



## ***Gabbroic shallow intrusions and lava-hosted xenoliths in the Mount Taylor area, New Mexico***

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# GABBROIC SHALLOW INTRUSIONS AND LAVA-HOSTED XENOLITHS IN THE MOUNT TAYLOR AREA, NEW MEXICO

FRASER GOFF<sup>1</sup>, JOHN A. WOLFF<sup>2</sup>, WILLIAM MCINTOSH<sup>1,3</sup>, AND SHARI A. KELLEY<sup>3</sup>

<sup>1</sup>Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, candf@swcp.com

<sup>2</sup>School of the Environment, Washington State University, Pullman, WA 99164

<sup>3</sup>New Mexico Bureau of Geology and Mineral Resources, NM Institute of Mining and Technology, Socorro, NM 87801

**ABSTRACT**—Recent detailed geologic mapping of six quadrangles encompassing Mount Taylor volcano has revealed three small shallow intrusive bodies of olivine gabbro and a scoria cone containing 0.5 m long blocks of similar olivine gabbro. These gabbros resemble a large gabbro plug within the amphitheater of Mount Taylor in age (3.26 to 2.68 Ma), mineralogy (plagioclase-clinopyroxene-olivine) and fine- to medium-grained texture (average grain size 0.55 to 1.25 mm). Major-element geochemistry indicates the shallow gabbros are similar to trachybasalt lavas erupted in and around Mount Taylor from 3.2 to 1.7 Ma. In contrast, shallow olivine gabbros do not chemically resemble medium- to coarse-grained gabbroic xenoliths (mostly orthopyroxene-bearing norite) found in some trachybasalt lavas around Mount Taylor. Co-magmatic trachybasalt and shallow gabbro bodies occur in other volcanic terrains (e.g., Stromboli, Italy). Coarser grained gabbroic xenoliths co-existing with trachybasalt lavas are noritic and are believed to have a mantle or deep crustal source (e.g., Colton crater, AZ and Mauna Kea, HI). Three small areas around Mount Taylor have unusual upheaved structure that we postulate may be caused by intrusion of shallow small volume gabbro bodies: San Fidel Dome, Devil Canyon Dome and American Canyon uplift. A low amplitude ( $\pm 20$  gamma) positive aeromagnetic anomaly above the Devil Canyon dome supports the interpretation that it is underlain by a magnetite-bearing mafic intrusion at depth.

## INTRODUCTION

Mount Taylor is an extinct composite stratovolcano that was active from about 3.3 to 2.5 Ma, located roughly 20 km NE of Grants (Fig. 1; Perry et al., 1990; Goff et al., 2010b). Mount Taylor is located near the SE margin of the Colorado Plateau and 60 km west of the north-trending Rio Grande rift. It is one of many Miocene to Quaternary volcanic complexes that comprises the northeast-trending Jemez volcanic lineament (Aldrich and Laughlin, 1984). The volcano (summit elevation 3445 m or 11,300 ft.) is composed primarily of alkali rhyolite to trachyandesite lava flows and subordinate tuffs surrounded by several mesas capped by alkali basalt, trachybasalt (hawaiiite) and

minor basanite ranging in age from 3.7 to 1.25 Ma (Fig. 2). The geochemistry and age of Mount Taylor and Grants Ridge volcanic products have been investigated in numerous reports (Baker and Ridley, 1970; Lipman and Moench, 1972; Crumpler, 1982; Perry et al., 1990; Shackley, 1998; Goff et al., 2010b). Wilson (1989) noted that Mount Taylor represents a prime example of an intraplate alkalic stratovolcano. Alternatively, western North America has been described as a broad extensional plate-boundary zone. Within this plate boundary zone, the Colorado Plateau may be viewed as a rafting microplate, with the Mount Taylor stratovolcano located on its weakly extended margin.

Hunt (1938) produced the first geologic map of the region and pointed out the spatial association between the Mount Taylor

stratovolcano and surrounding mafic lavas and cinder cones. Sears et al. (1941) described transgressive-regressive depositional relations in Upper Cretaceous sedimentary rocks beneath Mount Taylor. Geologic mapping of 1:24,000 quadrangles began in the 1960s, mainly supporting the regional uranium boom (e.g., Moench, 1963; Moench and Schlee, 1967; Lipman et al., 1979). Crumpler (1980a, 1980b) mapped a portion of Mesa Chivato several kilometers north of Mount Taylor and analyzed many of the lavas, cones and domes on the mesa. Crumpler (1982, Fig. 4) also published a geologic sketch map of the summit of Mount Taylor. Perry et al. (1990) published a more detailed geologic map of the summit and southwest flank of the

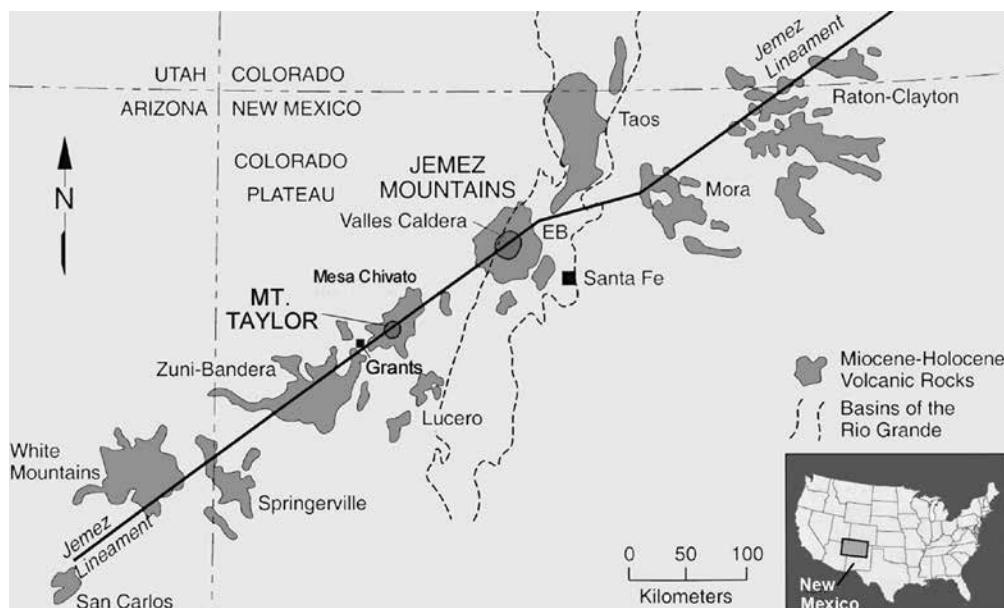


FIGURE 1. Map showing location of Mount Taylor with respect to other volcanic features of the Jemez Lineament and to basins of the Rio Grande rift (EB = Espanola Basin).

volcanic complex. Recent 1:24,000 scale geologic mapping (Goff et al., 2008, 2010a and in progress; McCraw et al., 2009; Osburn et al., 2009; Skotnicki et al., 2012) subdivides most of the volcanic units and forms a basis for revived volcanic and geochronologic studies of the Mount Taylor region (Goff et al., 2010b). The object of this paper is to describe the geology and geochemistry of recently recognized shallow, fine- to medium-grained gabbro intrusions, compare them to other alkali basalt-gabbro associations elsewhere in the world, and speculate on their geologic significance in creating small structural uplifts in the Mount Taylor volcano area.

