GEOMETRY AND PROGRESSIVE DEVELOPMENT OF A SHALLOW CRUSTAL INTRUSIVE COMPLEX, MOUNT HILLERS, HENRY MOUNTAINS, UTAH

By

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December, 2014

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The Henry Mountains of southeastern Utah are five topographic domes, each of which is a separate mid-Tertiary shallow crustal intrusive complex comprised of a cluster of component igneous intrusions. The intrusions were emplaced at shallow depths into flat-lying sedimentary strata of the Colorado Plateau. The lack of tectonic influence imposed on the intrusive bodies during or since emplacement makes the Henry Mountains an ideal place to study forceful magma emplacement in the shallow crust.

This study focuses on the internal structure of the Mount Hillers intrusive complex which has an estimated igneous rock volume of approximately 35 km^3. New geologic mapping demonstrates that the intrusive complex includes several component intrusions with distinct geometries. The largest component intrusion of the complex is a concordant, asymmetric laccolithic body with Permian sedimentary units contacting the southeastern roof and Jurassic sedimentary units contacting the northwestern roof. The different aged sedimentary units in contact with the upper portion of the main laccolithic body imply that the elevation of the base of the intrusion is not consistent within the stratigraphic section. The two areas with different-aged roof and floor units appear to be separated by a major but poorly exposed fault. Additionally, the

main asymmetric laccolithic body appears to be directly attached to and likely once fed smaller laccolithic bodies on its northern perimeter.

This improved understanding of the detailed internal structure of component laccolithic bodies of Mount Hillers provide constraints on the progressive developmental history of the intrusive complex. In the early stage of intrusive development, a network of sills and dikes was emplaced into subhorizontal strata. Next the main feeder dike of Mount Hillers (hypothesized to strike northeast) directly fed one southeast-radiating semicircular protolaccolith under Permian units. As the intrusion grew vertically, a fault may have developed parallel to and above the main feeder dike as the intrusion bent and uparched overlying host rock southeast of the fault. Once the intrusive body grew to a vertical thickness of ~1,500 meters, magma may have started to intrude laterally beneath Jurassic units to the northwest. The main laccolithic body then continued to grow vertically, simultaneously lifting different aged sedimentary roof units that are separated by a large fault. Late in the intrusive history, several relatively small tongue-shaped laccolithic intrusions were fed from and grew adjacent to the northern margin of the main asymmetric laccolithic body of Mount Hillers.

The Henry Mountains are where geologist G.K. Gilbert first recognized and documented that magma bodies can deform host rock. Gilbert used the term ‘laccolite’ (later ‘laccolith’) to describe plutonic bodies that make space for themselves in the shallow crust by lifting and uparching overburden. Since Gilbert’s early work, the Henry Mountains region has been the focus of considerable research on the geometry and growth of igneous intrusions in the shallow crust. The new work presented here reveals that intrusions that were once thought to be a clusters of separate igneous bodies may instead be an amalgamation of component laccolithic intrusions that make up a large and geometrically complex intrusive feature.

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A Thesis

Presented to the faculty of the Department of Geological Sciences

East Carolina University

In partial fulfillment of the requirements for the degree of

Master of Science in Geology

By

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December, 2014

B.S. East Carolina University

Greenville, NC

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1. Introduction

Pluton growth processes have been studied since the late 19th Century (e.g. Gilbert, 1877; Hunt et al., 1953; Hutton, 1987; Saint Blanquat et al., 1998; Rosenberg, 2004; Rocchi et al., 2010; Horsman et al., 2010). Great progress has been made in understanding how plutons develop in both brittle and ductile portions of the crust. However, many aspects of pluton construction remain poorly understood.

Pluton emplacement in the shallow crust is of particular interest for several reasons. (1) Plutons are related to the magma sources that feed volcanoes (e.g. Hawkesworth and Kemp, 2006). (2) Plutons are a fundamental element of crustal growth. (3) Fluids associated with plutons commonly precipitate economic mineral deposits. (4) Heat from active plutons can be harnessed to produce geothermal power (e.g. Wohletz and Heiken, 1992).

Recent evidence suggests that many intrusive bodies, both large and small, develop through the emplacement of multiple pulses of magma (e.g. Rocchi et al., 2010). However, many questions remain about how shallow crustal magma systems composed of multiple magma bodies develop over time. Commonly, magma bodies that presumably share the same feeder system are emplaced near each other as a cluster of intrusions. One of these clusters is typically referred to as an intrusive complex. As an intrusive complex develops, emplacement parameters can change depending on the stage of intrusive development. As new magma is introduced into the system, heating and deformation from early intrusions commonly influence how succeeding intrusions develop.

The focus of this research is to study the construction history of the shallow crustal intrusive complex of Mount Hillers in the Henry Mountains of southeastern Utah. The intrusive complex was emplaced at a depth of less than 5 km (Jackson and Pollard, 1988). The datasets from this study provide better constraints on the sequential emplacement of component magma bodies of Mount Hillers and provide an interpretive history of how the intrusive complex was constructed.

2. Background

2.1 Disciplinary background

In the latter part of the twentieth century, new evidence challenged traditional views about the emplacement of igneous intrusions in the upper crust. Earlier studies generally assumed that magmas ascend through the entire crust as diapirs driven by density contrasts (Miller and Paterson, 1999). As it became clear that diapiric ascent above the brittle-ductile transition in the mid-crust is mechanically problematic, hypotheses for magma ascent became dominated by sheetlike bodies in dike conduits, along vertical faults, or other structural discontinuities (Cruden, 1998**;** Grocott et al., 1999; Saint-Blanquat et al., 2001).

Magma supply rates are locally dependent on conduit length, conduit cross sectional area, and magma viscosity. Assuming reasonable ranges for each parameter (Petford, 1996; Cruden, 1998), large plutons can either develop rapidly, in 100,000 years or less (e.g. Petford et al., 2000; Cruden and McCaffery, 2001), or grow sporadically, taking millions of years to fully develop (Petford et al., 2000; Cruden and McCaffery, 2001; Rosenberg, 2004). Even though the duration of pluton emplacement can vary quite substantially, large magma bodies fed by conduits require several relatively smaller pulses of magma to grow into their full size (Saint Blanquat et al., 2011).

Although magma can ascend through faults and other vertical discontinuities, magma most commonly ascends from deep to shallower portions of the crust through vertical dike conduits (Rubin, 1995; Menand and Tait, 2002). As dike ascent is arrested, magma commonly continues to flow and switches direction from vertical to horizontal, forming a sill. Depending on the feeder conduit and various other factors, a network of sills and dikes may be emplaced and some sills may develop into larger plutonic bodies. These plutonic bodies may feed other dikes and sills. The sills may then develop into plutons and eventually an intrusive complex develops. Since sills are a prerequisite for most plutonic growth in the shallow continental crust, a review of the fundamentals processes of sill formation is essential in understanding how plutons grow.

Emplacement of individual sills is affected by local parameters. A favorable site for dike arrest and sill emplacement is at an interface between rigidity contrasts and/or lithologic discontinuities with a stronger and more rigid upper layer and a weaker lower layer (Kavanagh et al., 2006; Menand, 2011). After a sill is formed, another rigidity contrast is developed between the emplaced igneous rock and the host rock, thus a favorable interface forms for injection of later magma pulses. As additional magma is emplaced, sheets can stack vertically to create a tabular and generally concordant plutonic body. Plutonic bodies composed by the amalgamation of stacked sills are commonly observed in the field (John and Blundy, 1993; Belcher and Kisters, 2006; Rocchi et al., 2010). Previous studies have interpreted the dimensions of the final pluton to be controlled by the initial sill length while the thickness of the pluton is the accumulated thickness of the stacked sills (Horsman et al., 2005; Morgan et al., 2005). Sills can stack as a result of under-accretion, over-accretion, and mid-accretion which all have distinctive thermal implications (Menand, 2011). The initial sill is often referred to as the protolaccolith.

Plutons can also grow through vertical inflation. Once the sill reaches a critical length, which is usually dependent on depth of emplacement, subsequent magma injections can inflate the igneous body. Saint-Blanquat et al. (2001) report that the Papoose Flat pluton in eastern California experienced a period of inflation from forcibly emplaced under-accreted magma pulses. This model assumes that the pulses of magma were initially emplaced, horizontally and developed flow fabrics parallel to the bedding of the host rock. As subsequent horizontal pulses were emplaced concordantly with shallowly dipping host rock bedding as subsequent concordant pulses were emplaced, upder-accreted pulses rotated, lifted up, and strained earlier magma bodies along with the host rock.

2.1.1 Shallow Crustal Plutons: Laccoliths

In instances where fluid pressure in a magma body in the shallow crust exceeds the weight of the overlying host rock, the overburden can be lifted to make space for the intruding magma. A plutonic body characterized by both a subhorizontal floor and a roof that has been considerably uplifted is called a laccolith. Differentiating between a sill and a laccolith can be difficult because there is a gradational transition between the two features. Sills do uplift overlying rocks, but only do so minimally and without rotation. Additionally, sills have a distinctive sheetlike geometry while laccoliths can have a broad range of generally tabular geometries. Corry (1988) reports that most sills are usually between 1 to 10 m thick, while all laccoliths reported in literature are at least 30 m thick.

A laccolith was first idealized and described by Gilbert (1877) to be a radially symmetric mushroom-shaped intrusion with a subhorizontal base and a convex-up roof that makes space for itself by lifting and uparching overburden. However, the term laccolith is now used for a wide range of intrusive geometries. Laccoliths can have symmetric or asymmetric profiles and can also be circular, elliptical or irregular in plan view (Hunt et al., 1953; Corry, 1988). Three main geometric types of laccoliths exist: traditional, punched, and Christmas tree (Figure 1). These groups are end members of a continuum and differ in both geometry and emplacement mechanics.

-Traditional Laccoliths

An idealized traditional laccolith is an axisymmetric mushroom-shaped intrusion with a sub-horizontal base and a convex-up roof that concordantly domes overlying strata (Figure 1A). However, several documented traditional laccoliths are elliptical in plan view (Hunt et al., 1953; Corry, 1988). An idealized traditional laccolith begins as a sill that radiates an equal distance in all directions from a vertical dike. Once the sill reaches a critical size, it becomes mechanically easier to inflate and lift the overlying host rocks rather than to continue horizontal expansion. The diameter of the initial sill is mostly dependent on the depth of emplacement and the weight of the overburden. Accordingly, deeper traditional laccoliths are typically larger and are capable of lifting heavier overburdens.

-Punched Laccoliths

A punched laccolith is similar to a traditional laccolith in the early stages of development and begins as a single sill. As the sill grows into a laccolith, strata at the periphery of the domed roof are bent and fractured; and the fractures act as slip-planes (Figure 1B). The intrusion then grows by uplifting the roof along a steep cylindrical fault. An idealized punched laccolith is bounded by steep cylindrical faults and is piston-shaped with a floor and roof subparallel to the host strata (Figure 1B). Punched laccoliths are usually circular in plan view but can be elliptical. Circular punched laccoliths are typically thicker than elliptical punched laccoliths (Corry, 1988).

-Christmas Tree Laccoliths

Christmas tree laccoliths are emplaced as a suite of intrusions into different stratigraphic horizons (Figure 1C). The component laccoliths are generally smaller at shallower horizons and get progressively larger with depth, giving the suite a Christmas tree profile (Figure 1C). Idealized Christmas tree laccoliths have no peripheral faults and sedimentary units are continuous over the individual intrusions (Corry, 1988). Emplacement of intrusions at multiple depths in the crust makes stress at the periphery of a single sill minimal and large scale fractures do not develop. Over the suite of intrusions, a crustal graben may form in the later stages of emplacement (Corry, 1988) (Figure 1C). Laccoliths at different horizons in a Christmas tree arrangement may be emplaced at different times and do not always share the same feeder conduit (Rocchi et al., 2010). Nevertheless, the component intrusions of Christmas tree laccoliths usually collectively heat and displace the host rock.

2.2 Henry Mountains

The Henry Mountains are a set of five shallow crustal intrusive complexes in southeastern Utah (Figure 2). The Henry Mountains intrusions were emplaced at depths between 2-4 km into the flat laying strata of the Colorado Plateau in the center of a relatively undeformed structural basin (Hunt et al., 1953; Jackson and Pollard, 1988).

During and since magmatism in the Henry Mountains region, this part of Colorado Plateau has experienced very little tectonic deformation (Nelson et al., 1992). The structural features of the Henry Mountains are thus attributed entirely to forceful magma emplacement. Igneous fabrics that formed during emplacement record the last increment of strain imposed on the magma bodies.

Intrusive rocks, wall rocks, and contacts between them are exceptionally well exposed in many parts of the Henry Mountains. Three-dimensional geometries are readily interpreted for many intrusive bodies on the margins of each mountain dome because of good exposures of host rock contacts at the tops, bottoms, and sides of intrusions. Exposures of contacts between the intrusions and host rock decrease toward the center of each mountain dome.

The Henry Mountains intrusions were emplaced periodically, both temporally and spatially, over a duration of ~9 My from the Middle Oligocene to the Early Miocene. Zircon and titanite fission track dates for the Henry Mountains range from 20.0 ± 1.9 to 29.2 ± 2.3 Ma (Sullivan et al., 1997). U/Pb zircon dates show that the Mount Hillers intrusive center was emplaced rapidly in ~1 My at 24.7 ± 0.50 Ma (Paquette et al., 2010). There is no clear difference in zircon ages between intrusions from the different igneous bodies of Mount Hillers.

2.3 Stratigraphy

The stratigraphic section from Jackson and Noller (1991) was used to identify sedimentary units in the field (Figure 3). This section is similar to the stratigraphic section of Jackson and Pollard (1988) which is a compilation from the works of Hunt et al. (1953), Hintze (1963), Peterson et al. (1980), and Stokes (1980). My mapping identified geologic formations in the field but on the geologic maps generated in this report, formations are grouped into the Upper Cretaceous, Upper Jurassic, Middle Jurassic, Lower Jurassic, Triassic, and Permian sedimentary systems (Figure 3).

3. Previous Work on the Henry Mountains and Mount Hillers

Previous work on constraining the large-scale 3D geometries and emplacement mechanisms of the Henry Mountains include the investigations of Gilbert (1877), Hunt et al. (1953), and Jackson and Pollard (1988, 1989). My research has confirmed that the Mount Hillers intrusive complex is composed of numerous intrusions including a network of sills and dikes, a main laccolithic body, tongue-shaped traditional laccolithic bodies directly adjacent to and possibly connected to the main laccolithic body, and several distal satellite intrusions. This research is mostly focused on the main laccolithic body of Mount Hillers and the directly adjacent tongue-shaped laccolithic bodies. Since several of my field observations agree with some aspects of previous studies, a brief review of previous work is in order.

3.1 Gilbert (1877): Geology of the Henry Mountains

The pioneering work of Gilbert (1877) in the Henry Mountains was the first to recognize that intrusive magmas can deform host rock. Gilbert traveled from Salt Lake City by mule and spent only a few weeks in the Henry Mountains. He considered each of the Henry Mountains as a cluster of mushroom-shaped traditional laccoliths (Figures 4A and 4B). Gilbert (1877) considers all laccoliths of the Henry Mountains to be proportionally similar. The average thickness to length ratio is reported by Gilbert (1877) to be 1:7. The plan view for most laccoliths is shown as low eccentricity ovals with the ratio of the two diameters never exceeding 3 to 2 (Gilbert, 1877).

The southern two Henry Mountain intrusive complexes, Mount Ellsworth and Mount Holmes, are manifested by one laccolith and two laccoliths respectively. Gilbert (1877) describes the northern three mountains as clusters of several laccoliths, attributing ~30 laccoliths to Mount Ellen. Mount Hillers and Mount Pennell are both described as having one large laccolith accompanied by several smaller laccoliths north and northeast of the largest laccolith (Gilbert, 1877) (Figure 4A).

Gilbert (1877) reported that the large laccoliths of the Henry Mountains are commonly associated with sills and dikes (Figure 4C). Also, complications are reported on the geometries of larger laccoliths, such as the sole laccolith making up the Mount Ellsworth dome (Gilbert, 1877). The roof strata of Mount Ellsworth are cut by a population of minor faults around the central portion of the mountain. Prismoidal blocks of sedimentary strata are offset by faults with throws of no more than a few hundred feet. The faults are filled by dikes, presumably fed by the underlying laccolith, that were injected as the blocks of host rock were displaced. Even though the strata cannot be continuously traced over the entire mountain, the sequences of expected roof strata are recognizable throughout the faulted area. Gilbert (1877) concluded that the general architecture of Mount Ellsworth is that of a concordant mushroom-shaped traditional laccolith.

-Gilbert (1877) on Mount Hillers

Gilbert (1877) reports that 9 traditional laccoliths make up the Mount Hillers cluster. The largest laccolith of the group was called the Hillers laccolith which was reported to be the largest in the Henry Mountains (Gilbert, 1877). The three laccoliths directly adjacent to and north of the Hillers laccolith were called the A, B, and C laccoliths. The other intrusions include the D, Jerry Butte, Steward, Howell, and Pulpit laccoliths (Figure 5).

--*Gilbert (1877) on the Hillers Laccolith*

The Hillers laccolith was reported by Gilbert (1877) to have an igneous volume of ten cubic miles. Sedimentary strata contacting the southern side of the laccolith were reported to be dipping 80° to the south. Strata on the northern side of the Hillers laccolith were reported to be dipping much less than those on the southern side (Figure 6A) (Gilbert, 1877). Although Gilbert (1877) was unable to identify the strata just north of the summit, he inferred a concordant relationship between the Hillers laccolith and the host rock (Figure 6B).

--*Gilbert (1877) on the A, B and C Laccoliths*

Directly north of the Hillers laccolith are intrusions that Gilbert called the A, B, and C laccoliths. These smaller traditional laccoliths seemed to be so close to the Hillers laccolith that they merged topographically. Gilbert (1877) considered these smaller laccoliths to be emplaced into shallower stratigraphic horizons than the Hillers laccolith with laccolith A as the smallest and highest in the stratigraphic section and laccolith C the largest and the deepest (Figure 5).

The proximity of laccolith C to the Hillers laccolith troubled Gilbert at first. Initially, he considered laccolith C to be so close to the Hillers laccolith that he considered them to be part of the same body. After further investigation, the Henry’s Fork conglomerate (later renamed the Salt Wash member of the Jurassic Morrison Fm) was identified to overly laccolith C (Gilbert, 1877). This permitted him to classify laccolith C as its own intrusive body emplaced into a higher stratigraphic horizon than the Hillers laccolith (Figure 5B).

3.2 Hunt et al. (1953): Geology and Geography of the Henry Mountains Region, Utah

Hunt et al. (1953) were the first to systematically map the Henry Mountains region. He and his crew spent four field seasons in the Henry Mountains from 1935-1939. World War 2 delayed the publication of the results until 1953. The geologic map produced by Hunt et al. (1953) includes the entire Henry Mountains at a scale of 1:31,680 (1 mile = 2 inches).

Interpretations from Hunt et al. (1953) differ considerably from those of Gilbert (1877). Hunt et al. (1953) hypothesized that the main dome of each of the Henry Mountains is the result of the physical injection of a discordant central stock and the minor domes of each mountain are tongue-shaped laccoliths that were fed radially from the of the stock (Figure 7). The laccoliths described by Hunt et al. (1953) are considerably different from those described by Gilbert (1877) because they are not equidimensional and are directly connected to a stock.

-*Stocks as described by Hunt et al. (1953)*

Hunt et al. (1953) admitted that the origins of the mountain domes are unclear. They suggested that the large domes produced by the stocks are significantly different from the smaller domes arched over the well-exposed marginal laccolithic bodies. The stocks are reported be circular in plan view while the laccoliths are elliptical in plan view. According to Hunt et al. (1953), as the stock is injected, the sedimentary strata are either dragged up or pushed up and outward along the margin of the stock. This deformation consequently results in a structural dome (Figure 7). Accordingly, the sedimentary host rocks are deformed by a combination of radial compression and circumferential extension.

Hunt et al. (1953) claim the physical injection of the stock severely deforms the adjacent host rock into a complicated region of shattered sedimentary and igneous rocks. They considered this region too complicated to map in detail and mapped the area as the "*shatter zone*." The size of the shatter zone directly correlates to the size of the stock according to Hunt et al. (1953).

Different-aged strata were observed by Hunt et al. (1953) at the top of each mountain dome. They considered this to be strong evidence that the main igneous body of each of the Henry Mountains is discordant and is a stock. Hunt et al. (1953) stress that many supporters of the concordant traditional laccolith hypothesis proposed by Gilbert (1877) pay no attention to the offset strata near the peak of each mountain.

-*The Emplacement of Laccoliths as described by Hunt et al. (1953)*

Instead of being circular in plan view, Hunt et al. (1953) show that many well exposed minor intrusions of the Henry Mountains are tongue-shaped laccolithic bodies with their longest dimension away from the center of the mountain (Figure 8). These laccoliths are assumed to begin as irregular bulges at the periphery of the stock (Hunt et al., 1953). The magma is predicted to pierce the shatter zone and to radially inject into the host rock forming a laccolith by lifting and arching the overburden. Hunt et al. (1953) proposed three different growth models for the tongue-shaped laccoliths (Figure 9), but ultimately conclude that the laccoliths most likely extended and inflated simultaneously during emplacement (Figure 9C).

-Hunt et al. (1953) on Mount Hillers

Mount Hillers was reported to have the largest stock in the Henry Mountains (Hunt et al., 1953). South of the stock, Triassic-Jurassic strata are intruded by a network of sills and dikes. North of the stock, Hunt et al. (1953) identified the strata to be Late Jurassic and Cretaceous and to have lower dips than the strata to the south. The radiating tongue-shaped laccoliths are restricted to the north and northeast side of the stock (Figure 10). Immediately surrounding the Mount Hillers stock is the largest "shatter zone" of the Henry Mountains (Figure 10).

Although specific sedimentary units were not mapped in the shatter zone, Hunt et al. (1953) recognized and described blocks of known sedimentary units. Permian rocks crop out on the southern portion of the shatter zone near the Woodruff Mine and dip 55° to the south (Figure 11) (Hunt et al., 1953). To the north of the stock, members of the Jurassic Morrison Fm and the Cretaceous Dakota sandstone are identified and are reported to dip 45-50° on Summit Ridge (Figure 11) (Hunt et al. 1953). The western side of the shatter zone has similar strata to Summit Ridge but outcrops are poor in this area. The entire sequence of the strata to the west of the stock can be identified, but only in small outcrops and blocks of float. Permian strata to the south of the stock and Jurassic-Cretaceous strata to the north suggest to Hunt et al. (1953) that the southern Permian strata were uplifted significantly more than the younger northern strata.

--*Hunt et al. (1953) on Gilbert's A, B, and C laccoliths*

The mapping of Hunt et al. (1953) on the A, B, and C laccoliths displays more thorough relationships between the intrusive bodies and the host rock than previously described. These intrusive bodies are inferred by Hunt et al. (1953) to be attached to the Mount Hillers stock. Hunt et al. (1953) suggest that Gilbert’s laccolith A is better identified as 2 separate intrusive bodies; the Bulldog Peak intrusion (later renamed to Cass Creek Peak) and the Quaking Asp Creek laccolith (Figure 10). Hunt et al. (1953) report steeply dipping concordant strata to be exposed at localities around Bulldog Peak. The Bulldog peak intrusion is proposed by Hunt et al. (1953) to be a cross cutting body that was injected upward and outward from the stock (Figure 12A).

Laccolith B, renamed the Stewart Ridge laccolith by Hunt et al. (1953), was described as one of the largest tongue-shaped intrusions of the Henry Mountains (Figure 12B). Laccolith C was considered to be comprised of three different intrusions; the Chaparral Hills laccolith, the Specks Ridge laccolith, and the Specks Canyon laccolith (Figure 12C). The Specks Ridge intrusion was described by Hunt et al. (1953) as a thin laccolith, nearly 1.5 miles long and less than half a mile wide, which directly connects to the Chaparral Hills laccolith to the south (Figure 12C). Under the Chaparral Hills laccolith is the Jurassic Morrison formation. Under the Morrison Fm is the Specks Canyon laccolith which extends farther to the northeast than the Chaparral Hills laccolith (Figure 12C).

3.3 Jackson and Pollard (1988): The laccolith stock controversy

Jackson and Pollard (1988) investigated the deformation of the sedimentary strata on the flanks of several Henry Mountain domes to test the two main hypotheses about laccolith growth there: the laccolith model of Gilbert (1877) and stock model of Hunt et al. (1953). Jackson and Pollard (1988) created detailed geologic maps and cross sections for the three southernmost Henry Mountains; Mount Ellsworth, Mount Holmes and Mount Hillers. To determine how the strata responded to the emplacement of the main igneous bodies, Jackson and Pollard (1988) selected cross sectional transects not complicated by faults with map-scale displacements or large intrusions that disrupted the curvature of the beds.

Jackson and Pollard (1988) suggest the curvature of the sedimentary strata at each mountain dome represents a distinct stage in the response to the growth of the main intrusive body. They used field evidence, structural analysis, and geospatial models to suggest the domed host rocks were more likely deformed by the emplacement of a concordant laccolith than a discordant stock.

Jackson and Pollard's cross sections include the geology of one flank of each mountain dome (Figure 13). The other sides of the domes are inferred to mirror the studied mountain flank because concordant host rocks are observed near the tops of the domes. Importantly Jackson and Pollard (1988) infer that a single sedimentary unit forms the roof units of each main laccolithic dome. They also describe the strata at each of the studied flanks as having a concave-upward lower hinge and a concave-downward upper hinge. The two hinges are connected by a central limb with a constant dip (Figure 13). The two hinges on the mountain flank coupled with the concordant relationship to the main igneous body effectively suggest that a large, symmetrical, mushroomed-shaped intrusion underlies the domed strata.

-Detailed Mapping of Southern Mount Hillers

Jackson and Pollard (1988) mapped the southern portion of Mount Hillers on a scale of 1:10,000. The map includes the southern side of the main intrusive body of Mount Hillers and a network of sills and dikes. The only portion of the northern half of Mount Hillers that Jackson and Pollard (1988) mapped includes a section of strata that Hunt et al. (1953) identify as the

Jurassic Morrison Fm and the Cretaceous Dakota sandstone on Summit Ridge. However, Jackson and Pollard (1988) describe the strata on Summit Ridge as a continuous section of northerly dipping metamorphosed sedimentary rocks from the Late Permian Organ Rock Tongue of the Cutler Fm to the Upper Triassic Chinle Fm. The Organ Rock outcrop is inferred to be the roof contact between the northerly dipping strata and the main igneous body. The sedimentary units are described by Jackson and Pollard (1988) to progressively steepen northward from 13° at the Organ Rock to 24° and 40° up section, to "even steeper" at the youngest and farthest north Chinle Fm. The sedimentary strata of Summit Ridge are not included on the cross sectional interpretation of Mount Hillers (Figure 13C). However, the strata on Summit Ridge are used to support relationship between the main intrusive body and its host rock.

On the southern side of Mount Hillers, the Permian Cedar Mesa sandstone and Organ Rock members are closest to the center of the dome. These outcrops strike east-west and dip 45° to the south (Jackson and Pollard, 1988). The Cedar Mesa sandstone is inferred be the roof contact between the southerly dipping strata and the central igneous body. 300-400 meters south of the moderately dipping Cedar Mesa sandstone and Organ Rock tongue strata, the Organ Rock tongue dips 70° to the south. Jackson and Pollard (1988) interpret the moderately dipping Cedar Mesa sandstone and Organ Rock to be on the upper limb of the laccolith, while the steeply dipping Cedar Mesa and Organ Rock tongue are inferred to be part of the central limb (Figure 13C). The transitional region between the different dips is interpreted to be the upper hinge along which dips shallow toward the top of the laccolith.

Jackson and Pollard (1988) identify at least 10 concordant sills and thin laccoliths in the steeply dipping limb of their cross section. The concordant sills and thin laccoliths account for at least 200 m (~11%) of the thickness of the exposed central limb. The concordant sills are crosscut by radially striking vertical dikes. Paleomagnetism shows that the sills on the southern side of Mount Hillers were initially emplaced subhorizontally before cooling below 400°C. After the sills cooled, vertical growth of the main intrusion displaced the sills to their current subvertical positions (Jackson and Pollard, 1988). Farther south at the lower limb, Jackson and Pollard (1988) consider the subhorizontal Cretaceous strata to mark the lateral extent of the Mount Hillers dome, giving it a radius of 6-7 km. Early interpretations of new paleomagnetic results suggest the rotation history of the Gold Creek region is more complex than that interpreted for the Southern Flank of Mount Hillers (Thompson et al., 2013).

-*Jackson and Pollard (1988) Discredit the Stock Hypothesis*

To test how host rock would respond to the radial contraction imposed by the injection of a growing stock, Jackson and Pollard (1988) use a hypothetical stock with a diameter of 3 km to approximate the Mount Hillers stock. Jackson and Pollard (1988) claim a dome with a radius of 6 km, like that of Mount Hillers, would radially contract the host rock by nearly 50%. Additionally, upon injection of the stock the sedimentary strata proximal to the stock would likely be dragged upward.

