Volcanic evolution of Mount Taylor Stratovolcano, New Mexico: Facts and misconceptions


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VOLCANIC EVOLUTION OF MOUNT TAYLOR STRATOVOLOCAINO, NEW MEXICO: FACTS AND MISCONCEPTIONS

FRASER GOFF1, WILLIAM McINTOSH1,2, LISA PETERS2, JOHN A. WOLFE3, SHARI A. KELLEY2, CATHY J. GOFF4, AND G. ROBERT OSBURN5

1Department of Earth and Environmental Science, New Mexico Tech, 801 Leroy Place, Socorro, NM 87801; candf@swcp.com
2New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801
3School of the Environment, Washington State University, Pullman, WA 99164
4Independent Consultant, 5515 Quemazon, Los Alamos, NM 87544
5Earth and Planetary Science, Washington University, St. Louis, MO 63130

ABSTRACT—Mount Taylor (3445 m elevation) developed from roughly 3.2 to 2.5 Ma and is a composite stratovolcano (Mount Taylor stratovolcano, MTS) composed of coalesced basaltic trachyandesite to rhyolite domes, flows, plugs, dikes, interlayered ash, and comingled debris flows. The main edifice is surrounded by later cones and flows of (mostly) trachybasalt that erupted until 1.27 Ma. Contrary to previous interpretations, the summit trachyandesite flows of MTS (2.75 to 2.72 Ma) are not the youngest eruptions on the edifice. A variety of satellite domes, flows, radial dikes and a central plug of mostly trachydacite were intruded and erupted until 2.52 Ma. Thus, also contrary to previous studies, the youngest eruptions at MTS are not “andesitic.” An elongate, eastward-facing Amphitheater about 6.5 km long formed in the approximate center of MTS late in its development. The best explanation for formation of the MTS Amphitheater is erosion by mass wasting and fluvial incision. This feature did not form from large, centralised, late stage explosions, from Mount St. Helens-type lateral blasts with associated fall and ignimbrite, or from Pleistocene glaciation of the edifice, although it may have formed in part from an unrecognizable debris avalanche. Previous studies have speculated that MTS developed a single cone or bulbous dome that once attained a height of 4270 m, but it is more probable that the mixture of small, coalesced vents and domes forming the original summit never rose above 3800 m. Using this maximum elevation, an average diameter of 16 km for the volcano from recent mapping, and the formula for a right circular cone, the estimated volume of MTS is 85 km3 ± 20%. From this volume and the time span of intense MTS construction (0.76 Ma), the average eruptive (magmatic) flux rate is about 0.11 km3 per 103 years. These values for MTS are small compared to those of Cascades-type subduction zone stratovolcanoes, such as Mount St. Helens.

INTRODUCTION

Mount Taylor is an extinct composite stratovolcano that is part of the greater Mount Taylor–Mesa Chivato volcanic field (Hunt, 1938; Crumpler, 1980a, b) and is one of many volcanic fields that define the northeast-trending Jemez Lineament (JL, Figs. 1, 2; Mayo, 1958; Luedke and Smith, 1978; Goff and Kelley, 2020). Mount Taylor stratovolcano (MTS, 3445 m) forms a conspicuous topographic feature roughly 20 km northeast of Grants and is New Mexico’s second largest late Cenozoic volcanic complex after the Valles caldera and Jemez Mountains (Crumpler, 2010). The peak is sacred to the nearby Acoma, Laguna and Zuni pueblos and is known as “Turquoise Mountain,” or Tso Tsii, to the Diné (Navajo). The present name honors President Zachary Taylor, a major general who became U.S. president in March 1849 and who died prematurely in office in July 1850.

