ABSTRACT

We have investigated the mode of emplacement of iconic Devils Tower, which is a phonolite porphyry monolith in the state of Wyoming in the western United States. Our field survey of this structure and its geological setting, its radiometric dating, and the tectonomagmatic evolution of the region suggest a new genetic interpretation of the volcanioclastic rocks in the area and provide a basis for a new hypothetical emplacement scenario for Devils Tower. This interpretation was inspired by an analogy of the tower with a similar phonolite butte in the Cenozoic volcanic region of the Czech Republic and analogue modeling using plaster of paris combined with finite element thermal numerical modeling. Our results indicate that Devils Tower is a remnant of a coulée or low lava dome that was emplaced into a broad phreatomagmatic crater at the top of a maar-diabase volcano.

INTRODUCTION

Devils Tower is a dominant landmark of the northern Great Plains (Wyoming, USA). It represents the world’s finest example of columnar jointing in phonolite and possibly the longest columns developed in a volcanic rock (Fig. 1). The Cenozoic phonolite porphyry monolith forming Devils Tower is located in the western Black Hills in northeastern Wyoming (Fig. 2). The scientific debate on the origin of Devils Tower has lasted for more than 100 years.

The majority of previous studies of Devils Tower have concluded that it is a remnant of an intrusive body in the form of a mafic stock (Russell, 1896; Robinson, 1956), a laccolith (Pirsson, 1894; Jaggard, 1901), or a volcanic conduit (Carpenter, 1888; Halvorson, 1980); the latter interpretation is presented in many Earth science textbooks. Although conclusive evidence is lacking, it is generally accepted that it represents an intrusion of phonolite magma that was exposed after erosion of the surrounding weakly consolidated Mesozoic and Cenozoic sedimentary layers (e.g., Robinson and Davis, 1995; Sigurdsson, 2000). Corry (1988) claimed that Devils Tower is a volcanic neck that may have formed from solidified magma that extruded along a failure zone in the extended roof of a Christmas-tree laccolith. Lisene and Roggen (1990) and Rakovan (2006) suggested that the emplacement of phonolite magma was somehow associated with diatremes or phreatomagmatic volcanoes; however, they did not address the mode of Devils Tower emplacement. In contrast to all intrusive scenarios, Kiver and Harris (1999) argued that the tower could represent a remnant of a surficial lava body or welded pyroclastic material emplaced into the phreatomagmatic maar crater. Spry (1962) explained the inverted fan columnar jointing pattern on Devils Tower by cooling of an extrusive lava sheet above the conduit based on the mathematical model of Jaeger (1961).

Understanding the emplacement mode for Devils Tower requires additional study using modern techniques of structural analysis of magmatic fabrics and fracture systems that develop during cooling of magmatic bodies. Additional insight can be gained by studies of similar features around the world, such as those found in the Cenozoic volcanic provinces of western and central Europe. These features are located in the foreland of the Alpine belt (Cajz et al., 1999; Ziegler, 1994), and the emplacement mode of phonolite or trachyte bodies that are similar to Devils Tower has been interpreted primarily on the basis of spatial distribution of magmatic fabrics and their kinematics (Cloos and Cloos, 1927; Varet, 1971; Jančušková et al., 1992; Arber et al., 1993; Závada et al., 2009a). One of these well-exposed phonolite buttes (Bořeň phonolite body, Czech Republic) was recently investigated and interpreted as a remnant of a lava dome extrusion into the crater of a maar-diabase volcano by combined methods of magmatic fabrics and cooling fracture patterns (Závada et al., 2011).

The fact that Devils Tower is also associated with phreatomagmatic pyroclastic rocks similar in composition to those associated with diatremes elsewhere in the Black Hills (Effinger, 1934; Lisene and Roggen, 1990; Kirchner, 1996) and exhibits remarkable similarities with the Bořeň body (e.g., size, phonolitic composition, inverted fan pattern of columnar jointing) motivated us to undertake a new survey and analysis in Devils Tower area to consider alternative models for its emplacement. We propose a new emplacement scenario that is supported by a conceptual analogue model using plaster of paris as an analogue of magma that shows the internal flow pattern from magnetic fabrics of dispersed magnetic particles and serves as a template for numerical model of cooling that is matched with the Devils Tower columnar jointing pattern. Owing to the National Monument administrative limitations we could not carry out direct structural measurements or collect samples for a systematic anisotropy of magnetic susceptibility (AMS) study as intended.

CENOZOIC IGNEOUS AND VOLCANIC ACTIVITY IN THE BLACK HILLS UPLIFT

The Devils Tower phonolite monolith (Figs. 1A, 1C–1E) and Missouri Buttes, a group of five bodies of similar composition located 5 km
Devils Tower as a lava coulée?

Figure 1. Field photographs of Devils Tower and Missouri Buttes with orientation indicated. (A) Southwestern side of the tower shows vertical and horizontal joints of the base and curved columns plunging to the west. (B) Detail of the southwestern wall shows apparent compositional layering as dark horizontal streaks across the columns (stippled black line), and a suture between the upper and lower colonnades indicated by columns of the upper colonnade that split to two or three narrower columns of the lower colonnade (indicated by arrows). Dashed white lines indicate broad suture between both colonnades. (C) The asymmetrical shape of Devils Tower, with straight columns plunging at ~65° on the southeast and curved columns on the northwest, is seen best from the northeast. (D) In contrast, view from the northwest shows symmetrical shape of subvertical columns on both sides with slight bend to shallower plunge angles on their lower ends. B—base, S—shoulder, LC—lower colonnade, UC—upper colonnade. (E) Missouri Buttes, located ~5 km northwest from Devils Tower, represented by 5 separate phonolite bodies distributed along a periphery of a north-south elongated ellipse of short and long axes of 1 and 2 km, respectively. (F) Two northern buttes of Missouri Buttes in a view from the north.
northwest of Devils Tower (Fig. 1F), represent the westernmost products of Cenozoic igneous activity distributed along a northwest-southeast–trending belt within the Black Hills uplift (Fig. 2). The Black Hills uplift is structurally the highest segment of a nearly 1000-km-long arch that developed due to lithosphere-scale folding during the Laramide orogeny (Tikoff and Maxson, 2001) starting ca. 65 Ma (Flores and Ethridge, 1985; Lisenbee and DeWitt, 1993). Precambrian igneous and metamorphic rocks are exposed in the core of the Black Hills uplift and are overlain by a >1200-m-thick sequence of Paleozoic and Mesozoic sedimentary strata.

Alkaline igneous rocks in the Black Hills are part of the Great Plains alkaline province in South Dakota, Wyoming, Montana, and southern Alberta (Canada) that originated from parental mantle melts. These melts possibly ascended along the southwest edge of the subducting Kula slab through the Farallon-Kula slab window (Robinson et al., 1964; Robinson et al., 1964; DeWitt et al., 1989; Sutherland, 2008). There are six diatremes identified throughout the Black Hills area (Fig. 2) that represent different exposure levels of the original maar-diатreme volcanoes (Lisenbee and Roggenthen, 1990). The shallowest levels are exposed in the Missouri Buttes, Devils Tower, and Sugarloaf diatremes in the western part of the Black Hills (Fig. 2); deeper levels are exposed in the Maitland, Meadow Creek, and Tomahawk diatremes to the east (Lisenbee and Roggenthen, 1990). K-Ar dating of biotite from a pitchstone embedded in the Tomahawk diatreme indicates an age of 55.8 ± 1.4 Ma (Redden et al., 1983); 40Ar/39Ar dating of sanidines in phonolites from Devils Tower and Missouri Buttes provides indistinguishable plateau ages of 49.04 ± 0.16 and 49.24 ± 0.28 Ma, respectively (Duke et al., 2002).