As the stock grows in both height and diameter, a strong horizontal compressional force and a lesser vertical shear force are imposed onto the surrounding host rock. Jackson and Pollard (1988) schematically illustrate how strata would respond to such forces (Figure 14a). Closest to the center of the stock, bedding would be steeply bent upward because of the stock’s vertical shear component. Away from the stock, the sedimentary strata would respond to the strong compressional force by buckling into a series of broad open folds that decrease in amplitude away from the stock (Figure 14a). The hypothetical profile of the expected bedding orientation from the injection of a stock is plotted against the true bedding orientation of southern Mount Hillers (Figure 14b). The lack of broad open folds at the periphery of the mountain domes suggests that horizontal compression was not a significant contributor to host rock deformation.

Jackson and Pollard (1988) also compare the profile of their cross sectional transects to the bending of a circular elastic plate, with a fixed perimeter, which is pushed upward by a uniform driving pressure. The theoretical profile of the plate does not match the curvature of the peripheral limb of Mount Holmes in the early stage of doming. Jackson and Pollard (1988) hypothesize that the peripheral limb is underlain by sills and thin laccoliths that are not directly related to the doming process (Figure 13). The inferred sills and thin laccoliths would contribute to the inclination and deflection of the strata on the limb.

-*Model for Progressive Dome Growth*

Jackson and Pollard (1988) proposed a comprehensive model illustrating the sequential steps of the growth history for the main intrusive body of Mount Hillers. They suggested that a network of sills and dikes developed before the main intrusive body began to grow vertically (Figure 15a). Early vertical growth of the main laccolith lifted the overlying rocks by bending. The bending was probably aided by heating from older nearby overlying intrusions.

As the main laccolithic body grew (Figure 15b), overlying rocks were lifted and rotated as the host rock went through the early stages of bending. Bedding-plane faults and stratal stretching also initiated which lowered the effective mechanical thickness of the overburden and consequently aided the emplacement process. At this stage, Jackson and Pollard (1988) hypothesize that the large laccolith body grew vertically as well as laterally, continuing to grow to a radial extent of 4 km. Faults may have developed near the floor of the laccolith facilitating the emplacement of sills and dikes into the growing peripheral limb (Figure 15b).

Jackson and Pollard (1988) suggest that as Mount Hillers entered its final stages of vertical laccolith growth, the hinges tightened significantly to give the central limb a subvertical dip (Figure 15c). During this stage, radial and circumferential stretching became more influential to host rock deformation than bending. As stratal stretching further increased, radial dikes crosscut the steeply dipping sills and thin laccoliths. Near the upper hinge of the laccolith, blocks of host rock were displaced by minor faulting (Figure 15c). Satellite sills and thin laccoliths continued to intrude into the periphery of the dome to raise the long peripheral limb (Figure 15c).

4. Objective and Methods

The objective of this thesis is to better define the geometries of the main laccolithic bodies of Mount Hillers and the progressive development and emplacement history of the Mount Hillers intrusive complex. Specifically, this study aims to determine the relationship between the main intrusive body and the smaller laccolithic bodies directly north and adjacent to the main intrusive feature. A goal is to constrain the order in which the magma bodies developed and propose possible growth progressions for the laccolithic bodies. To accomplish this goal, I have: (1) studied the geometries of the intrusive bodies by creating a more detailed geologic map, (2) recognized textural variations in igneous samples to identify magma pulses that experienced different crystallization histories, and (3) interpreted magma flow patterns from preserved igneous fabrics.

4.1 Geologic Mapping

Mount Hillers is portrayed on two 1:24,000 scale quadrangle maps. The southern quadrangle is the Copper Creek Benches quadrangle and the northern is the Cass Creek Peak quadrangle. Jackson and Noller (1991) mapped the Copper Creek Benches quadrangle. The Cass Creek Peak quadrangle has not been mapped since the work of Hunt et al. (1953), and their work was published at a relatively coarse scale. My mapping in the southern portion of the Cass Creek Peak quadrangle completes the mapping of Mount Hillers at a scale of 1:24,000. Primary mapping goals were to improve details of the “shatter zone” area and to better define the internal structure of the main intrusive features of Mount Hillers.

Mapping was done in the summers of 2011, 2012, and 2013. Georeferenced aerial photographs with superimposed topographic contours were used to map geologic features in the field at a scale of 1:10,000. Field observations were compared with the compilation map of Larson et al. (1985), which is essentially the Hunt et al. (1953) Henry Mountains geologic map overlaid on a modern topographic base. Measurements of geologic features were taken with a pocket transit. After field work was complete, field maps were scanned and imported into ArcGIS to create a digital geologic map of Mount Hillers which incorporates the previous mapping of Jackson and Pollard (1988) in the southern Copper Creek Benches quadrangle.

4.2 Petrofabrics

Petrofabrics of the Henry Mountains igneous rock used in to interpret magma paleo-flow patterns. At Mount Hillers, millimeter-scale phenocrysts of plagioclase and hornblende are found in a very fine-grained matrix, all as part of rock with a bulk dioritic composition. Generally, as magma crystallizes the last increment of strain related to magma flow may be preserved. Flow dynamics often arrange phenocrysts in a preferred orientation to form a fabric. Both solid-state and magmatic fabrics can be used to interpret flow dynamics. In solid-state fabrics, phenocrysts are deformed by shearing along a frictional contact while the magma is still hot. In magmatic fabrics the phenocrysts remain intact with their original geometric configuration. Magmatic fabrics were more commonly observed at Mount Hillers their measurements were more useful for interpreting flow induced phenocryst alignments.

No tectonic strain is expected to have influenced mineral orientation or fabric development during, or after, magma emplacement in the Henry Mountains (Horsman et al., 2005; Saint-Blaquat *et al.*, 2006; Habert and Saint-Blanquat, 2013). Previous workers have attributed the igneous rock fabrics to reflect magma flow (Horsman *et al.*, 2005; Morgan et al., 2005, 2008). Depending on the type of flow dynamics, magmatic fabrics form as phenocrysts are aligned resulting in lineations, foliations, or a combination of both.

An idealized lineation is a one-dimensional fabric defined by the average orientation of the longest axes of hornblende and plagioclase phenocrysts (Figure 16). Lineations are interpreted in this study to reflect by necessarily directly record the paleo-magma flow direction (Paterson et al. 1995). An idealized foliation is a two-dimensional planar fabric in which the long axes of the phenocrysts align parallel to a plane but exhibit no specific preferred orientation in that plane (Figure 16).

Foliations can form in a variety of ways. The pole to the foliations plane can be interpreted to be the direction of flattening. If the foliation plane is subparallel to a dike wall, the lineation in the foliation plane may represent the direction of magma-flow for “normal” foliations (Rochette et al., 1992). Oblate imbrication fabrics can form in laminar flow near the contact of a dike wall or sill floor or roof contact. As magma flows in a certain direction, the large crystals stack up with each other at a low angle to the boundary surface. The crystal faces dip into the boundary surface in the direction of the flow source (Figure 17) (Knight and Walker, 1988).

4.3 Anisotropy of Magnetic Susceptibility (AMS)

Anisotropy of magnetic susceptibility (AMS) is used to quantify the magnetic fabric in igneous rock samples. Magnetic fabrics in the Henry Mountains have been reported to be in agreement with petrofabrics used to interpret paleo-magma flow directions (Horsman et al., 2005). The minerals that control the magnetic response for Henry Mountains porphyritic diorites are mostly Fe-Ti oxides, dominantly multi-domain magnetite (Horsman et al., 2005). Altered minerals formed by deuteric alteration of amphibole and feldspar phenocrysts during the last volatile phase which postdated emplacement and solidification (Engel, 1959). This magnetite mostly formed on the surfaces of the phenocrysts or along fractures and cleavage planes (Hunt et al., 1953; Engel, 1959; Horsman et al., 2005). Thus, the magnetic fabric measurement in these rocks commonly represents the mean orientation of phenocrysts.

The samples collected for AMS were selected because they were expected to exhibit only magmatic fabrics; samples with solid-state fabric patterns were avoided. Samples used for AMS were carefully oriented in the field and taken back to the laboratory for further analysis. The samples were cut into 25-mm-diameter cores that were then cut into 22-mm-long specimens. At least 5 specimens from each station were measured to provide a robust measure of magnetic fabric.

The low-field AMS components were measured with a MFK1-A Multi-Function Kappabridge at East Carolina University. The instrument produces a magnetic field by running a current through a wire coil. When a sample is placed inside the generated magnetic magnetic-field, magnetism is induced in the sample. This induced magnetism interacts with and alters the field generated by the instrument. By measuring the magnetic field change due to the presence of the sample, the instrument collects data about the magnetic properties of the sample. By measuring the sample in many different orientations, the MFK1-A Kappabridge calculates a tensor that describes the magnetic susceptibility (K) in three dimensions, such that $\mathbf{M} = K * \mathbf{H}$, where **M** is the induced magnetization of the sample and **H** is the inducing magnetic field produce by the instrument alone.

Depending on compositional and mineralogical properties of the sample, the magnetization detected by the sensor coil varies. The machine measures the anisotropy of magnetic susceptibility (AMS) by rotating the specimen 360° to measure the variation of susceptibility in two dimensions. This process is repeated two more times to create a total of three two-dimensional datasets all at 90° from each other. The three, two-dimensional datasets are then combined to create a three-dimensional ellipsoid that describes magnetic susceptibility variations in space. The AMS ellipsoid is characterized by long, intermediate and short principal axes which are K_1, K_2, and K_3 respectively. The quantity K_1 is interpreted as the magnetic lineation and K_3 is interpreted as the pole to the magnetic foliation plane.

Additional parameters can be calculated from the K_1, K_2, and K_3 values. Bulk magnetic susceptibility (K_b) is a measure of the abundance of magnetic grains and defined as the average of the three susceptibility axes; $K_b = (K_1 + K_2 + K_3)/3$. The mean shape factor of the AMS ellipsoid (T) quantifies the shape of the ellipsoid with respect to a sphere ($T = 0$). T is calculated by the equation $T = [2 \ln(K_2/K_3)/\ln(K_1/K_3)]-1$. $T = 1$ defines an infinitely oblate ellipsoid whereas $T = -1$ defines an infinitely prolate ellipsoid. The magnetic intensity of the AMS ellipsoid is quantified by calculating the mean degree of anisotropy (P'); $P' = \exp((2[(n_1 - n)^2 + (n_2 - n)^2 + (n_3 - n)^2])^{1/2})$ where $n_I = \ln K_i$ and $n = \ln(n_1 n_2 n_3)^{1/3}$ (Jelinek, 1981).

5. Results

5.1 New Field Mapping of Mount Hillers in the Southern Cass Creek Peak Quadrangle

I have confirmed many of the observations made by previous workers and have reevaluated any conflicting interpretations. The first issue is the apparent “concordance” or “discordance” of the main intrusive feature of Mount Hillers. Jackson and Pollard (1988) discredited the stock hypothesis of Hunt et al. (1953), but only used one small outcrop on Summit Ridge to infer that the northern part of the main igneous body mirrors the southern concordant relationship to theoverlying host rock strata.

New mapping of this study reveals that the sedimentary units on Summit Ridge are the Upper Cretaceous Dakota sandstone and the Upper Jurassic Morrison Fm as described by Hunt et al. (1953) (Figure 18). However, additional sedimentary formations identified on Summit Ridge include a continuous sequence from the Middle Jurassic Summerville Fm to the Upper Cretaceous Tununk shale member of the Mancos shale. These strata dip~25° to the north and the igneous body that underlies Summit Ridge is inferred to be concordant.

The main intrusive body of Mount Hillers is concordant to both the Permian strata to the south and the Jurassic-Cretaceous strata to the north. Additionally, these stratigraphic sequences with different ages are at similar elevations and are easily mistaken as the same units at a distance. The main intrusive feature of Mount Hillers appears to be an asymmetric laccolith which has different roof units and consequently different floor units on opposite sides of the mountain

New geologic mapping of the peripheral igneous intrusion just north and adjacent to the main intrusion of Mount Hillers generally agrees with the mapping of Hunt et al. (1953). However, the term “shatter zone” implies the injection of a stock and must be reinterpreted. In the following sections, my descriptions and interpretations of the geologic features of Mount Hillers are based on detailed mapping in the southern Cass Creek Peak quadrangle.

In describing the Mount Hillers intrusive complex, I find it useful to separate the mountain into a southern and northern province (Figure 19). Each province exhibits a distinct structural relationship between the igneous bodies and the host rock. The Southern Province includes the southern side of the main asymmetric laccolithic body of Mount Hillers which contacts the Permian Cedar Mesa sandstone. The Northern Province includes the northern half of the same main asymmetric laccolithic body and at least five smaller laccolithic bodies directly north and adjacent to it. The intrusions exposed in the Northern Province are all emplaced above the Jurassic Entrada sandstone. The main asymmetric laccolithic body of Mount Hillers is partly in both provinces. Because the main igneous body has different roof and floor units in separate provinces, I will refer to the southern half of the intrusion as the Copper Creek laccolith and the northern half as the Mordechai laccolith (Figure 19).

5.1.1 Southern Province

The Southern Province includes the southern half of the main asymmetric laccolithic body of Mount Hillers, also referred to as the Copper Creek laccolith. The two main areas of the province are the Southern Flank of Mount Hillers and the Gold Creek region. The oldest sedimentary unit exposed in the Southern Province is the Permian Cedar Mesa sandstone which is inferred to be the roof contact to most, if not all of the Copper Creek laccolith. Exposures of the Cedar Mesa have been identified on the Southern Flank of Mount Hillers (Jackson and Pollard 1988) and in the western drainages of Gold Creek (Figure 19). The northeastern extent of the Southern Province is the northernmost ridge of the Gold Creek region. The northwestern extent of the province is less well defined because of poor outcrops, but was mapped on the southern side of the ridge just south of Hansen Creek (Figure 19).

The Permian exposures on the Southern Flank of Mount Hillers and Gold Creek are separated by a large igneous body which is likely the southeastern portion of the Copper Creek laccolith (Figure 20). This terrain is extremely rugged and consists of many large intrusions that crop out as steep cliffs. The southeastern extent of the Copper Creek laccolith was not investigated fully in this study because of difficult accessibility. Additionally, much of the intrusion is in the Copper Creek Benches quadrangle outside the targeted mapping area (Figure 20). However, the oldest mapped sedimentary unit at the southeastern extent of the Copper Creek laccolith is the Lower Jurassic Wingate sandstone which crops out under a sill (Figure 20, MH185). Bedding was obscured in the Wingate due to metamorphism, but ~150 meters to the southeast of station MH185, the Lower Jurassic Kayenta Fm dips 58° to the southeast (Figure 20). It is unclear whether the porphyry at the southeastern extent of the Copper Creek laccolith has Permian-aged strata roof units or strata of some other age.

As described by Jackson and Pollard (1988), the strata overlying the Copper Creek laccolith have a concave-upward lower hinge and a concave-downward upper hinge that are connected by a central limb. On the Southern Flank of Mount Hillers, the central limb has a subvertical dip to the south (Figure 20). The dip of the central limb progressively diminishes as the strata wrap eastward and northward around the mountain. In the southern Gold Creek region, the central limb generally dips ~60° to the southeast (Figure 20). No upper limb strata are observed in southern Gold Creek. In the northern Gold Creek region, the central limb generally dips ~50° to the northeast (Figure 20). A cross section of the Southern Flank of Mount Hillers and the Gold Creek region is displayed on Figure 21 (see Figure 20 or 22 for transect location points).

On the northernmost east to west trending ridge of the Gold Creek region, continuous strata from the Middle Jurassic Summerville Fm to the Lower Jurassic Navajo sandstone dip ~55° to the northeast (Figure 20). Just east of these strata, a sizeable intrusive body marks the outer extent of the northern Gold Creek drainage (Figure 20). This intrusive feature appears to be mostly concordant along its eastern perimeter where it contacts the Salt Wash member of the Morrison Fm which dips 26°-32° away from the intrusion (Figure 20) (Hunt et al., 1953). Strikes of the Jurassic strata on top of the ridge indicate that the strata radially wrap around the of the Copper Creek laccolith outcrops abruptly stop in the valley just north of the ridge (Figure 20). North of this valley marks the beginning of the Northern Province where the Jurassic Salt Wash member of the Morrison Fm dips 48° to the northeast.

The northern section of Gold Creek region was originally mapped as “shatter zone” by Hunt et al. (1953). My mapping has identified the sedimentary units as isolated blocks that range from the Jurassic Entrada sandstone to the Permian Cedar Mesa sandstone. Toward the eastern extent of northern Gold Creek, the intrusive bodies are relatively smaller and sedimentary rocks cover a larger area and are relatively well intact. Closer to the center of the mountain, intrusive bodies become larger and sedimentary units crop out in smaller exposed blocks.

Along the Gold Creek drainage canyons, the host rock dips decrease from 44° observed in the Chinle Fm to 31° in the Cedar Mesa sandstone (Figure 20). The area between the changed dips is interpreted to be the upper hinge of the Copper Creek laccolith. In the upper hinge, the White Rim sandstone and the Organ Rock tongue are visible as breccias and float. The Cedar Mesa dips change from 31°E to 18°E to 34°E toward the summit (Figure 20). The variations in dip can either be attributed to minor faults separating blocks of host rock or to variable dips of the top contact of an irregular shaped intrusion.

Several smaller outcrops of porphyry intruded into the Kayenta Fm in the northern Gold Creek region are interpreted to be part of a large tongue-shaped intrusive body that I refer to as the Ward intrusion (Figure 20, MH131). This intrusion trends northwest-southeast and is concordant to the inclined strata (Figure 21). The sedimentary rocks are significantly metamorphosed beneath the Ward intrusion from the Kayenta downward contact to the Permian Cedar Mesa sandstone. The metamorphism is pervasive and does not appear to be attributed to local intrusive contacts. Metamorphism is more intense in the older units and the dips of the bedding planes become more poorly defined. Additionally, the metamorphosed units are thinned significantly between the Ward intrusion and the Cedar Mesa sandstone (Figure 21).

A well-developed breccia (MH268) with igneous and sedimentary clasts is observed on the crest of a ridge near the summit of the mountain (Figures 20 and 23A). The matrix is composed mostly of green shale and most likely belongs to the Organ Rock tongue. Quartz sand grains and plagioclase crystals are observed in the matrix (Figure 23B). The porphyritic clasts are composed of fine grained porphyry, are subrounded, and range up to 2 mm in diameter. Large sandstone clasts are angular and range up to ~10 mm in length (Figure 23A).

To the west of MH268 are outcrops of the Copper Creek laccolith. Just to the east of MH268, is a ~500 m linear igneous outcrop that was sampled for AMS (Figure 20). This intrusion extends along the ridge, and has no exposed host rocks. At first, the intrusion appears as a radially striking dike in map view (Figure 20). However, this intrusion exhibits an internal planar contact between two stacked magma pulses with different igneous textures (Figure 23C). This planar contact shares a dip that is similar to the slope of the ridge. This type of planar contact is expected in subhorizontal sheets, not in dikes.

-*Comparing the Southern Flank of Mount Hillers and Gold Creek*

The Southern Province is generalized as one large concordant laccolithic body with overlying host rock intruded by sills, dikes, and other minor irregular intrusions. The domed host rocks for both the Southern Flank and the Gold Creek region have the Permian Cedar Mesa sandstone as the roof unit. The roof to the Copper Creek laccolith is structurally characterized by a peripheral limb, a concave up lower hinge, a central limb, a concave down upper hinge, and a shallowly dipping upper limb (Figure 21). Even though the Southern Flank and Gold Creek are separated by the large southeastern exposure of the Copper Creek laccolith, the two flanks share the same general relationship to the Copper Creek laccolith that uplifted and deformed the host rocks in both areas.

The dip of the central limb progressively decreases as the Northern Province is approached from the southernmost flank of Mount Hillers. The Southern Flank of Mount Hillers is well ordered with at least 10 well identified concordant sills between sedimentary units (Jackson and Pollard, 1988) (Figure 20). The Gold Creek region is more inconsistently intruded by irregular intrusions and is less well ordered than the Southern Flank (Figure 21). Gold Creek has large tongue-shaped intrusions intruded into older sedimentary units, while the same older units of the Southern Flank of Mount Hillers are intruded by sills and dikes (Figure 20).

The oldest exposed sedimentary units are significantly metamorphosed in the Southern Province. Metamorphism on the Southern Flank of Mount Hillers extends from the Copper Creek laccolith contact to the base of the White Rim sandstone, a ~150 m distance (Jackson and Pollard, 1988). Metamorphosed units in the northern Gold Creek region extend from the Copper Creek laccolith contact to at least the Kayenta Fm (Figure 21). The strata are considerably thinned in Gold Creek and the zone of relatively intense metamorphism is at least 300 m thick.

5.1.2 *Northern Province*

The intrusions exposed in the Northern Province are emplaced above the Jurassic Entrada sandstone. The Northern Province includes the northern half of the main asymmetric laccolithic body of Mount Hillers, also referred to as the *Mordechai laccolith*. The Northern Province also includes the intrusions that contribute to the topographic dome of Mount Hillers just north of and adjacent to the Mordechai laccolith. These intrusions are Cass Creek Peak, Quaking Asp, Stewart Ridge, Chaparral Hills, Specks Ridge, and Specks Canyon (Figure 19). The satellite intrusions to the east and northeast of Mount Hillers are not considered part of the Northern Province because they are separate from the main topographic dome. The southern extent of the Northern Province was placed where the Jurassic-Cretaceous strata were last observed on top of the Mordechai laccolith.

5.1.2.1 Mordechai Laccolith

The Mordechai laccolith is defined as the northern portion of the main asymmetric laccolithic body of Mount Hillers. This area was mapped as the “shatter zone” by Hunt et al. (1953) because the area was considered too complicated to be shown at a scale of 1:31,680. My mapping in the “shatter zone” of the Northern Province has identified several faulted blocks of host rock that are inferred to be the roof rocks of the Mordechai laccolith. The sedimentary blocks usually include groups of different formations. For example, the continuous section of strata exposed on Summit Ridge extends from the farthest north Cretaceous Tununk shale to the Jurassic Summerville Fm closest to the summit (Figure 24).

The strata exposed above the Mordechai laccolith range in age from the Jurassic Summerville Fm to the Cretaceous Blue Gate shale member of the Mancos Fm. Being the oldest exposed sedimentary unit, the Summerville Fm is inferred to be the roof unit to most, if not all, of the Mordechai laccolith. This suggests the Entrada sandstone forms the floor of the intrusion. The Summerville Fm contacts the Mordechai laccolith on Summit Ridge. In others areas in the Northern Province, it is the oldest unit exposed. In some places the Jurassic Salt Wash member of the Morrison Fm is the oldest unit exposed, but is never in direct contact with the laccolith. The Mordechai laccolith is likely concordant to the oldest sedimentary unit at the base of the faulted roof blocks.

The peak of Mount Hillers is likely near the top and geographic center of the Mordechai laccolith as the strata of the faulted host blocks generally dip radially away from the peak (Figure 24). Just south of the summit of Mount Hillers, on the crest of a north-south trending ridge is a small outcrop of metamorphosed green shale and farther south is an outcrop of fine grained sandstone (Figure 24, MH232 and MH231 respectively). These outcrops are likely the Jurassic Summerville Fm to the north and the Salt Wash to the south. Bedding is not evident in these outcrops. However, since the older Summerville Fm crops out farther north, the strata likely dip to the south, away from the peak of Mount Hillers (Figure 24).

The geometry of the Mordechai laccolith is complicated by minor faults, dikes, sills and jostled blocks of host rock overlying the intrusive body. Additionally, the Mordechai laccolith is likely connected to the laccolithic bodies on its northern perimeter (Figure 25). The western side of the Mordechai laccolith is the only part of the intrusion that is not obviously connected to another intrusive body.

To the west of the Mordechai laccolith, a regional dip of 2° to the west is assumed where the Blue Gate shale is undisturbed by intrusions (location C on Figure 22 and Figure 25) (Hunt et al., 1953; Jackson and Pollard, 1988). Where the closest roof rocks are exposed at the westernmost extent of the laccolith, the Blue Gate dips 28° to the west (Figure 24). A lower hinge of bent strata is inferred to exist between these two dips (Figure 25 C-D). Consequently, the Mordechai laccolith is interpreted to be a punched/traditional hybrid laccolith exhibiting bending on its western perimeter and faulting on its northern perimeters (Figure 25).

Bedding generally dips shallowly on faulted blocks near the top of the intrusion and moderately on the sides of the intrusion (Figure 25). The three-dimensional roof geometry of the Mordechai laccolith is irregular and can be approximated by the positions of the Jurassic Salt Wash member of the Mancos Fm and the Jurassic Summerville Fm.

Minor faults are inferred to exist between nearly every adjacent host rock block. No fault plane attitudes around the Mordechai laccolith were measured because host rock blocks are either separated by dikes or faults are covered by talus. Nevertheless, offsets between strata usually share a similar pattern where blocks closer to the summit have a downthrown offset relative to the outer blocks (Figure 25, A''-E-D'). However, the opposite offset pattern also exists on the northwestern side of the Mordechai laccolith where the closest block towards the summit was raised more than the outer host blocks (Figure 25 D-D').

Dikes and breccias are common near faulted host blocks above the Mordechai laccolith. Breccias of the Northern Province typically have abundant sedimentary clasts. The size of quartz grains in each breccia is locally dependent on the grain size of the protolith and the amount of offset between the faulted blocks, smaller grains correlate to more offset (Figure 26).

Where the Mordechai laccolith contacts the host rock closest to the Southern Province to the southwest, the contact between host rock and the Mordechai laccolith is heavily faulted (Figure 24, MH325). Mapping specific units was difficult here because there were many minor faults and it was difficult to distinguish between the Jurassic Morrison and Summerville Fms.

In the center of several of the faulted blocks of host rock above the Mordechai laccolith, some shale units display no metamorphism (e.g. Figure 18). Other than minor contact metamorphism next to minor intrusions, metamorphism was only observed where the faulted blocks are known to be in direct contact with the Mordechai laccolith. The Summerville shale is assumed to be 55 m thick (Figure 3). On Summit Ridge, the Brushy Basin of the Morrison Fm is clearly not metamorphosed and cross sections suggest it to be about 140 meters from the top of the Mordechai laccolith.

5.1.2.2 Cass Creek Peak Intrusion

The Cass Creek Peak intrusion (called laccolith A by Gilbert (1877) and Bulldog Peak by Hunt et al. (1953)) was previously described as a bysmalith, with a piston-like geometry characterized by faulted sides. However, exposures of contacts with host rock are limited and I did not observe sufficient faulting to consider this intrusion a bysmalith.

To the northwest of the Cass Creek Peak intrusion is a very small outcrop of the Upper Cretaceous Tununk shale member of the Mancos Fm, which is the best evidence for the wall/roof host rock unit observed in this study (Figure 27). The Tununk shale dips 49° northwest and does not directly contact the Cass Creek Peak intrusion which is likely concordant with this unit (Figure 27; Figure 25 D’-I). The southeastern portion of the Cass Creek Peak intrusion contacts an overturned Tununk shale outcrop dipping 75° to the northwest that is also close to the Mordechai laccolith.

Just southeast of Cass Creek Peak and above the Mordechai laccolith, a continuous section of very well preserved strata from the Jurassic Summerville Fm to the Blue Gate shale member of the Mancos Fm dip 41° toward the Cass Creek Peak intrusion (Figure 27; Figure 25, E-D’). Beds from the Jurassic Summerville Fm to the Dakota sandstone are discordantly cut off by the Cass Creek Peak intrusion while the Tununk shale and the overlying units appear to be overturned by a concordant part of the Cass Creek Peak intrusion (Figure 25 E-D’). Host rocks above the intrusion were eroded away, however the roof unit is hypothesized to have been the Tununk shale. Since the Tununk is inferred to be the roof and wall of the intrusion, the Dakota sandstone is inferred to be at the floor.

On the northern perimeter of Cass Creek Peak outcrops of porphyry were sampled for AMS (Figure 27; MH150-153). These outcrops have no accompanying host rock units. These intrusions were previously mapped as concordant sills that were upturned from the emplacement of the Cass Creek Peak intrusion (Hunt et al., 1953). It is difficult to determine their true relation to the host rock, however they may be horizontal sills underlying the Cass Creek Peak intrusion. Southwest of Cass Creek Peak is a cliff of porphyry. The cliff face has the most drastic change in relief of Cass Creek Peak (Figure27; Figure 28). These rocks may simply be a large bulge in the Cass Creek Peak intrusion. Hunt et al. (1953) report a sedimentary outcrop next to this bulge, but the cliff was not visited in this study.

