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Geometry of the Trachyte Mesa intrusion, Henry Mountains, Utah: Implications for the emplacement of small melt volumes into the upper crust

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[1] The Trachyte Mesa intrusion is one of several small satellite bodies to the larger intrusions of the Henry Mountains, Utah. Most previous studies have worked under the assumptions that Trachyte Mesa is blister shaped and intruded into flat and gently NW dipping strata. In this study we combine structural and geophysical data sets to constrain the structural geology of the host lithologies and the unmodified geometry of the intrusion. Trachyte Mesa intrudes a series of northeast trending upright and open folds formed within the Jurassic Entrada Formation. Truncation of these folds at the contact with the overlying Curtis/Summerville formations indicates the folds are Middle Jurassic. Magnetic and 2-D resistivity surveys focused on the southwestern portion of the intrusion where it is concealed by overlying strata. These data clearly delineate the outline of the buried intrusion. The intrusion is 2.2 km long and 0.7 km wide with an average thickness of ~15 m (maximum ~40 m). The majority of the intrusion (both exposed and buried portions) is confined within the axis of a syncline bound to the NW and SE by anticlines. The intrusion does, however, overtop the hinge of the bounding anticline to the northwest in a few places along its length. In cross section the intrusion is characterized by concave-up top and bottom surfaces, except along portions where it overtops the bounding anticline. The geometry and structural position of the Trachyte Mesa intrusion suggest that preexisting structure and the density of the magma relative to that of host rocks fundamentally controlled the emplacement of this intrusion.

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1. Introduction

[2] The ascent and emplacement of melt through and into the crust requires that either discrete space be made or that crustal material be displaced/transferred through and/or around the ascending body through any number of material transfer processes [*Paterson and Fowler*, 1993]. Space making processes, which necessarily result in an increase in crustal volume, are limited to lowering the Moho or uplifting the Earth's surface. Roof or Earth's surface uplift is a common method of space creation for upper crustal intrusions. Sills and laccoliths (and all variations on this general theme) represent the purest examples of intrusions emplaced into the crust by roof/Earth surface uplift [e.g., *Gilbert*, 1877]. These intrusions typically exploit a bedding contact or other nearly planar structure (e.g., fault) to intrude along, raising the overlying column of rock as melt is progressively emplaced [*Corry*, 1988].

[3] Closely allied with sills and laccoliths are phacoliths, or saddle reef intrusions [*Buddington*, 1929], emplaced concordantly into the hinge zones of folds. Most studies of phacoliths or plutons emplaced into the hinge zones of folds conclude that the emplacement was synchronous with folding, such that the space created was filled with a corresponding volume of melt [e.g., *Vines and Law*, 2000] and/or the intrusion was folded during or following emplacement [*Buddington*, 1929]. Most studies of intrusions associated with folds also report that the intrusions are emplaced into the hinge zones of antiforms, similar to most saddle reef occurrences of ore deposits [e.g., *Windh*, 1995]. The Santa Rita Flat pluton may represent an example of an intrusion forming a saddle reef within a synform [*Vines and Law*, 2000]. *Paterson and Miller* [1998] report deeper midcrustal sheet-like intrusions from the Cascades that intruded parallel to the axial surfaces of synemplacement folds.

[4] Trachyte Mesa, Black Mesa and the Maiden Creek sill are a series of spatially associated small (<1 km^3) intrusions located to the northeast of Mount Hillers of the Henry Mountains of south central Utah (Figure 1b). They are commonly referred to as satellite intrusions to the much larger bodies holding up the peaks of the Henry Mountains. Since its original description by *Gilbert* [1877], Trachyte Mesa has been a fundamentally important intrusive body for the understanding of the mechanical and kinematic development of laccoliths. David Pollard and coworkers have revisited the Henry Mountains, and Trachyte Mesa in particular, several times in the past 35 years to help define the mechanics of sill and laccolith emplacement [e.g., *Johnson and Pollard*, 1973; *Pollard and Johnson*, 1973; *Koch et al.*, 1981; *Jackson and Pollard*, 1988, 1990]. More recently Sven Morgan and coworkers have focused on the contact and internal structures of the satellite intrusions northeast of Mount Hillers with the goal of understanding emplacement related processes as they apply to the assembly of larger intrusive bodies (e.g., plutons and batholiths [*Horsman et al.*, 2005; *Morgan et al.*, 2005, 2008; *de Saint Blanquat et al.*, 2006]).

[5] The Pollard and Morgan studies of the Trachyte Mesa intrusion add significantly to our understanding of the formation of laccoliths and the assembly of larger intrusions. However, in both sets of studies, the entraining Entrada Sandstone is typically described as being subhorizontal and flat [e.g., *Horsman et al.*, 2005]. Herein, we have completed a detailed study of structures characterizing the host Entrada Sandstone and the geophysically constrained geometry of the intrusion in concealed and unmodified portions which should fundamentally improve the understanding of the emplacement of such concordant intrusions into the upper crust. In both sets of studies by the Pollard and Morgan groups, the geometry of the Trachyte Mesa intrusion is assumed to be blister shaped, similar to that defined by *Gilbert* [1877], with a flat, northwest dipping (~9°) floor. *Morgan et al.* [2008] further describe the intrusion as having a flat top in central portions flanked by margins that dip away from Trachyte Mesa as monoclines. Herein, however, we characterize the structural geology of the host sandstone, documenting the existence of Jurassic folds, and constraining the geometry of the intrusion beyond the southwesternmost exposures where its unmodified cross-sectional shape closely parallels that of the folded host rock minus the uplifted roof over the axis of a syncline.