## GEOLOGY AND PETROGRAPHY OF GABBROS

As of this date gabbroic rocks in the Mount Taylor area are found as fine-to medium-grained, eroded plugs (volcanic necks?), as lenticular sill-like bodies, as  $\leq 0.5$  m long blocks in a single scoria cone, and as medium- to coarse-grained xenoliths in basaltic lavas and associated tephra (Fig. 2 and Table 1). All gabbroic rocks described in this paper are phaneritic and holocrystalline (AGI, 2005). Our textural criteria are: fine-grained ( $< 1$ mm), medium-grained (1- 5 mm), and coarse-grained (5-30 mm).

### Plug Southeast of Horace Mesa

A 300 m diameter plug of fine-grained gabbro intrudes Cretaceous rocks on the SE margin of Horace Mesa (site 1, Fig. 2; Goff et al., 2008). The crest of plug is distinguished on the topographic map by an elevation of 7815 feet, and informally referred to as "Peak 7815." Inspection of the gabbro shows it is equigranular containing plagioclase, oxidized olivine, augite and opaque oxides. A  $\leq 3$  m wide dike of trachybasalt extends several hundred meters north from the plug. Although basaltic lava flows and eroded scoria cones occur on Horace Mesa adjacent to the plug, the petrography of the gabbro (fine-grained, holocrystalline) is different from these units (aphanitic, olivine porphyritic) (Goff et al., 2008).

### Bombs in Eroded Scoria Cone South of Mount Taylor

An eroded scoria cone of porphyritic pyroxene-bearing trachybasalt located 10 km SSW of Mount Taylor (site 2, Fig. 2) contains abundant blocks of medium-grained gabbro up to 0.5 m long (Goff et al., 2008). Some blocks and smaller fragments are completely encased by vesicular trachybasalt while others are not. The gabbro displays slightly porphyritic, equigranular texture and consists of plagioclase, oxidized olivine, augite, and opaque oxides. Trachybasalt lava originating from the cone reveals different petrography containing conspicuous megacrysts of black augite and phenocrysts of olivine and plagioclase in a black glassy groundmass. Plagioclase from a large gabbro fragment is moderately well dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  at  $3.10 \pm 0.24$  Ma whereas the host trachybasalt is more precisely dated at  $2.78 \pm 0.03$  Ma. Thus, field observations and age data suggest that the trachybasalt magma disrupted a pre-existing gabbro intrusion

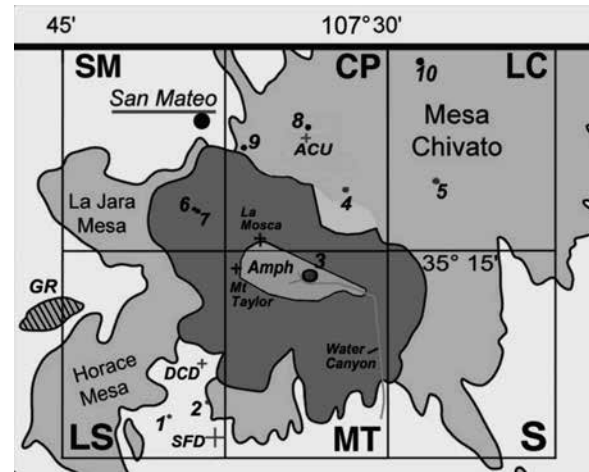


FIGURE 2. Map showing general distribution of volcanic rocks, major physiographic features, geologic quadrangles, sample locations (from Table 1) and suspected shallow gabbro bodies in the Mount Taylor volcano area: Light gray = mostly mafic volcanic rocks, dark gray = mostly trachyandesite to trachydacite volcanic rocks, GR (gray with diagonal) = rhyolitic rocks of Grants Ridge, Amph = volcanic and intrusive rocks in the Mount Taylor amphitheater, white = mostly Mesozoic sedimentary rocks. Quadrangles: CP = Cerro Pelon, LC = Laguna Cañoneros, LS = Lobo Springs, MT = Mount Taylor, S = Seboyeta, SM = San Mateo. Other features: ACU = American Canyon uplift, DCD = Devil Canyon Dome, SFD = San Fidel Dome.

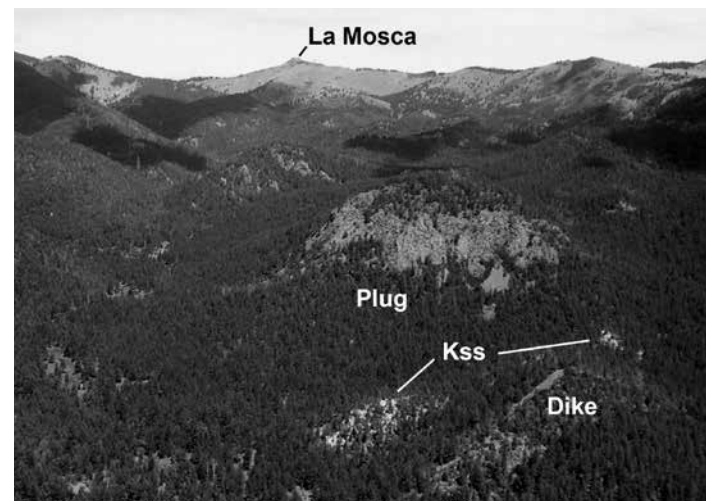


FIGURE 3. Photo looking WNW of gabbro plug in the Mount Taylor amphitheater; Kss = deformed Cretaceous sandstone beds dipping to east, Dike = trachydacite dike dated at 2.64 Ma.

at depth and the gabbro fragments were not heated for a long enough time to noticeably reset their radiometric age.

