between the “upper” and “lower colonnades” (Spry, 1962) that formed during cooling from the upper and lower boundaries of the original phonolite body. Detailed relief model of the Bořeň body was created using photogrammetric technique from aerial photographs and used for plotting and interpretation of the structural data.

3.1. Microstructural data acquisition

3.1.1. Magmatic fabric and orientation of cavities

The phonolite trachytic texture is defined by parallel alignment of groundmass fine sanidine laths (20–100 μm) and nepheline columnar crystals (20–100 μm) enclosing phenocrysts of sanidine, nepheline, clinopyroxene (aegirine–augite) and sodalite that range in size from...
The phonolite groundmass is disrupted by microscopic cavities that are about 0.5–1 cm long and have lenticular shapes with smooth or irregular ragged boundaries (Fig. 5B). Cavities are aligned in a specific direction and are typically developed in the vicinity of phenocrysts or sometimes even crosscut the phenocrysts (Fig. 5B). The cavities are similar to those described by Smith et al. (2001) in dacite lava and are typically filled with secondary minerals such as zeolite and natrolite. Phenolite from the Želenický Hill revealed euhedral crystals of aegirine augite growing into the cavities (Fig. 5C).

For the purpose of microstructural analysis of magmatic fabric, we at first attempted to employ the AMS (anisotropy of magnetic susceptibility). Unfortunately, this technique had to be discarded, because in the phonolite rocks of interest, the AMS has no relationship with the flow-induced magmatic fabric or this relationship is difficult to interpret. Microscopic and microprobe analysis revealed that the main carriers of the magnetic susceptibility are titanomagnetite grains (10–50 μm) that originated probably from decomposition reaction of residual amphibole crystals and relatively large inclusions of magnetite (250–400 μm) in large sodalite crystals. Population of small titanomagnetite grains in the groundmass is absent in the studied phonolites, in contrast to other trachytes and phonolites in the Želechův Kristův vrch (Ulrych et al., 2000; Závada et al., 2009b). This can be explained by gravity driven separation of the magnetite crystal fraction in the magmatic reservoirs before ascent and groundmass crystallization of the phonolite magma, so that only magnetite crystals enclosed within light sodalite grains or amphibole pseudomorphoses were carried up.

The crystallographic preferred orientation (CPO) of groundmass sanidine and nepheline crystals was measured from oriented thin sections on a scanning electron microscope CamScan S4 on Faculty of Sciences (Charles University, Prague). Acquired EBSD patterns were recorded and indexed using the Channel5 software of HKL Technology (Schmidt and Olensen, 1989). Crystallographic models of Scambos et al. (1987) and Simmons and Peacor (1972) were used for sanidine and nepheline, respectively. Each thin section was calibrated using a silicone monocrystal and only measurements with angular deviation below 1 were accepted. CPO was measured at least from 120 crystals throughout the thin-section in 12 samples located on E–W and N–S profiles across the cupola. All data were rotated to geographic coordinates and are presented on lower hemisphere stereographic projections. Rotations, plotting and calculation of the eigenvalues and eigenvectors of the CPO data was done using the software developed by D. Mainprice (ftp://www.gm.univ-montp2.fr/mainprice/CareWare_Unicef_Programs/).

Fabric of the phonolite reveals numerous lenses to sigmoidal shaped cavities (Fig. 5) that are similar to those described by Smith (2000) and Smith et al. (2001) in trachyte and dacite. Cavities were traced and digitized from micrographs in ArcView GIS environment using extension Poly and statistically evaluated using the PolyLX Matlab toolbox (Lexa et al., 2005). Orientation of cavities was reconstructed from their alignment in three mutually perpendicular thin sections.

3.1.2. Results of microstructural analysis

Preferred orientations of poles to (010) and (001) planes of sanidine crystals in rocks with trachytic texture reliably indicate pole to flow planes (magmatic foliation) and flow direction (magmatic lineation), respectively, of the lava (Závada et al., 2009b). Sanidine groundmass fabric is typical with well clustered poles to (010) and girdle-like distribution of poles to (001) planes (Fig. 6). Nepheline crystals have hexagonal columnar shape and preferred orientation of their poles to (0001) planes well corresponds with clusters of poles to (001) planes of sanidines for all but two samples (Fig. 6), therefore this crystallographic direction of nepheline is also considered as a good indicator of magmatic lineation.

Diagrams of the measured CPO fabric that were rotated into geographic coordinates (Figs. 6 and 7) reveal that the magmatic fabric is subhorizontal in the elevated, southern and eastern part of the cupola (samples B82, B92, and B94) and at the eastern toe of this elevated plateau (sample B83). Samples B41 and B43 collected in the central part of the cupola below the elevated plateau (at the toe of vertical columns), reveal folded fabric marked by several maxima of (010) directions (Závada et al., 2009b). The trachyte fabric defined by alignment of (010) sanidine faces dips vertically on western and northern part of the body and strikes parallel with the margin (samples B37 and B97). On northern and southern slope of Bolfěň (samples B65 and B93), the fabric dips at moderate angles to the north and south, respectively. Eastern slope of Bolfěň is marked by alternating steep (sample B24) and flat fabrics (sample B96). Magmatic lineations indicated by V, eigenvectors of poles to (001) planes of sanidines and poles to (0001) of nephelines trend approximately in N–S direction in samples collected on the N–S profile through the cupola (samples B65, B41, B43, B92 (only...
nepheline), B94) and also in its eastern flat part (sample B82). On northern and eastern margins (samples B37 and B97), lineations are subhorizontal and parallel to the strike of the vertical fabrics.

Cavities in the phonolite lava typically dip at higher angles than the sanidine fabric (or in opposite direction for steep fabric in sample B97) and follow a similar strike direction (Fig. 7). Cavities dip at moderate to steep angles on the margins of the exposed body and strike subparallel with the nearest margin. On the periphery of the flat and elevated part of the cupola (samples B24, B43, B92, and B83), cavities are sigmoidal, with their central and tail parts oriented at high angle and subparallel, respectively, to the trachytic fabric. In central part of the elevated plateau (sample B46), vertical cavities cut through horizontal fabric and strike E–W.

