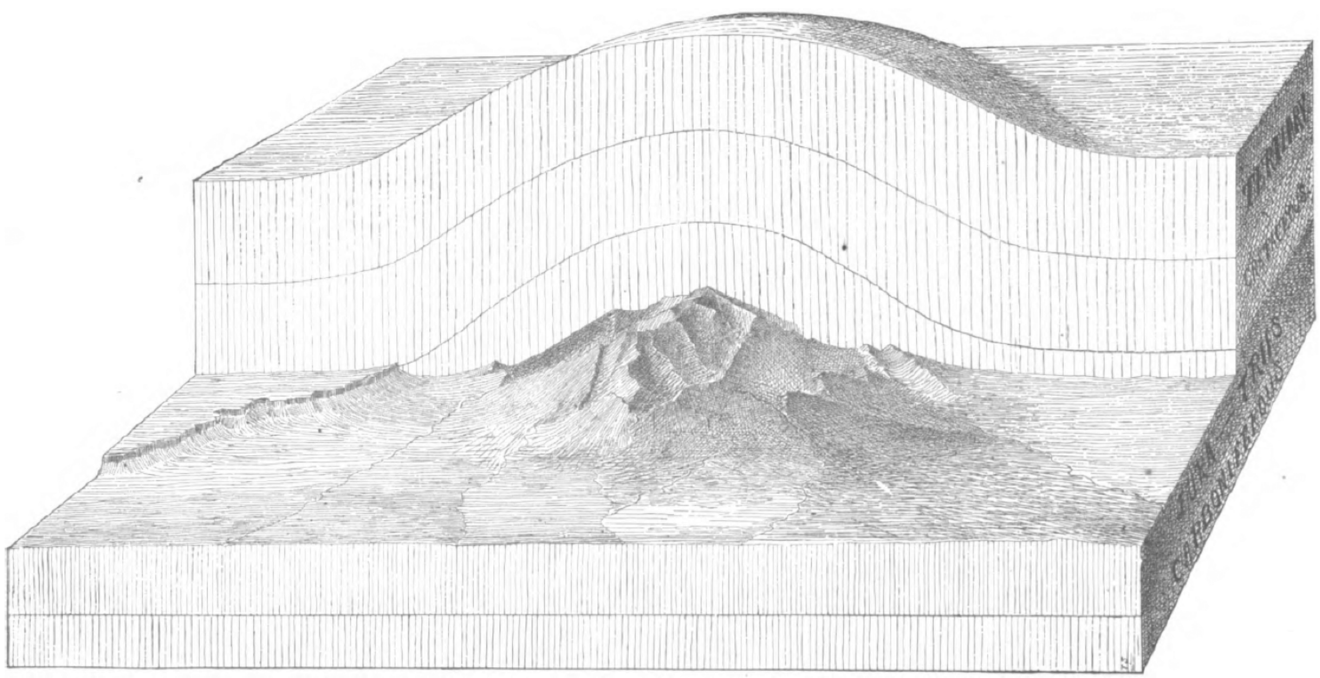
EMPLACEMENT AND ASSEMBLY OF SHALLOW INTRUSIONS, HENRY MOUNTAINS, SOUTHERN UTAH

Field guide for the 2010 LASI IV conference, Utah, U.S.A.



from Gilbert (1877)

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ABSTRACT

Exceptional exposures of igneous intrusions of the Henry Mountains of southern Utah allow for the detailed study of three-dimensional pluton geometries as well as igneous emplacement and assembly processes. Examination of the geometry, fabric, and wallrock structures of relatively small intrusions (<3 km map-view diameter) suggests that several plutons in the region (Maiden Creek sill, Trachyte Mesa laccolith, Black Mesa bysmalith) represent snapshots of a continuum of pluton geometry recording volume increase through emplacement of successive magma pulses. Intrusions begin as thin sills and inflate into laccoliths through incremental injection of magma sheets. Space is made through wallrock strain and upward rotation. Further sheet emplacement leads to the formation of a subvertical fault at the margin of the inflating intrusion. This fault accommodates piston-like uplift of the intrusion roof and results in the formation of an intrusion geometry referred to as a bysmalith. Margins of laterally propagating igneous sheets are commonly comprised of numerous finger-like magma lobes that coalesce into contiguous sheets with further lateral growth. As intrusion volume grows through incremental assembly, pluton geometry becomes increasingly simple (fewer marginal lobes, etc.) and evidence for pulsed assembly becomes progressively more cryptic. Thermal modeling suggests these relatively small intrusions were assembled on time scales of weeks to years.

These intrusions grew as ‘satellites’ on the margin of the larger Mt Hillers intrusive complex. Satellite intrusions are not evenly distributed around the main intrusive centers. For example, numerous satellite intrusions exist on the NW half of the Mt Hillers intrusive center, but the SE half is devoid of them. No clear explanation exists for this spatial variation in satellite intrusion development. The main intrusive center is a large laccolith comprised of numerous sills and dikes above a voluminous central pluton. The central pluton includes an enigmatic ‘shattered zone’ of complexly intermingled sedimentary host rock and magmas with a wide range of textures. Geochronology suggests all of Mt Hillers, including the satellite intrusions, was assembled within no more than ~1 m.y. from several geochemically distinct magma pulses. Evidence from the satellite intrusions demonstrates that each of these pulses is itself emplaced on shorter time scales as a series of pulses.

INTRODUCTION

The intrusions of the Henry Mountains of south-central Utah provide an exceptional setting for the study of igneous emplacement processes. The igneous bodies intrude the well-documented flat-lying stratigraphy of the Colorado Plateau and therefore displacement of the wall rocks resulting from emplacement of magma is well constrained (e.g., Gilbert, 1877; Hunt et al., 1953; Pollard and Johnson, 1973; Jackson and Pollard, 1988; Habert and de Saint Blanquat, 2004; Horsman et al., 2005). The intrusions are mid-Tertiary in age (Nelson et al., 1992; Paquette et al., this meeting) and therefore postdate the minor Laramide orogenic activity that affected this part of the Colorado Plateau. Consequently, fabric within the intrusions primarily reflects finite strain produced by magmatic flow during emplacement and lacks a significant syn- or post-tectonic overprint.

The Henry Mountains are the type locality to examine laccoliths since G.K. Gilbert originated the term *laccolite* (1877) based on his pioneering work here in the 1870s. Gilbert concluded that the igneous rocks of the Henry Mountains were actually *intrusive*, a groundbreaking thought at the time. Additionally, he was one of the earliest workers to recognize that magmas can deform their wall rocks. He outlined a two-stage process of magma emplacement whereby the initial intrusion is sill-like, but with continued injection of magma, vertical growth is initiated and horizontal spreading ceases. The details of the growth of these intrusions have been debated ever since. It is the purpose of this trip to reexamine some of the same intrusions that Gilbert studied and to illustrate that at least in some intrusions, abundant evidence exists for the growth of the igneous body by the stacking of multiple magma sheets.

On this field trip we will examine several small (<3 km map-view diameter) intrusive bodies as well as the margin of one of the main intrusive centers. All of the locations we will visit are located on the eastern half of Mt Hillers. The satellite intrusions will include the Maiden Creek sill, Trachyte Mesa laccolith, the Black Mesa bysmalith, and the Sawtooth Ridge intrusion. We refer to these bodies (and others) as satellite intrusions because they are located between on the margins of the main body, and their magma volumes are small relative to the main intrusive centers. These satellite intrusions, on a much smaller scale, resemble the intrusive centers in composition, shape, and style of emplacement (contact geometries are similar). This similarity will become apparent when we visit the margin of and discuss the history of the main Mt Hillers intrusive body on the second day.

Our work differs from previous studies in that we have studied the fabrics within the intrusions as well as the structures and geometry of the intrusions. This different approach allowed us to recognize the role of discrete magma pulses, observed in the field as magma sheets, in constructing these igneous bodies. We hypothesize that three satellite intrusions – the Maiden Creek sill, Trachyte Mesa laccolith, and the Black Mesa bysmalith (from smallest to largest) –record different stages in the evolution of a sheeted intrusion with increasing magma input. Alternatively stated, the Black Mesa bysmalith may have originated as a sill (a Maiden Creek stage) that became a laccolith (a Trachyte Mesa stage) before evolving into its present bysmalith form (an overinflated cylindrical intrusion with a vertical fault as a contacts). Numerous rock exposures illustrate the multiple sheet-like construction of the Maiden Creek Sill and Trachyte Mesa laccolith. Evidence for pulsed construction of the Black Mesa bysmalith also exists but is more cryptic.

HISTORY OF HENRY MOUNTAINS GEOLOGY

The Henry Mountains of south-central Utah are a 90-km-long and 30-km-wide Tertiary igneous complex on the Colorado Plateau (Fig. 1). Although they are the largest of seven laccolithic ranges found on the Colorado Plateau (Stokes, 1988), their isolated location ensured that they were the last surveyed and last named range in the lower 48 states. John Wesley Powell called them the Unknown Mountains on his first trip down the Colorado River in 1869 (Kelsey, 1990). On his second voyage down the Colorado River, in 1871-1872, Powell named the mountains after Joseph Henry, a close friend and secretary of the Smithsonian Institution. The first non-native set foot in the Henrys in 1872, when A.H. Thompson, a geographer from Powell's second party, explored the northern peaks; Mount Ellen is named after Thompson's wife (Fillmore, 2000). In 1875, as the second director of the U.S. Geological and Geographical Survey (the precursor agency to the U.S. Geological Survey), Powell assigned Grove Karl Gilbert to study the 'volcanic' mountain range, and Gilbert made a two-week trip in 1875 and a two-month trip in 1876 (Fillmore, 2000).

This work resulted in a classic publication (Gilbert, 1877) in which Gilbert concluded that the igneous rocks of the Henry Mountains were actually intrusive and deform adjacent wallrocks, a groundbreaking thought at the time. He outlined a two-stage process of magma emplacement whereby the initial intrusion is sill-like, but with continued injection of magma, vertical growth is initiated and horizontal spreading ceases. The details of the growth of these intrusions have been debated ever since. This 1877 publication also introduced several fundamental concepts of geomorphology.

Hunt et al. (1953), after extensive detailed mapping on horseback in the Henry Mountains in the 1930s, produced the first comprehensive geologic maps of the region and reinterpreted the five main intrusive centers as discordant stocks rather than concordant laccoliths. Despite this disagreement, Hunt et al. (1953) concurred with Gilbert that the relatively small intrusions peripheral to the large intrusive centers were sills and laccoliths fed from the large central intrusions. This early detailed work also identified the ‘shattered zones’ at the center of the large intrusions, where igneous and sedimentary rocks are very complexly intermingled.

Johnson and Pollard (1973) and Pollard and Johnson (1973) applied dynamic analysis to the processes of sill and laccolith formation, elaborating considerably on concepts introduced by Gilbert (1877). These workers relied primarily on observations of deformed sedimentary strata to constrain models of stress evolution and intrusion development. The resulting models make field-testable hypotheses about intrusion geometry.

The ‘laccolith-stock controversy’ was revisited by Jackson and Pollard (1988). Detailed mapping, structural analysis, and geophysical work led to an interpretation more in agreement with Gilbert (1877) than Hunt et al.

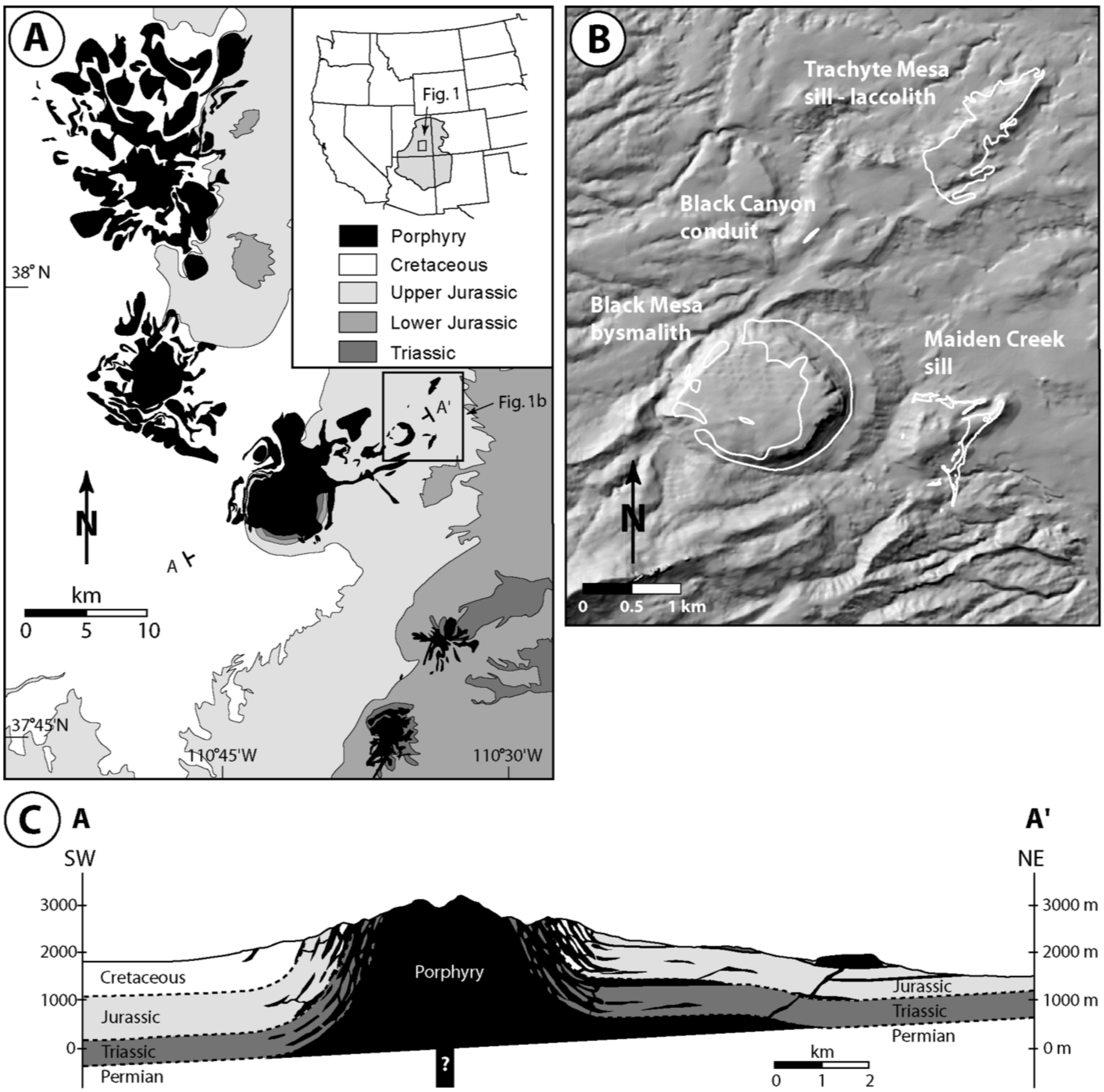

Figure 1 – (a) Simplified geologic map of the Henry Mountains region. Location of (a) shown by inset map. Location of (b) shown by box. Location of cross section A-A’ in (c) shown by tick marks. (b) Shaded relief map of the eastern portion of Mt Hillers. Outlines of the three satellite intrusions and the conduit discussed in the text are outlined in white. (c) Schematic cross section through Mt Hillers, oriented NE-SW.

(1953) – i.e. the five main intrusive centers are concordant 'floored' laccoliths and not stocks. Additionally, these workers established that early sills on the margin of Mt Hillers cooled while still sub-horizontal and were rotated by subsequent underlying intrusions to their present sub-vertical orientation. Although earlier workers inferred that multiple magma pulses were required to construct each intrusive center, this observation provided the clearest example yet of the pulsed nature of assembly in the Henry Mountains.

Regional interpretations of the significance of magmatism in the Henry Mountains changed considerably when modern geochronology and geochemistry were applied to the rocks (Nelson et al., 1992; Nelson and Davidson, 1993). Revised ages of the intrusions made it clear that mid-Tertiary Colorado Plateau magmatism was part of voluminous regional magmatism in the North American Cordillera. Geochemical data demonstrated that the Henry Mountains magmas have arc-like affinities and that each intrusive center has a distinct isotopic signature.

Recent work has relied for the first time on detailed study on both the intrusive bodies and adjacent host rock. Results from this work provide constraints on the timing of pluton assembly (Saint Blanquat et al., 2006), evolution of space-making mechanisms (Morgan et al., 2008), and magma flow kinematics development during progressive intrusion growth (Horsman et al., 2009). Ongoing work is designed to address, among other topics, 4-d growth of intrusive centers, the significance of the 'shattered zone,' and magma rheology.

HENRY MOUNTAINS GEOLOGY

The Henry Mountains are comprised of five distinct intrusive centers that were emplaced into nearly flat-lying stratigraphy (regional dips of 1–2° W). Ten kilometers to the west of the range, the stratigraphy is abruptly upturned in the Waterpocket Fold, a Laramide-age monocline. The peaks of the Henry Mountains reach heights of over 3350 m (11,000 ft), while the elevation of the surrounding flat-lying rocks of the plateau is roughly 1500 m (5000 ft). One striking aspect to the Henry Mountains, besides their size and nature of origin, is the abruptness with which the mostly Mesozoic wall and roof rocks rotate upward on the flanks of the intrusions; this is readily observed from Highway 95 and Highway 276, which parallel the mountain chain. Although the mapped intrusions have steep margins, deflection of the sedimentary strata from the regional orientation demonstrates that at depth the intrusions extend over a much greater area than what is actually exposed.

From N to S, the five intrusive centers of the Henry Mountains are Mt Ellen, Mt Pennell, Mt Hillers, Mt Holmes, and Mt Ellsworth. The northern three intrusive centers are considerably larger than the southern two in elevation, diameter, and magma volume. The total volume of igneous rock in all the intrusions is ~69 km^3.

Mount Hillers is the best exposed of the five Henry Mountains intrusive centers and presently forms a topographic dome with a diameter of ~15 km and a vertical displacement of sedimentary rocks of ~2.5 km. Several steep, narrow canyons cut into Mount Hillers and expose cross sections through numerous intrusions radiating away from the center of the dome. The sedimentary rocks on the top have also been eroded away partially exposing the igneous core.

The sedimentary section (Fig. 2) in the Henry Mountains is ~2.7 km thick and is dominated by sandstones and shales that range in age from Permian to Cretaceous (Peterson et al., 1980; Jackson and Pollard, 1988). Jackson and Pollard (1988) determined that at the time of intrusion, the region was buried by no more than 3–4 km of sedimentary overburden.

The igneous rock throughout the Henry Mountains is remarkably consistent in bulk composition. Approximately 95% of the igneous outcrop has a bulk diorite composition (58-63% Si02), with the remaining ~5% is principally rhyolite porphyry and syenite that cross-cuts earlier diorite on Mt Pennell (Hunt et al., 1953; Hunt, 1988; Nelson & Davidson, 1992). Texturally, the rock is a plagioclase-hornblende porphyry. Phenocrysts constitute 25-55% of the rock and consist of 20-40% feldspar (An20 to An60), 5-15% hornblende, and 1-3% of epidote or clinopyroxene, titanite, and oxides. The matrix constitutes 45-75% of the rock, and is a fine-grained, equigranular light gray groundmass of plagioclase, hornblende, quartz, alkali feldspar, oxides, and trace apatite and titanite. Calcite is present in miarolitic cavities in association with feldspar and quartz. Most xenoliths are mafic (amphibolite, garnet amphibolite, tonalite) but rare felsic xenoliths are present. Sedimentary xenoliths are rare. Although bulk composition is very consistent throughout the range, groundmass abundance and phenocryst size vary considerably between different intrusions and sometimes within a single intrusion. This textural variation can sometimes be used to recognize distinct magma pulses.

At the core of four of the five intrusive centers, a so-called 'shattered zone' is exposed. Most exposures of the shattered zone are characterized by a complex intermingling of meter-scale bodies of sedimentary rock with centimeter- to meter-scale regions of igneous rock with a wide range of different textures. The general character of the shattered zone suggests it was a low viscosity, possibly fluid-rich environment. It appears to be a late-stage feature of the assembly of an intrusive center, and may represent emplacement of the last, fluid-rich magma bodies. As we will discuss on the second day of this field trip, the previously mapped extent of the shattered zones (up to ~35% area of the Mt Hillers igneous rock) is probably much too large. Overall, the role of the shattered zones in the assembly history of the intrusions remains enigmatic, but work is underway to address this issue.

Hornblende $^{40}Ar/^{39}Ar$ ages for the Henry Mountains intrusions range from approximately 31 to 23 Ma (Nelson & Davidson, 1992). No clear pattern exists in terms of spatial migration of emplacement ages. Preliminary U/Pb ages on zircon from several samples on Mt Hillers (Paquette et al., this meeting) are indistinguishable from one another and suggest that the entire intrusive center was assembled in less than approximately 1 m.y. during the Oligocene-Miocene transition at 24-25 Ma. Recent petro-geochemical studies suggest that the magmas are the result of the melting of the lower crust of the Colorado Plateau, and that an arc-like geochemical signature is inherited from one or more Proterozoic (1.4-1.8 Ga) subduction events, as shown by in-situ geochronological data on inherited zircon cores.

FIELD TRIP

OVERVIEW OF DAY 1

In the morning we will examine the Maiden Creek sill, and in the afternoon we will examine the Trachyte Mesa laccolith (Fig. 3). **Note**: This road log begins in Hanksville, Utah. Mile markers on Highway 95 start at 0 at the intersection with Highway 24 in Hanksville.