5.1.2.3 Stewart Ridge Laccolith

Hunt et al. (1953) identified the Stewart Ridge laccolith to be one of the largest subordinate tongue-shaped intrusions of the Henry Mountains. Since its long dimension is trending away from the mountain peak, Hunt et al. (1953) hypothesized this laccolith was fed from the south and injected to the north. Exposures of roof strata are observed at the nose of the intrusion where the Tununk Fm dips 27-35° to the north (Hunt et al., 1953) (Figure 27). Farther north from the nose of Stewart Ridge, the dip of the host rock diminishes to the regional dip, suggesting an absence of additional intrusions to the north.

On the western side of Stewart Ridge, an outcrop of the Ferron sandstone member of the Mancos Fm dips 23° to the northwest (Figure 27). This outcrop is inferred to overlie the Tununk shale which is likely in contact with the northwestern roof of the Stewart Ridge laccolith. On the southeastern side of the intrusion, the Tununk Fm is exposed on a ridge just east of the Stewart

Ridge and dips 41° to the east (Figure 27). Although the Tununk shale does not directly contact porphyry, the projected strike and dip make the Tununk Fm a likely roof unit for the southern portion of the Stewart Ridge laccolith. Although the exposures of host units are sparse, the Tununk Fm is assumed to be the roof contact to all of the Stewart Ridge laccolith. Consequently, the Dakota sandstone is inferred to be the floor (Figure 25).

The topography of Stewart Ridge is useful for distinguishing an upper and lower portion of the intrusion. The general south to north topography is a structural terrace where the two upper ridges transition into a lower lobate structure with a subhorizontal roof (Figure 27). The lower lobate portion of Stewart Ridge has a wide and broad crest with minor elevation changes on its roof and the igneous textures in the porphyry are similar and consistent. The only exception to this generalization is MH200 which has unusually abundant large plagioclase phenocrysts (Figure 29A). MH200 is likely either an underlying sill parallel to the base of the Stewart Ridge laccolith or an earlier sill upturned by the intrusion (Figure 27).

The southern upper portion of Stewart Ridge has two well pronounced ridges of porphyry separated by a drainage (Figure 27). The texture of most of the western ridge porphyry is identical to that of the lower Stewart Ridge lobe (Figure 27, MH187; Figure 29B). At the southernmost extent of Stewart Ridge, on the western ridge directly north of the Mordechai laccolith there is a contact between rocks with the dominate Stewart Ridge texture and another texture (Figure 27, MH190; Figure 29C). Where Stewart Ridge meets the Mordechai laccolith, the faulted blocks of Mordechai roof strata appear to be discordant to the Stewart Ridge intrusion. The roof units of the Mordechai laccolith exposed just south of Stewart Ridge range from the Jurassic Salt Wash member of the Morrison Fm to the Tununk shale of the Mancos Fm and dip 57° to the north (Figure 27).

The eastern portion of Upper Stewart Ridge consists of porphyry with a finer grained texture than that of the rest of Stewart Ridge (Figure 29D) and has a different weathering pattern. The eastern ridge almost resembles a shale outcrop pattern from a distance (Figure 29E). Most porphyry outcrops on Mount Hillers weather into angular cobble to boulder sized debris like that of the western portion of Upper Stewart Ridge (Figure 29E). The eastern portion of Upper Stewart Ridge weathers into subrounded pebbles and cobbles (Figure 29F). This weathering pattern was not observed anywhere else on Mount Hillers. Additionally, some cobbles of porphyry have sandstone inclusions (Figure 29F).

To the east of the Stewart Ridge laccolith, rocks of the eastern intrusions dip 28° to the northwest (Figure 27). The projected strike and dip of these strata are interrupted by the Stewart Ridge intrusive body to the west (Figure 25 I’’-I’). Since the floor of Stewart Ridge is expected to be the Dakota sandstone, which is younger than the formations above the Chaparral Hills intrusion, a fault likely exists between the two intrusions (Figure 25). The fault postdates the emplacement of the Stewart Ridge laccolith. Topographically, the eastern side of the lower portion of Stewart Ridge is much steeper than the western side and displays an excellent exposure of porphyry (Figure 27 and Figure 30). This steep elevation change resembles a fault scarp (Figure 30). I did not scale the apparent fault scarp because I did not realize its significance in the field at the time.

5.1.2.4 Chaparral Hills, Specks Ridge, and Specks Canyon Intrusions

The area called laccolith C by Gilbert (1877) was considered to be three different intrusions by Hunt et al. (1953); the Chaparral Hills laccolith, the Specks Ridge laccolith, and the

Specks Canyon laccolith (Figure 27). This study maps this area on a coarser scale than Stewart Ridge and Cass Creek Peak due to time constraints. The complexity of these three intrusions deserves more detailed mapping for future work. This study mapped the Chaparral Hills laccolith and the Specks Ridge laccolith with confidence, but the Specks Canyon laccolith was sky mapped. My observation generally agree with previous mapping of Hunt et al. (1953).

The Chaparral Hills laccolith is northeast of and directly connected to the Mordechai laccolith (Figure 25). Both of these intrusions are inferred to have the Entrada sandstone as their floor unit and the Summerville Fm as the roof unit. The Chaparral Hills laccolith begins past the most distal exposure of faulted blocks of host rock at the outer limits of the Mordechai laccolith (Figure 25). Hunt et al. (1953) divided the Chaparral Hills laccolith into an upper western portion and lower eastern portion and only described the lower portion of the intrusion.

The upper western part of the Chaparral Hills laccolith is exclusively porphyry with no observed exposures of host rock. The upper Chaparral Hills laccolith is heavily covered in talus and in-place porphyry is only exposed on the crests of ridges. Because there are no exposures of host rock, it is difficult to determine the true form of upper part of the Chaparral Hills laccolith. The geographic distribution of porphyry outcrops and talus may suggest the intrusion is symmetrical in plan view. The laccolithic body may have been emplaced above the lower Chaparral Hills laccolith (Figures 25 and 27).

Where the upper part of the Chaparral Hills laccolith transitions into the lower part, the topographic profile resembles a less idealized version of the Stewart Ridge terrace pattern where the floor of the intrusion flattens out below the upper part of the intrusion. At the roof of the lower part of Chaparral Hills, the Tununk shale and Dakota sandstone are exposed. The Jurassic

Brushy Basin and Salt Wash members of the Morrison Fm are exposed on the eastern side of the Chaparral Hill laccolith and are projected to underlie the Cretaceous strata as the roof of the lower part of the laccolith (Figure 25 I’’’-I’’). The Jurassic Summerville formation is probably under the entire package of roof strata but is covered by Quaternary units (Figure 25 H-G).

In the top of the roof above the Lower Chaparral Hills laccolith, at least three dikes, presumably fed by the underlying laccolith, discordantly cut through the shallowly dipping Tununk shale (Figure 25 I’’’-I’’ and Figure 27). At the eastern side of Lower Chaparral Hills a series of sills concordantly intrude the Salt Wash member of the Morrison Fm.

The Specks Ridge intrusion is only exposed in small outcrops in an area dominated by Quaternary deposits (Figure 27). Even though outcrops of porphyry are limited, Hunt et al. (1953) mapped Specks Ridge as a northward trending laccolith because the topography likely indicates a partially exposed intrusion. Specks Ridge is ~2.5 km in length and ~750 m in width suggesting a finger shaped intrusion rather than one with a mushroom shape. The Specks Ridge laccolith likely connects to the Chaparral Hills laccolith to the south (Hunt et al., 1953).

The Specks Canyon laccolith was completely sky mapped in this study. Specks Canyon is the farthest northeast intrusion and is 60 to 90 meters lower in the stratigraphic section than the Chaparral Hills and Specks Ridge laccolith. Hunt et al. (1953) report that the Specks Canyon laccolith intruded into the Summerville formation. Toward the northwest side of the Specks Canyon laccolith, Hunt et al. (1953) report that the intrusion is slightly discordant to the Summerville and Salt Wash roof strata that dip 16° to the northwest (Hunt et al., 1953).

5.1.3 Major Faulting

Concordant Jurassic-Cretaceous strata on the northern portion of the main asymmetric laccolithic body of Mount Hillers and concordant Permian strata to the south are interpreted to be offset by major faulting. The major fault is considerably different from the minor faults observed on Mount Hillers and defines a boundary between the Southern and Northern Provinces (Figure 19). The host rocks overlying the Copper Creek laccolith in the Southern Province have been uplifted significantly more than those in the Northern Province. I refer to the main fault at Mount Hillers as the *Charles Fault* in honor of Charles B. Hunt. Hunt et al. (1953) were the first to correctly identify different aged sedimentary strata at the top of the main intrusive body of Mount Hillers.

My geologic mapping constrains the location of the Charles Fault by identifying the northern extent of Permian strata and the southern extent of Jurassic-Cretaceous strata (Figure 19). No contacts were seen in Permian and Jurassic-Cretaceous units and the Charles Fault, mostly due to poor exposures and separating intrusions. Additionally, portions of the Charles Fault may be concealed by intrusions that postdate the time that the roof strata were offset.

The Charles Fault is probably irregular in form but generally strikes northeast. The fault surface was not exposed but the proximity of exposed Permian and Jurassic-Cretaceous strata in the northwestern portion of the Gold Creek drainage (Figure 19) indicates that the fault is probably steeply dipping to the northwest.

Between the middle Jurassic units of the northwester Gold Creek area and the upper Cretaceous and upper Jurassic units of the eastern portion of the Mordechai laccolith, a ridge of porphyry is close to the northeastern extent of the Charles Fault (Figure 27; MH171). This igneous body is most likely a dike that invaded the fault zone and is referred to as the Charles Fault dike. No direct contacts between the dike and host rock were observed.

The Charles Fault dike rocks have several different porphyritic textures in the outcrop (Figure 31). These represent inclusions of igneous rocks that must have been already solidified before being reworked in a later pulse of magma. Nowhere else on Mount Hillers was this inclusion pattern observed.

The Charles Fault dike rock has an aphanitic matrix and is light brown and with fine grained plagioclase pheoncrysts. The inclusions are subangular to rounded and vary in size but none are larger than a half a meter in length. The textures of the inclusions are regular textures observed at Mount Hillers and are characterized by larger phenocrysts (Figure 31). The matrices of the inclusions are either light-grey or dark-grey. These observations suggest that the Charles Fault dike contains at least four generations of intrusive rock.

5.2 Igneous Textures

The porphyritic diorite at Mount Hillers exhibits a variety of textures. Hornblende and plagioclase phenocrysts range in both size and abundance. Plagioclase phenocrysts can range in size from <1 mm to 10 mm. Hornblende phenocrysts can be smaller than 1 mm and are rarely larger than 5 mm. Varying textures suggest different crystallization histories where the larger phenocrysts require longer growth times at depth. Textural variations can be used to differentiate between different magma batches. Additionally, contacts between different igneous units within individual magma bodies necessitate pulsed emplacement construction (Figure 32).

Igneous textures of Mount Hillers are generally similar in outcrops in close proximity. For example, the Cass Creek Peak textures are similar throughout the entire intrusion and are also similar to those of the Lower Stewart Ridge lobe. Textural variation increases near the peak of Mount Hillers. The largest textural variations observed between nearby porphyry outcrops were in the western drainages of Gold Creek. Here igneous outcrops within 300 m of each other show considerably different phenocryst sizes and percentages. A detailed study quantifying of igneous textures goes might help to discriminate between different magma batches.

5.3 Anisotropy of Magnetic Susceptibility Results

The AMS samples from Mount Hillers were collected throughout a large area encompassing many igneous bodies with different temporal and spatial emplacement histories. Local factors likely influenced magma flow conditions in each out outcrop sampled for AMS. Thus the magnetic fabrics are dependent on local geology and must be interpreted accordingly. AMS results are reviewed in six separate zones that share similarities between magnetic fabric results, intrusive structures, and geographic distribution (Figure 33). The AMS ellipsoids were classified as either prolate ($0 > T > -1$) or oblate ($0 < T < 1$) and plotted as lineations or foliations on lower hemisphere equal area stereonets.

5.3.1 AMS Zone A: Cass Creek Peak and Quaking Asp Laccolith

Cass Creek Peak and Northern Quaking Asp Laccolith

- Observations

Stereonet Aii represents seven AMS ellipsoids from porphyries of Cass Creek Peak and the northern Quaking Asp laccoliths (Figure 34 Aii). The prolate Cass Creek Peak ellipsoids generally show moderately to shallowly plunging lineations that point radially away from the summit of Mount Hillers (Figures 34 Ai and Aii). There are three varieties of oblate ellipsoids. MH150 and MH212 are foliations that dip shallowly to the south, MH151 is steeply dipping and strikes subparallel to the wall of the Cass Creek Peak intrusion, and MH152 is a foliation on a northwest trending ridge near the center of Cass Creek Peak, that strikes subparallel to the ridge trend and dips moderately to the southwest (Figure 34 Aii).

- Interpretations

The lineations of Cass Creek Peak trend to the northwest and west, away from the summit of Mount Hillers. These are interpreted as paleo-magma flow directions, suggesting that magma flowed away from the summit area of Mount Hillers. The lineation direction becomes increasingly westward farther away from the summit (Figure 34 Ai). These samples were taken at high elevations and are likely attributed solely to growth events in the Cass Creek Peak intrusion. The shallow plunges of the lineations at high elevations of the intrusion are interpreted to be attributed to the emplacement of subhorizontal to slightly inclined stacked sheets (Figure 34 Ai).

The foliations MH150 and MH212 are both north of the Cass Creek Peak intrusion and both dip shallowly to the south (Figure 34 Aii). These samples were taken from approximately the same elevation and assumed to be below the floor of the Cass Creek Peak intrusion. The shallowly dipping foliations may represent magnetic imbrication fabrics at the floors of subhorizontal intrusions that underlie the Cass Creek Peak intrusion. A shallowly southward dipping imbrication fabric which intersects a subhorizontal boundary surface indicates that the magma flowed from south to north (Figure 34Aii).

The subvertical dip of MH151 is parallel and adjacent to the wall of Cass Creek Peak laccolith. This is a common fabric observed at the walls of intrusive bodies (Paterson et al., 1998). The moderately dipping foliation MH152 is just northeast of the large topographic bulge of Cass Creek Peak laccolith (Figure 34Ai). The MH152 foliation may represent a dike-like body in which magma flowed upward and to the northeast away from the southwestern bulge of Cass Creek Peak. If the interpretation of MH152 is correct, the lineations MH153 and MH247 may share a similar emplacement history to the MH152 foliation and previous interpretations of these lineations may have to be reevaluated.

<u>Southern Quaking Asp Laccolith</u>:

- Observations

Stereonet Aiii represents four prolate ellipsoids from concordant sills intruded into the roof strata of the northwestern side of the Mordechai laccolith (Figure 34Ai and 34Aiii). The lineations of these fabrics all point away from the summit of Mount Hillers. Exposed roof rocks throughout the ridge are approximately dipping 34° to the northwest (Figure 34 Aiii).

- Interpretations

The lineations of the sills above the northwestern portion of the Mordechai laccolith all plunge similarly to the dip of the host rock (Figure 34Aiii). The lineations are interpreted to indicate magma flow subparallel to the orientation of the bedding planes. Evidence to determine if the beds were horizontal or tilted during emplacement is inconclusive. The northwestern trends of the lineations suggest that magma most likely flowed to the northwest away from the peak of Mount Hillers.

5.3.2 AMS Zone B: Stewart Ridge Laccolith, the Northeastern Perimeter of the Mordechai Laccolith, and the Chaparral Hills Laccolith

Stewart Ridge Laccolith

- Observations

The AMS measurements of the Stewart Ridge laccolith are grouped into those from the lower and upper portion of the laccolith (Figure 35 Bii and Biii respectively). Samples from the southern lower portion all show steeply dipping, oblate fabrics (Figure 35Bii). The MH202, MH204, and MH205 foliations on crests of the lower lobe of Stewart Ridge laccolith generally strike north-south and dip steeply to the east (Figure 35Bii). MH200 strikes subparallel to the host rock wall and dips subvertically. Two samples taken at the southern top portion of Stewart Ridge show prolate fabrics while one sample is oblate. MH188 plunges moderately to the south and MH245 plunges subhorizontally to the east. MH187 strikes east-west and dips subvertically (Figure 35Biii).

- Interpretations

The steeply dipping foliations on the crest of the southern Lower Stewart Ridge are interpreted to have developed during the inflation process (Figure 35Bii). The axial hinge zone is hypothesized to have inflated the most, consequently steep foliations are expected near the axial hinge (Figure 35Bii). MH200 has a foliation strike subparallel to the host rock wall which is interpreted to have formed as magma contacted the wall. MH187 and MH188 suggest a vertical flow pattern while MH245 suggests flow away from the summit of Mount Hillers (Figure 35Biii).

The Northeastern Perimeter of the Mordechai laccolith and The Chaparral Hills laccolith:

- Observations

Five oblate fabrics and one prolate fabric were measured at stations on the intrusions of the northeastern perimeter of the Mordechai laccolith and the Chaparral Hills laccolith. MH196 was sampled from what is most likely a concordant sill intruded into strata dipping ~50 to the northeast. The lineation MH196 plunges subhorizontally to the northeast (Figure 35Biv). MH192 and MH243 are generally trending north-south with subvertical dips to the west. The strikes of MH157, MH177, and MH23 follow the trend of the ridges they were sampled from and are steeply dipping (Figure 35Biv).

- Interpretations

The lineation MH196 points away from the summit of the mountain but the porphyry here is intruded into inclined strata. The lineation is expected to have a plunge subparallel to the bedding plane if the magma was emplaced parallel to the bedding plane. There is no preferred interpretation for MH196. MH192 and MH243 share similar strikes and dips (Figure 35Bi and Biv). I hypothesize MH192 and MH243 are part of the same north-south striking dike in which magma flowed subvertically upward through the host rock. The steeply dipping foliations of the upper Chaparral Hills laccolith may be near the axial hinge of a set of stacked laccolithic intrusions (Figure 35Bi and 35Biv). MH23 is from a dike that intruded into the Cretaceous roof rocks of the bottom portion of the Chaparral Hills laccolith. The northward dip of MH23 may suggest that magma flowed upward from north to south (Figure 35Biv).

5.3.3 AMS Zone C: Central Portion of the Mordechai Laccolith

- Observations

Five oblate fabrics and one prolate fabric in Zone C near the center of the Mordechai laccolith (Figure 36). MH 219 and MH222 are shallowly dipping. These were sampled from intrusive bodies, presumably dikes near minor faults. MH219 and MH222 both have east-west strikes but dip in opposite directions (Figure 36 Cii). MH222 has a foliation similar to the strike and dip of the sedimentary host rock (Figure 36 Ci and Cii). MH233, MH285a, and MH285b were sampled near the summit of Mount Hillers. These foliations all strike northwest and are steeply to moderately dipping (Figure 36 Ci and Ciii). MH285a and MH285b were sampled from beneath beds of the Summerville Fm. MH230 is a lineation shallowly dipping to the northeast (Figure 36Ciii).

- Interpretations

The foliation plane of MH222 is subparallel to the orientation of the bedding plane of the host rock. The foliation plane may indicate flow subparallel to the bedding plane. However the intrusion is exposed where sedimentary units are offset by a minor fault. The fault was expected to be a subvertical fracture that separated two blocks of host rock modeled after the minor faults of Mount Ellsworth (Koch, 1981). MH219 is an oblate fabric perpendicular to the bedding of the host rock and no other evidence is offered for flow in a vertical dike (Figure 36Cii).

The consistent, steeply dipping foliations of MH233, 285a, and 285b suggest upward magma flow near the peak of the Mount Hillers. The plunge and trend of MH230 may suggest magma moved upward in the summit area to the southwest (Figure 36Ciii).

5.3.4 Zone D: Northwestern Gold Creek Area and the Charles Fault Dike

- Observations

AMS measurements were made in three regions of zone D: intrusions near the inferred Charles Fault, intrusions exposed in the northern Gold Creek drainage, and intrusions along a northwestern ridge of the Gold Creek area (Figure 37 Dii, Diii and Div respectively). There are two prolate fabrics and one oblate fabric near the Charles Fault dike. The oblate fabric MH170 strikes in the same direction as the trend of the porphyry ridge it was sampled from and dips moderately to the northeast (Figure 37Di and Dii). MH169 is south of the Charles Fault and plunges subhorizontally to the north-northeast. MH172 is northwest of the Charles Fault and plunges subhorizontally to the west-northwest (Figure 70 Di and Dii).

Exposures pf intrusive bodies of the northern Gold Creek drainage are limited but three are dipping oblate fabrics and one shallowly plunging prolate fabric were measured in the northern Gold Creek drainage (Figure 37 Diii). MH161 was sampled from the Ward intrusion exposed on both sides of an incised drainage (Figures 38 A and 38 B). The floor of the intrusion is not exposed, however MH161 was sampled ~5 m above the lowest elevation in the drainage (Figure 38A). MH163 trends subhorizontally to the east. MH260 and MH259 are both oblate fabrics that dip shallowly to the east and southeast respectively (Figure 37Diii).

MH269 and MH265 are both oblate fabrics that steeply dip to the north-northeast and north respectively. MH269 is from an intrusion that is likely part of the main intrusive body at the top of Mount Hillers. MH266 was sampled from an apparent sill-like body which has exposure of two stacked porphyry sheets (Figure 23C).

- Interpretations

The prolate fabric MH169 points to the north-northeast in the direction of the satellite intrusion. MH169 is at a higher elevation than the satellite intrusions, but could indicate the direction that magma flowed in conduits south of the Charles Fault to feed satellite intrusions to the north and east. Conversely, north of the Charles fault, MH172 points to the west (Figure 37Di and Dii). This fabric may represent magma flow from the Charles Fault into the Northern Province.

MH161 and MH163 may indicate magma that flowed subhorizontally away from the Charles Fault (Figure 37Di and Diii). However, there are no local host rock exposures and interpretations may be oversimplified. MH260 and MH259 possibly may indicate subhorizontal emplacement.

MH265 and MH269 share similar foliation orientations. They may represent magma flow upward and away from the Charles Fault (Figure 37Di and Div). MH266 likely is a local fabric near an undulatory margin of a sheeted intrusion.

5.3.5 Zone E: Eastern Gold Creek

- Observations

The eastern Gold Creek area is divided into five subregions based on local geology and AMS results (Figure 39Ei). Most of the subregions are populated by relatively small intrusions that have intricate relationships to the host rock. Four oblate fabrics were measured on the northeastern side of Gold Creek (Figure 39Eii). MH69, MH53, and MH68 dip steeply and strike in the direction of the trend of the porphyry ridge (Figure 39 Ei and Eii). MH166 is shallowly dipping to the north and perpendicular to the strike of the ridge (Figure 39 Eii).

MH164 is from an intrusion that has shale inclusions and the AMS measurement is likely unrepresentative because of the incorporated shale inclusions (Figure 39Eiii). MH77 and MH52 are northern dipping oblate fabrics in part of a dike that cuts at least two sills (Figure 39Eiii). The southeastern Gold Creek area has mostly consistent southwesterly trending prolate fabrics and southwesterly dipping oblate fabrics (Figure 39Eiv). Figure 42Ev displays AMS values that were sampled from intrusions that have a complicated relationship to the host rock and show no dominate fabric patterns. MH183 was sampled from an intrusion that lies over the Wingate sandstone (Figure 40). The strike of MH183 is parallel to the wall rock contact. MH185 and MH181 have no such clear pattern (Figure 39Evi).

- Interpretations

On northeastern Gold Creek the subvertically dipping oblate fabrics and likely a vertical magma flow pattern (Figure 39Eii). However, the bedding of host rock in this region dips ~50° which does not correlate with the AMS measurements. On Figure 39Eiii, the northern dipping foliations may indicate that the dike cutting the two intrusions came from the north and flowed to the south.

The intrusions of southeastern Gold Creek are emplaced into strata that generally strike north and dip ~60° to the east. The AMS measurements of southeastern Gold Creek are consistent, but they do not show a clear correlation to the geometry of the intrusions and host rock. Likewise, the intrusions in Figure 39Ev have no clear pattern or interpretation.

The fabric measurement from MH183 would indicate that magma flowed toward the wall contact and the geometry of the intrusion indicates that the intrusion then transitioned to subhorizontal (Figure 40). The opposite would be expected from field observations because the intrusion would more likely flow downward after the change in flow direction. MH181 and MH185 have no clear interpretation.

5.3.6 Zone F: Other

- Observations

The remaining AMS measurements were from intrusions on the outer perimeter of Mount Hillers. MH207, MH208, and MH209 were from the Sawtooth Ridge satellite intrusion. MH208 and MH209 are prolate fabrics plunging moderately to the northwest and southeast respectively.

MH207 is an oblate fabric striking east-west and dipping subvertically to the south. MH293 was sampled from the Specks Ridge intrusion and is an east-west striking oblate fabric that dips subvertically to the north (Figure 41Fi and 41Fii).

MH34 and MH36 were sampled from the western bulge of the Mordechai laccolith. MH34 is an oblate fabric that strikes northeast and dips moderately to the southeast. MH36 is a prolate fabric that plunges subvertically to the southeast (Figure 41Fiii).

- Interpretations

The AMS measurements from the Sawtooth Ridge intrusion are inconclusive (Figure 41Fii). More AMS data for Sawtooth Ridge are needed to make a useful interpretation. MH293 of the Specks Ridge intrusion has no useful interpretation. The inferred geometry of the Specks Ridge is a long fingerlike intrusion trending north-south. The east-west steeply dipping oblate fabric has no useful interpretation (Figure 41Fii). MH34 and MH36 of the western bulge of the Mordechai laccolith may indicate that magma flowed away and upward from the Charles Fault from the southeast to the northwest (Figure 41Fii).

6. Discussion

6.1 Model for Progressive Development of the Mount Hillers Intrusive Complex

Laccolithic bodies that comprise the two provinces of Mount Hillers likely grew during different stages of intrusive development by pulsed magma emplacement. The main intrusive body of Mount Hillers was emplaced into relatively undeformed host rock and is concordant to two different aged roof units and two different aged floor units. In my proposed model, the Copper Creek laccolith lifted Permian units in the Southern Province before the shallower northern strata was intruded to form the Mordechai laccolith. Soon thereafter, the northern intrusions grew from the northern perimeter of the Mordechai laccolith. This study also hypothesizes that early protolaccoliths are an important factor controlling the final geometry of intrusions. The formation of a protolaccolith is likely highly influenced by its feeder system and mechanical characteristics of the host rock.

6.1.1 Early Stages of Intrusive Development at Mount Hillers and the Formation of the Copper Creek and Mordechai Laccoliths.

In the early stages of intrusive development at Mount Hillers, an incipient network of sills and dikes was emplaced in subhorizontal sedimentary units. Most of the early sills on the Southern Flank of Mount Hillers are intruded into Permian-Middle Jurassic units below the Summerville Fm (Figure 19). Evidence is lacking to confirm that sills and dikes exist in unexposed Permian-Middle Jurassic units of the Northern Province. However, the asymmetric nature of the Copper Creek laccolith may reflect a lack of early intrusive activity in the Northern

Province. Perhaps early dikes and sills are less abundant in the unexposed Permian- Middle Jurassic units of the Northern Province.

I hypothesize that Mount Hillers has only one main feeder dike that transported magma upward to the shallow portion of the crust. My study does not constrain the size and shape of the main feeder dike, but it may exhibit a sheetlike geometry that strikes northeast. After the network of sills and dikes was established, magma from the main feeder dike could have directly emplaced the proto-Copper Creek laccolith in a southeastern direction beneath the Permian Cedar Mesa sandstone.

The proto-Copper Creek laccolith likely took shape as a semicircular sill in which magma flowed radially away from the main feeder dike (e.g. Figure 42A). The straight edge of the semicircular sill likely shared the same northeast-southwest orientation as the strike of the main feeder dike. The proto-Copper Creek laccolith may have extended to a radial length of more than 1,500 meters the overlying host rock was lifted. Once the proto-Copper Creek laccolith ceased horizontal expansion, the intrusion grew vertically and lifted the host rock. A bulge likely formed on the northwestern side of the protolaccolith, directly above the presumed location of the main feeder dike. This region eventually developed into the northeast striking Charles Fault. The early geometry of the Copper Creek laccolith likely had an asymmetric profile and may have resembled the Mount Marcellina intrusion in the West Elk Mountains of Colorado (Figure 42B) (e.g. Cross, 1895).

The early asymmetric Copper Creek laccolith was likely the only laccolithic body that existed at Mount Hillers in the beginning stages of intrusive development (Figure 43A). Once the Copper Creek laccolith grew to a vertical thickness of ~1,500 m, a new protolaccolith may have been emplaced above the Copper Creek laccolith. This protolaccolith likely extended under the Summerville shale in the Northern Province and the Cedar Mesa sandstone in the Southern Province (Figure 43B). This protolaccolith may have been fairly symmetrical radially and had a diameter of up to 4,000 meters (Figure 43B). As this protolaccolith grew vertically, it likely lifted roof rocks of both the Southern and Northern provinces simultaneously. This consequently created an asymmetric laccolithic body with two different floor units and two different roof units (Figure 43B).