The maar-diатremes consist of a maar crater, surrounding tephra ring, and the underlying diatreme. The diatreme is filled with country-rock and juvenile magmatic clasts and was eventually injected by late-stage intrusions (Lorenz, 2003; White and Ross, 2011; Valentine and White, 2012). There are six diatremes identified throughout the Black Hills area (Fig. 2) that represent different exposure levels of the original maar-diатreme volcanoes (Lisenbee and Roggenthen, 1990). The shallowest levels are exposed in the Missouri Buttes, Devils Tower, and Sugarloaf diatremes in the western part of the Black Hills (Fig. 2); deeper levels are exposed in the Maitland, Meadow Creek, and Tomahawk diatremes to the east (Lisenbee and Roggenthen, 1990). K-Ar dating of biotite from a pitchstone embedded in the Tomahawk diatreme indicates an age of 55.8 ± 1.4 Ma (Redden et al., 1983); 40Ar/39Ar dating of sanidines in phonolites from Devils Tower and Missouri Buttes provides indistinguishable plateau ages of 49.04 ± 0.16 and 49.24 ± 0.28 Ma, respectively (Duke et al., 2002).

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The volcaniclastic rock shown in Figure 4 is rich in juvenile phonolite clasts and country-rock clasts from different underlying lithostratigraphic units and the crystalline basement (e.g., shale, limestone, granite, phonolite, and schist) that are all encased in a matrix of angular crystal fragments (as large as 3 mm) of quartz, microcline, sandine, hornblende, aegirine-augite, oligoclase, and fine phonolite fragments. The clasts range in diameter from microscopic to 1 m (Fig. 4C). Similar volcaniclastic deposits were found during earlier surveys in trench excavations of a 150-m-long elliptical knoll, trending west-southwest from the edge of the main talus on the west-southwestern side of Devils Tower (Effinger, 1934), and revealed a variety of clasts similar to that in the Missouri Buttes outcrops, although the matrix was extremely weathered.

![Figure 2. Schematic map of the Black Hills, which represent a lithospheric-scale uplift exposing Precambrian basement in its core and the entire section of the Phanerozoic sedimentary cover. Cenozoic igneous centers associated by domes in the host rocks are aligned in west-northwest–east-southeast direction across the uplift. Stars show locations of the six diatremes in the Black Hills (after Lisenbee and Roggenthen, 1990).](image-url)

![Figure 3 (on following page). Geological map and a cross section of the investigated area redrawn after Halvorson (1980) and Sutherland (2008) with Missouri Buttes (MB) and Devils Tower (DT), and indicating sampling sites and dip marks of the sedimentary strata (m—meters above sea level). The upper surface of the Fall River datum, redrawn after Robinson et al. (1964), is indicated by solid and dashed red contours that are marked with elevations in meters. The cross section reveals an earlier hypothetical interpretation of the igneous structures (Lisenbee and Roggenthen, 1990; DeWitt et al., 1989).](image-url)
Devils Tower as a lava coulée?

Geosphere, April 2015

Figure 3.
**TABLE 1. STRATIGRAPHIC TABLE OF THE LITHOLOGICAL UNITS OVERLYING THE PRECAMBRIAN BASEMENT**

<table>
<thead>
<tr>
<th>Lithology (description)</th>
<th>Average thickness (m)</th>
<th>Stratigraphic position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black, generally silty gray residual sedimentary rocks can be interbedded with numerous palaeosols and local gypsum beds</td>
<td>68</td>
<td>Upper Cretaceous</td>
</tr>
<tr>
<td>Black, light brown-gray sandstone and siltstone with thin beds of black to brown shale</td>
<td>27</td>
<td>Lower Cretaceous</td>
</tr>
<tr>
<td>Yellowish-gray and nonresistant fine-grained sandstone</td>
<td>15</td>
<td>Lak Member</td>
</tr>
<tr>
<td>Redwater Shale Member</td>
<td>60</td>
<td>Redwater Shale Member</td>
</tr>
<tr>
<td>Skokie Shale Member</td>
<td>123</td>
<td>Skokie Shale Member</td>
</tr>
<tr>
<td>Sundance Formation</td>
<td>84</td>
<td>Sundance Formation</td>
</tr>
<tr>
<td>Millard Formation</td>
<td>6</td>
<td>Millard Formation</td>
</tr>
<tr>
<td>Box Butte Member</td>
<td>76</td>
<td>Box Butte Member</td>
</tr>
<tr>
<td>Waterhouse Springs Formation</td>
<td>42</td>
<td>Waterhouse Springs Formation</td>
</tr>
<tr>
<td>Barlow Canyon Formation</td>
<td>5</td>
<td>Barlow Canyon Formation</td>
</tr>
<tr>
<td>Minnelusa Formation</td>
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</tr>
<tr>
<td>Minnelusa Formation</td>
<td>467</td>
<td>Minnelusa Formation</td>
</tr>
</tbody>
</table>

*Note: Lines between rows correspond to unconformities. Compiled after Robinson et al. (1964), Halvorson (1980), DeWitt et al. (1989), and Sutherland (2008).*

Local doming of the area is inferred from the nonplanar topology of the Fall River Formation datum (Robinson et al., 1964) that is characterized by several domes and depressions. The first dome, located 2 km southwest of Missouri Buttes, has a diameter of ~1.6 km and a relief of 90 m; the second dome, located 1 km north of Missouri Buttes, has a relief of 60 m (Fig. 3). The third and fourth domes are characterized by a relief of only ~30 m and are located 2–3 km to the south of Missouri Buttes and 1 km west of Devils Tower, respectively. The last dome is associated with a phonolite sill exposed in the Barlow Canyon area (4 km northwest of Missouri Buttes, not shown in Fig. 3) that was emplaced under the Hulet Sandstone Member of the Sundance Formation (Robinson et al., 1964; Halvorson, 1980). Drilling in the central part of the first dome encountered phonolite porphyry at 467 m in the Pennsylvanian–Permian Minnelusa Formation (Robinson et al., 1964). These intrusions are regarded as comagmatic with Devils Tower and Missouri Buttes on the basis of compositional similarity (Halvorson, 1980). In contrast, a 60 m depression in the Fall River Formation datum surrounds Missouri Buttes. Another depression (~30 m) surrounds Devils Tower and is characterized by a gentle dip of sedimentary strata toward the tower (Fig. 3).

**DEVILS TOWER AND MISSOURI BUTTES PHONOLITE BODIES**

**Devils Tower**

Devils Tower is a steep-sided phonolite monolith whose top (elevation of 1558 m above sea level [asl]) rises almost 250 m above the underlying sedimentary rocks of the Sundance Formation (Figs. 1A, 1C, 1D). The base is elliptical with axes measuring 304 m (north-northwest–south-southwest) and 228 m. The plateau at the top of Devils Tower measures 90 m by 55 m. Steep columnar jointing characterizes the upper 180 m of Devils Tower. In contrast, the lower section, subsequently referred to as the base (Fig. 1D), is affected by three joint systems (vertical radial, vertical circumferential, and horizontal) that divide the cliffs of the base into blocks ~3 m in size (Dutton and Schwartz, 1936). The walls of Devils Tower consist of two tiers of columns, like those typically developed into basalt lava flows (DeGraff and Aydin, 1987), that merge ~70 m below the top plateau (Fig. 1B). The area above the base, which is also called the shoulder (Fig. 1D), consists of columns of the lower tier with diameters of 2–3 m. These columns taper to widths of only 1.5 m at the contact with the upper tier, where they frequently merge into one thick column (~3 m
wide) of the upper tier (Fig. 1B). Subvertical columns of the lower tier flare outward and plunge 50°–85° at the shoulder. The thick vertical columns of the upper tier display bumpy surfaces with horizontal ledges and abundant horizontal or irregular cross joints, which are accentuated by spheroidal weathering. Blocks that have fallen from the upper part of Devils Tower form the majority of the talus (Dutton and Schwartz, 1936). Devils Tower appears almost symmetrical when viewed from the northwest, with the plunge of the columns at the shoulder being ~75° (Fig. 1D). From the northeast (Fig. 1C), the columns of the northwest side of Devils Tower are gently curved, being nearly vertical at the top and plunging ~50° at their lower end, while the columns on the southeast side are straight, plunging at 65°–75°. Joints of the vertical radial system of the base frequently merge with the tensional joints of the columns. This transition is also locally marked by broad joint surfaces curving upward with transverse ribs (Dutton and Schwartz, 1936).