In southern flat part of the cupola (sample B94), the horizontal fabric is disrupted by microscopic shear zones dipping shallowly to the north. While the cavities outside the 0.5 cm wide shear zones dip shallowly to SW, cavities within the shear zone are steep. Similarly, on the eastern margin (sample B122), 0.1 cm wide subvertical shear zones with N–S strike and west side–up sense of shear divide domains with subhorizontal fabric and cavities along large faces of phenocrysts dipping shallowly to the east. On one locality on the northern slope of the Bořeň body (close to sample locality B65, Fig. 7) the trachyte fabric is disaggregated into separate domains up to several centimeters in diameter with discordant internal fabrics.

4. Analogue modeling of magma emplacement into maar-diatreme structures

Detailed analysis of fractures and fabric systems throughout the Bořeň phonolite body motivated the second part of this complex study, which combines the analogue modeling and finite element numerical modeling of cooling for selected geometries of magma intrusions into model maar-diamente volcanoes. Our earlier studies revealed that the understanding of internal structure and fabric pattern of eroded volcanic bodies can be conveniently resolved using analogue modeling (Závada et al., 2009a,b). Flow induced fabrics can be analyzed from disrupted color layering of the analogue material corresponding to flow planes, and AMS fabric, which records the local deformation/flow shapes, flow planes and flow directions from the particles of admixed magnetite dust (Závada et al., 2009a).

The Bořeň body represents a remnant of an eroded phonolite body that was emplaced close to the paleosurface and probably intruded a maar-diamente structure. To evaluate the similarity of the analogue models with the original (Bořeň body), at first, the shape of Bořeň and its relative dimensions in the probable maar-diamente crater together with its internal fabric pattern on NW–SE and SW–NE profiles were projected over the vertical sections of the sliced analogue models. Although an unknown volume of the phonolite was already eroded, the original vertical dimension of Bořeň is indirectly indicated by the level of the suture between the two collonades of columns that formed during cooling of the body. This suture should correspond to the half-height of the original body, if we assume that the rate of cooling from its top and bottom boundary was similar. In the second step, for models that fulfill the dimensional preconditions and reveal similar fabric pattern as the Bořeň body, thermal modeling of cooling was employed to further test the similarity between the models and the original. The columnar jointing pattern developed on Bořeň was compared with the cooling patterns given by the thermal models. A rough preliminary outline of the original shape for the Bořeň phonolite can be already estimated, considering the fact that the joints confining the columns grow perpendicular to the margins of original volcanic bodies during conductive cooling (Jaeger, 1961; DeGraff and Aydin, 1987). The “inverted fan” like columnar jointing pattern should form during cooling of a body with flat roof and a base that dips moderately to the vertical axis of the body. In other words, it should resemble a body with outward flaring funnel shaped stem and a horizontal roof.

4.1. Experimental apparatus and analogue materials

To model emplacement of magma into maar-diamente structures, we employed a modified hydraulic squeezer apparatus used earlier for modeling of lava domes (Závada et al., 2009a) and plaster of Paris as an analogue of magma. Plaster suspensions are good analogues for magmas that consist of low viscosity melt and large volume proportion of crystals. Suspensions of plaster powder and water are characterized by similar viscosities when their yield strength is exceeded regardless of their mixing ratio (Závada et al., 2009a). However, increasing mixing ratio of the plaster powder and water (the thickness) is marked by increasing yield strength of the suspension. Physical characteristics and preparation of the analogue material with admixed magnetite dust for tracing of AMS fabric and coloring are described in our earlier experimental work (Závada et al.,...
During the experiment, the plaster of Paris suspension is squeezed out from a container at the bottom of the apparatus by a hydraulic squeezer force transmitted over a steel frame and a loading board with a central hole (Fig. 8). The plaster then intrudes into a steel cone that is mounted on a vertical feeding conduit (20 cm long and 4 cm wide) and filled with a mixture of sand and solid angular plaster chunks (<1 cm in diameter). This loose material represents the phreatomagmatic lapilli tuff or agglomerate, which is poorly consolidated and agitated several times by subsequent phreatomagmatic explosions shooting debris jets from the root zone towards the surface (Lorenz, 1986; Zimanowski, 1998; Ross et al., 2008). The tapering angle of the cone of 70° was chosen to mimic the diatreme slope in hard rock environment (Lorenz, 2003; Schulz et al., 2005). Above the 30 cm long cone, a broader crater was modeled from kaoline clay to reflect relatively smaller dip angle of phreatomagmatic crater in soft-rock environment (Lorenz, 2003; Schulz et al., 2005). Above the 30 cm long cone, a broader crater was modeled from kaoline clay to reflect relatively smaller dip angle of phreatomagmatic crater in soft-rock environment (Lorenz, 2003; Auer et al., 2007) like the Cretaceous marlstones in the surroundings of the Borëph body. For five of the experiments, a “lid” of clay and sand layers was created at the top of the sand filled steel cone and in the lower part of the broader crater to study the mechanical effect of stratified maar sediments on emplacement mode and shapes of the intrusions/extrusions into the maar-diatremes (Table 1). Experimental runs were controlled manually keeping the extrusion rate as slow as possible except for first four models. The last 15 runs were captured as movies on a digital camera. The measured parameters are the initial load of the squeezer preceding each experiment, extrusion duration and maximum load of the squeezer at the end of each experiment. The three last experiments (D-31, D-32, and D-33) were motivated by the result of one earlier experiment (D-18), where the intrusion of plaster branched in the diatreme (Table 1, Fig. 9). In these experiments, the source container was filled with three different plaster portions of different mixing ratio. A cylindrical cake of the thick plaster (mixing ratio of plaster powder:water = 2.5) placed in the middle of the source container was surrounded by an annulus of more diluted plaster portion (2.3) and the thinnest (2.2) filling the corners of the rectangular container outside of the annulus. This setup was designed to mimic extrusion of magma from a magmatic chamber that is stratified in terms of increasing crystal content in its shallower levels. After each experimental run, solidified model bodies were excavated, sliced vertically and photographed. Outlined geometries of the models and traces of their flow planes from disrupted colored plaster is presented in Fig. 9.

4.2. Experimental results

Experiments with relatively thick plaster of mixing ratio 2.5 (weight of plaster powder/water) that were squeezed up rapidly resulted in emplacement of asymmetric extrusions with a thick stem.