[6] The results of this study indicate that the geometry of the final Trachyte Mesa intrusion was primarily dictated by the geometry of preexisting structures, namely folds, within the Jurassic Entrada Sandstone. In sections 2–4 we will introduce the geology of the Henry Mountains before describing the methods employed and presenting the results of a combined structural and geophysical investigation of the Trachyte Mesa intrusion

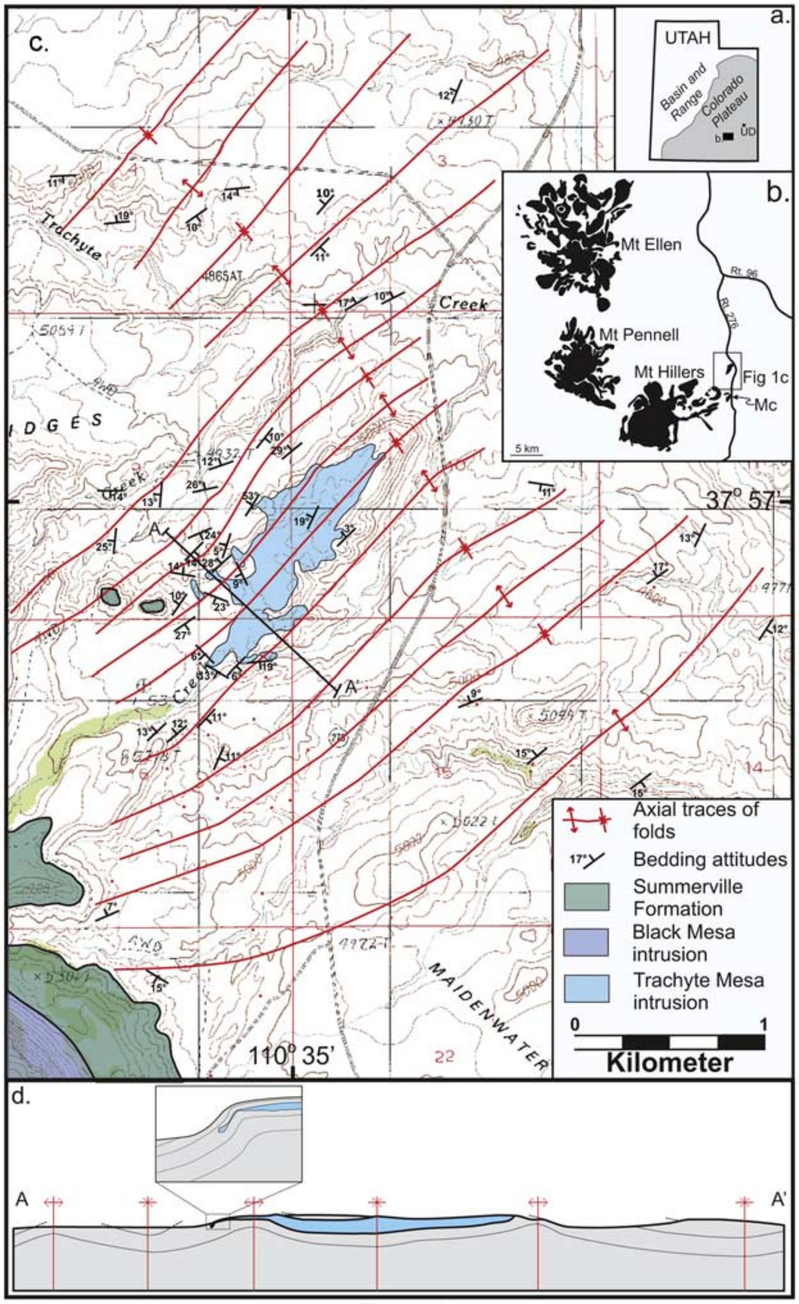

Figure 1. (a) Map of Utah with location of the northern Henry Mountains (Figure 1b) showing position relative to the Colorado Plateau, Basin and Range Province, and Upheaval Dome (UD). (b) Map showing the distribution of intrusive bodies of the northern Henry Mountains including the Maiden Creek Sill (Mc) and the location of the study area (Figure 1c). Modified from *Morgan et al.* [2008], copyright 2008, with permission from Elsevier. (c) Geologic map of Trachyte Mesa and surrounding area including folds within the Entrada Sandstone, the contacts with the overlying Summerville Formation, and a portion of Black Mesa. The white portion of the map is underlain by the Entrada Sandstone. Background map is the Black Table U.S.G.S. 7 1/2 min Quadrangle with a contour interval of 40 feet (~12 m). Position of the trace of the syncline drawn through the intrusion is estimated on the basis of the average wavelength of the adjacent folds. (d) Schematic cross section of the Trachyte Mesa intrusion including an expanded view of the WNW exposure.

and the surrounding Jurassic stratigraphy. We conclude with a discussion of implications of the newly defined geometry of the Trachyte Mesa intrusion for existing models and the ultimate processes responsible for the emplacement and final geometry of the intrusion.

2. Background Geology

[7] The Henry Mountains of south central Utah comprise a series of intermediate to felsic intrusions emplaced into the generally flat lying stratigraphy of the Colorado Plateau. The Henry Mountains are the largest of seven such intrusive mountain ranges on the Plateau and adjacent Basin and Range Province in southern Utah. *Gilbert* [1877] was the first to describe the igneous rocks in the Henry Mountains following two trips to the range 5 years earlier. Gilbert carefully detailed the structural uplift of the Mesozoic host rocks surrounding the igneous intrusions. He concluded that the intrusions had been emplaced onto a flat floor with the space for the intrusions being created by the domal uplift of the overlying column of rocks. He created the term "laccolite" to describe these blister-shaped intrusions. Gilbert's interpretation that the large intrusions (laccoliths) formed by the uplift and rotation of the overburden derives from observations of the smaller, satellite intrusions that flank the larger bodies. In these smaller bodies Gilbert inferred the sequential development of the larger intrusions from flat tabular sills through inflation and concordant uplift of the overlying strata.

[8] In recent years Sven Morgan, Michel de Saint Blanquat, and coworkers have conducted detailed structural studies of some of the satellite intrusions along the eastern flank of Mount Hillers [e.g., *Habert and de Saint Blanquat*, 2004; *Horsman et al.*, 2005; *de Saint Blanquat et al.*, 2006; *Morgan et al.*, 2005, 2008]. Their research into these intrusions has primarily focused on the contact structures, and magmatic and subsolidus fabrics within the Trachyte Mesa, Maiden Creek, and Black Mesa intrusions. They argue that the intrusions represent a continuum of laccolith growth from sills to laccoliths to bysmaliths (i.e., punched laccoliths or laccoliths that have uplifted roof strata along subvertical faults). They further argue that these intrusions are constructed through the emplacement of multiple sheets.

