
Progressive Construction of Laccolithic Intrusive Centers: Henry Mountains, Utah, U.S.A

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Abstract

The intrusions of the Henry Mountains of southern Utah provide an exceptional setting for the study of igneous emplacement processes in the shallow crust. The five separate intrusive centers intruded the flat-lying stratigraphy of the Colorado Plateau at 2–4 km depth. The intrusions are Oligocene in age and postdate the minor Laramide orogenic activity that affected this part of the Colorado Plateau. These intrusions can therefore be interpreted as having formed through purely magmatic processes, with no tectonic involvement or modification. Each of the five separate intrusive centers in the Henry Mountains preserves a different stage in the evolution of an igneous system constructed in the shallow crust. Each intrusive center is comprised of numerous small intrusive bodies surrounding a large laccolithic body assembled from several magma pulses. Collectively, the five intrusive centers provide a series of snapshots of the progressive growth of an igneous system in the shallow crust. A compilation of data from these intrusive centers allows development of a generalized model for progressive construction of a magmatic system in the shallow crust. This model involves three main stages. First, an early network of dikes and sills is intruded. Second, a relatively voluminous laccolithic central igneous body begins to form. The central laccolith may initiate though inflation of a sill that grew to a radius sufficient to lift the overburden, as hypothesized in traditional growth models. However, field evidence suggests progressive laccolith growth in the Henry Mountains involved numerous rapidly emplaced magma pulses separated by periods

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of no appreciable activity. In the final stage, satellite intrusions, many with a tongue-like geometry, are emplaced radially outward from the margin of the main laccolith, initiating in the lower hinge region where bending and fracturing of overburden is most intense. The step-wise assembly of these intrusive centers from multiple discrete pulses of magma calls into question the applicability of theoretical models of laccolith growth that presuppose the entire intrusion remains in a liquid state throughout the full emplacement history.

Keywords

Laccolith • Sill • Emplacement • Pluton • Magmatism

1 Introduction

In recent years, it has become generally accepted that many igneous intrusions in the shallow crust are assembled from a series of discrete, sequentially emplaced magma pulses, and did not exist as a single “big tank” system. While the pulsed assembly of intrusions is not a new topic (e.g. Hamilton and Myers 1967; Pitcher and Berger 1972; Hardee 1982; Wiebe 1988), recent field and theoretical work has appreciably improved our understanding of these processes by documenting the incremental assembly of intrusions over scales ranging from batholiths to individual sills (e.g. Cruden and McCaffrey 2001; Saint Blanquat et al. 2001, 2011; Glazner et al. 2004; de Silva and Gosnold 2007; Lipman 2007; Bartley et al. 2008; Vigneresse 2008; Rocchi et al. 2010). Other studies have used radiogenic isotope and chemical diffusion methods to study timescales of pulsed pluton assembly and thereby constrain magma fluxes (Coleman et al. 2004; Matzel et al. 2006; Miller et al. 2007; Walker et al. 2007; Turner and Costa 2007; Michel et al. 2008).

The utility of studying ancient igneous systems is immediately apparent when we compare results from these studies with those from geodetic studies of modern systems. Three characteristics are shared by many of the magma systems, both old and new: pulsed construction, tabular geometry, and lateral magma transport. As described above, pulsed construction of

ancient intrusions is apparent over a wide range of spatial scales. In modern systems, cyclic surficial displacement of up to a few centimeters per year is commonly observed near active volcanoes (Dzurisin 2003). This displacement occurs on timescales of months to years, even during periods of volcanic quiescence, and is commonly inferred to be the result of injection of magma bodies (e.g. Dvorak and Dzurisin 1997; Pritchard and Simons 2004a) or expansion and contraction of geothermal systems at depth (e.g. Wicks et al. 1998; Battaglia et al. 2006).

The tabular geometry of ancient intrusions is clear from 3-d reconstructions of many plutons of all sizes, irrespective of the tectonic context or composition of magmas involved (McCaffrey and Petford 1997; Petford et al. 2000; Cruden and McCaffrey 2001). Similarly, modern subsurface magma bodies commonly have shallowly dipping ($<20^\circ$), sheet-like geometries (Wicks et al. 2002; Dzurisin et al. 2006; Lundgren and Lu 2006) and lie at less than 10 km depth, with most between 3 and 6 km (e.g. Dzurisin 2003; Lu et al. 2005; Froger et al. 2006).

Finally, the importance of lateral transport of magma in the shallow crust is clear from the existence of sill complexes in many tectonic settings (e.g. Thomson and Hutton 2004; Hansen and Cartwright 2006) and the considerable distances sills can sometimes transport magma (e.g. Elliott et al. 1999). In modern systems, forward modeling of geodetic data from volcanoes suggest

dilating magma chambers that produce surface deflections may be offset many kilometers from vent regions. Offset distances are generally less than 10 km but range up to at least 13 km (Curtis 1968; Nishi et al. 1999; Nishimura et al. 2001; Lu et al. 2002; Wicks et al. 2002; Masterlark and Lu 2004; Pritchard and Simons 2004b).

The similarity between modern shallow igneous systems and their ancient counterparts suggests there is much to learn about modern systems from ancient systems and vice versa. We can observe the roots of modern volcanic systems only through indirect processes like geodesy and geophysics. While the roots of ancient systems are sometimes exposed, it is commonly difficult to study processes involved in their formation. In particular, syn-emplacement tectonic processes commonly modify or entirely overprint evidence of magmatic processes (Barbey 2009), making it difficult to study the construction of ancient intrusive systems (Paterson et al. 1998).

This paper describes examples of upper crustal igneous systems emplaced in a setting that allows for relatively straightforward interpretation of intrusive processes: the Henry Mountains of southern Utah. This region experienced effectively no syn- or post-emplacement tectonism. Additionally, the host rocks consist of initially flat-lying sedimentary rocks; all host rock deformation is due entirely to intrusive processes. This setting presents an opportunity to study pluton growth where all associated deformation and magma flow were driven solely by interaction between magma and host rock.

Perhaps the most compelling aspect of studying the Henry Mountains intrusions is the fact that igneous systems there preserve a range of total emplaced magma volume. Systems with small total igneous volumes can be interpreted as an early stage of development of a magmatic system in the shallow crust, while those with larger volumes represent more advanced stages of development. Thus the Henry Mountains provide an opportunity to piece together a progressive history of development and growth of an igneous system in the shallow crust.

2 The Henry Mountains

2.1 Regional Magmatism

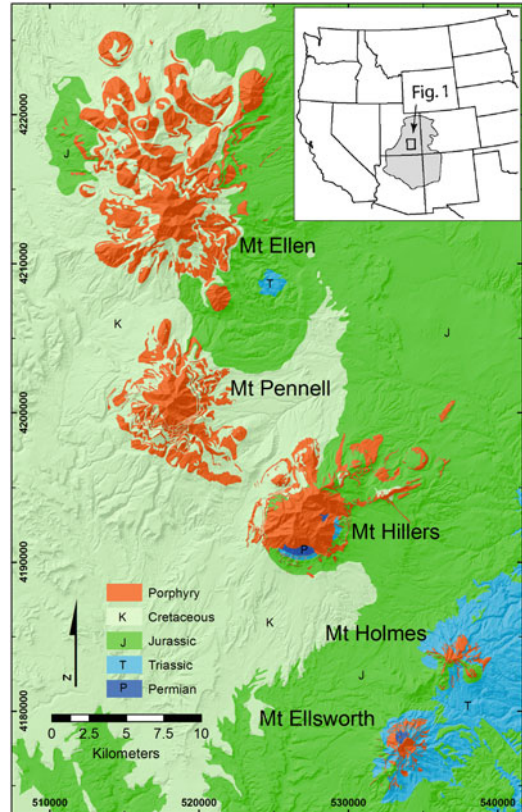
The intrusions of the Henry Mountains of southern Utah are part of a regional group of igneous complexes, all of late Eocene to Oligocene age (Nelson et al. 1992), that intruded into the shallow crust of the Colorado Plateau. Other igneous complexes of this group in the vicinity include the La Sal Mountains (Hunt and Waters 1958), the Abajo Mountains (Witkind 1964), and Navajo Mountain (Condie 1964). The main intrusions in all of these igneous complexes are generally regarded to have a laccolith geometry, with a largely concordant sub-horizontal base and a bell-shaped upper surface beneath uplifted and rotated host rock (Gilbert 1877).

Nelson and Davidson (1993) suggest all of these intrusive complexes are part of a widespread late Paleogene magmatic episode in the North American Cordillera. Although late Paleogene magmatism was voluminous around the margins of the Colorado Plateau (Armstrong and Ward 1991), magmatism on the plateau includes only a few hundred cubic kilometers of igneous rock, a considerable portion of which is now exposed in the laccolithic intrusive centers of the Henry, La Sal and Abajo Mountains.

2.2 Henry Mountains Geology

The intrusions exposed in the Henry Mountains (Fig. 1) were emplaced at $\sim 2\text{--}4$ km depth into the nearly flat-lying stratigraphy of the Colorado Plateau (Jackson and Pollard 1988). Magmatism lasted from approximately 32 to 23 Ma (Nelson et al. 1992) and postdates the relatively minor regional deformation on the Colorado Plateau during the Laramide orogeny. These temporal and spatial relationships, along with the exceptional exposure of both plutons and host rock, make the Henry Mountains ideal for examination of upper crustal magma emplacement without the complications of synmagmatic tectonic deformation.

Fig. 1 Simplified geological map of the Henry Mountains region. Modified from Hunt et al. (1953). Inset shows the location of the Henry Mountains region on the Colorado Plateau. UTM coordinates, zone 12, datum NAD83



The Henry Mountains are comprised of five intrusive centers (Fig. 1), each of which is an amalgam of smaller component intrusions (Hunt et al. 1953). Geophysical data and structural analysis of deformed host rock demonstrate that each intrusive center is a large laccolithic body with a sub-horizontal concordant base (Jackson and Pollard 1988). The first-order geometry of the intrusions in the Henry Mountains was, however, the subject of considerable debate for some time (e.g. see Jackson and Pollard 1988; Hunt et al. 1988). While this debate has been largely resolved, the differing interpretations are presented in some detail in the Discussion section below because the debate is quite instructive.