Many researchers have mapped and conducted volcanic and petrologic studies at Mount Taylor starting with Dutton (1885); see Goff et al. (2019) for a comprehensive list. Because of the abundant uranium resources hosted in Jurassic rocks beneath and around the volcano, the New Mexico Bureau of Geology and Mineral Resources produced a series of 7.5-minute geologic quadrangles beginning in 2007 (Goff et al., 2008, 2012, 2014a; McCraw et al., 2009; Osburn et al., 2010; Skotnicki et al., 2012), which resulted in a detailed 1:36,000-scale compilation of the Mount Taylor and southwest Mesa Chivato region (Goff et al., 2019). During this mapping, 107 new 40Ar/39Ar dates and 216 new major and trace element chemical analyses were obtained. Toward the end of the mapping campaign, we also employed a portable flux gate magnetometer to acquire magnetic polarities of important volcanic units. The polar
ties provided an independent check on the dates (see booklet in Goff et al., 2019, for all radiometric and magnetic polarity results). This paper summarizes the geology, dates, chemistry and magnetic polarities of MTS, presents a revised volcanic evolution for its development, and comments on the origin of MTS Amphitheater (Fig. 3). Volcanism on Mesa Chivato and Grants Ridge is not covered herein.

**GEOLOGIC BACKGROUND**

Jurassic and Cretaceous non-marine and marine sedimentary rocks underlie MTS and Cretaceous strata interfinger with each other around and beneath MTS. The Jurassic Westwater Canyon Member of the Morrison Formation is host to abundant uranium ores that made the Grants district the largest uranium-producing area in the United States from 1951–1980. This district still ranks second in the United States in uranium reserves (Kelley, 1963; McLemore, 2011; McLemore and Chenoweth, 2017). Several hundred boreholes drilled by mining companies through volcanic rocks west and north of MTS traced uranium-bearing Jurassic strata beneath the volcano flanks east of the Mt. Taylor Mine at San Mateo (Goff et al., 2019). The upper Cretaceous section is a transgressive-regressive sequence (Sears et al., 1941; Kelley, 1963; Owen and Owen, 2003) that records a gradual transition from open marine conditions to marginal marine and deltaic settings. Coal production from Upper Cretaceous strata in the map area covered by Goff et al. (2019) was small and limited to the eroded basins south and southwest of MTS (Hoffman, 2017, fig. 10).

MTS overlies the southeast margin of the Laramide San Juan Basin and also lies in a transition zone of extension between the Colorado Plateau to the northwest and the Rio Grande rift (RGR) to the east (Olsen et al., 1979; 1987; Thompson and

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**FIGURE 2.** Map of Mount Taylor volcano region showing simplified geology and locations of six recently completed 1:24,000 quadrangles: CP = Cerro Pelón, LC = Laguna Cañoneros, LS = Lobo Springs, MT = Mount Taylor, S = Seboyeta, and SM = San Mateo. Modified from Goff et al. (2019).

**FIGURE 3.** Photo taken from an airplane during the winter of 2008 looking northeast across the Amphitheater of MTS toward Mesa Chivato; LM = La Mosca, MT = Mount Taylor; WC = Water Canyon. Photo courtesy of Kirt Kempter.
Zoback, 1979; Aldrich and Laughlin, 1984). Recent interpretation of 3D seismic structure beneath the RGR to a depth of 200 km (Sosa et al., 2014) suggests that the transition zone is a broad low velocity region and that an upwelling sheet or linear bulge of hot mantle material underlies the JL. This upwelling mantle sheet has probably fed the volcanic centers along the JL, including Mount Taylor and Mesa Chivato (Fig. 1).

**ANALYTICAL METHODS**

Recent mapping of Mount Taylor and surrounding areas was enhanced by petrographic examination of 150 polished thin sections. These observations constrain mineral assemblages and textures in many volcanic units and allow us to assign rock names to units that were not chemically analyzed. Phenocrysts in MTS eruptive products are similar to those in mildly alkalic volcanic terrains erupted in or near some continental rifts (Table 1; Wilson, 1989, fig. 11.12).

In this paper, we highlight 62 of 107 40Ar/39Ar dates (Table 2) obtained during the 2007–2013 quadrangle mapping projects, including only those dates that illustrate the development and evolution of MTS proper. Dates from the Grants Ridge rhyolite center and greater Mesa Chivato are not discussed herein (see Goff et al., 2019, for these results). All dates in Table 2 are calculated using the Fish Canyon Tuff sanidine neutron flux interlaboratory monitor (FC-2) with an assigned age of 28.201 Ma (Kuiper et al., 2008).