[9] The Trachyte Mesa intrusion is one of the most commonly cited examples of a classic small-scale, tongue-shaped laccolith [e.g., *Hunt*, 1953; *Pollard and Johnson*, 1973; *Koch et al.*, 1981; *Corry*, 1988] with both an apparent flat floor that dips gently to the northwest and a convex up roof, flat in the middle, with overlying stratigraphy folded over at the edges [*Morgan et al.*, 2008]. *Morgan et al.* [2008] note that a primary capping (a buff-colored, coarse-grained (our description)) sandstone is observed over much of the top of the intrusion. While numerous studies of the Trachyte Mesa intrusion cite the elastic/brittle ductile properties as playing a significant role in the final shape of the intrusion [e.g., *Pollard and Johnson*, 1973; *Koch et al.*, 1981], none offer any suggestion as to why the ascent of this intrusion was arrested at the base of this sandstone unit. *Corry* [1988] argues that these intrusions are emplaced at a crustal level where the weighted mean density of the overlying column of rock equals that of the intruding magma. According to *Kavanagh et al.* [2006] and *Menand* [2008], however, these sill and laccolithic intrusions will form at the contact between two units with a positive rigidity contrast. Because the Trachyte Mesa intrusion forms the basis for several mechanical and kinematic models of laccolith formation, it is important to document the structural setting into which the intrusion was emplaced and the geometry of the intrusion in unexposed portions that have escaped erosion.

3. Structural and Geophysical Results

[10] The goal of this study is to accurately define the geometry of the Trachyte Mesa intrusion, both exposed and buried portions. The structural component to this study focuses on the geology within the Jurassic Entrada Sandstone, host unit to the Trachyte Mesa intrusion, and the northwestern and southeastern terminations of the Trachyte Mesa intrusion. A full description of the internal geology of the intrusion and upper/lower contact structures is given by *Morgan et al.* [2005, 2008]. The geophysical component of this study focuses on the buried portion to the southwest of the limit of exposure because it is believed that in this area the intrusion has not been modified by erosion, as it has in the exposed portions to the northeast, thus affording the best opportunity to constrain the geometry of the intrusion.

3.1. Structural Geology

[11] The relevant stratigraphy of the study area includes the Jurassic Entrada Sandstone, which is overlain by the Jurassic Summerville Formation.

Within the area surrounding the Trachyte Mesa intrusion mapping focused on the Entrada Sandstone. Useful exposures were limited in some parts of the field area because of small slope failures along drainages, and soil development and vegetation on the intervening mesas. Limited exposure notwithstanding, mapping of the Entrada Sandstone in the vicinity of the Trachyte Mesa intrusion reveals a series of gentle to open folds with axial traces that trend NE–SW (Figure 1). Fold limbs typically dip less than 30° except for areas immediately adjacent to the Trachyte Mesa intrusion. The folds have a crest-to-crest wavelength that ranges from ~0.3 km to ~0.8 km with the shortest wavelengths observed on the NW side of the Trachyte Mesa intrusion. The folds are noncylindrical and may exhibit some minor interference from a weakly developed set of northwest trending folds as suggested by slight deviations in the strike of bedding throughout the field area. Clear definition of a second set of folds will require additional mapping in an area with slightly better exposure than that studied herein.

[12] Northeast trending folds bound and transect the intrusion with anticlines approximately coincident with the northwestern and southeastern margin and a syncline inferred to coincide with the long axis of Trachyte Mesa. Mapping to the south of Trachyte Mesa suggests a similar structural relationship exists for the Maiden Creek Sill described by *Horsman et al.* [2005] and *Morgan et al.* [2005]. While detailed mapping of the folds identified in this study on a regional scale is virtually unknown, they can be observed in the exposures of the Entrada Sandstone on the east side of the Henry Mountains from at least as far north as Hanksville (~50 km north of Trachyte Mesa) to as far south as Lake Powell (~26 km). Additionally, the folds can be identified from satellite imagery (e.g., Google Earth) extending at least an additional 25 km south of Lake Powell.

[13] *Hunt* [1953] was the first to describe these folds in the Henry Mountains region and he points out that they are truncated at the contact with the overlying Curtis/Summerville formations (Figure 2a) indicating a Jurassic (Callovian?) age for these structures.