The majority of the igneous rock throughout the Henry Mountains is remarkably consistent in bulk composition. Approximately 95 % of the exposed igneous rock has a bulk andesite/trachyandesite composition, with 58–63 % SiO_2

and 5–7 % $\text{Na}_2\text{O} + \text{K}_2\text{O}$. The remaining $\sim 5\%$ of exposed igneous rock is principally rhyolite and syenite porphyry cross-cutting earlier andesitic porphyry on Mount Pennell (Hunt et al. 1953; Hunt 1988; Nelson and Davidson 1993; Ward 2014). Texturally, the dominant igneous rock is a plagioclase-hornblende porphyry. Phenocrysts generally constitute 20–35 % of the rock and consist of 15–25 % feldspar (An20 to An60), 5–15 % hornblende, and 1–2 % accessory minerals including clinopyroxene, titanite, apatite, oxides, quartz and calcite. The groundmass makes up 50 % or more of the rock and is composed of microlites of feldspar with a grain size of ~ 20 – $30\ \mu\text{m}$, as well as lesser amounts of amphibole and oxide grains of similar or smaller size. Xenoliths are present at many outcrops and usually comprise 1–2 % by volume. Most xenoliths are mafic (amphibolite, garnet amphibolite, tonalite) but rare sedimentary xenoliths exist, usually in close proximity to contacts with host rock.

The sedimentary section in the Henry Mountains region consists of approximately 4.5 km of Cambrian to Upper Cretaceous strata above Proterozoic-age crystalline basement (Hunt et al. 1953; Doelling 1975; Peterson et al. 1980). The lowermost known igneous intrusions of the Henry Mountains were emplaced into Permian sandstones of the Cutler Formation. The uppermost exposed igneous intrusions were emplaced into Cretaceous shale of the Blue Gate member of the Mancos Shale. The total stratigraphic thickness between the lowermost and uppermost intrusions is approximately 2700 m. At the time of emplacement, the lowermost intrusions (into Permian strata) were overlain by an estimated 3.5–4 km of sedimentary overburden (Jackson and Pollard 1988).

Host rock metamorphism in the Henry Mountains is minimal and very localized. Appreciable metamorphism (e.g. shale to slate) of sedimentary strata is found only immediately adjacent to the largest volumes of igneous rock, and is then confined to the nearest 100–200 m of strata. Adjacent to component intrusions with volumes smaller than $\sim 1 \text{ km}^3$, very little evidence of metamorphism can be found farther than a few tens of centimeters from igneous-sedimentary contacts. This lack of metamorphism implies very rapid emplacement and cooling of the magma, which is consistent with the shallow depth.

3 Snapshots of Intrusive Center Architecture

Each of the five Henry Mountains intrusive centers is cored by a broadly dome-shaped laccolithic body that has tilted and uplifted surrounding sedimentary host strata. A network of sills, dikes, and other relatively small-volume intrusions structurally overlie the main laccolithic dome. The five intrusive centers differ in the total volume of igneous rock emplaced and consequently the amount of host rock deformation. This variation in igneous volume and host rock deformation can be interpreted to represent a series of snapshots in the progressive development of an igneous system in the shallow crust. In this section, three of the

five Henry Mountains intrusive centers are described in some detail: an early-stage center (Mount Ellsworth), and intermediate-stage center (Mount Hillers), and an advanced-stage center (Mount Ellen). These descriptions focus primarily on the geometry of the intrusions and structural relationships with host rock.

3.1 Mount Ellsworth

At the Mount Ellsworth intrusive center (Figs. 2a and 3a), stratigraphy is uplifted a maximum of approximately 1800 m, and deflection from the regional bedding orientation extends over an area with a diameter of approximately 10 km (Fig. 4). The dome is slightly elliptical in plan view, with elongation in a NNE-SSW direction. Host rock strata are well preserved over much of the upper surface of the laccolithic dome. Strata dip shallowly ($<20^\circ$) atop the topographic dome and on the margins dip consistently outward, away from the center. Strata consistently dip more steeply on the northwest side of the intrusive center (maximum of $\sim 55^\circ$) than on the SE side (maximum $\sim 40^\circ$). The total igneous rock volume of the intrusive center is estimated at $\sim 18 \text{ km}^3$ based on deflection of stratigraphy from the regional orientation.

Igneous rock is exposed near the summit of Mount Ellsworth over an area of roughly 1.5 km^2 . This area is interpreted to be an exposure of the crest of the main laccolithic intrusion (Koch 1981; Jackson and Pollard 1988). On the north and west sides of the intrusive center a network of sills and subsidiary dikes is intruded into outward-dipping Permian and Triassic strata. On the south and east sides of the intrusive center, the proportional area of exposed igneous rock is less and consists largely of radial dikes, small sills, and a few irregularly shaped bodies, generally intruded into Upper Triassic and Lower Jurassic strata. Thus, the overall geometry of the igneous rock is an almost radially symmetric central laccolithic body underlying a network of sills and dikes intruded into overburden host rock strata.

The exposures on Mount Ellsworth provide clear evidence of overburden faulting during the relatively early stage of laccolith growth

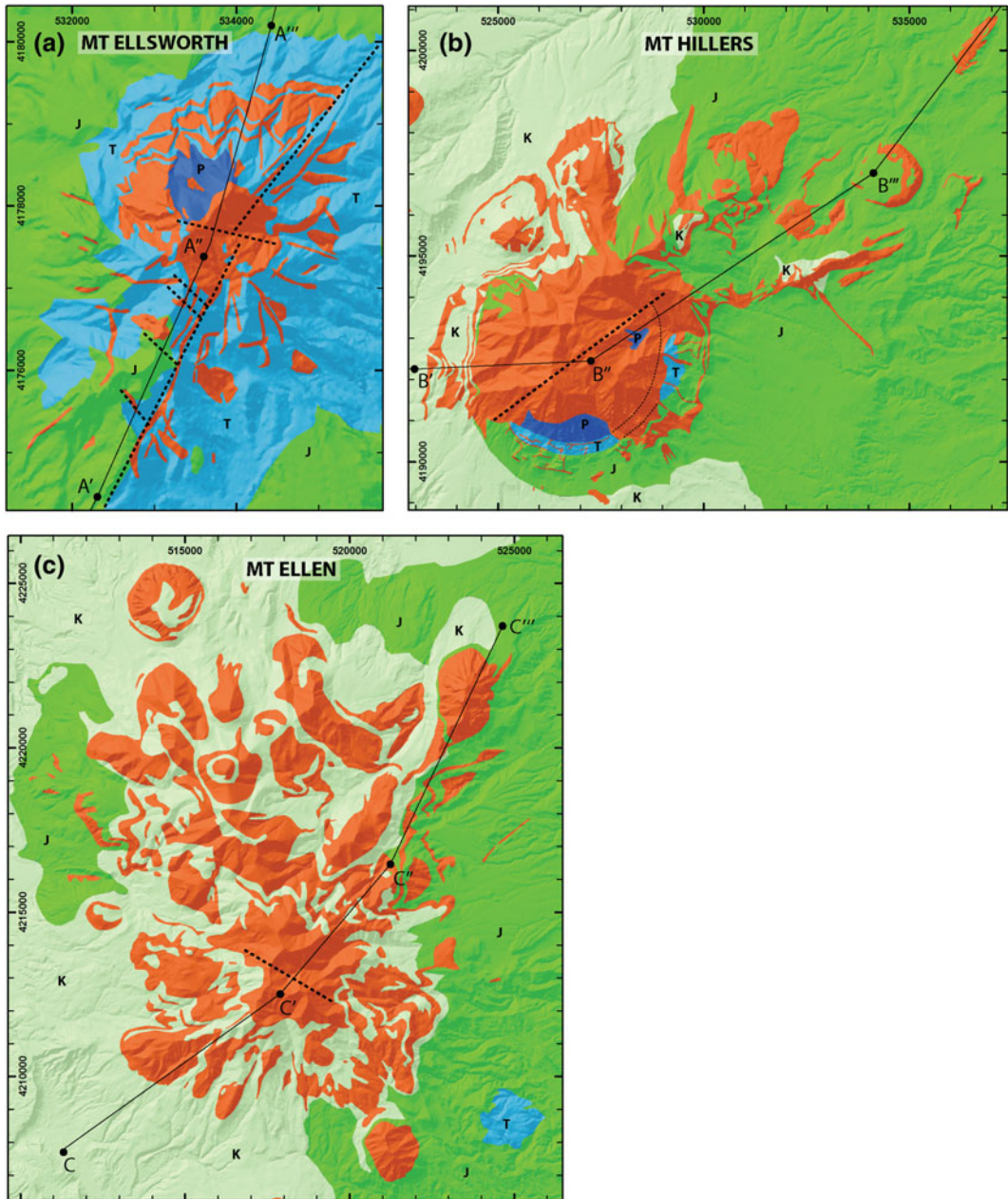


Fig. 2 Simplified bedrock geological maps of selected Henry Mountains intrusive centers. Rock unit colors correlate with those in Fig. 1. Endpoints and direction changes are indicated on each map for cross sections shown in Fig. 3. **a** Map of the Mount Ellsworth intrusive center. Modified from Koch (1981) and Jackson and

Pollard (1988). **b** Map of the Mount Hillers intrusive center. Modified from Larson et al. (1985), Broda (2014), and Thornton (2015). **c** Map of the Mount Ellen intrusive center. Modified from Dubiel et al. (1985), Morton (postdated early sills), and Maurer (2015). UTM coordinates, zone 12, datum NAD83

preserved there. One important result of the faulting is the moderately asymmetric geometry of the laccolith roof. At the same elevation near

the top of the intrusive center, older strata (Permian) are exposed in the northwestern portion of the laccolith roof than in the southeastern portion