### Gabbro Plug in Mount Taylor Amphitheater

A 0.5 km diameter, circular body of fine-grained gabbro (0.65 mm plagioclase) intrudes, from oldest to youngest, basanite, altered rhyolite, trachybasalt and volcanoclastic sediments to the

TABLE 1. Locations (UTM NAD 27), Ar/Ar ages and petrography (vol-%) of gabbro and selected gabbroic xenoliths in the Mount Taylor region, New Mexico.

Sample	07SK-LS5	F07-74	F08-43	F09-25	F12-32	F94-MT4B	F07-70G	F08-90	F10-06	F12-24	F12-24
Location	SE Horace Mesa	South Mt. Taylor	Amphitheater	NE Mt Taylor	SW Mesa Chivato	West Flank	West Flank	N Mt Taylor	NW Flank	Mesa Chivato	Mesa Chivato
Site, Fig. 2	1	2	3	4	5	6	7	8	9	10	10
Type	Gabbro plug	Gabbro block	Gabbro plug	Gabbro ledge	Gabbro plug (?)	Gabbro xeno	Gabbro xeno	Gabbro xeno	Gabbro xeno	Gabbro xeno	Gabbro xeno
Field Name	Olivine gabbro	Olivine gabbro	Olivine gabbro	Olivine gabbro	Olivine gabbro	Norite <sup>5</sup>	Norite <sup>5</sup>	Troctolite <sup>6</sup>	Pyroxenite	Norite <sup>5</sup>	Websterite <sup>7</sup>
Northing	3892841	389355	3901456	3907843	3907712	3906408	3906243	391178	3906473	3916914	3916914
Easting	256725	25889	267302	269383	276048	258149	258372	26792	263879	274892	274892
Age, Ma <sup>1</sup>	nd	3.10 ± 0.24	<3.26 Ma	2.68 ± 0.07?	nd	1.74 ± 0.03 <sup>1</sup>	1.74 ± 0.03 <sup>1</sup>	2.30 ± 0.13 <sup>1</sup>	1.79 ± 0.04 <sup>1</sup>	nd	nd
Ave grn (mm) <sup>2</sup>	0.55 x 0.1	1.25 x 0.18	0.65 x 0.1	0.9 x 0.15	1.0 x 0.13	≤10 x 2 plag	≤6.3 x 1.8 plag	1.5 x 1 plag	≤3.3 x 3 opx	≤6.3 x 5.5 plag	≤2.5 x 2 opx
Phenos (mm) <sup>3</sup>	<1 % (1.0 x 0.25)	7 % (≤7 x 2.5)	2 % (≤1.4 x 0.9)	None (ophitic)	5 % (5.5 x 2.6)	na	na	na	na	na	na
<b>Modal analyses (vol-%)</b>											
Points	500	500	500	500	500	100	100	100	100	100	100
Plagioclase	59	57	45	55	57	81	42	60	0	64	4
Clinopyroxene	12	8	22	16	14	0	2?	11	46	0	76
Orthopyroxene	0	0	0	0	0	15	50	0	38	22	10
Olivine	16	20	18	16	14	0	0	22	5	9	0
Iron ore	13	15	15	13	15	4	6	7	11	5	4
Iddingsite <sup>4</sup>	14	13	9	1	2			2		9	8

nd = not determined; na = not applicable

<sup>1</sup> Age of xenolith is age of enclosing basalt if known.

<sup>2</sup> Average grain size = average dimension of plagioclase laths unless otherwise stated; plag = plagioclase and opx = orthopyroxene.

<sup>3</sup> Phenocryst content and average or maximum size.

<sup>4</sup> Value is amount of olivine that is iddingsite.

<sup>5</sup> Norite = a gabbro in which pl/(pl+px+ol) is between 10 and 90% and opx/(opx+cpix) is greater than 95%.

<sup>6</sup> Troctolite = a gabbro that is chiefly labradorite and olivine with little or no pyroxene.

<sup>7</sup> Websterite = a pyroxenite containing mostly clinopyroxene, subordinate orthopyroxene and <5 % olivine.

west, and Cretaceous sandstone and shale to the east within the Mount Taylor amphitheater (site 3, Fig. 2; Fig. 3). Interestingly, the gabbro grades upward into basalt, and the intrusion is capped at the very top by scoriaceous basalt (Hunt, 1938). The adjacent Cretaceous rocks (interpreted to be lower Gallup Sandstone and Mancos Shale) dip steeply to the east and appear to be deformed and altered by intrusion of the gabbro. The basanite was previously dated by K-Ar at  $3.26 \pm 0.31$  Ma (Perry et al., 1990). A fresh, undeformed trachydacite dike cutting the sandstone has a  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $2.64 \pm 0.06$  Ma (Osburn et al., 2009) and apparently post-dates the gabbro. Thus, the gabbro plug was almost certainly intruded between 3.2 and 2.6 Ma. The gabbro forming most of the intrusion is equigranular, slightly porphyritic and slightly ophitic, containing plagioclase, slightly altered olivine, augite and opaque oxides. The gabbro also contains small ( $\leq 2.5$  cm diameter), sparse ultramafic to gneissic xenoliths.

### Gabbro Intrusion Northeast of Mount Taylor

A poorly exposed lens-shaped ledge of gabbro lies beneath an eroded scoria cone in a small faulted basin northeast of Mount Taylor (site 4, Fig. 2; Goff et al., 2010a). From available exposures, it is not entirely clear if the gabbro intrudes into the cone, or if it is older. The gabbro is well dated at  $2.68 \pm 0.07$  Ma and the overlying trachybasalt from the cone is dated at  $2.37 \pm 0.14$  Ma. The non-overlapping age data imply that the lava unconformably buried the gabbro, but similar chemical compositions (discussed later) suggest that the gabbro and lava may be comagmatic. The gabbro is fine-grained (0.9 mm plagioclase), equigranular and ophitic containing interlocking crystals of plagioclase, augite, relatively fresh olivine and opaque oxides (Fig. 4a). The trachybasalt has small plagioclase phenocrysts in a groundmass of felty plagioclase, augite, olivine, opaque oxides and abundant glass.

### Gabbro Intrusion in Southern Mesa Chivato

Another eroded gabbro intrusion is exposed in an unnamed ravine between a complex of scoria cones, flows and dikes in southern Mesa Chivato (site 5, Fig. 2; Goff et al., in progress). The gabbro underlies the above-mentioned units but as of yet, no units are dated. The gabbro does not appear to be petrographically related to the overlying units, although that observation

needs further scrutiny. The gabbro is medium-grained (1.0 mm plagioclase), equigranular and slightly porphyritic, and consists of plagioclase, fresh olivine, augite and opaque oxides.