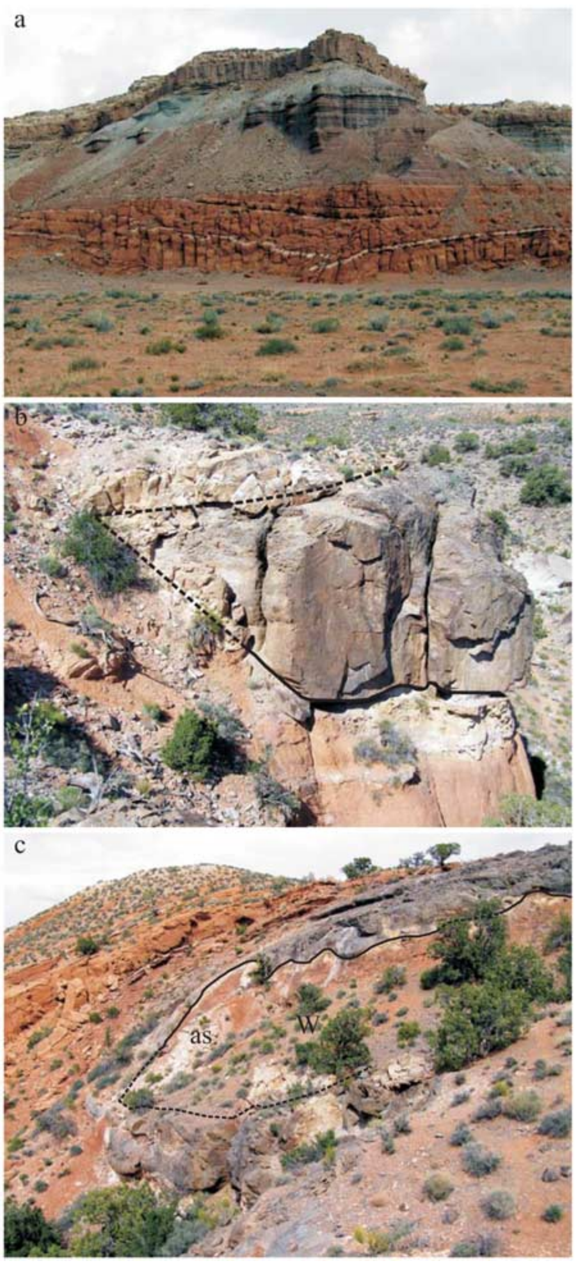

Figure 2. (a) Photo of the Entrada-Summerville contact between Trachyte Creek and Black Wash showing the angular unconformity between the two units. The angular discordance is ~10° in the center left portion of the photo. Photo taken from an exposure of the contact located ~5 km northwest of the intersection of Route 96 and Route 276 in an area initially described by *Hunt* [1953] and illustrated in his Figure 16. Bushes in the foreground are ~0.5 m tall. (b) Cross-sectional view of the southeastern margin of the Trachyte Mesa intrusion where it pinches out against the northwestern limb of an anticline. Note the buff-colored, coarse-grained sandstone atop the intrusion and hydrothermally altered sandstones underlying the intrusion. Maximum thickness of the intrusion in this photo is ~4 m. (c) Oblique view (to east) of the WNW exposure. Basal contact is highlighted with thick black line (dashed where inferred) revealing a window (W) into the altered (as) and unaltered underlying sandstones. Total vertical relief of the exposure in this photo is ~30 m from top on the right to bottom on the left.

Note that in some locations outside of the study area the Curtis Formation is present between the Entrada Sandstone and the Summerville Formation [*Hunt*, 1953]. The contact between the Entrada Sandstone and the Summerville Formation is typically obscured by colluvium in the area of Trachyte Mesa, but is well exposed around Lake Powell and the area west of the Route 96 north of the intersection with Route 276.

[14] The origin of these Jurassic folds remains unresolved because of the lack of any detailed study of them on a regional scale, particularly in the area west of the Henry Mountains. One possible cause for the formation of these folds is deformation related to the impact that formed Upheaval Dome at the north end of Canyonlands National Park (Figure 1a) [e.g., *Alvarez et al.*, 1998]. However, distortions associated with the impact near Upheaval dome are restricted to lower members of the Entrada, whereas the folds along the eastern side of the Henry Mountains include the entire Entrada Sandstone [*Hunt*, 1953]. An additional complicating factor is that the fold axial traces trend toward Upheaval Dome and not normal to this direction as anticipated if they formed as a result of an impact at that site. Doug Sprinkle (Utah Geological Survey, personal communication, 2008), who has identified these folds in the Entrada throughout the region and noted their relationship with the overlying Curtis/Summerville formations in the Lake Powell area, suggests that the folds may be an indication of eastward propagation of early Sevier age deformation [e.g., *Royse*, 1993] or the slightly older "Elko Orogeny" of the Middle Jurassic [*Thorman and Peterson*, 2003]. Either possibility seems consistent with the apparent regional extent to the folds (>90 km based on geomorphic expression of the folds observed in satellite images) and the NE–SW trend of fold axes, subparallel to faults of this age observed in eastern Nevada and western Utah. However, a much more regional and detailed study of these folds beyond what is presented herein is required before their causative origin may be constrained.

[15] Since the Trachyte Mesa intrusion appears to be largely confined between the crests of two anticlines, it is important to describe in detail the geometry of the contact between the intrusion and host rocks along these margins. On the southeast side, the intrusion appears to terminate against the hinge of the anticline except for one small overspill at the southeasternmost extent of the intrusion. Figure 2b shows a rare cross-sectional view of the southeastern margin of the intrusion where a buff-colored, coarse-grained sandstone unit that is observed capping the Trachyte Mesa intrusion in all but a few exposures merges with in-place exposure of the underlying red sandstone with only a few centimeters of elevation change. The underlying intrusion pinches out as the underlying red sandstone member rises up to meet the buff-colored unit.

[16] The Trachyte Mesa intrusion overtops the hinge of the northwest bounding anticline in a number of locations along this side of the mesa (e.g., Figure 1d). This may be due to the fact that the entire package, intrusion and folded stratigraphy, exhibit a slight (2–5°) northwesterly dip. The best, and most often discussed [e.g., *Hunt*, 1953; *Koch et al.*, 1981; *Corry*, 1988; *Morgan et al.*, 2005, 2008] exposure of this margin is here referred to as the west–northwest (WNW) exposure (Figures 2c and 3). The intrusion near the top of the WNW exposure (i.e., near the hinge of the bounding anticline) cuts down section at the anticline hinge to a stratigraphic level ~2 m below the buff-colored, coarse-grained sandstone unit. To the northwest of the anticline hinge (Figure 2c), the upper contact of the intrusion again follows bedding, changing dip directions down the northwest limb of the anticline, thinning dramatically from as much as 40 m thick to ~2 m at the hinge to <30 cm thick as it descends the northwestern limb of the anticline. The intrusion does thicken again to ~2 m at the lowest point of the exposure. Near the bottom of the exposure the intrusion is characterized by multiple bulbous extrusions jutting into the surrounding sandstone. In other exposures of this margin narrow, meter-scale, dikes intrude upward (subvertical) from these northwest dipping sheets.