Directions to Stop 1.1

Starting in Hanksville at the intersection of Highways 95 and 24, drive east (and south) on Utah Highway 95.

Mile marker* 2 *(while driving by). At two o'clock (treating the car, in map view, as a clock, the front of the car is twelve o'clock, passenger side is three o'clock, etc.) is the Mount Ellen intrusive center. This is the northernmost of the five intrusive centers in the Henry Mountains. The two prominent mountains located at the periphery of Mount Ellen are Table Mountain, a mesa on the north end of the intrusive center, and Bull Mountain, a more cylindrical mountain on the east side of the intrusive center. Both mountains are bysmalith intrusions similar to Black Mesa, which we will observe later.

Mile marker 13 (while driving by). Shallowly dipping striped sediments E of here are the Jurassic Carmel, Summerville, and Morrison Formations. The desert floor we are driving on is the Jurassic Entrada Sandstone.

Mile markers 17–18 (while driving by). Reddish sandstones of the Entrada Formation in a small canyon.

***Mile marker 26* – Reset odometer to zero.** Turn right onto Utah Highway 276 toward Ticaboo. Mile markers start at 0 at the intersection with Utah Highway 95. Drive 1.7 mi to a small rise in the road and pull over

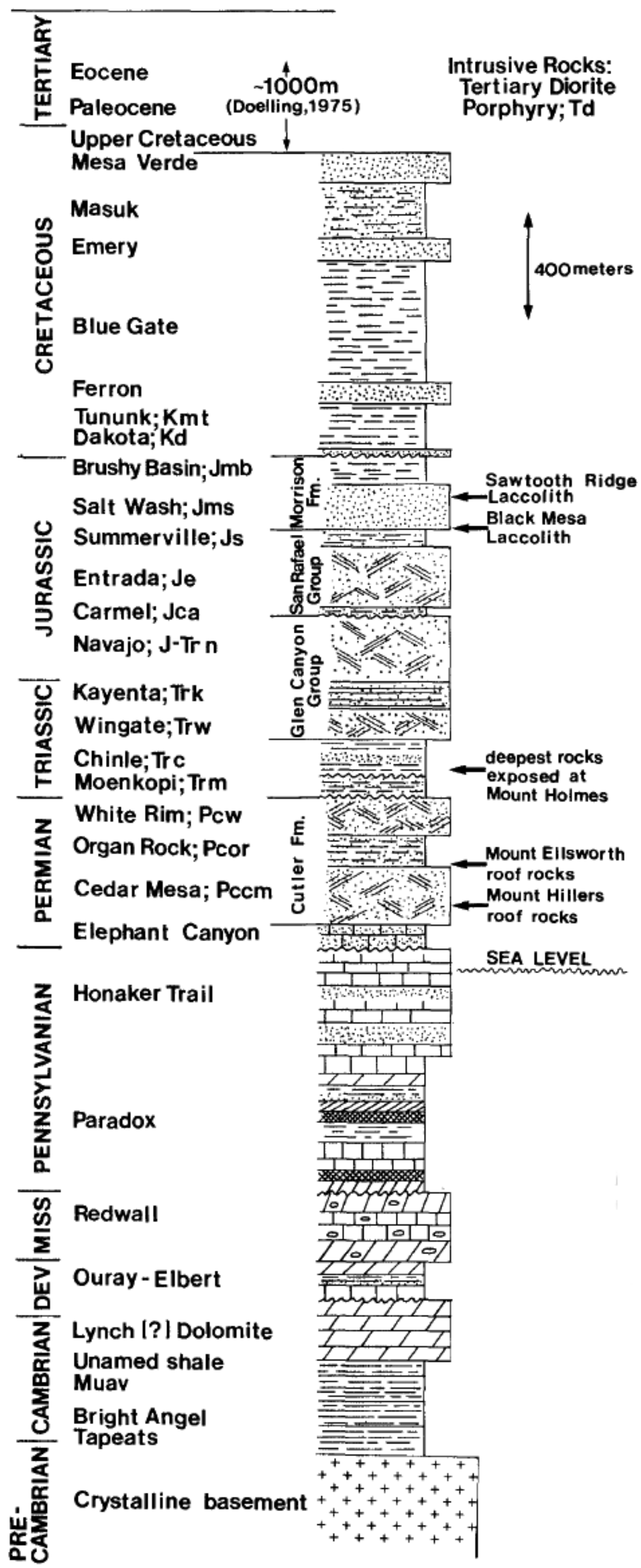

Figure 2 – Stratigraphic column for the Henry Mountains region at the time of emplacement (~25 Ma). Approximate structural levels of selected igneous intrusions are indicated. From Jackson and Pollard (1988).

on the side of the road for Stop 1.1.

Stop 1.1: Overview of Henry Mountains Intrusive Centers

All five intrusive centers of the Henry Mountains are visible from this point. Looking due south along the road (and calling this 12 o'clock), Mt Holmes is at 12, Mt Ellsworth at 12:30, Mt Hillers at 1, Mt Pennell at 3, and Mt Ellen at 5 o'clock. Each of these intrusive centers is composed of many component igneous intrusions. Mts Ellsworth and Holmes are the smallest intrusive centers, and the exposed igneous rocks include dikes, sills and a few relatively small laccoliths. These two intrusive centers are interpreted to record a relatively early stage of development compared to the three larger northern centers. At Mt Holmes and Mt Ellsworth, sedimentary rocks dominate the margins and can be traced almost to the top. The sedimentary layering is moderately inclined for several kilometers away from the exposed igneous rock, indicating that at depth the areal extent of the intrusions is much great than at the surface.

The northern three mountains are interpreted to be more mature intrusive centers, each with many more component intrusions than the southern mountains. These component intrusions include a wide range of sizes and geometries. The sedimentary strata are best exposed at the base of these intrusions and intermittently exposed through the middle elevations, where they commonly dip radially away from the core of the mountain at moderate to steep angles. Of the five intrusive centers, Mt Hillers generally has the best exposures of both component intrusions and contacts with sedimentary rock. Consequently, this field trip will focus on examining Mt Hillers.

Looking from this vantage point at the east flank of Mount Hillers, the Black Mesa and Sawtooth Ridge intrusions are visible on the skyline. A sheer cliff forms the east side of the Black Mesa bysmalith. Sawtooth Ridge is noted by its prominent jagged edge against the skyline. Directly in front of us (middle ground), the

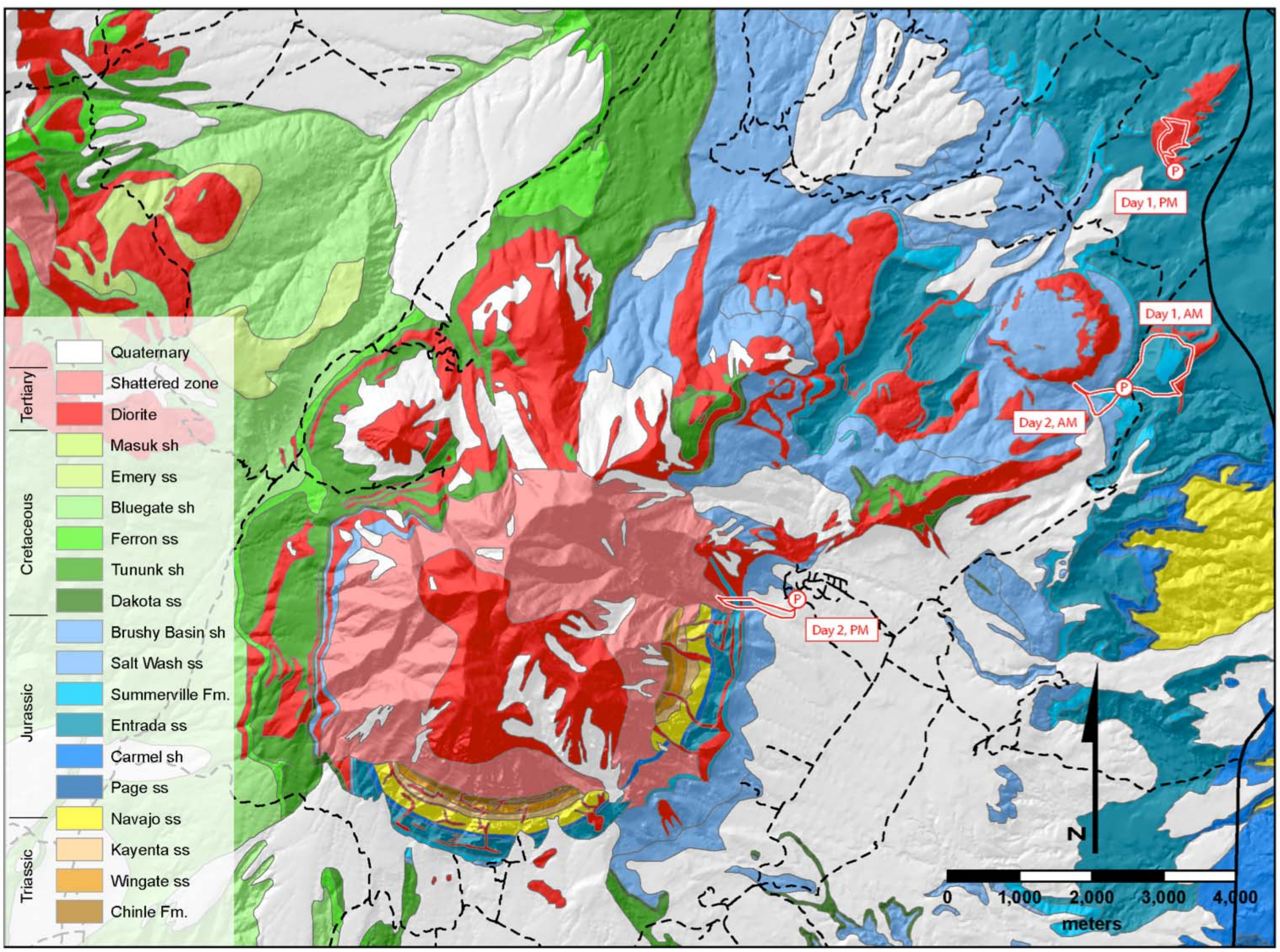

Figure 3 – Simplified geologic map of Mt Hillers. Parking locations (labeled P) and approximate routes for AM and PM of both days are indicated. Solid lines are paved roads and dashed lines are unpaved. Geology modified from Larson et al. (1985).

Trachyte Mesa intrusion is exposed, several kilometers away from the main Mt Hillers intrusive center. The Maiden Creek sill is exposed just east of Black Mesa. We refer to these small component bodies as satellite intrusions because they are not directly connected to the main body of Mt Hillers at the surface. Our strategy for this field trip is to visit the least-developed intrusions first (i.e. the earliest stages in a possible continuum of development of an inflating magma chamber and/or intrusion), and visit the more-developed intrusions later. From here we visit the Maiden Creek sill for Stops 1.2–1.9, break for lunch, and then spend the afternoon at the Trachyte Mesa laccolith for Stops 1.10–1.17.

Directions to Stop 1.2

Continue south on Rt. 276. At mile 6.7, turn right onto a dirt road. This is immediately (<100 m) before mile marker 7 on Utah Highway 276. At mile 9.7, park on side of dirt road where road turns SE and there is some room to park in the bend. Walk ESE down the stream valley for ~0.5 km (Fig. 4) until igneous rocks are seen in the stream bottom.

PART I: THE MAIDEN CREEK SILL

Stop 1.2: Composition and Top Contact of the Maiden Creek Sill

GPS (UTM): 536090, 4195836. Note: all locations are UTM zone 12, with datum NAD27. Main points: (1) Composition and texture of the Maiden Creek sill. (2) The cross-sectional geometry of the body is a ~25 m thick sill in this location. (3) The top contact contains solid-state fabric in the uppermost ~3 cm, while fabric is magmatic farther from the contact. Lineation and foliation are generally parallel in both fabric types.

This stop provides a good spot to view the basic cross-sectional geometry of the Maiden Creek sill (Fig. 5). The planar, horizontal top contact of the intrusion with the overlying Entrada Sandstone is well exposed at the next stop. We will soon examine the planar, horizontal bottom contact of the intrusion in the steep-walled gorge ~150 m east of here. Where top and bottom contacts are exposed, the intrusion is generally ~25–40 m thick. Here near the S margin of the sill thickness is ~25 m. The horizontal, concordant top and bottom contacts of the intrusion lead us to call this a sill. However, the map view geometry of the intrusion is quite complex, as will become apparent shortly.

This stop also provides an introduction to the igneous rock of the Henry Mountains. As almost everywhere in the Henry Mountains, the rock has a bulk dioritic composition and in hand sample is a generally homogeneous plagioclase-hornblende porphyry in which phenocrysts of feldspar and amphibole lie in a fine-grained gray matrix (Fig. 6; see also Hunt et al., 1953; Engel, 1959; Nelson et al., 1992). In the Maiden Creek sill, feldspar phenocrysts make up 30%–35% of the rock by volume and are generally euhedral laths 0.2–1 cm in diameter. Amphibole phenocrysts make up 5%–15% of the rock by volume and are euhedral needles 0.1–0.5 cm in length. Other phenocrysts include <5% by volume euhedral augite, euhedral to subhedral oxide grains (principally magnetite), which generally have a maximum diameter of 0.2 mm and make up <2% of the porphyry by volume, and apatite and sphene, both of which are generally euhedral and <1% by volume. The fine-grained matrix generally makes up 50% or more of the rock and is composed primarily of microcrystalline feldspar, amphibole, and oxides.

Because of the well-exposed upper contact of the intrusion at this location, we can examine the relationship between the contact and fabric development in the igneous rock. The outermost ~3 cm of the intrusion generally have well developed solid-state fabric, which is defined here by the cataclastic stretching of feldspar and amphibole phenocrysts (Fig. 7A). These deformed phenocrysts define a prominent lineation. Greater than ~3 cm from the contact, solid-state fabric is essentially nonexistent and magmatic fabric is developed instead. This magmatic fabric is defined by the preferential alignment of undeformed phenocrysts, particularly elongate amphibole crystals (Fig. 7B). In locations where both solid-state and magmatic fabrics are exposed, foliation and lineation orientations in both fabric types of fabric are generally parallel. Similar observations will be seen on the margins of the Trachyte Mesa laccolith at Stop 1.15.

Directions to Stop 1.3

Head NE down the N side of the drainage (Fig. 4) for ~100 m until you are on relatively flat-lying sedimentary rocks. You should have an overview (looking S across the stream bed) of the N-facing side of the stream canyon and ~4 m high towers on the N side of the streambed.

Stop 1.3: Lateral Terminations

GPS (UTM): 536186, 4195897. Main points: (1) There are two stacked bulbous terminations on the lateral margin of the sill, suggesting different magma sheets. (2) Wall rocks are rotated upward on the margin of the intrusion. (3) The margin here belongs to an NS-elongated part (finger-like lobe) of the Maiden Creek sill.

Looking S from this vantage point, the lateral contact of the intrusion with the surrounding Entrada sandstone is beautifully exposed (Fig. 6A). The contact is complex; it is composed of two vertically stacked bulbous igneous terminations. As we will observe at other locations on the intrusion, this geometry is typical of most exposed lateral contacts of the Maiden Creek sill. We suggest that this geometry is likely produced by the stacking of separate igneous sheets; two separate sheets wlll be observed at Stop 1.9.

The relationships between the sedimentary host rock and the intrusion are better preserved at this location than at most others on the Maiden Creek sill. The sedimentary rock here tilts upward above each of the upward-facing portions of each bulbous sheet termination (Fig. 6A). This observation indicates that at least some of the host-rock displacement necessary for emplacement of the intrusion is accomplished through tilting and uplift of the sedimentary strata.

The lateral margin exposed here forms the eastern edge of a NS-elongated portion of the Maiden Creek sill (which we will refer to as a *finger*, following Pollard et al., 1975) that projects out from the main body of the intrusion. The ridge immediately E of here is defined by another NS-elongated finger. The lateral contact we have been considering and others in this area demonstrate that the current geometry of the fingers is very similar to the original emplacement geometry, i.e., the lobate map-view geometry of the intrusion (Fig. 5) was *not* formed by erosion of a once-contiguous sheet.

Directions to Stop 1.4

Walk ~100 m ESE downhill to the streambed and continue into Secret Nap Spot gorge until you encounter an abrupt 10 m drop along the streambed.

Stop 1.4: Cross Section in Secret Nap Spot Gorge

GPS (UTM): 536250, 4195886. Main points: (1) A complete cross section through one finger exists here. (2) The bottom contact is conformable and not deformed. (3) No stoping is visible in the igneous rock.

Exposed at this stop is a complete cross section through one of the fingers of the Maiden Creek sill.

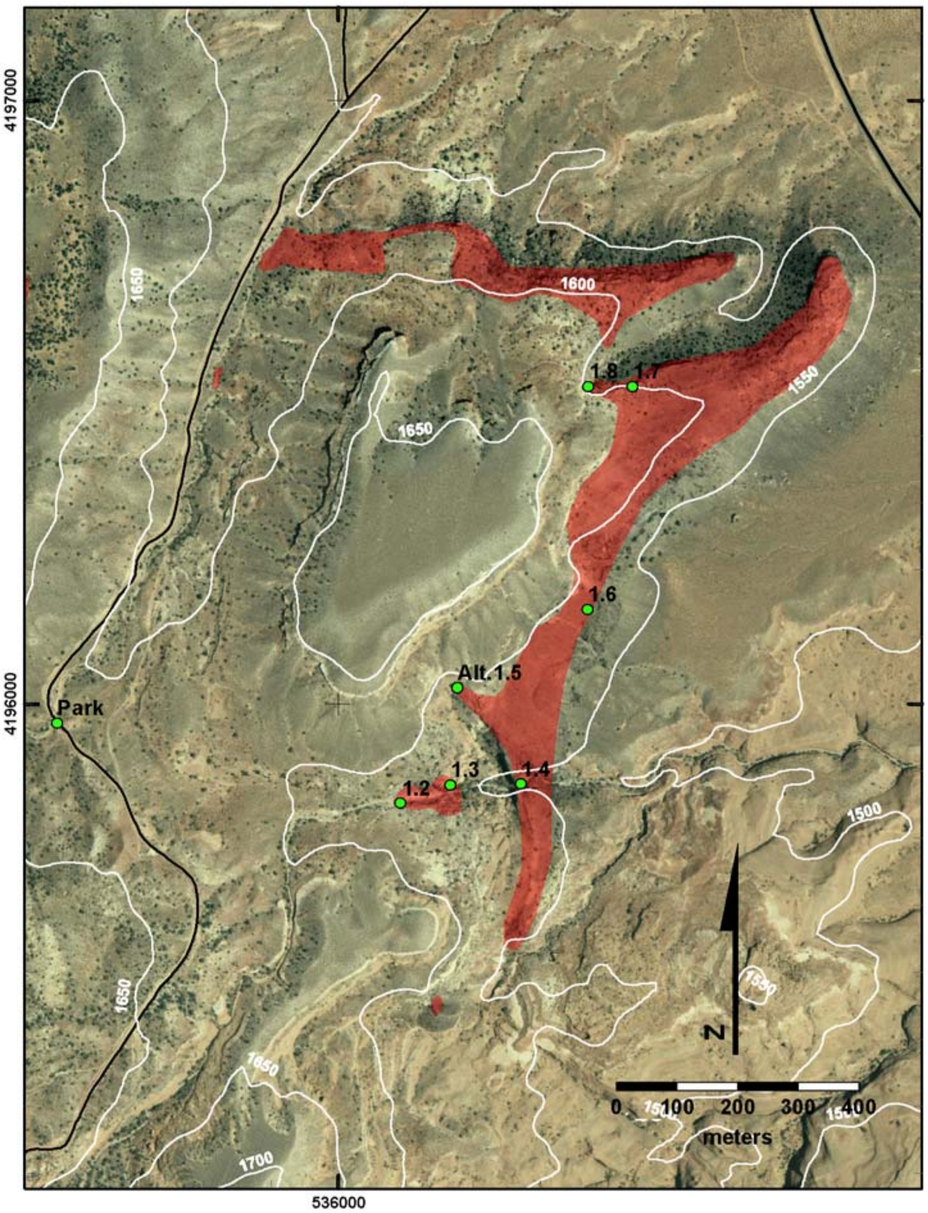

Figure 4 – Location of field trip stops on the Maiden Creek sill. Base map is an aerial photograph of the region. Outcrop of igneous rock indicated with red highlighting. Green circles indicate approximate stop locations and are labeled with stop numbers. Thick black lines are paved roads. Thin black lines are dirt roads. White lines are topographic contours with 50 m interval. UTM zone 12, datum NAD27.

Although overlying sedimentary rocks are not clearly exposed atop the cliff faces here, they are in place nearby, as we will observe shortly. Examining the cliff faces, it is clear that there are no xenoliths of sedimentary rock within the intrusion. Sedimentary xenoliths are exceedingly rare in all of the intrusions we will be examining. This suggests that stoping is not an important space-making mechanism in these intrusions.

Also exposed here is the concordant horizontal bottom contact of the Maiden Creek sill with the underlying Entrada Sandstone (here a shale). The bedding in the host rock below the contact is essentially undeformed.

Clear evidence for three fingers (like this one) exists on the margins of the Maiden Creek sill and strong evidence for a fourth finger (which we were atop at Stop 1.2) exists. Preserved contacts demonstrate that the finger-like lobes project out from the main body of the intrusion and are not merely erosional remnants of a main body that was once larger and has been dissected by streams. No clear textural difference exists between the main body of the intrusion and the finger-like lobes.