To help constrain our geochronology, we measured the magnetic polarity of many samples by handheld (portable) fluxgate magnetometer (all rock types) and Brunton™ compass (basaltic rocks only; Table 2). We used a μMAG™ digital magnetometer built by MEDA, Inc. (Dulles, VA). Many volcanic rocks in the Mount Taylor region were erupted during the magnetic polarity flip from the Gauss Normal Chron to the Matuyama Reverse Chron at 2.581 Ma (Gee and Kent, 2007, table 3). Unfortunately, our magnetic polarity measurements started late in the mapping campaign and many hard-to-access locations were not revisited. Note that this report employs the Plio–Pleistocene boundary of 2.58 Ma in accordance with recent international stratigraphic changes (Cohen et al., 2013).

We also acquired 216 major and trace element chemical analyses of volcanic rocks in the Mount Taylor region using a combination of XRF and ICP-MS methods and analyzed by Washington State University (Fellah, 2011) and ALS Laboratories (Reno, Nevada, see their website for methods). Table 2 lists normalized silica and total alkali contents of 56 dated map units that were key in constraining the evolution of MTS. Complete geochemical data and interpretations will be published at a future time.

**VOLCANIC EVOLUTION, MOUNT TAYLOR STRATOVOLCANO**

**Previous Work**

Previous investigations of MTS rocks were conducted by Hunt (1938), Baker and Ridley (1970), Lipman and Mehnert (1979), Crumpler (1982), and Perry et al. (1990). The alkalic (i.e., Na₂O + K₂O–rich) chemistry of MTS rocks was noted by all researchers except Baker and Ridley (1970), who mistakenly called the rocks “calc-alkaline.” Through the years, rock classification schemes (i.e., “rock names”) used by past workers have varied widely, leading to considerable confusion (see Goff et al., 2019, p. 6). Beginning with Hunt (1938), all subsequent studies claimed that the youngest eruptions of the MTS are those that form the high-elevation stack of lavas at the summit (i.e., Mount Taylor proper). Consequently, all previous researchers (e.g., Crumpler, 2010, p. 57) have stated that the youngest MTS summit flows are “andesitic to latitic” in mineralogy and chemistry, post-dating all earlier eruptions of “dacite, quartz latite and rhyolite.” As noted below, our investigation revealed a different sequence of eruptions.

**Rock Classification from Chemistry**

For our Mount Taylor project (Table 1 and Fig. 4), we have used the internationally accepted classification scheme of Le Bas et al. (1986), previously published chemistry, and our own chemical analyses to rename and categorize the volcanic units.

**Table 1. Phenocryst mineralogy of volcanic rocks, Mount Taylor stratovolcano, New Mexico (Goff et al., 2019).**

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<th></th>
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<th>Basalt</th>
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X = major, x = minor, tr = trace; Tbasalt = trachybasalt, Tandesite = trachyandesite, Tdacite = trachydacite.
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<td>Qyatb Tdacite, east Amph</td>
<td>Qxgi Oliv gabbro plug</td>
<td>Tbi Tdacite</td>
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**Phase 2: Older lavas and domes**

**Phase 1 (late) to Phase 3 (early): Pyroclastic rocks**

**Phase 1: Mount Taylor floor**

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1. From geologic map of Goff et al. (2019)
2. Tbasalt = trachybasalt, Tandesite = trachyandesite, Tdacite = trachydacite
4. LTF = laser total fusion, LSH = laser step heat, FSH = furnace step heat, BSH = bulk step heat
5. Mean Square Weighted Deviation
6. All dates use the Fish Canyon Tuff sanidine neutron flux interlaboratory monitor (FC-2) with an assigned age of 28.201 Ma (Kuiper et al., 2008).
7. N = normal polarity, R = reverse polarity, brun = brunton compass, fgate = flux gate magnetometer, nd = not determined
8. Polarity and age match within error of the date (see Gee and Kent, 2007, or Goff et al., 2019, table 2).
9. Silica = SiO\(_2\), normalized wt%, TAS = total alkalis, Na\(_2\)O + K\(_2\)O, normalized wt%, na = not analyzed
10. Unit Tpota was dated at two different locations several kilometers apart to verify age continuity.
11. Date site is off map to southeast but unit is exposed in Water Canyon.
Thus, most alkali basalts (hawaiites) are now called trachybasalts; basaltic andesites (mugearites) are called basaltic trachyandesites; andesites (latites) are called trachyandesites; and quartz latites are called trachydacites. The only volcanic rocks that we have not renamed are rhyolites and basanites, although we reserve the name trachyte for a few of the most alkali-rich rocks that plot in the trachydacite-trachyte field (Fig. 4).