The five gabbros described above all classify as olivine-augite gabbro (Table 1). Olivine is conspicuous but iddingsite alteration varies. Except for the gabbro plug in the amphitheater, four of the five contain >50 % modal plagioclase and none contain orthopyroxene. All textures are equigranular, fine- to medium-grained (Fig. 4A). Some are slightly porphyritic and one is distinctly ophitic.

### Gabbroic Xenoliths in Trachybasalt Lavas

Many of the coeval mafic lavas that surround Mount Taylor stratovolcano contain a variety of ultramafic, mafic, and metamorphic xenoliths. Some also contain large plagioclase and augite megacrysts (i.e., large crystals with rounded and reacted margins). Table 1 (sites 6-10, Fig. 2) presents data on six medium- to coarse-grained gabbro xenoliths from four of these lavas. The peridotite-bearing trachybasalt from the west flank of Mount Taylor ( $1.74 \pm 0.03$  Ma) is the subject of another paper in this volume (Goff and Goff, this volume). This lava also contains xenoliths of gabbro, metamorphosed sandstone, etc. as well as megacrysts of augite and plagioclase, clots of olivine (which appear to be disaggregated peridotite), and xenocrysts of quartz (Baldrige et al., 1996; McCraw et al., 2009; Goff et al., 2010a). Gabbro xenoliths are  $\leq 8$  cm in diameter with most  $\leq 2$  cm. They consist of coarse-grained, equigranular to slightly banded norite (Fig. 4b), some very plagioclase-rich, and contain plagioclase, hypersthene, and opaque oxides (Table 1, samples F94-MT4B and F07-70G).

Similar petrographic distinctions are displayed by gabbroic xenoliths from three other trachybasalt lavas highlighted in this paper. One of the flows is found north of Mount Taylor (site 8, Fig. 2). All xenoliths in this flow ( $2.30 \pm 0.13$  Ma) appear to be medium- to coarse-grained, equigranular gabbro but some are olivine-rich (sample F08-90). Another flow ( $1.79 \pm 0.04$  Ma) lies on the NW flank of Mount Taylor and includes a wide variety of xenoliths (site 9). The gabbro we chose for study (F10-06) is rich in apple-green chrome diopside and hypersthene, having a medium-grained, slightly banded texture. Yet another flow located in southern Mesa Chivato (site 10, F12-24, undated) also contains a wide variety of xenoliths including gabbro. Of those, some are coarse-grained hypersthene and plagioclase-rich (norite) while others are medium-grained, plagioclase-poor and extremely clinopyroxene-rich (websterite). We have not attempted to date any of the xenoliths but assume they originate from previously crystallized materials at depth.

Gabbroic xenoliths found in lavas around Mount Taylor are completely different from the gabbroic intrusive rocks previously described (Table 1). Mineral compositions vary widely but most xenoliths are predominately norite (hypersthene gabbro). Some contain considerable olivine while others contain none. Texturally, the gabbroic xenoliths are much coarser-grained (Fig. 4B) and some are weakly banded.

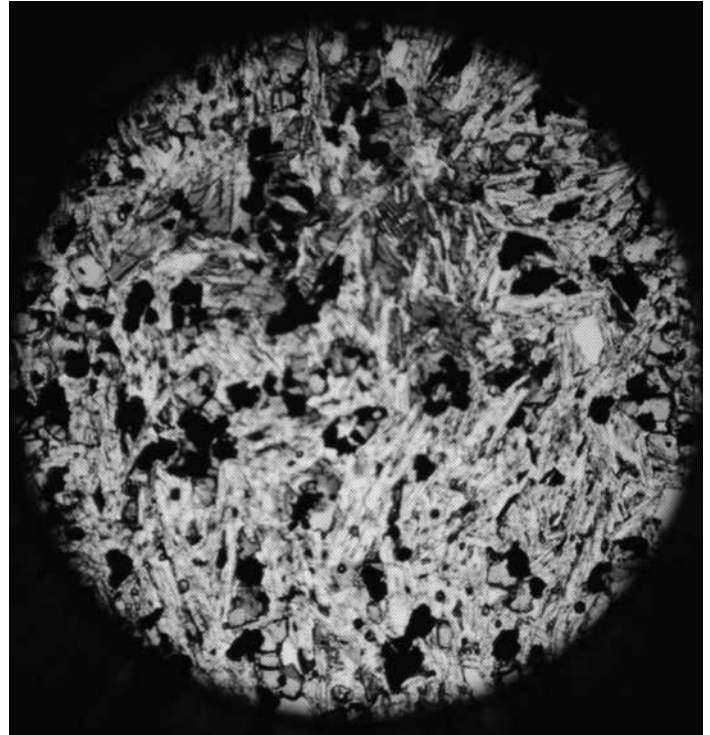


FIGURE 4A. Photomicrographs of gabbro and gabbro xenolith, field of view = 5 mm. A. Gabbro intrusive F09-25 showing equigranular, slightly ophitic texture of white plagioclase, dark gray augite, light gray olivine, and black opaque oxides.

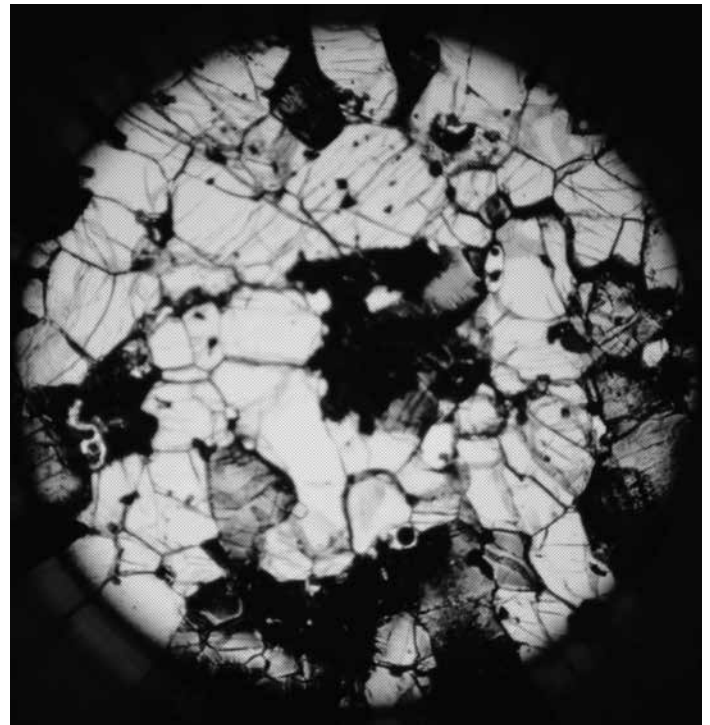


FIGURE 4B. Medium-grained pyroxenite xenolith (F10-06) of pale gray clinopyroxene (visually identified as chrome diopside), dark gray hypersthene, much of which is oxidized to black color, and tiny black granules of chrome spinel. A small amount of intergranular olivine is also present.