In the Mordechai laccolith's initial stage of vertical growth, the mechanisms of host rock deformation were likely bending and uparching. In this earliest stage, the entire outer extent of the Mordechai laccolith likely had a lower and upper hinge connected by a central limb. The lower hinge over the Mordechai laccolith is still preserved on the southeastern side of the intrusion (Figure 25).

Soon after its initial stages of vertical growth, a fault may have developed on the northern side of the Mordechai laccolith (Figure 43B). This fault effectively turned the Mordechai laccolith into a punched-traditional laccolith hybrid with arched strata above the southwestern side of the intrusion. Faulting of host rock is hypothesized to have initiated at the lower hinge where strain was most concentrated. The fault at the northern side of the Mordechai laccolith is significantly different from the Charles Fault mainly because the Charles Fault is presumably directly involved with the main feeder dike. Additionally, the fault that initiated at the northern distal end of the Mordechai laccolith was emplaced into a shallower and cooler host rock horizon with no nearby sills to warm the host rock (Figure 43B).

The roof rocks of the Mordechai laccolith may have broken into faulted blocks early in the intrusive history. Faulting of overlying strata can be caused by the emplacement and growth of sills (Hansen and Cartwright, 2006). The early faulting above the roof of the young Mordechai laccolith is unknown but schematically illustrated in Figure 43B.

6.1.2 The Formation of Stewart Ridge, Cass Creek Peak, Chaparral Hills, Specks Ridge, and Specks Canyon Intrusions

The tongue-shaped Stewart Ridge laccolith is hypothesized to be directly fed from the Mordechai laccolith. The Stewart Ridge laccolith was likely radially injected from south to north as a sill with a high degree of ellipticity. If the Stewart Ridge laccolith was fed from a vertical dike, the Stewart Ridge laccolith would likely be nearly circular in map view.

While the Mordechai laccolith lifted its faulted roof rock blocks, bedding planes at the intrusion’s northern perimeter were in contact with the growing magma body. As growth of the magma body and faulting persisted, eventually the tongue-shaped proto-Stewart Ridge laccolith was emplaced between the Dakota sandstone and the Tununk shale (Figure 43C). The proto-Stewart Ridge laccolith may have extended over 3,000 meters to the north. The Proto-Stewart Ridge laccolith may have bent and uplifted strata at its distal tip while simultaneously activating faulted roof rock blocks above the intrusion (Figure 43C). Additionally, the Mordechai laccolith may have experienced inflation and deflation while magma was delivered to Stewart Ridge and other northern intrusions. This may have influenced the development of faulted roof blocks above the Mordechai laccolith.

Once the proto-Stewart Ridge laccolith was established, I hypothesize that Stewart Ridge and the main intrusive body of Mount Hillers grew vertically simultaneously (Figure 43 C-D). During this stage of growth, faulted blocks may have rotated and slipped (Figure 43 C-D). After the lower portion of Stewart Ridge was empaced and cooled, another protolaccolith with a smaller radius may have over-accreted and the Upper Stewart Ridge may have grown vertically (Figure 43E).

The Cass Creek Peak and Stewart Ridge intrusions have the same floor and roof units and are texturally similar, but there are major differences between the two intrusions. Cass Creek Peak is much smaller and is more radially symmetric. Also, the Tununk wall rock of Cass Creek Peak is overturned just northwest of the Mordechai laccolith (Figure 25 E-D'). The proto-Cass Creek Peak laccolith may have been fed from a vertical dike. After Cass Creek began to develop, interaction with the Mordechai laccolith may have complicated intrusive development. Evidence to determine relative ages of the Cass Creek Peak and Stewart Ridge laccoliths is inconclusive.

The exposed fault of the eastern side of Stewart Ridge suggests that the Chaparral Hills laccolith postdates the Stewart Ridge laccolith (Figure 25 I''-I'). The Chaparral Hills laccolith has the same floor units as the Mordechai laccolith and is likely a continuation of the Mordechai laccolith. The Chaparral Hills laccolith is also likely responsible for feeding the Specks Ridge and Specks Canyon intrusions.

Many intrusive events are poorly constrained and could have happened during different stages of intrusive development. Bending of strata on faulted roof blocks above laccolithic bodies could have occurred in various stages of the emplacement process, but is only represented in stage E of Figure 43. Additionally, dikes and sills were likely emplaced into the strata above the laccolithic contacts during various times (Figure 43 D and E). The cross sectional interpretation of the Mount Hillers intrusive complex is displayed on Figure 43 F.

6.2 Duration of Growth for Intrusive Bodies at Mount Hillers

The model of intrusive development presented in section 6.1 infers that larger magma bodies took longer to develop than smaller intrusions and stayed hotter for a longer period of time. Evidence of this is preserved in the host rocks exposed in the Southern and Northern Provinces.

In the Southern Province, metamorphism and ductile thinning of Permian to Lower Jurassic sedimentary units suggest the Copper Creek laccolith offered a prolonged heat source during emplacement. The Permian units of the Southern Flank of Mount Hillers are significantly metamorphosed from the bottom of the Cedar Mesa sandstone contact to the base of the Permian White Rim sandstone, a distance of ~150 m perpendicular to the intrusive contact in cross section (Jackson and Pollard, 1988). This metamorphism is likely attributed to long term exposure to the underlying Copper Creek laccolith.

Metamorphism in the western Gold Creek extends at least 300 meters in cross section from the Cedar Mesa sandstone to the contact between the Lower Jurassic Kayenta Fm and the bottom of the Ward intrusion (Figure 21 A”-B). The Ward intrusion may have been fed through and emplaced radially away from the Charles Fault, likely while the host rocks were already inclined. The strata in the western Gold Creek region are thinned 40-50% in the metamorphic zone between the Ward intrusion and the Copper Creek laccolith (Figure 21 A’’-B). This metamorphism is likely attributed to long-term exposure to the underlying Copper Creek laccolith and may have also been influenced by the Ward intrusion and or by the proximity of the Charles Fault.

The Northern Province laccoliths have smaller thicknesses than the Copper Creek laccolith and were emplaced into a shallower host rock horizon. The highest degree of metamorphism in the Northern Province is observed above the Mordechai laccolith where the zone of metamorphism is no more than 50 meters thick. The northern intrusions likely cooled faster than the Copper Creek laccolith and were active for a shorter duration.

6.3 Emplacement of Laccolithic Intrusions in Different Host Rock Environments

The Southern Province was likely a warmer host rock environment than the Northern Province during magmatism. Many of the Southern Province sills were emplaced into a relatively deeper host rock horizon. These sills likely have larger radii and cooled more slowly than the shallower sills. Intruding sills into different host rock horizons heats the host rock and makes it easier to deform (Corry, 1988). Additionally, long term heat exposure from the Copper Creek laccolith may have helped the sills of the Southern Province retain heat (Jackson and Pollard, 1988). The elevated temperature in the Southern Province may have aided host rock bending and prevented significant faulting of the southern and eastern roof rocks of the Copper Creek laccolith.

The Northern Province was likely cooler than the Southern Province and brittle fracture was more common. There are many well pronounced faulted roof blocks on top of the Mordechai laccolith. The Mordechai laccolith was likely a very active environment that fed magma to northern intrusions. The faulted roof blocks on top of the Mordechai laccolith may indicate that magma entered and exited the area several times.

According to the emplacement model presented in section 6.1, protolaccoliths are not always smaller in shallower horizons. The proto-Mordechai laccolith was estimated to be up to 4,000 meters in length. The proto-Stewart Ridge laccolith could have been up to 3,000 meters at its longest dimension. The proto-Copper Creek laccolith was estimated to be 1,500 meters in length. If the model in section 6.1 is correct, it is clear that the sizes and shapes of proto-laccoliths are influenced by local parameters and are not exclusively dependent on depth of emplacement.

6.4 Comparing Breccias of the Northern and Southern Province

Breccias are most common above the main intrusive body of Mount Hillers. The breccias in the Southern Province are represented by MH268 (Figure 20) and the breccias in the Northern Province are represented by MH325 (Figure 24). The breccias in the Southern Province consist of Permian units and porphyry clasts found above the Copper Creek laccolith. Breccias in the Northern Province consist mostly of clasts of the Upper Morrison formation and are found above the Mordechai laccolith. The igneous clasts of the Southern Province breccias were solidified before they were incorporated into the breccia.

There were minor irregular intrusions in close proximity to the breccias, but no well-defined dikes were recognized directly adjacent to the breccias (Figure 20 and Figure 24). The Southern Province breccias were likely the result of many cycles of cracking in the roof host blocks. The Northern Province breccias do not exhibit igneous clasts and were probably not reactivated as much as those in the Southern Province. Alternatively, the breccias on Mount Hillers could have been related to injection of magma along fault planes. However, no well-defined dikes were observed near faults.

Gilbert (1877) and Koch (1981) reported minor faults and breccias near the summit of Mount Ellsworth of the Henry Mountains, an intrusive complex with only one laccolithic body (Figure 2). The faults and breccias of Mount Ellsworth were interpreted to be caused by roof collapse over a relatively deep intrusive body (Gilbert, 1877; Koch, 1981). The minor faults that developed between the blocks of host rock also facilitated injection of dikes fed from the underlying magma body.

The breccias that developed on top of the main intrusive body of Mount Hillers may have formed as the underlying magma inflated, stretching the host rocks. Many of the magma bodies are built by several successive incorporations of new magma pulses (Saint-Blanquat, 2006). The underlying magma body probably experienced several cycles of inflation and deflation which would have jostled blocks of host rock and resulted in sufficient fracturing to produce breccias. The Southern Province likely experienced more cycles of inflation and deflation than the Northern Province.

7. Conclusions

The Mount Hillers intrusive complex is composed of many laccolithic bodies that contribute to the main topographic dome of the mountain. At least six laccolithic bodies have been recognized in the Southern and Northern Provinces; all are likely directly connected to one another. The main intrusive body of Mount Hillers is a concordant and asymmetric laccolith with two different roof units and two different floor units. Magma that eventually developed into the smaller laccolithic intrusions of the Northern Province likely passed through the Mordechai laccolith vicinity before reaching a final emplacement destination.

Good evidence for early intrusive development at Mount Hillers is seen in the Southern Province. Before the semicircular proto-Copper Creek laccolith grew vertically, an incipient network of sills and dikes was emplaced into subhorizontal host strata. It is inconclusive if a similar network existed in the Northern Province before the Copper Creek laccolith grew vertically. I hypothesize that there were fewer early sills and dikes in the Northern Province which may have created a subtle rheological contrast between the two provinces. This contrast may have aided in the development of the Charles Fault. Additionally, the host rocks in the Southern Province were warmed by the early network of sills and dikes. As a result, the host rock above the Copper Creek laccolith experienced large scale bending while the Copper Creek laccolith grew vertically by large scale brittle fracture.

Once the main intrusive body grew to a vertical thickness of ~1,500 meters, it intruded under the Middle Jurassic Summerville Fm to the north to create an asymmetric laccolithic body with two different roof units. The laccolith may have uplifted its two different roof units simultaneously. Not long after the Mordechai laccolith began to grow vertically, the proto-Stewart Ridge laccollith was emplaced under the Upper Cretaceous Tununk shale. Stewart Ridge and the main intrusive body may have also simultaneously grown vertically. The relationship between the Cass Creek Peak intrusion and the Mordeachai laccolith is not very well understood. However, the proto-Cass Creek Peak laccolith may have been fed from an underlying dike before the Mordechai laccolith grew substantially.

The Chaparral Hills laccolith likely postdated the emplacement of Stewart Ridge and Cass Creek Peak. Magma likely migrated to the northeast after these laccolithic bodies were fully developed. Chaparral Hills was also likely responsible for feeding the Specks Ridge and Specks Canyon intrusions. After these intrusions developed, the distal satellite intrusions were emplaced even farther to the north and east.

The progressive growth of the Mount Hillers intrusive complex clearly demonstrates that this shallow crustal magma system developed by emplacement of multiple pulses of magma. The results of this study can be useful for understanding growth of the other intrusive complexes, including the nearby Mount Pennell and Mount Ellen complexes in the Henry Mountains. Possibly, main intrusive bodies of the larger intrusive complexes may have also been fed by a main feeder dike and experienced faulting to eventually develop into asymmetric laccolitic bodies with different roof and floor units. Perhaps, Mount Pennell and Mount Ellen once experienced the stage of intrusive development currently exposed at Mount Hillers. However, the main intrusive body of Mount Hillers is reported to be the largest in the Henry Mountains (Gilbert, 1877; Hunt et al., 1953) and may exhibit a geometry unique in the Henry Mountains.

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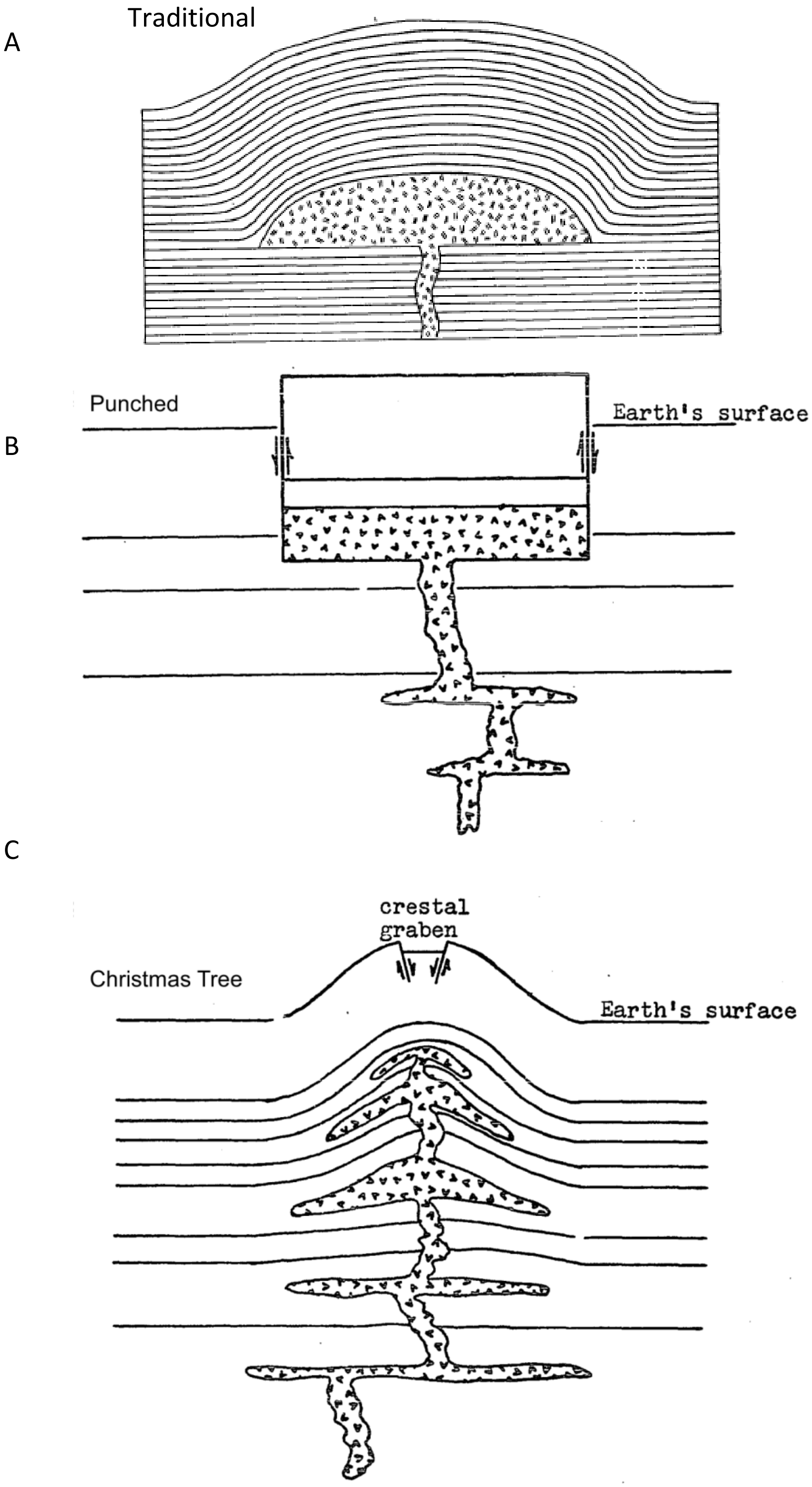


Figure 1: Schematic cross sectional diagrams of: A) Traditional laccolith; B) Punched laccolith; C) Christmas tree laccolith. Modified from Gilbert (1877) and Cory (1976).

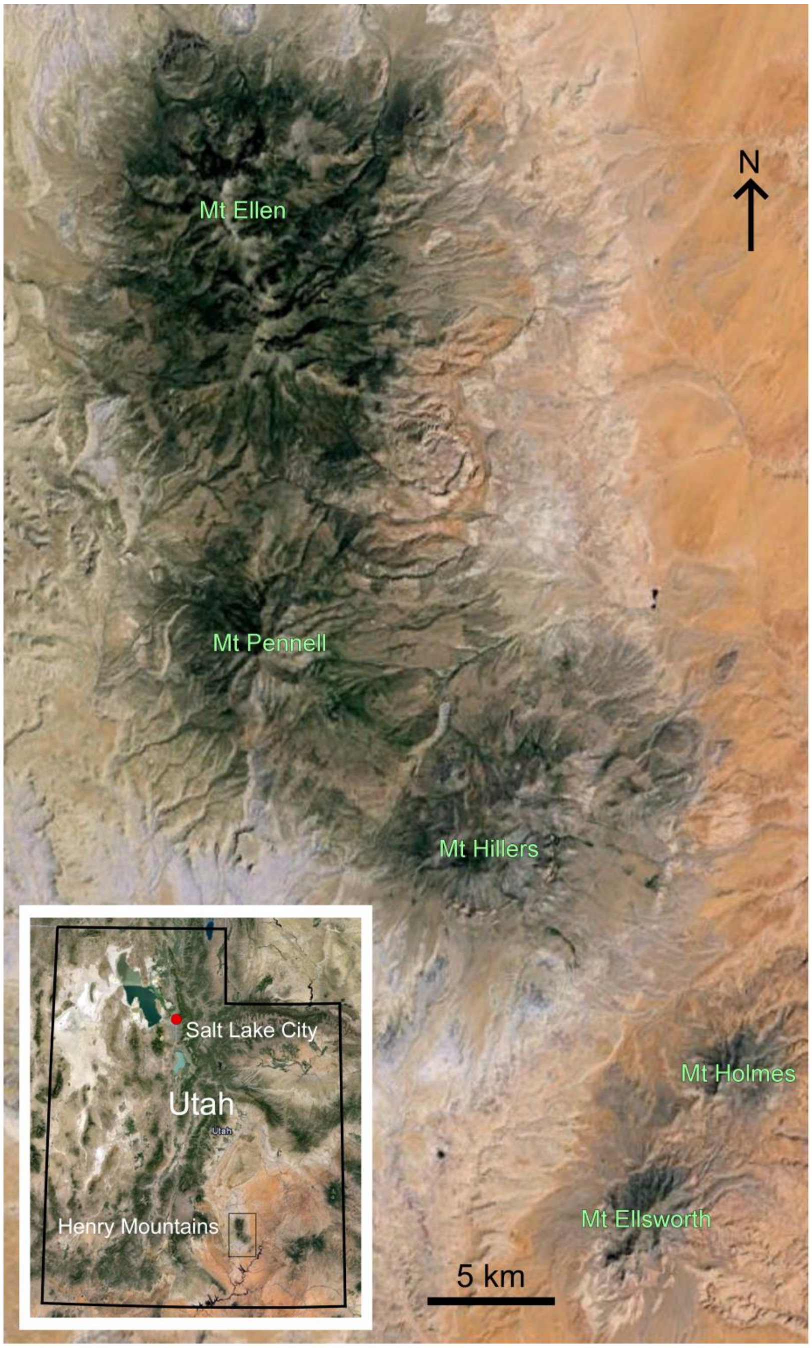
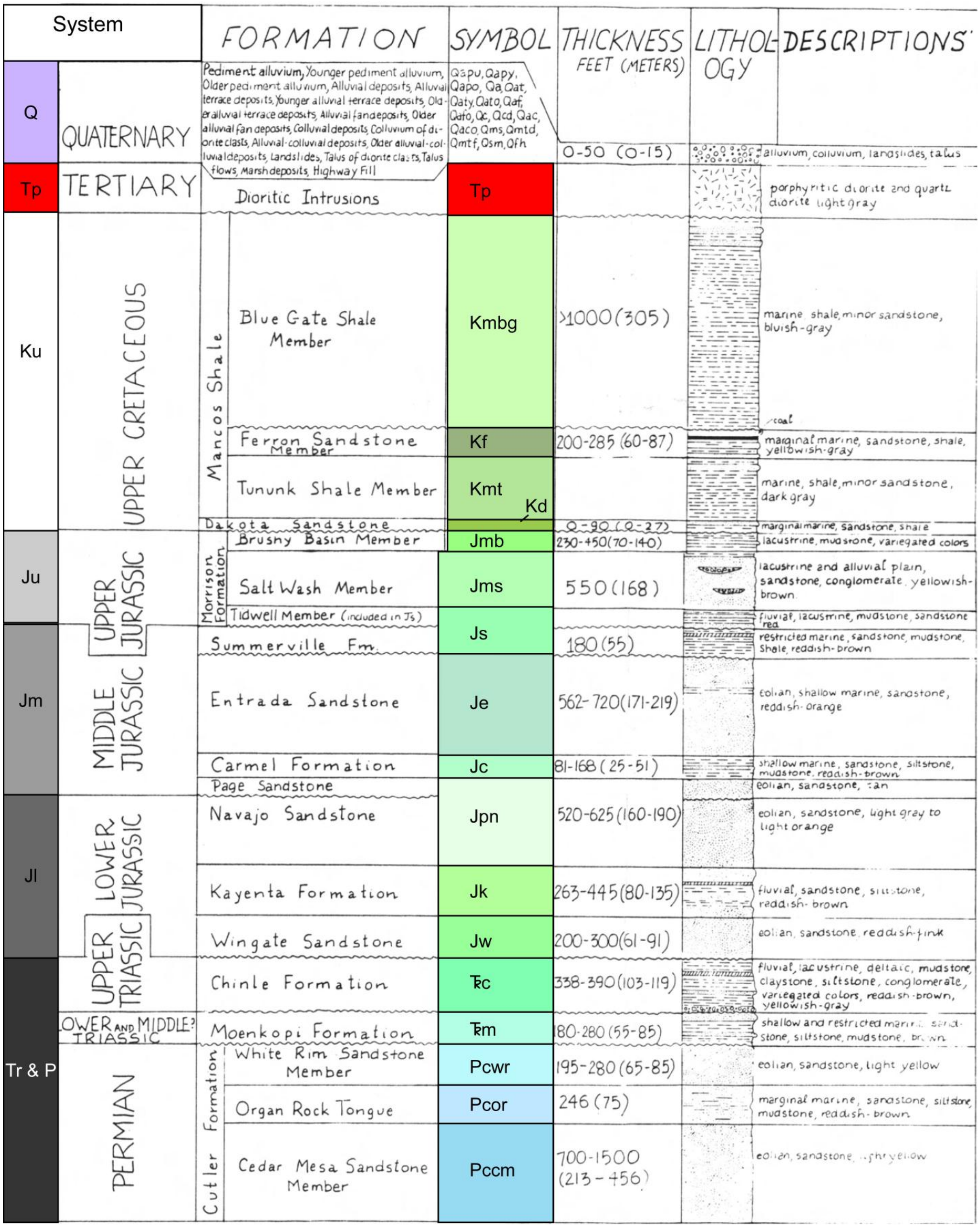


Figure 2: Location Map of the Henry Mountains. (Google Earth)



System			FORMATION	SYMBOL	THICKNESS FEET (METERS)	LITHOLOGY	DESCRIPTIONS
Q	QUATERNARY		Pediment alluvium, Younger pediment alluvium, Older pediment alluvium, Alluvial deposits, Alluvial terrace deposits, Younger alluvial terrace deposits, Older alluvial terrace deposits, Alluvial fan deposits, Older alluvial fan deposits, Colluvial deposits, Colluvium of diorite clasts, Alluvial-colluvial deposits, Older alluvial-colluvial deposits, Landslides, Talus of diorite clasts, Talus flows, Marsh deposits, Highway Fill	Qapu, Qapy, Qapo, Qa, Qat, Qaty, Qato, Qaf, Qafo, Qc, Qcd, Qac, Qaco, Qms, Qmtd, Qmtf, Qsm, Qfh	0-50 (0-15)		alluvium, colluvium, landslides, talus
Tp	TERTIARY		Dioritic Intrusions	Tp			porphyritic diorite and quartz diorite light gray
Ku	UPPER CRETACEOUS	Mancos Shale	Blue Gate Shale Member	Kmbg	>1000 (305)		marine shale, minor sandstone, bluish-gray coal
			Ferron Sandstone Member	Kf	200-285 (60-87)		marginal marine, sandstone, shale, yellowish-gray
			Tununk Shale Member	Kmt			marine, shale, minor sandstone, dark gray
			Dakota Sandstone	Kd	0-90 (0-27)		marginal marine, sandstone, shale
Ju	UPPER JURASSIC	Morrison Formation	Brushy Basin Member	Jmb	230-450 (70-140)		lacustrine, mudstone, variegated colors
			Salt Wash Member	Jms	550 (168)		lacustrine and alluvial plain, sandstone, conglomerate, yellowish-brown
			Tidwell Member (included in Js)	Js			fluvial, lacustrine, mudstone, sandstone red
Jm	MIDDLE JURASSIC		Summerville Fm.		180 (55)		restricted marine, sandstone, mudstone, Shale, reddish-brown
			Entrada Sandstone	Je	562-720 (171-219)		eolian, shallow marine, sandstone, reddish-orange
			Carmel Formation	Jc	81-168 (25-51)		shallow marine, sandstone, siltstone, mudstone, reddish-brown
Jl	LOWER JURASSIC		Page Sandstone	Jpn			eolian, sandstone, tan
			Navajo Sandstone		520-625 (160-190)		eolian, sandstone, light gray to light orange
			Kayenta Formation	Jk	263-445 (80-135)		fluvial, sandstone, siltstone, reddish-brown
	UPPER TRIASSIC		Wingate Sandstone	Jw	200-300 (61-91)		eolian, sandstone, reddish-pink
Tr & P			Chinle Formation	TRc	338-390 (103-119)		fluvial, lacustrine, deltaic, mudstone, claystone, siltstone, conglomerate, variegated colors, reddish-brown, yellowish-gray
	LOWER AND MIDDLE? TRIASSIC		Moenkopi Formation	TRm	180-280 (55-85)		shallow and restricted marine, sandstone, siltstone, mudstone, brown
	PERMIAN	Cutler Formation	White Rim Sandstone Member	Pcwr	195-280 (65-85)		eolian, sandstone, light yellow
			Organ Rock Tongue	Pcor	246 (75)		marginal marine, sandstone, siltstone, mudstone, reddish-brown
			Cedar Mesa Sandstone Member	Pccm	700-1500 (213-456)		eolian, sandstone, light yellow

Figure 3: Stratigraphic section of Mount Hillers. (Modified from Jackson and Noller, 1991)

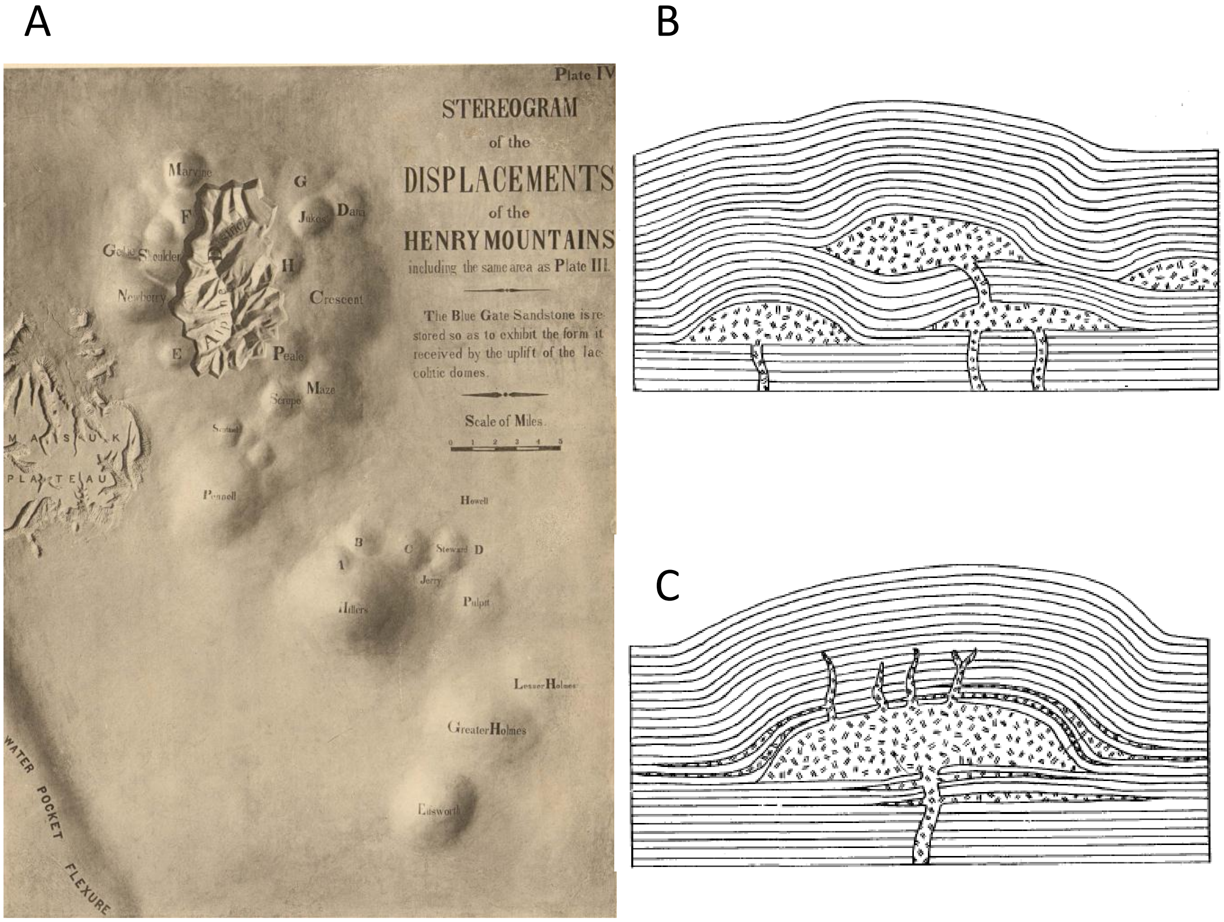


Figure 4: A) Gilbert's vision of the topographic displacement made by clusters of laccoliths of the Henry Mountains. The Blue Gate sandstone is restored to show the amount of uplift. Lack of knowledge of the central portion Mount Ellen is shown by no restoration and instead showing actual topography (Gilbert, 1877). B) Schematic cross section of clustered laccoliths (Gilbert, 1877). C) Schematic cross section of a more realistic laccolith which is accompanied with dikes and sills (Gilbert, 1877).