[17] As a consequence of the emplacement of the Trachyte Mesa intrusion, the overlying strata at the WNW exposure must have been rotated. However, bedding dip angles of the strata overlying the intrusion in this area range to a maximum of 28° while the steepest angles measured in the limbs of folds away from the intrusion commonly have maximums of ~25°. Total rotation of the strata overlying the intrusion at the WNW exposure is, therefore, inferred to be no more than ~5° in most places. One bedding measurement taken along the margin of the intrusion yielded dip of 52° toward the northwest. This measurement was taken near another exposure of the bottom part of the intrusion as it had flowed over the hinge zone of an adjacent anticline, similar to the bottom section revealed in

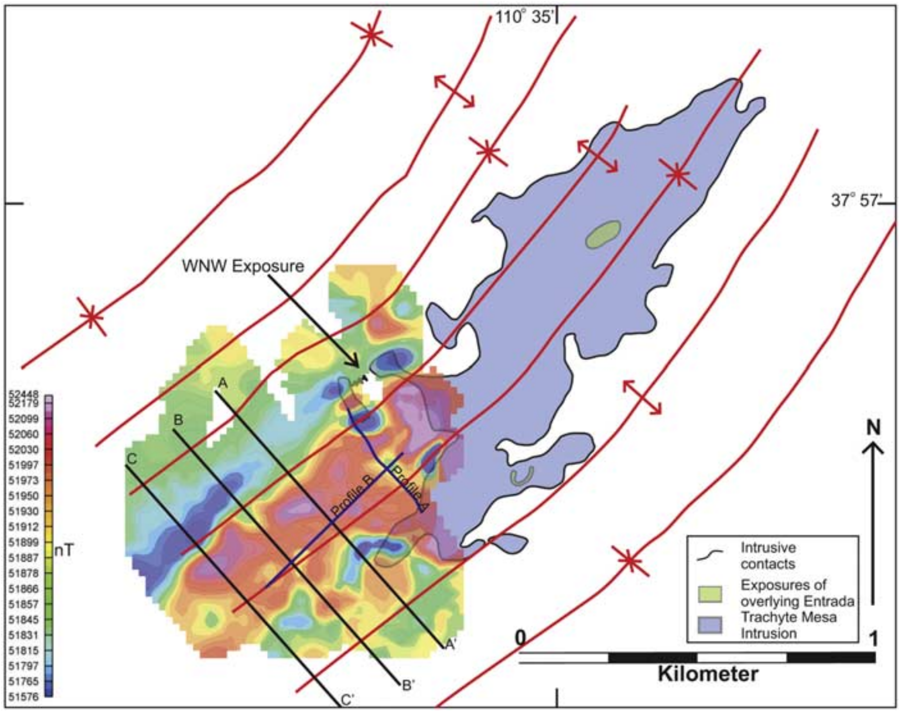

Figure 3. Map of the Trachyte Mesa intrusion including fold traces with the magnetic map overlain. Heavy purple lines show the locations of the resistivity experiments. Magnetic map shown as anomaly in the total magnetic field (nanoteslas). Lines A–A', B–B', and C–C' correspond to the magnetic models shown in Figure 4. Magnetic and resistivity data can be obtained from the authors upon request.

Figure 2c. This seems to be a very local rotation as attitudes at similar contacts all dip less than 30°.

[18] The description of structures associated with the margins of the Trachyte Mesa intrusion given above differs markedly from those presented in previous studies. This is particularly true for the WNW exposure. Regardless of the specific mechanism (i.e., inflation of a single intrusive body [e.g., *Koch et al.*, 1981] or incremental emplacement of multiple sheets [*Morgan et al.*, 2008]) the resulting interpretation for either group of researchers is that the monoclinal folds at the margins of the Trachyte Mesa intrusion result from its emplacement. This interpretation is inconsistent with two key observations from this study. First, close inspection of the WNW exposure demonstrates that most of the middle section of the WNW exposure has been eroded revealing a window through the intrusion (Figures 1d and 2c). Behind the intrusion within this window there are no additional sheets of the intrusion, only remnants of altered Entrada Sandstone overlying unaltered Entrada Sandstone. In fact, at the bottom of this exposure is a narrow (meter wide) slit in the bulbous portion of this part of the Trachyte Mesa intrusion where one can clearly observe that the lowest portions of the intrusion horizontally terminate against Entrada Sandstone. In this locality the bulbous portion of the intrusion is certainly not being fed from behind by a subhorizontal sill. Rather, the intrusion is conformable to bedding and descending along the bedding plane. Second, the folds in this area are not formed as a consequence of the intrusion as they can be observed for tens of kilometers away from Trachyte Mesa and shown to have been cut off at an angular unconformity with overlying Jurassic sequences (Figure 2a). These folds are, therefore, much older than the Tertiary Trachyte Mesa and other Henry Mountains intrusions.

3.2. Geophysical Survey

[19] The Trachyte Mesa intrusion is concealed beneath fluvial gravels and a thin section of Entrada Sandstone to the southwest of the main exposed body of the intrusion. While the intrusion in this area is beyond direct observation it does provide a unique opportunity to constrain the geometry of the intrusion where it has not been modified by subsequent erosion. A geophysical investigation of the Trachyte Mesa intrusion was conducted as a part of a field course in geophysics of the University of South Florida, Dept. of

Geology during the summer of 2007. A variety of techniques were employed including magnetics and 2-D resistivity.

[20] Previous field studies identified magnetic anomalies west of the Trachyte Mesa intrusion [*Morgan et al.*, 2005], suggesting that the intrusion continues for at least several hundred meters west of outcrops of the intrusion. We conducted a high-resolution magnetic survey, consisting of approximately 25,000 measurements of the total intensity of the Earth's magnetic field distributed over an area of approximately 1 km^2 in order to map the lateral extent and shape the intrusion in the shallow subsurface away from outcrops, estimate the thickness of the intrusion in these areas by modeling the magnetic anomalies, and to search for possible feeder dikes. Magnetic measurements were made with a cesium vapor magnetometer and station locations were determined using a differential GPS (L1 band), with all GPS readings differentially corrected using a <2 km baseline. Magnetic drift was monitored at several stations during the survey and was found to be very small (<10 nT) compared to the amplitudes of mapped and modeled anomalies (300–400 nT).