### Other Gabbros and Trachybasalts

For comparison, we collected a sample from a 0.5 m long block of gabbro enclosed by vesicular porphyritic lava during a recent trip to the Island of Stromboli (Italy). The sample is located on the NW side of the island on the NE edge of the Sciara del Fuoco escarpment. The gabbro is coarse-grained having interlocking crystals of pale gray plagioclase, dark green augite, olivine, biotite, opaque oxides, apatite, and possibly some tiny interstitial Kspar. The enclosing lava contains phenocrysts of plagioclase, augite, and olivine in a groundmass of small plagioclase, augite, Fe-Ti oxides and glass. These materials are from the Upper Vancori period of Stromboli development (roughly 13.8 ka; Cortés et al., 2005).

We also include, for comparison, data from two alkali-rich basaltic sites we recently visited, which are known to contain mafic and/or ultramafic xenoliths: Colton crater (Crater 160) from the San Francisco volcanic field in Arizona (Cummings, 1972; Van Kooten and Buseck, 1978) and Mauna Kea volcano on the Big Island, Hawaii (Wolfe et al., 1997; Fodor and Galar, 1997). Colton crater is a complex maar volcano with a broad, open crater exposing interesting stratigraphy in the crater wall and a small cinder cone preserved on the crater floor. The volcanic rocks associated with the xenoliths (cinder beds, flows, palagonite tuffs and dikes) are alkali basalt bordering on trachybasalt (Van Kooten and Buseck, 1978). The mafic xenoliths consist of dunite, websterite, gabbro and norite (Cummings, 1972).

The summit of Mauna Kea, Hawaii is covered with several large scoria cones and flows of trachybasalt (hawaiite) composition (Wolfe et al., 1997). Many of these rocks contain

relatively coarse-grained mafic and ultramafic xenoliths of peridotite, dunite, norite and gabbro (Fodor and Galar, 1997). The trachybasalts are primarily part of the Laupahoehoe volcanics, the culminating sequence of post-shield volcanism at Mauna Kea (Wolfe et al., 1997). Most of these trachybasalts are very fine-grained and dense but in appropriate light, they display a felty sheen of tiny aligned plagioclase crystals.

### CHEMISTRY OF GABBROS

Chemical analyses, total alkali contents and Mg numbers of gabbros, gabbro xenoliths, and associated lavas from Mount Taylor, Stromboli, Colton crater and Mauna Kea are listed in Table 2. Because of their high total alkali contents relative to silica, the four Mount Taylor shallow gabbro intrusives and gabbro block from the scoria cone range from gabbro through monzogabbro to monzodiorite/monzonite using the classification scheme of Cox et al. (1979; Fig. 5). Stromboli biotite-olivine-augite gabbro plots on the same trend, although it has higher  $K_2O$ , and is classified as monzogabbro. In contrast, all gabbro xenoliths found in basaltic lavas including those from Mount Taylor are chemically different and are classified as gabbro to gabbrodiorite. Except for a sample of norite from Colton crater, gabbroic xenoliths have exceptionally low total alkali contents.

Several mafic lavas from Mount Taylor chemically resemble the compositions of Mount Taylor shallow gabbros (Table 2). The former classify as alkali-rich basalt through trachybasalt (hawaiite) to basaltic trachyandesite on a plot showing total alkalis versus silica in volcanic rocks (Le Bas et al., 1986). Most Mount Taylor mafic rocks are trachybasalt; few are basaltic trachyandesite (Goff et al., 2008). The small, fine-grained gabbroic plug SE of Horace Mesa ("Peak 7815," sample 07SK-LS5) is classified as a monzodiorite, but otherwise it is chemically very similar to a basaltic trachyandesite lava (sample F07-17) located several kilometers north on Horace Mesa. Another chemically similar pair of rocks comprises the gabbro intrusive (F09-25) and the overlying scoria cone lava (F09-23) north of Mount Taylor. This chemical similarity suggests that the gabbro and overlying lava may be comagmatic or cogenetic, but relatively precise age determinations more rigorously (?) support the interpretation that the gabbro and lava represent different pulses of basaltic magma with different crystallization histories. In contrast, the monzogabbro bomb (F07-74) found in the scoria cone south of Mount Taylor is quite distinct chemically from the porphyritic trachybasalt (F07-61) vented from the cone. The difference in chemistry provides further evidence that the younger trachybasalt erupted through a shallow pre-existing

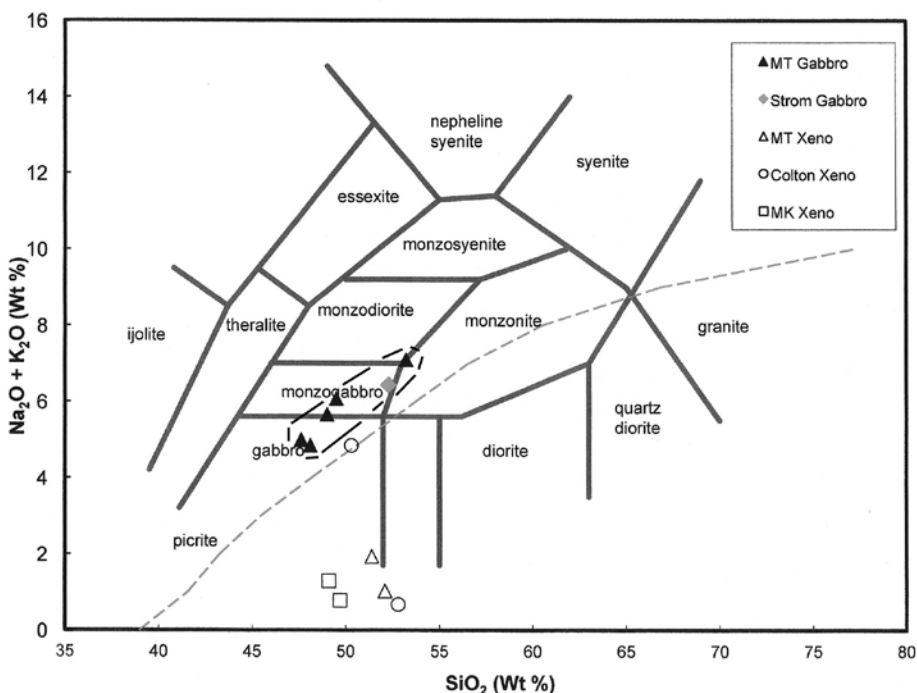


FIGURE 5. Plot of total alkalis vs. silica for gabbroic rocks in Table 2 (after Cox et al., 1979). Upper dashed line encloses range of compositions for various mafic lavas in Table 2. Lower dashed line separates calk-alkalic (lower) from alkalic compositions.