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that have partially pushed aside the clastic filling of the model diatreme (models D-2 and D-4, Fig. 9, Table 1). Medium initial overpressure (model D-15) and slow extrusion of plaster resulted in thick stem in the upper part of the crater and emplacement of two large extrusive lobes. Experiments without the initial overpressure and slow pressure build up either failed to extrude or produced single extrusive dome emplaced close to the periphery of the crater (models D-7 and D-8, Fig. 9). In one of the slow pressure build-up experiments, the plaster was apparently stuck in the upper part of the conduit and suddenly released to inflate above the crater to final diameter of 40 cm in 1–2 s after the squeezer attained a load of 120 bar (model D-11). This body pierced a thin cover of clay and sand layers imitating the maar sediments. In two experiments, dried clay layers above the model diatreme worked as a competent “lid” that was only slightly uplifted by a plaster plug that rose along one wall of the steel cone. The plaster then extruded laterally from below the rotated lid (models D-9 and D-12, Fig. 9). In other two experiments, where initial loading started at 20 bar, a large teardrop shaped cryptodome formed (models D-6 and D-14, Figs. 9 and 10), which pushed upwards and sideways the entire filling of the crater and reached an aspect ratio (height to radius of the dome above the diatreme crater) of 1.3 (model D-6). Both cryptodomes have similar shapes, although one (D-14) had to pierce a thin and incompetent lid of model maar sediments. These experiments, together with experiments D-9 and D-12 lasted for 3–5 min and were terminated at maximum load of 125 bar.

Extrusions of plaster slurries prepared with mixing ratios ranging between 2.15 and 2.4 were squeezed slowly, without the initial overpressure and lasted from 12 to 240 s. The maximum load of the squeezer at the end of each experiment did not exceed 75 bar. Experiments with diluted plaster of mixing ratio 2.15 and 2.2 (models D-16 and D-17) formed a shallow lava lake fed by a narrow conduit 4 cm wide and an extrusion with flat-roofed top and a stem 7 cm wide, respectively. In another experiment (model D-18, Fig. 9), growth of one extrusive dome on crater periphery with diameter of 10 cm stopped although the load was continuously increasing and another dome formed on the opposite side of the crater after some additional load build up. The newer extrusive dome then grew in diameter and merged with the first dome. Excavation of the solidified model then revealed two distinct intrusion paths that bifurcated at the bottom of the steel cone (model D-18, Fig. 10). Models D-19 and D-21 (Fig. 9) together with models D-25, D-26 and D-27 prepared with plaster of mixing ratio 2.3 formed coulées or lava lakes.
Table 1

<table>
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<tr>
<th>Plaster thickness</th>
<th>Experiments</th>
<th>Degree of initial load</th>
<th>Duration</th>
<th>Maximum load</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>2.5</td>
<td>D-1, D-2, D-3, D-4</td>
<td>Large (25–50 bar)</td>
<td>5 s</td>
<td>50 bar</td>
<td>Thick stem, asymmetric single extrusion lobe</td>
</tr>
<tr>
<td>2.5</td>
<td>D-15</td>
<td>Medium (25 bar)</td>
<td>150 s</td>
<td>60 bar</td>
<td>Thick stem, extrusive dome formed by two extrusive lobes</td>
</tr>
<tr>
<td>2.5</td>
<td>D-7, D-8</td>
<td>Low or none (&lt;10 bar)</td>
<td>150–180 s</td>
<td>100 bar</td>
<td>Narrow stem, symmetrical extrusive dome on crater periphery</td>
</tr>
<tr>
<td>2.5</td>
<td>D-5</td>
<td>Low or none (&lt;10 bar)</td>
<td>180 s</td>
<td>120 bar</td>
<td>Narrow stem, extrusive dome</td>
</tr>
<tr>
<td>2.5</td>
<td>D-6</td>
<td>Medium (50 bar) for first 3 s</td>
<td>220 s</td>
<td>130 bar</td>
<td>Thick stem, teardrop shaped intrusion-cryptodome</td>
</tr>
<tr>
<td>2.5</td>
<td>D-9, D-12</td>
<td>Low or none (&lt;10 bar)</td>
<td>150 s</td>
<td>125–150 bar</td>
<td>Thick lid (3 layers of dried kaoline 0.5 cm thick interlayered with sand)</td>
</tr>
<tr>
<td>2.5</td>
<td>D-11</td>
<td>Low or none (&lt;10 bar)</td>
<td>3 s</td>
<td>120 bar</td>
<td>Thin lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand)</td>
</tr>
<tr>
<td>2.5</td>
<td>D-14</td>
<td>Medium (50 bar) for first 3 s</td>
<td>300 s</td>
<td>125 bar</td>
<td>Thin lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand)</td>
</tr>
<tr>
<td>2.15</td>
<td>D-16</td>
<td>None</td>
<td>12 s</td>
<td>50 bar</td>
<td>Thick lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand)</td>
</tr>
<tr>
<td>2.2</td>
<td>D-17</td>
<td>None</td>
<td>210 s</td>
<td>75 bar</td>
<td>Extrusion similar in shape to experiment D-24, stem 7 cm wide</td>
</tr>
<tr>
<td>2.2</td>
<td>D-18</td>
<td>None</td>
<td>190 s</td>
<td>75 bar</td>
<td>Extrusion of two individual extrusive domes on crater periphery, second dome extruded 25 s after the first dome, inflated and merged with the first dome</td>
</tr>
<tr>
<td>2.3</td>
<td>D-19, D-21</td>
<td>None</td>
<td>60–240 s</td>
<td>50 bar</td>
<td>Lava lake fed by a narrow stem that pierced the model diatreme at the periphery of the maar crater</td>
</tr>
<tr>
<td>2.3</td>
<td>D-25, D-26, D27</td>
<td>None</td>
<td>90–210 s</td>
<td>70 bar</td>
<td>Asymmetrical “coulées” or “lava lakes” fed by stems about 8 cm wide</td>
</tr>
<tr>
<td>2.4</td>
<td>D-22, D-23, D-24</td>
<td>None</td>
<td>100–160 s</td>
<td>75 bar</td>
<td>Extrusive dome fed by a stem 7–12 cm wide</td>
</tr>
<tr>
<td>2.5 + 2.3 + 2.2</td>
<td>D-31, D-32, D-33</td>
<td>None</td>
<td>180–240 s</td>
<td>80 bar</td>
<td>Experiment imitating extrusion of magma from a stratified magmatic chamber, with thick (2.5) plaster in the center of the source container, surrounded by annulus of thinner plaster portions — 2.3 and 2.2 on the periphery; extrusive domes similar to D-24 or successive extrusion of lobes from a thick stem (D-32)</td>
</tr>
</tbody>
</table>