**Petrography of Devils Tower**

The analcime phonolite forming Devils Tower is holocrystalline and coarsely porphyritic with a gray to olive-gray aphanitic and trachytic groundmass around phenocrysts of anorthoclase as much as 16 mm long (average 30 vol%), aegirine-augite (6 vol%) zoned to aegirine, spheine (1.2 vol%), and rare amphibole. The groundmass consists of anorthoclase, low albite, K-feldspar, analcime (average whole rock 15 vol%), aegirine, nepheline, and nosean (Halvorson, 1980). Secondary (alteration) products are represented by calcite, zeolite, hematite, clay, and analcime. Vertical or high-angle plunges (>75°) of magmatic lineations defined by alignment of the phenocrysts characterize the bottom part of the tower below 1420 m asl. In contrast, one sample collected on the northeast part of the tower, at an elevation of 1450 m, revealed horizontal magmatic lineation (Halvorson, 1980).

Figure 4. Outcrops of the volcaniclastic rocks in the surroundings of Missouri Buttes and Devils Tower. (A) Rounded block of granite photographed at the DT-2 site. (B) The valley between Missouri Buttes locally hosts blocks of volcaniclastic deposits as long as 2 m. Hammer is 30 cm long. (C) A large rounded boulder of granite (in foreground) was found in phreatomagmatic deposits (in background) at a saddle between the two northern Missouri Buttes. (D) Outcrops of volcaniclastic deposits ~0.8 km west of Missouri Buttes show angular clasts, as much as 30 cm long, of various lithologies encased in earthy brown matrix; a metamorphic rock clast is next to the hammer. The hammer is 30 cm long. Letters in the lower left corner of pictures refer to sampling sites in Figure 3.
Missouri Buttes

Missouri Buttes consist of five phonolite and alkali trachyte bodies distributed along the perimeter of a north-south elongated ellipse with axes of ~2 km and 1 km (Fig. 3). The highest in elevation is the northwestern butte, reaching 1637 m asl. The three southern buttes encompass a triangular elevated plateau and are separated from the two northern buttes by a V-shaped valley. Aerial photographs reveal that the buttes are affected by steep joint systems breaking the igneous mass into plates or slabs. This joint system strikes at an azimuth of 075° in all buttes except for the northeast butte (Halvorson, 1980) where this strike is 040°. Margins of the bodies display blocky jointing forming thin slabs, where radial vertical and peripheral vertical joint systems intersect. From the blocky margin inward, horizontal columnar jointing is typically developed, with a maximum column diameter of 1 m. The jointing also displays portions marked by apparent vertical columns in the central part of the northeast butte, although such columns are typically four sided and do not show smooth transitions with the surrounding horizontal columns. Field observations by Halvorson (1980) did not reveal any upturned beds that would suggest warping of the sedimentary layers around the phonolite buttes.

The southwest and west-central buttes were identified as alkali trachyte, in contrast to the other three buttes (and Devils Tower) recognized as analcime phonolite. Both types are holocrystalline with an average phenocryst content of 44%. The phenocrysts consist of sanidine (20%–32%), anorthoclase (5%–14%), aegirine-augite (4%–12%), accessory sphene, nepheline, and rare magnetite enclosed in aegirine-augite. The groundmass is randomly oriented or locally trachytic and consists of aegirine and sanidine laths mixed with isotropic analcime (Halvorson, 1980).

SAMPLING AND METHODOLOGY

A field survey of the area was carried out with a permit from the U.S. National Park Service that allowed sampling of sedimentary rocks in the area around Devils Tower National Monument, and collection of only one specimen of the phonolite in the blocky talus at the base of the tower. This sample was taken from a large column fragment that apparently cleaved off and collapsed from the upper tier of columns on the tower. The axis of the column was recorded and marked on the sample. Field surveying and sampling conducted in the Missouri Buttes area focused on the outcrops of volcaniclastic rocks, their structural position, composition, and texture. Three samples of the volcaniclastic rocks were collected for detailed microscopic and backscattered electron (BSE) investigation and imaging. In addition, two samples from the Tomahawk diatreme (Fig. 2) were donated by Alvis Lisenebee (South Dakota School of Mines and Technology) for comparison with volcaniclastic rocks from Missouri Buttes. These samples were collected from a layered tuff at a road cut on the southern edge of the structure (TD-1) and a lapilli tuff from the central part of the Tomahawk diatreme (TD-2).

A Cameca SX-100 microprobe (Department of Electron Microanalysis, Geological Institute of Dionyz Stur, Bratislava, Slovak Republic) was used for BSE imaging of selected areas of polished thin sections. Mosaics of micrographs of the volcaniclastic rocks in two thin sections were created for simple modal analysis discriminating the content of lithic fragments (sedimentary, granitic and/or metamorphic clasts), juvenile magmatic clasts, K-feldspar, plagioclase and quartz crystals, and pores. Clast shapes were manually digitized in ArcView GIS (geographic information systems; www.esri.com) software and statistically processed using the PolyLX toolbox in Matlab (Lexa et al., 2005). Bulk densities (D_b) and porosities (Φ) for the volcaniclastic rocks in the Missouri Buttes area and the Devils Tower phonolite were measured and calculated by the triple weighing method; weighing the samples dry (A), saturated and suspended in water (B), and saturated and weighed in air (C), and then calculated using the following equations: D_b = [A/(C – B)] × ρ, and Φ = [(C – A)/(C – B)] × 100, where ρ refers to the density of water.

The phonolite sample collected from the collapsed columnar block at Devils Tower was also evaluated for AMS and bulk magnetic susceptibility variations in the temperature range of 190 to 720 °C. The AMS fabric data are presented using the eccentricity (P), shape (T), and mean bulk susceptibility (K_m) of the AMS ellipsoid (Nagata, 1961; Jelínek 1981). The magnetic parameters and methodology are described in the Supplemental Information (SI) File.

ANALOGUE MODELING

In the second part of this integrated study we employed analogue modeling to constrain possible shapes of magmatic bodies that form by intrusion of magma into a maar-diatreme with steeply dipping walls filled with chaotic volcaniclastic deposits. Although this scenario is

Figure 5. Photographs of the sections through samples. Volcaniclastic rocks collected reveal abundant fragments of different lithologies and various sizes. (A, B) Rocks from the central part of Missouri Buttes. Note apparent amoeboidal vesicles in sample MB-C2. (C) Rock from the outcrops 0.8 km west of the buttes. Note the large unweathered phonolite clast in the top part of sample MB-D.
hypothesized, it is supported by a genetic interpretation of the volcaniclastic deposits that is presented herein. The materials and experimental setup resemble the instructive experiments of the intrusion and erosion of laccoliths in the Black Hills (Jaggar, 1901). The advantage of our analogue modeling approach is that the internal flow geometry, shape, intensity, and direction of flow in the models can be studied with AMS, because we add fine magnetic dust to the analogue magma that works as a tracer of magnetic fabric in the models. Our analogue modeling is not scaled, because the intrusion and/or extrusion time for Devils Tower and the viscosity of the phonolite magma are unknown.

**THERMAL MATHEMATICAL MODELING**

We created two-dimensional (2-D) finite element thermal models of conductive cooling for various shapes of intrusive and/or extrusive bodies based on the geometry of intrusion shapes suggested previously and selected analogue models in this study. Because columnar joints grow perpendicular to isotherms in cooling igneous and volcanic bodies (Jaeger, 1961; DeGraff and Aydin, 1987), we analyzed the match between the modeled thermal structure and the observed columnar jointing pattern on Devils Tower. Thermal models were constructed using Comsol and Fracture (Kohl and Hopkirk, 1995) software. An initial temperature of 850 °C used in all model runs corresponds to slightly higher temperatures than the dry solids of phonolite magmas (Taylor and MacKenzie, 1975), because we assume that the emplaced magma was already devolatilized (see discussion of Phonolite magma properties herein). In the final step, a 3-D thermal model was constructed for the geometry of the analogue model with the best fit to the corresponding 2-D thermal structure and the columnar jointing pattern on Devils Tower. The purpose of this 3-D model was to confirm the results of the 2-D thermal modeling and to evaluate the heat budget associated with emplacement of the magma body. Additional information on the setup of the thermal models and associated thermo physical parameters is provided in the SI File (see footnote 1).