TABLE 2. Major element analyses of gabbros, gabbroic xenoliths and associated mafic rocks from Mount Taylor area, NM, Colton Crater, AZ, Mauna Kea, HI and Stromboli, Italy. Locations are in UTM coordinates, NAD 27 where known.

Sample	07SK-L55	F07-17	F07-74	F07-61	F08-43	F08-90	F09-25	F09-23	F12-32	F12-24	F12-55 <sup>4</sup>	F12-56 <sup>4</sup>	F07-70	F07-70G	F10-06W	SF-5	9	27	HR-67	A3-1	A12	
Location	SE Horace Mesa	N Horace Mesa	S Mt Taylor	S Mt Taylor	Amphitheater	N Mt Taylor	NE Mt Taylor	NE Mt Taylor	Mesa Chivato	Mesa Chivato	Stromboli	Stromboli	West Flank	West Flank	NW Flank	Colton	Colton	Colton	Mauna Kea	Mauna Kea	Mauna Kea	
Northing	3892841	3901870	389355	3892388	3901456	391178	3907843	3907280	3907712	3916914	na	na	3906243	3906243	3906473	na	na	na	na	na	na	na
Easting	256725	257931	25889	260623	267302	26792	269383	268705	276048	274892	na	na	258372	258372	263879	na	na	na	na	na	na	na
Type	Gabbro plug	Trachy-basalt	Gabbro block	Trachy-basalt	Gabbro plug	Trachy-basalt	Gabbro ledge	Trachy-basalt	Gabbro plug (?)	Trachy-basalt	Gabbro block	Mafic lava	Trachy-basalt	Gabbro xeno	Gabbro xeno	Trachy-basalt	Websterite xeno	Norrite xeno	Trachy-basalt	Gabbro xeno	Gabbro xeno	
Geochem Name	Monzodiorite	BTrachy-andesite	Monzobasalt	Basalt gabbro	Gabbro	Trachy-basalt	Gabbro	Trachy-basalt	Monzobasalt	Trachy-basalt	Monzobasalt	BTrachy-andesite	Trachy-basalt	Gabbro	Gabbro	Basalt	Gabbro	Gabbro-diorite	Trachy-basalt	Gabbro	Gabbro	
Major elements (wt-%)																						
SiO <sub>2</sub>	53.2	54.1	49.0	48.1	48.1	49.1	47.6	47.6	49.5	49.3	52.3	53.2	48.0	51.4	52.1	48.8	50.3	52.8	48.75	49.1	49.69	
TiO <sub>2</sub>	2.39	2.07	2.86	2.86	2.44	3.24	3.34	3.30	3.15	2.47	0.92	0.93	2.23	0.59	0.19	2.43	0.91	0.81	3.23	0.97	0.62	
Al <sub>2</sub> O <sub>3</sub>	16.7	16.5	17.5	15.8	15.1	17.1	16.5	16.8	17.3	15.6	16.0	17.20	15.6	9.50	6.14	14.4	5.88	14.8	16.99	9.97	7.8	
FeO <sup>#1</sup>	10.4	10.0	10.6	11.8	11.1	12.5	12.9	12.9	11.8	11.1	7.73	7.52	11.1	10.6	5.82	10.10	4.57	7.26	10.00	10.7	8.33	
MnO	0.20	0.188	0.163	0.177	0.170	0.185	0.180	0.177	0.18	0.18	0.15	0.15	0.164	0.18	0.15	0.16	0.14	0.19	0.20	0.19	0.17	
MgO	3.18	3.07	4.64	6.95	8.53	4.47	5.65	5.39	4.37	7.01	5.76	4.63	8.26	18.3	21.3	7.69	16.20	6.77	5.01	16.7	18.24	
CaO	5.79	6.09	8.76	8.73	9.15	7.03	8.24	8.12	6.83	8.41	10.1	9.12	8.52	7.40	13.2	10.7	18.77	9.47	7.65	11.0	14.39	
Na <sub>2</sub> O	4.99	4.51	4.08	3.64	3.45	4.01	3.67	3.77	4.36	3.78	2.32	2.80	3.90	1.61	0.91	3.55	0.67	3.73	4.20	1.25	0.76	
K <sub>2</sub> O	2.10	2.31	1.58	1.34	1.39	1.66	1.32	1.30	1.71	1.44	4.11	3.88	1.62	0.32	0.11	1.29	nd	0.72	1.65	0.04	0.02	
P <sub>2</sub> O <sub>5</sub>	0.99	1.20	0.778	0.663	0.596	0.645	0.629	0.600	0.77	0.70	0.67	0.63	0.683	0.08	0.03	0.80	0.14	0.68	0.81	0.03	0.03	
Normal-ized total	99.94	100.04	99.96	100.06	100.03	99.94	100.03	99.96	99.97	99.99	100.06	100.06	100.08	99.98	99.95	99.92	99.94	100.04	100.00	99.95	100.05	
Total alkalis	7.09	6.82	5.66	4.98	4.84	5.67	4.99	5.07	6.07	5.22	6.43	6.68	5.52	1.93	1.02	4.84	0.67	4.45	5.85	1.29	0.78	
Mg <sup>#</sup> , % <sup>2</sup>	35.3	35.4	43.8	50.9	57.8	38.9	43.8	42.7	39.8	52.9	57.0	52.3	57.0	75.5	91.5	57.6	81.2	55.2	44.0	73.6	79.6	
Data Source <sup>3</sup>	ALS	F11	F11	F11	F11	F11	F11	F11	ALS	ALS	ALS	ALS	F11	ALS	ALS	VB78	C72	C72	W97	FG97	FG97	

1 FeO\* = all Fe recalculated as FeO.

2 Mg<sup>#</sup> = 100 {Mg/(Mg + Fe<sub>2</sub>)} on molar basis.

3 ALS = ALS Group, Reno, NV; F11 = Fellah (2011), VB78 = Van Kooten and Buseck, 1978; C72 = Cummings, 1972; W97 = Wolfe et al., 1997; FG97 = Fodor and Galar, 1997.