Extrusions of all models prepared with mixing ratio of 2.3 were “molded” by the elastic talus of uplifted crater filling and all resulted in similar shapes of extrusive domes; the talus of model phreatomagmatic tephra was pushed aside and was partly overridden by the rising plaster during growth of these extrusions. Last stages of D-22 and D-24 experiments were marked by emplacement of distinct portions (lobes) of the analogue material like in our earlier experiments on growth of complex lava domes (Závada et al., 2009a). Plaster models that pierced through the crater center had relatively wider stem below the extrusive part (models D-22 and D-24, Fig. 9). Three last experiments (D-31, D-32, and D-33), which imitated extrusion of magma from a stratified magma chamber, resulted in extrusive domes similar in shape to model D-24 (D-31 and D-33) or successive emplacement of plaster lobes into the crater from a thick stem (D-32, Fig. 9).

Plaster thickness Experiments Degree of initial load Duration Maximum load Description

2.5 D-1, D-2, D-3, D-4 Large (25–50 bar) 5 s 50 bar Thick stem, asymmetric single extrusion lobe
2.5 D-15 Medium (25 bar) 150 s 60 bar Thick stem, extrusive dome formed by two extrusive lobes
2.5 D-7, D-8 Low or none (<10 bar) 150–180 s 100 bar Narrow stem, symmetrical extrusive dome on crater periphery
2.5 D-5 Low or none (<10 bar) 180 s 120 bar Narrow stem, extrusive dome
2.5 D-6 Medium (50 bar) for first 3 s 220 s 130 bar Thick stem, teardrop shaped intrusion-cryptodome
2.5 D-9, D-12 Low or none (<10 bar) 150 s 125–150 bar Thick lid (3 layers of dried kaoline 0.5 cm thick interlayered with sand), rotation of the rigid lid was followed by limited lateral extrusion of analogue magma
2.5 D-11 Low or none (<10 bar) 3 s 120 bar Thin lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand), thick stem, teardrop shaped intrusion
2.5 D-14 Medium (50 bar) for first 3 s 300 s 125 bar Thin lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand), thick stem, teardrop shaped intrusion
2.15 D-16 None 12 s 50 bar Thin lid (3 layers of moist kaoline 0.2 cm thick interlayered with sand), narrow stem, lid disrupted into rafts floating on a “lava lake”
2.2 D-17 None 210 s 75 bar Extrusion similar in shape to experiment D-24, stem 7 cm wide
2.2 D-18 None 190 s 75 bar Extrusion of two individual extrusive domes on crater periphery, second dome extruded 25 s after the first dome, inflated and merged with the first dome
2.3 D-19, D-21 None 60 s–240 s 50 bar Lava lake fed by a narrow stem that pierced the model diatreme at the periphery of the maar crater
2.3 D-25, D-26, D-27 None 90–210 s 70 bar Asymmetrical “coulées” or “lava lakes” fed by stems about 8 cm wide
2.4 D-22, D-23, D-24 None 100–160 s 75 bar Extrusive dome fed by a stem 7–12 cm wide
2.5 + 2.3 + 2.2 D-31, D-32, D-33 None 180–240 s 80 bar Experiment imitating extrusion of magma from a stratified magmatic chamber, with thick (2.5) plaster in the center of the source container, surrounded by annulus of thinner plaster portions — 2.3 and 2.2 on the periphery; extrusive domes similar to D-24 or successive extrusion of lobes from a thick stem (D-32)

Only models D-22 and D-24 were selected for thermal modeling and further detailed comparison of their internal fabrics on the basis of the previously stated preconditions of similarity with the Boleň phonolite body. In contrast, models D-15 and D-11 were discarded due to their unrealistically rapid emplacement, although even these satisfy the preconditions.

4.3. Internal fabrics in model extrusive domes

In lower parts of the solidified models D-22 and D-24, where plaster intruded into the cone from the steel conduit, the channel that transferred the plaster to the higher levels is either locally attenuated (D-22) or doubly curved (D-24). Both models reveal an upward widening vertical stem with irregular walls. The upper part of the stems for both bodies flares into an extrusion above the model maar-diatreme crater.

Fig. 9. Shapes of experimental bodies in vertical sections with contours depicting their internal flow planes as indicated by disrupted color banding. Note that some extrusion shapes are characterized by two similar experiments depicted by different color contours (D-2–D-4; D-6–D-14; D-7–D-8; D-9–D-12; and D19–D-21). For description of experimental conditions and development of the experiments see Table 1. Thick red contours for some of the models indicate superposed landscape of Boleň body above the probable diatreme crater. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
For the AMS analysis, model D-24 was drilled in one vertical section and model D-22 (Fig. 11) was cut along two vertical and mutually perpendicular sections. All sections were drilled in a hexagonal grid of 1 cm spacing, but for both sections of model D-22 only every other core in a row and in every other vertical column was measured. The core samples are 0.8–1 cm long and have 1 cm in

Fig. 10. Photographs of selected experimental intrusions into maar-diatreme structures before slicing. Scalebars are 10 cm long. Z and X axes indicate the top and front directions of the models within the experimental apparatus.

Fig. 11. Photographs of vertical sections and AMS pattern of the selected analogue models. Landscape profiles through the Bořeň body depicted in Fig. 6 are superposed on both sections of the D-22 model. Magnetic foliations and lineations represent the $K_1$, $K_2$ sections of AMS ellipsoids and $K_1$ directions, respectively. Because magnetic foliations regularly dip at high angle from the sections, their dip angle is not plotted.

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diameter. The eccentricity (P parameter) and shape (T parameter) of the AMS ellipsoid can be characterized by the following parameters (Nagata, 1961; Jelínek, 1981).

\[
P = K_1 / K_3 = (2\eta_1 - \eta_1 - \eta_1) / (\eta_1 - \eta_1)
\]

where \(K_1 > K_2 > K_3\) are the principal susceptibilities, \(\eta_1 = \ln K_1, \eta_2 = \ln K_2, \eta_3 = \ln K_3\). The P parameter indicates the intensity of preferred orientation of magnetite particles in pluster models. If \(0 < T < 1\), the AMS ellipsoid is oblate (the magnetic fabric is planar); \(T = +1\) means that the AMS ellipsoid is rotationally symmetric (uniaxial oblate). If \(-1 < T < 0\) the AMS ellipsoid is prolate (the magnetic fabric is linear); \(T = -1\) means that the AMS ellipsoid is uniaxial prolate. If \(T = 0\), the ellipsoid is neutral.