Each finger is 200–400 m long and is distinctly elongate with respect to both its cross-sectional thickness and map view width (Fig. 4). In longitudinal cross section, each finger thins progressively away from the main body. The finger shown in cross section A-A’ on Figure 5B thins from ~30 m thick near the main body to ~7 m thick over a distance of ~400 m. This thinning occurs as the base of the intrusion cuts up through the sedimentary section while the top of the intrusion resides at an approximately consistent bedding-parallel stratigraphic level.

Directions to Stop Alt.1.5

Backtrack out of the gorge and then walk ~175 m NW up a smaller canyon developed in sedimentary rocks. Walk up the creek bed until igneous rock is encountered.

Stop Alt.1.5: Igneous-Sedimentary Contact on a Lateral Termination

GPS (UTM): 536186, 4196016. Main points: (1) Solid-state deformation occurs locally on lateral contact. (2) Very little deformation or metamorphism occurs in

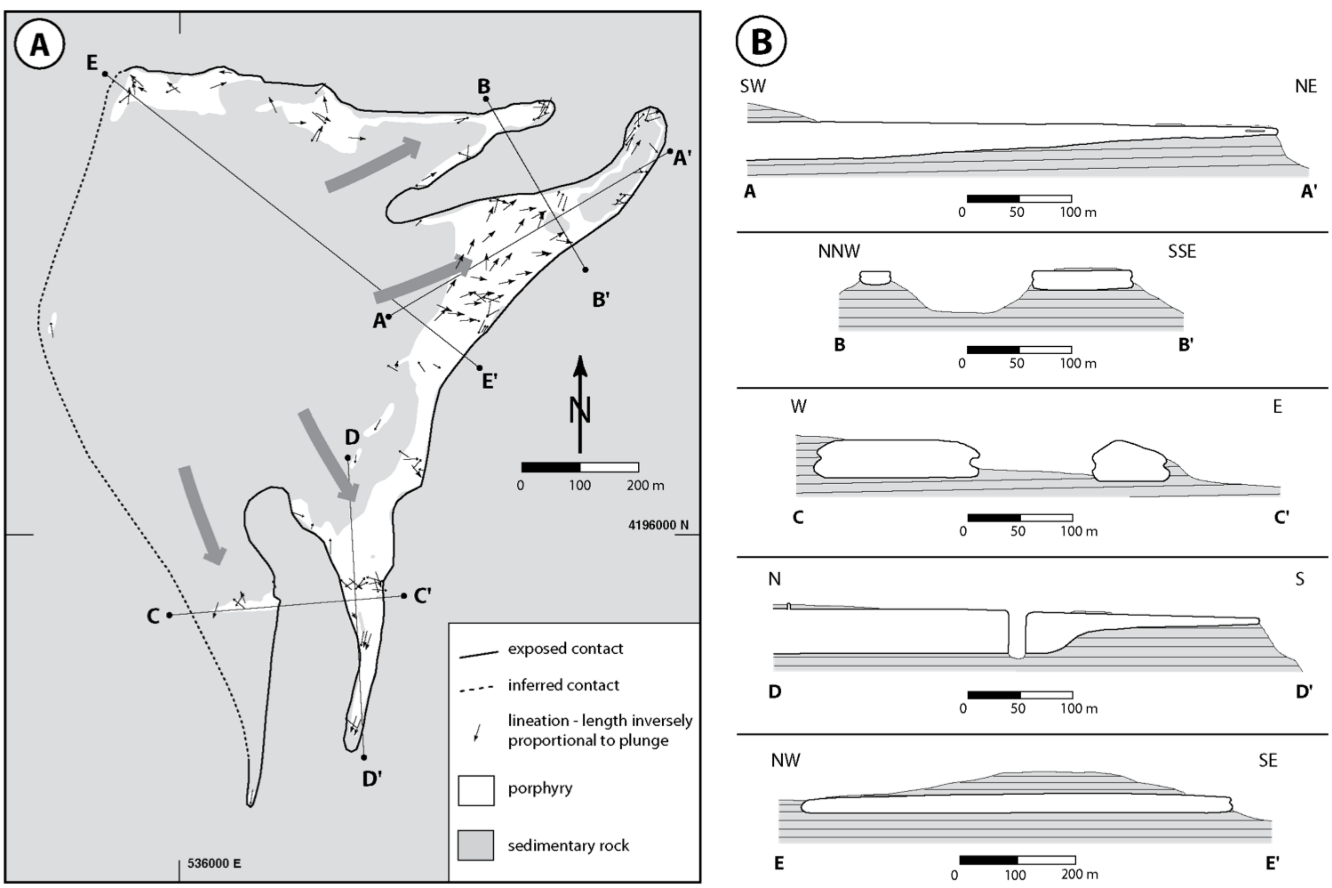

Figure 5 – Geologic map and cross sections of the Maiden Creek intrusion. Lineations shown with black arrows include both field measurements and magnetic fabric results, with arrow length inversely proportional to plunge. Locations of cross sections shown in (b) are indicated. Large grey arrows indicate inferred primary magma flow directions based on intrusion geometry and fabric patterns. (b) Cross sections through the intrusion. Note that the scale of cross section E-E’ is different from that of others.

wall rocks.

The lateral contact of the intrusion with the host rock is exposed at this stop. Solid-state fabric in the outermost few centimeters of the intrusion is prominently developed. In general, the solid-state fabric patterns are complex and probably reflect the nature of the emplacement process, which accommodated both lateral and vertical expansion and longitudinal propagation of the sheet. As we observed at Stop 1.2 atop the intrusion, fabric patterns at the top (and bottom) contacts tend to be more consistent and predictable than those observed at the lateral contacts. This difference is presumably related to the more complex flow patterns operating during emplacement in the bulbous lateral sheet terminations than at the planar top and bottom margins of the sheet. Similar relationships are seen at Trachyte Mesa laccolith – intense host rock deformation exists at the lateral margins and little deformation at the bottom and top margins.

Directions to Stop 1.6

Walk several hundred meters NE (Fig. 4) until a cliff is encountered (edge of the intrusion). Notice along the walk the *in situ* horizontal sedimentary rock atop the intrusion.

Stop 1.6: Geometry of Intrusion

GPS (UTM): 536426, 4196131. Main points: (1) The Maiden Creek intrusion consists of 100-m-scale, finger-like lobes that emanate from a central intrusion. (2) The top of the intrusion is relatively flat and concordant. The bottom of the intrusion cuts upsection, resulting in thinning of the intrusion along its length (longitudinal axis). (3) Bulbous terminations are stacked upon one another on lateral margins of main part of the sill,

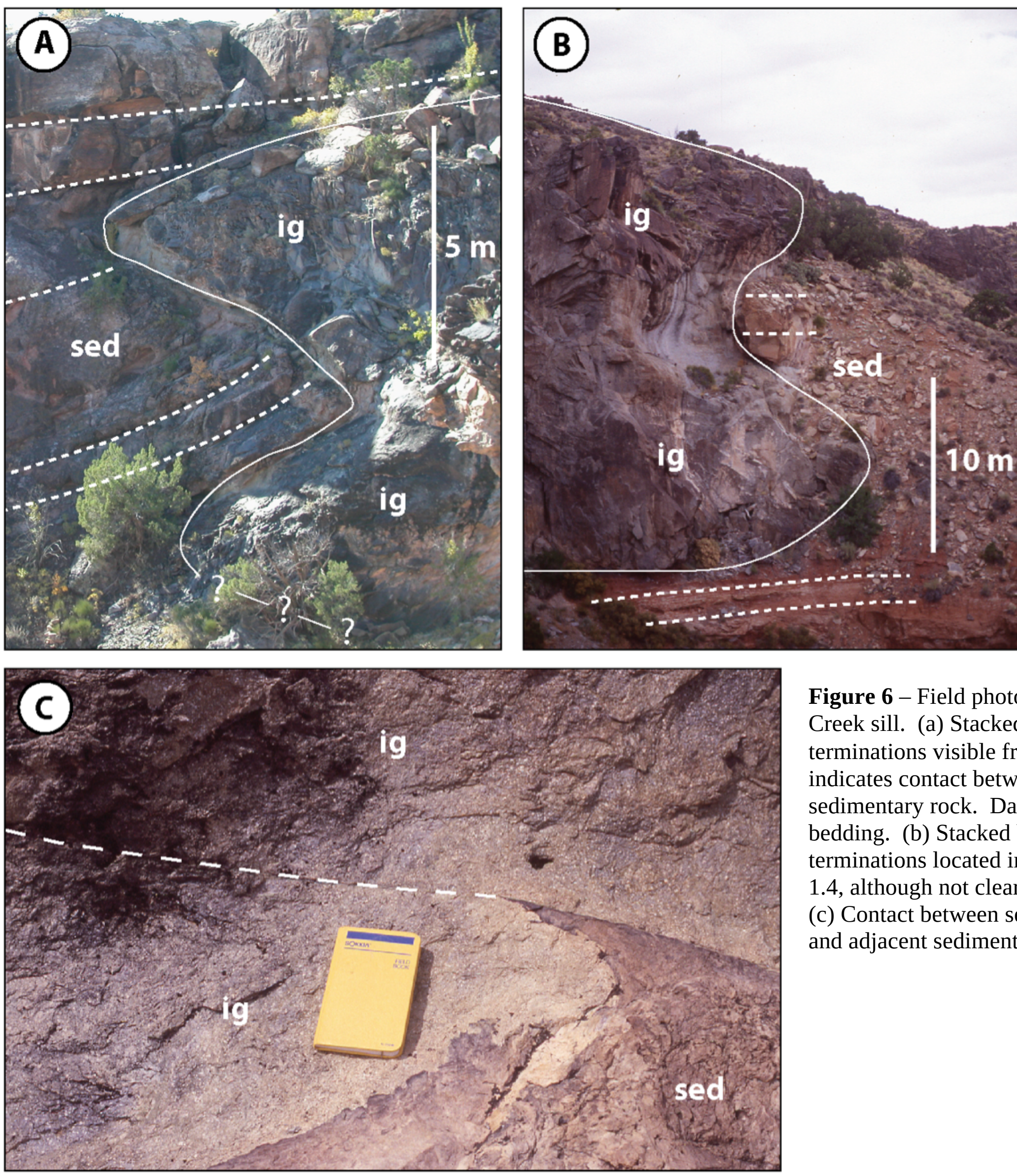

Figure 6 – Field photographs of the Maiden Creek sill. (a) Stacked bulbous lateral terminations visible from Stop 1.3. Solid line indicates contact between igneous and sedimentary rock. Dashed lines indicate bedding. (b) Stacked bulbous lateral terminations located immediately E of Stop 1.4, although not clearly visible from there. (c) Contact between separate igneous sheets and adjacent sedimentary rock.

suggesting that different magma sheets exist throughout the area of the intrusion. (4) Meter-scale topography exists locally on the top of the intrusion.

From this vantage point, much of the eastern side of the Maiden Creek sill is visible. We will discuss several noteworthy features of the intrusion. First, looking S from here, the southeastern finger of the intrusion (which we looked at in cross section at Stop 1.4) can be clearly seen. The top of the finger is relatively flat and concordant, and flat-lying sedimentary rock is still in place in several locations atop this part of the intrusion. Although not clearly visible from here, the bottom contact of the finger cuts up-section along its length, resulting in thinning of the intrusion. Each of the fingers of the Maiden Creek sill has a similar geometry

These fingers radiate from the main body of the Maiden Creek sill, resulting in a complex map-view geometry (Fig. 5). The main body of the intrusion (which we are now atop) is roughly elliptical in map view and has a relatively simple sill-like geometry in cross section. This region of the intrusion is consistently 30–40 m thick. At least four separate, finger-like lobes project out from this main body. Each of these fingers is ~30–40 m thick where it begins to project out from the main body and thins progressively to a thickness of 5–10 m as distance from the main body increases (Fig. 5). These fingers extend 200–400 m out from the main body of the intrusion and are distinctly elongate with respect to both their map view width and their cross-sectional thickness. The numerous extant lateral contacts with sedimentary host rock demonstrate that the current map pattern (Fig. 5) of the intrusion is very similar to the original intrusive geometry. This complex geometry may be a common characteristic of sills in general (e.g., Marsh, 2004) that often goes unrecognized because the lateral margins of most sheet intrusions are rarely as well preserved as those seen on the Maiden Creek sill.

Also visible from this vantage are the two well-exposed vertically stacked bulbous lateral terminations along the eastern margin of the sill (Fig. 6B). The lateral contacts with adjacent sedimentary rocks are locally preserved. As discussed earlier, these bulbous lateral terminations suggest that at least two magma sheets are stacked upon one another throughout the intrusion. These two sheets can be observed individually as they thin to the NE and separate into individual sheets for several tens of meters (NE end of cross section A-A' on Fig. 5B; Stop Alt.1.9). These intercalated sedimentary strata are observed in a few places and are typically found halfway between the base and the top of the sill, at the same location where the two bulbous terminations meet. Rare igneous-igneous contacts can be traced away from these screens of wall rock (Fig. 6C). These internal contacts are marked by a 1–2-cm-thick zone of intense foliation and solid-state deformation. We will not visit the outcrop illustrated in Figure 6C, because one must climb down

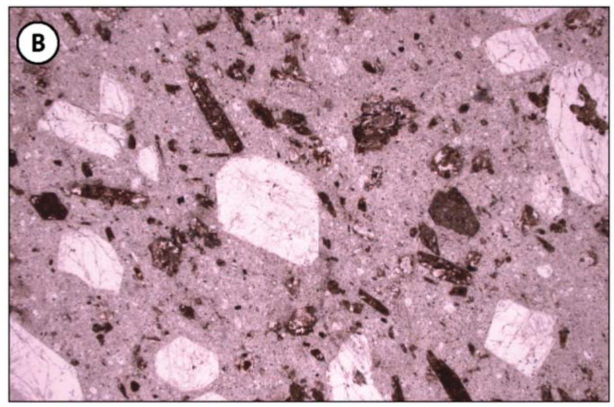

Figure 7 – (a) Solid-state fabric development in the outer few centimeters of an igneous – sedimentary contact. (b) Photomicrograph of magmatic fabric. Field of view approximately 5 cm across. Plane-polarized light.

this cliff face, but we will see the two separate sheets from the road on Stop Alt.1.9.

One final feature visible from here is the locally developed meter-scale topography of the top surface of the sill. Nascent dikes (?) extending up from the roof of the intrusion occur in two places (one visible just W of here, the other on the NW exposed corner of the intrusion). Also present are meter-scale ridges, generally oriented parallel to the strike of the edge of the intrusion. Johnson and Pollard (1973) interpreted similar ridges atop the Trachyte Mesa intrusion to record the position of the edge of that intrusion at various stages of progressive emplacement.

Directions to Stop 1.7

Walk 200–300 m N, essentially on the top contact of the intrusion with host rock. Head for the overlook of a gully between two prominent NE–SW-oriented ridges (Fig. 4).

Stop 1.7: Emplacement of the Maiden Creek Sill

GPS (UTM): 536494, 4196351. Main points: (1) Magmatic flow was subparallel to the fingers. (2) Areal extent of the first sheet seems to have controlled the extent of the second sheet. (3) Space was made primarily by upward vertical movement of the overburden.

The gully below us to the N is bordered by two ridges, each of which is held up by a finger of the Maiden Creek sill. Excellent lateral contacts of both fingers are preserved at the SW end of this gully; we will visit one of these contacts at the next stop.

Because the current outcrop pattern closely corresponds to the original shape of the sill, an ideal opportunity exists to study the relationships between igneous fabric, emplacement processes, and intrusion geometry. Fabric results described here are summarized from Horsman et al. (2005), who used several techniques to analyze the fabric within the sill. Throughout the intrusion, solid-state fabric is confined to the outermost ~3 cm of the intrusion (and the few internal contacts adjacent to the screens of wall rocks). At distances greater than ~3 cm from the contact with the sedimentary host rock, magmatic fabric is almost exclusively developed. The boundary between the regions of solid-state and magmatic fabric is gradational over 1–2 cm.

Magmatic fabric is a more reliable tool than solid-state fabric for studying magmatic flow during emplacement because the solid-state fabric records both magmatic flow and the interaction of the magma with the wall rock. Solid-state fabric is consequently more complex and difficult to interpret than magmatic fabric, which reflects primarily finite strain produced by late-stage magmatic flow during emplacement (Horsman et al., 2005). With these caveats in mind, the fabric results for the Maiden Creek can be considered.

Magmatic lineation in a finger of the sill is generally subparallel to the elongation direction of the finger (Fig. 5). Field-measured lineations and AMS (anisotropy of magnetic susceptibility) lineations are generally subparallel (for the details of the fabric and a discussion of AMS see Horsman et al., 2005). Magmatic foliation in the fingers is generally subhorizontal. Consistent magmatic fabric patterns are also observed in the main body of the sill, where magmatic lineation radiates outward and foliation is generally subhorizontal. We interpret these patterns to record general flow of magma away from an unexposed source region to the W into the main body and then out of the main body and into each finger. We cannot distinguish whether the fingers are late ancillary intrusions fed by the main body or if the main body is a region that has coalesced into a sheet of magma by amalgamation of propagating fingers (e.g., Pollard et al., 1975).

We infer that the Maiden Creek sill consists of two separate, sequentially emplaced sheets. The two sheets have almost exactly the same geometry and extent. Their similar cross-sectional geometry allows us to conclude that the pulses of magma were essentially identical in volume. This observation suggests that the emplacement and extent of the first sheet controlled the extent of the second sheet.

We envision the following scenario. The emplacement of the first sheet produced a weak, hot region surrounding the igneous body. During intrusion of the second igneous sheet, the adjacent heated sedimentary rock was relatively weak and failed before more distal nearby cooler sediments. Consequently, after the emplacement of the first sheet, subsequent pulses of magma from the same feeder system intruded immediately adjacent to a previously intruded sheet. By this process, a thick body of igneous rock with a complex lobate three-dimensional geometry can be assembled. The consequence is that the amount of magma intruding at any one time remains relatively small.

Uplift of overburden is the dominant space-making mechanism. However, when viewed in cross section, there is insufficient deflection of the layers on the margins (layers that rotate up at the contact with the Maiden Creek sill) to accommodate the amount of vertical space required by the thickness of the sill. This observation indicates that other mechanisms, such as lateral displacement and strain of adjacent host rocks may be responsible for some of the additional space making. We will observe these processes at the next outcrop and at the Trachyte Mesa intrusion.

Directions to Stop 1.8

Walk generally NW and descend into the small canyon between the these two fingers of the sill. Head upstream to the W, where the lateral contact of the finger on the S side of the canyon is very well exposed.

Stop 1.8: Lateral sheet contact

GPS (UTM): 536429, 4196544. Main points: (1) The finger-like lobes grew both in both longitudinal and transverse directions. (2) Space-making mechanisms for the lobes include both roof uplift and wallrock strain (volume change through porosity redection).

This outcrop provides an opportunity to examine in detail the lateral contact of a finger-like lobe and to consider how space was made during lobe propagation. The small faults and fractures seen here in the host rock clearly record lateral growth of the lobe (Fig. 8). On the S side of the outcrop, the lateral margin of the lobe has a blunt, wedge-like geometry with an internal angle of approximately 60°. Locally this contact is step-like and includes small faults that extend into both the intrusion and the host rock. A region of relatively intact sandstone lies within this wedge-shaped region and is bounded above and below by faults. Outside of this wedge region, the host rock in pervasively fractured, as demonstrated by the spectacular pencil cleavage. These structures demonstrate that this lobe made space for itself, in part, by straining adjacent sandstone host rock. At the microstructure scale, the porosity in these rocks has been reduced by up to half (see Stop 2.14 for a discussion of similar deformation on the Trachyte Mesa intrusion).

Notice that strata of the Entrada sandstone overlying this outcrop are not folded at the margin of the lobe. The same is true ~50 m NE of here at the margin of the lobe on N side of the canyon. The primary space-making mechanism for the entire sill was roof uplift, but local space problems like that seen at this outcrop were accommodated by porosity reduction in the sandstone host rock. We hypothesize that as the intrusion was growing, under the regionally uplifted roof it was relatively easy to laterally displace highly fractured host rock to accommodate transverse lobe growth.

Directions to Stop Alt.1.9

Return to the top of the mesa and head W (contouring) until the road is seen. Walk to the road and then southward to the cars. Turn cars around and head back N and E on dirt road until intersection with Utah Highway 276. **Set odometer to zero** and turn right (S) on Highway 276. Drive ~0.6 mi and park on the side of the road (Fig. 4). Look to the W toward the top of the mesa that terminates close to the road.

Stop Alt.1.9: Separate Sheets of the Maiden Creek Sill

Main point: (1) Separation of the Maiden Creek sill into an upper and lower sheet supports our model of two pulses of magma, one stacked upon the other.

Looking up at the top of the mesa, from the W to the E, the NE finger of the Maiden Creek sill splits into an upper and a lower sheet. These two thinner sheets extend for several tens of meters before terminating at the same lateral extent, and they both terminate along similarly oriented faults. A several-meter-thick, horizontal sedimentary block separates the two sheets (cross section A-A' on Fig. 5B). To the W of this intercalated sedimentary block, within the thick (stacked) sheet, a 2–3 cm thick solid-state igneous-igneous contact can be traced from the edge of the block for several meters and defines the boundary between the lower and upper sheets. Immediately to the E of the termination of these two sheets, another very thin sheet appears at a topographic level intermediate between the upper and lower sheets and extends for several tens of meters before thickening at the margin of the mesa. We suggest that the separation of one thick finger into an upper and a lower sheet, as well as the internal contact to the W of this split, supports our hypothesis that the Maiden Creek sill was constructed by stacking two sheets that share the same areal extent.