**RESULTS**

**Petrographic and Microstructural Description of Collected Samples**

**Devils Tower**

The sample of the phonolite collected from the fallen block at Devils Tower (Fig. 3, DT-1) reveals phenocrysts as much as 1 cm long surrounded by olive-green groundmass with dark green crystals as large as 2 mm of aegirine-augite. The upper face of the column and a section cut through the specimen perpendicular to the axis of the column showed lenticular cavities as much as 2 mm long and 0.5-mm-thick cavities. A thin section of sample DT-1 revealed that these lenticular and locally triangular, wedge-shaped cavities with irregular edges occur locally in the vicinity of the porphyroclasts and are preferentially aligned in directions at high angles with respect to the trachytic fabric in the groundmass (Fig. 6A, inset). Some of these zeolite-filled cavities are designated as miarolitic, because they contain aegirine-augite needles that grew inward from the surrounding matrix. Phenocrysts of feldspars are clearly locally dismembered to rotated rectangular fragments that are displaced in the direction of the trachytic fabric. Local alteration of feldspar to analcime is clearly visible in the vicinity of the voids between the fragments (Fig. 6A, inset).

**Missouri Buttes**

Two volcaniclastic rock samples collected at Missouri Buttes (Fig. 3), MB-C1 and MB-C2 (Figs. 5A, 5B), revealed decomposed phonolite fragments, as much as 3 cm in diameter, encased in a rusty brown matrix. Sample MB-C2 contains abundant amoeboidal pores as much as 1 cm in diameter in the matrix. Both samples contain a great variety of fragments in terms of size, shape, texture, and composition. In thin section, the clasts are subangular to rounded and consist mostly of phonolite, granite, gneiss, gabbro, carbonate, dolomite, slate, limonitized siltstones, sandstone, fine-grained pumice (all average 0.5 mm in size, with maximum size 1 cm), angular K-feldspar (either anorthoclase or microcline), plagioclase, and quartz crystals (Figs. 6B, 6C). Amoeboidal vesicles in the matrix of MB-C1 and MB-D samples are partly or entirely filled with chalcedony.

The textures of phonolite fragments range from aphanitic (Fig. 6B), with rare acicular euhedral phenocrysts of feldspar laths and aegirine-augite, both randomly oriented around the circular pores, to porphyritic types with trachytic (Fig. 6D) texture of the same minerals with elongated pores. Clast shape can sometimes be described by vescularity; nonvesicular clasts are typically subrounded and smooth in contrast to vesicular clasts that are angular (Figs. 6B, 6C). Large euhedral crystals contained in the phonolite clasts are frequently crosscut at the edges of the host fragments (Fig. 6B). A few phonolite clasts are surrounded by irregular dark rims (Fig. 6E). One clast contains a large euhedral feldspar crystal in its core (Fig. 6F). BSE images revealed that the majority of phonolite fragments are cryptocrystalline and pilotaxitic porous aggregates formed by radial to dendritically grown alkali feldspar laths, some of them with albite rims, between 20 and 500 μm long (Figs. 7A–7C). Some of the magnetic fragments show phenocrysts enclosed in a porous mixture of lath-shaped alkali feldspars and calcite (Fig. 7D).

Bulk density measurements for samples MB-C1 and MB-C2 (Figs. 6B, 6C), revealed values of 1.874 g/cm³ and 1.539 g/cm³ and corresponding porosities of 28 vol% and 37.5 vol%, respectively. Results of the fragment size analysis for the MB samples are presented in Table 3.

**Tomahawk Diatreme**

The layered tuff (TD-1) from the Tomahawk diatreme is light brown and contains a mixture of microcrystalline juvenile rhyolite fragments with phenocrysts of plagioclase and resorbed quartz and clasts of Precambrian metamorphic rocks (Fig. 6G). There was also a small amount of Phanerozoic sedimentary rock and trachyte encased in a fine-grained matrix (200–500 μm) of angular quartz, feldspar, and plagioclase crystals and biotite. The layers in the sample are characterized by the constituent fragment grain size with a maximum diameter of 1 mm. A second sample (TD-2) revealed a similar texture consisting of matrix clasts of 0.5–1 mm surrounding fragments of rhyolite as much as 1.5 cm in diameter (Fig. 6H). The microstructural characteristics are similar to the Missouri Buttes samples in terms of size and shape of the fragments, presence of country-rock fragments, and abundance of plagioclase, microcline, and quartz crystals in the matrix.

The Missouri Buttes samples could be characterized as lithic-rich lapilli tuffs due to the abundance of lithic (country rock) fragments, with the sum of sedimentary and Precambrian lithics almost equal to the amount of Tertiary magmatic fragments (Table 2). Both localities of volcaniclastic rocks investigated at Missouri Buttes contain vesicles in the tuffaceous matrix (samples MB-C2 and MB-D); no porosity was observed in the fine-grained matrix of the Tomahawk diatreme.

**Magnetic Fabric and Mineralogy of Devils Tower Phonolite**

Variation of the mean magnetic susceptibility (Km) for phonolite sample DT-1 revealed a stable decrease with temperature from ~200 °C to 0 °C and a distinct drop at ~590 °C, the Curie temperature (Fig. 8A). The susceptibility variation displayed on this graph (Fig. 8A) suggests...
Figure 6. Micrographs of the magmatic and volcaniclastic specimens collected at Missouri Buttes and Devils Tower. (A) Devils Tower phonolite sample DT-1 shows large phenocrysts of anorthoclase and aegirine-augite surrounded by miarolitic cavities. The inset shows a sketch of the micrograph with miarolitic cavities in yellow, feldspar phenocrysts in gray, analcimized feldspar patches as hachured areas, and aegirine-augites in green. Rose diagram shows the preferred orientation of 40 cavities traced in the thin section cut parallel with K1K3 plane of the magnetic ellipsoid. (B) Three types of phonolite and/or trachyte clasts; a dark aphanitic type at left, porphyritic with trachytic texture in the center, and vesicular with irregular edges at lower right. (C) Volcaniclastic deposits in the central part of Missouri Buttes reveal a mixture of fragment types of angular and subrounded clasts of different lithologies; fragments of phonolite pumice (p), dolomite (Dol), basement granite (Gr), and quartz (qtz). (D) Trachytic texture of alkali feldspar laths in a trachyte clast. (E) A clast of phonolite surrounded by apparent dark dust is interpreted as an incipient armored lapilli. (F) A euhedral anorthoclase crystal with irregular optical extinction is embedded in phonolite pumice. (G) Layered structure of sample TD-1 collected at the southwest margin of the Tomahawk diatreme showing igneous and lithic rock fragments. (H) Layered sample from the Tomahawk diatreme reveals large clasts (to 1.5 cm in diameter) of rhyolite with a jagged boundary of the enclosed quartz crystal.
that the magnetic signal is carried by some oxidized magnetic phase, either titanomagnetite or maghemite. Clearly, magnetite can be excluded due to the absence of a Verwey transition (rapid increase of $K_m$ at $-150 \degree C$; e.g., Tarling and Hrouda, 1993). The AMS stereoplot of the DT-1 sample (Fig. 8B), where the axis of the sampled column is vertical (star symbol), reveals an angular difference of $20^\circ$ between the mean minimum susceptibility direction ($K_3$) and the column axis. In addition, the magnetic lineation ($K_l$) and intermediate mean susceptibility ($K_i$) directions plunge at shallow angles of $18^\circ$ and $8^\circ$, respectively. These results, together with alignment of the trachytic fabric subparallel to the $K_l$ lineation (Fig. 8B), imply an originally shallowly dipping magmatic fabric in the upper part of Devils Tower.