The internal concave traces of flow planes envisaged by the disrupted colored plaster correlate with the strike alignment of magnetic foliations (Fig. 11). Second section of model D22 also reveals lastly emplaced lobe forming a bulge on the surface of the body. In the extrusive parts of both models, the pattern of magnetic foliations and lineations resembles that in our earlier models of plaster extrusions above a sand layer (Závada et al., 2009a); magnetic lineations dipping to the center of the bodies at the base of the extrusions and lineations perpendicular to the vertical sections in upper parts of extrusive lobes. Contour diagrams of P and T parameters for both models reveal highly anisotropic \((P = 1.24 - 1.45)\) and oblate \((T = 0.4 - 1)\) fabrics in the central columnar domains extending to the top of the extrusions and fabrics with low anisotropy in a narrow domain encompassing the highly anisotropic internal part. These low intensity fabric domains reveal neutral to prolate shapes with \(T\) ranging from \(-0.55\) to 0.1 and are also locally marked by lineations with high plunge angles from the vertical section.

5. Columnar joint patterns constrained by thermal mathematical modeling

Finite element thermal mathematical modeling of cooling was carried out for models D-22, D-24, and also for model D-6, since a teardrop shape of the Bořeň body and other phonolite intrusions was suggested in earlier works (Kopecký, 1978, 1991; see the profile in Fig. 1). For both models D-22 and D-24, thermal models and analysis of the thermal structure was done for two perpendicular vertical sections and compared with the columnar jointing pattern on the NW–SE and SW–NE sections through the Bořeň phonolite body (profiles depicted in Fig. 6). Similar comparison was done also for a three-dimensional thermal model using simplified geometry of D-22.

All thermal models were provided with thermophysical parameters of rocks collected around the Bořeň body: the basement orthogneiss, Cretaceous marls, Tertiary basanites, phreatomagmatic lapilli tuff collected at Zlatník Hill (Fig. 2a) and the phonolite (Table 2).

Thermal conductivities and capacities of the samples were measured in laboratories of Institute of Geophysics ASCR using an instrument, which is based on optical scanning method (Popov et al., 1999). Thermal models were constructed using software Comsol and Fracture (Kohl and Hopkirk, 1995). Initial temperature 1100 °C of the phonolite bodies in the model was calculated from composition stability in minerals of the Żelienkić Hill phonolite by Pazdernik (1997). Latent heat of the phonolite of 300 kJ (Calcins et al., 2008), corresponding to the heat released during crystallization of lava, was also implemented in the model. A layer covering the extrusions about 8–16 m thick is included in thermal models for bodies D-22 and D-24 to account for possible presence of glassy and porous pumice that was locally found in massive phonolite outcrops on the nearby Kaškovej phonolite body. We assume that the same porous pumice found on Kaškov could have formed a continuous carapace on the top of Bořeň body, where it worked as an effective thermal insulant impeding the thermal flow during cooling of the phonolite. Similarly, porous scoria forming capping units on the peperitic lava lake at Ság-hegy in Hungary (Martin and Németh, 2004). We provide comparison for the rate of cooling below the roof of phonolite extrusion in the D-22 thermal with and without the surficial pumice layer. These rates of cooling are also compared with that above the base of the same body.

To determine the temperature at which the columnar joints in the phonolite formed, the thermal expansion coefficient was measured from three 0.8 cm wide and 1 cm long samples drilled perpendicular to the phonolite magmatic fabric and measured for thermal variation of thermal expansion coefficient α by Marcel Potužák on Ludwig-Maximilian University in Münich using Netzsch DIL 402C dilatometer. The measured curves of all three samples revealed almost identical ascending trend of α value with increasing temperature and two distinct peaks at 620 and 920 °C (Fig. 12). The first peak at 620 °C is interpreted to reflect transient expansion of the sample due to the loss of water from secondary minerals filling the cavities in the phonolite. Large increase in thermal expansivity coefficient value indicated by the peak at 920 °C is considered to reflect the temperature corresponding to formation of columnar joints in cooling phonolite lava. To trace the trends of columnar joints that would form during

![Fig. 12. Variation of thermal expansion coefficient with increasing temperature measured on the Bořeň phonolite sample. Peak on the curve at 620 °C is interpreted to reflect the transient expansion of the sample due to loss of water released from secondary minerals in the cavities. Second peak at 920 °C is interpreted to reflect the temperature corresponding to formation of columnar joints in cooling phonolite lava.](image_url)
cooling of the model bodies, we draw lines perpendicular (Jaeger, 1961; Spry, 1962; DeGraff and Aydin, 1987) to the 920 °C isotherms plotted at 10 (and 50) year time intervals (Fig. 13). Only conductive cooling was considered, because no precipitates were found on columnar joint faces, which would indicate circulation of fluids in the cooling front and contribution of convective cooling (DeGraff and Aydin, 1993).

Thermal model constructed for the geometry of a large crypto-dome that pushed upwards and sideways the entire filling of the model maar (model D-6, Fig. 13) revealed that the columnar joints growing from the margins of the body converge into an elliptical and vertically elongated core that is centered at the basement orthogneiss–marlstone contact. Superposed landscape contour of the SW–NE profile through the Bořeň body with columnar joint pattern

![Fig. 13. Thermal models constructed for selected shapes of analogue models with displayed isotherms of 920 °C spaced at 10 year intervals for models D-6 and D-22 and 50 year intervals for model D-24. Thick red contour and thick dashed black lines indicate the relief and trend of columnar jointing on the Bořeň body. Thin black lines indicate trends of columnar jointing that are perpendicular to the 920 °C isotherms as resolved from the thermal model. See Table 2 for the lithology codes. Green lines indicate the contact between the cooling fronts in the models. Spots A and B mark two points where the rate of cooling was evaluated (Fig. 15). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image1)