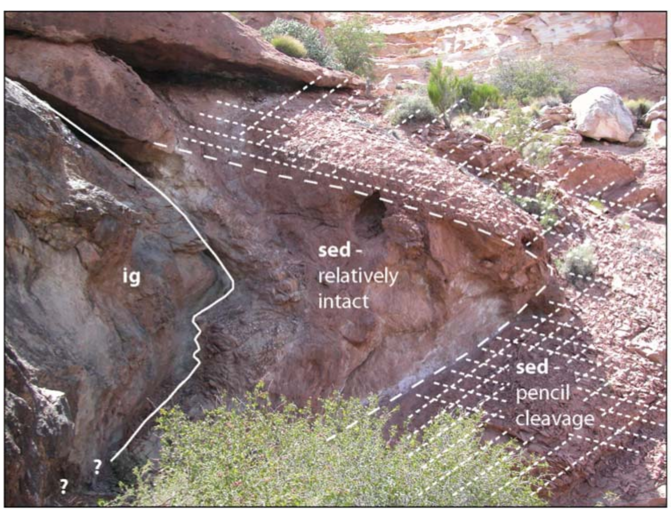

Figure 8 – Annotated photograph of the lateral contact between igneous and sedimentary rock at Stop 1.8. Solid line indicates contact between igneous and sedimentary rock. Long dashed line indicates boundary between relatively intact and pervasively fractured host rock.

PART II: TRACHYTE MESA LACCOLITH

Directions to Stop 1.10

Set odometer to zero. Turn around and head back N on Utah Highway 276. At mile 1.6, just beyond (N) the rise in the road, turn left and drive SW onto a dirt road (Fig. 9). At mile 2.0, stop on the dirt road when it approaches within ~40 m of a gully north of the road (Stop 1.10). Looking ~NW across the gully, there is a clear exposure of a meter-thick sandstone bed intercalated with igneous sheets at the top margin of the Trachyte Mesa laccolith.

Stop 1.10: View of the Southeast Margin of the Trachyte Mesa Laccolith

GPS (UTM): 536703, 4199129. Main point: Intercalated beds of Entrada Sandstone and igneous sheets within the margin of the Trachyte Mesa laccolith.

This is an excellent view of the sheeted nature of the Trachyte Mesa laccolith and the planar basal contact (Fig. 10A). The cliff face below the intrusion is the red Entrada Sandstone. The thickest and lowest sheet of the Trachyte Mesa laccolith is 8 m thick here. Directly above this basal sheet is a 1-m-thick bed of Entrada Sandstone. Directly above this sandstone layer are at least two more sheets. These two upper sheets have distinctively different erosional morphologies.

Directions to Stop 1.11

Continue SW on dirt road for ~0.2 mi. Park at clearing by large juniper tree with GPS location (UTM): 536254, 4198926. The road becomes less traveled beyond the juniper tree. At this point, the field trip will continue by foot. Head in direction 330 (azimuth) directly toward Bull Mountain (the last peak along the range moving toward the NE) on the E flank of Mount Ellen. Continue for ~300 m until you intersect a streambed. Walk downstream until the bed of the stream is igneous rock.

Stop 1.11: Top Contact of the Trachyte Mesa Laccolith

GPS (UTM): 536086, 4199194. Main points: (1) The composition and texture of the Trachyte Mesa laccolith are very similar to the Maiden Creek sill. (2) The upper igneous contact with undeformed and unmetamorphosed sandstone is well exposed. (3) The sandstone layer on the top contact here can be traced over much of the top of the laccolith.

The top contact of the intrusion is exposed and dips to the SW beneath sedimentary strata of the Entrada Sandstone. The exposed thickness of the intrusion increases greatly from SW to NE along the streambed as the top contact rises 20 m over a lateral distance of 100 m. The base of the intrusion is not exposed, but it is assumed to be very shallow (just a few meters?) beneath the southwestmost exposure of igneous rock. We assume this because the basal contact is exposed to the NE, outside of the stream gorge, along the cliff that was viewed from the road driving in. Wetmore et al (2009) suggest the intrusion just SW of here is approximately 10–15 m thick based on inversion of magnetic data.

The top several centimeters of the contact of the Trachyte Mesa laccolith have been eroded at this location. At other locations where the actual top of the intrusion has not been eroded, there is a 2–3-cm-thick carapace of solid-state deformation. Very limited (several centimeters or less) erosion occurred here, as evidenced by the upper contact with the sedimentary rocks exposed on the hillside.

The texture and composition of the Trachyte Mesa laccolith are very similar to the Maiden Creek sill. The rock has a micro-granular porphyritic texture with euhedral phenocrysts (up to 7 mm) of hornblende and plagioclase. The groundmass consists dominantly of

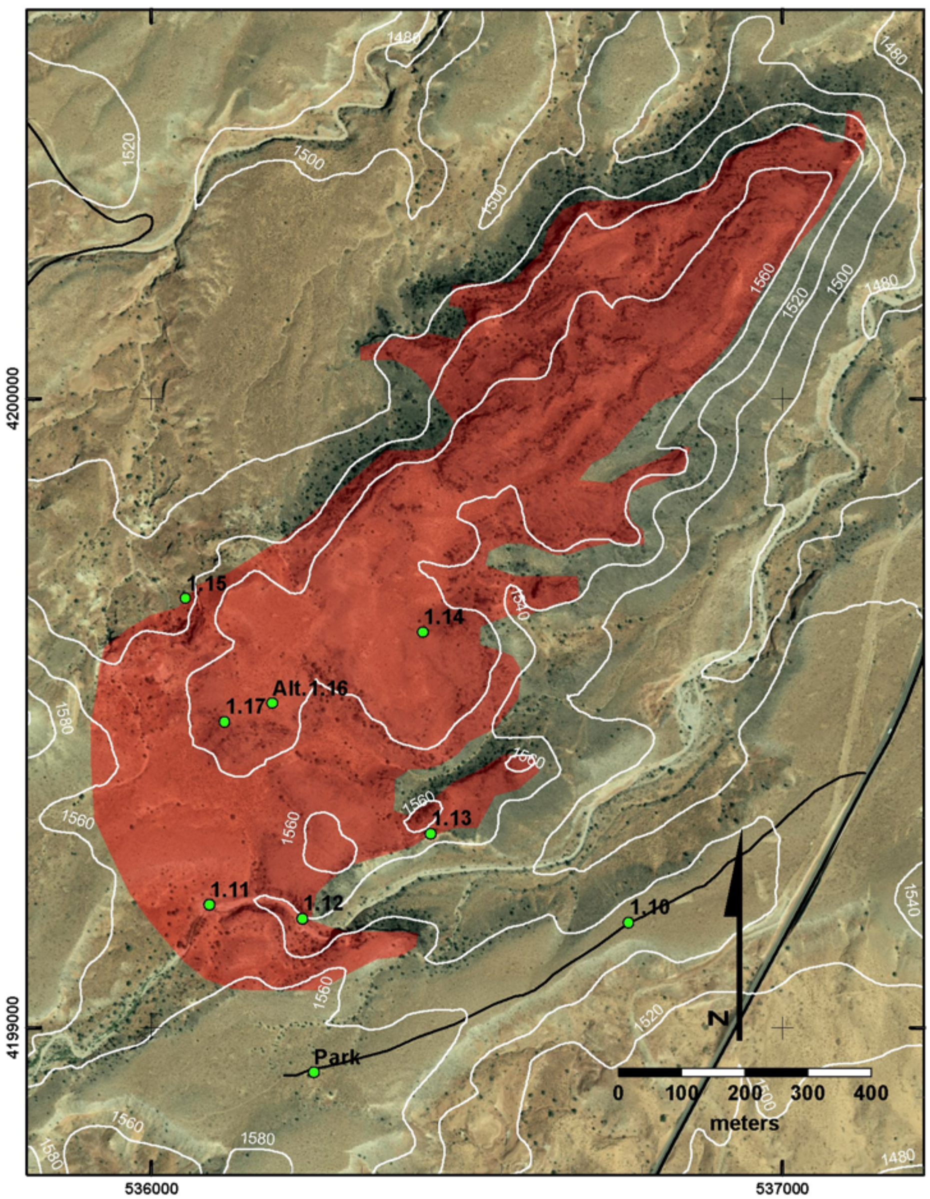

Figure 9 - Location of field trip stops on the Trachyte Mesa intrusion. Base map is an aerial photograph of the region. Outcrop of igneous rock indicated with red highlighting. Green circles indicate approximate stop locations and are labeled with stop numbers. Thick black lines are paved roads. Thin black lines are dirt roads. White lines are topographic contours with 20 m interval. UTM zone 12, datum NAD27.

microlaths of plagioclase and oxides (mostly magnetite). Most of the plagioclase phenocrysts exhibit concentric zonation. Many of the hornblende phenocrysts and larger oxides are partially or completely altered to finer-grained oxides and calcite. A few pyroxene and apatite phenocrysts are observed.

The sandstone at the upper contact is essentially unmetamorphosed and undeformed. However, within several centimeters of the intrusion, we often observe millimeter-scale nodules that resist weathering. These features exist locally throughout the region adjacent to intrusions. These nodules of sandstone have their pore spaces filled with calcite cement. We interpret the nodules to be late-stage features produced by percolation of deuteric fluids from the intrusion into the host rock. Oxides and hornblende in the igneous rock have also been partially replaced with calcite, providing further evidence of the effects of the late-stage fluids.

The sandstone layer is full of centimeter-scale holes and larger cavities. This tafoni weathering seems to be a marker for this particular sandstone layer. This weathered ~1-m-thick sandstone layer can be traced over the top of the Trachyte Mesa laccolith and over to the NW margin.

Directions to Stop 1.12

Walk downstream for 150 m, through a gorge that turns to the SE. Stop just past a 1 m drop in the creek bed and continue onto two large (~4 m diameter) boulders for an overview.

Stop 1.12: Differential Erosion of Sheets

GPS (UTM): 536236, 4199158. Main points: (1) Geomorphic evidence exists for multiple intrusive sheets. (2) The sedimentary layer beneath the intrusion is massive sandstone. (3) The basal contact is concordant and climbs upward to the SE because the sedimentary beds are tilted down to the NW.

The walls of the gorge we just walked through weather differently at different elevations. The upper part of the gorge, on both sides, has vertical cliff faces with multiple vertical joint faces. Approximately halfway down, both walls of the gorge step toward the center of the drainage. Several meters downward, the gorge walls become vertical once again. This differential erosion is best expressed on the N side of the gorge, where the jointing is also different between the top, middle, and bottom sections of the gorge walls. The middle section, which resists erosion and where there are very few joints, also increases in thickness gradually from the W to the E (downstream) and resembles a sill. This erosional profile may be the consequence of differential erosion of distinct igneous sheets. The differences in jointing within each 'step' down the walls of the gorge suggest the corresponding sheets cooled at different rates or at different times. Similar erosional and jointing patterns are routinely used to differentiate between basalt flows (e.g.

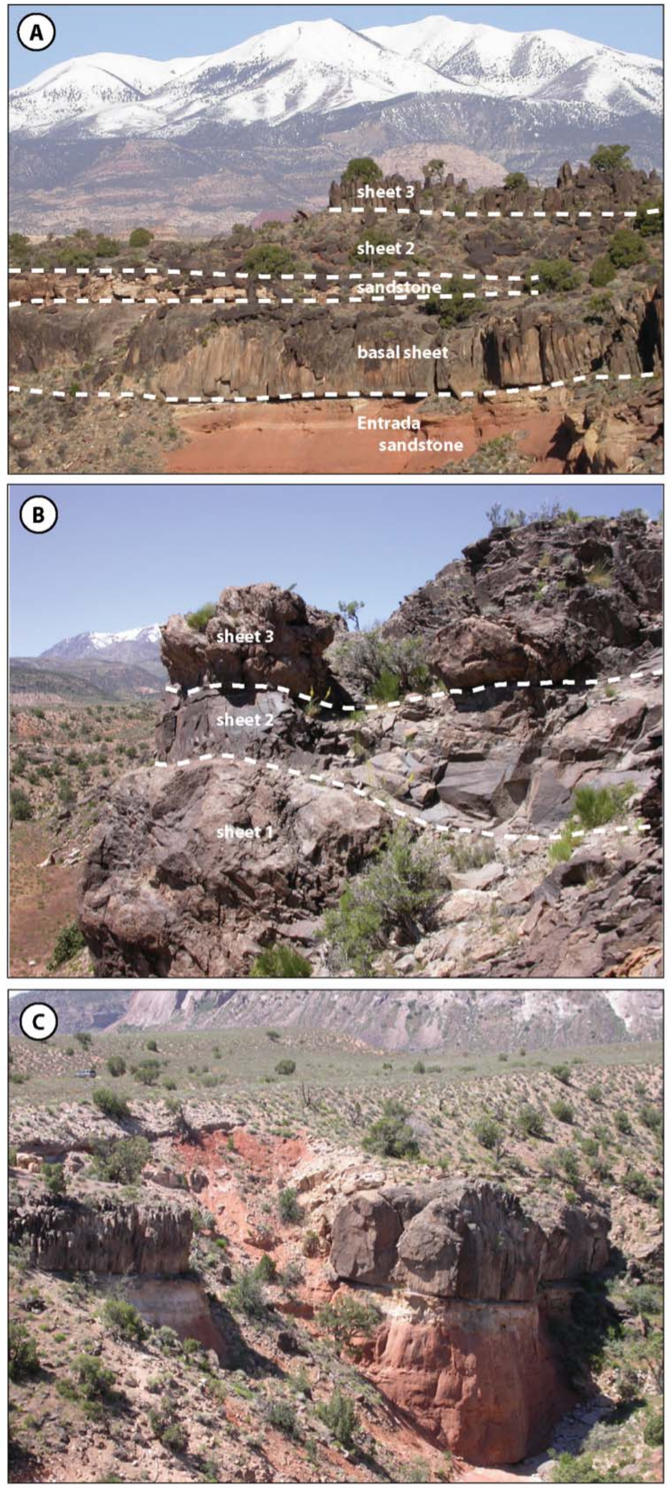

Figure 10 – Field photographs from the Trachyte Mesa intrusion. (a) Three igneous sheets and an intercalated sandstone layer above massive sandstone. The bottom sheet is ~ 8 m thick. View from Stop 1.10. We will examine these rocks at Stop 1.13. (b) Late, undeformed igneous sheet (sheet 2) between sheets filled with cataclastic bands. The middle sheet is ~1 m thick. (c) Two finger-like lobes viewed in cross section, separated by sedimentary host rock.

Cañón-Tapia and Coe, 2002). However, evidence here for distinct sheets is not entirely clear. AMS data from multiple vertical profiles along the walls of the gorge (see Morgan et al., 2008), suggest a stacked series of 2-4-m-thick sheets may exist here, but contacts between the hypothetical sheets are not apparent. If the intrusion is sheeted here, the lack of solid-state fabric may be a consequence of relatively slow cooling between magma pulses due to being located far from the margins of the body.

At the E edge of the gorge, the stream cuts through the margin of the laccolith. A small (<1 m) dropoff exists where the streambed changes from igneous to sandstone. Standing on the edge of the cliff, the basal contact is not exposed on the cliff wall below, but looking SE at the contact on the far cliff-face the basal contact is well exposed high on the cliff. The contact is concordant and bedding is dips ~9° to the NW. This NW dip to the bedding is consistent with the observation that the NW margin of the Trachyte Mesa laccolith is several tens of meters lower topographically than the SE margin. The top surface of the NE half of the Trachyte Mesa laccolith also dips to the NW. The top surface of the Trachyte Mesa laccolith in the SW has a relatively flat top.

This massive sandstone layer found beneath the contact is observed everywhere the basal contact is exposed. The base of the Trachyte Mesa laccolith is exposed around most of the SE margin and in a few places around the NW margin. Because the 1-m-thick sandstone layer is usually observed at the upper contact (except for Stop 1.13), and the massive sandstone layer is always found at the base, we believe the Trachyte Mesa laccolith is largely emplaced at a consistent stratigraphic level throughout its extent.

Looking SE at the far cliff face, the top contact is exposed on the cliff face and reveals a much thinner part of the Trachyte Mesa laccolith than in the gorge. This part of the Trachyte Mesa laccolith is actually a NE-trending finger, one of four such fingers along the SE margin. We will view the termination (cross-sectional view) of this finger from Stop 1.13.

Directions to Stop 1.13

Head back upstream toward Stop 1.11, but turn N up a tributary gorge after ~40 m. Head ~50 m up this gorge until you are atop of the intrusion. Walk toward an azimuth of 075 for ~250 m to the cliff that marks the SE extent of the mesa. Find the only place along the cliff-face where you can scramble down several meters without scaling the cliff. You will also find 1-m-thick blocks of sandstone along the top edge of the cliff face here. This is the cliff face we saw from Stop 1.10 (on the dirt road coming in) that has sandstone between sheets of the Trachyte Mesa laccolith.

Stop 1.13: Sheets, Fingers, and Intercalated Sandstone along the SE Margin of the Trachyte Mesa Laccolith

GPS (UTM): 536437, 4199312. Main points: (1) This margin of the Trachyte Mesa laccolith is composed of several sheets. (2) Early sheets are full of cataclastic bands, which may be a result of the emplacement of later sheets. (3) The contact between sheets is marked by a thin, solid-state shear zone. (4) Separate sheets erode differentially here, producing an irregular erosional profile. (5) The 1-m-thick sandstone layer, usually found at the top contact, is intercalated with thin igneous sheets near the top of the mesa. (6) Looking across the valley to the SW, the end of the fingers that we saw from the side at Stop 1.12 are visible. These fingers are similar in shape to the ones observed at the Maiden Creek sill.

Immediately SW of the sandstone blocks intercalated with higher level sheets, scramble down the margin several meters. Look SW at an irregular cross-sectional view of the rocks that make up the top margin of the mesa here. Figure 10B is a photo of these rocks and outlines the borders of the sheets as they form the margin of the mesa. The middle sheet is ~1 m thick and undeformed. The top and bottom contacts are marked by a 2-cm-thick solid-state shear zone of intense foliation defined by aligned plagioclase crystals that are cataclastically crushed and elongated. These contacts between sheets can be traced for at least 100 m to the SW. The sheets below and above are full of cataclastic bands that do not cross into the middle sheet. This brittle deformation suggests that emplacement of thr middle sheet involved high strain rates or that the magma already there had crystallized to a greater degree than the incoming sheet. In either case, the deformation supports forceful emplacement of the middle sheet. Clues to the mechanisms of forceful emplacement will be observed at Stop 1.14.

Scramble up to the top of the cliff again and walk several meters NE to examine the 1-m-thick sandstone blocks intercalated between sheets. Note how they are undeformed and unmetamorphosed and resemble the sandstone layer on the top contact observed at Stop 1.10. This may indicate that, although most of the laccolith was emplaced at the same stratigraphic level (just below this sandstone layer), some thin higher-level sheets were emplaced just above this sandstone layer.

Looking to the SW across the valley below, the southernmost finger is exposed and extends toward the NE (obliquely toward the viewer). Erosion reveals a cross-sectional view of this finger, which resembles two fingers side-by-side in shape (Fig. 10C). Sedimentary wall rocks are immediately to the left (SE) of this pair of fingers. The shape of these fingers resembles the fingers at the Maiden Creek sill. Approximately 15 m to the N of this exposure is another finger extending along the same trend (NE), but this finger is thinner. The link from this finger to the ‘double’ finger is unclear.

Directions to Stop 1.14

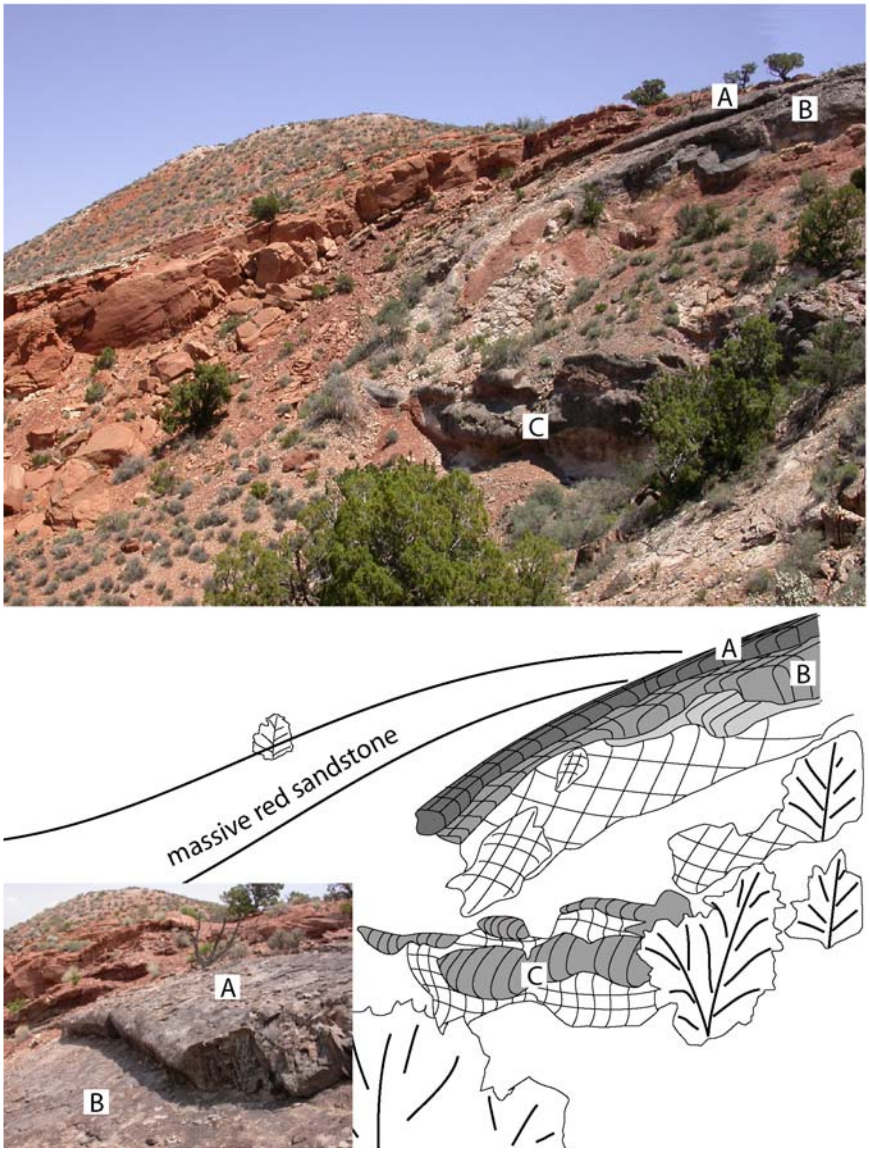

Figure 11 – Photograph and sketch of the outcrop at Stop 1.15. Massive red sandstone of the Entrada Sandstone (on left) rises up over the contact to become the roof of the intrusion. Sheets labeled A and B are geometrically sill-like, while sheet C is tongue-like. In the sketch, the white cross-hatched region indicates thin-bedded sandstones found below the massive red sandstone and just above the contact. The bulbous sheet to the left of letter C in the photograph is ~2 m thick. Inset photo was taken at the top of the intusion and is close-up of sheets A and B. Sheet A is ~50 cm thick.