The total-alkali versus silica plot (Fig. 4) displays the restricted group of dated MTS samples prepared for this paper (Table 2; see Fellah, 2011, fig. 8 or Goff et al., 2019, fig. 8 for comprehensive plots that include Grants Ridge and Mesa Chivato). Figure 4 shows a fairly linear trend between basalt/trachybasalt and trachydacitic end-members. Basanites form a separate group, and there is a separate trend for pyroclastic rocks and rhyolites, with the caveat that such rocks may have lost alkali elements during post-eruptive weathering or alteration. Note that, for the most part, MTS rocks are alkalic, not calc-alkalic as previously stated by Baker and Ridley (1970).

**Construction of Mount Taylor Stratovolcano**

Our new dates and magnetic polarity measurements indicate that the main edifice and satellite domes of MTS were erupted from about 3.2–2.5 Ma, more or less in agreement with previous researchers, although dissimilar in many details (Lipman and Mehnert, 1979; Perry et al., 1990; Crumpler, 2010). Thus, construction of MTS was essentially complete by the end of the Pliocene at 2.5 Ma, but erosion since that time has decapitated the highest points of the original complex and carved out the Amphitheater (Fig. 3).

MTS is surrounded by and interlayered with mostly mafic lava flows, scoria cones, and a few centers of more silicic composition, which are not discussed further in this paper. Overall, the most common mafic rock is trachybasalt (hawaiite). The few eruptions of basanite and basalt generally occur relatively early in the eruptive history, while trachybasalt is predominant in later eruptions (Figs. 4, 5, 6).

Our dates and those of others show that initial but sporadic volcanism in the Mount Taylor region began at about 4.49±0.08 Ma (Picacho Peak basanite plug and dikes; Hallett et al., 1997) and ended at about 1.27±0.19 Ma (Cerro Pelón trachybasalt cone and flow). Again, this age range generally agrees with the range determined by previous researchers (e.g., Lipman and Mehnert, 1979), but the details are considerably different.

What follows are descriptions of the four phases of eruptions that formed the MTS. Unit name identifiers are from Goff et al. (2019).
Phase 1, the volcano floor (3.74–2.93 Ma)

Phase 1 volcanism (Figs. 5, 6) began with the eruption of two widespread flows of basanite that initially formed mesa caps (units Tbae and Tbaw, 3.74–3.66 Ma, Table 2), as documented by previous workers (Lipman and Moench, 1972; Perry et al., 1990). Next came eruption of a trachydacite dome exposed in the bottom of upper Rinconada Canyon (unit Tbhtd). The date for this unit (3.28±0.20 Ma) has a relatively large error, but the magnetic polarity is normal, suggesting an age <3.22 Ma (Table 2). Following emplacement of this dome, another widespread eruption of basanite occurred in the eastern sector of the present Amphitheater (unit Tbaa, 3.24±0.04 Ma), as well as eruptions of alkali basalt (unit Toab, 3.23±0.12 and 3.18±0.04 Ma), now exposed in upper Rinconada Canyon and in the bottom of the central to eastern Amphitheater. Both the later basanite and coeval flows of alkali basalt flowed many kilometers down ravines associated with an earlier Water Canyon (not shown on Fig. 6 for clarity; see Goff et al., 2019). Within what is now the eastern Amphitheater, a small trachyte dome (unit Ttr, 3.16±0.01 Ma) was erupted, followed by emplacement of rhyolite domes and intrusions in the western and central Amphitheater (units Trw and Tre, 3.03±0.11 and 2.93±0.04 Ma, respectively). Small volume rhyolite to trachydacite ignimbrite and fall deposits (units Trt, 3.10±0.20 Ma, and Twst, ranging from 3.04–2.74 Ma) filled early paleocanyons and paleoravines, particularly in the Water and San Mateo canyon areas, and sporadically covered mesa tops around the volcano (Dunbar et al., 2013; Kelley et al., 2013). Products of individual pyroclastic eruptions are <1 km³ in volume and probably originated during silicic dome eruptions. No large pyroclastic deposits, vents, craters or caldera have been identified at MTS, although thickness trends point to a source or sources in the west-central part of the early edifice.