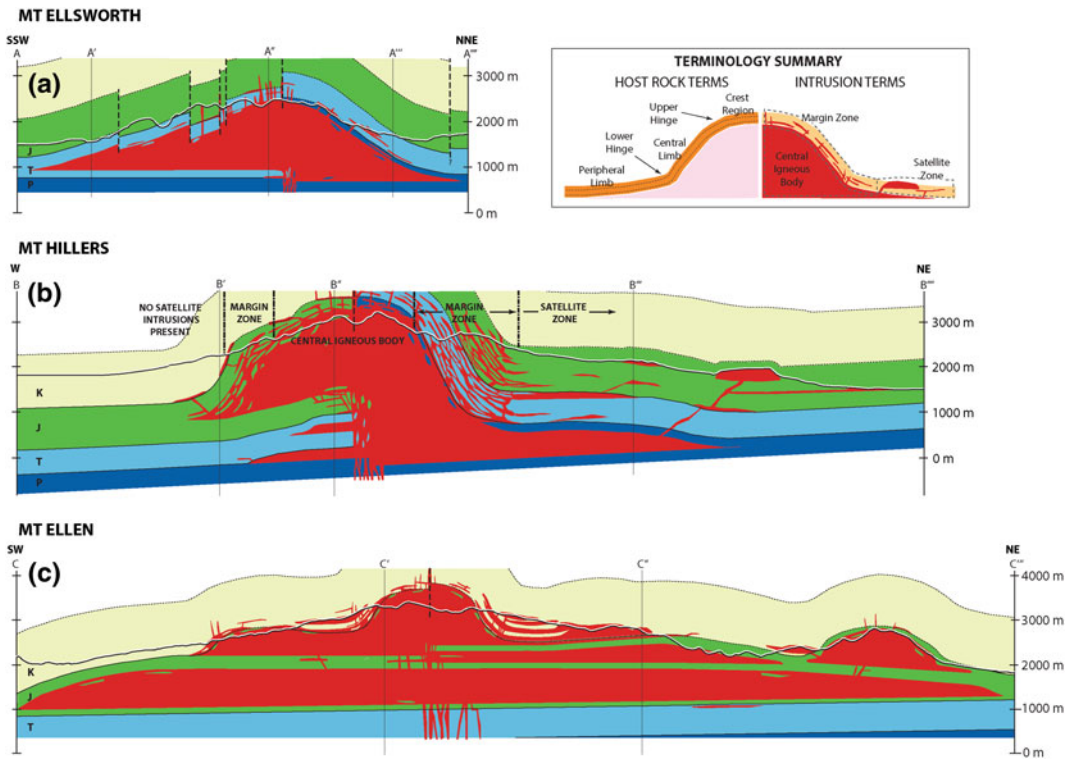


Fig. 3 Cross sections through selected Henry Mountains intrusive centers. Rock unit colors correlate with those in Fig. 2. *Thick black line* shows modern topography. Section line landmarks are indicated on both the cross sections here and maps in Fig. 2. The inset presents an outline of some basic terminology useful for description of host rock

deformation (*on the left*) and regions of a generic intrusive center (*on the right*). **a** Cross section through the Mount Ellsworth intrusive center, modified from Koch (1981). **b** Cross section through the Mount Hillers intrusive center, modified from Broda (2014). **c** Cross section through the Mount Ellen intrusive center, modified from Morton (1986)

(Triassic). These regions are separated by a fault zone (Koch 1981), and the largest component fault stretches for several kilometers in a NNE-SSW direction and has a maximum throw of over 500 m. One interpretation of these observations is that the base of the main laccolithic body is intruded at different stratigraphic levels in the northwestern and southeastern portions of the intrusive center (e.g. Fig. 3a).

In addition to the main NNE-SSW fault, several other faults offset the host rock stratigraphy of the roof with smaller amounts of throw. Vertical displacement on most faults, determined by offset of stratigraphy, increases toward the center of Mount Ellsworth. Many of the faults in strata of the laccolith roof are intruded by dikes. The greatest abundance of dikes is found near the

crest of the laccolith dome, where the maximum amount of extension is expected during inflation and growth (Pollard and Johnson 1973). Age relationships between faults and igneous bodies are complex, but generally suggest faulting postdated early sills and was contemporaneous with or older than most of the dikes (Koch 1981).

3.2 Mount Hillers

At the Mount Hillers intrusive center (Figs. 2b and 3b), stratigraphy is uplifted a maximum of approximately 2500 m, and deflection from the regional bedding orientation extends over an area with a diameter of approximately 12 km. The first-order map-view geometry of the dome is

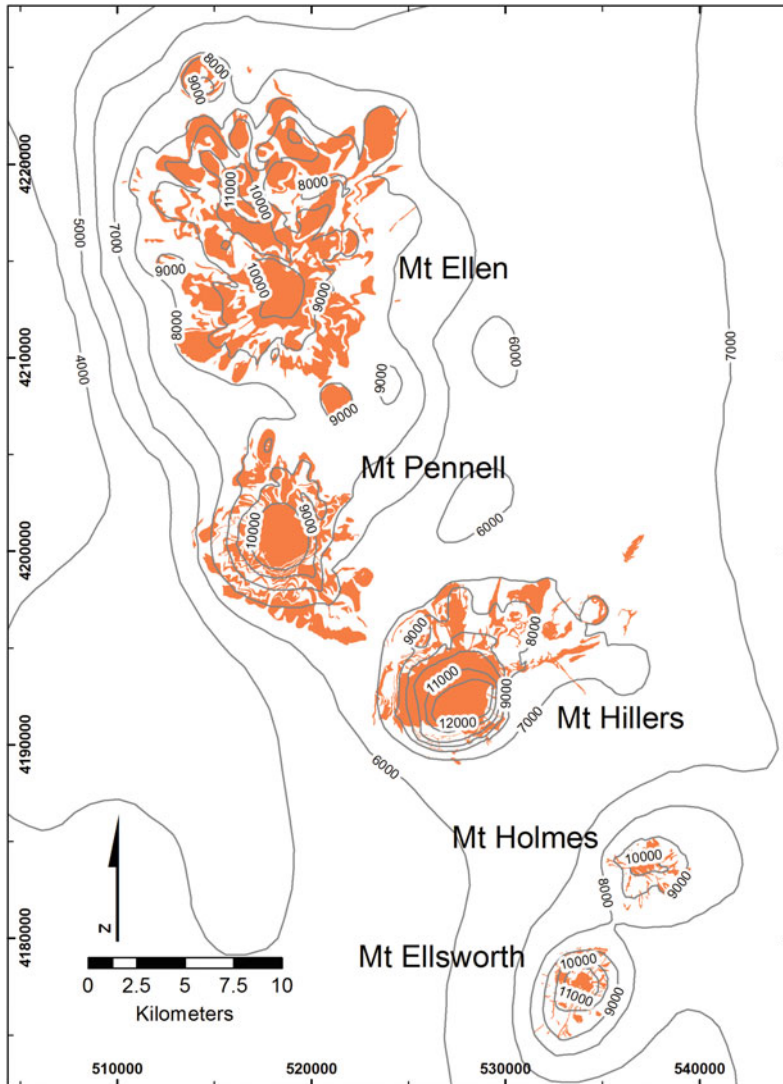


Fig. 4 Structure contour map for the Henry Mountains region. The patterns clearly show deflection of host rock from the regional shallow dip to the W due to intrusive centers. Contours are in 1000 foot intervals and are

drawn for the top of the Cretaceous Ferron sandstone member of the Blue Gate Shale. Contours simplified from Hunt et al. (1953). UTM coordinates, zone 12, datum NAD83

moderately asymmetric (Fig. 4), with elongation in a WSW-ENE direction. The maximum dip of host rock strata on the southeast side of the dome is generally steeper (maximum $\sim 90^\circ$ dip) than the northwest side (maximum $\sim 45^\circ$ dip). On the north and east sides of Mount Hillers, several smaller asymmetric domes are superimposed on the margins of the main dome. These smaller domes represent local deflection of stratigraphy

by intrusions radiating outward from the main laccolithic body. The total igneous volume of the Mount Hillers intrusive center is estimated at $\sim 35 \text{ km}^3$ (Broda 2014). Interpretation of U-Pb zircon geochronology data from 10 samples suggests assembly of the Mount Hillers intrusive center spanned no more than approximately 1 m.y., from $24.75 \pm 0.5 \text{ Ma}$ (Paquette et al. 2010).

Igneous rock is exposed over an area of $\sim 10 \text{ km}^2$ near the center of the Mount Hillers intrusive center. This igneous rock is interpreted to be part of the main laccolithic intrusion (Jackson and Pollard 1988; Broda 2014). The roof strata of the Mount Hillers laccolith are preserved locally at the crest of the dome, where they dip shallowly ($<20^\circ$). The geometry of the host rock strata implies the laccolith is asymmetric in cross section. On the SE side of the intrusive center, the upper contact of the main laccolithic body lies within the upper portion of Permian strata. On the NW side of the intrusive center, the upper contact of the main laccolithic body lies within Jurassic strata, approximately 1000 m higher in the stratigraphic section (Broda 2014). Assuming these strata record the stratigraphic level of the main laccolith, the intrusion must have a highly asymmetric base that is approximately 1000 m deeper in the crust on the southeast portion than the northwest portion of the intrusion. This geometry is different from the symmetrical interpretation favored by previous authors (cf. Gilbert 1877; Hunt et al. 1953; Jackson and Pollard 1988), but is based on considerably more detailed mapping.

Faulting of preserved host rock strata overlying the main laccolith dome is readily apparent in some locations. Most prominently, the distinct regions of the main Mount Hillers laccolith, with different strata preserved and bedding dips, are interpreted to be separated by a SW- to NE-striking subvertical tear fault (Broda 2014). Smaller faults, both radial and tangential, are apparent from local offset or repetition of stratigraphic units. The boundary zones between repeated or missing units are commonly filled with igneous rock, which presumably intruded along faults. The strata immediately overlying the crest of the laccolith dome are modestly metamorphosed (e.g. shale to slate, sandstone to quartzite), but individual sedimentary units are clearly recognizable.