Walk due N for ~400 m to a small rise in the center of the Trachyte Mesa laccolith where there is a view of the NE half of the laccolith.

Stop 1.14: Plateaus (Sheets?) on Top of the Trachyte Mesa Laccolith

GPS (UTM): 536428, 4199643. Main point: (1) The top of the Trachyte Mesa laccolith is composed of several plateaus, which may represent distinct magma sheets.

The top of the Trachyte Mesa laccolith is characterized by a series of small-scale plateaus and ridges. On the scale of the intrusion, these features are small irregularities on a relatively flat, subhorizontal surface. On the outcrop-scale, relatively flat areas (hundreds of square meters) often terminate at an escarpment, which rises up several meters (or less) to the next plateau or defines an elongate ridge. Ridges can be curved or straight and are commonly continuous for several hundred meters.

Looking to the NE from Stop 1.14, two main plateaus that shape comprise the top of the NE half of the mesa. Looking to the ENE, the first plateau is slightly lower in elevation and ends at the SE margin of the mesa. There is very little vegetation and abundant exposure of igneous rock. This surface is dipping slightly to the NW. Moving to the NNE, a small (1–2 m) cliff defines a slightly higher, second plateau. Both of these plateaus can be traced to the NE, where they become more narrow and then further to the NE more expansive again. We suggest that these plateaus may represent individual magma sheets because their geometries are sheet-like and they terminate along steep margins, similar to the terminations of known sheets (with wall rocks) at Maiden Creek sill. Some plateaus even terminate in bulbous margins.

Directions to Stop 1.15

Walk toward an azimuth of 260 for ~200 m toward the NW margin of the mesa. At the edge of the mesa you will find a basin that opens to NW, and you will have a cliff below you. Avoid the cliff in front of you and carefully make your way down, keeping to the left (SW) side of the exposure until you are ~1/3 of the way down, and standing on igneous rock. Looking from here to the NE you will have an overview of a thick (6 m) continuous red sandstone bed that rises up onto the top of the intrusion.

This is a very informative but complex outcrop, and there are several stops here. The basal and top contacts of the Henry Mountains intrusions are often observable, but this is one of the few locations in the region (and the only location on the Trachyte Mesa laccolith) where the wall rocks are preserved, well-exposed, and easily accessible as they are rotated upward to become the roof of the intrusion. There is also evidence for sheeting at this location and evidence for the relative timing of sheet emplacement and associated deformation.

Stop 1.15a: Overview of Lateral Termination

GPS (UTM): 536029, 4199604. Main points: (1) Geometry of the lateral termination of the intrusion. (2) Both sill-like sheets and tongue-like sheets are exposed here.

The edge of the laccolith is superbly exposed here (Fig. 11). At all other margins of the Trachyte Mesa laccolith, we assume the edge of the mesa is close to the actual termination of the laccolith, but this is only an assumption based on the shape of the margin (in many places the termination is bulbous). The thickness of the Trachyte Mesa laccolith is 43 m here, which is probably close to the maximum thickness of the intrusion. The valley floor is at the approximate level of the base of the intrusion. The top of the intrusion is composed of at least two, and possibly three sill-like sheets here. We differentiate between (1) sill-like sheets, which extend for tens of meters in two dimensions and are a maximum of three meters thick (A and B on Fig. 11); and (2) tongue-like sheets, which have a much smaller aspect ratio than sill-like sheets and are only exposed at the base of the laccolith here (C on Fig. 11). Looking NE, sill-like sheets extend from the top of the mesa (in the SE) to beyond the edge of the mesa and rotate downward and form the actual NW margin of the intrusion.

Most of the top sheet (A on Fig. 11) abruptly terminates ~1/4 of the way down the margin. The top sheet is ~50 cm thick and the termination is not tapered, but wall-like (the front surface is perpendicular to the top surface of the sheet). We assume the shape of this sheet is not erosional, but actually represents the true shape of the sheet because the thin (2–3 cm) cataclastic carapace is preserved locally along the top and wall-like frontal face. Further down the margin, the middle sheet (B on Fig. 11) continues until ~1/3 the way down to the valley floor and the slope of the margin becomes steeper. This sheet is irregularly eroded and is <1 m thick. The bottom sheet is also thin (<1 m) and extends slightly further down the slope. The bottom sheet may be part of the overlying (middle) sheet. In the middle third of the slope, there are sandstone layers concordant to the top of the lowest sheet with a dip-slope of ~65°. These sedimentary strata continue to the valley floor as a dip slope. Note that the white colored sandstone layer displays tafoni weathering (centimeter-scale holes and larger cavities) similar to the sandstone layer at Stop 1.11 although the sandstone layer is thinner here, possibly as a result of strain. This sandstone layer comprises the inner part of the contact zone.

The bottom third of this margin is composed of the sandstone beds discussed above, but they are sharply cut by tongue-like igneous sheets (C on Fig. 11). These tongue-like sheets are subhorizontal and are exposed for a maximum of several meters as they protrude outward from the sandstone dip slope. The frontal margins of these sheets are bulbous and some form nearly perfect hemispheres whereas some are more rectangular. Below these tongue-like sheets the sandstone strata dip at high angles (60–70°), but they are intensely deformed by multiple faults and currently erode into centimeter-scale blocks and slivers. Thin selvages of these cataclastically deformed sandstones are found on the frontal margins of some tongue-like sheets where they are even more intensely faulted and sheared.

Twenty to 30 m to the NE, a ~6-m-thick massive red sandstone layer can be seen as it rises up from a relatively flat-lying position in the NW to become the top of the intrusion in the SE (Fig. 11). This sandstone bed rises up over the igneous sheets discussed above and comprises the outer part of the contact zone. Below this massive sandstone layer is a 3-m-thick package of thinner sandstone and shale beds. At the base of this package is a 50-cm-thick sandstone bed that marks the inner contact zone. The actual contact with the intrusion is intensely sheared and faulted, and there are bedding-parallel faults between most or all of the different sedimentary layers here. The margin of the intrusion is also intensely sheared at the contact here and locally pieces of sandstone and porphyry are mixed and sheared into a fine-grained, intensely foliated rock.

It is important to note that the sandstone beds at the immediate contact with the laccolith, in the middle portion of the slope, have a much steeper dip than the massive red sandstone does on the outer part of the contact. We suggest this attests to the resistance to bending of the thicker, and possibly stronger, massive sandstone bed and leads to a space problem between the two layers. This space problem may result in the emplacement of the tongue-like sheets and will be discussed later.

The entire hillside you are standing on, which defines the edge of the mesa here, is a composite of many subhorizontal sill-like igneous sheets. Most of the igneous rock (and thus most of the internal contacts) is covered by a manganese oxide coating. The irregular shape of the slope often corresponds with the sheets. Look for areas of exposure along ridges and bumps that might be contacts. These sill-like sheets can be traced for many meters laterally and are commonly about 1 m thick with a maximum thickness of 2–3 m. Contacts between sheets are 2–3 cm wide and are defined by a strong foliation containing highly elongated and shattered plagioclase phenocrysts that are parallel to the subhorizontal sheets. Some sheets are deformed by abundant cataclastic bands; some sheets are undeformed. These observations are similar to the deformation observed surrounding the sheet at Stop 1.13. No clear order exists to the sequence in which the sheets have intruded. Based on the assumption that undeformed sheets are later than deformed sheets, later sheets intrude at various levels within the stack.

In summary, an entire cross section of the contact is revealed here. We are standing on the innermost portion, where sheets are stacked. Another 20–30 m to the NE, the sedimentary strata at the inner contact are exposed and have been rotated to high angles by the stacking of the sheets. Moving another 10–20 m NE, the outer part of the contact is exposed where a thicker sandstone layer is rotated upward and onto the top of the intrusion.

Directions to Stop 1.15b

Continue to carefully hike down the slope to the valley floor. Walk to the NE to examine the tongue-like sheets protruding through the sandstones at the base of the cliff discussed above.

Stop 1.15b: Late Stage Magma Tongues

GPS (UTM): 536059, 4199621. Main points: (1) Sheets at the valley floor are tongue-like in shape. (2) These tongue-like sheets intrude through inclined (not flat-lying) sedimentary rocks and indicate that these sheets are late. (3) Sheets have bulbous margins.

These tongue-like sheets protrude through and deform the inclined sandstones (Fig. 11), indicating these sedimentary layers had already been rotated to their presently inclined position prior to being intruded. Because these inclined sandstones mark the lateral termination of the laccolith, these tongue-like sheets are viewed as being very late in the emplacement of the Trachyte Mesa laccolith (they postdate the formation of the lateral termination). In contrast, the sill-like sheets on top are concordant to the sandstone that represents the margin, and therefore we believe those sill-like sheets represent the earliest emplacement of magma at this margin. The sedimentary rocks below the tongue-like sheets are intensely faulted and the lateral margins of some of these sheets are also marked by faults. The bulbous margin of some of these tongue-like sheets indicates they are exposed very close to their outer contact.

Directions to Stop 1.15c

Walk 20–30 m to the NE toward the massive red sandstone. Hike up the talus-covered slope between the exposed sheets to the SW and the red sandstone to the NE until you can walk onto the upper igneous sheets. You are almost at the top of the mesa here.

Stop 1.15c: Early Sheet Intrusion and Deformation of Overlying Sedimentary Rocks

GPS (UTM): 536075, 4199631. Main points: (1) There is intense solid-state deformation of the upper 2–3 cm of the sill-like sheets and magmatic textures beneath. (2) The sill-like sheet intrusions are early and tilted and their slickensided surfaces exhibit evidence for late slip. (3) There is intense brecciation of the sandstone bed immediately at the contact. (4) Flexural slip occurs on bedding planes and igneous-sedimentary contacts. (5) Thinning of the massive red sandstone bed is accommodated on the grain-scale (grain size reduction and porosity collapse).

Below the slickenside surface, the uppermost contact of these sheets exhibits a 2–3-cm-thick zone where the plagioclase crystals are intensely fractured, and in places completely shattered into micron-scale pieces, and these pieces were dragged along the foliation. On a macroscopic scale, the very fine grain size of the plagioclase pieces defining the foliation can be easily misinterpreted as ductile deformation of the plagioclase grains. On the surface, these pieces of plagioclase are dragged to form the obvious lineation that trends NW, perpendicular to the margin here. Shattered plagioclase grains have also been flattened to form a foliation, but the lineation is much stronger than the foliation, similar to the magmatic fabric found throughout the main body of the intrusion.

The top surfaces of the sill-like sheets on the margin here are composed of thin (<1 cm), green (chlorite?), very fine grained, striated, polished surfaces forming the contact between the sheets and the sedimentary cover. This low-grade slickenside surface suggests that these upper sheets were emplaced early in the emplacement of the Trachyte Mesa laccolith, and were subsequently uplifted, rotated, and sheared during flexural slip along contacts by later emplacement of the main body of the intrusion below. Supporting this hypothesis is the observation that the sedimentary layers below these sheets are also rotated into the same inclined position, presumably by the igneous mass behind them. The other possibility is that these sheets intruded late, but followed bedding planes. In this case, as the bedding rotates downward at the margin, sheets followed bedding and intruded downward as they encountered the already formed margin.

The sedimentary layers above the contact are deformed to varying degrees. Immediately above the contact, a 50-cm-thick sandstone layer is faulted and locally intensely brecciated. Some of this deformation might be related to the early emplacement of the top sheet, which terminates abruptly at this location, or it might be due to the later emplacement and inflation of the main igneous mass. There are faults between most (or all?) of the sedimentary layers between the contact and the massive red sandstone layer, suggesting that flexural slip has occurred to partly accommodate the upward rise and rotation of these layers. Immediately at the contact, the intrusion is also intensely sheared, but only for the top few centimeters. Approximately 1/3 the distance down the margin there is a zone of mixed sedimentary and igneous rock (top sheet) that is intensely sheared. Shear bands that cut across the foliation indicate that the sedimentary rocks were moving up and over the intrusion to the SE.

Detailed two-dimensional strain analysis (normalized Fry; Erslev, 1988) was completed on 32 sandstone samples taken from massive red sandstone layer (Fig. 12), which is a high-porosity (>10%) sandstone. Porosity data were collected from analysis of thin section photomicrographs. Strain ratios generally increase toward the middle and upper portions of the massive red sandstone layer and then slightly decrease at the top. Two-dimensional porosity data were also collected on most of the same samples.

The thinning of the massive red sandstone is a result of grain fracturing and grain boundary sliding, which together induce a porosity decrease. In Figure 12, there is a correlation between the increase in strain ratios and the decrease in porosity along the massive red sandstone layer. Microstructurally, there is a qualitative increase in fractures as porosity decreases and strain ratios increase. Fractures mostly emanate from grain contacts and in the

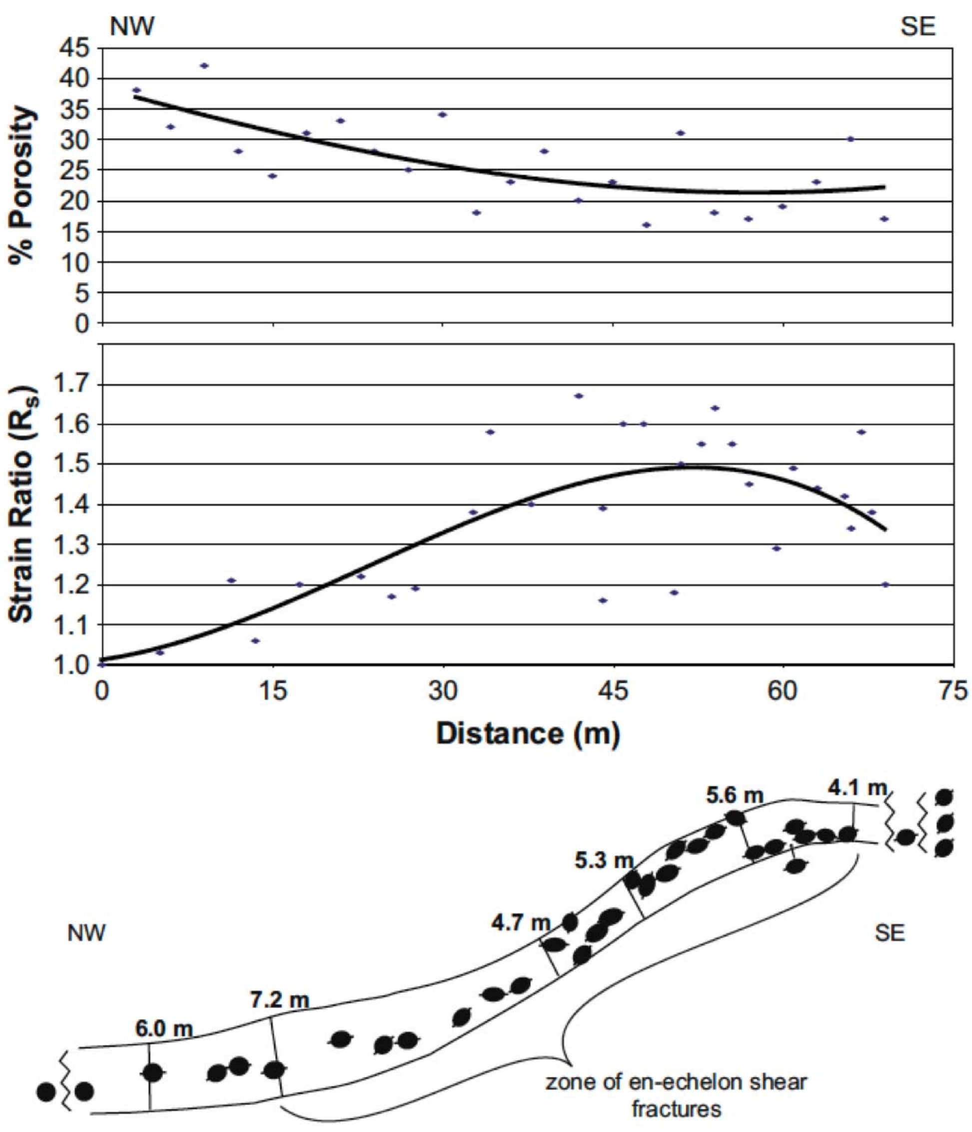

Figure 12 - Sample locations and measurements of thickness, finite strain, and porosity along the red sandstone bed at Stop 1.15. Strain ellipses and strain ratio based on normalized Fry analysis. Curves are best-fit third order polynomials (R^2 = 0.49 for porosity curve and 0.56 for strain ratio curve).

highly attenuated part of the sandstone later some grains are completely crushed. Crushed grains are not observed from samples at the NW end of the layer. We associate all of this deformation to emplacement of sheets and subsequent vertical inflation of the laccolith. The observation that the strain decreases as the sandstone rolls over on to the top of the intrusion is inconsistent with the 'rolling hinge' model of Hunt et al. (1953). In this model (one of three Hunt et al. proposed for emplacing laccoliths) an already thickened intrusion advances laterally as sedimentary rocks are rolled up and over the front of the advancing massive sheet.

Return to Stop 1.15a: Evolution of a Lateral Termination

Figure 13 includes an interpretative cross section of the margin at Stop 1.15. We envision an incremental assembly model for the Trachyte Mesa laccolith whereby vertical growth occurs through stacking of magma sheets. All the sill-like sheets stopped their lateral migration at generally the same location, similar to our observations at the Maiden Creek sill. There is one outcrop of a thin sheet located ~130 m N of the base of the mesa here, and this is why we place the lowermost sheet on our cross section. There does not seem to be any order to the vertical sequence of the sheets, except that the earliest sheets were lifted and rotated by subsequent, underlying sheets.

The vertical stacking of sheets causes the mechanically strong massive red sandstone at the marginal contact to bend upward and results in a low-pressure triangle-shaped zone at the base of and in front of the marginal contact. The low-pressure zone is created because the more massive sandstone layer is thick and strong and resists bending, and therefore does not conform exactly to the subvertical outward margin of the growing laccolith. The thinner bedded sandstones and shales immediately at the contact are more readily deformed and conform to the outermost shape of the contact. Because the magma is under high pressure, the decrease in pressure at these voids is immediately filled by tongue-like sheets, which at this time originate from the exterior margin of the accumulating stack. In our model, these tongue-like sheets were emplaced solely as a result of this low-pressure zone. This implies that changes in magma pressure are communicated throughout the growing body, even though the body as a whole is constructed of individual sheets. This idea of magma pressure communication is supported by the observation that all the tongue-like sheets at the base arrested at the same outward distance from the Trachyte Mesa laccolith, even through they were midway through deforming upturned sandstone layers. Once these tongues filled the low-pressure zone, it once again becomes more favorable to create sheets on top or elsewhere. Therefore in our model, the location and type of sheet is partly controlled by the strength, position, and orientation of the wall rocks, which are continually changing as more sheets are emplaced. The accumulation of sheets results in a flat-topped laccolith, which is actually the most common shape for the top of a laccolith (Corry, 1988).

Directions to Stop Alt.1.16

From the edge of the mesa here, walk toward an azimuth of 150 for 200 m until you see an ~1-m-thick sandstone bed eroding into blocks on top of the laccolith.

Stop Alt.1.16: Sandstone Roof of the Trachyte Mesa Laccolith

GPS (UTM): 536184, 4199544. Main points: (1) The current exposure of the top of the Trachyte Mesa laccolith is at or very close to the actual upper contact. (2) The same ~1-m-thick sandstone bed can be found at the upper contact on the SE, top, and NW margins, and bits and pieces of it can also be found throughout the top in the NE half of the mesa.

This sandstone bed here resembles the sandstone observed at Stop 1.10, Stop 1.12, and Stop 1.15c and is lying at the contact with the igneous rock of the Trachyte Mesa laccolith below.