Phase 2, the stratovolcano grows (2.88–2.78 Ma)

During phase 2, the growing stratovolcano erupted a mixture of trachyandesite, trachydacite, and trachyte lavas and domes, and associated small volume ignimbrites and tuffs (Figs. 4, 5, 6). Two previously unrecognized trachytes (Tbht and Tcpt; Table 2) were dated at 2.85±0.04 and 2.84±0.08 Ma, respectively. The second trachyte is overlain by a thick trachydacite flow (unit Tpetd) dated at 2.83±0.04 Ma, which contains abundant mafic enclaves. Field relations and other dates bracket the early Phase 2 dome eruptions to be between 2.88 and 2.78 Ma. Small volume ignimbrites (e.g., unit Ttdt ranging from 2.81 to 2.73 Ma) continued to fill in preexisting ravines and depressions and are also found in scattered outcrops around the volcano interlayered with trachybasalt and minor basalt lavas, and with early volcaniclastic rocks shed off the developing volcano.

The defining units ending Phase 2 consist of a series of “plagioclase” or “big feldspar” mafic eruptions, often called “plagioclase basalt” (2.81–2.78 Ma). Baker and Ridley (1970) first described these flows. What we call classic plagioclase basalts (Table 2, Figs. 4, 5, 6) are borderline trachybasalt to basaltic trachyandesite in composition. We found that most MTS rocks previously called plagioclase basalt range from basaltic trachyandesite to trachyandesite in composition (Goff et al., 2019). The classic varieties are among the latest eruptions of this group, but these rocks are interlayered within the uppermost intermediate flows making up Phase 2 (e.g., unit Tptd dated at 2.80±0.05 Ma). “Plagioclase basalt” is most common on the central to eastern flanks of MTS, exposed in canyons cutting its southern flank, and on the bluff east of San Mateo Basin.

Phase 3, the final stratovolcano eruptions (2.75–2.52 Ma)

Continued effusion of intermediate composition lavas and domes from 2.75–2.52 Ma characterized volcanic activity for Phase 3. These eruptions originated in part from a composite stock generating radial dikes that developed beneath the central to western Amphitheater (Fig. 6). Our new dates and chemical analyses show that trachyandesite and trachydacite were coeval in time and space. For example, what is now the Mount Taylor summit was built of successive flows of hornblende trachyandesite (units Tha and Thtas, 2.75±0.01 to 2.72±0.02 Ma) erupted from a buried or obliterated vent in the western Amphitheater. “La Mosca” (3,365 m; Fig. 3) is constructed by a small intrusion exposed in the northwest Amphitheater wall (unit Tpbt, 2.73±0.03 Ma) that produced a thick flow of trachydacite (Tpbd). These are presently the two highest peaks of MTS, but...
due to subsequent erosion, the maximum height of the edifice was higher than now.

During this period, eruptions of ignimbrite and pyroclastic fall deposits virtually ceased. A trachydacite ignimbrite at the head of Lobo Canyon (unit Tdtd) previously identified by Lipman and Mehnert (1979) was dated at 2.73±0.06 Ma. The youngest pyroclastic deposit we found was a relatively thin trachydacite to alkali rhyolite fall deposit east of MTS (e.g., unit Tdtd, 2.717±0.002 Ma). A few dome collapse breccias (glowing avalanche deposits?) are recorded in the larger dome eruptions (i.e., sugary enclave trachydacite, unit Tsetd), but such deposits appear to be a minor component of MTS. In contrast, rapid erosion of the growing volcano formed large aprons and fans of water-transported debris flows and other volcanic sediments interlayered with lava flows. These deposits radiate in all directions away from the volcano, but are thickest to the east and southeast toward the ancestral drainage of the Amphitheater. Possibly, the debris flow sequence contains unrecognizable debris avalanche deposits from Phase 3 domes.