The strata deflected from their regional orientation by the main structural dome of the Mount Hillers intrusive center are locally very well exposed. For example, on the south and east sides of the intrusive center, strata from Permian

to Cretaceous age dip consistently outward from the center of the dome and are intruded by a network of sills and dikes (Thornton 2015). The boundary is diffuse between this region of both sedimentary and igneous rock and the inner region of solely igneous rock, which is inferred to be the main laccolith body. Along a radial profile, the relative abundance of igneous rock increases toward the center of the structural dome, which corresponds to deeper levels in the outward-dipping stratigraphic section. However, an abrupt increase in the relative abundance of igneous rock occurs within Permian-age strata of the Cutler Formation. No host rock strata from deeper in the stratigraphic section are exposed, leading to the conclusion that this is the stratigraphic level of the main laccolith intrusion on the SE side of the tear fault that divides the intrusive center.

3.3 Mount Ellen

The Mount Ellen intrusive center (Figs. 2c and 3c) is the largest of the Henry Mountains in aerial extent and igneous rock volume. In general, the Mount Ellen intrusive center is more deeply eroded and somewhat less well exposed than the two centers already described. However, the basic geometries of component igneous bodies can be constrained, and exposure of both igneous and sedimentary rock is locally excellent. Stratigraphy is uplifted a maximum of approximately 2000 m over a region with a diameter of 15–20 km (Fig. 4). The dome is elongated in map view in a NW-SE direction, but numerous relatively small (usually $<3 \text{ km}$ across) bulges project radially outward from the main dome. The total igneous volume responsible for the doming is estimated at approximately 100 km^3 .

The oldest sedimentary rocks exposed within and deformed by the Mount Ellen intrusive center are sandstones of uppermost Triassic to lowermost Jurassic age, which are locally exposed near the outer perimeter of the structural dome. The deepest intrusions must therefore be within or below Triassic strata. Morton (1984, 1986) hypothesized that unexposed intrusions of

the Mount Ellen intrusive center emplaced relatively deep in the crust have generally sill-like shapes, while those emplaced into younger strata tend to have more convex roofs (e.g. Fig. 3c). Similar to the smaller intrusive centers, strata generally dip outward from the middle of the intrusive center, but local variation from this trend is common around relatively small component intrusive bodies. Exposures are generally insufficient to recognize faulting of sedimentary host rock like that observed at the Mount Ellsworth and Hillers intrusive centers. However, in the exposure area interpreted to be at the core of the main laccolithic dome (near location C' on Figs. 2c and 3c), the contact between igneous and sedimentary rock is locally discordant (Hunt et al. 1953) and a steeply dipping tear fault with a throw of 200 m or more is probably the simplest explanation. This geometric complexity suggests the central igneous intrusion is asymmetric in cross section and that emplacement was locally accommodated by faulting.

More generally, the geometry of the upper surface of igneous rock at the Mount Ellen intrusive center, as inferred from deflection of stratigraphy, is considerably more complicated than at any of the four smaller-volume intrusive centers of the Henry Mountains (Fig. 4). The NW- to SE-elongated central dome is surrounded in nearly all directions by numerous radiating tongue-shaped lobes, which in some cases extend outward several kilometers from the main dome. Deflection of stratigraphy suggests individual radiating intrusions have volumes ranging up to approximately 3 km³ (Copper Ridge laccolith—Maurer 2015). In some cases, these radiating intrusions are themselves assembled from multiple component magma pulses (Maurer 2015).

4 Discussion

The three Henry Mountains intrusive centers described here can be interpreted as snapshots in the progressive construction of an igneous system in the shallow crust through emplacement of multiple component pulses of magma. The total

igneous rock volume for each intrusive center (see Table 1) can therefore be used as a rough measure of the degree of development. The Mount Ellsworth intrusive center, with the smallest igneous rock volume of the three described in detail above, then represents a relatively early stage of development of a generalized igneous center. The Mount Hillers intrusive center represents an intermediate stage of development in which host rock has been uplifted and deformed considerably more, and additional lobes of magma began to intrude radially outward from the margin of the main laccolithic body. The Mount Ellen intrusive center records an advanced stage of development, with a relatively voluminous and geometrically complex central laccolithic body and radiating intrusions extending out in nearly all directions.

Previous authors working in the Henry Mountains also interpreted the intrusive centers to represent different stages along a progression of growth (Hunt et al. 1953; Jackson and Pollard 1988). However, earlier interpretations of first-order intrusion geometries differed from those favored here, in some cases considerably. Therefore, to provide context for the interpretations favored here, a brief review of previous authors' interpretations is presented here.

4.1 Earlier Interpretations of Intrusive Center Geometry and Development

The subsurface geometry of the intrusions in the Henry Mountains has been the subject of long-standing debate. The first-order laccolithic geometry of igneous intrusions in the Henry Mountains was initially proposed by Gilbert (1877), who coined the term “laccolite” based on his observations there. He hypothesized a two-stage laccolith emplacement process where an initial sill grew laterally until it reached a critical radius, where horizontal spreading ceased and the roof began to inflate, uplifting and rotating overlying host rock. The end result was an intrusion with a subhorizontal base and a dome-shaped roof (Fig. 5a).

Table 1 Characteristics of Henry Mountains intrusive centers

Intrusive center	Development stage	Approx. igneous volume (km ³)	Approx. diameter (km)	Max. vertical deflection (m)	Central limb, max. bedding dip	Satellite intrusions?
Mt Holmes	Early	18	9	~1200	~25°	No
Mt Ellsworth	Early	23	10	~1800	~55°	No
Mt Pennell	Intermediate	30	12	~2000	~80°	Yes, N and E sides
Mt Hillers	Intermediate	35	12	~2500	~90°	Yes, N and E sides
Mt Ellen	Advanced	100	20	~2000	~90°	Yes, all directions

In contrast to Gilbert's (1877) interpretation, the broad domal geometry of each intrusive center was hypothesized by Hunt et al. (1953) to be result of radial expansion of a highly discordant stock. In this emplacement model, a sub-vertical cylindrical stock intruded early in the history of each intrusive center and expanded radially, uplifting and bending the host strata into the domal pattern observed (Fig. 5b). The intrusive volume estimates provided in Hunt et al. (1953) rely on this concept of a central stock extending to considerable depth and are therefore inaccurate (Koch 1981).

One of the major observations used by Hunt et al. (1953) to prefer the stock model over Gilbert's (1877) original laccolith model is the locally discordant nature of the major contact between the main central igneous body and overlying host rock. To reach this conclusion, Hunt et al. (1953) relied on an idealized model of a laccolith that always remains concordant, with a smooth domed roof, despite acknowledging that some laccoliths are in fact asymmetric and discordant (see their Fig. 66). As described in detail above, the main laccolith bodies in the Henry Mountains are locally discordant, especially near the centermost region of the roof of each intrusive center, where radial and tangential faulting related to extension of the host rock is common. In each of the cases described here, different host rock units in the main laccolith roof

are juxtaposed across a fault zone. This geometry suggests the base the main laccolith body lies at different stratigraphic levels in different regions of the intrusive center (e.g. Fig. 3).

Another feature of each intrusive center original described by Hunt et al. (1953) is a so-called "shatter zone" generally located around the margin of the regions they mapped as stocks. This term should be abandoned, both because it unnecessarily implies a genesis process (fracturing) and because it misleadingly suggests the areas are chaotic. Careful mapping demonstrates that the region in question in each intrusive center is comprised of numerous igneous sheets and occasional intercalated sedimentary rock bodies, still in correct stratigraphic order (e.g. Ward 2014; Broda 2014). While igneous breccias and other evidence of fracturing during emplacement do exist, they are relatively rare and always localized. To avoid further confusion, we use descriptive terminology for intrusive center architecture rather than terms implying genetic processes for Henry Mountains intrusions.

The two models (laccolith vs. stock) for the first-order geometry of Henry Mountains intrusions were tested by Jackson and Pollard (1988, 1990). Detailed host rock mapping and structural analysis led to an interpretation more in agreement with the laccolith model of Gilbert (1877)—i.e. the five intrusive centers are largely concordant "floored" laccoliths and not stocks (Fig. 5c).