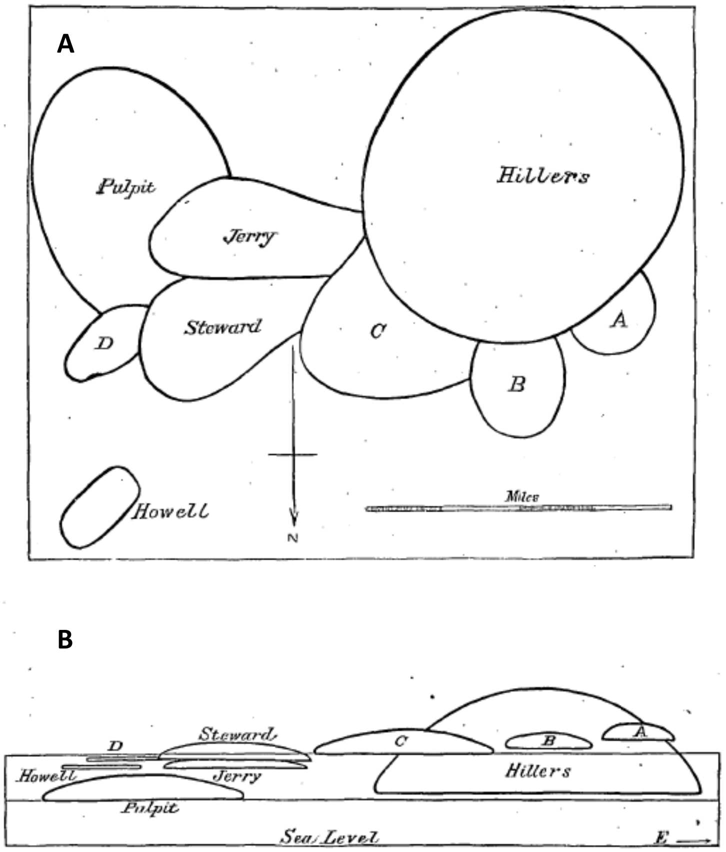


Figure 5: A) Map view of the Hillers cluster of laccoliths described by Gilbert. B) Cross section of Gilbert's interpretation of the Hillers laccolith cluster. (Modified from Gilbert 1877)

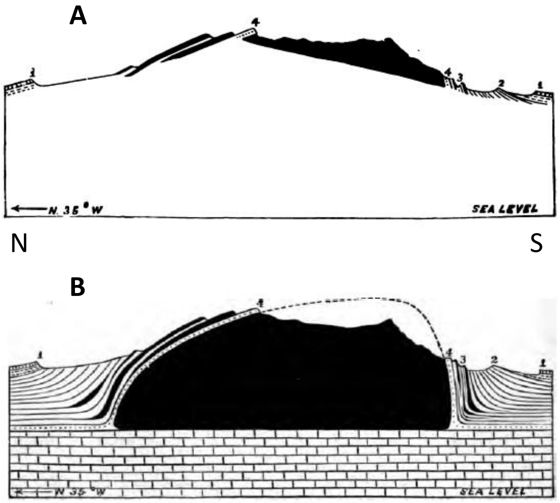


Figure 6: Gilberts cross section (A) and interpretation (B) of the Hillers laccolith. (Gilbert, 1877)

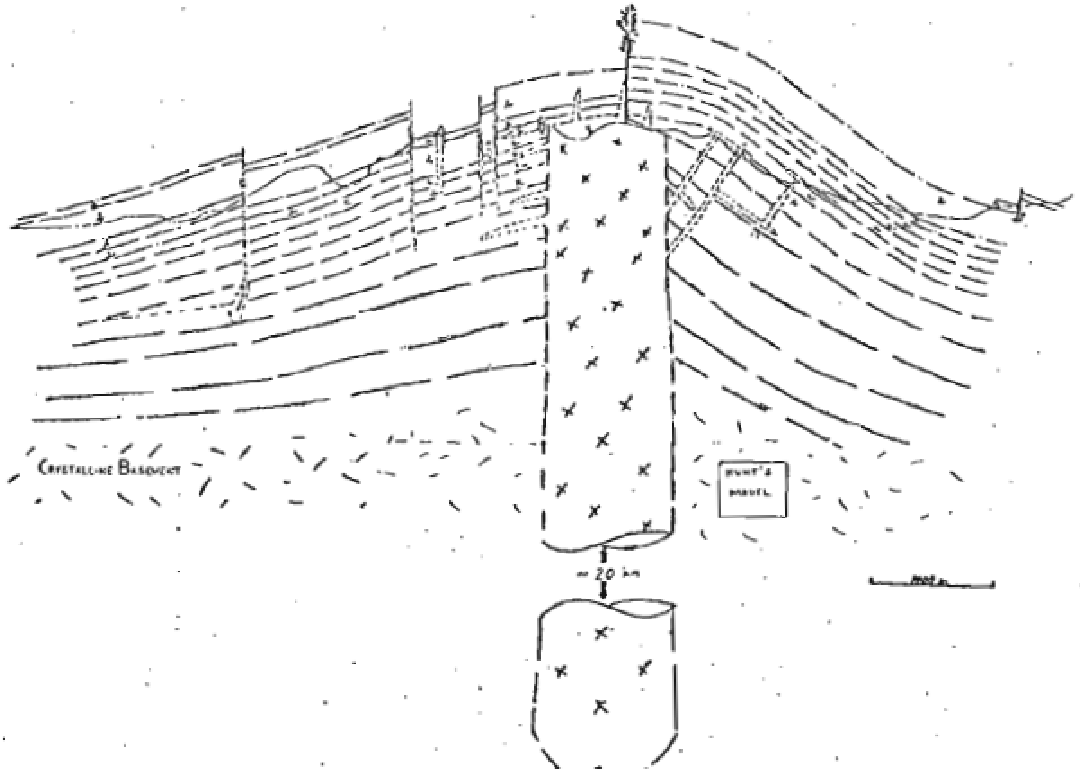


Figure 7: Ideal cross section of a physically injected stock that discordantly domes sedimentary strata. This stock is a schematic of Hunt's interpretation of the Mount Ellsworth dome (Koch, 1981).

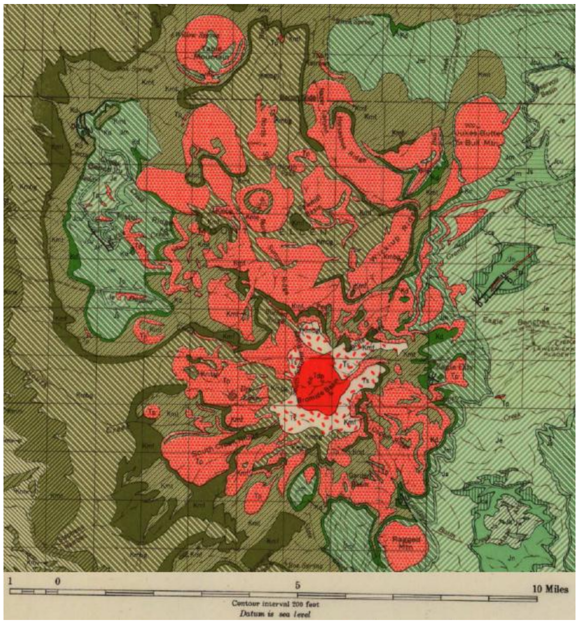


Figure 8: Hunt's geologic map of the Mount Ellen stock and radiating subordinate intrusions with their long axes trending away from the stock. Stock = dark red, subordinate intrusions = light red, shatter zone = speckled white and red, host rock = green. (Hunt et al., 1953)

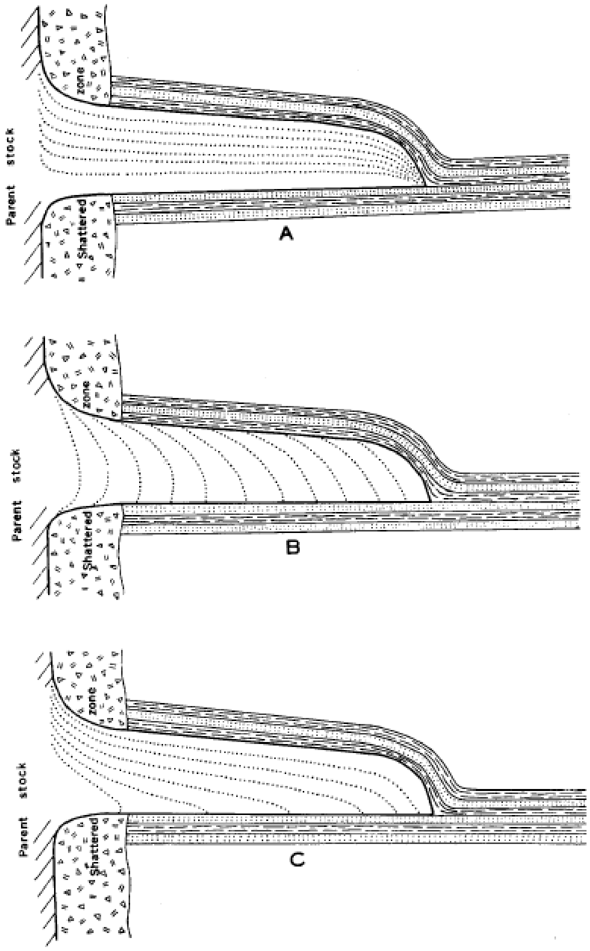
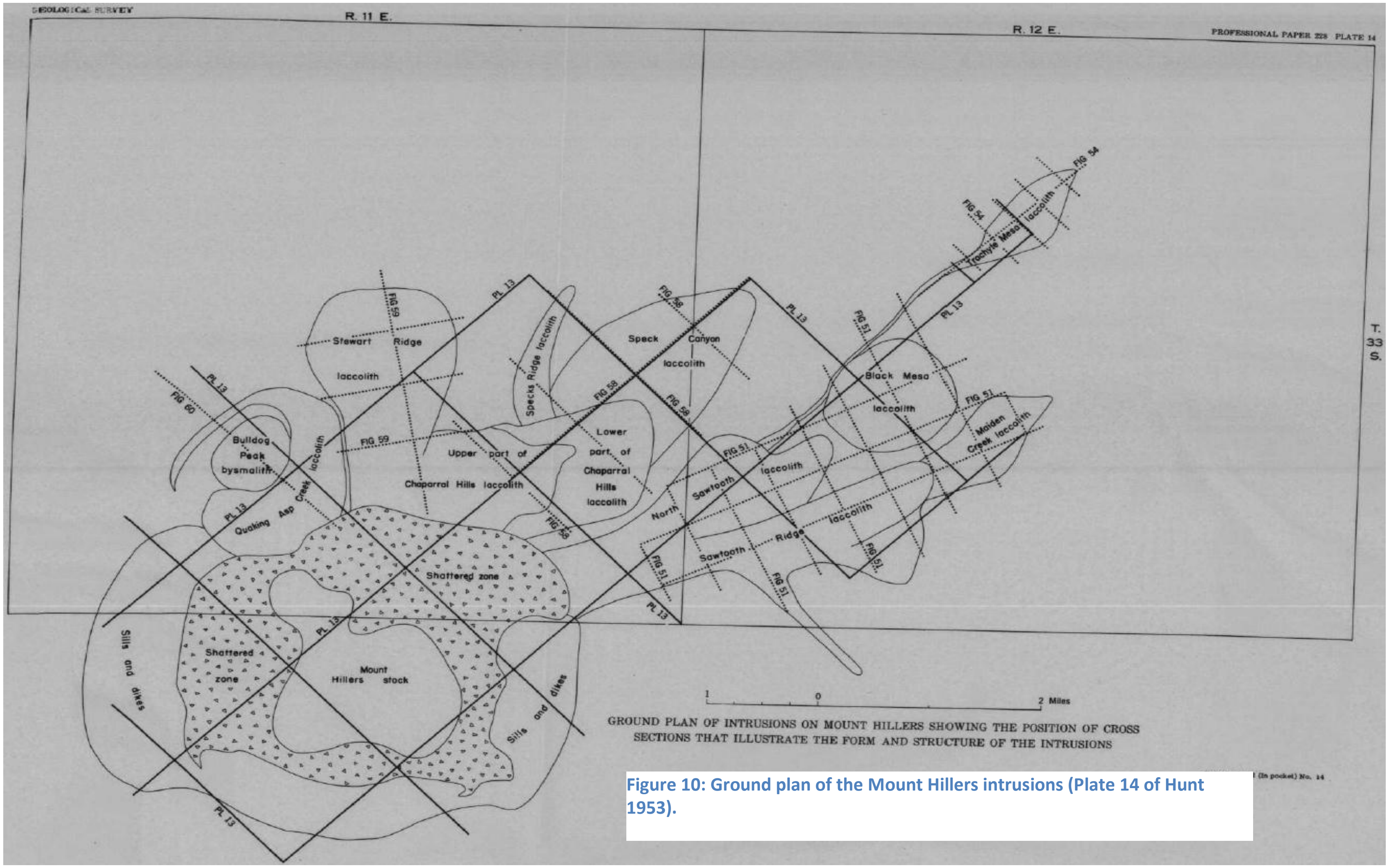


Figure 9: Hunt's mechanism for laccolith emplacement. Dotted lines indicate proposed growth techniques. See text for explanation. (Hunt et al., 1953).



GROUND PLAN OF INTRUSIONS ON MOUNT HILLERS SHOWING THE POSITION OF CROSS SECTIONS THAT ILLUSTRATE THE FORM AND STRUCTURE OF THE INTRUSIONS

Figure 10: Ground plan of the Mount Hillers intrusions (Plate 14 of Hunt 1953).

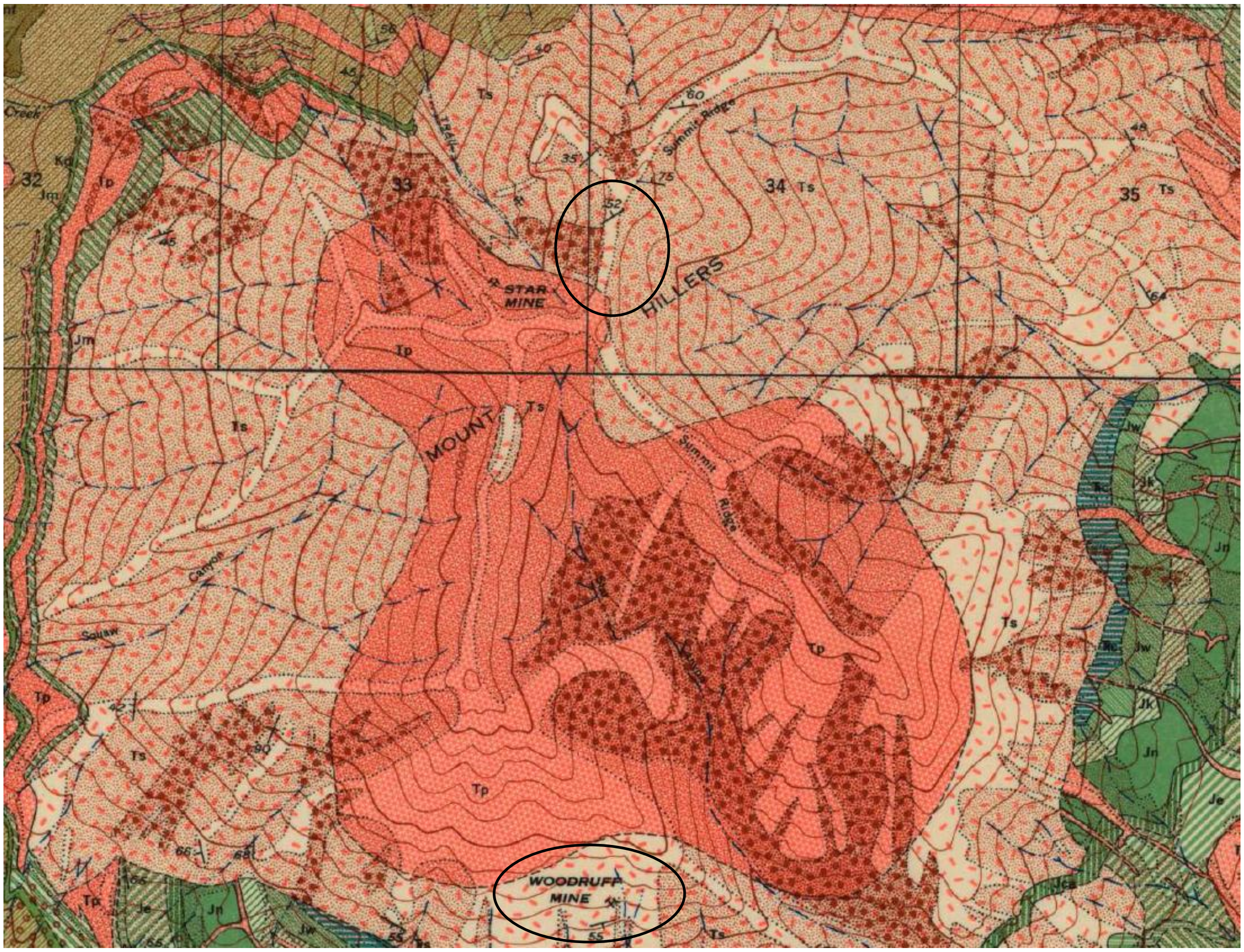


Figure 11: Hunt's map of the Mount Hillers shatter zone. Speckled pink = shattered host rock. Red = Tertiary poryphyry. Brown= Cretaceous. Green = Jruassic. Blue = Triassic. Permian strata described by hunt are located near the Woodruff Mine and dipping 55° south circled in black. Jurassic-Cretaceous strata are dipping 45-50° north on Summit Ridge are circled in black to the north. (Plate 12 from Hunt 1953).

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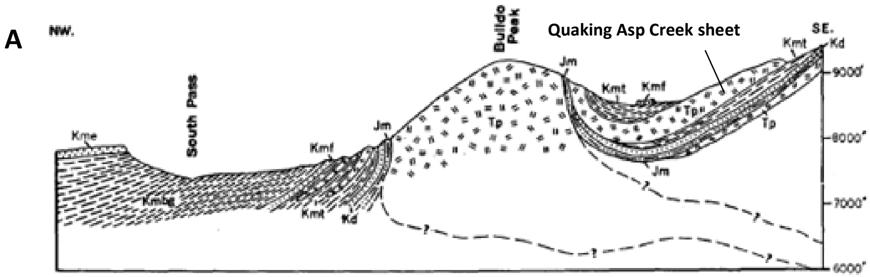
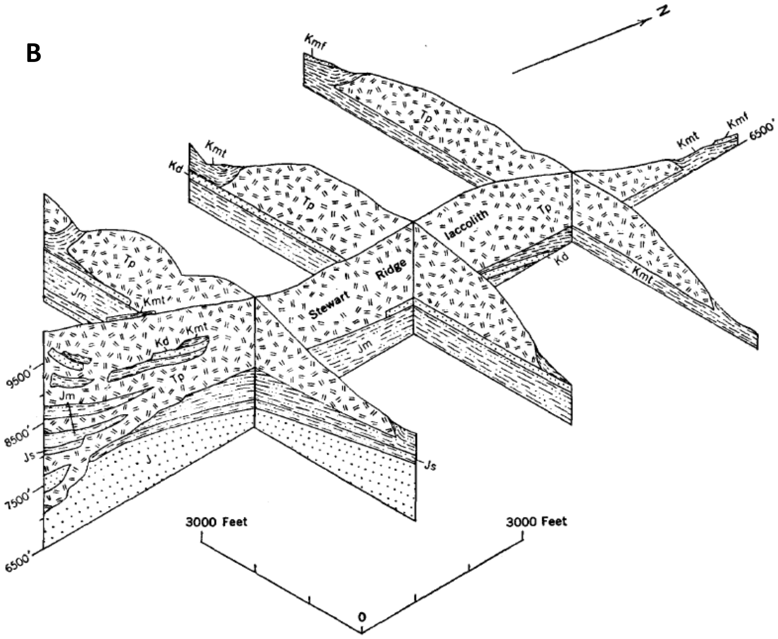




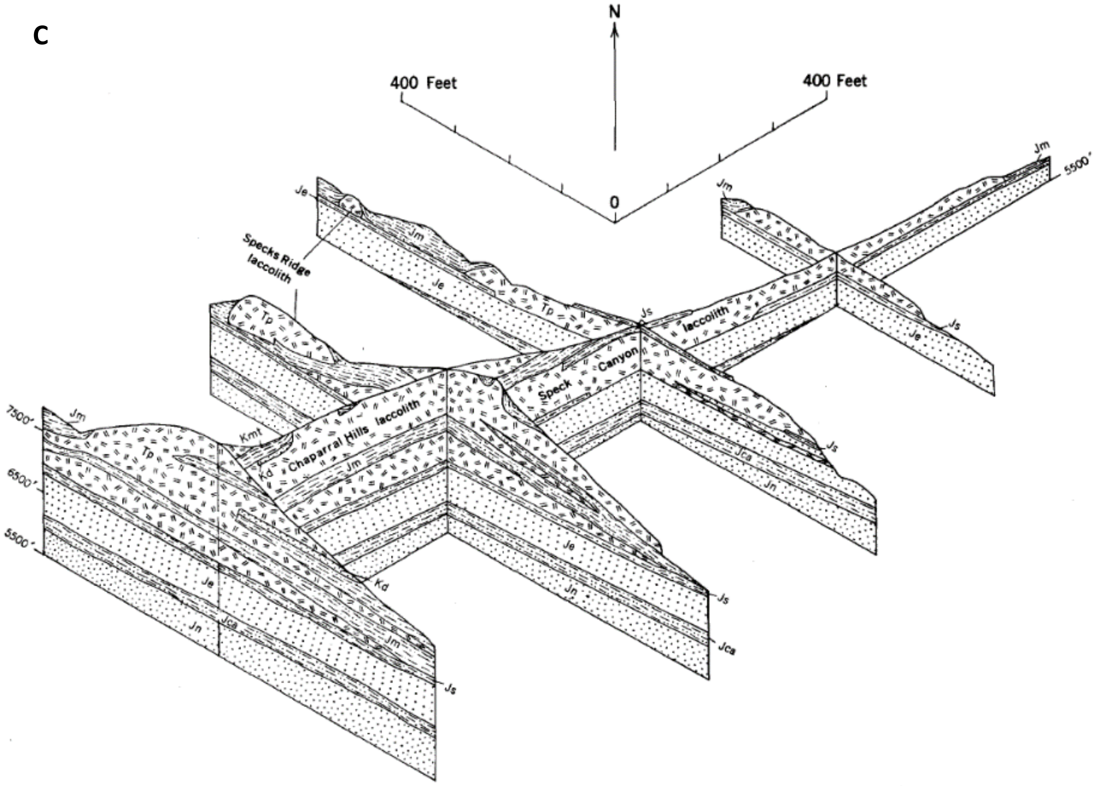


Figure 12: A) Figure 14B: Hunt's cross sectional interpretation of Bulldog Peak and the Quaking Asp Creek laccolith. The Quaking Asp Creek sheet was not originally labeled by Hunt in original figure. B) Hunt's fence diagram of the Stewart Ridge laccolith. See text for description. C) Hunt's fence diagram of the Specks Ridge laccolith, Specks Canyon laccolith, and the Chaparral Hills laccolith (Hunt et al., 1953)

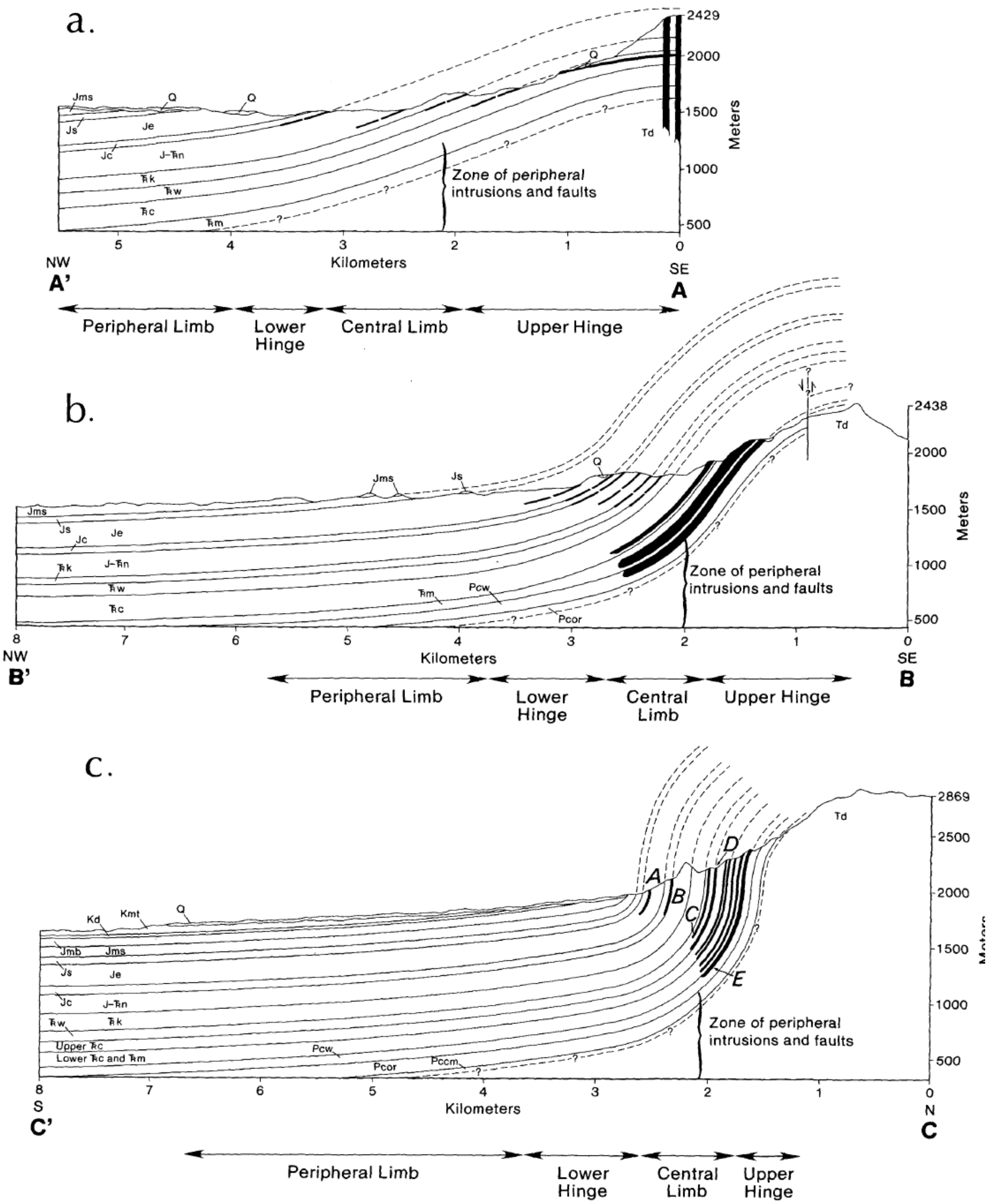


Figure 13: Cross sections of Henry Mountain domes; A) Mount Holmes, B) Mount Ellsworth, and C) Mount Hillers. (Jackson and Pollard, 1988)