[21] The resulting magnetic map (Figure 3) clearly shows the intrusion continues under a thin veneer of Entrada Sandstone to the SW on the same trend and with roughly the same width as seen in outcrops, for approximately 800 m. Individual magnetic lines run SW of this point indicate the intrusion does not extend significantly further than the SW edge of the mapped area. The map pattern of magnetic anomalies is consistent with a uniformly magnetized body with normal remanent magnetization. Peak anomalies along SE–NW profiles, perpendicular to the trend of the anomaly, have remarkably uniform amplitudes, on order of 300–400 nT, over much of the map area (Figure 4). Some complexities in the magnetic map are interpreted to reflect topographic variation on the top of the intrusion, similar to the variation seen to the NE in outcrop [see *Morgan et al.*, 2005].

[22] Two-dimensional magnetic models of three profiles across the intrusion were made assuming a normal vector of remanent magnetization and an equivalent susceptibility contrast of $k = 0.004$ between the Trachyte Mesa intrusion and the surrounding Entrada Sandstone. Models with these constraints that fit the data well indicate that the intrusion is 40–50 m thick near its centerline and tapers toward the edges of the intrusion, mimicking the pattern observed in outcrop (Figure 4). In profiles A–A' and B–B' the best fit model uses a nearly horizontal upper surface, with thickness variations accounting for undulations of the lower contact of the intrusion. The model of profile C–C' has a very similar form, but the NE limb of the intrusion dips gently to the NW. Variations on these modeled geometries are possible; for example a lower susceptibility contrast would require a thicker intrusion. The magnetic anomaly expected for an intrusive body with a shape similar to those described by *Koch et al.* [1981] and *Morgan et al.* [2008] (i.e., blister shaped) is also shown in Figure 4 (profile D–D'). The observed magnetic data from profile A–A' is used for comparison because it is derived from the transect closest to the exposed portion of the intrusion studied by these researchers. It is clear from the discordance between the observed and calculated data that such a geometry is incompatible with the magnetic data. However, the magnetic data do constrain the shape of the Trachyte Mesa intrusion to geometries similar to those shown in profiles A–A', B–B', and C–C' from Figure 4, given the assumption that a single intrusive body with uniform magnetization creates these anomalies.

[23] The magnetic data do not reveal any short-wavelength anomalies that could be unequivocally associated with feeder dikes beneath the intrusion. In fact, narrow feeder dikes would be extremely difficult to detect. For example, the magnetic signature of a 1-m-wide dike feeding the intrusion along its centerline would be swamped by the signal of the overlying intrusion.

[24] Two-dimensional resistivity profiles were acquired with a Campus Imager 50 resistivity system with 46 electrodes. Readings were made with Wenner traverse geometry. For the NW–SE profile A (Figures 3 and 5) electrode spacing was 5 m; for the longer SW–NE profile B electrode spacing was 10 m and two overlapping profiles were merged for a single inversion. Apparent resistivities were inverted for terrain resistivity using default parameters with the Res2dInv code of Geotomo Software [*Loke and Barker*, 1996].

[25] Resistivity data indicate lower-resistivity sediments over a higher-resistivity unit inferred to be the Trachyte Mesa intrusion. The low-to-high transition in resistivity suggests the sediment-intrusion contact lies at ∼10–20 m depth through the imaged zone (Figure 5). Depth to top of intrusion appears to increase systematically to the southwest along profile B. The resistivity data suggest that the top of the Trachyte Mesa intrusion locally consists