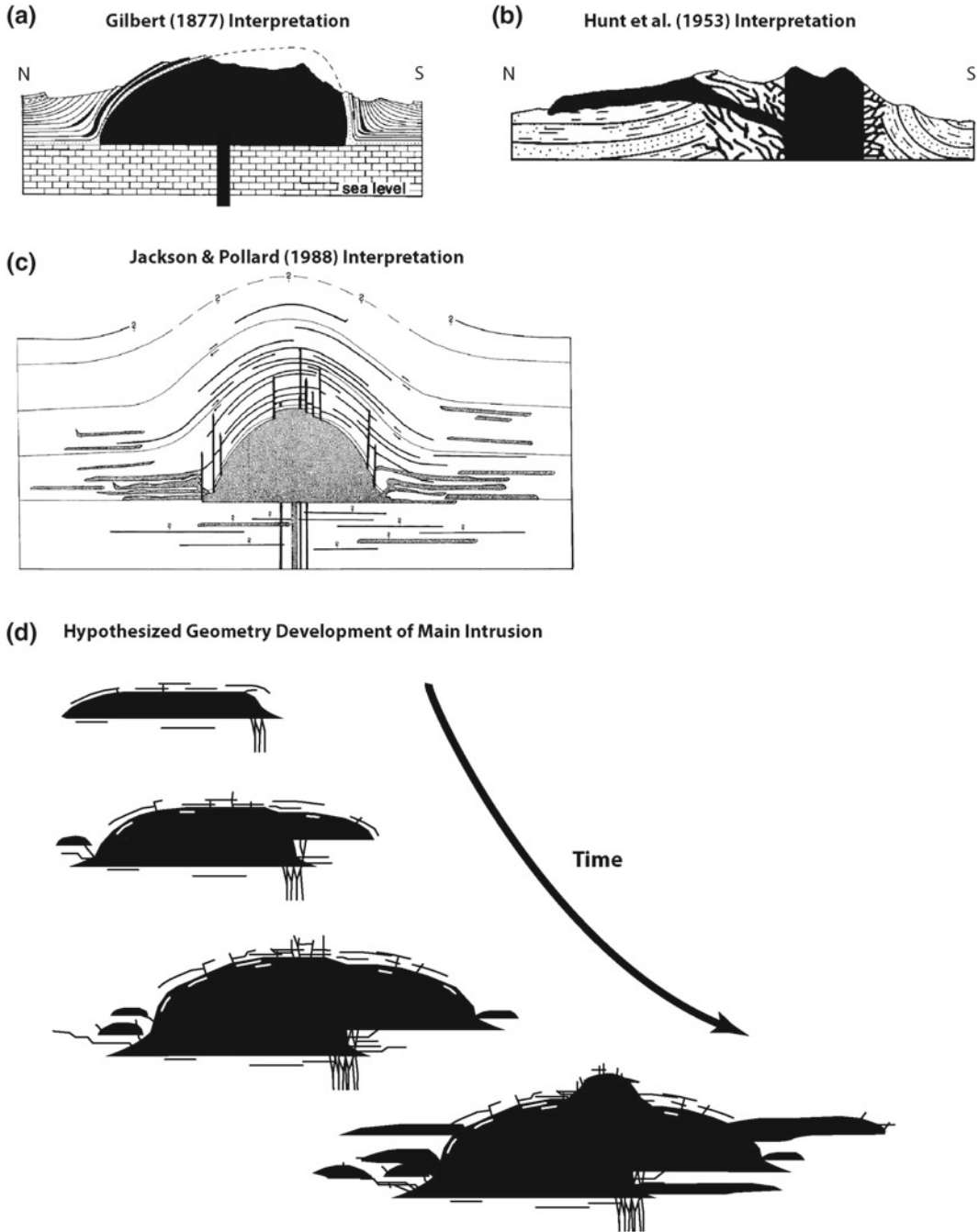


Fig. 5 Evolution of hypotheses about Henry Mountains intrusion center cross sectional geometry. **a** Idealized geometry of the Mount Hillers intrusive center, presumably along a general N to S profile. The main intrusion has classic laccolith shape with a planar concordant floor and a domed roof, and no satellite intrusions are shown. Modified from Gilbert (1877). **b** Schematic geometry of the Mount Hillers intrusive center along a general N to S profile. The main intrusion is a discordant stock surrounded by a “shatter zone,” and a prominent and

voluminous satellite intrusion extends laterally outward. Modified from Hunt et al. (1953). **c** Idealized geometry of a generic Henry Mountains intrusive center. The main intrusion has a classic laccolith shape, but it is surrounded by an extensive network of sills and dikes. Modified from Jackson and Pollard (1988). **d** Hypothesized evolution of cross sectional geometry of the main intrusive body and directly associated intrusions for a generic intrusive center in the shallow crust. Based on interpolation from geometries of Henry Mountains intrusive centers

One especially important observation from Jackson and Pollard (1988) was that radial expansion of a stock would result in buckling of strata in cross-sectional view, rather than the geometrically simpler bending pattern observed (see their Fig. 18). Jackson and Pollard (1988) also suggested, based on analysis of a limited suite of paleomagnetic data, that steeply dipping sills on the margins of the Mount Hillers intrusive center cooled while still sub-horizontal and were rotated by later underlying intrusions. Although earlier workers inferred that multiple injections of magma were responsible for assembly of each Henry Mountains intrusive center, this observation provided the first evidence of a protracted, pulsed emplacement history.

4.2 Generalized Architecture of an Intrusive Center

The general structure of a generic, fully developed Henry Mountains intrusive center can be divided into three regions (see inset on Fig. 3). However, as we describe below in the more detailed descriptions of these regions, not all of the intrusive centers reached a state of development in which all three regions are developed (Table 1). The most voluminous part of an intrusive center is the *central laccolithic body* (generally analogous to the area mapped as “stock” by Hunt et al. 1953), which has an overall domal, laccolithic geometry. Surrounding the central intrusion is a *margin zone* of host rock intruded by a complex network of sills, dikes, and other relatively small igneous bodies. Around the margin of the intrusive center is a *satellite zone*, including relatively small sills, laccoliths and other bodies generally intruded into shallowly dipping host rock. The satellite intrusions are fed from the central intrusion, but are not always physically connected to it at the surface. Mount Hillers includes well-developed and well-exposed examples of all three component zones (e.g. Fig. 3b). The other two large intrusive centers, Mounts Ellen and Pennell, also include examples of all three component zones.

The two smaller centers, Mounts Holmes and Ellsworth, are preserved at an earlier stage of development and do not include any significant satellite intrusions.

4.3 Central Laccolithic Body

The central laccolithic body in each intrusive center in the Henry Mountains generally has a bell-shaped upper surface in cross section. This geometry can be seen most clearly by studying deflection of host rock strata (see inset on Fig. 3). Along a radial profile from the outside of the dome toward the inside, the geometry of the host rock overlying a laccolithic intrusion typically includes a shallowly dipping *peripheral limb*, a more steeply dipping *central limb*, and a relatively shallow-dipping crest region atop the laccolith (Jackson and Pollard 1988, 1990). These three regions are typically separated by two hinges: a *lower hinge* between the peripheral and central limbs, and an *upper hinge* between the central limb and the *crest region*. In the host rock overlying the main laccolith body, curvature is higher and fracturing more intense in these hinge regions than in the adjacent limbs (Jackson and Pollard 1990). Minor faulting is observed throughout the deformed host rock, but faulting is especially well-developed in the crest region. There, faults juxtapose host rock of different stratigraphic level and are commonly intruded by dikes. Roof faulting appears to be an important process in laccolith dome growth, and faulting has long been recognized as an important mechanism for accommodation of magma emplacement (e.g. Grocott et al. 2009; Kloppeberg et al. 2010). As first noted by Gilbert (1877), roof faulting is required to accommodate the extension of strata above a growing laccolith (e.g. Pollard and Johnson 1973).

The lower surface of the central laccolithic body is never exposed in the Henry Mountains. However, constraints on the general geometry of this surface are available from two independent data sets. The lower surface of each central laccolithic body appears to be largely concordant

with sub-horizontal host rock strata based on interpretation of aeromagnetic data (e.g. Jackson and Pollard 1988). In more detail, however, careful mapping and structural analysis of preserved host rock strata (e.g. Broda 2014) suggest the base of each main laccolithic body is stepped. The inferred height of the floor step follows from the stratigraphic separation between sedimentary units juxtaposed in the laccolith roof. For the three intrusive centers described in detail here, this inferred floor step height ranges from ~ 200 m at Mount Ellen (on Fig. 3c, Jurassic and Cretaceous strata are juxtaposed in the roof) to ~ 500 m at Mount Ellsworth (on Fig. 3a, Permian and Triassic strata are juxtaposed) and ~ 1000 m at Mount Hillers (on Fig. 3b, Permian and Jurassic strata are juxtaposed).

Each central laccolithic body is comprised almost exclusively of igneous rock. The only exposed sedimentary material is generally metamorphosed xenoliths up to a few centimeters in size, and these are rare. The texture of the igneous rock sometimes changes dramatically over spatial distances of just a few meters (Broda 2014), with distinct differences in phenocryst abundance, mean phenocryst size, and ground-mass grain size. In some cases these changes are gradual but in most instances a clear contact exists. Cross-cutting relationships between distinct textures are usually complex, but in some cases consistent relative ages of two different textures can be inferred (e.g. Ward 2014). The variation in textures within each central laccolithic body suggests it was assembled from the emplacement of separate magma pulses (e.g. Pownall et al. 2012), with sufficient time in some cases between injections for earlier pulses to cool enough that magma mingling is minimal or non-existent.

4.4 Margin Zone

The margin zone of each intrusive center includes a complex, but not chaotic, intermingling of igneous rock and sedimentary host rock. Blocks of isolated sedimentary rock are almost always found in the correct stratigraphic order

when moving from the margin to the core of each intrusive center. Similar isolated blocks or “rafts” of sedimentary strata were identified in 3-d well data from laccoliths of the Halle Volcanic Complex in Germany by Schmiedel et al. (2015). The 3-d well data allowed these authors to recognize that many of the sedimentary rock rafts are prolate in geometry and up to 1400 m long and 500 m thick. No clear pattern of raft size or geometry is immediately apparent in the Henry Mountains.

The transition between the margin zone and the central laccolithic body is gradual. Toward the core of the intrusive center exposures of sedimentary host rock become progressively less abundant relative to igneous rock. The exceptional exposure of the host rock strata overlying the crest of the main laccolithic body at Mount Ellsworth suggests that sills and dikes of the margin zone are developed over essentially the entire bell-shaped upper surface of the laccolith dome. Similar exposures at the Mount Holmes intrusive center are consistent with this observation (unpublished mapping by Murdoch 1984; Jackson and Pollard 1988).

Taken together, these data suggest that the dip of sedimentary strata and sills in the margin zone varies both in space and time. At a given stage in the development (e.g. as observed at a single intrusive center in the Henry Mountains) the dip profile along a radial section is bell-shaped, with a shallow dip on the peripheral limb, a steeper dip on the central limb, and once again a shallow dip over the crest of the laccolith dome. Comparing dip profiles between different time steps (preserved at different intrusive centers), the dip of the central limb appears to increase along with the igneous volume of the central laccolithic body. The dip within the peripheral limb and crest region appears to remain relatively shallow throughout the growth of the dome.

Evidence of any appreciable amount of host rock metamorphism is absent throughout most of the margin zone. This situation changes considerably in close proximity to the central laccolithic body. Typically, within the 100–200 m of stratigraphic section immediately above the exposed outer margin of the main laccolithic

body, the degree of host rock metamorphism increases substantially. In this region shale has been metamorphosed to slate and sandstone to quartzite. An excellent example of this concentrated zone of metamorphism is preserved on the south side of Mount Hillers (Thornton 2015), where Permian-age strata form the roof of the main laccolithic body. There sedimentary host rock within the ~100–200 m of strata structurally overlying the intrusion has undergone considerable metamorphism. The transition to relatively unmetamorphosed sedimentary rock is narrow but gradual; farther from the main intrusion host rock shows little or no field evidence of metamorphism.