![Fig. 14. A simplified three-dimensional thermal model roughly reflecting the geometry of analogue model D-22 revealing distribution of temperature after 200 years of cooling. Oblique top view of the finite-element model geometry (A) – lithology codes are indicated in Table 2, vertical profiles of the thermal model correspond to the NW–SE (B) and SW–NE (C) sections through the Bořeň body. Thick white contour and dotted white lines indicate the relief and trend of columnar jointing on the Bořeň body. Directions and relative dimensions of arrows correspond to the direction and degree of thermal flux, respectively.](image2)
measured in the field reveals complete mismatch between the results of thermal model and the reality. The columnar joint trends in the thermal model are perpendicular to the trends of columns measured in the field. Thermal model for extrusion D-24 (Fig. 13) indicates a close match between the columnar jointing on the NW–SE profile of Bořeň body and that inferred from the thermal model. However, in perpendicular section compared with SW–NE transect of the elevated plateau of Bořeň, relative dimensions of the model do not correspond to the dimensions of exposed phonolite body, although the resolved columnar jointing pattern roughly matches with the real one. Comparison of the thermal model results for experiment D-22 in both perpendicular vertical sections and NW–SE and SW–NE transects of the elevated plateau on Bořeň indicates a close match between the model and reality, except the low-angle difference between the columns implied by the thermal model of the second section and upper collonade on NE side of the body (Fig. 13). The contact height between the upper and lower cooling fronts is consistent with the suture level between the upper and lower collonades according to both thermal models D-24 and D-22.

A three-dimensional thermal model corresponding with D-22 experiment (Fig. 14) indicating topology of isotherms after 200 years of cooling confirms the results of the previous two-dimensional models (Fig. 13). The hot core is centered at the suture level between the two collonades on the superimposed profile of Bořeň and the isotherms are mostly perpendicular to the trends of columns in the field. The 3D thermal model (Fig. 14) implies that the cooling of the phonolite monolith to 100 °C and 20 °C lasted 4000 and 10,000 years, respectively.

The presence of an insulating pumice cover greatly reduces the degree of cooling of the phonolite extrusions. This is depicted in Fig. 15. The rate of cooling of a point 5 m below the roof of the phonolite extrusion with shape of model D-22 is 2.7× faster than in equivalent extrusion that is covered by 8 m thick layer of pumice. In contrast, degree of cooling close to the top and bottom parts (A and B) of the extrusion is similar, when it is covered with the insulating layer.

6. Discussion

Combined techniques of structural analysis of fabric and cooling joint systems on the Bořeň phonolite body together with systematic analogue modeling of magma intrusion into phreatomagmatic craters and thermal mathematical modeling of cooling for different shapes of bodies obtained by analogue modeling provide a unique possibility to pinpoint the original shape, the internal flow kinematics and emplacement dynamics for the Bořeň phonolite body. Our results bring interesting insight into emplacement mode of crystalline magma into phreatomagmatic craters in general.

The analogue modeling results imply that the intrusion and extrusion style depends primarily on the yield strength (thickness) of the analogue magma and initial overpressure build-up in the analogue magma chamber prior to extrusion. Since none of the phonolite extrusions into phreatomagmatic craters were witnessed, it is impossible to scale the experiments. Nevertheless, the analogue modeling approach proved as a very instructive method for understanding the physics of complex mechanical interaction between the non-Newtonian magma and loose (Coulomb-like) phreatomagmatic tephra filling the funnel shaped volcanic craters. In our approach, we present the scaling analysis to constrain possible timescales for emplacement of the Bořeň phonolite assuming that the dynamic similarity between model D-22 and original was closely approached on the basis of their similar relative dimensions and internal fabrics.

Suspensions of plaster powder and water proved as convenient analogues of magmas with high crystal content such as phonolites or trachytes (Závada et al., 2009a,b). We attempted to mimic the geometry of phreatomagmatic craters as revealed by geological and geophysical surveys (Schulz et al., 2005; Lorenz and Kurszlaukis, 2007), although the slope angle of the upper part of the maar-diatreme established in the Cretaceous sediments is hypothetical.

6.1. Shapes of the extrusions

Cooling and solidification of lava can significantly influence shapes of extrusions by formation of solid crust which inhibits lateral spreading and rise of new lava (Griffiths and Fink, 1993; Sakimoto and Zuber, 1995). For intermediate lava compositions and typically andesite lavas, the effect of cooling on lava solidification is negligible, because the cooling is controlled by degassing induced crystallization (Sparks et al., 2000). Hale (2008) numerically modeled lava dome extrusion simplifying the rheology of an andesite lava dome to Newtonian viscous fluid, which was confined laterally by deformable talus growing by rockfalls and disintegration of the solid surface. For crystal-rich phonolites investigated in this study, degassing induced crystallization and solidification could also have accompanied their emplacement. Degassing and accumulation of the gases in the surficial parts of the phonolite extrusions is reflected by the presence of pumice on the top of Kaňkov hill, similar to the surficial vesicular pumice layers in obsidian lava domes (Fink, 1983). Since the original thickness and the mechanical properties of the pumiceous layer are not known, it is difficult to consider its influence on lava dome extrusion dynamics. Nevertheless, utilization of isothermal material like plaster of Paris for modeling lava domes of intermediate composition is justified with the process of degassing induced crystallization and solidification (Sparks et al., 2000). The volume of aggrading talus from the solidified phonolite blocks around the extrusions (Hale, 2008) would be probably negligible in contrast to the volume of phreatomagmatic tephra talus which is pushed aside behind the expanding extrusions. In summary, we can consider that the shapes and emplacement dynamics of the isothermal experimental extrusions into maar-diatreme structures can closely represent their natural phonolite lava equivalents.

Most of the extrusions prepared with suspensions of mixing ratio 2.5 are considered as unrealistic equivalents to natural phonolite
extrusions, because these were emplaced rapidly within only few seconds (D-2, D-4, and D-11) or were confined by too competent “lid” of maar sediments (D-9 and D-12, Fig. 9). In the experiments with thick plaster and medium to large initial overpressure (25–50 bar), the plaster pushed upwards and sideways large portion or the entire volume of the crater filling, while in experiments with low or no initial overpressure, the plaster formed narrow conduit below an extrusive dome. Although quite large magma overpressures would be required to form the cryptodomes D-6 and D-14 or extrusive domes D-7 and D-8, their geometries could correspond to high aspect ratio remnants of phonolite bodies in the České středohoří Mountains or other Tertiary volcanic provinces in the foreland of Alpine orogeny (Cloos and Cloos, 1927; Camus, 1975; Arbaret et al., 1993). In contrast, extrusion of the same material on flat surface would result in low aspect ratio lava domes or flows (Závada et al., 2009a) like the phonolite coulée forming the Ryzelský Hill (Fig. 1).