Toward the middle to end of Phase 3 (2.72–2.52 Ma), a series of satellite domes and flows erupted on the margins and flanks of the volcano (e.g., unit Tpota, 2.69±0.02 Ma, average of two dates). These eruptions are mostly trachydacite (Table 2) and match the chemistry and age of several radial dikes exposed within and on the margins of the Amphitheater (2.71 to 2.66 Ma). The last magmatic products emitted from the composite stock are: 1) a trachydacite to alkali rhyolite plug intruded into the western Amphitheater (unit Tqtd, 2.60±0.02 to 2.56±0.02 Ma); 2) the Spud Patch trachydacite satellite dome, erupted on the northern flank of MTS (unit Tsptd, 2.55±0.06 Ma); and 3) an enclave-rich trachyandesite intrusion and flow emplaced on the southwestern margin and flank of MTS (unit Teta, 2.52±0.07 Ma, borderline trachydacite, Figs. 4, 6). The last three magmatic units have reverse magnetic polarity, whereas older Phase 3 rocks have normal polarity. Thus, the youngest magmatism of MTS captures the fundamental change in magnetic polarity at 2.58 Ma (Fig. 5; Gee and Kent, 2007).

Within the eastern Amphitheater floor, a large circular plug of fine-grained olivine gabbro (unit Qxgi, 1.98±0.05 Ma) intruded and uplifted adjacent Cretaceous rocks and caused noticeable hydrothermal alteration of both sandstone and shale (Goff et al., 2019). When viewed from the Amphitheater floor, this columnar-jointed intrusion superficially resembles the famous Devils Tower, Wyoming. It is not clear if this magma
breached the surface to produce a flow. The top of the plug is somewhat vesicular (Hunt, 1938), but any flow that may have erupted from this intrusion has been completely eroded. The gabbro chemically resembles “true” basalt (≤5 wt% alkalis). This is the youngest Phase 3 magmatic event within the Amphitheater and is shown as such on Table 2 and Figure 4 even though it is a mafic intrusion.

Phase 4, terminal mafic volcanism (2.50–1.27 Ma)

Although intermediate to silicic dome and flow eruptions forming MTS ceased at 2.52 Ma, our mapping and dating campaign identified many flank eruptions of mafic flows, cones, and plugs that erupted afterward (Table 2). With few exceptions, these younger eruptions consist of trachybasalt (Fig. 4). A group of peridotite-bearing cones and flows (unit Qyxtb, 1.86–1.75 Ma) erupted from vents northwest, north and northeast of MTS (Goff et al., 2019). Three aphyric trachybasalts erupted on the north and southwest flanks of MTS (units Qyh and Qatb, 1.73, 1.77, and 1.80 Ma). These were followed by a group of distinctive fine-grained quartz-bearing trachybasalts that vented around MTS from 1.65–1.54 Ma (unit Qfqtb). The youngest mafic eruption that we could identify is the cone and flow of Cerro Pelón (unit Qyatb, 1.27±0.19 Ma).

FORMATION OF THE AMPHITHEATER

Controversy still revolves around the origin of MTS Amphitheater (Fig. 3). Four theories have been offered: 1) some form of explosion(s) (Crumpler, 2010, p. 57), 2) a lateral blast or sector collapse (Crumpler, 1982, p. 294; Crumpler, 2010), 3) glaciation (Ellis, 1935; Pierce, 2004), or 4) mass wasting/fluvial erosion (Hunt, 1938; Lipman and Mehnert, 1979; Perry et al., 1990).