Large portions of the margin zone were generally included in the so-called “shatter zone” of Hunt et al. (1953). The outer edge of each shatter zone mapped by Hunt et al. (1953) was drawn at the base of an arbitrarily chosen sedimentary unit (e.g. the Triassic Chinle formation on Mount Hillers, Hunt et al. 1953). More detailed mapping (e.g. Gwyn 2011; Ward 2014; Broda 2014) reveals a clearer general architecture that in turn provides better constraints on the construction history.

4.5 Satellite Zone

The satellite zone lies outside the margin zone and, where present, typically includes a series of isolated, relatively small-volume intrusions (generally $<3 \text{ km}^3$) distributed outside the edge of the main laccolith dome. These intrusions lie within shallowly dipping ($<20^\circ$) host rock strata of the peripheral limb, usually within the 2–3 km immediately outside the lower hinge region. The Trachyte Mesa intrusion (Morgan et al. 2008; Wetmore et al. 2009) of the Mount Hillers intrusive center is a notable exception, being located ~10 km from the nearest exposures of intrusions in the main laccolithic body or margin zone.

The satellite zone is not developed at the two smallest volume Henry Mountains intrusive centers, Mounts Holmes and Ellsworth. These two main laccolithic domes are relatively smooth and do not show evidence either at the surface or at

depth of smaller, second-order intrusions around their margins (Fig. 4). Perhaps the emplacement of satellite intrusions proceeds only when the main laccolithic dome has grown enough that further bending and uplift of host rock to accommodate emplacement of new magma becomes mechanically unfavorable compared to injection around the heavily fractured lower hinge region. This general spatial and temporal pattern was observed by Henry et al. (1997) in the Solitario lacco-caldera of the Trans-Pecos region. There emplacement of satellite intrusions occurred during the final stage in the episodic magmatic history of the intrusive center and was localized in the vicinity of the ring fault bounding an earlier caldera.

The satellite zone does exist at the two intermediate-stage intrusive centers, Mounts Hillers and Pennell. There the first-order laccolithic domes each have superposed on them a few second-order tongue-shape bodies protruding radially outward (Fig. 4). Some of these bodies have inflated enough to dome overlying strata. In these cases strata along the distal margin dip away from the intrusive center and strata above the proximal margin commonly dip back toward the intrusive center (Hunt et al. 1953). In a few cases, these bodies have inflated enough to develop in to bysmaliths, which lift overlying host rock in a piston-like manner (e.g. Saint Blanquat et al. 2006). Many of the tongue-shaped bodies can be directly connected with the larger main laccolithic body, and are clearly fed laterally. A similar overall lobate geometry was inferred for the Trawenagh Bay Granite (Stevenson et al. 2007). Lobate growth has also been observed in analog models of laccolith emplacement (Currier and Marsh 2015).

The progressive growth of satellite intrusions on Mount Hillers was studied in detail by Horsman et al. (2010). Exceptional 3-d exposure of the satellite intrusions there allowed development of a general construction history through detailed analysis of bodies with different geometries. The intrusion shapes are interpreted as snapshots of the progressive development of an initially tabular igneous body in the shallow crust. In the earliest stage of development, intrusions initiate as sills with complex, lobate,

map-view geometries (Horsman et al. 2005). Many of these relatively small intrusions are constructed from multiple magma pulses intruded as component sills. The initial pulse closely controls the geometry of subsequently pulses due to introduction of strong mechanical anisotropy. Magma flow patterns are closely related to details of intrusion geometry and radial or fanning patterns are common. In the next stage of evolution, a laccolith shape develops as additional magma sheets are emplaced (Morgan et al. 2008; Wetmore et al. 2009). Sheet boundaries can be recognized near fast-cooling intrusion margins but become more cryptic in the slower cooling center of the body. Magma flow patterns commonly include a central conduit that feeds flow toward the laterally growing margins of the intrusion. In the final stage, as still more magma intrudes, the body becomes over-inflated and may develop into a bysmalith by lifting overlying host rock in a piston-like manner along a cylindrical fault (e.g. Saint Blanquat et al. 2006). Magma flow patterns become simpler and more consistent as intrusion geometry stabilizes, with a central conduit again feeding magma to intrusion margins. The work of Maurer (2015) largely supports this general model.

4.6 Stocks or Laccoliths?

The new detailed mapping of the Henry Mountains discussed here suggests the first-order geometry of the central laccolithic body in each of the five intrusive centers is neither a fully discordant stock, as proposed by Hunt et al. (1953), nor an idealized concordant and axisymmetric laccolith, as proposed by Pollard and Johnson (1973) and Jackson and Pollard (1988). Instead, each intrusive center is cored by a main laccolithic body with a slightly to moderately asymmetric cross sectional geometry. Clear evidence of the cross-sectional asymmetry of each intrusive center is given by the different stratigraphic units juxtaposed near the crest of the main laccolithic body. This crest region is where radial and tangential faulting would be

concentrated during doming of overburden (e.g. Jackson and Pollard 1990). These faults were apparently exploited as preferential magma migration pathways, leading to a concentration of dikes and other more discordant bodies near the crest of each intrusive center.

Localization of faulting and dike intrusion near the crest of each main laccolith likely occurred throughout a considerable portion of the assembly history. Consequently, breccias incorporating both sedimentary and igneous clasts, as well as other evidence of brittle fracture processes, are concentrated near the core of each intrusive center. These observations led Hunt et al. (1953) to interpret the presence of a “shatter zone” near the core of most of the intrusive centers, which they attributed to radial expansion of the hypothesized central stock. These regions, however, are better interpreted as areas of concentrated, repeated magma intrusion and local faulting during progressive growth of the first-order laccolith dome.

4.7 Progressive Growth of Intrusive Centers

The synthesis of observations presented here allows an interpretation of the geometric development of a generalized Henry Mountains intrusive center during its progressive growth. Two essential aspects of the assembly process in the Henry Mountains were recognized by previous workers. First, each intrusive center was assembled from numerous sequentially emplaced component intrusions, or magma pulses (Hunt et al. 1953; Hunt 1988). Second, early sub-horizontal sills were rotated upward by later, underlying intrusions to create the observed large and complex, but broadly laccolithic, shapes (Jackson and Pollard 1988).

The three intrusive centers described in detail here can be interpreted to represent snapshots of distinct stages in the progressive assembly of a laccolithic igneous system in the shallow crust. The Mount Ellsworth intrusive center represents a relatively early stage of development, after initial uplift and rotation of the overburden host strata has

started. The upper surface of the main laccolithic body has a bell-shaped geometry in cross section, but the amplitude of uplift is relatively small compared to the area over which strata are deflected. The juxtaposition of different sedimentary units at the same elevation at the crest of the laccolith dome suggests portions of the main intrusion have different thicknesses. This thickness variation is likely due to the base of the laccolith having intruded at different stratigraphic levels in the distinct portions of the body.

A well-developed margin zone exists at the Mount Ellsworth intrusive center, with a network of sills dipping away in all directions from the middle of the intrusive center. Dikes near the summit of Mount Ellsworth clearly cross cut earlier altered porphyry bodies, suggesting dike ascent in that region persisted until relatively late in the laccolith growth history. No dikes or satellite intrusions are exposed on the periphery of Mount Ellsworth and none in the subsurface are apparent from deflection of overlying host rock strata (Fig. 4). No evidence of intrusions of any geometry exists above the well-preserved outer hinge of the main laccolith dome, where most satellite intrusions on other intrusive centers seem to emerge from the central igneous body. This suggests that at this stage of laccolith dome development it is still more mechanically favorable to accommodate additional magma through further uplift of the main roof than through ascent in the fracture networks in the lower hinge region (e.g. Jackson and Pollard 1990).

The Mount Hillers intrusive center represents an intermediate stage of development. The central laccolithic body there is clearly comprised of multiple magma pulses with distinct, cross-cutting textures (Broda 2014). Each significant pulse was probably a few cubic kilometers in volume. The upper surface of the main laccolith is bell-shaped, but has a larger ratio of amplitude to width than the less mature Mount Ellsworth intrusive center. Sedimentary strata from different stratigraphic levels are juxtaposed at the crest of the main laccolith across a fault zone, again suggesting the presence of topography on the base of the intrusion. A well-developed margin zone surrounds the entire intrusive center. Satellite intrusions are

present around the NE half of the intrusive center, but are essentially absent on the SW side. The volume of these satellite intrusions can be as large as $\sim 1.5\text{--}2\text{ km}^3$, although many are considerably smaller.

The Mount Ellen intrusive center represents the most advanced stage of development present in the Henry Mountains. The overall geometry of the main laccolith dome is generally similar to the intermediate stage of development preserved at Mount Hillers, although at Mount Ellen the crest of the dome is elongated in a NW-SE direction, instead of being nearly axisymmetric. The satellite zone, however, is very different from the less developed intrusive centers, with many more intrusions and a much larger areal extent and total igneous rock volume. Satellite intrusions extend out in all directions from the central intrusive body at Mount Ellen (cf. Currier and Marsh 2015), whereas at Mount Hillers they are restricted in radial direction. The satellite zone at Mount Ellen is so much more advanced in development that it somewhat obscures the geometry of the central laccolithic body. Magma feeding the most distal satellite intrusions, if fed primarily from the central laccolithic body, must have travelled laterally several kilometers (e.g. Magee et al. 2012). In cross section, the Mount Ellen intrusive center is quite similar to the geometry of the Elba Island laccolith complex (e.g. Rocchi et al. 2010).