Directions to Stop 1.17

Walk 100 m WSW to small knob of igneous rock. Looking NE there is an overlook of the SW half of the Trachyte Mesa laccolith and looking SW there is a plateau of alluvium that extends to the SW.

Stop 1.17: Overview of Internal Fabric, Feeder Conduits, and Assembly of the Trachyte Mesa Laccolith

GPS (UTM): 536132, 4199471. Main points: (1) Magmatic fabric characterizes most of the intrusion. (2) The Trachyte Mesa laccolith can be divided into two zones based on orientation of magnetic lineations. The dominant orientation is to the NE, parallel to the long axis of the intrusion, and is found mainly in a linear zone running down the axis of the intrusion. (3) Magnetic anomaly data support a NE-oriented pipe-like body at depth under the alluvium to the SW. This body is along a line extending from Mount Hillers toward Trachyte Mesa laccolith and possibly supplied magma to the intrusion.

This is a good vantage point to discuss the fabric of the Trachyte Mesa laccolith and the AMS pattern collected from on top of the intrusion. Microstructures from the surface of this outcrop support the interpretation of a magmatic (versus solid state) fabric. Phenocrysts of undeformed, euhedral plagioclase are mostly not in contact with other crystals. The lineation, which is much stronger than the foliation (L > S), is defined by elongate hornblende phenocrysts. In sections perpendicular to both foliation and lineation, it is often difficult to define the foliation.

The AMS (magnetic) lineations from the top of the Trachyte Mesa laccolith are very shallowly plunging and vary in orientation from SE to NE with the strongest concentration to the NE (Fig. 13). Magnetic foliations are subhorizontal. Based on patterns, we have divided the lineations from the Trachyte Mesa laccolith into two domains. The NE half of the intrusion contains a central linear zone where the lineations are consistently parallel to the long axis of the intrusion (trending NE). Away from this central zone, lineations fan and diverge outward to the NNW and ESE. In the SW half of the intrusion, the pattern of lineations is more complex but seems to define a central zone that curves but is approximately E-W. South of this zone, the lineations fan outward to the S. Figure 13 also shows inferred flow paths based on the magnetic lineations.

The magnetic lineation map from the top of the Trachyte Mesa laccolith (Fig. 13) suggests that the magma from the top sheets flowed along the long axis of the intrusion and spread radially outward to both sides. This pattern is particularly apparent in the NE half of the intrusion. In the SW half, the pattern of magma flow is more complex. We suggest this radial pattern is consistent with a linear centralized source that feeds sheets or fingers

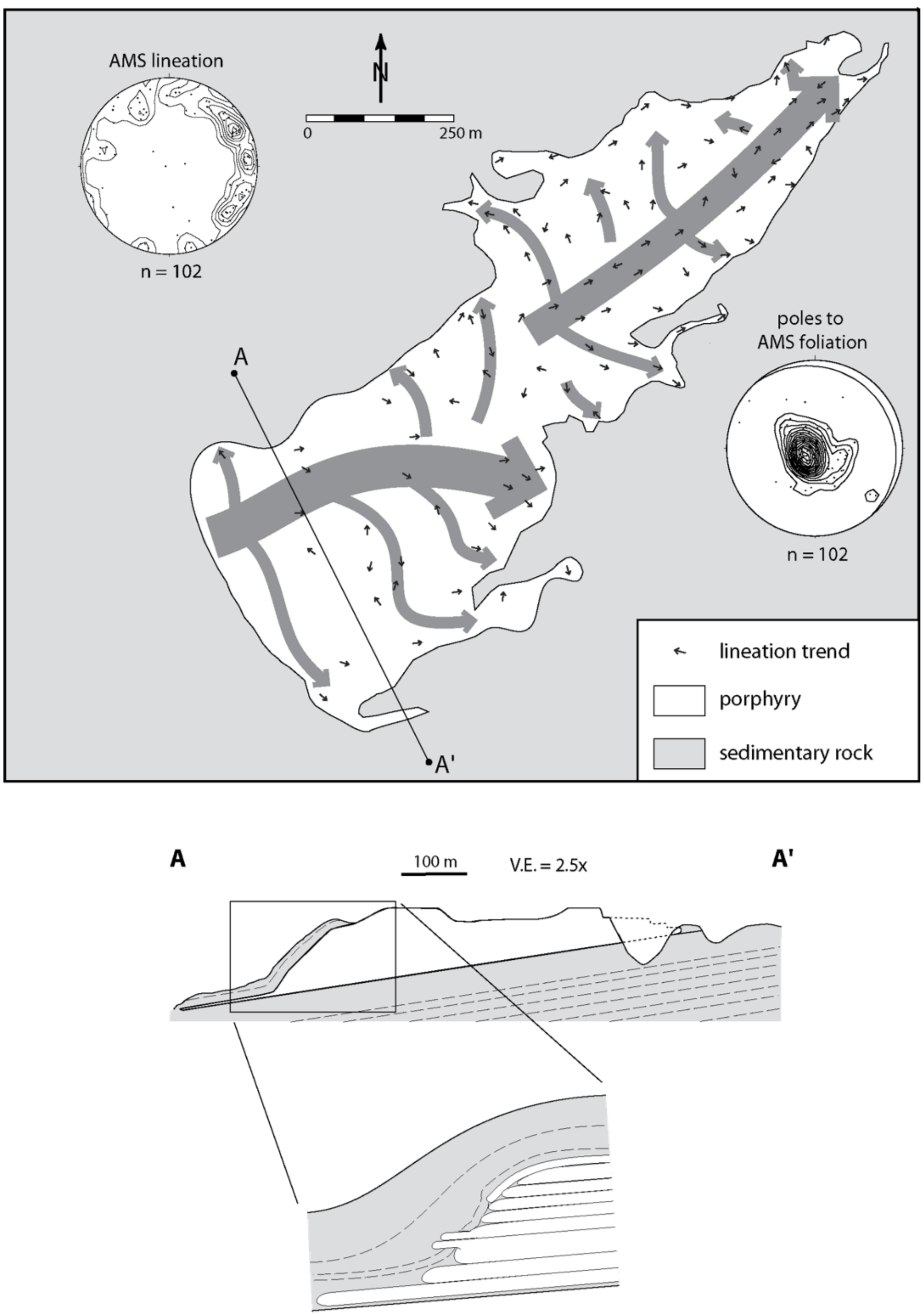

Figure 13 – Geologic map of and cross section through the Trachyte Mesa intrusion. Stereonets on the map show magnetic lineation orientations (upper left) and poles to magnetic foliation (lower right). Small black arrows on the map indicate magnetic lineation trends. Large gray arrows are inferred magma flow directions. Location of cross section A-A' indicated. The cross section is drawn with 2.5 times vertical exaggeration. Inset shows relationships between igneous sheets at Stop 1.15, with folded early sheets and emplacement of late sheets through steeply inclined sedimentary layers.

to both sides, but originates from the SW and is flowing generally to the NE. The magnetic lineations are also subparallel to the long axis of the plateaus in the NE half of the intrusion (Fig. 13), supporting the hypothesis that the plateaus represent sill-like sheets.

The map (Fig. 13) of the Trachyte Mesa laccolith illustrates that finger-like shapes protrude outward from the main body both parallel and perpendicular to the long axis, similar to what is observed at the Maiden Creek sill and consistent with the flow pattern inferred from the AMS lineations. We do not believe that all these fingers are merely erosional remnants because (a) the thicknesses of some differ considerably from the main intrusion, and (b) some of their lateral margins bulge, similar to the true terminal margins (where wall rocks are exposed on the margins) of sheets observed elsewhere. The NE tip of the Trachyte Mesa laccolith is also shaped into two small 'pinchers,' similar to how fingers seem to 'pinch' at the NE margin of the Maiden Creek sill (cf. Fig. 5).

To test possible the possible subsurface extent of the Trachyte Mesa laccolith, two groups have collected magnetic anomaly data over part of the alluvial plateau to the SW of the exposed intrusion. Nugent et al. (2003) concluded that several subhorizontal elongate igneous bodies extend SW of the exposed intrusion toward Mt Hillers at a depth of ~12 m. Wetmore et al. (2009) also conclude that the intrusion extends beneath the alluvium but their higher resolution data allow improved constraints on the depth, thickness, and geometry of the subsurface bodies. Overall, the magnetic data suggest the Trachyte Mesa intrusion extends at least 250 m SW of the current exposure as a body with a thickness of up to 30 m.

The dominant lineation orientation in the Trachyte Mesa intrusion is along a line that can be traced directly back to Mt Hillers, 12 km away, which is also parallel to the long axis of the intrusion. The magnetic anomaly data SW of the intrusion are consistent with a magma tube (finger?) originating from Mt Hillers, which intersects the Trachyte Mesa laccolith at the location the magnetic lineations emanate from. Dikes are rare in the Henry Mountains and have not been observed anywhere near these satellite intrusions The Trachyte Mesa laccolith may have originated as one long finger that began to branch outward into smaller fingers. Fingers expand their margins and coalesce with other fingers, which may be what we are observing at the NE margin of the Trachyte Mesa laccolith and Maiden Creek sill, where two fingers crystallized before completely coalescing. Fingers therefore evolve into sheets that are meter-scale in thickness. Once a sheet is emplaced, more sheets follow, but their sequence into the stack of sheets is not necessarily orderly, and partly based on wall-rock geometry and deformation.

A small outcrop of diorite porphyry exists approximately halfway between Mount Hillers and the Trachyte Mesa laccolith, described (with cross sections) by Hunt et al. (1953) and (with fabric data) Horsman et al., (2010). The igneous body is linear in map-view and aligned along a line connecting Mount Hillers to the Trachyte Mesa laccolith. One lateral margin of this body is exposed along a 2-m-high cliff with an irregular step-like contact. The base of the intrusion is not exposed. The other side of this body, where exposed, is very irregular in shape. The top is flat. The elevation of this body is much higher than the elevation of the Trachyte Mesa laccolith, but the position between Mount Hillers and the satellite Trachyte Mesa laccolith, as well as its alignment suggests a connection between Mount Hillers and the laccolith. While it is unlikely this intrusion actually represents the feeder for Trachyte Mesa, it may be a shallow portion (small dike?) of a larger, deeper intrusion that did feed magma from Mt Hillers to Trachyte Mesa.

End of First Day

Walk SE back toward Stop 1.11 and return to vehicles. Drive ~0.5 mi NE on dirt road toward Highway 276. Turn left on Highway 276 and drive N 5.8 mi to Highway 95. Turn left on Highway 95 and drive 26 mi NNW back to Hanksville.

DAY 2: BLACK MESA BYSMALITH, AND THE MAIN MT HILLERS INTRUSIVE CENTER

In the morning we will examine the NE margin of the Sawtooth Ridge intrusion and visit part of the Black Mesa bysmalith. In the afternoon we will conclude with an examination of the main Mt Hillers intrusive center in the Gold Creek area.

PART III: SAWTOOTH RIDGE INTRUSION AND BLACK MESA BYSMALITH

Directions to Stop 2.1

We are returning to the same location where we parked yesterday to examine the Maiden Creek intrusion (see directions for Stop 1.2). Figure 14 shows the location of the stops on the Sawtooth Ridge and Black Mesa intrusions. After parking the car, walk uphill toward an azimuth of 225 (~SW) for ~400 m. Once a reasonably flat plateau is reached, ascend the tallest knob of porphyry for a good view of the Sawtooth Ridge and Black Mesa intrusions.

Stop 2.1: Sawtooth Ridge Intrusion and Black Mesa Bysmalith Overview

GPS (UTM): 535387, 4195607. Main points: (1) Sawtooth Ridge exhibits evidence for multiple intrusive sheets with bulbous terminations. (2) Black Mesa is a bysmalith (fault-bounded intrusion) with flat-lying sedimentary rock on top. (3) There are weathering differences between the top ~40 m of the Black Mesa bysmalith and the main part of intrusion (~200 m). We suggest these differences may reflect the sheeted nature of the top. (4) The magma conduit to the Black Mesa bysmalith must be from the bottom of the intrusion in order to raise the sedimentary roof rocks.

Our primary goal at this location is to discuss the Black Mesa intrusion. However, a beautiful cross section through the Sawtooth Ridge intrusion is visible from here and we will briefly discuss this exposure before moving on to consideration of Black Mesa.

The cliff face WSW of here provides a cross sectional view of a distal portion of the Sawtooth Ridge intrusion (Fig. 15). The Sawtooth Ridge intrusion is a highly elongate, narrow body with a jagged top from which the intrusion gets it name. In map view, the elongate direction of Sawtooth Ridge points radially away from the central part of the Mount Hillers intrusive center. At Stop 2.8 we will have the opportunity to view the entirety of Sawtooth Ridge from a distance, from the dike-like SW exposures to the pipe-like NE exposures. Regional mapping of the SW end of the Sawtooth Ridge intrusion (Gwyn, unpublished mapping) suggests it may be fed by a series of dikes from the margin of Mt Hillers. The cliff face here on the NE end of the ridge exposes the complex cross-sectional shape of this intrusion (Fig. 15). From this vantage point, the general direction of magma flow during emplacement of this portion of the Sawtooth Ridge was presumably ENE, or out of the cliff and toward the viewer (assuming the magma flowed primarily parallel to the long axis of the intrusion). The geometries on the SW and NE ends of the intrusion suggest magma flow switched from dike-like feeders into the subhorizontal pipe-like igneous body seen here. Bedding in the sedimentary wall rocks is bent and faulted over the top of the intrusion. Two ~5 m thick igneous sheets, each of which ends in a bulbous termination, are clearly visible extending out from a more massive central body. We interpret these lateral extensions as separate sheets, based on our observations of other satellite intrusions in the region.

Figure 14 – Field photograph of NE margin of Sawtooth Ridge, including the lateral contact of the intrusion with surrounding sedimentary rock. Cliff is ~30 m high.

Looking WNW, the Black Mesa bysmalith is visible as a cylindrical pluton 1.7 km in diameter and with a maximum thickness of ~250 m (Figs. 16 and 17). Differential erosion between the surrounding sedimentary rocks and the igneous rocks has produced a very distinct mesa that outlines the intrusion (Fig. 16). In detail, the Black Mesa bysmalith is transitional between two forms of intrusions (Fig. 18).

Along the W side, not visible from here, the sandstones of the Morrison Fm. are geometrically continuous from the top to the bottom of the pluton, despite detailed cross sections showing that the wallrocks are faulted (Fig. 18a). No cataclastic shears or faults were observed in the diorite. The contact has a staircase geometry which shows a monoclinal bending (e.g. Koch et al., 1981): two narrow hinges, one concave at the base, and one convex at the top of the pluton, separated by planar and outward dipping beds of sandstone. The intensity of faulting is highest at the lower concave and upper convex hinges, and minimum or absent in the outward dipping wallrocks between the base and the top of the pluton, which appear as being rigidly rotated.

The E side, which you are looking at, is a bysmalith: a piston-like, cylindrical intrusion that accommodated upward wall rock displacement mainly through faulting. Wallrocks are horizontal up to approximately one hundred meters from the contact, then they are progressively rotated, until being vertical to slightly reversed at the diorite contact (Fig. 18b). Toward the base of the pluton, the contact is marked by steeply dipping normal and reverse faults with pluton-up movement, which separate moderately outward dipping wallrocks from massive diorite deformed by horizontal and vertical cataclastic shear bands. Above, the wallrocks are more vertical, and the contact appears to be geometrically concordant (vertical wallrock bedding, i.e. parallel to the contact), but is marked by a network of anastomosing subvertical faults, both in wallrocks and in diorite. In general, the intensity of fracturing increases toward the more vertical part of the contact. The vertical wallrocks contain a network of shallowly dipping fractures and faults that could be interpreted as rotated remnants of the initial stages of faulting. Fault slip is generally down-dip.

From this vantage point, one can observe two different erosional patterns on the lateral margin of the Black Mesa bysmalith. The top (~40 m) of the intrusion has a layered look, while the remainder of the pluton looks massive (see Stop Alt.2.4 for details on this topic).

Directions to Stop 2.2

Walk downhill ~300 m toward 355° and into the stream valley that runs E-W on the SE side of Black Mesa. Stop in the stream valley.

Stop 2.2: Bottom of Black Mesa Bysmalith

Figure 15 – Field photograph of SSE margin of Black Mesa intrusion taken from Stop 2.1. Cliff is ~130 m high.

GPS (UTM): 535159, 4195936. Main point: (1) Sedimentary rocks below the intrusion are undeformed.

The Black Mesa bysmalith is surrounded by subhorizontal strata, which abruptly change orientation and become subvertical at the contact. The roof of the bysmalith is flat, slightly N-dipping, and covered by concordant sedimentary strata of the Morrison formation. The presence of this formation at the base and the top of the intrusion in a flat-lying geometry led Hunt et al. (1953) and Jackson and Pollard (1988) to conclude that the floor of the intrusion is close to the current bottom exposure. Based on the stratigraphic section compiled by Jackson and Pollard (1988), who estimated thicknesses through regional correlation, a maximum of 2.5 km of sedimentary rocks overlay the Morrison formation at the time of emplacement, which constitutes the lithostatic load over the roof of Black Mesa bysmalith.

At this stop, we will examine the sedimentary strata of the Morrison formation at approximately the same level as the base of the intrusion. The rocks here are essentially undeformed and unmetamorphosed.

Directions to Stop 2.3

Follow the stream valley uphill and to the W for ~0.5 km. Walk due N out of the stream bed and uphill for ~200 m toward the cliff that delineates the southern margin of the Black Mesa bysmalith.

Stop 2.3: Cataclastic Bands on the Margin of the Black Mesa Bysmalith

GPS (UTM): 534876, 4196032. Main point: (1) Subhorizontal cataclastic bands on the margin of the Black Mesa bysmalith are similar to those observed at the Trachyte Mesa laccolith, where they delineate separate magma sheets.

On the cliff face of the Black Mesa bysmalith here, there are 1–2-m-thick subhorizontal zones rich in anastomozing cataclastic bands separated by 10–20 m of undeformed igneous rock (Habert and Saint Blanquat, 2004; Saint Blanquat et al., 2006). On the margins of the Trachyte Mesa laccolith, sheets are partly identified by similar zonation of brittle deformation and no deformation. However, sheets are also delineated at the Trachyte Mesa laccolith by 2–3-cm-thick shear zones at the contacts, and this is not observed here.

Directions to Stop Alt.2.4

Walk W ~0.5 km, contouring around the cliff and up to the saddle on the SSE margin of the Black Mesa bysmalith.

Stop Alt.2.4: Black Mesa Bysmalith in the Saddle

GPS (UTM): 534040, 4196106. Main points: (1) Despite textural differences, composition and fabric of the Black Mesa bysmalith are very similar to the Maiden Creek sill and the Trachyte Mesa laccolith. (2) Complex relationship (more intrusions) with main Mount Hillers body. (3) AMS lineation have shallow plunges on top and moderate to steep plunges on side, which corresponds with a geomorphic distinction between top and margin of intrusion.

A typical specimen of the Black Mesa bysmalith is a diorite porphyry with a microgranular porphyritic texture and consists of ~45% phenocrysts (35% oligoclase, 8% hornblende, 2% clinopyroxene, and ~55% groundmass (mostly plagioclase and hornblende).

The magmatic fabric at Black Mesa bysmalith is ubiquitous and defined by the preferred orientation of plagioclase and hornblende phenocrysts. The lineation is strong but the foliation is sometimes difficult to recognize in the field, similar to the Maiden Creek sill and the Trachyte Mesa laccolith. Fabric orientation varies with vertical position in the body. Subhorizontal foliations occur at the top and the bottom of the intrusion, and steeper, outward and inward-dipping foliations occur around intrusion margins. The preferred orientation of hornblende is the most obvious field structure and defines an easily measurable lineation.

Ductile and/or cataclastic deformation is observed near the top of the pluton-wall rock contact, where the outermost few centimeters of the intrusion are sheared. Along the margins at vertical contacts, undeformed hornblende phenocrysts are aligned parallel to vertical fault striations, suggesting that fault movement was synmagmatic. Shear sense indicators show that magma moved upward relative to wall rocks during the emplacement, which is in agreement with the tilting of the surrounding wall rocks.

This fabric is characterized, on the scale of the intrusion, through the use of AMS and image analysis. The magnetic foliations on the surface of the pluton define an outward dipping dome-shaped pattern, which is concordant with the pluton margins. Thus, the pluton margin exerted a strong influence on flow and/or deformation within the interior of the evolving pluton. Steep foliations, that are sometimes inward dipping, are found along the eastern margin of the pluton and could be related to vertical flow due to peripheral fault activity.

The magnetic lineations are more instructive. Magnetic lineations within the pluton are characterized by a trimodal distribution of trends and dip (Fig. 19; also see Habert et al., 2004; Saint Blanquat et al., 2006): (1) lineations localized on the very top of the intrusion are horizontal and have a general WNW-ESE trend; (2) lineations from sites below the roof of the Black Mesa bysmalith are horizontal and have a NNE-SSW trend; and (3) lineations localized along the eastern margin and within late dikes are vertical.

Located at the SSW end of the Black Mesa bysmalith, and in apparent morphological continuity with it, is a diorite ridge or saddle (Figs. 14 and 17). Hunt et al. (1953) suggested this was a lateral injection zone that supplied the intrusion with magma. Our data do not support this interpretation. First, detailed mapping indicates that these two bodies are separated by the host rock of the Morrison Formation. Second, the two bodies have different phenocryst contents and are of different petrographic facies (epidote versus cpx facies). Last, the presence of a lateral feeder zone should have induced a symmetry in the internal fabric pointing toward the feeder, presumably toward the SSW, which is not observed in the AMS patterns (e.g., the lineation pattern is not radial from where the diorite body would connect to the body).