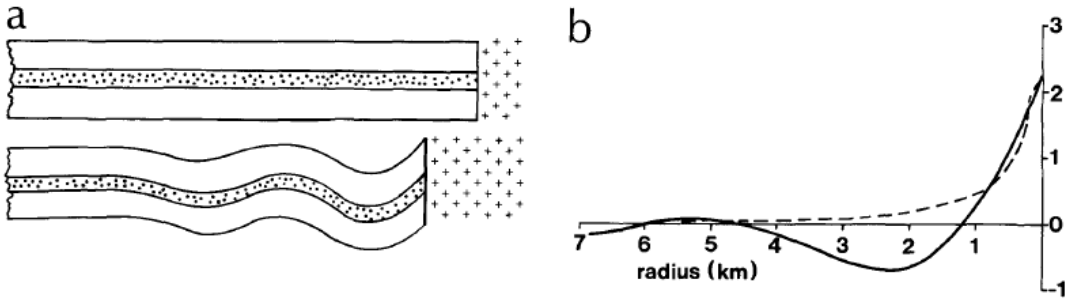


Figure 14: A) Theoretical response of a confined layer subjected to horizontal compressional force and a lesser vertical shear force. B) Scaled hypothetical response of host rock to the injection of a stock (solid line) and the mapped bedding orientation of Mount Hillers (dashed line). (Jackson and Pollard, 1988)

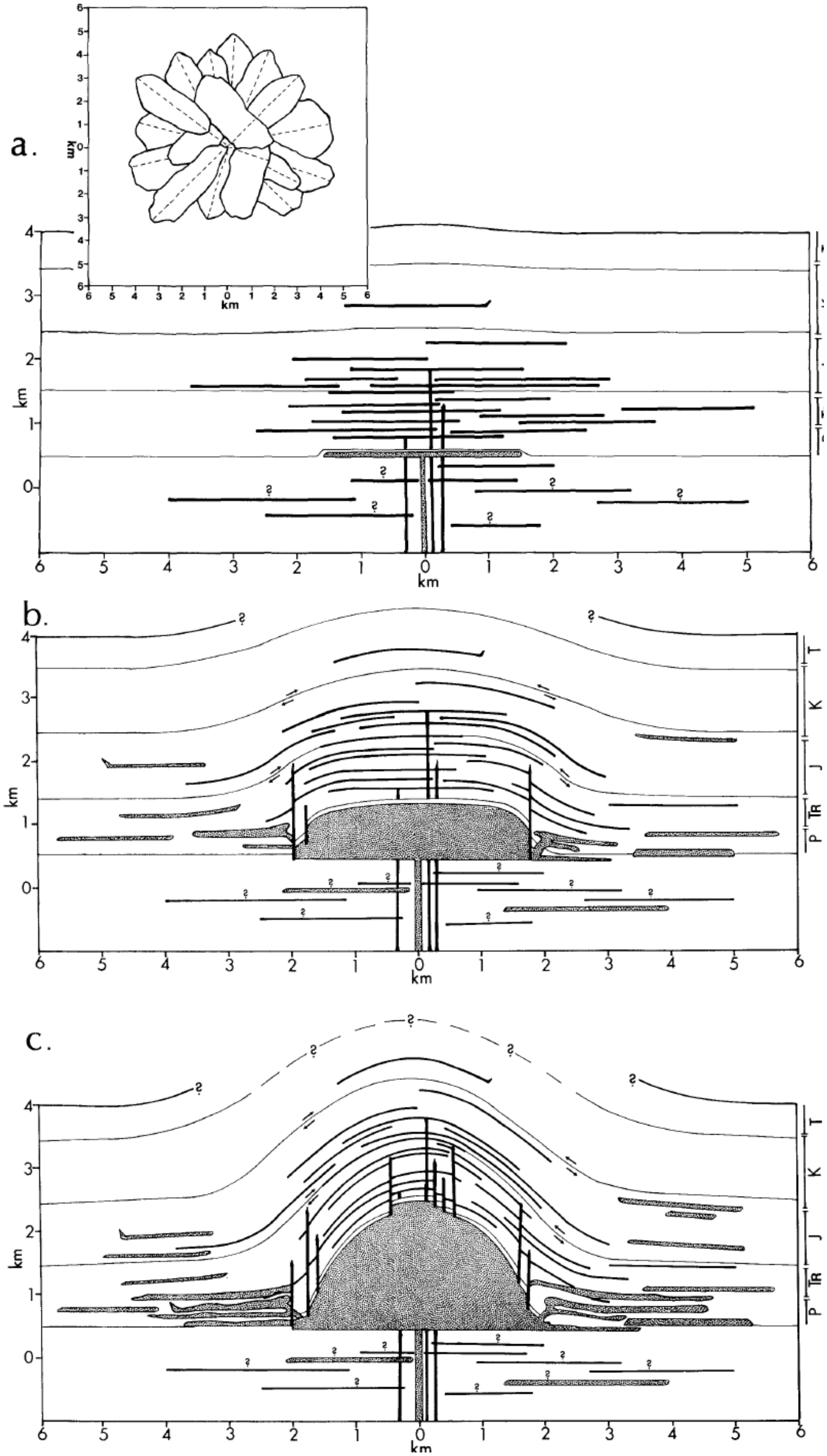


Figure 15: Jackson and Pollard's hypothesis for the stages of growth for the main intrusive body. A) The initial stage of intrusive development characterized by the emplacement of a network of sills and feeder dikes. Most of the sills are tongue-shaped and radiate from the center of the main dike feeders. The formation of a symmetrical sheeted intrusion develops at the base of the Cutler formation. B) Intermediate stage of domal growth. Stratal stretching and bedding plane faults are initiated above the main intrusive feature. Faults toward the perimeter of the dome allow for the emplacement of peripheral intrusions of sills and thin laccoliths which uplift the peripheral limb. C) The major stage of a growing laccolith are characterized by steeply dipping central limbs and faulted blocks at the top of the dome. (Figure taken from Jackson and Pollard 1988)

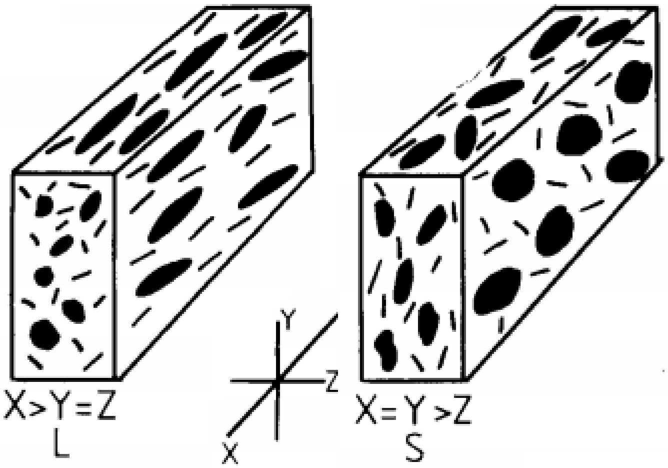


Figure 16: Schematic diagram of linear fabrics (L) and foliated or schistose fabrics (S). Figure modified from Hutton (1987).

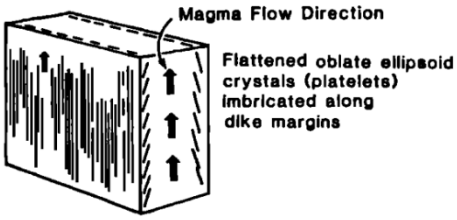


Figure 17: Schematic diagram of an imbrication fabric. (Modified from Knight and Walker 1988).

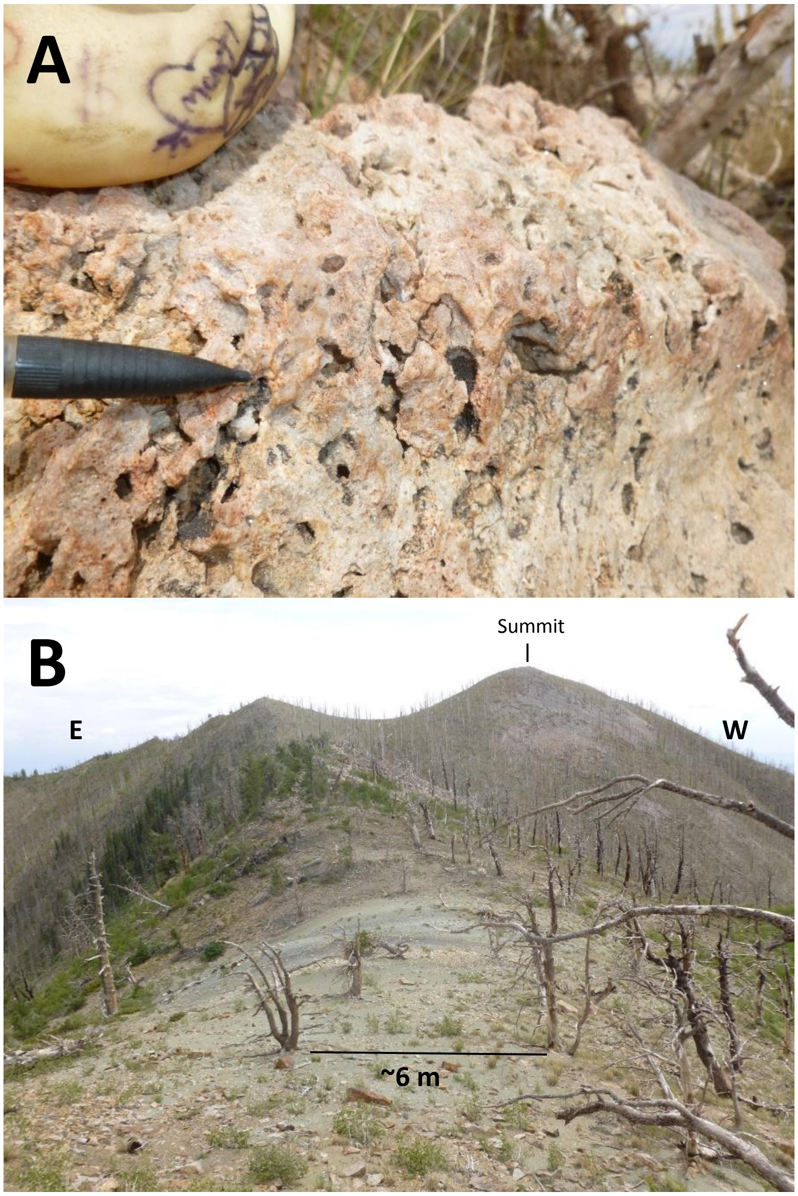


Figure 18: Pictures of sedimentary units on Summit Ridge. A) Fossiliferous Dakota sandstone. The molds of fossils are distinctive to the Dakota sandstone. sandstone. Fossil shells of the Dakota are reported to include Gryphaea, Exogyrs, Inoceramus, and some gastropods (Hunt et al. 1953). The Dakota sandstone is directly north and adjacent to the younger B) Brushy Basin shale of the Morrison formation. The Brushy Basin shale is characterized by red, purple, buff, green, brown, white, yellow, and black (Hunt et al. 1953). Highest point in the picture is the summit of Mount Hillers.

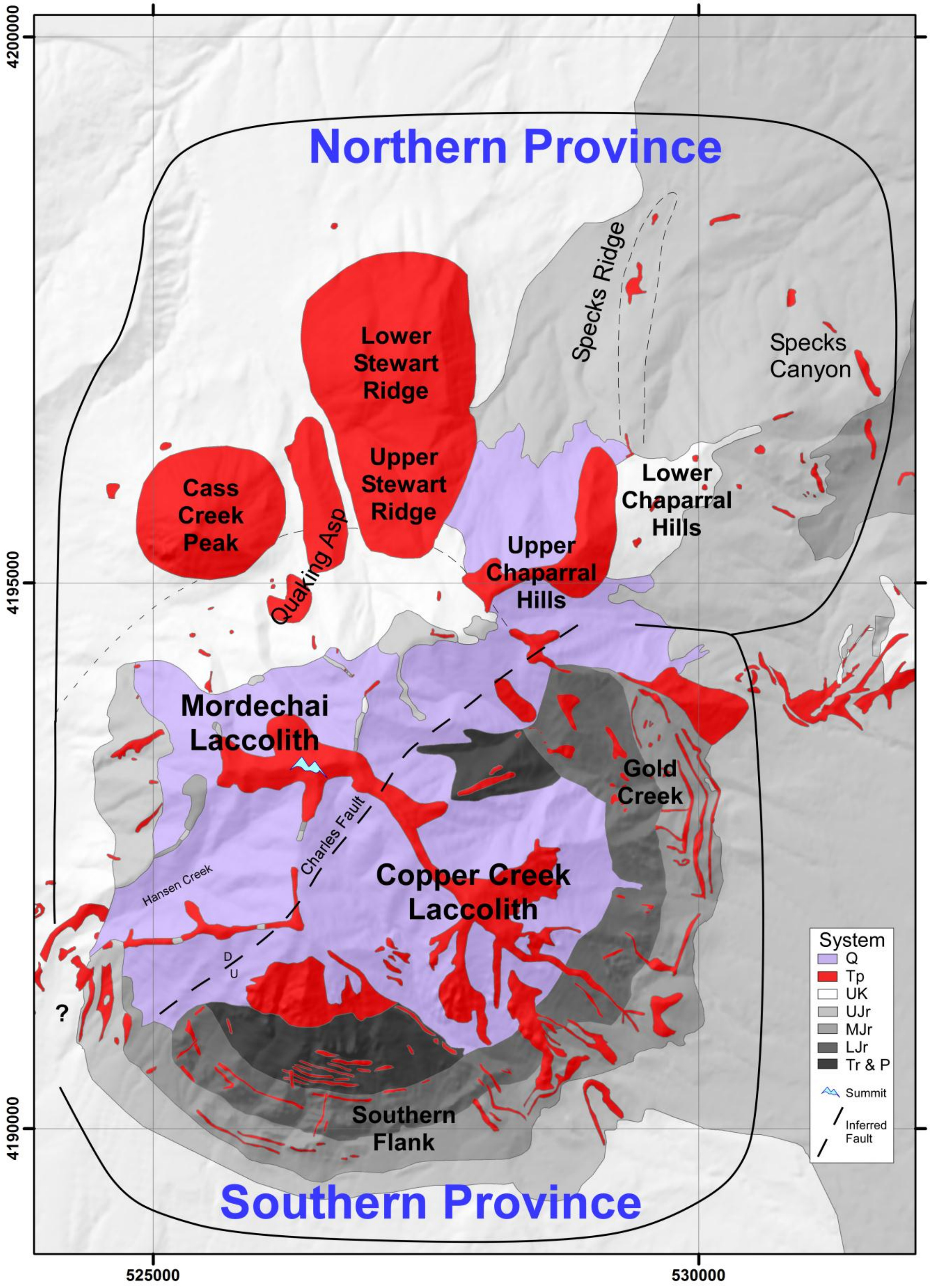


Figure 19: Location map of the Northern and Southern Provinces of Mount Hillers.

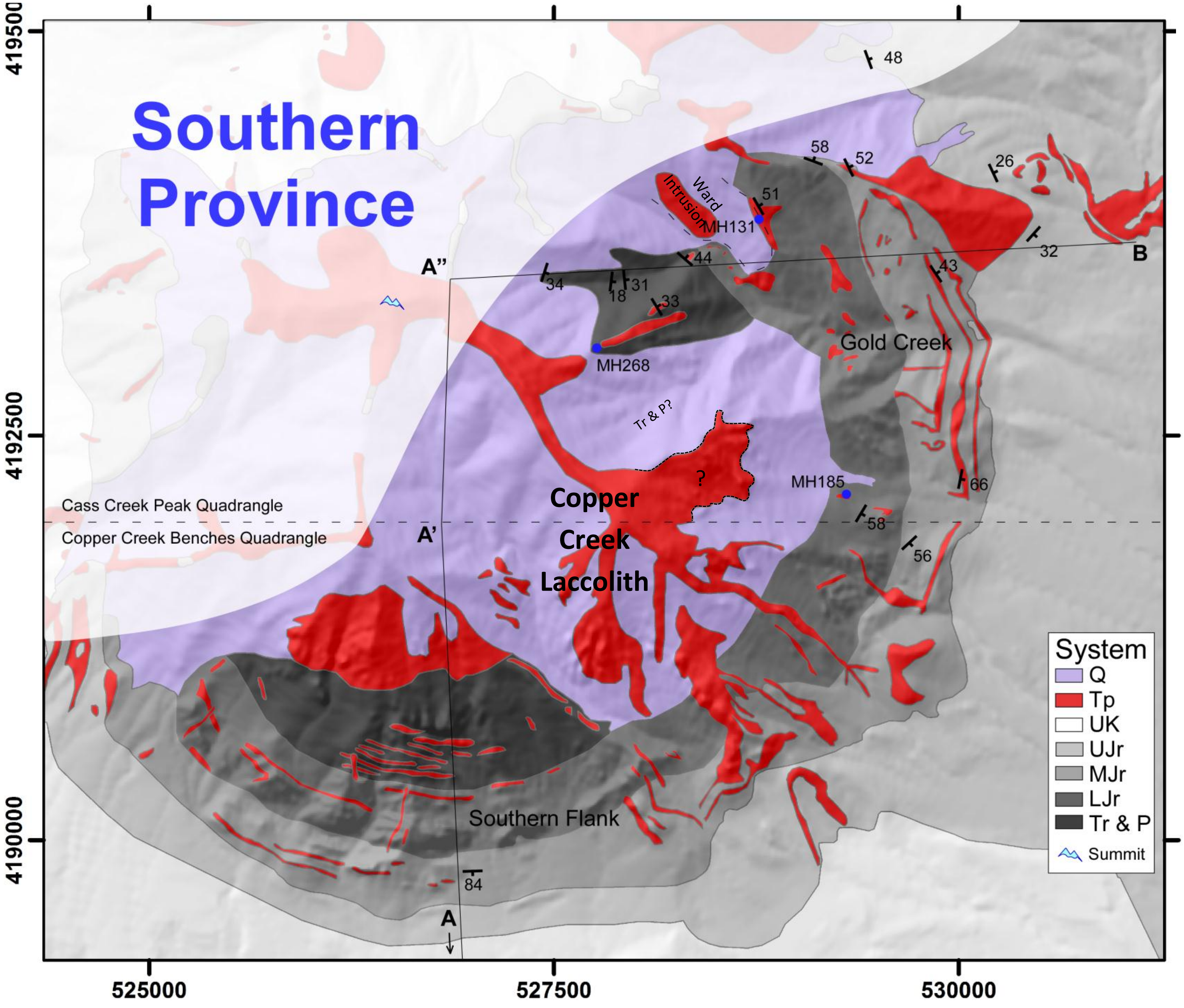


Figure 20: Map of the Southern Province of Mount Hillers.

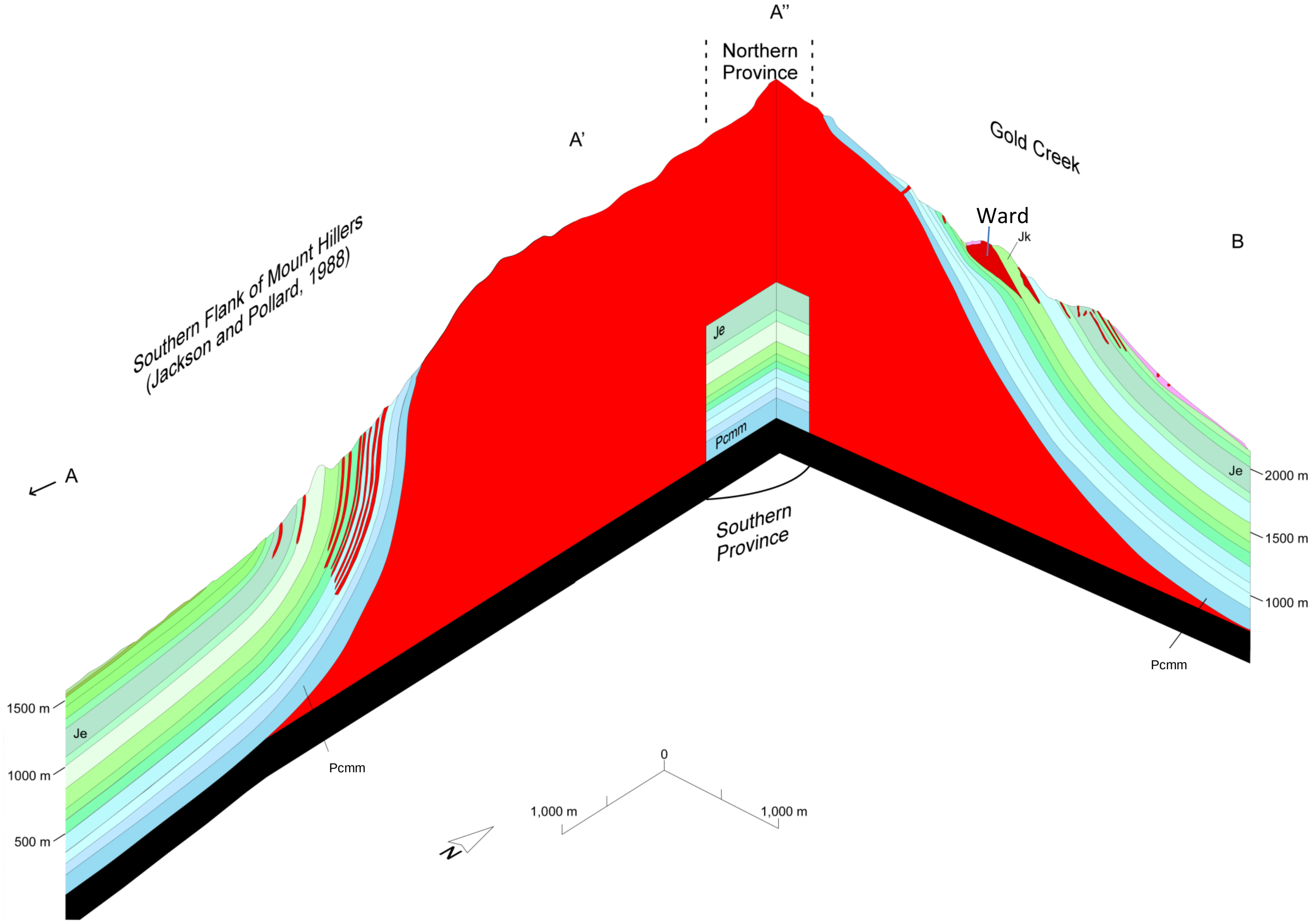


Figure 21: Cross sectional interpretation of the Southern Flank of Mount Hillers and Gold Creek. A-A'' is a modified cross section of Jackson and Pollard (1988). A''-B is the Gold Creek region. See figure 22 for transection locations. See Figure 3 for color scheme. Black unit is unknown. Pink unit is Quaternary.

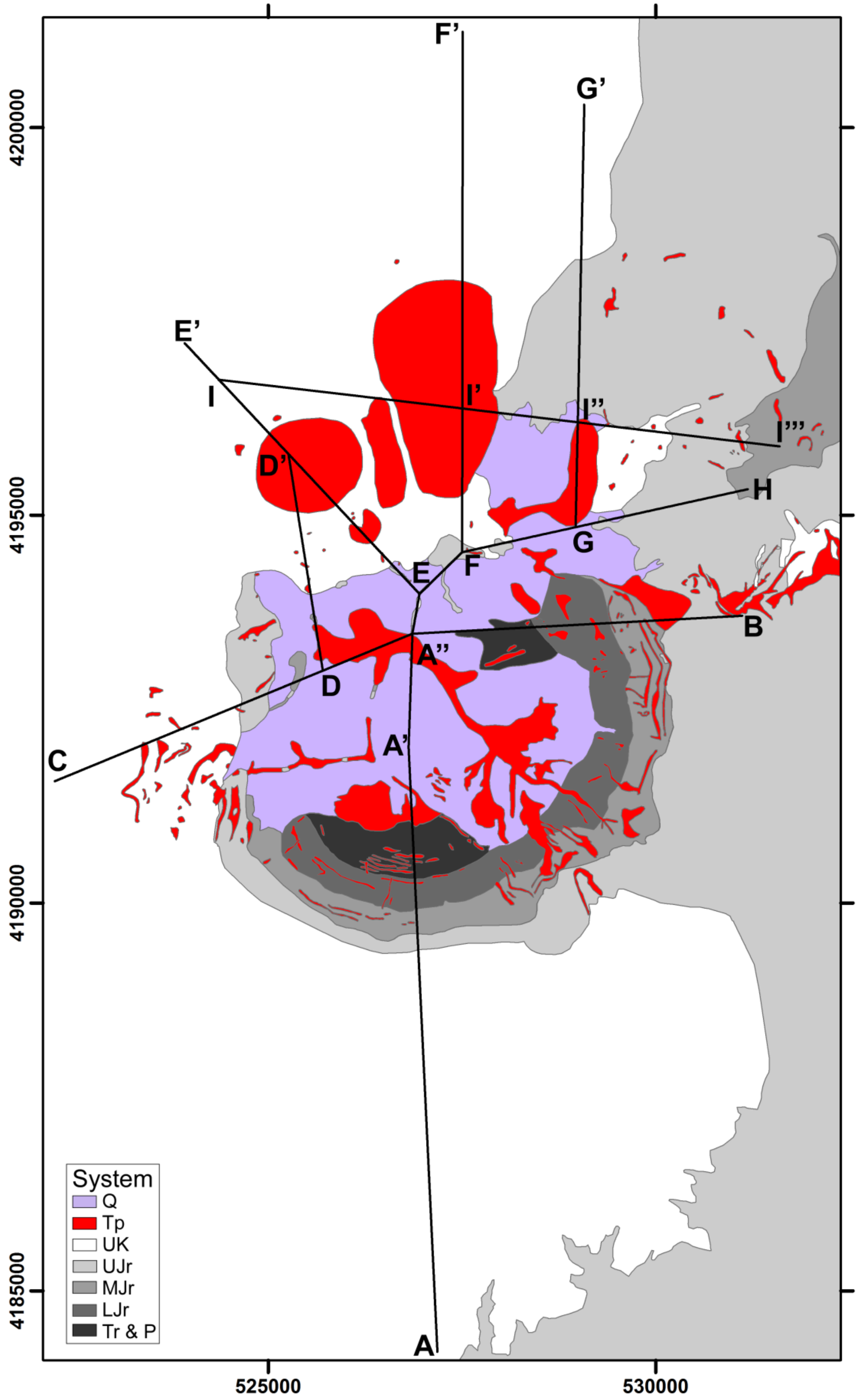


Figure 22: Transection location points for Figure 21 and Figure 24

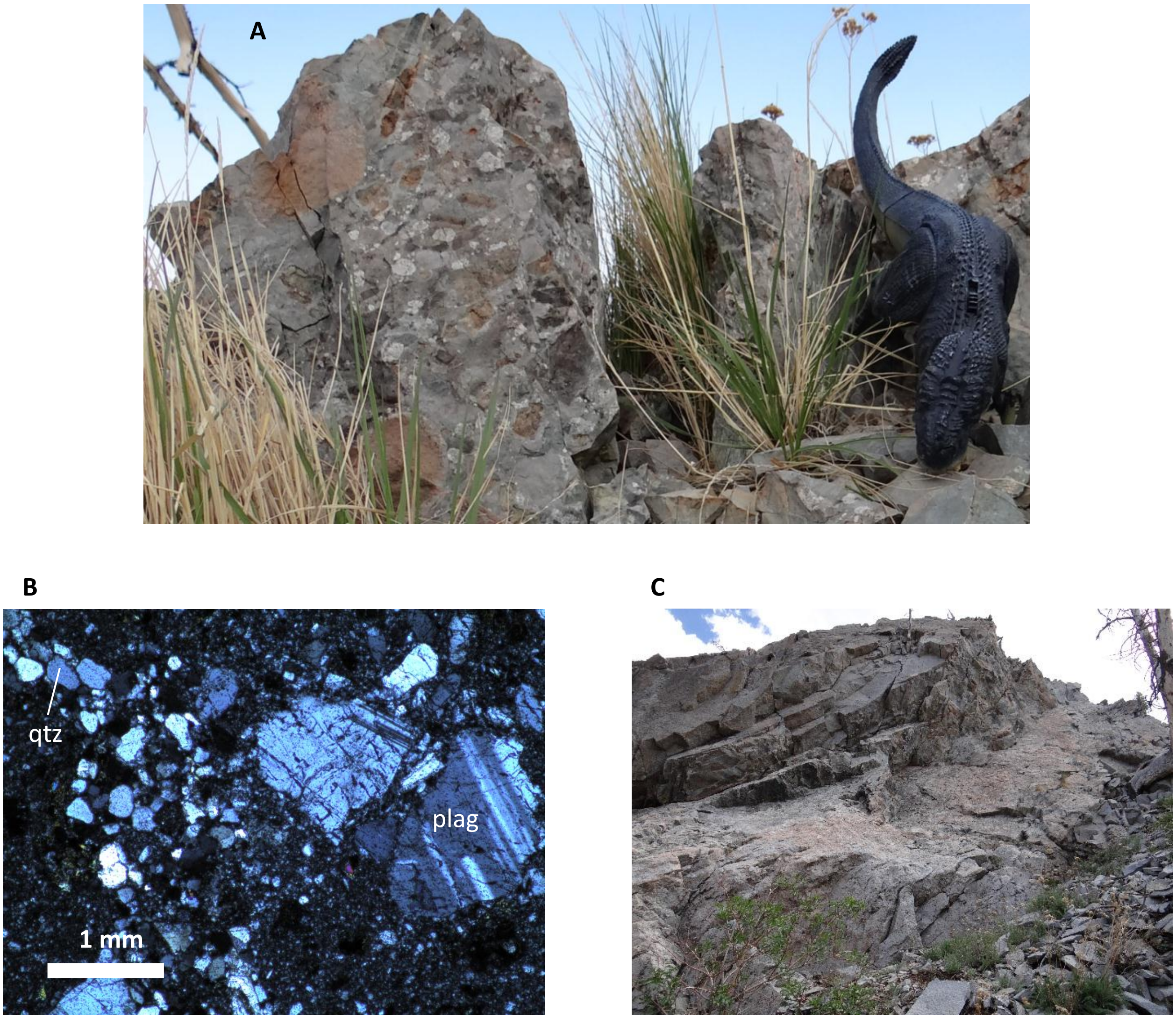


Figure 23: *Breccia of Mount Hillers in the Southern Province.* ***A)*** *Outcrop of an in-place breccia. Matrix is composed of a green metashale from the Organ Rock tongue. Clasts are composed of both porphyry and sandstone.* ***B)*** *Cross polarized thin section showing sand grain and plagioclase clasts in a shaley matrix.* ***C)*** *Intrusion just east of the breccia outcrop. This intrusion is composed of two stacked sheets and is most likely a sill with a dip similar to the topographic slope.*