4 Collected by F. Goff and C.J. Goff in October 2012 from NW side of island; approximate age is 13.8 ka (Cortés et al., 2005).



gabbro intrusive, as described above. Monzogabbro blocks and enclosing vesicular lava from the lower NW flank of Stromboli are very similar chemically indicating that they are probably part of the same magmatic event (Cortés et al., 2005).

A plot of total alkalis versus Mg# (Fig. 6) provides another means to evaluate similarities and differences among the various gabbros, gabbro xenoliths, and lavas. Generally speaking, values of Mg# (defined as  $100 \times \{Mg/[Mg + Fe^{2+}]\}$  on a molar basis) that are  $\geq 65$  indicate primitive (or primary) magma compositions, whereas Mg# values  $\leq 60$  indicate evolution of magma from a primitive source (Wilson, 1989). The chemical data of Table 2 group into two clusters. The first cluster includes all fine- to medium-grained, olivine-augite gabbros and related lavas around Mount Taylor, the Stromboli gabbro-lava pair, Colton lava, Mauna Kea lava, and one Colton xenolith. They have high total alkalis and lower Mg# values between 58 and 35.

The second cluster includes five of six gabbro xenoliths listed in Table 2 including the two analyzed xenoliths from Mount Taylor. These xenoliths have very low total alkalis and very high Mg# values of 73 to 92. In fact, sample F10-06, the gabbro xenolith containing abundant chrome diopside, has the highest Mg# of all listed samples. These five xenoliths apparently have upper mantle or lower crustal sources (Cummings, 1972; Baldrige, 1979; Fodor and Galar, 1997; Schmidt et al., 2010; Schrader et al., 2010).

### HIDDEN SHALLOW GABBRO BODIES

We have mapped two areas of domed Cretaceous strata and one unusual volcanic uplift in the Mount Taylor area, which we believe are magma-driven and may be manifestations of shallow gabbroic intrusions. These are the San Fidel and Devil Canyon Domes south of Mount Taylor, and the American Canyon uplift north of Mount Taylor (Fig. 2).

#### San Fidel Dome

San Fidel Dome was first recognized by Hunt (1938, p. 74) and the SE edge was mapped by Lipman et al. (1979). The entire feature is elliptical, about 3 x 2 km trending northeast (Goff et al., 2008). The northern side and crest of the dome is covered by pyroxene trachybasalt (F07-61, Table 2), the same trachybasalt dated at 2.78 Ma that hosts gabbro blocks (F07-74) at its source scoria cone (described above). The southern portion of the dome is eroded down to Cretaceous Mancos Shale in the core of the structure. Well-exposed high-angle faults separate flat lying Cretaceous rocks surrounding the dome from folded and faulted rocks within it (Fig. 7). Total uplift is 370 m determined by the difference in elevation between uplifted lava at the crest of the dome and non-deformed lava beneath the scoria cone. A dike of extremely olivine-rich basalt (olivine nephelinite) trending N80E cuts flat-lying Cretaceous rocks west of the dome but terminates abruptly at the dome margin faults (Goff et al., 2008; Goff et al., this volume). Southeast of the dome, porphyritic trachydacite flows and intrusive rocks are exposed (Lipman et al., 1979), which are dated at  $2.63 \pm 0.10$  Ma (Osburn et al., 2009).

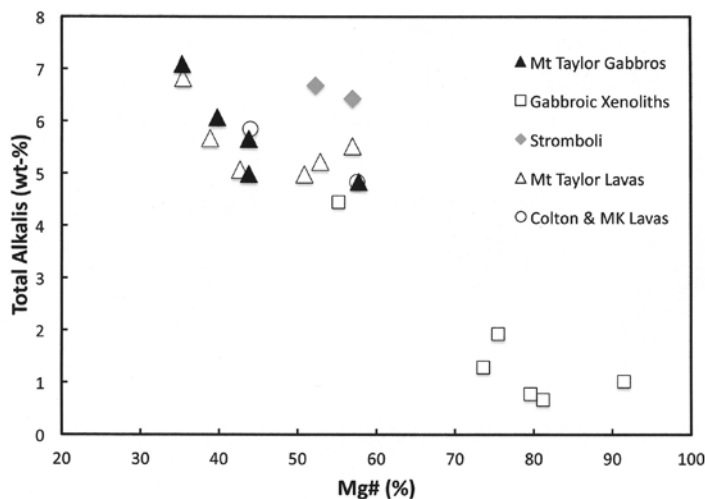


FIGURE 6. Plot of total alkalis vs. Mg# for all rocks in Table 2.

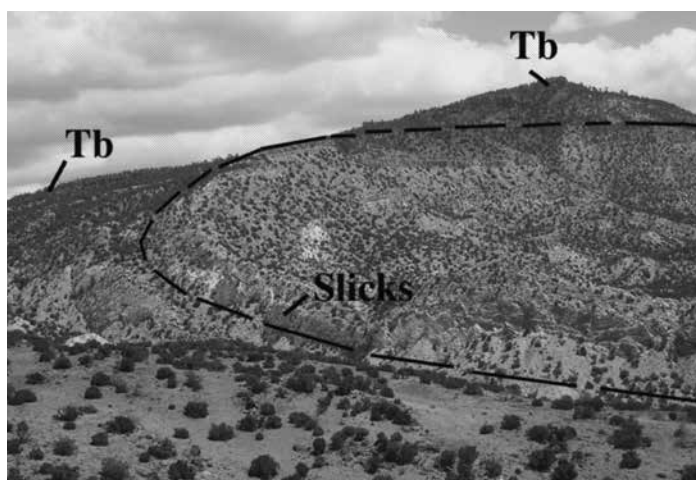


FIGURE 7. Photo looking NNE across the eroded southern core of San Fidel Dome composed of uplifted and deformed Cretaceous rocks. Black dashed line accentuates domal uplift. Slicks = slickensides on steeply west-dipping Mancos shale beds; Tb = uplifted pyroxene-porphyrific trachybasalt lava dated at 2.78 Ma at crest and west flank of dome.

No intrusive rocks or dikes are found in the eroded southern core of the dome, but the folded and uplifted Cretaceous rocks contain localized hydrothermal alteration of opal/chalcedony, calcite, clays, and Fe-Mn oxides (Goff et al., 2008, Fig. 9). The State 36-1 oil test well that was drilled in the eroded southern core of the dome to 900 m (2953 ft), did not intersect any igneous rocks but did encounter a repeated section of Cretaceous rocks that we interpret as thrust faulting caused by magma intrusion (Fig. 8).