Experiments with plaster suspensions of mixing ratio 2.15–2.3 resulted in different extrusion shapes ranging from asymmetric extrusions fed by stems of variable width to lava lakes and branched intrusions. These different final geometries likely reflects light differences in the packing density of the loose diatreme filling and inhomogeneities in the plaster suspension. The “intrusion branching” encountered in one of the experiments (D-18) could explain the merging phonolite cupolas of Hněvín and Široký Hills (Fig. 1) or centrically distributed phonolite bodies of Missouri Buttes (WY, USA) (Halvorson, 1980). In nature, the intrusion branching could be induced by subsequent rise of magma batches (e.g. from a stratified magma chamber) each with relatively lower yield strength owing to decreasing crystal content. However, this explanation is not fully supported by the last three experiments. In composite experiment D-32, the flow diverged in the upper part of the diatreme, while in earlier experiment D-18 (homogeneous suspension, mixing ratio 2.2), intrusion branched in the lower part of the diatreme. Alternatively, branching of magma emplaced in volcanic craters could be also explained by sluggish or unsteady ascent rate of magma allowing the short-lived conduits to solidify.

6.2. Fabric development in the extrusions

Interpolation of magmatic fabric manifested by alignment of sanidine and nepheline (Fig. 6) throughout the investigated Bořeň body evinces a concave cupola with flat fabrics in the SE-central part and steep fabrics on the margins. Similar cupola shaped fabric pattern resulting from the uplift plug-flow is typical for most of the analogue models (Fig. 9). However, the internal fabric pattern, relative dimensions of the body and the thermal structure best corresponds with model D-22. For detailed comparison of fabric throughout the Bořeň body and the analogue model D-22, we inspected sections cut parallel to the mirror symmetry of the exposed phonolite body (note the indicated profiles in Fig. 6) and the analogue model and also sections perpendicular to the first section and transecting the elevated plateau for the Bořeň body. A number of samples from the central and SE-central part of Bořeň measured for CPO revealed magmatic lineations with shallow plunges and N-S to NW–SE trends (Fig. 6, samples B-24, B-65, B-41, B-43, B-82, and B-94). Same fabric pattern is characterized by the AMS in analogue model D-22 (note lineations subparallel with the 1st section and at high angle to the 2nd section in upper parts of the model in Fig. 11). Fabric in both analogue models measured for AMS (Fig. 11) revealed highly anisotropic domain associated with flat and oblate fabrics in the central columnar part of the stems below the extrusive parts of the models surrounded by domains with low anisotropy, neutral to prolate shaped fabric and subhorizontal lineations encircling the central part. This fabric could be explained by divergent flow on the periphery of the plug flow domain during ascent of the viscously flowing material within an upward widening stem (Fig. 11). In contrast, fabric in the margins of the models, which are vertical and parallel with their boundaries (Figs. 11 and 16) can be explained by shearing and mechanical coupling of the vertically ascending material with the surrounding loose substrate. The flow kinematics in the extrusive parts of the models is similar to previous analogue and numerical modeling results (Buisson and Merle, 2004; Závada et al., 2009a) and originate due to circumferential stretching in the upper lateral parts and radial stretching at the base of the extrusions (Buisson and Merle, 2002). The outlined pattern of flow kinematics throughout the extrusions emplaced into maar-diatremes (Fig. 16) will be distorted for asymmetric extrusive bodies like both models D22 and D24 (Fig. 11).

Second measured microstructural elements are the lenticular to sigmodal cavities in the phonolite lava. Detailed structural mapping of these cavities throughout a single volcanic body was not carried out before. The origin of mostly vertical cavities throughout the Bořeň cupola and sigmodal cavities dipping at low angle toward cupola periphery is best illustrated using analogue model D-11. Although this model was previously discarded for further analysis because of unrealistically rapid emplacement, it reveals macroscopic vertical cavities increasing in abundance and dimensions from the bottom of the stem towards the apical part of the extrusion and local sigmodal cavities in the central part (Fig. 17). Similarly oriented, but less distinct and fewer cavities are also present in model D-22. Large cavities in model D-11 formed due to fast lateral diffusence and divergent flow of plaster during extrusion from the narrow conduit. Since the general kinematic framework of emplacement for both models is virtually identical and independent of the emplacement velocity, we can use the cavities in model D-11 for the kinematic interpretation of cavities throughout the Bořeň cupola.

The cavities form due to strain incompatibilities in the vicinity of inhomogeneities (like larger phenocrysts in the phonolite) and reflect the shear thickening rheology of the extruding material (Smith, 2000; Smith et al., 2001). In other words, cavities form in places, where local shearing of the material cannot be fully accommodated by sliding along the groundmass microphenocrysts, which are mostly represented by lath-like sanidine crystals in phonolite magma, or platy hemihydrate particles in plaster suspensions. Incipiently opening cavities drain the groundmass from residual interstitial liquids, which is reflected by minute aegirine–augite crystals growing into the cavities from the Želenický Hill phonolite (Fig. 5c). The result of this liquid transfer is hardening and transition from ductile to brittle deformation of the solid–liquid system at low melt volumes and is analogous to cavitation controlling creep failure of metamorphic rocks deformed in grain boundary sliding regime (Závada et al., 2007; Rybacki et al., 2008). Progressing failure of the cavitated lava should be manifested by increased abundance of cavities, faulting and dismemberment of the homogeneous texture by ductile tearing and
break up of the homogeneous fabric into individual domains that are differentially rotated and bend, fold or extend separately, which is evident from the phonolite texture in the margins of the cupula, specifically on locality B65.

Lenticular cavities form parallel to local maximum compressive stress direction during shearing of the crystal-rich lava (Fig. 17c). Sigmoidal cavities that dip at shallow angles to the periphery of the cupula (samples B43, B92, and B94 on Bořeň, Fig. 7; upper part of model D-11, Fig. 17) are interpreted as distorted lenticular cavities that formed due to non-coaxial diffuence of lava. Increasing rate of layer parallel stretching from the core to the apical part of the extruding cupula, indicated by upwardly diverging serrated layers of colored plaster (Fig. 17b), generates non-coaxial flow with top to the periphery sense of shear. Fast non-coaxial flow, associated with high shear stresses (Smith, 1997), results in dilation hardening and produces cavities inclined at low angle to the sandine crystal fabric (Fig. 17c). Resumed, but limited ductile flow at decreased shear stress then deforms the originally lenticular cavities into sigmoidal shape. Sigmoidal cavities with different strike of central and tail parts suggest that the sense of shear changed during the lava extrusion (Fig. 7).