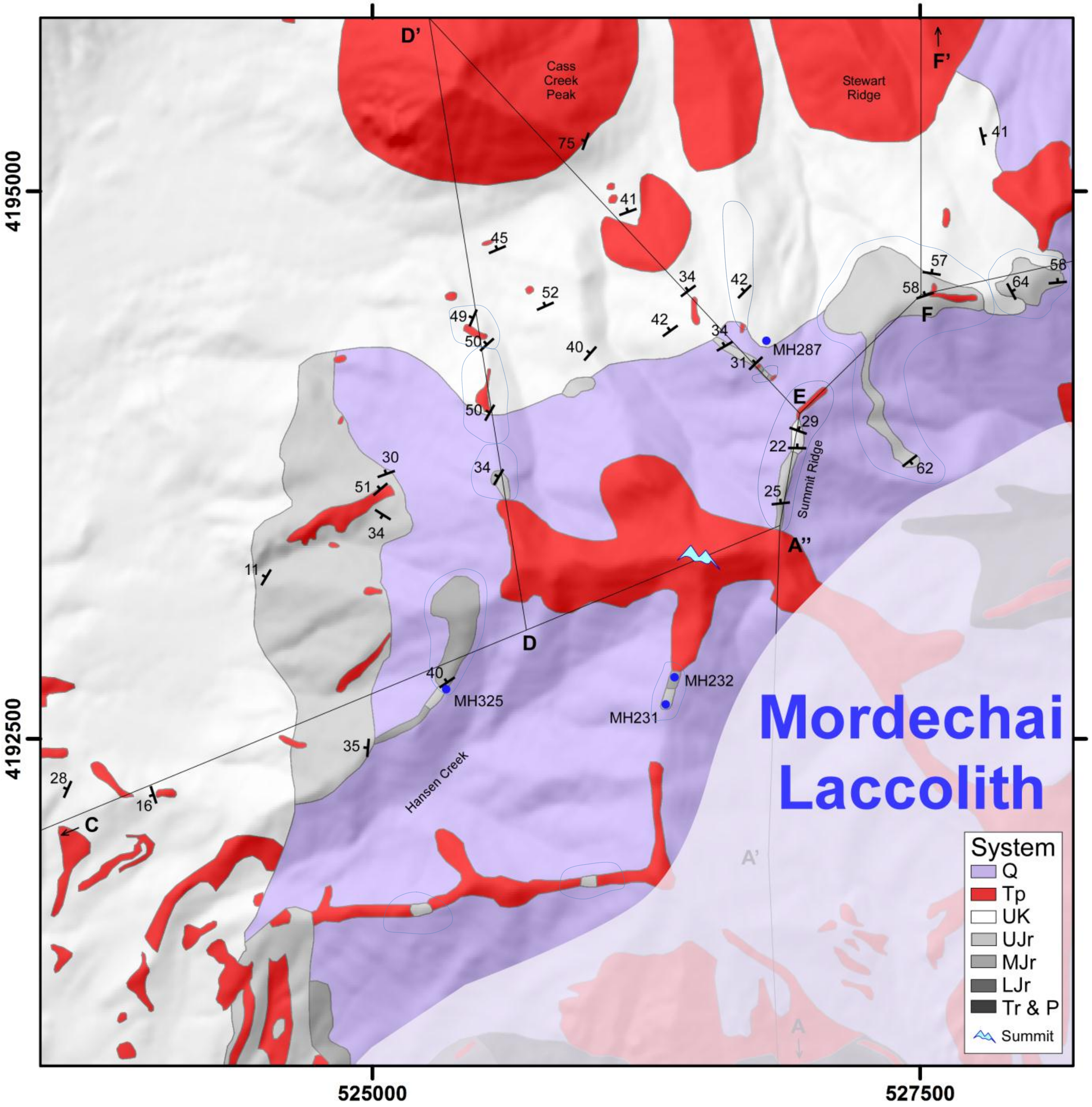


Figure 24: Map of the Mordechai laccolith. Thin blue lines indicate definitive faulted host blocks.

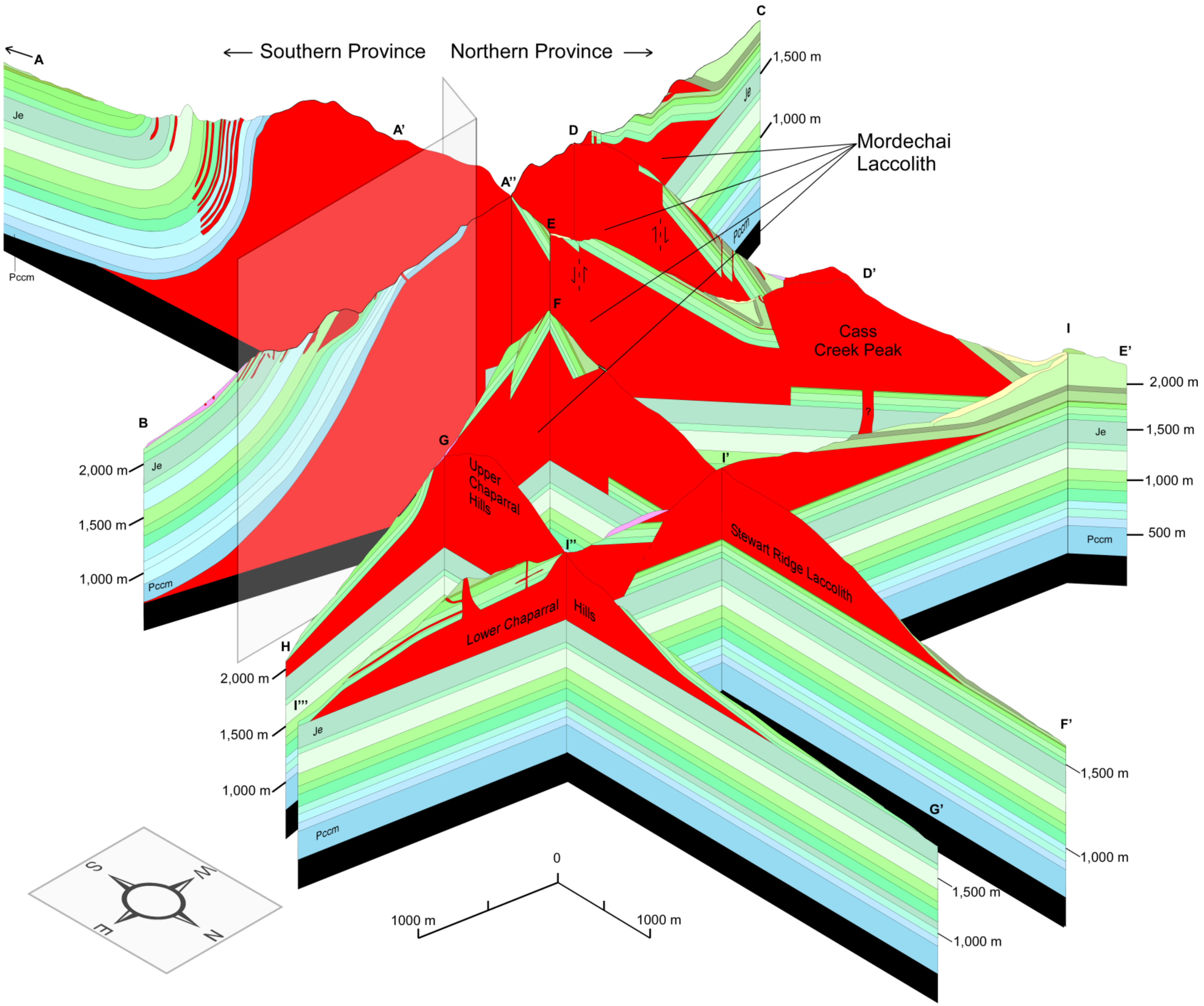


Figure 25: Interpretive fence diagram of the Southern and Northern Provinces. See Figure 3 for color scheme and Figure 22 for transect location points. Black unit is unknown. Pink unit is Quaternary. **NOTE:** The Specks Ridge and Specks Canyon laccoliths are not represented in this figure but may be connected to the Chaparral Hills laccolith.

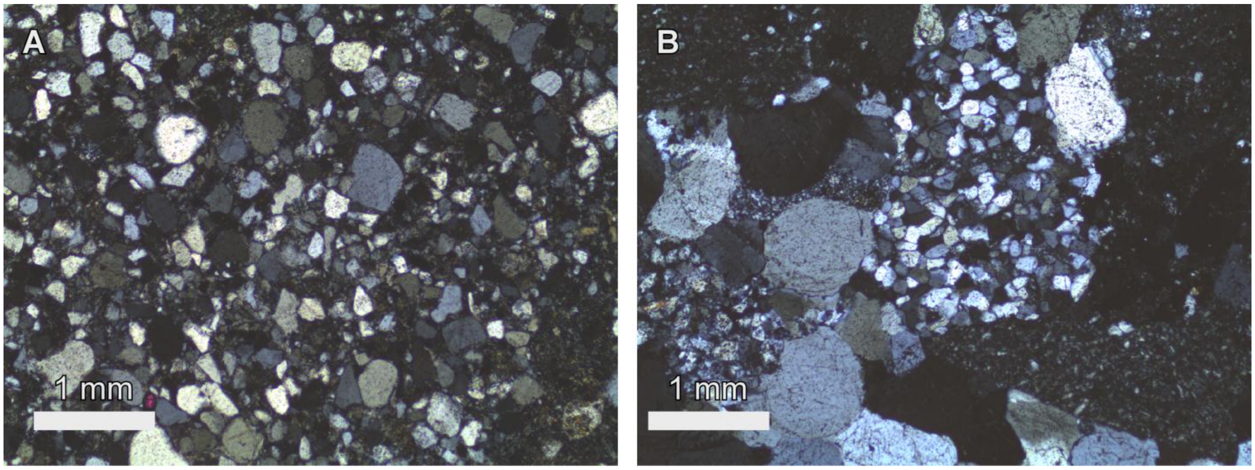


Figure 26: Breccias of the Mordechai laccolith. **A)** MH287. **B)** MH325. See Figure 24 for location map. Both breccias have clasts of quartz grains.

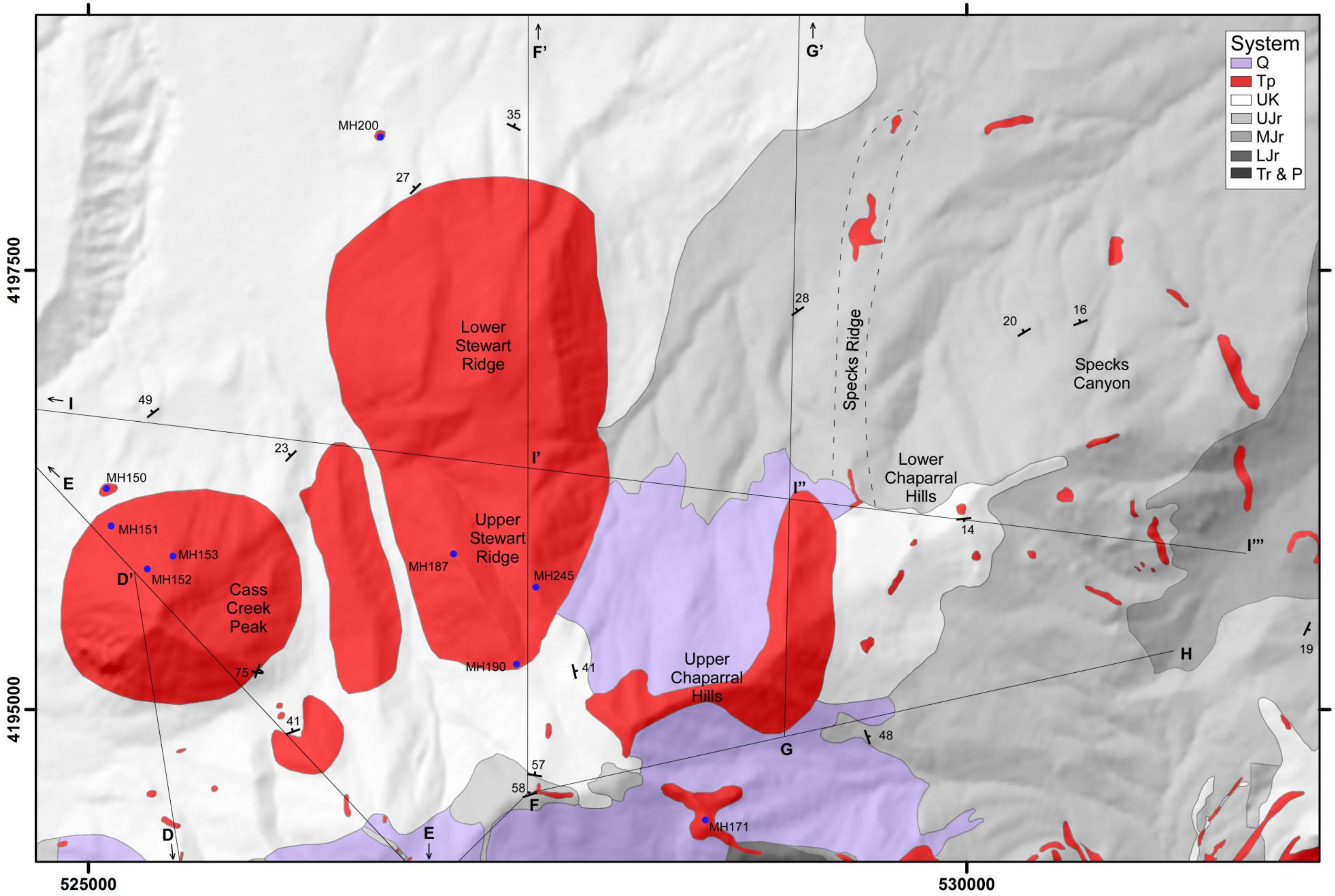


Figure 27: Map of the laccolithic bodies of the Northern Province excluding the Mordechai laccolith.

Figure 28: Picture of the bulge of southwestern Cass Creek Peek. Picture is looking north-northwest.

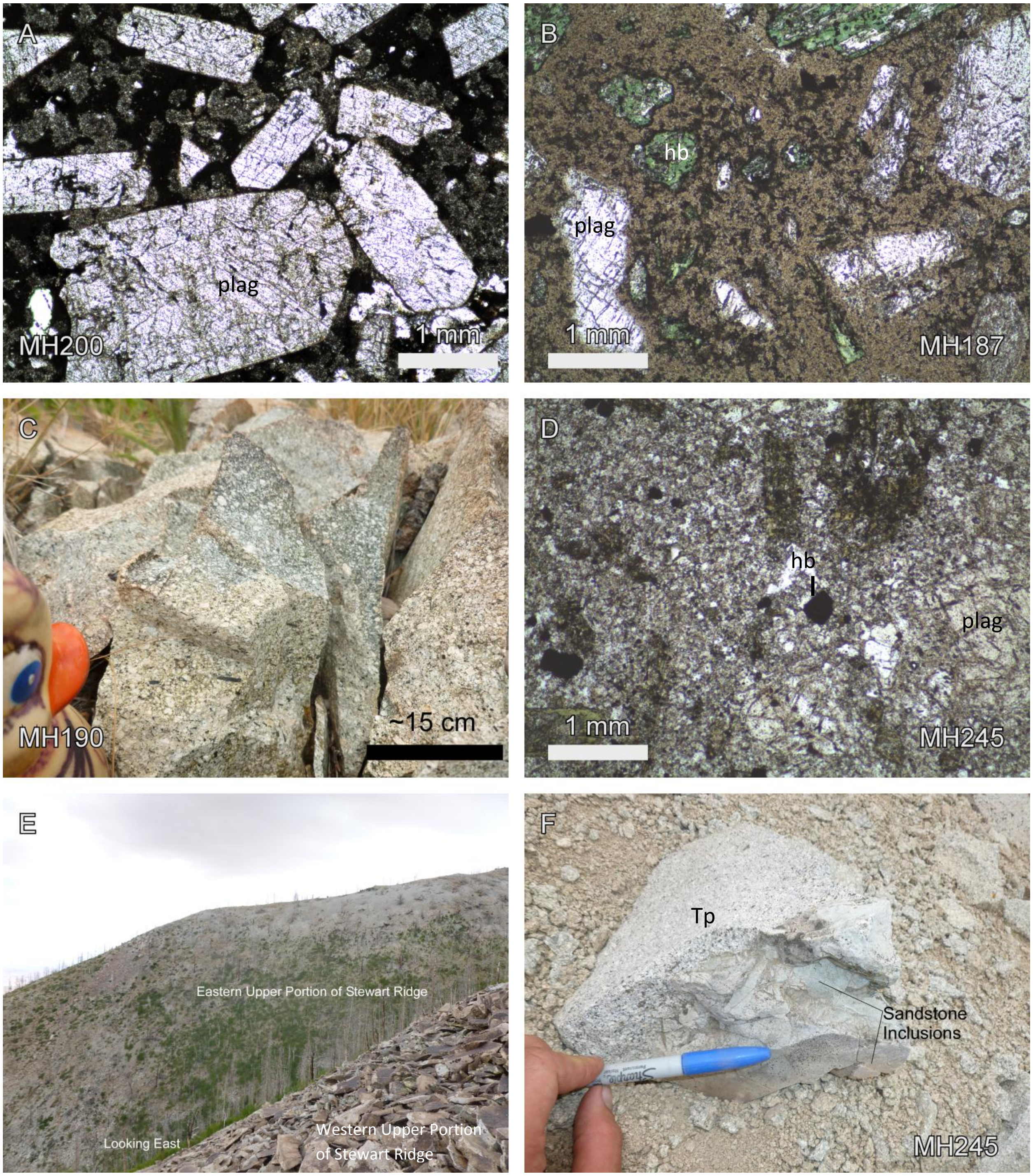


Figure 29: A) Texture of MH200 porphyry. **B)** Representative texture of the southern lower and most of the western upper portion of Stewart Ridge. **C)** Contact of two textures at MH190. **D)** Representative texture of the eastern upper portion of Stewart Ridge. **E)** Outcrop pattern of the eastern upper portion of Stewart Ridge. **F)** Sandstone inclusion of MH245.

Figure 30: Picture of the eastern portion of lower Stewart Ridge.

Figure 31: MH 171 showing inclusions with different igneous textures. See Figure 27 for location point.

Figure 32: MH 41- Contact between two igneous textures and a shale unit. ***A)*** *Medium grained diorite comprised of 30-40% phenocrysts with average plagioclase crystals 2 mm large and hornblendes smaller than or equal to 1 mm.* ***B)*** *Medium grained porphyry comprised of 45-55% phenocrysts with average plagioclase crystals 1-2mm large and low abundance of hornblendes less than 1mm in length.* ***C)*** *Metashale unit that is slightly brecciated at the contact of the porphyry. Layer of breciation is nearly 1 foot thick.*

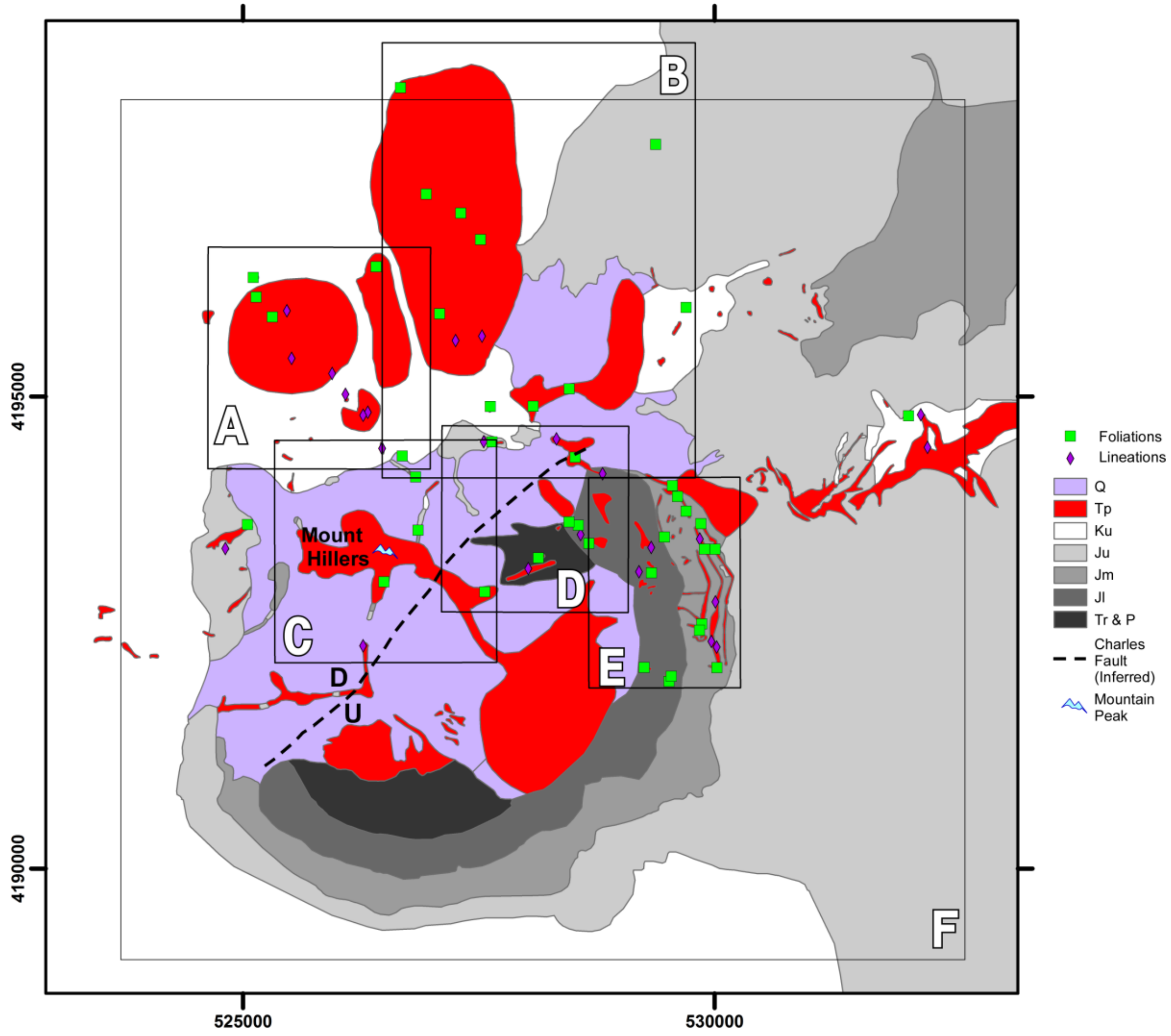


Figure 33: *Location map of the AMS zones A-F. The map also identifies the sample locations and the distribution of foliations (T>0) and lineations (T<0).* ***Zone A:*** *Cass Creek Peak and Quaking Asp laccolith.* ***Zone B:*** *Stewart Ridge laccolith, the northeastern side of the Mordechai laccolith, and the Chaparral Hills laccolith.* ***Zone C:*** *Central Portion of the Mordechai laccolith.* ***Zone D:*** *Northwestern Gold Creek and the Charles Fault Dike.* ***Zone E:*** *Eastern Gold Creek.* ***Zone F****: Other. Overlap between zones does not always incorporate all samples. Q= Quaternary; Tp= Tertiary Porphyry; Ku= Upper Cretaceous; Ju= Upper Jurassic; Jm= Middle Jurassic; Jl= Lower Jurassic; Tr & P= Triassic and Permian.*

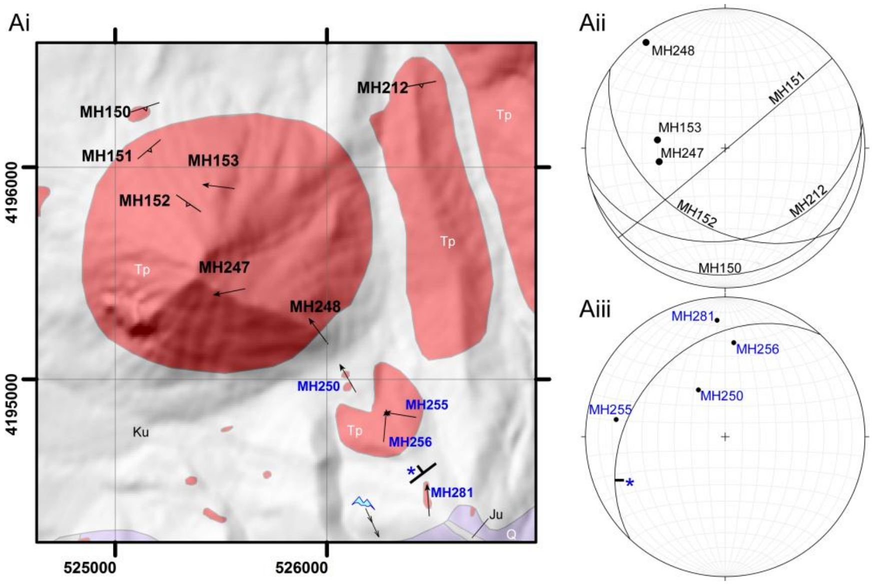


Figure 34: *AMS Results from Zone A.* ***Ai)*** *Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets* ***Aii and Aiii****. Q= Quaternary; Tp= Tertiary Porphyry; Ku= Upper Cretaceous; Ju= Upper Jurassic. *= The average strike and dip value of sedimentary units on the ridge for* ***iii*** *locations. Summit symbol indicated the direction of Mount Hillers summit ~1,200 meters from the symbol.*