The duration of assembly of the Henry Mountains intrusive centers is not yet well constrained by geochronology. However, a limited dataset suggests the Mount Hillers intrusive center was assembled over approximately 1 m.y. (Paquette et al. 2010). The Christmas-tree-shaped laccolith complex on Elba Island, Italy was assembled in stages over a similar period of time (Rocchi et al. 2010). The laccolith-caldera system of the Solitario in the Trans-Pecos region was also assembled in stages over approximately 1 m.y. (Henry et al. 1997). The magma fluxes implied by the total volumes of these intrusions and the duration of assembly agree well with typical fluxes estimated for magma emplacement in continental crust in a wide variety of tectonic settings (Saint Blanquat et al. 2011).

5 Conclusions

The Henry Mountains of southern Utah provide an opportunity to study in detail the development of magmatic systems in the shallow crust driven solely by magmatic processes. The complications commonly associated with syn-tectonic magma emplacement are absent. The region can therefore serve as a relatively simple, end-member example of magma emplacement processes in the shallow upper crust.

Each of the five separate intrusive centers in the Henry Mountains preserves a different stage of the evolution of an igneous system constructed in the shallow crust. Each intrusive center is comprised of numerous small intrusive bodies surrounding a central laccolithic body assembled from several magma pulses. Collectively, the five intrusive centers provide a series of snapshots of the progressive growth of an igneous system in the shallow crust. A compilation of data from these intrusive centers allows development of a generalized model for progressive construction of a magmatic system in the shallow crust. This model involves three main stages. First, an early network of dikes and sills is intruded. Second, a relatively voluminous laccolithic central igneous body begins to form. The central laccolith may initiate though inflation of a sill that grew to a radius sufficient to lift the overburden, as hypothesized in traditional growth models. However, field evidence suggests progressive laccolith growth in the Henry Mountains involved numerous rapidly emplaced magma pulses separated by periods of no appreciable activity. In the final stage, satellite intrusions, many with a tongue-like geometry, are emplaced radially outward from the margin of the main laccolith, initiating in the lower hinge region where bending and fracturing of overburden is relatively intense. As additional magma is emplaced into an advanced-stage intrusive center, the satellite zone expands laterally and perhaps vertically while the geometry of the main laccolithic body remains essentially unchanged.

One important question raised by this work is whether or not theoretical models of laccolith

initiation and growth are applicable to these intrusive centers. In particular, the intrusive centers in the Henry Mountains and elsewhere appear to have been assembled from multiple discrete pulses of magma, many of which may not have been liquid at the same time. This observation calls into question the applicability of theoretical models of laccolith growth that presuppose the entire intrusion remains in a liquid state throughout the entire history (e.g. Pollard and Johnson 1973; Bungler and Cruden 2011). Interestingly, the geometric predictions of the models (e.g. bell-shaped upper laccolith surface) generally agree well with observations in the Henry Mountains, despite the apparent disconnect between the inferred step-wise assembly of the intrusions and the single-magma-body assumption of the models.

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References

- Armstrong RL, Ward P (1991) Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: the temporal and spatial association of magmatism and metamorphic core complexes. *J Geophys Res Solid Earth* 96:13201–13224
- Barbey P (2009) Layering and schlieren in granitoids: a record of interactions between magma emplacement, crystallization and deformation in growing plutons. *Geol Belg* 12:109–133
- Bartley JM, Coleman DS, Glazner AF (2008) Incremental pluton emplacement by magmatic crack-seal. *Trans R Soc Edinb Earth Sci* 97:383–396
- Battaglia M, Troise C, Obrizzo F, Pingue F, De Natale G (2006) Evidence for fluid migration as the source of deformation at Campi Flegrei caldera (Italy). *Geophys Res Lett* 33(1)
- Broda RJ (2014) Geometry and progressive development of a shallow crustal intrusive complex, Mount Hillers,

- Henry Mountains, Utah. Unpublished M.S. thesis, East Carolina University, p 100
- Bunger AP, Cruden AR (2011) Modeling the growth of laccoliths and large mafic sills: role of magma body forces. *J Geophys Res: Solid Earth* 116(B2)
- Coleman DS, Gray W, Glazner AF (2004) Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. *Geology* 32:433–436
- Condie KC (1964) Crystallization pO₂ of syenite porphyry from Navajo Mountain, southern Utah. *Geol Soc Am Bull* 75:359–362
- Cruden AR, McCaffrey KJW (2001) Growth of plutons by floor subsidence: implications for rates of emplacement, intrusion spacing and melt extraction mechanisms. *Phys Chem Earth* 26(4–5):303–315
- Currier RM, Marsh BD (2015) Mapping real time growth of experimental laccoliths: The effect of solidification on the mechanics of magmatic intrusion. *J Volcanol Geoth Res* 302:211–224
- Curtis GH (1968) The stratigraphy of the ejecta from the 1912 eruption of Mount Katmai and Novarupta, Alaska. *Geol Soc Am Mem* 116:153–210
- de Silva SL, Gosnold WD (2007) Episodic construction of batholiths: insights from the spatiotemporal development of an ignimbrite flare-up. *J Volcanol Geoth Res* 167:320–335
- Doelling HH (1975) Geology and mineral resources of Garfield County, Utah. *Utah Geol Min Surv Bull* 107:175
- Dubiel RF, Bromfield CS, Church SE, Kemp WM, Larson MJ, Peterson F, Gese DD (1985) Mineral resource potential map of the Mt. Ellen-Blue Hills Wilderness Study Area and Bull Mountain Study Area, Garfield and Wayne counties, Utah. USGS Miscellaneous Field Studies map, MF-1756A
- Dvorak JJ, Dzurisin D (1997) Volcano geodesy: the search for magma reservoirs and the formation of eruptive vents. *Rev Geophys* 35:343–384
- Dzurisin D (2003) A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle. *Rev Geophys.* doi:[10.1029/2001RG000107](https://doi.org/10.1029/2001RG000107)
- Dzurisin D, Lisowski M, Wicks CW, Poland MP, Endo ET (2006) Geodetic observations and modeling of magmatic inflation at the Three Sisters volcanic center, central Oregon Cascade Range, USA. *J Volcanol Geoth Res* 150:35–54
- Elliott DH, Fleming TH, Kyle PR, Foland KA (1999) Long distance transport of magmas in the Jurassic Ferrar large igneous province, Antarctica. *Earth Planet Sci Lett* 167:89–104
- Froger J-L, Remy D, Bonvalot S, Legrand D (2006) Dynamic of long term multi-scale inflations at Lastarria-Cordon del Azufre volcanic complex, central Andes, revealed from ASAR-ENVISAT interferometric data. *Earth Planet Sci Lett.* doi:[10.1016/j.eps.2006.12.012](https://doi.org/10.1016/j.eps.2006.12.012)
- Gilbert GK (1877) Report on the geology of the Henry Mountains. U.S. Geographical and Geological Survey, Rocky Mountains Region, p 160
- Glazner AF, Bartley JM, Coleman DS, Gray W, Taylor ZT (2004) Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today* 14:4–11
- Grocott J, Arévalo C, Welkner D, Cruden A (2009) Fault-assisted vertical pluton growth: Coastal Cordillera, north Chilean Andes. *J Geol Soc* 166:295–301
- Gwyn N (2011) Progressive assembly of complex intrusions in the shallow crust, Henry Mountains, Utah. Unpublished M.S. thesis, East Carolina University, p 100
- Hamilton WB, Myers WB (1967) The nature of batholiths. U.S. Geological Survey Professional Paper 554-C, p 30
- Hansen DM, Cartwright J (2006) The three-dimensional geometry and growth of forced folds above saucer-shaped igneous sills. *J Struct Geol* 28:1520–1535
- Hardee HC (1982) Incipient magma chamber formation as a result of repetitive intrusions. *Bull Volcanol* 45 (1):41–49
- Henry CD, Kunk MJ, Muehlberger WR, McIntosh WC (1997) Igneous evolution of a complex laccolith-caldera, the Solitario, Trans-Pecos Texas: Implications for calderas and subjacent plutons. *Geol Soc Am Bull* 109(8):1036–1054
- Horsman E, Morgan S, Saint-Blanquat (de) M, Habert G, Hunter RS, Nugent R, Tikoff B (2010) Emplacement and assembly of shallow plutons through multiple magma pulses, Henry Mountains, Utah. In: Clemens JD (ed) 6th Hutton Symposium on the Origin of Granite and Related Rocks, Geological Society of America Special Paper 472, p 117–132
- Horsman E, Tikoff B, Morgan SS (2005) Emplacement-related fabric and multiple sheets in the Maiden Creek sill, Henry Mountains, Utah. *J Struct Geol* 26:1426–1444
- Hunt GL (1988) Petrology of the Mt Pennell central stock, Henry Mountains, Utah. *Brigham Young Univ Geol Stud* 35:81–100
- Hunt CB, Waters AC (1958) Structural and igneous geology of the La Sal Mountains, Utah. U.S. Geological Survey Professional Paper, n. 294i, p 85
- Hunt CB, Averitt P, Miller RL (1953) Geology and geography of the Henry mountains region, Utah. USGS Professional Paper 228, p 234
- Hunt CB, Jackson MD, Pollard DD (1988) The laccolith-stock controversy: new results from the southern Henry Mountains, Utah: discussion and reply. *Geol Soc Am Bull* 100:1657–1659
- Jackson MD, Pollard DD (1988) The laccolith-stock controversy: new results from the southern Henry Mountains, Utah. *Geol Soc Am Bull* 100:117–139
- Jackson MD, Pollard DD (1990) Flexure and faulting of sedimentary host rocks during growth of igneous domes, Henry Mountains, Utah. *J Struct Geol* 12:185–206