**DISCUSSION**

The reconstruction of the original shape of volcanic bodies and their emplacement level, specifically Devils Tower, requires understanding of the geological evolution of the entire volcanic complex, physical properties of the magma, erosion estimates, geological setting at the time of emplacement, structural deformation of the area, and internal fabrics of the volcanic or magmatic body together with the internal fracture pattern that developed during its cooling. Here we link all of these considerations in a discussion evaluating the different hypotheses for the origin of Devils Tower and associated features previously presented. Our approach of combined thermal mathematical and analogue modeling was used to constrain the physical conditions controlling the final shapes of investigated bodies characterized by distinct patterns of internal magmatic fabrics and cooling joints and can be tested in particular for Devils Tower. We put forward an original hypothesis suggesting that Devils Tower could represent a remnant of a lava extrusion into a maar crater of a pre-existing maar-diatreme volcano (Fig. 9).
Regional Deformation

The depressions in the Fall River Formation datum (Fig. 3) coincide with sedimentary strata dipping toward both Missouri Buttes and Devils Tower over a radius of ~1 km and were interpreted earlier to reflect magma chamber roof subsidence (Halvorson, 1980). An alternative explanation could be marginal screen collapse (Fig. 9) around the periphery of phreatomagmatic volcanoes (Lisenbee and Roggenthen, 1990; Lorenz, 2003; Lorenz and Kurszlaukis, 2007). High dip angles of the Redwater Shale Member at what is known as “fossil hill” ~1 km north-northwest of Devils Tower (Fig. 3) could thus be explained by block tilting in marginal screen rather than by folding due to emplacement of a shaft-like intrusion or magmatic stock (Robinson and Davis, 1995).

Genetic Interpretation of the Volcaniclastic Deposits

Jaggar (1901), who mapped volcaniclastic deposits in the Missouri Buttes area as agglomerates, suggested that they extend throughout the central area of Missouri Buttes. Jaggar (1901), as well as Effinger (1934) and Robinson and Davis (1995), interpreted this rock type as an initial portion of emplaced magma that was rich in entrained country-rock fragments and later formed the marginal part of the intrusive bodies. Phonolite magma around the entrained country-rock fragments in the marginal parts of the intrusions was interpreted to be later decomposed into an earthy brown rock. Halvorson (1980) described this volcaniclastic material as alloclastic breccia that represents pyroclastic deposits lining the vents of eroded volcanoes; he also attributed the two volcaniclastic rock outcrops 0.8 km west of the western buttes (MB-D;

<table>
<thead>
<tr>
<th>Rock fragments</th>
<th>MB-C1</th>
<th>MB-D</th>
<th>TD-1</th>
<th>TD-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary igneous</td>
<td>29.4</td>
<td>29.8</td>
<td>39.2</td>
<td>45.3</td>
</tr>
<tr>
<td>Sedimentary</td>
<td>19.1</td>
<td>6.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Precambrian basement</td>
<td>11.5</td>
<td>13.0</td>
<td>5.2</td>
<td>5.6</td>
</tr>
<tr>
<td>K-feldspar crystals</td>
<td>3.0</td>
<td>6.6</td>
<td>4.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Plagioclase crystals</td>
<td>0.8</td>
<td>1.6</td>
<td>8.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Quartz crystals</td>
<td>2.6</td>
<td>3.3</td>
<td>8.1</td>
<td>7.3</td>
</tr>
<tr>
<td>Pores</td>
<td>0.6</td>
<td>0.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Other minerals</td>
<td>33.7</td>
<td>38.7</td>
<td>33.9</td>
<td>28.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100.0</td>
<td>100.0</td>
<td>99.9</td>
<td>100.3</td>
</tr>
</tbody>
</table>

Note: Rock fragments in percentage. MB—Missouri Buttes; TD—Tomahawk diatreme. Data for TD-1 and TD-2 samples are taken from analyses of other samples from the same localities by Kirchner (1996).

Figure 8. (A) Thermomagnetic curve of the sample DT-1. $K_b$ is the bulk susceptibility of the sample measured (Nagata, 1961). (B) Corresponding lower hemisphere equal-area stereoplot of the anisotropy of magnetic susceptibility (AMS) measured from six cubic specimens. Axis of the sampled phonolite column is marked by the star symbol. $P$ and $T$ correspond to the eccentricity and shape, respectively, of the AMS fabric (definitions in the SI File [see footnote 1]).
phreatomagmatic deposits and phreatomagmatic breccia pipes with reiterated breccia formation pulses by hydrovolcanic explosions (Tâmaș and Mileș, 2002); and, (13) similarity of the rocks we investigated to the Tomahawk diatreme samples (Figs. 6G, 6H) that were interpreted as phreatomagmatic deposits (Lisenbee and Roggenthen, 1990; Kirchner, 1996).

In agreement with Lisenbee and Roggenthen (1990) and Kirchner (1996) for the Tomahawk diatreme, we suggest that the influence of gas pressure release from the magma had only a minor effect on the fragmentation of the magma. However, juvenile phonolite and/or trachyte fragments with internal vesicles and irregular boundaries indicative of gas pressure release– driven fragmentation can be found locally (Fig. 6B), but vesicular clasts are typically found in diatreme deposits (Ross and White, 2012).

**Erosion in the Black Hills and Emplacement Level for Phonolite Magma**

The area of the Black Hills was part of a foreland basin that contained a 2000–2500-m-thick sequence of Phanerozoic sediments (Lisenbee and DeWitt, 1993) prior to uplift during Laramide orogenesis. The combined thickness of eroded layers from the Mowry Shale (youngest Cretaceous member exposed at Missouri Buttes) to the Fox Hills Formation in the Black Hills monocline ~10 km west of the map area is ~1850 m (Halvorson, 1980; DeWitt et al., 1989). Considering the: (1) widespread and rapid erosion of the weak muddy upper Cretaceous foreland sediments in the Black Hills before emplacement of Devils Tower (Smith et al., 2008; Fan et al., 2011); (2) a sufficient time span (16 m.y.) for erosion between the onset of the Black Hills uplift to the emplacement of the phonolite bodies; and (3) discordant contact of phreatomagmatic deposits at Missouri Buttes with underlying Cretaceous sediments (Fig. 3), the phreatomagmatic deposits 1 km west of Missouri Buttes can be interpreted as remnants of surface deposits, possibly a tuff ring surrounding the original maar. The proximity of the present exposure level to the Cenozoic paleosurface in the western part of the Black Hills is also supported by surface volcanic facies of welded ash tuff (Fashbaugh, 1979; Halvorson, 1980) at Sundance Mountain, 33 km south-east of Devils Tower.

**Analogue Modeling and AMS Analysis**

The emplacement of the Devils Tower lava body is, in our hypothetical scenario, considered as the final stage of phreatomagmatic
maar-diatreme volcano evolution, when the influx of water triggering the phreatomagmatic explosions in the root zone of the volcano ceases, either due to change in hydrological regime (drop of water table) or, less likely, the increase of lithostatic pressure in the deeper root zone of the diatreme (Konečný and Lexa, 2003; Lorenz, 2003; Martin and Németh, 2004, 2005; Auer et al., 2007; Valentine and White, 2012).

To evaluate the similarity of the experimental models created by intrusion of model magma (plaster of paris) into model diatremes with a simple hydraulic squeezer apparatus (Fig. 10) and the original (Devils Tower), the shape of Devils Tower and its relative dimensions in the hypothetical maar-diatreme crater were projected to fit within the vertical sections of the sliced analogue models (Fig. 11).