First, the Amphitheater did not form from a single large explosion or series of explosions as occurred at Valles caldera (Smith and Bailey, 1966; Goff et al., 2014b). There are no late, widespread ignimbrite (ash-flow) sheets or pyroclastic deposits covering the 2.75 to 2.52 million-year-old landscape (i.e., the Phase 3 domes and flows) bordering the Amphitheater, and there are no late-stage circular collapse faults within the inner margins of the Amphitheater. Although non-welded pyroclastic eruptions occurred early in the development of MTS (3.10 to 2.78 Ma; Table 2; Fig. 4), they are volumetrically small (<1 km³) and mostly restricted to paleocanyons northwest and southeast of the Amphitheater. These early pyroclastic deposits are covered by later Phase 2 dome and flow eruptions forming MTS. In contrast, our very rough estimate of the original volume of the Amphitheater, assuming a maximum summit elevation of 3800 m, is 9 km³ (see below), a volume many times larger than any pyroclastic deposits we observed. This eroded material has been incorporated within the large fan of volcaniclastic sediments that flanks the east and southeast margin of the Amphitheater (see map of Goff et al., 2019).

Second, the Amphitheater did not develop from a Mount St. Helens-type lateral blast deposit (i.e., sector collapse with simultaneous magmatic explosion). Our detailed mapping of MTS identified no late-stage, blast-type pumice deposits or ignimbrites east and southeast of the volcano or elsewhere (e.g., Hoblitt et al., 1981). It is possible that relatively small sector-collapse deposits slid off some of the evolving Phase 2 domes, but we did not observe hummocky landslide or debris avalanche deposits characteristic of catastrophic stratovolcano sector collapse (Voight et al., 1981). Perhaps they are merely hidden in the more voluminous sedimentary debris flow deposits flanking the volcano. Siebert (1984) pointed out that recently formed volcanic amphitheaters formed by debris avalanches have characteristic shapes and breach width approximately equaling the crater width. In contrast, the breach width/crater width of the MTS Amphitheater is about 0.25 (Perry et al., 1990), which could be attributed to significant post-debris avalanche erosion.

Third, the Amphitheater was not carved by Pleistocene glaciation as claimed previously by Ellis (1935) and reiterated more recently by Pierce (2004). Our detailed mapping and early work by Hunt (1938) identified no glacial deposits such as moraines anywhere in or around MTS, nor did we find them above or interlayered in the upper debris flow deposits east and southeast of Water Canyon. The Amphitheater is certainly not U-shaped with a flat floor like classic glacially carved valleys (Fig. 3). More recently, Meyer et al. (2014) tried to find evidence for glaciation (including striated clasts or bedrock) but concluded that glaciation “was unlikely to have occurred for any significant period in the eastern Amphitheater of the mountain where is was previously inferred.”

Based on our recent detailed mapping in combination with new dates, we concur with Hunt (1938), Lipman and Mehnert (1979), and Perry et al. (1990) that the Amphitheater most likely developed by simple erosion of the original summit with deposition of the eroded material in the large fan of volcaniclastic sediments east of Water Canyon. Stratovolcanoes with erosional amphitheaters tend to have broad craters with narrow breaches such as observed at MTS (Siebert, 1984; Perry et al., 1990). Doming and fracturing accompanying late-stage injection of radial dikes and the trachydacite-to-alkali rhyolite plug from the composite stock in the west-central part of the volcano probably facilitated erosion. We note that the main trend of 148 radial dikes within MTS is N65°W to N25°W, or approximately parallel to the trend of the Amphitheater (Goff et al., 2019). Magma-induced hydrothermal alteration coinciding with late MTS intrusive activity was observed in many intermediate composition boulders in surrounding debris flows. This alteration likely destabilized the core of the volcano. Emplacement of the late gabbro intrusion beneath the eastern Amphitheater further damaged and weakened the edifice (Goff et al., 2019, p. 17, 29, 32-34). Erosion of the original edifice has created a large eastward-facing basin and has deposited large aprons of volcaniclastic debris around the present MTS.

HOW HIGH WAS PLIOCENE MOUNT TAYLOR

Extrapolation of the exterior morphology of MTS by Crumpler (1982, 2010) suggests the Pliocene summit was once a large bulbous dome, pyroclastic cone or combination thereof, much higher in elevation than now, perhaps as high as 4270...
m (14,000 ft) or 825 m higher than today’s summit. On the other hand, Perry et al. (1990) observed that present MTS has shallow exterior slope angles of 10 to 12° and contains very minor pyroclastic layers in the summit area, the latter observation verified by our mapping (Goff et al., 2019). The margin of the Amphitheater, including Mount Taylor proper and La Mosca, is composed of many coalesced domes and flows of variable elevation between 3000 and 3443 m. Extrapolation of slope angles from different points around the margin to a hypothetical maximum elevation in the past is somewhat equivocal, but it is our interpretation that MTS never exceeded 3800 m in elevation.