- Kloppenburg A, Grocott J, Hutchinson D (2010) Structural setting and synplutonic fault kinematics of a Cordilleran Cu-Au-Mo porphyry mineralization system, Bingham Mining District, Utah. *Econ Geol* 105:743–761
- Koch FG (1981) The structure of the Mount Ellsworth intrusion, Henry Mountains, Utah. Unpublished M.S. thesis, Stanford University, p 132
- Larson MJ, Bromfield CS, Dubiel RF, Patterson CG, Peterson F (1985) Geologic map of the Little Rockies Wilderness Study Area and the Mt Hillers and Mt Pennell Study Areas and vicinity, Garfield County, Utah. USGS Miscellaneous Field Studies map, MF-1776B
- Lipman PW (2007) Incremental assembly and prolonged consolidation of Cordilleran magma chambers: evidence from the Southern Rocky Mountain volcanic field. *Geosphere* 3(1):42–70
- Lu Z, Wicks CW Jr, Dzurisin D, Power JA, Moran SC, Thatcher WR (2002) Magmatic inflation at a dormant stratovolcano: 1996–1998 activity at Mount Peulik Volcano, Alaska, revealed by satellite radar interferometry. *J Geophys Res* 107. doi:10.1029/2001JB000471
- Lu Z, Masterlark T, Dzurisin D (2005) Interferometric synthetic aperture radar study of Okmok Volcano, Alaska, 1992–2003: magma supply dynamics and post-emplacement lava flow deformation. *J Geophys Res* 110:8–10
- Lundgren P, Lu Z (2006) Inflation model of Uzon caldera, Kamchatka, constrained by satellite radar interferometry observations. *Geophys Res Lett* 33. doi:10.1029/2005GL025181
- Magee C, Stevenson CT, O'Driscoll B, Petronis MS (2012) Local and regional controls on the lateral emplacement of the Ben Hiatt Dolerite intrusion, Ardnamurchan (NW Scotland). *J Struct Geol* 39:66–82
- Masterlark T, Lu Z (2004) Transient volcano deformation sources imaged with interferometric synthetic aperture radar: application to Seguam Island, Alaska. *J Geophys Res* 109:B01401. doi:10.1029/2003JB002568
- Matzel JEP, Bowring SA, Miller RB (2006) Time scales of pluton construction at differing crustal levels: examples from the Mount Stuart and Tenpeak intrusions, North Cascades, Washington. *Geol Soc Am Bull* 118(11/12):1412–1430
- Maurer E (2015) Geometry and construction history of the Copper Ridge laccolith, Mount Ellen, Henry Mountains, Utah. Unpublished M.S. thesis, East Carolina University, p 104
- McCaffrey KJW, Petford N (1997) Are granitic intrusions scale invariant? *Geol Soc (Lond) J* 154:1–4
- Michel J, Baumgartner L, Pultitz B, Schaltegger U, Ovtcharova M (2008) Incremental growth of the Patagonian Torres del Paine laccolith over 90 k.y. *Geology* 36:459–462
- Miller JS, Matzel JEP, Miller CF, Burgess S, Miller RB (2007) Zircon growth and recycling during the assembly of large, composite arc plutons. *J Volcanol Geoth Res* 167:282–299
- Morgan S, Stanik A, Horsman E, Tikoff B, Saint-Blanquat (de) M, Habert G (2008) Emplacement of multiple magma sheets and wall rock deformation: Trachyte Mesa intrusion, Henry Mountains, Utah. *J Struct Geol* 30(4):491–512
- Morton LB (1984) Geology of the Mount Ellen quadrangle, Henry Mountains, Garfield County, Utah. *Brigham Young Univ Geol Stud* 331:67–95
- Morton LB (1986) Provisional geologic and coal resources map for the Mt. Ellen quadrangle, Henry Mountains, Garfield County, Utah. Utah Geological and Mineral Survey Map 90, 15 p., 3 pl., scale 1:24,000
- Nelson ST, Davidson JP (1993) Interaction between Mantle-Derived Magmas and Mafic Crust, Henry Mountains, Utah. *J Geophys Res* 98:1837–1852
- Nelson ST, Davidson JP, Sullivan KR (1992) New age determinations of central Colorado Plateau laccoliths, Utah: recognizing disturbed K-Ar systematics and re-evaluating tectonomagmatic relationships. *Geol Soc Am Bull* 104:1547–1560
- Nishi K, Ono H, Mori H (1999) Global positioning system measurements of ground deformation caused by magma intrusion and lava discharge: the 1990–1995 eruption at Unzendake volcano, Kyushu, Japan. *J Volcanol Geoth Res* 89:23–34
- Nishimura T, Miyazaki S-I, Sagiya T, Tada T, Miura S, Tanaka K, Hirasawa T (2001) Spatio-temporal distribution of interplate coupling: east off northeastern Japan deduced from GPS observation. *Geophys J* 36:254–256
- Paquette JL, Saint-Blanquat (de) M, Delpech G, Horsman E, Morgan S (2010) LA-ICPMS U-Pb zircon dating of Mount Hillers laccolith and satellite intrusions: short-length emplacement and large Proterozoic inheritance. LASI 4 conference: Physical geology of subvolcanic systems: laccoliths, sills, and dykes
- Paterson SR, Fowler TK, Schmidt KL, Yoshinobu AS, Yuan ES, Miller RB (1998) Interpreting magmatic fabric patterns in plutons. *Lithos* 44:53–82
- Peterson F, Ryder RT, Law BE (1980) Stratigraphy, sedimentology, and regional relationships of the Cretaceous System in the Henry Mountains region, Utah. In Picard MD (ed) *Henry Mountains Symposium: Utah Geological Association Guidebook*, p 151–170
- Petford N, Cruden AR, McCaffrey KJW, Vigneresse JL (2000) Granite magma formation, transport and emplacement in the Earth's crust. *Nature* 408:669–673
- Pitcher WS, Berger AR (1972) The geology of Donegal: a study of granite emplacement and unroofing. Wiley
- Pollard DD, Johnson AM (1973) Mechanics of growth of some laccolith intrusions in the Henry Mountains, Utah, II: bending and failure of overburden layers and sill formation. *Tectonophysics* 18:311–354
- Pownall JM, Waters DJ, Searle MP, Shail RK, Robb LJ (2012) Shallow laccolithic emplacement of the Land's End and Tregonning granites, Cornwall, UK: evidence from aureole field relations and PT modeling of cordierite-anthophyllite hornfels. *Geosphere* 8:1467–1504

- Pritchard ME, Simons M (2004a) Surveying volcanic arcs with satellite radar interferometry; the Central Andes, Kamchatka, and beyond. *GSA Today* 14:4–11
- Pritchard ME, Simons M (2004b) An InSAR-based survey of volcanic deformation in the central Andes. *Geochem Geophys Geosyst* 5(2):Q02002. doi:10.1029/2003GC000610
- Rocchi S, Westerman DS, Dini A, Farina F (2010) Intrusive sheets and sheeted intrusions at Elba Island, Italy. *Geosphere* 6:225–236
- Saint-Blanquat (de) M, Habert G, Horsman E, Morgan S, Tikoff B, Launeau P, Gleizes G (2006) Mechanisms and rates of non tectonically-assisted emplacement in the upper-crust: the Black Mesa pluton, Henry Mountains, Utah. *Tectonophysics* 428:1–31
- Saint-Blanquat (de) M, Horsman E, Habert G, Morgan S, Vanderhaeghe O, Law R, Tikoff B (2011) Multiscale magmatic cyclicality, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs. *Tectonophysics* 500:22–33
- Saint-Blanquat (de) M, Law RD, Bouchez JL, Morgan SS (2001) Internal structure and emplacement of the Papoose Flat pluton: an integrated structural, petrographic, and magnetic susceptibility study. *Geol Soc Am Bull* 113(8):976–995
- Schmiedel T, Breitreuz C, Götz I, Ehling BC (2015) Geometry of laccolith margins: 2D and 3D models of the Late Paleozoic Halle Volcanic Complex (Germany). *Int J Earth Sci* 104:323–333
- Stevenson CT, Owens WH, Hutton DH (2007) Flow lobes in granite: the determination of magma flow direction in the Trawenagh Bay Granite, northwestern Ireland, using anisotropy of magnetic susceptibility. *Geol Soc Am Bull* 119:1368–1386
- Thomson K, Hutton DHW (2004) Geometry and growth of sill complexes: insights using 3-d seismic from the North Rockall Trough. *Bull Volcanol* 66:364–375
- Thornton E (2015) Timing, internal flow characteristics, and emplacement mechanisms of the intrusive sheet network on the southern margin of Mount Hillers, Henry Mountains, southern Utah. Unpublished M.S. thesis, East Carolina University, p 104
- Turner S, Costa F (2007) Measuring timescales of magmatic evolution. *Elements* 3:267–272
- Vignerresse JL (2008) Granitic batholiths: from pervasive and continuous melting in the lower crust to discontinuous and spaced plutonism in the upper crust. *Trans R Soc Edinb Earth Sci* 97:311–324
- Walker BA, Miller CF, Claiborne LL, Wooden JL, Miller JS (2007) Geology and geochronology of the Spirit Mountain batholith, southern Nevada: implications for timescales and physical processes of batholith construction. *J Volcanol Geoth Res* 167:239–262
- Ward M (2014) Geometry and construction history of a complex intrusive center in the shallow crust, Mount Pennell, Henry Mountains, Utah. Unpublished M.S. thesis, East Carolina University, p 130
- Wetmore PH, Connor CB, Kruse SE, Callihan S, Pignotta G, Stremtan C, Burke A (2009) Geometry of the Trachyte Mesa intrusion, Henry Mountains, Utah: implications for the emplacement of small melt volumes into the upper crust. *Geochem Geophys Geosyst* 10(8)
- Wicks CW Jr, Dzurisin D, Ingebritsen SE, Thatcher WR, Lu Z, Iverson J (2002) Magmatic activity beneath the quiescent Three Sisters volcanic center, central Oregon Cascade Range, USA. *Geophys Res Lett* 29. doi:10.1029/2001GL014205
- Wicks C, Thatcher W, Dzurisin D (1998) Migration of fluids beneath Yellowstone caldera inferred from satellite radar interferometry. *Science* 282 (5388):458–462
- Wiebe RA (1988) Structural and magmatic evolution of a magma chamber: the Newark Island layered intrusion, Nain, Labrador. *J Petrol* 29:383–411
- Witkind IJ (1964) Geology of the Abajo Mountains area, San Juan County, Utah. U.S. Geological Survey Professional Paper, p 125