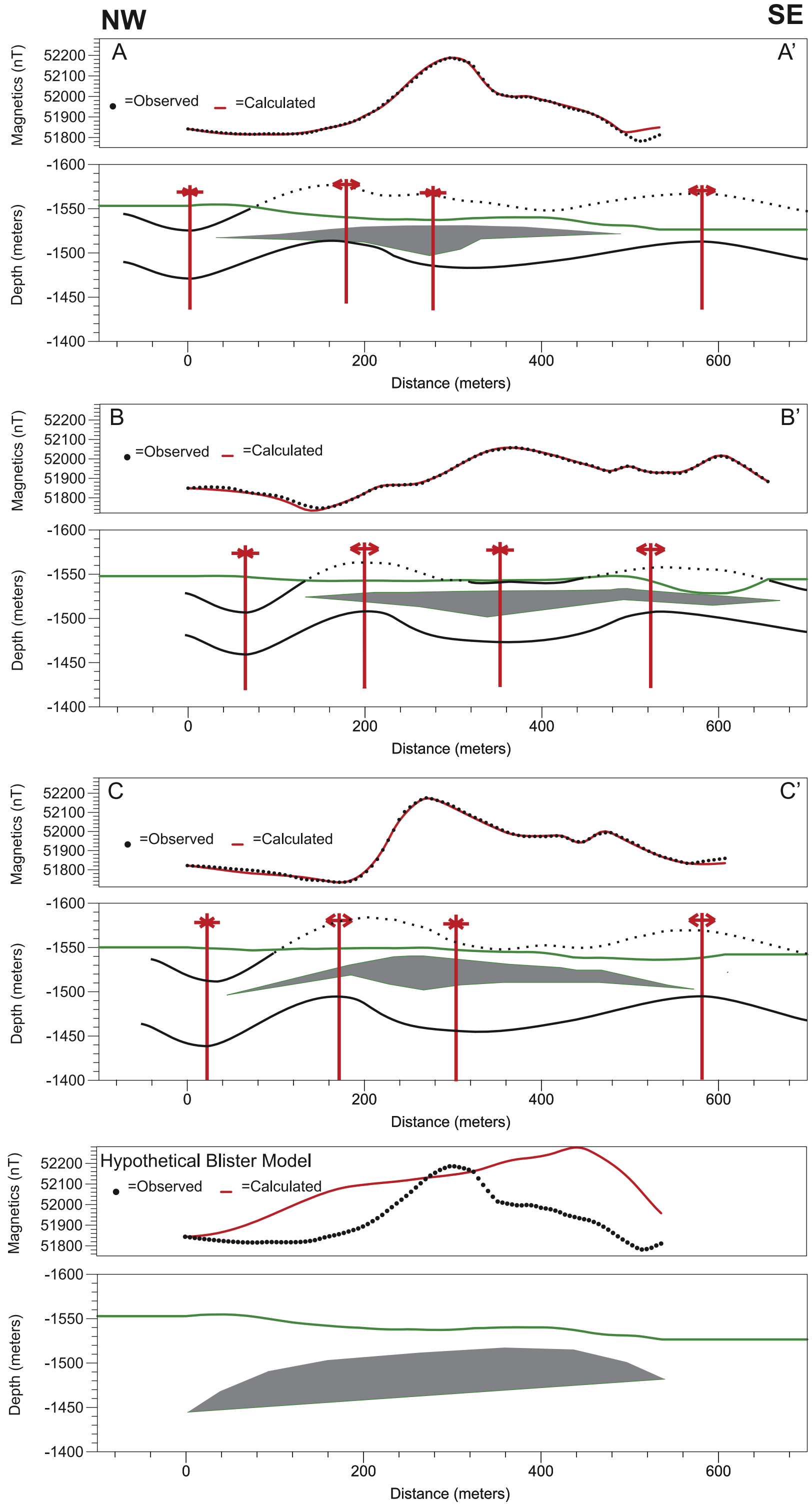

Figure 4. Two-dimensional, best fit magnetic models of three profiles (A–A', B–B', and C–C') across the intrusion constructed assuming a normal vector of remanent magnetization and an equivalent susceptibility contrast of k = 0.004 between the Trachyte Mesa intrusion and the surrounding Entrada Sandstone. Shown in each section is the surface topography (green) and folds (black solid) with eroded sections (black dots) projected above topography. The Hypothetical Blister Model is a theoretical cross section with calculated magnetic anomaly expected for the geometry of the Trachyte Mesa intrusive as described by *Morgan et al.* [2008]. The observed data used in the Hypothetical Blister Model is taken from profile A–A′.

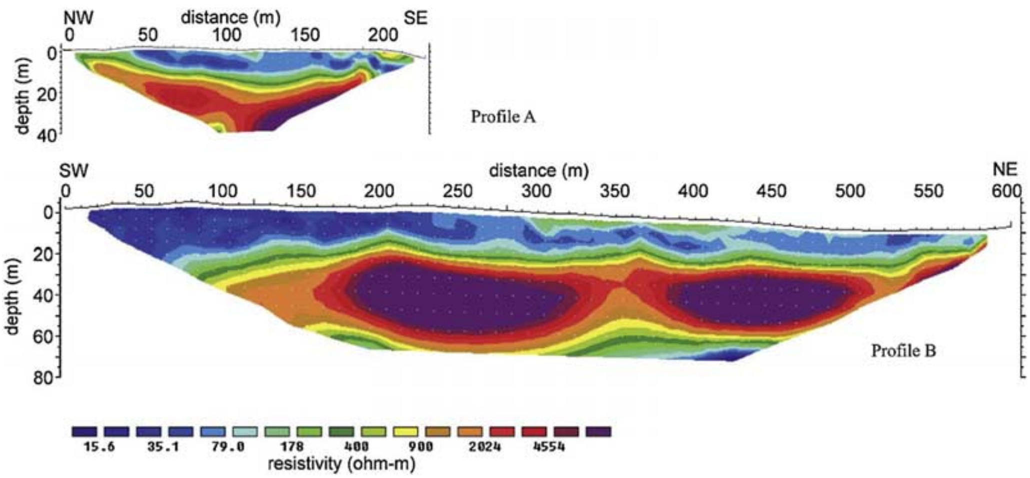

Figure 5. Profile A shows resistivity from the NW–SE transect shown in Figure 1, and profile B shows resistivity along the NE–SW profile. The vertical axes represent depth below the elevation of the endpoint of the traverse. The low-to-high transition in resistivity suggests the sediment-sill contact lies at ~10–15 m depth through the imaged zone. Depth to top of sill appears to increase systematically to the southwest along profile B. The resistivity data suggest that the top of the sill locally consists of a series of concave-up segments some 150–200 m long. On profile B, resistivity increases with depth below ~55–60 m, perhaps corresponding to the base of the sill. Resistivities at these depths are less well resolved, however, than the gradient at the top of the sill.

of a series of concave-up segments some 150–200 m long. On profile B, resistivity crease with depth below ~55–60 m, perhaps corresponding to the base of the intrusion. Resistivities at these depths are less well resolved, however, than the gradient at the intrusion top.

[26] Overall, the resistivity and magnetic data are best fit by quite consistent models that share basic features: an intrusion that persists hundreds of meters southwest of its exposure, with the top some 10–20 m below the surface, a thickness on the order of 40 m, and margins that pinch over hundreds of meters.

4. Discussion and Summary

[27] The structural and geophysical data reported herein suggest that the geometry of the Trachyte Mesa intrusion is strongly influenced by that of structures preexisting within the hosting Entrada sandstone. Jurassic folds within the Entrada Sandstone possess axial traces that subparallel the long axis of the combined exposed and buried portions of the Trachyte Mesa intrusion. On the basis of the limited cross-sectional exposures of the Trachyte Mesa intrusion, the geometry of the basal contact appears to parallel that of the folds with the lowest elevations near the axis of the syncline and the highest close to or coincident with the hinges of the bounding anticlines (Figures 1 and 3). Magnetic data and models (Figure 4) also support the geometric correlation between the folds and the basal contact of the intrusion.

[28] Similarly, structural and geophysical observations demonstrate that the thickest portion of the intrusion is approximately coincident with the inferred trace of the syncline axis and thins markedly near the anticline hinges (Figures 2a, 2b, and 4). Transects A–A’ and B–B’ of Figure 4 clearly illustrate this relationship. The thickest part of the intrusion in transect C–C’ is approximately 50 m removed (toward the NW) from the inferred trace of the syncline. This may reflect an error in our attempt to locate the position of the trace through the intrusion, where lack of exposure requires the position to be determined through extrapolation based on the location of adjacent folds, and/or the simplified geometry used in generating the magnetic model depicted in the C–C’ transect.