6.3. Thermal structure of the models and natural phonolite bodies

Application of finite element thermal modeling on shapes of bodies obtained using analogue modeling is a powerful tool for structural analysis of fabric and fracture patterns of irregular volcanic bodies. Fracture patterns that develop during cooling of irregular volcanic bodies were previously solved theoretically and only for simplified geometries (Jaeger, 1961; Spry, 1962). Our modeling results imply that if columnar joints would form in the teardrop shaped cryptodomes, they would converge to their cores. In contrast, thermal models for the extrusive domes predict that cooling joints growing from the upper and lower boundaries of the bodies will confine columns of upper and lower columnades divided by a subhorizontal suture (Fig. 13). Columns of the upper columnade are typically wider than the outward flaring columns of the lower columnade on the phonolite “towers” like Bořeň or Devils Tower (WY, USA). This contrasts with thick basal columns and thinner columns in the upper parts of basalt lava flows (DeGraff and Aydin, 1987; Lyle, 2000) that develop by slow conductive cooling at the base and faster conductive and convective cooling progressing from the upper surface and master joints in the upper columnade, respectively (DeGraff and Aydin, 1993; Lyle, 2000). Thicker columns of the upper columnade on Bořeň body are attributed to relatively slower cooling of the top part due to presence of an insulating layer of pumice and blocky lava. Insulating properties of blocky covers derived from the lava are well known from acidic lava flows (Harris et al., 2002). The reconstruction of the original thickness for the insulating carapace layer is impossible, because, (1) thermal properties of this layer are probably not well represented by thermal properties measured from a hand–specimen of phonolite pumice, and (2) the relationship between column width and thermal gradient is known only qualitatively (DeGraff and Aydin, 1993). Nevertheless, our evaluation of the cooling with the 8 m thick insulating layer (Fig. 15) revealed that for the initial period of cooling (8 years in point A) the cooling is slower than at the bottom of the extrusion, which is compatible with thicker columns at the top of Bořeň body.

6.4. Emplacement dynamics of the Bořeň body constrained by analogue and thermal modeling

Considering that the original shape of the Bořeň phonolite body is best reflected by the analogue model D-22 on the basis of their relative dimensions within the probable maar-diatireme crater, similar fabric pattern and thermal structure, we attempt to estimate the emplacement time of the Bořeň body using the scaling principles of analogue modeling (Hubbert, 1937; Ramberg, 1981). Assuming that the impact of cooling on the emplacement dynamics of Bořeň phonolite was negligible, that the dynamic similarity between the model and original was attained and that the inertial forces are negligible for slowly emplaced magma and analogue material, time of Bořeň extrusion $t_x$ can be calculated by the following equation: $t_x = (\delta \psi / \phi \lambda) t_m$, where $\delta$, $\lambda$, $\psi$ are the ratios between model and original for densities, sizes and viscosities (Table 3) and $t_m = 160$ s is extrusion time for the model. Considering viscosities of the residual melt in the phonolite of $10^4$–$10^5$ measured for crystal free phonolite glasses (Giordano et al., 2001), extrusion time for the Bořeň body ranges between 6 and 66 days. We can also indirectly calculate the yield strength of phonolite magma from the shape of Ryželský Hill coulée (height 100 m, radius 1250 m) using Nye’s analytical solution for axisymmetric dome in static balance.

**Table 3**

<p>| Physical properties of analogue model D-22, the Bořeň phonolite body and the scaling ratios. Properties of analogue material are taken from Závada et al. (2009a), viscosity of phonolite melt from Giordano et al. (2001). Viscosity of the model material refers to viscosity of water in the plaster suspension. |
|---------------------------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th><strong>Size (m)</strong></th>
<th><strong>Model</strong></th>
<th><strong>Original</strong></th>
<th><strong>Model ratios</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Magma properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity (Pa·s)</td>
<td>0.001</td>
<td>$10^{-4}$</td>
<td>$\psi = 10^{-7}$</td>
</tr>
<tr>
<td>Density (kg·m$^{-3}$)</td>
<td>2300</td>
<td>2530</td>
<td>$\delta = 0.91$</td>
</tr>
<tr>
<td>Yield strength (Pa)</td>
<td>195</td>
<td>99,277</td>
<td>$\sigma = 3.6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

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(Nye, 1952; Závada et al., 2009a), which gives a value of 99,277 Pa. Because the model ratio of yield strength calculated from equation 
\[ \sigma = \dot{\gamma} \cdot \lambda (Humbert, 1937) \] is \( \sigma = 3.6 \times 10^{-4} \), value of yield strength for the model material should be 35 Pa. This value is only about six times less than 195 Pa measured for plaster suspensions with mixing ratios of 2.4 (Závada et al., 2009a), which further justifies the dynamic similarity between model and original and our scaling approach.

6.5 Conclusions

Combined techniques of structural analysis of fractures and fabrics on natural phonolite bodies together with analogue and thermal mathematical modeling revealed that the Bořeň phonolite body probably represents a remnant of an asymmetric extrusive dome emplaced into a phreatomagmatic maar-diamente crater within time period of 6–66 days and cooled down to a background temperature in 10,000 years. Series of analogue experiments revealed that intrusion of magma into maar-diamares can result in emplacement of cryptodomes, extrusive domes or branched intrusions producing extrusive domes on crater periphery. Analysis of internal fabric of analogue models corresponding to Bořeň body revealed a domain of circumferential flow around highly anisotropic fabric associated with upward plug-flow in the vertical stems underlying the extrusive domes. Mostly vertical microscopic cavities throughout the exposed body resulted from rapid lateral diffuence of the magma above the maar crater. Comparison of thermal models with columnar jointing pattern on the Bořeň phonolite body suggests that the extrusive domes or lava lakes emplaced into maar-diamente craters are marked by subhorizontal suture between the colunndanes of columns. The vertical level of the suture between the colunndanes, dimensions of the erosive remnant and the host maar, together with internal fabrics and orientation of the columns in the solidified lava allow to reconstruct original dimensions and shape of the bodies emplaced into maar-diamares.

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References