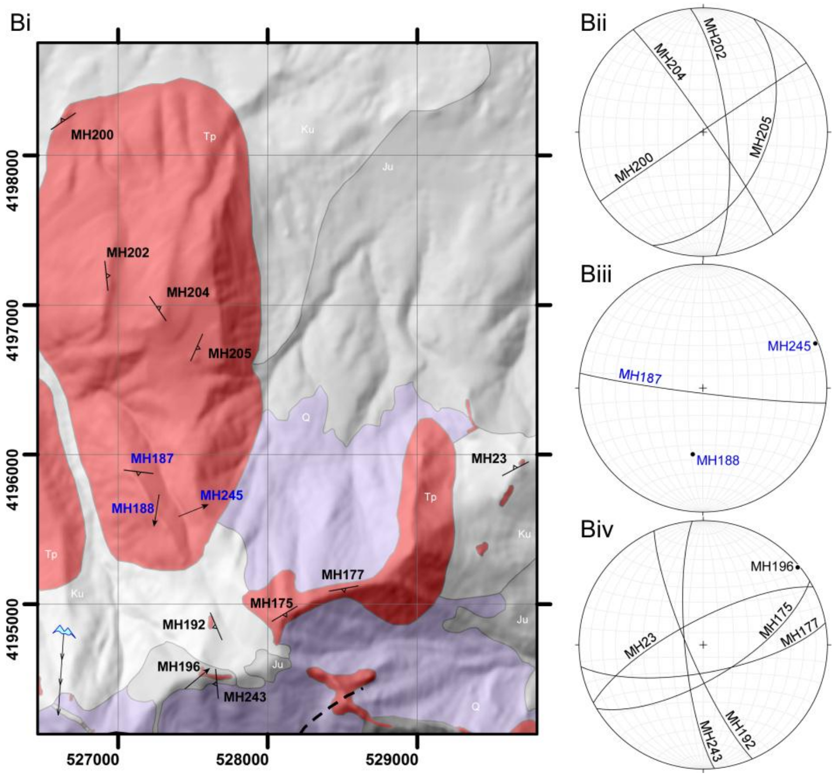


Figure 35: *AMS Results from Zone B.* ***Bi)*** *Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets* ***Bii, Biii,*** *and* ***Biv****. Q= Quaternary; Tp= Tertiary Porphyry; Ku= Upper Cretaceous; Ju= Upper Jurassic. Summit symbol indicated the direction of the summit of Mount Hillers ~1,500 meters from the symbol.*

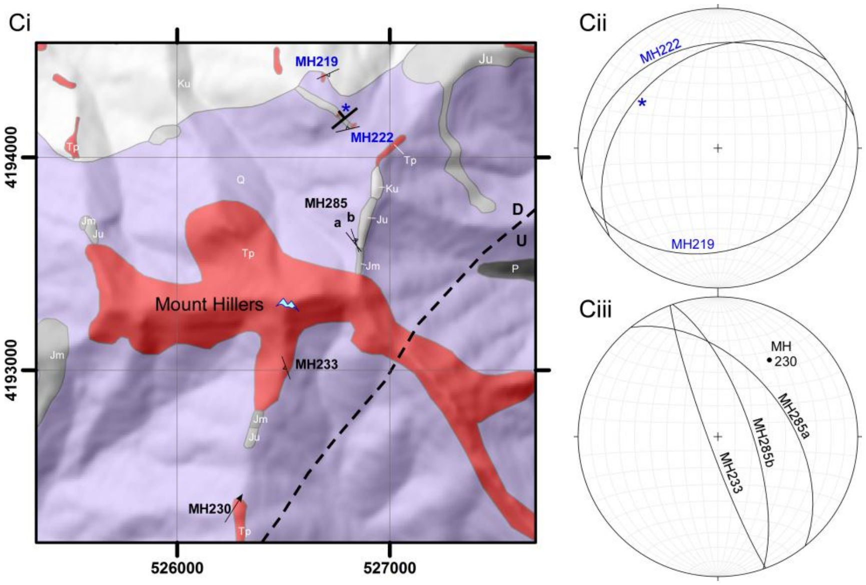


Figure 36: *AMS Results from Zone C.* ***Ci)*** *Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets* ***Cii*** *and* ***Ciii****. Q= Quaternary; Tp= Tertiary Porphyry; Ku= Upper Cretaceous; Ju= Upper Jurassic; Jm= Middle Jurassic; P= Permian*

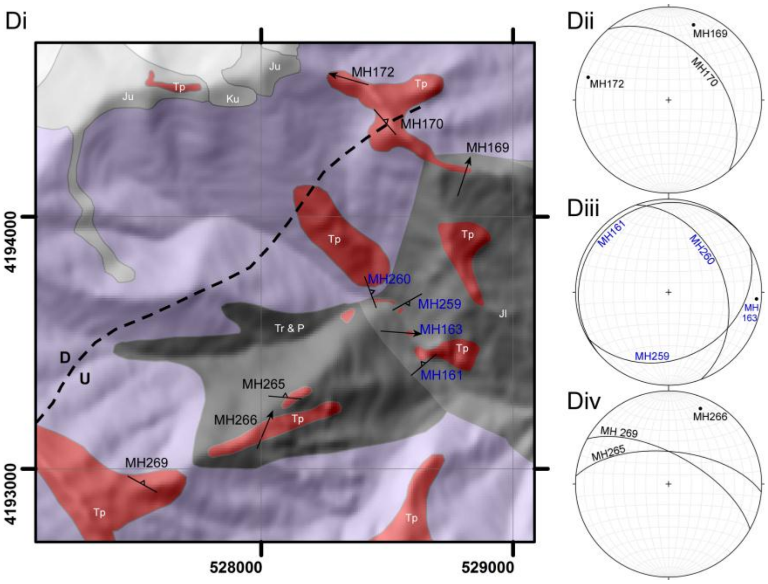


Figure 37: *AMS Results from Zone D.* ***Di)*** *Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets* ***Dii, Diii,*** *and* ***Div****. Q= Quaternary; Tp= Tertiary Porphyry; Ku= Upper Cretaceous; Ju= Upper Jurassic, Jl= Lower Jurassic, Tr & P= Triassic and Permian.*

Figure 38*: A) Drainage from which MH161 was sampled. Picture is looking west.* ***B)*** *Drainage is incised 80-120 m. Picture is looking south.*

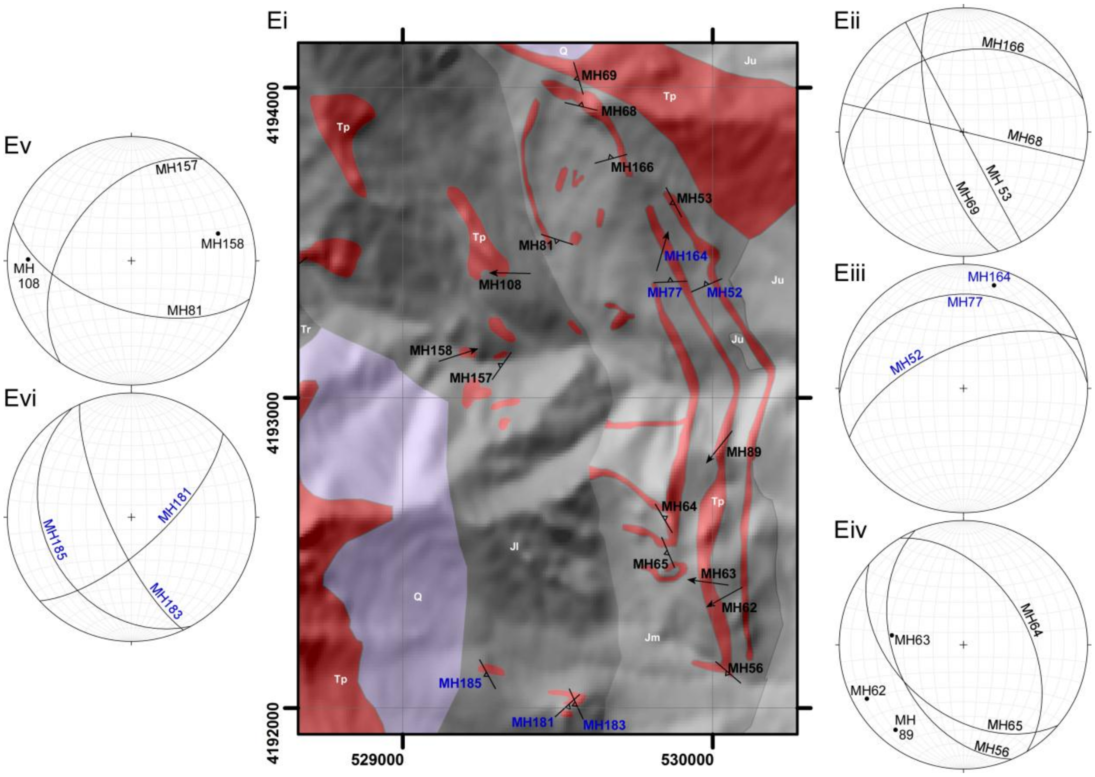


Figure 39: AMS Results from Zone E. ***Ei)*** *Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets* ***Eii-Evi****. Q= Quaternary; Tp= Tertiary Porphyry; Ju= Upper Jurassic; Jm= Middle Jurassic; Jl= Lower Jurassic; Tr= Triassic.*

Figure 40: location site of MH183.

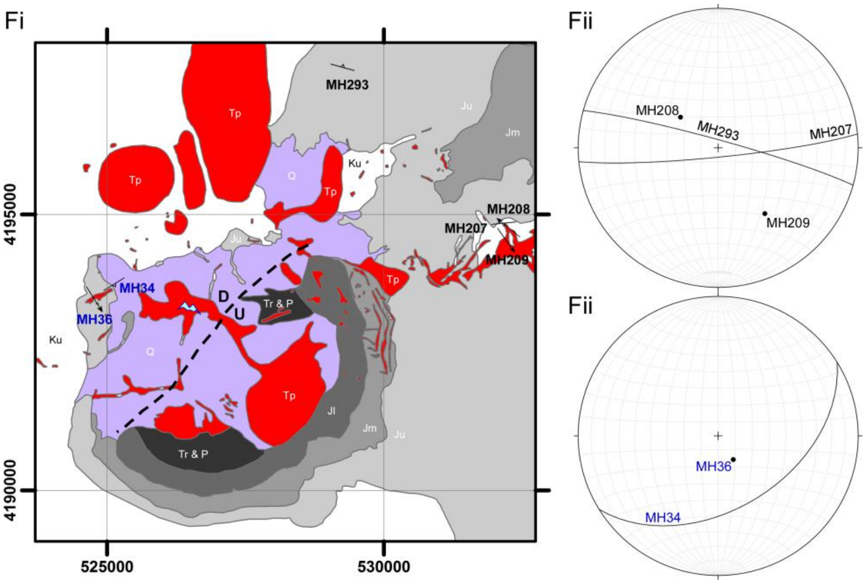


Figure 41: *AMS Results from Zone F. Ei) Location map showing local geology superimposed on a shaded relief map. Foliations and lineations of stations are mapped in the respective colors represented by the stereonets Fii and Fiii. Q= Quaternary; Tp= Tertiary Porphyry; Ju= Upper Jurassic; Jm= Middle Jurassic; Jl= Lower Jurassic; Tr= Triassic.*

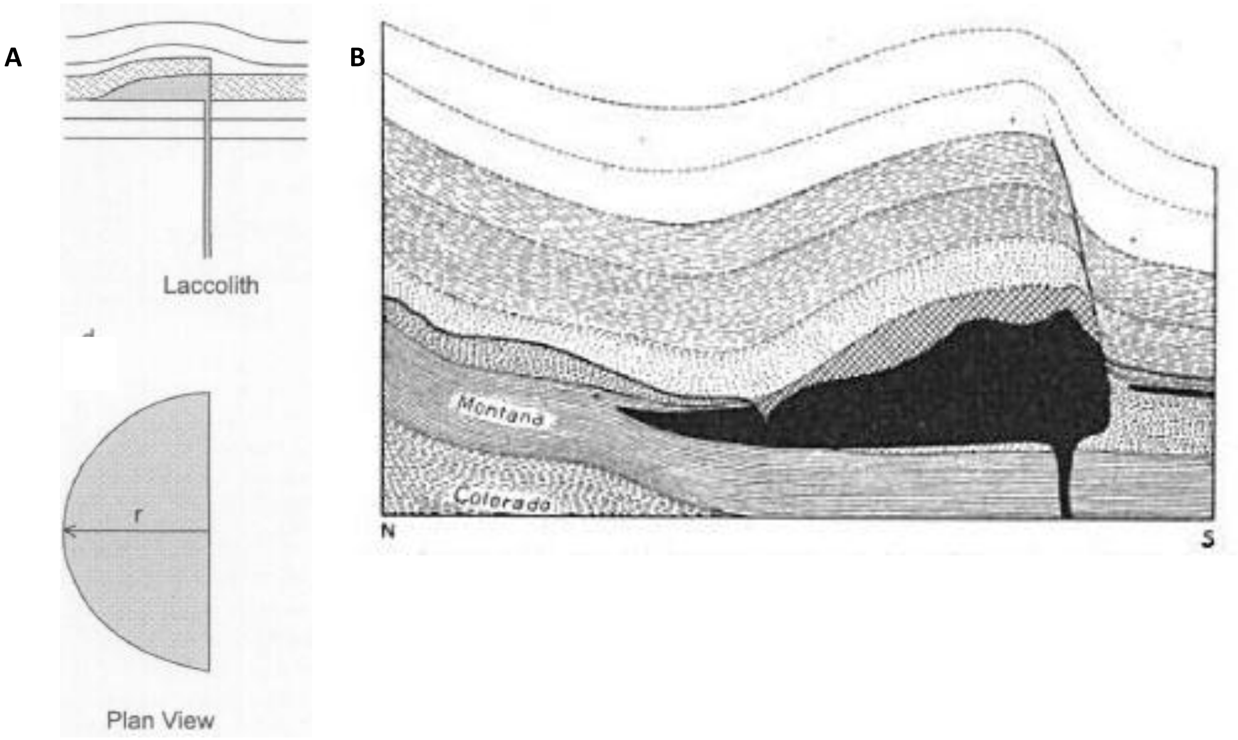
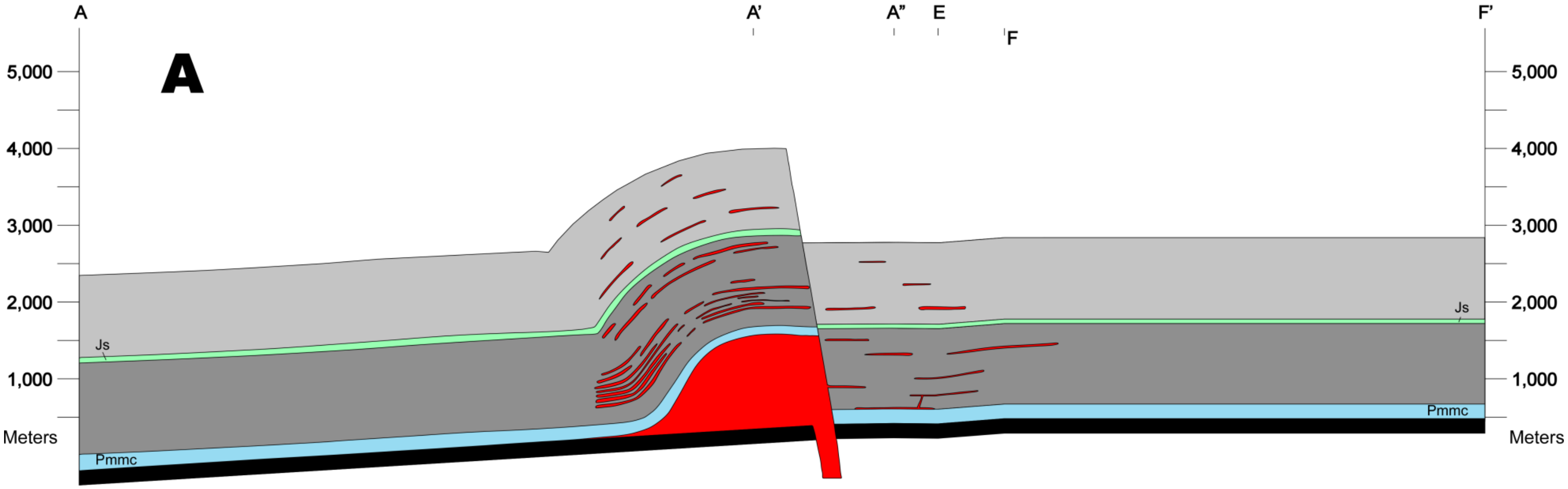


Figure 42: A) Model of an asymmetric laccolith that is semicircular in plan view (Grocott et al., 1999). **B)** Cross sectional interpretation of an asymmetric Mount Marcellina laccolith in the West Elk Mountains of Colorado (Cross, 1895).

Figure 43 (Next 3 pages)**:** Progressive development of the Mount Hillers intrusive complex. This figure only projects deformation 1,000 meters above the Summerville formation and does not project deformation of host rock to the paleo-surface. The Jurassic Summerville formation (green) and the Permian Cedar Mesa of the Cutler formation (Blue) are identified as marker layers. The steps of development shown begin after the early Copper Creek laccolith of the southern province has already developed. Stages of emplacement are then broken down into six steps (See text for explanation). There is no vertical exaggeration in these cross sections. **Note:** apparent changes in regional dip of sedimentary strata are a consequence of changing cross sectional orientation along the length of the profile.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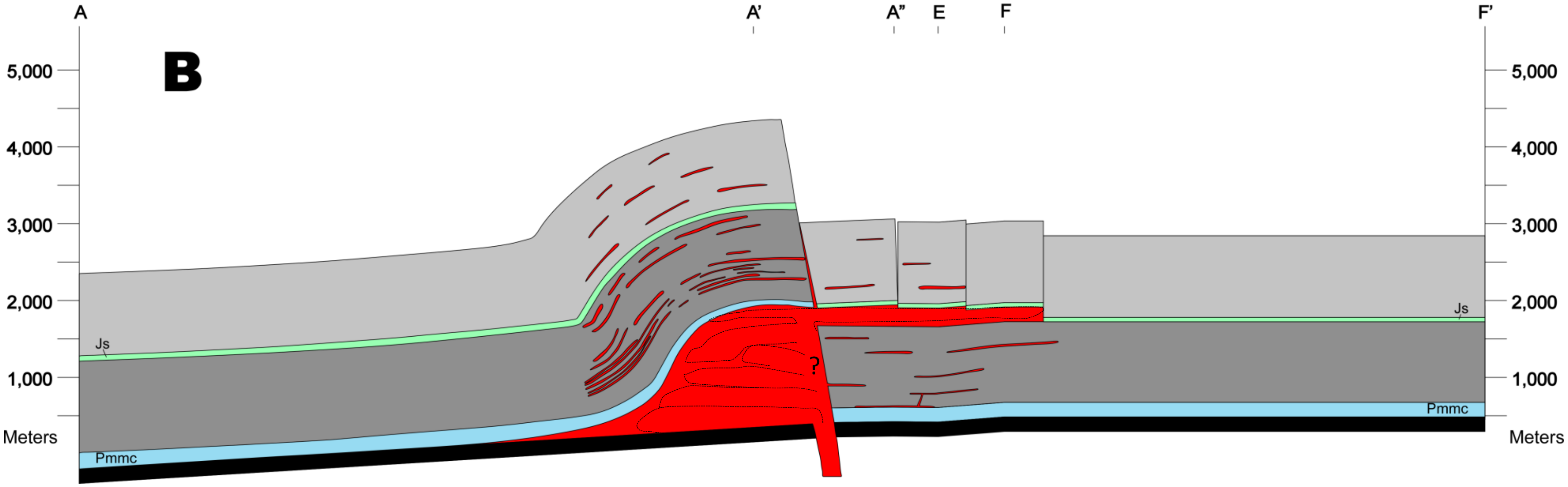
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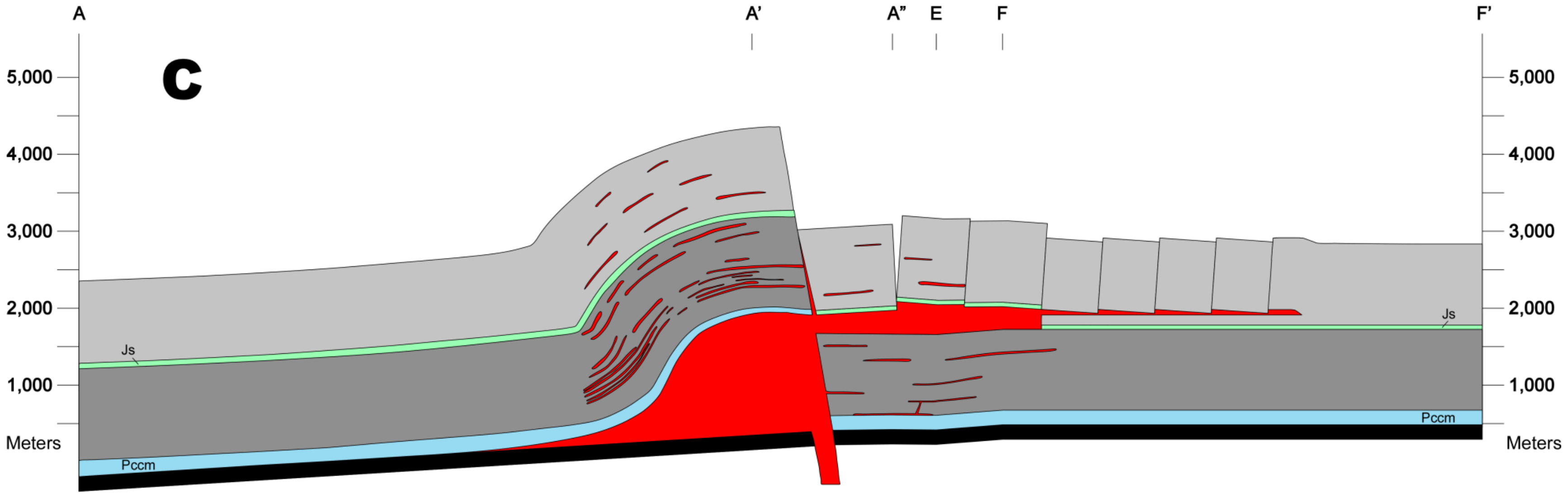
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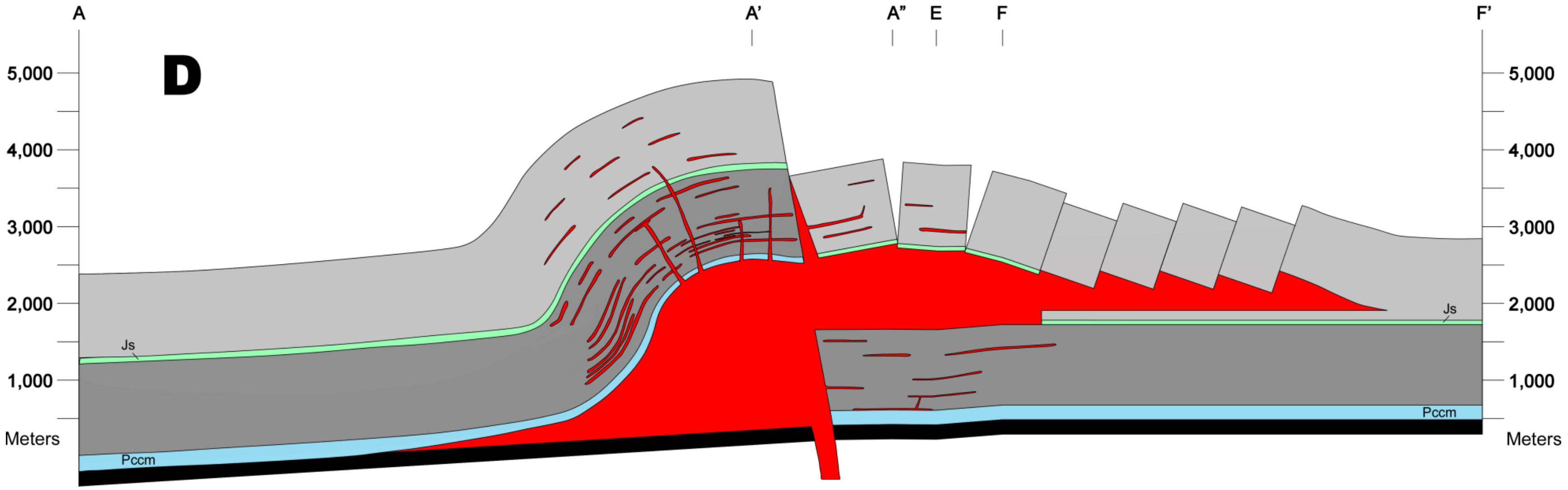
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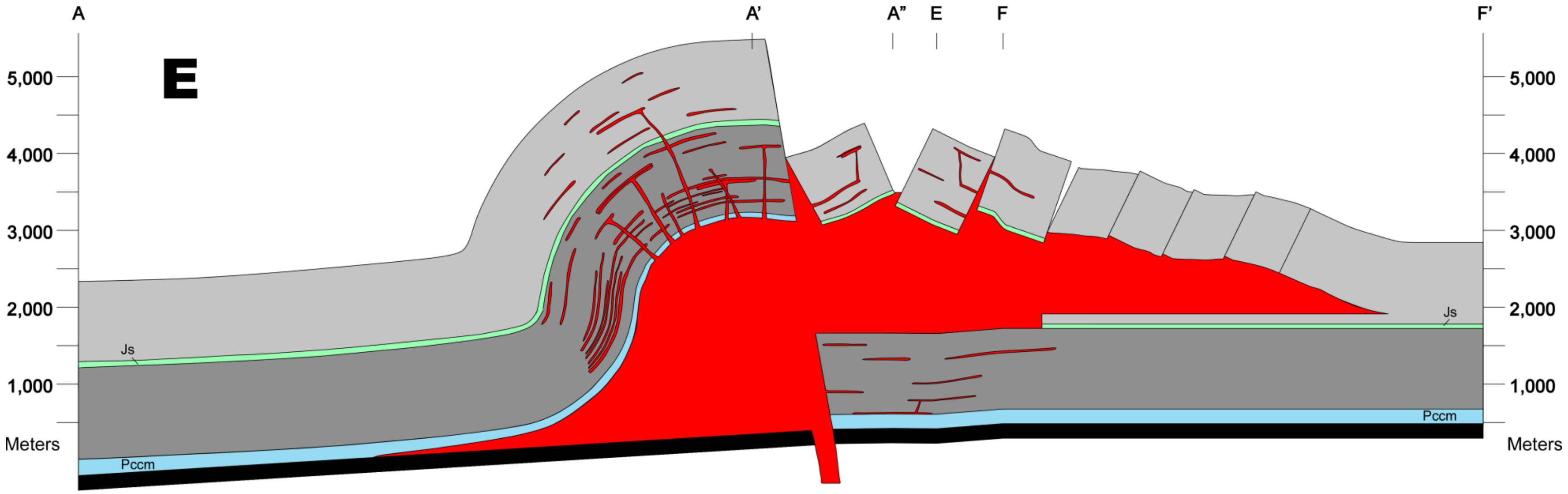
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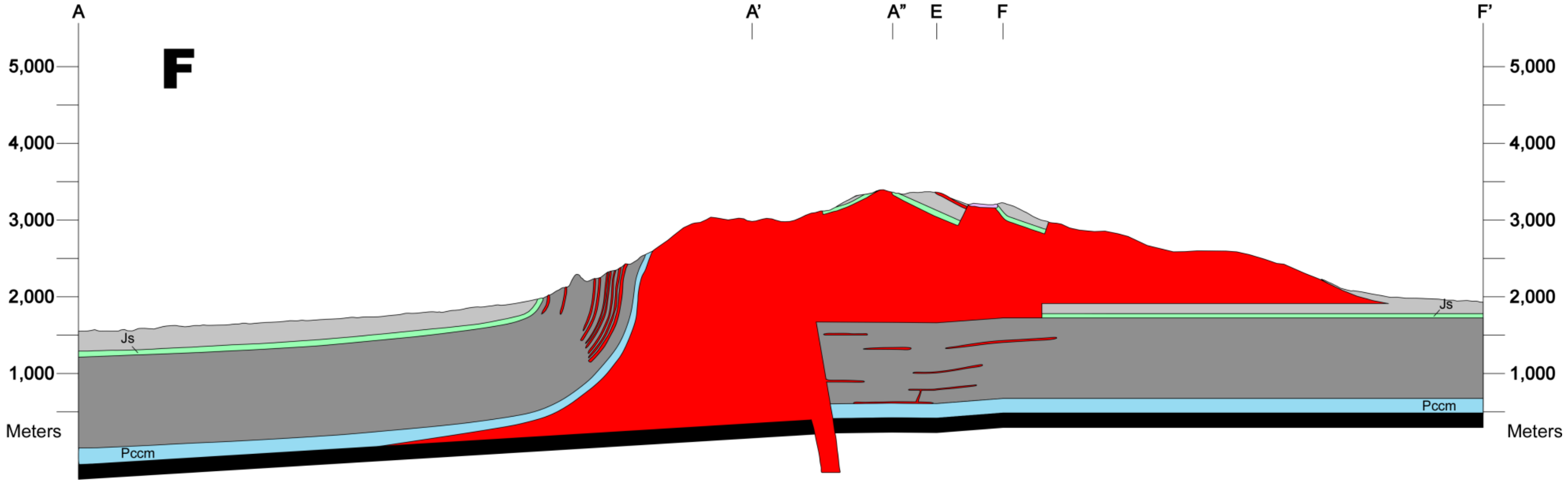
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