Our observation of a bilateral symmetry of the fabric pattern supports a model where magma is injected from a conduit situated below the Black Mesa bysmalith. This is consistent with an earlier suggestion by Pollard and Johnson (1973) for a vertical feeder dyke below the bysmalith. The exact nature, geometry, and orientation of this feeder are not possible to determine precisely with our data. There are, however, the two planes of symmetry of the fabric (NNE- SSW or WNW-ESE) that may provide some constraints on the orientation of the feeder

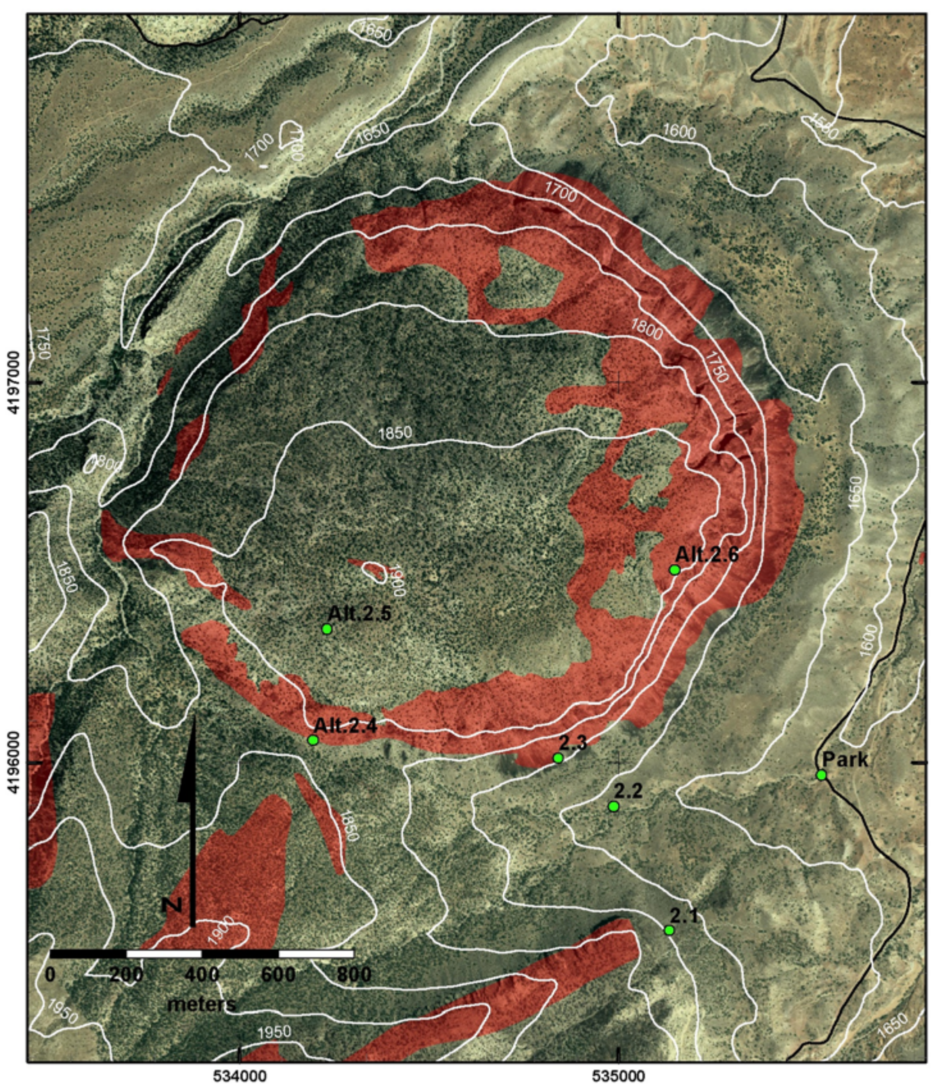

Figure 16 - Location of field trip stops on the Sawtooth Ridge and Black Mesa intrusions. Base map is an aerial photograph of the region. Outcrop of igneous rock indicated with red highlighting. Green circles indicate approximate stop locations and are labeled with stop numbers. Thin black lines are dirt roads. White lines are topographic contours with 50 m interval. UTM zone 12, datum NAD27.

zone. Moreover, the asymmetry of the 3-d shape of the pluton, with its thickness increase from west to east, suggests a NNE-SSW planar feeder, not exactly in an axial position but in a slightly off-axis position toward the east.

Directions to Stop ALT.2.5

Walk ~200 m N to any of several outcrops of Morrison Formation sandstone.

Stop ALT.2.5: Flat-Lying Sedimentary Rocks on Top of the Black Mesa Bysmalith

GPS (UTM): 534147, 4196333. Main point: (1) Flat-lying sedimentary rocks of the Morrison Formation on the top of the Black Mesa bysmalith require an upward translation of up to ~250 m (on the E side of the intrusion) with very little rotation or distortion.

The roof of the Black Mesa bysmalith is flat, slightly N-dipping, and covered by concordant sedimentary strata of the lower part of the Morrison formation. These strata are equivalent to the flat-lying, unmetamorphosed strata surrounding the base of the intrusion. This geometry requires that these wall rocks were translated vertically with very little any rigid-body rotation or internal distortion.

The asymmetric form of the intrusion, with its gently

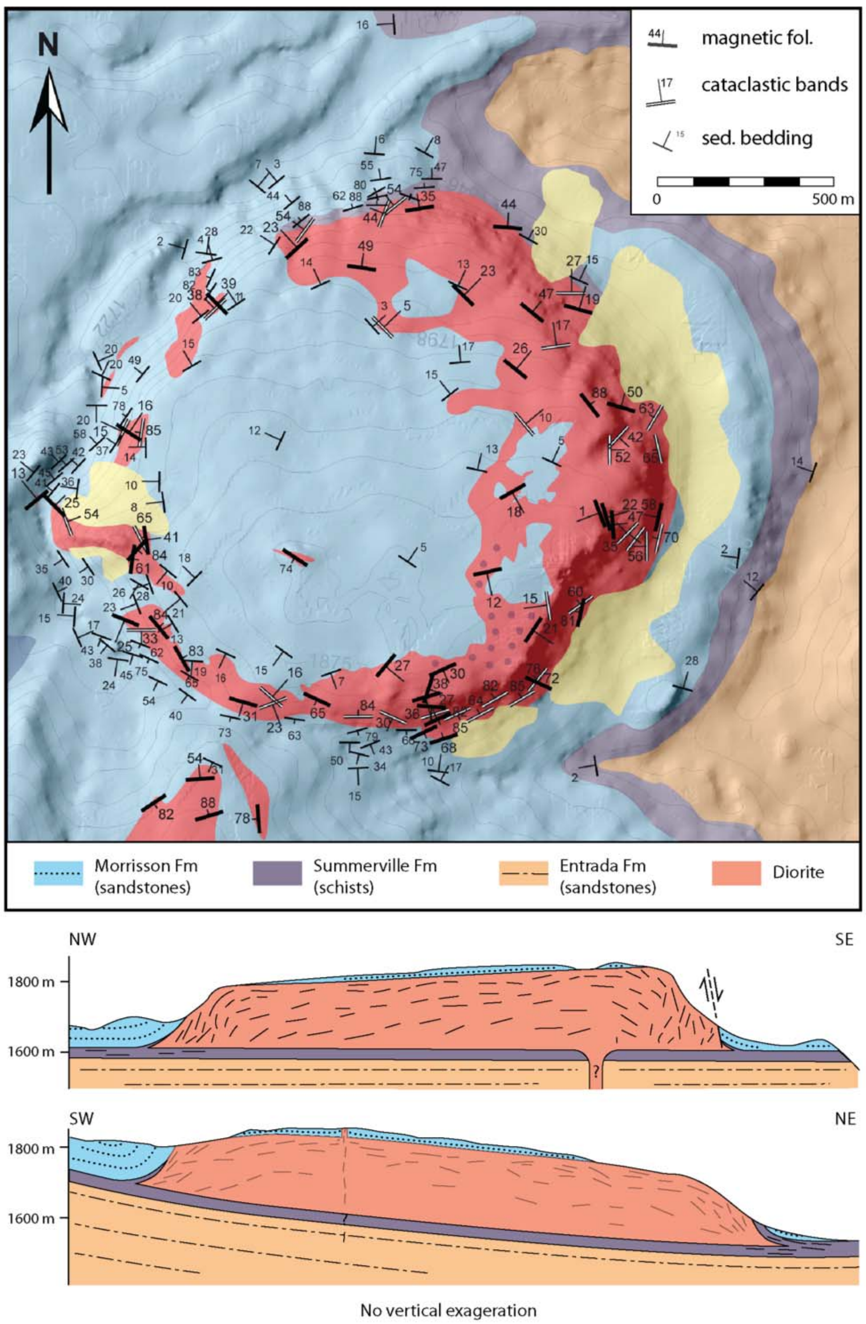

Figure 17 – Geologic map of and cross sections through the Black Mesa intrusion.. On the cross sections, thin black lines inside the intrusion indicate approximate fabric orientation.

N-dipping roof (Figs. 17) is associated with a thickness increase toward the E, and can be attributed to the combination of (1) a primary asymmetry developed during assembly, with more magma injected at the eastern part of the pluton (see above), and (2) a tilt toward the NE due to the growth of Mount Hillers. A very clear stretching lineation trending N310 is measurable in the diorite at the contact, which is different from the N010 measurement obtained by AMS on a sample taken 20 cm below the contact.

Directions to Stop ALT.2.6

Walk toward 080 (ENE) for ~1 km. Please stop when you reach the top of a precipitous drop-off.

Stop ALT.2.6: Overview and Assembly of the Black Mesa Bysmalith

GPS (UTM): 535202, 4196654. Main points: (1) Comparison of evidence for sheeting in the Black Mesa bysmalith with the Maiden Creek sill and the Trachyte Mesa laccolith. (2) Assembly model for the Black Mesa bysmalith.

This location provides an overview of the three principal bodies that we have investigated on this field trip: The Maiden Creek sill, the Trachyte Mesa laccolith, and the Black Mesa bysmalith. We envision that each of these bodies represents a snapshot of the growth history of a small shallow pluton during progressive assembly: (1) sill intrusion, (2) inflation through stacking of sheets and accommodated by overburden bending, and (3) inflation accommodated by roof lifting along peripheral faults. The Maiden Creek sill records evidence only of the first episode, the Trachyte Mesa laccolith records the first two stages, and the Black Mesa bysmalith records evidence for all three. The clear recognition of individual magma injections may be lost in the third stage. We hypothesize, however, that this mechanism may continue to function during the later stages of emplacement. Given that the emplacement history of Maiden Creek sill and the Trachyte Mesa laccolith were covered earlier, we focus primarily on Black Mesa bysmalith.

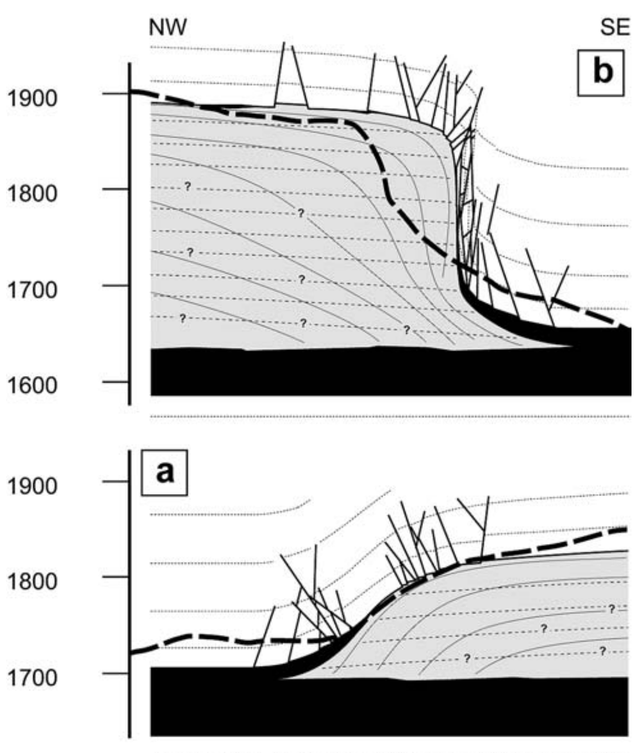

Figure 18– Cross sections through the margins of the Black Mesa intrusion. (a) Western margin. (b) Eastern margin. Thick dashed line indicates modern topography.

The study of the mechanisms of emplacement of the BMb, deduced from its internal texture and fabric, is hampered by the fact that we have no access to the real core of the pluton. However, given that (1) we observe rapid and localized change of fabric orientation (rotation of the finite strain principal axes) only at the pluton contact and a homogeneous fabric pattern everywhere else (see above), and (2) the relatively simple circular and tabular 3-d shape of the intrusion, we can reasonably hypothesize that no major changes of fabric pattern occur toward the pluton's centre.

The comparison of the foliation and lineation patterns allows us to propose a spatial partitioning of the internal fabric of the BMb in four main zones. Domain 1 is located on the very top of the pluton, where we have observed WNW-ESE magmatic and cataclastic lineations, associated with sub-horizontal, contact-parallel foliations. Domain 2 constitutes the main body of the pluton, and is characterized by a magmatic fabric with sub-horizontal to outward-dipping foliations and sub-horizontal to moderately plunging NNE-SSW lineations. Domain 3 is located along the east and south-east margin of the pluton, and characterized by sub-vertical to inward-dipping foliation associated with sub-vertical lineations. Domain 4 is constituted by rare late-stage WNW-ESE dikes of microdiorite, characterized by sub-vertical foliations and lineations, that cut all the previous types of fabric.

Several observations allow us to chronologically interpret this spatial variation of the internal fabric : (1) the geometry of the wallrocks, which show clearly their vertical displacement due to the growth of the pluton, and consequently imply under-accretion of magma pulses; (2) the mutual cross-cutting relationships and relative position of the four different fabric domains; and finally (3) our data from the adjacent MC sills and TM laccolith. Considered together, these observations allow us to infer a relative chronology from domain 1 to the latest pulses in domain 4. At the top of the pluton, domain 1 contains the oldest fabrics that were formed during the intrusion of the very first magma pulse, and then show the strain record associated with the initial sill emplacement. Domains 2 and 3 cannot be separated temporally based solely on structural data; they are volumetrically the more important and contain an "inflation" fabric formed during pluton growth accommodated respectively by wallrocks bending, faulting and rotation in domain 2, as observed now in the west part of the BMb, and by roof lifting along peripheral faults in domain 3, as shown by the association of vertical magmatic lineation foliation and the vertical pluton-up faults along the south-east margin of the pluton. Finally, the dikes of domain 4 cross-cut all of the above fabrics, represent the latest intrusion within the pluton, and are thus the youngest features.

If our model of accretion of magma pulses from below (and not laterally) is correct, then the upper part of the pluton represents the oldest magma sheet. Consequently, the kinematics at the pluton-wallrock interface represents the kinematics of the initial magma intrusion. In this case, the WNW-ESE magmatic and cataclastic lineations at the top of the pluton are the record of the relative movement between the magma and the wallrocks during the formation of the initial sill. Due to the strong temperature contrast between magma and host-rocks at that time, the external part of the first pulse was chilled and cataclastically deformed during sill growth. At a few centimeters below the upper contact, the lineation rotates progressively to a NNE-SSW orientation and is magmatic. We believe this lineation orientation records the stretching direction within the flowing magma, rather than the relative displacement between the flowing magma and the wall rock. This interpretation implies that within less than 10 cm, the magmatic flow becomes essentially unaffected by the kinematics at the upper contact. The distinction between the different fabric development environments is explained in Figure 20 based on distance from the upper contact. In the first centimeters below the contact, the fabric records the magmatic flow direction (particle paths on Fig. 20b). As the thermal gradient within the magma decreases, fabric orientation remains consistent but changes from solid-state to magmatic in character. At greater distances from the contact, fabric records the stretching direction within the magma itself (see the strain ellipses in Fig. 20a). Because the magma is diverging away from the feeder, the stretching direction is at a high angle to the flow direction of individual particles. The foliations within the evolving sill would have been oriented parallel to the sill plane, i.e. parallel to the sub-horizontal sediments. Close to the sill margin, and induced by the lateral propagation of the intrusion, the fabric could rotate to be more parallel to the contact. It should be noted that the sill occupies a particular structural position, as it is located at a weak interface, the Summerville Fm., between two rigid layers of sandstones, the Entrada Fm. below and the Morrison Fm. above.

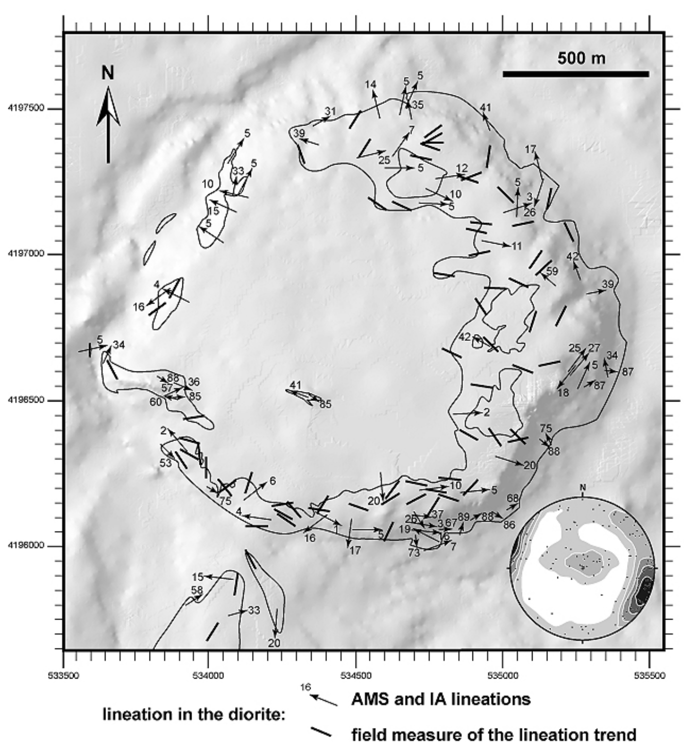

Figure 19– Map of field and magnetic (AMS) and image analyss (IA) fabrics in the Black Mesa bysmalith.. Inset stereonet shows contoured lineation orientation data.

Except for the outermost few centimeters (see above), there are no major structural changes between the upper part of the pluton (the initial sill) and the layers situated below. This observation suggests that, after the first sill intrusion, the mechanism of growth did not change radically during emplacement. Thus, either all the magma was injected after a single pulse or the body consists of a series of sheets that either coalesced or show similar fabrics. We support the latter model, primarily because of our field observation of distinct sheets in the pluton and in the nearby smaller igneous bodies (Maiden Creek, Trachyte Mesa).

In our model, the final horizontal size of the BMb is mainly achieved at the end of the intrusion of the initial sill, and bending of wallrocks occurs only at the tip of the intruding pulse. The wallrocks suffer mainly vertical translation, and only minor thinning because of the small area increase. This forcible emplacement mechanism is mainly indicated for the BMb by (1) the foliation pattern and its concordance with the pluton–wall rock contact, (2) the deformation pattern within and around the pluton, and (3) the syn-magmatic nature of deformation at the pluton margin. Our proposed kinematic model is that each pulse of magma intruded horizontally below the previous one, nearly at the base of the growing pluton. The overlying, already-intruded sheets and wallrocks are mainly uplifted, and only slightly deformed by subsequent magma intrusions. Due to the strong margin control, the magmatic foliation dip increases toward the external contact. The magmatic lineation is parallel to the feeder long axis in the pluton centre and parallel to the contact at the pluton margins. We note that the control exerted by the contact was less marked in the north part of the pluton, where the lineation remain NNE-SSW, i.e. parallel to the feeder horizontal long axis. A slight bending and thinning is observable in this "cap" of pre-existing, overlying intrusion by (1) the curvature of the lineation pattern at the top of the pluton, (2) the elliptical shape of the foliation pattern, and (3) some shear criteria and small scale horst and graben structures at the upper contact.

Margins of the BMb are not similar all along the periphery of the pluton. The "bysmalithic" faults assisted growth stage phase is therefore more complex than previously described by Hunt et al. (1953) and Pollard and Johnson (1973), and a simple piston model is not appropriate. The lineation along the eastern margin is subvertical, and the foliation is parallel to the contact and subvertical to steeply inward deeping. These structures are markedly different from those observed in the western part of the pluton and probably are the result of a different emplacement mechanism (e.g. "bysmalith" versus "sheeted laccolith"). This change in the mode of space accommodation between the sheeted growth and the fault-assisted growth stages may be the result of dissimilar magma supply rates in the different parts of the pluton. The input of more magma in the east may have induced a rupture in the continuity of wallrocks and the development of margin parallel faults, producing the asymmetric pluton geometry we observe. The origin of this asymmetry in magma input can be explained by an asymmetric position of the feeder (see above).

In summary, the Black Mesa bysmalith appears to have gone through a sill phase, a sheeted-laccolith phase, and finally a bysmalith phase only along its eastern margin (Fig. 21). There is evidence for the first two phases within the Black Mesa bysmalith, but there is no definitive evidence for sheeting during the final bysmalith phase. However, the relatively large volume of magma present during inflation of Black Mesa bysmalith would cool relatively slowly and be unlikely to preserve evidence of contacts between sheets emplaced in rapid succession (Habert & de Saint Blanquat, 2004; Saint Blanquat et al., 2006).