Although the crater dimensions of the hypothetical diatreme under Devils Tower are not known, the typical maximum depths of 1–2 km would correspond to craters 1–1.5 km wide (Lorenz, 2003; Valentine and White, 2012). The vertical scaling of the original body that formed Devils Tower in our modeling is constrained by the level of the suture between both colonnades 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 cooling gradients at the top and bottom margins of the body were similar. In the second step,

Figure 10. Experimental apparatus used for analogue modeling of magma injection into maar-diatreme structures. The apparatus consists of a hydraulic squeezer (A), a steel frame transferring the load of the squeezer (B) on a rectangular steel plate with a central circular aperture, a container for analogue magma (C), a steel conduit attached to the steel plate (D) above the aperture, and a cone-shaped crater filled with analogue diatreme debris (E). During the experiment, the analogue magma (plaster of paris) evacuates from the container by the force of the squeezer through the conduit and intrudes the analogue debris in the cone-shaped crater, i.e., the diatreme. A shallower maar crater atop the model diatreme was partly filled with alternating sand and clay layers to simulate the sediments of the maar in some of the experiments. For additional explanation of the experimental setup, see the SI File (see footnote 1).

Figure 11. Shapes and internal fabrics redrawn from vertical sections of the experimental bodies. Note that outlines of similar experiments are displayed as superposed on each other and are marked by contours of different colors. Mixing ratio corresponds to the weight proportion of hemihydrate powder and water used for preparation of the plaster of paris in the experiments.
for the selected analogue models that fulfill the above defined dimensional preconditions, finite element thermal models of cooling were created to further test the similarity of the thermal structure of the models with columnar jointing pattern on the original (Devils Tower).

Of the total 27 analogue experiments that were created with the plaster of paris as the analogue magma, 10 are shown in Figure 11; 7 models shown are overlap with the outlines of 9 additional models that were very similar in geometry. The shapes of the experimental bodies varied primarily due to different thickness of the plaster defined by mixing ratios (MR) of the hemihydrate powder and water, initial overpressure, and setup of the experimental maar-diatreme (Fig. 11; Fig. SI-1 and Table SI-1 in the SI File [see footnote 1]). The details of the experimental runs and movies capturing some of the experiments are presented in the SI File (see footnote 1). In summary, experiments created with relatively dense plaster (MR ~ 2.5) required relatively high overpressures of the squeezer (to 130 bar) to form tear-drop-shaped cryptodomes (D-6, D-14), small extrusive domes with narrow stems (Fig. 11; Table SI-1 [see footnote 1]; D-5, D-6, D-7, D-8, D-14), or asymmetric extrusions that escaped from under a tilted lid of maar-sediments (D-9, D-12). A few initial experiments that were created quickly (5 s) at moderate initial overpressures resulted in asymmetric extrusions with thick stems (D-1, D-2, D-3, D-4; Table SI-1 [see footnote 1]; only D-2 and D-4 are shown in Fig. 11).

For the second series of experiments with more diluted plaster (MR ~ 2.15–2.4), the experiments revealed similarly shaped asymmetric coulées (D-16, D-17, D-24), low lava domes with thick stems (D-15, D-22), or relatively symmetrical low lava domes or coulées with narrow feeding conduits (D-19, D-21, D-23). All these were created at relatively low loading pressures of the squeezer (<80 bars). In one experiment, the feeding conduit in the diatreme apparently bifurcated after creation of the first dome to produce another dome at the opposite side of the maar (D-18; Fig. 11). A few of the models had to be discarded for later analysis due to leaks in the injection system during the experiment (D-10, D-13) or rapid burst of the magma, when the inlet was stuck or the intrusion conduit in the diatreme suddenly expanded or bifurcated (D-11, D-20).

For the thermal mathematical modeling, the above-defined dimensional preconditions for the models excluded a majority of the experiments (Fig. 11), because they were: (1) performed too quickly, in 5–10 s (D-2, D-4); (2) displayed shapes of cryptodomes that required high magma overpressures for their buildup (D-6, D-14); (3) displayed stems that were too wide (D-22); and (4) revealed unrealistically inflated edifices (D-11) that emplaced rapidly (3 s) after reaching relatively high magma overpressures. The original shape for Devils Tower can be roughly estimated considering that the joints confining the columns grow progressively to the margins of original volcanic bodies during conductive cooling (Jaeger, 1961; DeGraaff and Aydin, 1987). The latter intuitive reconstruction suggests a laterally (rather than vertically) extensive intrusion or extrusion with relatively flat surface at the top and a base that dips toward the vertical axis of the body (Pirsson, 1894; Jaggar, 1901; Spry, 1962).

One of the models (D19; Figs. 11 and 12) that revealed an excellent match of its thermal structure from preliminary finite element thermal models of cooling (described in the following) with the columnar jointing pattern on Devils Tower was further investigated in detail for internal AMS fabric. This model could be characterized as a lava coulée or low lava dome that filled the bowl-shaped crater of the maar (Figs. 12A, 12B) and was fed by a narrow conduit that penetrated along the walls of the experimental diatreme. The conduit revealed bifurcating protrusions and local corner flow (Figs. 12C, 12D), where the intruding plaster slightly uplifted the loosely packed filling of the diatreme. The flow in the conduit was then channeled into a thin tube-like neck 10 cm below the extrusion. The disrupted color banding pattern of the model in the vertical section (Fig. 12D) shows an onion-peel-like internal fabric above the conduit and concave flow planes facing the margins of the body. The AMS fabric of this body revealed a pattern similar to our earlier experiments on coulées and low extrusive lava domes (Závada et al., 2009b). The magnetic foliations regularly dip at high angles to the inspected vertical section, and their trends conform to the stretched and disrupted color banding in the model, defining flattened concave flow planes verging to the margins of the experimental coulée (Fig. 13).

### Columnar Joint Patterns Constrained by Thermal Numerical Modeling of Cooling

Thermal numerical models of cooling were created for four geometries representing different emplacement scenarios of Devils Tower to test the match between the thermal structure of the models and columnar jointing pattern on the tower. Three of the geometries, suggested previously, represent intrusions of phonolite magma into Jurassic–lower Cretaceous strata (Fig. 14), specifically: (1) a magmatic stock of unspecified shape with horizontal dimensions “not greatly exceeding the present aerial extent of the tower” (Russell, 1896; Robinson, 1956, p. 13); (2) a volcanioc conduit that transferred the phonolite magma to higher levels of an eroded volcano (Carpenter, 1888; Halvorson, 1980); or (3) a laccolith, emplaced approximately between the Jurassic and lower Cretaceous sedimentary layers (Pirsson, 1894; Jaggar, 1901). The last model (Fig. 14D), based on the results of our study, is a large lava coulée emplaced into the maar crater of a phreatomagmatic volcano. The shape of the last model mimics the analogue model extrusion D-19 (Fig. 12, Movie SI-1 [see footnote 1]) with the flat base of this model positioned at the base of the tower within a hypothetical 1-km-wide crater at the level of the Sundance Formation that tapers toward the underlying rock formations.

Inspection of the intrusive models (Fig. 14) with superposed lines drawn perpendicular to the isotherms and profile of Devils Tower scaled to match the extent of the intrusions revealed that: (1) for a magmatic stock (Fig. 14A), columnar jointing should converge radially inward, creating a rosette pattern of columnar jointing in vertical cross section (Spry, 1962); (2) the cooling of the volcanic conduit (Fig. 14B) should develop two tiers of horizontal columns in vertical cross section or a chevron pattern of columnar joints that are slightly bent upward to form a cusp at the vertical contact suture (Spry, 1962), (3) cooling of a laccolith above the conduit (Fig. 14C) could produce two fans of columnar joints; one growing and converging from the base upward, where the conduit fed the laccolith with magma (inverted fan), and a second one growing in the opposite direction from the concave roof. Comparison of the columnar jointing patterns resolved from the thermal models for the three intrusive geometries and that of Devils Tower (Figs. 14A–14C) reveals a rough match only for the laccolith. However, for laccoliths that have concave roofs, we expect that the upper columnade columns would converge slightly downward, but the opposite is displayed at Devils Tower.