WHAT WAS THE VOLUME OF THE STRATOVOLCANO

Perry et al. (1990) estimated the pre-erosional volume of MTS at 23 km³ and the volume of eroded material at 3 km³, mostly from the Amphitheater. The geometric parameters for these calculated estimates are not given in their paper, but, in any event, these estimates seem unrealistically small to us and don’t account for a maximum edifice elevation of 3800 m described above. From our recent mapping, the average diameter of MTS, including flanking mafic flows and interlayered debris flow deposits, is about ±16 km. If we assume an average base elevation of 2500 m and a maximum height of 3800 m, the relief of the volcano was once 1300 m. Inserting these values into the formula for a right circular cone, the estimated maximum volume of MTS was more reasonably about 85 km³ with an estimated error of ±20%. The average slope angle of the original edifice was 9°, essentially equivalent to the Perry et al. (1990) calculation of 10° to 12°, but slope angles near the summit and margins of the Amphitheater are quite variable. For comparison, the estimated original volume of Mount Rainier, Washington, is about 140 km³ (before erosion), the volume of Mount Adams, Washington, is 290 km³, and that of Mount Shasta, California, is 350 km³ (Orr and Orr, 1996).

WHAT WAS THE ERUPTIVE FLUX OF THE STRATOVOLCANO

From the volume of the volcano (85 km³) and the time span of intense stratovolcano construction (0.76 Ma), we calculate an average eruptive (magmatic) flux rate of 0.11 km³ per 10³ years. For comparison, the eruptive flux of the San Francisco volcanic field in Arizona is 0.2 km³ per 10³ years (Tanaka et al., 1986), the long-lived Jemez volcanic field is 0.3 to 0.4 km³ per 10³ years (Gardner and Goff, 1984), and the incredibly active Mount St. Helens is 4.6 km³ per 10³ years (Lipman and Mullineaux, 1981). Thus, the eruptive flux of MTS is much smaller than most Cascade-type subduction zone volcanoes.

CONCLUSIONS

Major conclusions of our recent studies are:
- The summit trachyandesite lavas of MTS erupted 2.75 to 2.72 Ma and are not the youngest eruptions of the volcano. After summit activity waned, volcanism continued for another 200–230 ka around and within the edifice.
- Consequently, the youngest eruptions at MTS did not become progressively “andesitic” with time as previously thought. The summit stack of trachyandesite flows is equivalent in age to the trachydacite flow and intrusion that form La Mosca (2.71 Ma). Our dates and chemistry show that dome, flow and dike eruptions from 2.72 to 2.52 Ma are predominately trachydacite, originating from a composite stock. In fact, one of the youngest igneous events is the emplacement of the trachydacite to alkali rhyolite plug in the western Amphitheater.
- When growth of MTS ceased at 2.52 Ma, the style and chemistry of volcanism transformed to eruptions of primarily trachybasalt cones and flows surrounding the volcano. The youngest eruption anywhere near MTS is Cerro Pelón at 1.27 Ma.
- The elongate, eastward-facing Amphitheater in the approximate center of MTS formed by fluvial and mass-wasting erosional processes in Quaternary time. It did not form from large centralized explosions, from lateral blasts, or from Pleistocene glaciation of the edifice. Injection of late-stage radial dikes and various intrusive bodies and coincidental development of magma-induced hydrothermal alteration weakened the central edifice causing accelerated erosion. An alternative interpretation of precise age data could allow intrusive doming and sector collapse on the east flank to initiate erosion of the MTS amphitheater at about 2.56 Ma.
- It is our contention that the amalgam of small, coalesced flows and domes forming the original summit area of MTS never rose above 3800 m. Our estimated volume of MTS is roughly 85 km³±20%.
- The volume and eruptive flux (0.11 km³ per 10³ years) of MTS was considerably smaller than presently active Cascade-type subduction zone stratovolcanoes.

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