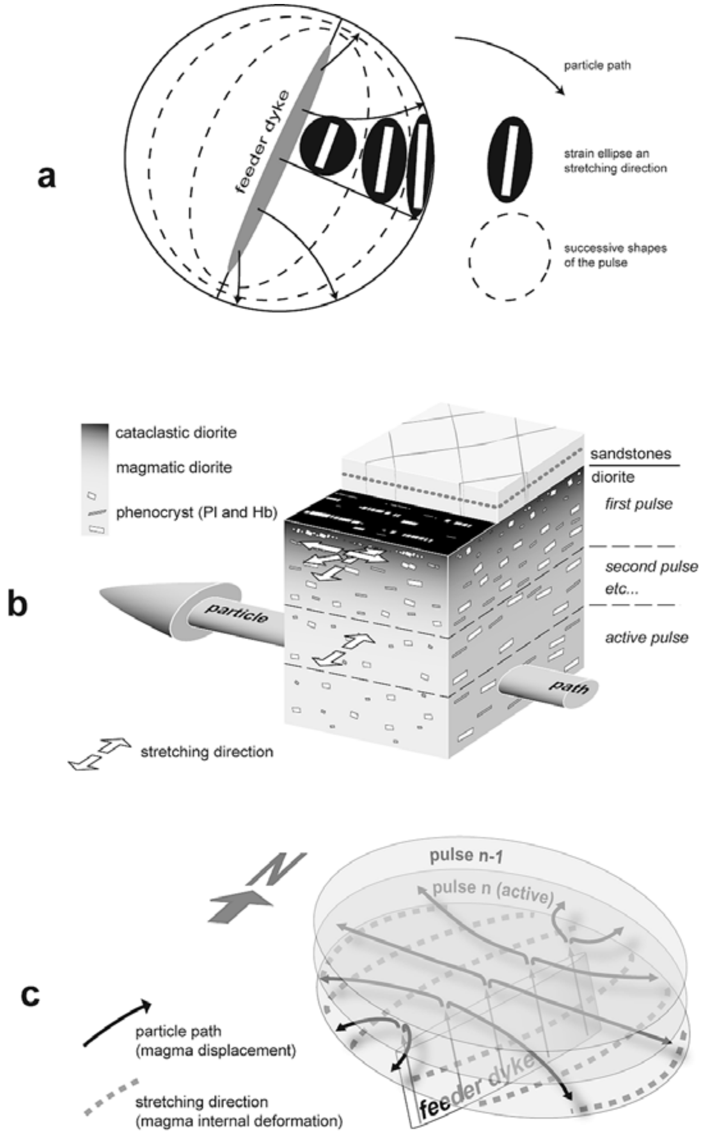

Figure 20– (a) Theoretical relationship between strain and magma flow in a growing sill. (b) Kinematic interpretation of the internal structure of Black Mesa bysmalith. (c) Kinematic interpretation of inflation of the intrusion – not exactly to scale.

Directions to Stop 2.7

Return to the parked cars at the base of Black Mesa. Drive N on this dirt road (back the way we came) until the intersection with Utah Highway 276. Turn right and drive S for 9 miles to the turnoff for the Starr Springs BLM campground. Turn right onto this dirt road and drive 3.3 miles N back toward Mt Hillers. When you reach an intersection between two well-graded dirt roads, turn W (left). Drive 1.5 miles and park when the road bends modestly to the left (SW).

Stop 2.7: View of S face of Mt Hillers

GPS (UTM): 527840, 4188177. Main points: (1) Roof uplift is the primary space-making mechanism for the central Mt Hillers intrusion. (2) Previous work suggests early sills were rotated upward by subsequent emplacement of underlying magma.

The S face of Mt Hillers is visible from this location. The steeply dipping white beds of the Jurassic Navajo sandstone provide photogenic evidence of the primary space-making mechanism for the magma of the central Mt Hillers intrusion: roof uplift. Igneous sills and dikes are intruded into the Navajo sandstone and older sedimentary units. The oldest sedimentary units exposed on the S side of Mt Hillers, the Cedar Mesa member of the Permian Cutler Formation (Jackson, 1991), provides an estimate of the depth of the bottom of the main Mt Hillers intrusion (Jackson & Pollard, 1988). This depth also correlates fairly well with the approximate structural level of the base of the intrusive center estimated from inversion of aeromagnetic data (Jackson & Pollard, 1988).

Paleomagnetic analysis indicates the sills visible on the S face of Mt Hillers were intruded and cooled while still subhorizontal (Jackson & Pollard, 1988). This result implies the magma of the central Mt Hillers intrusion was emplaced after these early sills and rotated them to their current steeply dipping orientation. Thus, multiple magma pulses must be responsible for assembly of the Mt Hillers intrusive center as well as the satellite intrusions already discussed.

Directions to Stop 2.8

Drive back to the intersection 1.5 miles E of here. Turn left (N) and drive 0.2 miles to the next intersection, passing the ruins of Starr Springs ranch. At the intersection, turn right on the dirt road (turning left leads to the campground, where water, picnic tables, shade, and primitive toilets are available). Drive generally N along this well-maintained dirt road for 3.1 miles to the second intersection with a well-maintained dirt road. Turn left (W) toward Mt Hillers. Drive 0.4 miles and park where the road bends very gently to the left.

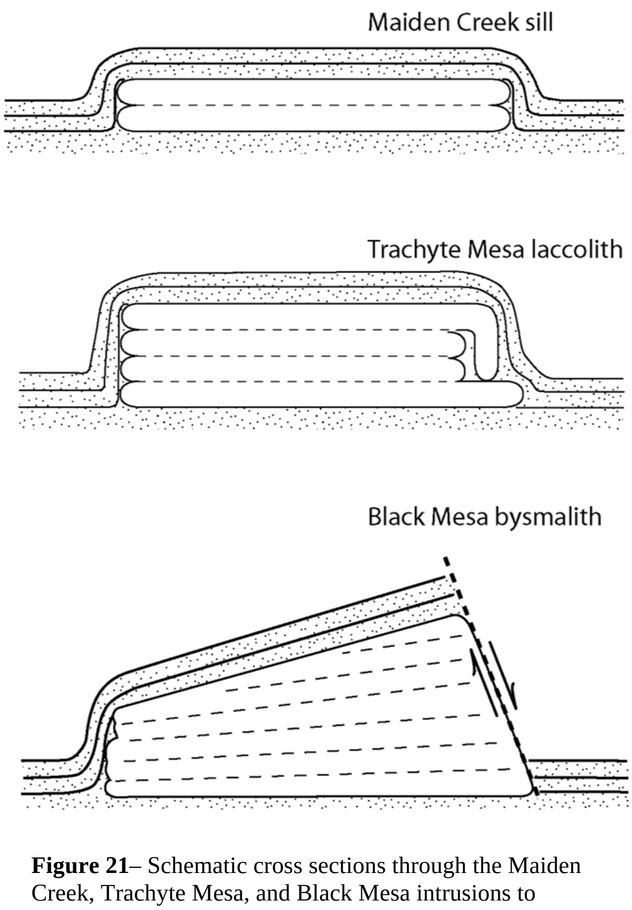

Figure 21– Schematic cross sections through the Maiden Creek, Trachyte Mesa, and Black Mesa intrusions to illustrate idealized emplacement mechanisms and our preferred assembly histories. Intrusions not drawn to scale. The number of pulses show is intended to demonstrate relationships between successive pulses rather than actual number.

Stop 2.8: View of E face of Mt Hillers, including Gold Creek and Sawtooth Ridge

GPS (UTM): 531924, 4192973. Main points: (1) Satellite intrusions exist only on the NW half of Mt Hillers. (2) The sharp transition between regions with and without satellite intrusions does not correspond with any structural features on the central Mt Hillers intrusion.

Satellite intrusions only occur around approximately half of the margin of the central Mt Hillers intrusion (Fig. 3). On the E, SE, and S sides of Mt Hillers, no satellite intrusions exist but the sedimentary rocks are rotated to steep dips. In contrast, on the NE, NW and W sides of Mt Hillers, satellite intrusions do exist and extend several kilometers from the main intrusive body. We previously hypothesized that the transition between regions with and without satellite intrusions corresponded with a scissor or tear fault in the sedimentary section. Detailed mapping in the Gold Creek and Trail Canyon regions W of Sawtooth Ridge disproved this hypothesis (Gwyn, unpublished mapping). Moderately to steeply dipping sedimentary rocks can be traced across this boundary.

One explanation for the existence of satellite intrusions N of this region may be the presence of relatively major dikes on the margin of the main Mt Hillers intrusion. Several dikes exist in this region and appear to feed the W end of Sawtooth Ridge. Direct ties between the dikes and Sawtooth Ridge are currently being investigated using geochemistry. Mapping N of this transition is insufficiently detailed to demonstrate a greater abundance of dikes or other intrusions that may feed the satellite intrusions. S of the Gold Creek drainage, however, the outermost igneous rock on the margin of Mt Hillers is a sill; one minor, ~2-m-wide dike exists above this sill, but its connection to the main body is not exposed and it does not feed any satellite intrusions.

Directions to Stop 2.9

Drive 1.0 miles generally W toward Mt Hillers, following the main dirt road. Shortly after the road turns and heads E away from the Mt Hillers, park near a small man-made pond. Bringing along supplies for several hours, walk up the steep dirt road ~200 m to the ridge crest. Hike W uphill along the top of the ridge on the N side of Gold Creek. Walking generally on the S side of the ridge crest provides the best views. Continue walking uphill for approximately 1.1 km and 250 meters in elevation gain along an azimuth of ~085. Stop at the first good outcrop of porphyry. Use of a GPS and the coordinates below will ensure a minimum of wandering.

Stop 2.9: Gold Creek overlook

GPS (UTM): 529893, 4193097. Main points: (1) Roof uplift is the primary space-making mechanism for the central Mt Hillers intrusion. (2) The so-called 'shattered zone' at the core of the central Mt Hillers intrusion is much smaller in area than previously mapped. (3) The significance of the shattered zone remains enigmatic.

Looking S across Gold Creek canyon, the margin of the main Mt Hillers intrusive center is exposed in spectacular fashion along a nearly continuous series of outcrops (Fig. 23). At the E end of the exposure, white sandstone of the Salt Wash member of the Jurassic Morrison Formation bends gradually from shallow to steep dips. Below the Salt Wash sandstone is the outermost sill of the main Mt Hillers intrusive center. This ~5-m-thick sill bends similarly to the overlying sedimentary rocks. Careful examination of the geometry of this sill suggests it is comprised of a series of en echelon flattened lobes. The long axis of the lobes is oblique to the margins of the sill. This geometry suggests the sill may be comprised of numerous fingers of magma that have coalesced into a continuous sheet, as described for other locations by Pollard et al. (1975).

Below (to the W of) this outmost sill is a series of alternating sedimentary units and sills. Dip magnitude increases gradually to the W from ~45°E to ~80°E. No clear pattern exists in terms of where the sills intrude with sedimentary section (shale to sandstone contact, sandstone to shale contact, within a sedimentary unit, etc.) although most intrude along contacts between layers of different composition. Note that dikes connect some of these sills.

Looking W up Gold Creek canyon, the series of alternating sedimentary units and sills / dikes continues for several hundred meters. Much of the region beyond the prominent cliffs of white sandstone (the Triassic / Jurassic Navajo sandstone) was mapped by previous workers (Hunt et al., 1953; Larson et al., 1985) as 'shattered zone,' or complexly intermingled igneous and

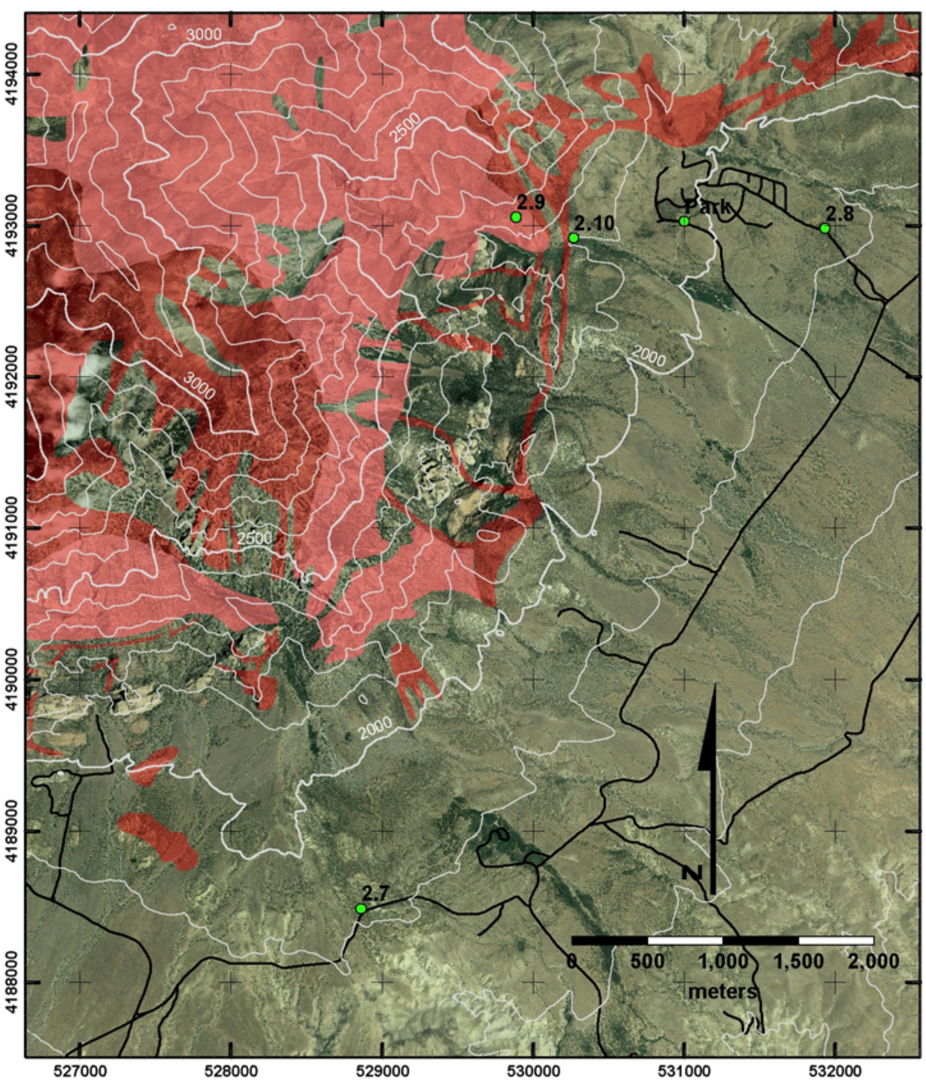

Figure 22 – - Location of field trip stops on the E side of the main Mt Hillers intrusive center. Base map is an aerial photograph of the region. Outcrop of rock mapped as Tertiary porphyry indicated with red highlighting. Rock mapped as Tertiary 'shattered zone' indicated with pink highlighting. Green circles indicate approximate stop locations and are labeled with stop numbers. Thin black lines are dirt roads. White lines are topographic contours with 100 m interval. Geology from Larson et al., 1985. UTM zone 12, datum NAD27.

sedimentary rock. However, recent detailed mapping (Gwyn, unpublished mapping) demonstrates that the regional stratigraphy (Fig. 2) is coherent and mappable, despite being complexly intruded by porphyry, much farther into the main intrusion center than previously realized. The relative abundance of porphyry increases toward the central portion of the intrusive center and sedimentary outcrops become progressively smaller and more isolated. Thus, the boundary between the shattered and non-shattered zones appears to be gradational in this region. The highest elevations visible on Mt Hilxlers W of here are shattered zone.

Four of the five Henry Mountains intrusive centers have a mapped shattered zone (Hunt et al., 1953). Most exposures of the shattered zone are characterized by a complex intermingling of meter-scale bodies of sedimentary rock with centimeter- to meter-scale regions of igneous rock with a wide range of different textures. The general character of the shattered zone suggests it was a low viscosity, possibly fluid-rich environment. It appears to be a late-stage feature of the assembly of an intrusive center, and may be associated with emplacement of the last, fluid-rich magma bodies.

Directions to Stop 2.10

Walk back downhill generally to the E and descend toward Gold Creek. Stop at the E-most sill in the drainage, exposed between the underlying red-brown laminated siltstone and mudstone of the Summerville Formation, and the overlying massive beds of grey sandstone of the Salt Wash member of the Morrison Formation.

Stop 2.10: Outermost sill, Gold Creek

GPS (UTM): 530208, 4192909. Main points: (1) Textures in the porphyry are commonly different between distinct sills in this region. (2) This sill may be comprised of numerous fingers of magma that have coalesced into a continuous sheet. (3) Solid-state fabric at the contact with the surrounding sedimentary host rock is highly oblique to the inferred E-ward magma flow direction.

The outermost sill here has a very high phenocryst percentage and must have had an exceptionally high viscosity if it was this crystal-rich during emplacement. Mafic xenoliths are relatively abundant. In general, xenoliths (both mafic and sedimentary) are very rare in the satellite intrusions but fairly common in the main Mt Hillers intrusive center. Another difference between the satellite intrusions and the main Mt Hillers body is that the igneous texture varies considerably over short spatial distances. In particular each of the sills in Gold Creek canyon has a texture different from each of the others. We interpret these different textures to represent separate magma pulses, which suggests each sill is a distinct pulse.

On the S wall of the canyon, this sill appears to be formed from numerous elliptical, en echelon lobes. As mentioned at Stop 2.9, if present, these lobes may represent previously distinct magma fingers that have coalesced into a contiguous sheet (Pollard et al., 1975). The orientation of the contacts between these fingers might therefore be useful in determining the approximate sill propagation direction. These contacts have not been investigated; perhaps we will have time to do so now.

Immediately atop this outcrop, the contact with the overlying sandstone (Salt Wash member of the Jurassic Morrison Formation) is very nicely exposed. Immediately adjacent to the contact, a solid-state lineation is developed in the porphyry. This lineation is approximately parallel to the strike of the contact (and bedding in the sandstone). Interpreting this lineation is not straightforward. It is probably related to early sill growth rather than subsequent tilting during growth of the laccolith and emplacement of the underlying main intrusive body. The lineation may therefore record an approximate direction of magma propagation during sill emplacement (and perhaps therefore finger propagation direction?). However, we have found that solid-state lineations are commonly difficult to interpret unequivocally. They change orientation of short spatial distances, perhaps because they record relative displacement between the magma body and the wallrock, which is undoubtedly complex in a growing intrusion and may be unrelated to bulk magma propagation direction.

Figure 23– Photographic panorama of the igneous and sedimentary rock exposed on the S side of Gold Creek. View from Stop 2.9.

End of Trip

Retrace your steps to the cars. Head back E on the dirt road until the intersection with the main dirt road. Turn right and drive S back to the Starr Springs ranch ruins and eventually to Utah Highway 276. Turn left and drive north on Highway 276, then turn left on Highway 95 and drive north to Hanksville.

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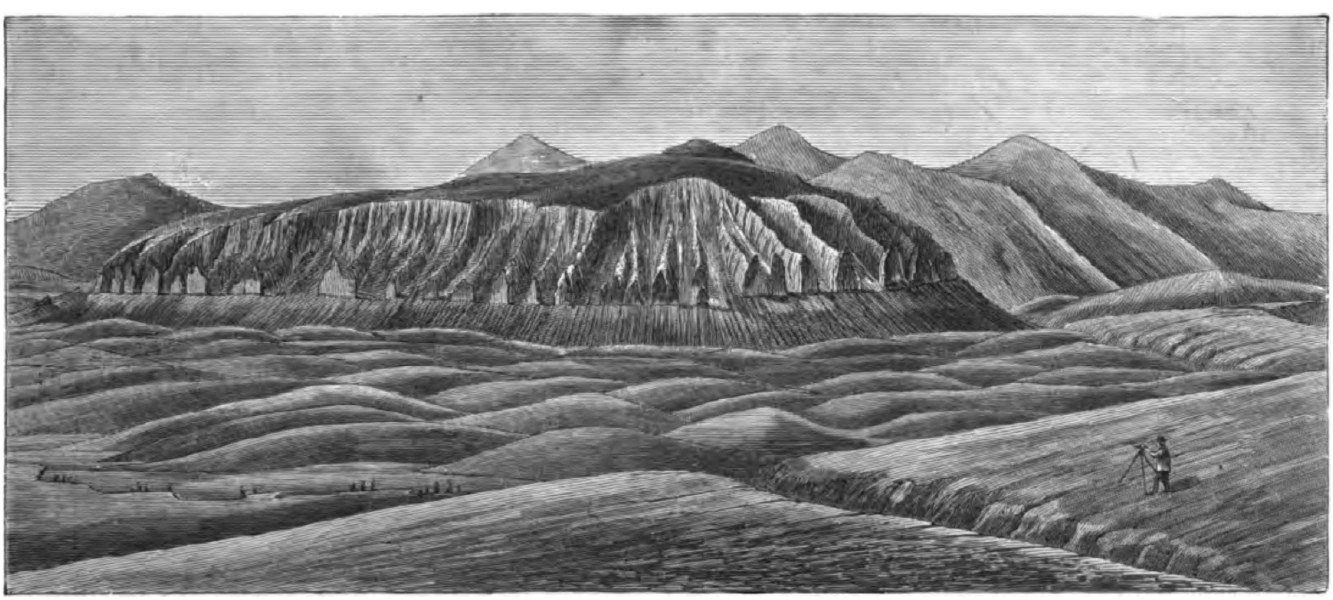

from Gilbert (1877)