The thermal model created for our experimental extrusion D-19 (Fig. 14D) reveals a nearly perfect match between the resolved columnar jointing pattern (inverted fan; Spry, 1962) and columnar jointing on Devils Tower just above the flaring conduit, where the flow extruded laterally. Cooling of the coulée from its top flat surface would create vertical columns growing inward, where they would meet with the curved columns of the inverted fan colonnade. In contrast to the laccolith, the fact that the columns on Devils Tower converge toward the top of the tower could reflect a rather shallowly convex or sagged top surface in the central part.
of such an extrusion. Spry (1962) also explained the inverted columnar jointing pattern on Devils Tower by cooling of an extrusive lava sheet above the conduit; however, in his view, the tower would represent a remnant of only the lower half of such a sheet, interpreting the entire columnar section of the tower as the lower colonnade that formed by cooling from the base of the sheet.

The 3-D thermal model that was constructed for the geometry of model D-19 also revealed that the total cooling time in the center of the hot core at the suture between the cooling fronts above the feeding conduit (Fig. SI-1 [see footnote 1]) corresponds to ~4000 yr.

**Emplacement Mode of Devils Tower**

The volcaniclastic deposits found at Missouri Buttes are traditionally regarded as analogues to deposits found in the vicinity of Devils Tower (Effinger, 1934; Robinson, 1956; Halvorson, 1980). The exotic clasts (e.g., granite, limestone conglomerates, etc.) found at the DT-2 locality (Fig. 3) can thus be explained as material ejected from lower stratigraphic levels to their present position by the phreatomagmatic explosions. The discordant contact of the phreatomagmatic deposits west of Missouri Buttes and almost identical ages for both Devils Tower and Missouri Buttes, ca. 49 Ma (Duke et al., 2002), further imply that their emplacement level and evolution of their magmas or emplacement time were similar. It is thus logical to assume that both Missouri Buttes and Devils Tower could be interpreted as magmas emplaced at shallow levels of two individual maar-diatreme volcanoes.

Furthermore, summarizing the field evidence and genetic interpretation of the volcaniclastic deposits in the area together with the analogue modeling results based on the hypothetical reconstruction here (Figs. 11 and 14), we suggest that Devils Tower could represent a remnant of an extrusion, i.e., a lava coulée or low lava dome into a maar of a maar-diatreme volcano. Alignment of diatremes along faults is a
common feature of magma-water interaction processes established in hard-rock environments represented by limestones or granites (Lorenz, 2003; Auer et al., 2007; Závada et al., 2011).

Alternatively, Devils Tower could be also explained as a remnant of a laccolith (Pollard and Johnson, 1973; Corry, 1988), emplaced within the maar-diатreme structure and surrounding host rocks. However, this seems improbable due to the rather shallow level for the base of Devils Tower in the succession of surrounding rocks and the reconstructed maar-diатreme volcano; the recent top surface of Devils Tower matches the level of phreatomagmatic outcrops at Missouri Buttes. This level is interpreted as the paleosurface at the time of Devils Tower emplacement. Furthermore, it is difficult to consider that a laccolith would be emplaced at the currently exposed level, because emplacement of sills or laccoliths is likely controlled by rigidity contrasts of the host-rock strata rather than...
by the level of neutral buoyancy (Kavanagh et al., 2006). This assertion is supported by the fact that the majority of the laccoliths and sills in the Black Hills formed by phonolites are found in the Paleozoic–Mesozoic section (Halvorson, 1980; Lisenbee and DeWitt, 1993). Corry’s (1988) hypothesis that Devils Tower could represent a neck formed from magma that invaded the extended roof of a laccolith can be discarded, because the surrounding strata are not dipping away from this structure, as would be expected for this scenario. In addition, laccoliths are frequently fed by dike-like bodies growing as fluid-filled cracks (Corry, 1988; Price and Cosgrove, 1990) rather than cylindrical pipes. Cooling of a laccolith fed by such a dike would thus result in a so-called “tower” that is elongated horizontally (a wall).
Internal Fabrics of Devils Tower

Sample DT-1 (Fig. 6A), which could only be oriented with respect to the axis of collapsed column, implies originally subhorizontal fabrics (Fig. 8) for the upper part of Devils Tower, in agreement with the data of Halvorson (1980); subhorizontal above the elevation of ~1460 m asl and subvertical in the lower part (Fig. 15). Horizontal fabrics at similar heights on the southwest side of the tower can be also reflected by the possible compositional layering that is visible approximately at the level where the thick columns of the upper colonnade split to two or three columns in the lower colonnade (Fig. 1B).

Closer inspection of the internal fabric map for analogue model D-19 with superposed profile of Devils Tower (Fig. 13A) reveals that onion-peel like arrangement of flow planes above the flaring feeding conduit would easily explain vertical fabrics at the bottom part of the tower and exclusively horizontal fabrics from about its half-height upward, although similar fabric patterns also characterize the intrusive scenarios, i.e., stock, volcanic conduit, and laccolith (Fig. 14). The bottom boundary of the domain represented by horizontal fabrics in the thermal model for D-19 (Fig. 14D) roughly corresponds to the suture between both columnar jointing colonnades. The comparison of the fabric pattern for model D-19 (Fig. 12B) with Devils Tower further reveals that the top part of the tower can be associated with horizontal oblate and relatively strongly anisotropic fabric, which implies uniaxial deformation and/or flow of magma with vertical maximum compressive stress. This is compatible with the microstructure of the DT-1 sample that reveals phenocrysts dismembered and stretched along the trachytic fabric (Fig. 16B), and abundant mioriolitic cavities that are aligned preferentially at high angles to the general trend of trachytic fabric in the groundmass (Fig. 6A). These cavities form due to strain heterogeneities in the vicinity of phenocrysts in the phono-lite, and reflect the shear thickening rheology of the material that extrudes at low confining pressures (Smith, 2000; Smith et al., 2001; Závada et al., 2011). Therefore, although formation of these cavities cannot be excluded for any of the scenarios considered (Fig. 14), their abundance should in general increase with decreasing emplacement depth.

Cooling Dynamics of the Original Magmatic Body

The mutually orthogonal sets of columnar joints in the base of the tower (vertical radial and vertical peripheral joint sets) can be explained to form by cooling at the base of the original extrusion, when the thermal gradient between the hot extrusion and relatively cool diatreme filling was relatively high. We presume that the subvertical joint sets of the base formed perpendicular to the original base of the extrusion. Smooth transitions at the shoulder of the tower between the vertical joints of the base and the joints composing the wide columns of the lower colonnade suggest that some of the incipient tensile joints of the lower colonnade were established on the orthogonal joints of the base and that both blocky and columnar joint systems formed at similar cooling conditions. The thinning-upward columns of the lower colonnade on Devils Tower suggest that the rate of cooling associated with formation of these columns increased during solidification of the entire magmatic body. This can be possibly explained by a faster solidification due to degassing driven crystallization (Sparks et al., 2000), while some portion of the gasses that escaped from the crystalizing magma circulated in the columnar fracture system of the lower colonnade between the base of the body and the solidus envelope (Fig. 16B), providing faster convective cooling of the lower colonnade (DeGraff and Aydin, 1993). For the upper colonnade, fluid content of lava is low (due to low pressure) and any exsolved gasses would escape into the atmosphere, which is compatible with stable width of the upper colonnade columns. Even more likely, the fluids providing the convective cooling could have been released from the wet base of the original maar buried by the extrusion. Faster cooling of the lower colonnade would also explain why the suture of both colonnades is at about two thirds of the Devils Tower height, if we assume that the present summit of Devils Tower roughly corresponds to the original top surface of the extrusive body.