Presumably, the dome and associated alteration are caused by emplacement of an underlying shallow intrusive body (Hunt, 1938; Lipman et al., 1979) younger than 2.78 Ma (Goff et al., 2008). Lipman et al. (1979) interpret the intrusive body as trachydacite (their "porphyry of San Jose Canyon"), but our interpretation due to the presence of the marginal nephelinite dike, gabbro blocks in the scoria cone, and other shallow gabbros in the area, is that the intrusive body is possibly gabbro (Fig. 8). Alternatively the underlying intrusion could be a composite body of gabbro and

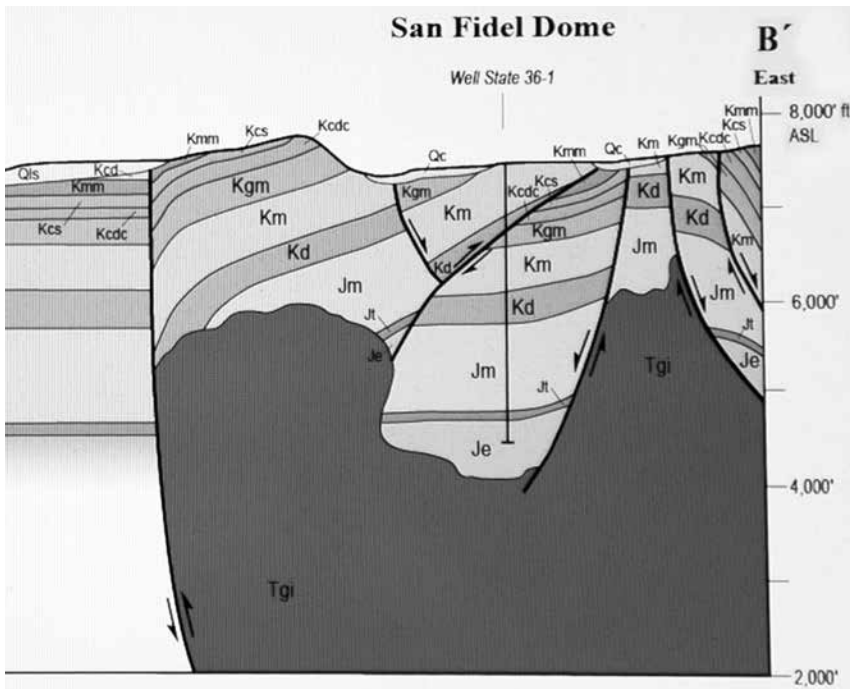


FIGURE 8. Blow-up of east end of cross section B-B', Lobo Springs quadrangle (Goff et al., 2008) showing subsurface interpretation of structure beneath southern part of San Fidel Dome; Tgi = possible gabbroic intrusion that we believe is the cause of the uplift (but see Lipman et al., 1979). Western boundary fault has displayed alternating normal to reverse faulting through time. K = Cretaceous and J = Jurassic rocks (see Goff et al., 2008 for complete descriptions).

a 2.63 Ma monzonite magmatically equivalent to the “porphyry of San Jose Canyon.”

### Devil Canyon Dome

Devil Canyon Dome was also first recognized by Hunt (1938). It is located about 5 km north of San Fidel Dome (Fig. 2) in upper Rinconada Canyon. The dome is about 1.5 km in diameter and is recognized by an arcuate upwarp of locally faulted Cretaceous strata (Goff et al., 2008). Several mafic dikes with different strike directions cut across the NE crest of the dome and some of the Cretaceous rocks display weak, low-grade hydrothermal alteration. We suspect that possible emplacement of shallow gabbro related to Mount Taylor volcanism has formed the dome, dikes and alteration. A relatively low amplitude ( $\pm 20$  gamma), 400 m-wide positive aeromagnetic anomaly, coincident with the Devil Canyon dome (GeoMetrics, 1979; line 242, p. AL53) supports the interpretation of a magnetite-bearing mafic intrusion at depth under the dome (R.M. Chamberlin, written commun, 2013).

### American Canyon Uplift

American Canyon uplift is located about 7 km north of the amphitheater of Mount Taylor at a sharp west bend of the namesake canyon (Goff et al., 2010a). The uplift is defined by two, north-trending, down-to-the-west faults that expose over 75 m of volcanoclastic sediments along the south wall of the

canyon. Two scoria cones and associated flows cover the north wall. The eastern cone erupted flows containing gabbroic xenoliths (site 8, Fig. 2; F09-90, Table 1), which are dated at  $2.30 \pm 0.13$  Ma. The sediments south of the canyon are ultimately capped by an aphyric lava flow dated at  $1.76 \pm 0.05$  Ma. Both of the dated flows are offset by the easternmost fault mentioned above. This area is unusual because no other place north of Mount Taylor displays such a thick section of sediments surrounded and capped by relatively young flows. We suspect that emplacement of a small gabbroic intrusion  $<1.76$  Ma has caused uplift of the sediments and flows in this area.

### CONCLUSION

In addition to a 0.5 km diameter gabbro plug previously identified in the amphitheater of Mount Taylor (Hunt, 1938), smaller, shallow gabbro intrusions have now been found both SW and NE of the volcano. Shallow gabbros and the gabbro blocks found in a young scoria cone are similar in texture and mineralogy to each other and they are similar in chemistry to co-magmatic trachybasalt lava flows erupted around the volcano. In this respect, shallow Mount Taylor gabbros resemble the gabbro-lava pair from Stromboli, Italy. Because shallow fine-to medium grained gabbro intrusions are relatively common in and around Mount Taylor, we infer that similar hypabyssal gabbro intrusions have caused structural upheaval beneath the San Fidel and Devil Canyon domes, and perhaps the American Canyon uplift.

In contrast, shallow Mount Taylor gabbro intrusions are different in texture, mineralogy, and chemistry to coarser grained gabbro xenoliths that occur in the trachybasalt lavas around Mount Taylor. Most of the gabbro xenoliths contain hypersthene and are norite or related cumulate rocks. They resemble gabbro xenoliths found in alkalic basalt lavas from Colton crater, Arizona and Mauna Kea volcano, Hawaii, which have a mantle-crustal origin (Cummings, 1972; Fodor and Galar, 1997). The coarser grained Mount Taylor xenoliths probably originate at depths of 35 to 50 km from near the crust-mantle interface or from crystallized magma reservoirs deep beneath the volcano (Schrader et al., 2010; Schmidt et al., 2010), a postulated depth of origin similar to gabbroic xenoliths throughout the Rio Grande rift region (Laughlin et al., 1971; Baldrige, 1979).

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