[29] Magnetic data preclude the geometry of the Trachyte Mesa intrusion envisioned by previous studies including a flat, northwest dipping basal contact and blister-shaped, but flat upper contact (Figure 4, Hypothetical Blister Model). Such a geometry would produce an anomaly similar to the red (calculated) line in the Hypothetical Blister Model of Figure 4, which was calculated using the geometry described by *Morgan et al.* [2008]. This geometry would produce a flat, but sloping magnetic anomaly with a maximum coincident with the point where a thick portion of the intrusion is

closest to the surface. The margins would also be characterized by steep gradients, sharper where they are shallowest (i.e., on the SE side of the intrusion). By contrast, if the basal contact is concave-up and coincident with the thickest portion of the intrusion, the most pronounced magnetic anomalies will likewise be coincident (e.g., Figure 4, lines A–A', B–B', and C–C').

[30] While the magnetic data require that the basal contact of the intrusion possess a concave-up geometry with the structurally lowest point close to the inferred axial trace of the syncline, the upper surface can and does exhibit some variation along the long axis of the intrusion. Magnetic and resistivity data suggest that in profiles oriented normal to the fold traces, most of the buried portion of the intrusion is characterized by flat (Figure 4, lines A–A' and B–B') or even concave-up (Figure 5, profile A) upper contacts. Transect C–C', however, is characterized by a convex up upper contact with an apex immediately above the lowest point on the basal contact. This indicates a greater volume of magma was emplaced into this portion of the Trachyte Mesa intrusion, suggesting the possibility that the C–C' profile is more proximal to the point of dike injection than the other profiles. A point source within the trough of the syncline is consistent with the interpretation that intrusive features observed at the WNW exposure result from the work required of the intrusion to intrude down the northwest limb of the anticline. Additionally, the interpretation that the dike intrudes near the axis of the syncline and beneath the buried part of the intrusion is consistent with the inferred flow directions based on AMS data reported by *Morgan et al.* [2008].

[31] The geometry and structural position of the Trachyte Mesa intrusion within the folded Jurassic Entrada Sandstone may, in fact, reveal some information about the density of the intruding melt relative to that of the host rocks it was emplaced into at the time of injection. The location of the Trachyte Mesa intrusion at its final crustal level at the time of intrusion likely reflects the arrest of upward propagation of the feeder dike at the interface between the buff-colored, coarse-grained sandstone and the underlying red sandstone. This may be due to in the rigidity between the two bounding units [e.g., *Kavanagh et al.*, 2006] or simply because bedding planes represent easily exploited structural anisotropies. Observations of successive lit-par-lit intrusions (sills?) in the upturned strata on the margins of the larger intrusions (e.g., Mount Hillers [*Hunt*, 1953; *Jackson and Pollard*, 1988]) emplaced between units with alternating relative rigidity contrasts, appear to minimize the role of rigidity contrasts in the siting of sills and laccoliths as defined by *Kavanagh et al.* [2006] and *Menand* [2008]. Regardless of the mechanical reason(s) for the crustal level into which the Trachyte Mesa intrusion was emplaced, since it does generally conform to the geometry of the folds, with the majority of the intrusive mass residing within the trough of the syncline, it suggests that the density of the magma was somewhat more than the weighted mean density of the overlying column of rocks [cf. *Corry*, 1988] or density of the local sedimentary section [*Lister and Kerr*, 1991]. Measured density of the intrusive rock is 2580 ± 10 kg m^{-3}; given that the intrusion is nonvesicular and phenocryst-rich (30–35% by volume with phenocrysts up to 1 cm) it is unlikely the magma was significantly less dense at the time of intrusion. Typical density values for sedimentary rocks that make up the section such as sandstones, shales, siltstones and limestones are 2200–2500 kg m^{-3}, giving an approximate density contrast range of +100–300 kg m^{-3}. In contrast, if the intruding magma was less dense than the sedimentary section and confined to a specific stratigraphic layer (i.e., beneath the buff-colored sandstone), then it should have ponded within the lowest-pressure site beneath that layer, beneath the hinge of an anticline. This would be similar to ore deposits precipitated from fluids or hydrocarbons that commonly migrated to the shallowest crustal level (i.e., the hinge zone of the anticlines or corners formed at the intersection of faults and drag folds) under a capping unit.

[32] An alternative explanation for the ultimate position of the intrusion is that topography at the surface was such that there was lower lithostatic load over this position. Given that as much as 4 km of overburden has been removed by erosion since the emplacement of the Trachyte Mesa intrusion, the surface topography at the time of emplacement cannot be uniquely determined. However, it is safe to assume that the presence or geometry of the folds likely had no direct influence on that topography since they are truncated at the contact with the overlying Curtis/Summerville contact. Thus, it would be absolutely fortuitous for a valley, deeper than the amplitude of the folds, to have existed in the exact position overlying the axis of the syncline into which the Trachyte Mesa intrusion is emplaced.

[33] Other observations support the notion that intrusion density influenced its final position within the Entrada folds. The intrusion only overtops the anticline where the syncline has filled to the level of the anticline hinge or, as in the case of the west–northwest exposure, where the intrusion cuts down section rather than ascends up along the limb following the buff-colored sandstone. This situation may have developed late during emplacement as the feeder dike closed, isolating the magma and dropping hydrostatic pressure [e.g., *Lister and Kerr*, 1991]. Thus, the magma flowed to the lowest position beneath the capping buff-colored sandstone even though this potentially required the intrusion to lift a slightly thicker (∼30–50 m or ∼1% more) column of crust during emplacement. Thus, the geology of the intrusion and surrounding sedimentary section is consistent with emplacement of a pressurized dike of comparatively higher density than the overlying integrated section.

[34] The observations of the Trachyte Mesa intrusion presented in this study indicate that preexisting structures can have a fundamental influence on emplacement and geometry of intrusion at shallow crustal levels. Since the intrusion is considerably younger (>100 Ma) than the folds, the kinematics of their formation did not play a role in creating space for the magma as has been inferred for other intrusions. Rather, space the Trachyte Mesa intrusion was created through roof uplift due to the driving pressure of the magma. The preexisting folded geometry of the contact between the buff-colored and red sandstones, along with density contrasts between the magma and the host rock ultimately controlled the final position and geometry of the intrusion.

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