Asymmetry and Erosion of Devils Tower

The asymmetry of Devils Tower, clearly visible on the southeast-northwest profile (Fig. 1C), could be easily explained in our structural framework by the asymmetry of the original extrusion (Fig. 16). For example, in two models prepared with relatively diluted plaster suspension (D-19, D-21; Fig. 11), the analogue magma rose within a tube-like conduit parallel to the walls of the model diatreme. While the extrusive lobes on the right sides of both experimental bodies (Fig. 16; B side in Fig. 12D) are confined by the shallow angle of the maar crater walls, the opposite sides are molded by a mound of popped-up diatreme filling that evacuated in front of advancing model magma (Movie SI-2, experiment D-21 [see footnote 1]). The resulting contact between the extrusion and the mound could be characterized as rounded and as somewhat steeper than

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**Figure 15.** Diagram showing the orientation of magmatic fabrics (magm. f.) on Devils Tower measured by Halvorson (1980) and by us (this study). Our study indicates only subhorizontal fabrics of unknown plunge direction above elevation (contours) of 1490 m. Redrawn after Halvorson (1980).
Figure 16. Schematic block diagrams explaining the geological origin of Devils Tower and sketches of typical microstructures and mesoscale outcrops in the maar-diatremes volcanoes. (A) Phreatomagmatic eruptions excavate host rocks that are shattered and expelled together with fragments of phonolite magma within debris jets from the root zone (1) of a maar-diatreme volcano. Pilotaxitic porous texture of feldspar aggregates reflects the rapid undercooling in this domain. Collapsing debris jets (3) form typical surge deposits (2) in the maar with variety of juvenile magmatic, sedimentary, and basement rock fragments and that can contain armored lapilli. The explosions excavate a cone-shaped diatreme with steep walls filled with phreatomagmatic deposits and a circular crater on the surface (maar) surrounded by a tuff ring (4), which is typical with matrix-dominated phreatomagmatic tuffs or agglomerates with large variety of clast sizes. Ejection of the debris from depth causes collapse (5) of the diatreme walls (marginal screen) and explains the bending of horizontal strata toward the tower. (UC—upper Colonnade, LC—lower colonnade, J—Jurassic, T/P—Triassic–Permian.) (B) The explosive activity shifts to a purely effusive phase of the volcano, when the ingress of groundwater necessary to trigger the phreatomagmatic explosions is insufficient or the lithostatic pressure at increasing depth is too high. The magma intruding the maar is extruded on the surface and forms a lava coulée (dome flow) filling the entire maar-diatreme crater. Faster convective cooling in the lower colonnade is provided by fluids exsolved during crystallization of phonolite groundmass or released from the wet base of the maar (6). Associated microstructure sketch shows dilated trachytic texture of the phonolite with miarolitic cavities indicating horizontal stretching during the late stage of emplacement in the upper part of Devils Tower (7). The black lines indicate the trends of columnar jointing resolved from the two-dimensional thermal mathematical model. Dashed black lines on the front vertical section (B) indicate the isotherms. (C, D) Two perpendicular vertical cross sections across the lava coulée explain the possible role of the asymmetry of the original extrusion, also manifested by model D-21 (Fig. 11), on the resulting columnar jointing pattern. Note that in the section in D, where the extrusion had to overflow a mound of uplifted phreatomagmatic deposits, the cooling should produce curved columns (thin black lines in C and D) of the lower colonnade on the northwest side and straight columns on the southeast, where the extrusion was constrained by the flat and shallowly inclined surface of the maar walls. Dashed red lines indicate the suture between the thermal fronts. The phreatomagmatic volcano and the lava coulée are eroded to leave behind only the central part of the solidified lava coulée just above the feeding conduit, where the cooling produced the inverted-fan columnar jointing pattern, which is more resistant to erosion.
on the opposite wall at the same level (Fig. 16). Thus in such a scenario, the curved columns of the northwest wall of Devils Tower would form by cooling from the surface of the uplifted mound, while the straight columns of the southeast walls would form by cooling from the shallowly inclined and flat bottom of the extrusive lobe emplaced along the walls of the maar crater. This hypothetical structural analysis would further imply that: (1) the forming extrusive flow advanced from southeast to northwest, finally forming an ~270-m-thick lava coulée; (2) most of the original extrusion was eroded from the northwest side of the remaining phonolite monolith forming the tower; and (3) the diatreme should underlie the talus at the northwest side of the tower. The erosion of the tower advanced from the lateral margins on the circumference of the extrusion toward the interior by progressive collapse of tilted subvertical columns that cleaved off the remaining phonolite body primarily by frost wedging (Tharp, 1987; Matsuoka, 2008). The remaining monolith in its present form consists of columns leaning against the central axis of the tower and thus represents a relatively stable structure resistant to frost erosion.

**Phonolite Magma Properties**

The suggested extrusive form, a coulée or low lava dome, for the Devils Tower phonolite would be characterized by almost completely devolatilized and dehydrated magma. The topology of dry solidus curve of Taylor and MacKenzie (1975) for phonolite and experimental modeling of phonolite composition by Freise et al. (2003) constrain the minimum temperature of extruding phonolite to be at least ~850 °C. Phonolite magma of ~850 °C with <1 wt% H2O corresponds to melt viscosities of ~10^{-6}–9 Pa·s (Whittington et al., 2001; Romano et al., 2003; Giordano et al., 2004). Incorporating the influence of phenocrysts (total 36 vol%) on melt viscosities of 10^{-6}–9 Pa·s produces magma viscosities of ~4.5 × 10^{-9} Pa·s following the equation of Dingwell et al. (2003) with infinite viscosity at 0.6 phenocryst volume fraction. Such viscosities are typical for the suggested morphology of the coulée and/or low lava dome (Fink, 1980), although the extrusion shape is also dictated by the yield strength and cooling rate of the magma and the topography of the basal surface (Blake, 1990; Griffiths and Fink, 1997; Kerr et al., 2006). Both the viscosity and yield strength of the magma likely further increased during flow at final stages of emplacement as the magma continuously crystalized; this is recorded by the weak trachytic texture of groundmass crystals. The transition from pseudo-plastic to final dilatant (strain-thickening) rheology (Smith, 2000; Závada et al., 2011; Petford, 2009; Picard et al., 2011) is evidenced by the miarolitic cavities in the vicinity of large phenocrysts (Fig. 7A). Since the aspect ratio of isothermal Bingham suspension bodies is dictated by the yield strength (Blake, 1990; Závada et al., 2009b), the original shape of the Devils Tower phonolite extrusion could be successfully reproduced by our experiments if we assume that the cooling rate was rather slow with respect to emplacement time of this relatively volumetric phonolite body, so that the cooling carapace (Griffiths and Fink, 1993; Fink and Bridges, 1995) did not significantly hinder the growth and lateral flow of magma in the maar crater.

**CONCLUSIONS**

The evaluation of structural setting and microstructural analysis of the magmatic and phreatomagmatic rocks collected in the area suggests that emplacement of the Devils Tower phonolite monolith is associated with activity of a Cenozoic maar-diatreme volcano. The combined methods of analogue modeling simulating magma intrusion into maar-diatremes and thermal mathematical modeling of cooling of magmatic bodies revealed that Devils Tower can be explained as a remnant of a low lava dome or coulée emplaced into the maar of a maar-diatreme volcano. This new hypothesis is illustrated by a perfect match of the columnar jointing pattern displayed on Devils Tower and the thermal structure of the numerical model (Fig. 14D). Although this hypothesis requires testing and further analysis and discussion, the model explains the asymmetry of Devils Tower and can be tested in the future by geophysical methods such as combined gravity, magnetic, and magnetotelluric surveys.

Our scenario is further corroborated by another complex structural study of a similar phonolite butte (Fig. 17A) in the Cenozoic volcanic province in central Europe (Závada et al., 2011). Another analogous butte is found in the French village of Ardèche in the Massif Central (Roche de Borée) (Fig. 17B); however, no structural or petrological data are available for this feature. Although our explanation for the geo-

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**Figure 17.** Phonolite bodies similar to Devils Tower in Cenozoic volcanic provinces in Europe. (A) Phonolite body Bořeň (Czech Republic), view from the west, interpreted as a remnant of an extrusive lava dome emplaced into a maar-diatreme crater (Závada et al., 2011). The level of the contact between the colonnades of columns (UC—upper colonnade, LC—lower colonnade) is indicated by thick dashed line. (B) Roche de Borée in Ardèche, Massif Central (France), a phonolite body of similar shape and vertical columnar jointing in the upper part. Photographs by K. Mach.
logical origin of Devils Tower is substantially different from previous published hypotheses, we have presented an approach that gives clear logical origin of Devils Tower is substantially different from previous published hypotheses, we have presented an approach that gives clear

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REFERENCES CITED


