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Emplacement and assembly of shallow intrusions from multiple magma pulses, Henry Mountains, Utah

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ABSTRACT: This paper describes three mid-Tertiary intrusions from the Henry Mountains (Utah, USA) that were assembled from amalgamation of multiple horizontal sheet-like magma pulses in the absence of regional deformation. The three-dimensional intrusion geometries are exceptionally well preserved and include: (1) a highly lobate sill; (2) a laccolith; and (3) a bysmalith (a cylindrical, fault-bounded, piston-like laccolith). Individual intrusive sheets are recognised on the margins of the bodies by stacked lobate contacts, and within the intrusions by both intercalated sedimentary wallrock and formation of solid-state fabrics. Finally, conduits feeding these intrusions were mostly sub-horizontal and pipe-like, as determined by both direct observation and modelling of geophysical data.

The intrusion geometries, in aggregate, are interpreted to reflect the time evolution of an idealised upper crustal pluton. These intrusions initiate as sills, evolve into laccoliths, and eventually become piston-like bysmaliths. The emplacement of multiple magma sheets was rapid and pulsed; the largest intrusion was assembled in less than 100 years. The magmatic fabrics are interpreted as recording the internal flow of the sheets preserved by fast cooling rates in the upper crust. Because there are multiple magma sheets, fabrics may vary vertically as different sheets are traversed. These bodies provide unambiguous evidence that some intrusions are emplaced in multiple pulses, and that igneous assembly can be highly heterogeneous in both space and time. The features diagnostic of pulsed assembly observed in these small intrusions can be easily destroyed in larger plutons, particularly in tectonically active regions.

KEY WORDS: fabric analysis, laccolith, magma flow, pluton emplacement, sill

A subtle but fundamental shift is occurring in our perception of how igneous bodies intrude into the crust. Specifically, it involves the concept of assembly, which recognises that all plutons may not have existed as a single large magma bodies (e.g. Coleman *et al*. 2004; Glazner *et al*. 2004). Rather, plutons may grow through amalgamation of sequentially intruded sheets (e.g. Mahan *et al*. 2003; Michel *et al*. 2008) or relatively small magma pulses with a variety of geometries (e.g. Matzal *et al*. 2006).

A brief historical review provides the context for this issue. During the past two decades, much work has concentrated on a four-part sequence of magma generation, segregation, ascent, and emplacement (Petford *et al*. 2000). This sequence developed partially in response to the increasing lack of evidence for the upward movement of magma through the crust as diapirs. Diapiric transport of magma inherently combines both the ascent (vertical movement) and emplacement (transition to sub-horizontal movement) of magma bodies. The concept of diapirism is no longer generally regarded as a major ascent process in the upper crust, but the concept of intrusion of magma as a single large pulse lingers. While large magma bodies must exist to result in large-volume ignimbrite flows (e.g. Lipman 1984, 2007), there is no compelling reason to make the *a priori* assumption that all plutons were single magma bodies.

For the purposes of this article, *emplacement* is described as the displacement of the surrounding rocks that allows a pluton to attain its three-dimensional geometry (Fig. 1). For this reason, emplacement mechanisms typically describe space-making mechanisms (e.g. roof lifting, floor depression, stoping), and it is generally recognised that multiple emplacement mechanisms facilitate the emplacement of any pluton (Hutton 1988, 1997; Paterson & Fowler 1993). *Assembly* is defined as the process of pluton construction through magmatic addition. Assembly can occur in a single magmatic pulse or as an amalgamation of sequentially emplaced magma pulses. Within the context of these definitions, emplacement and assembly are different concepts. A pluton emplaced by roof lifting could have been assembled from a single pulse of magma or a series of pulses (Fig. 1).

A major problem remains: the assembly of plutonic bodies is often cryptic. Glazner *et al*. (2004) argue that the range of ages in the Tuolumne Intrusive Suite in the Sierra Nevada batholith, California, is larger than would be expected from a

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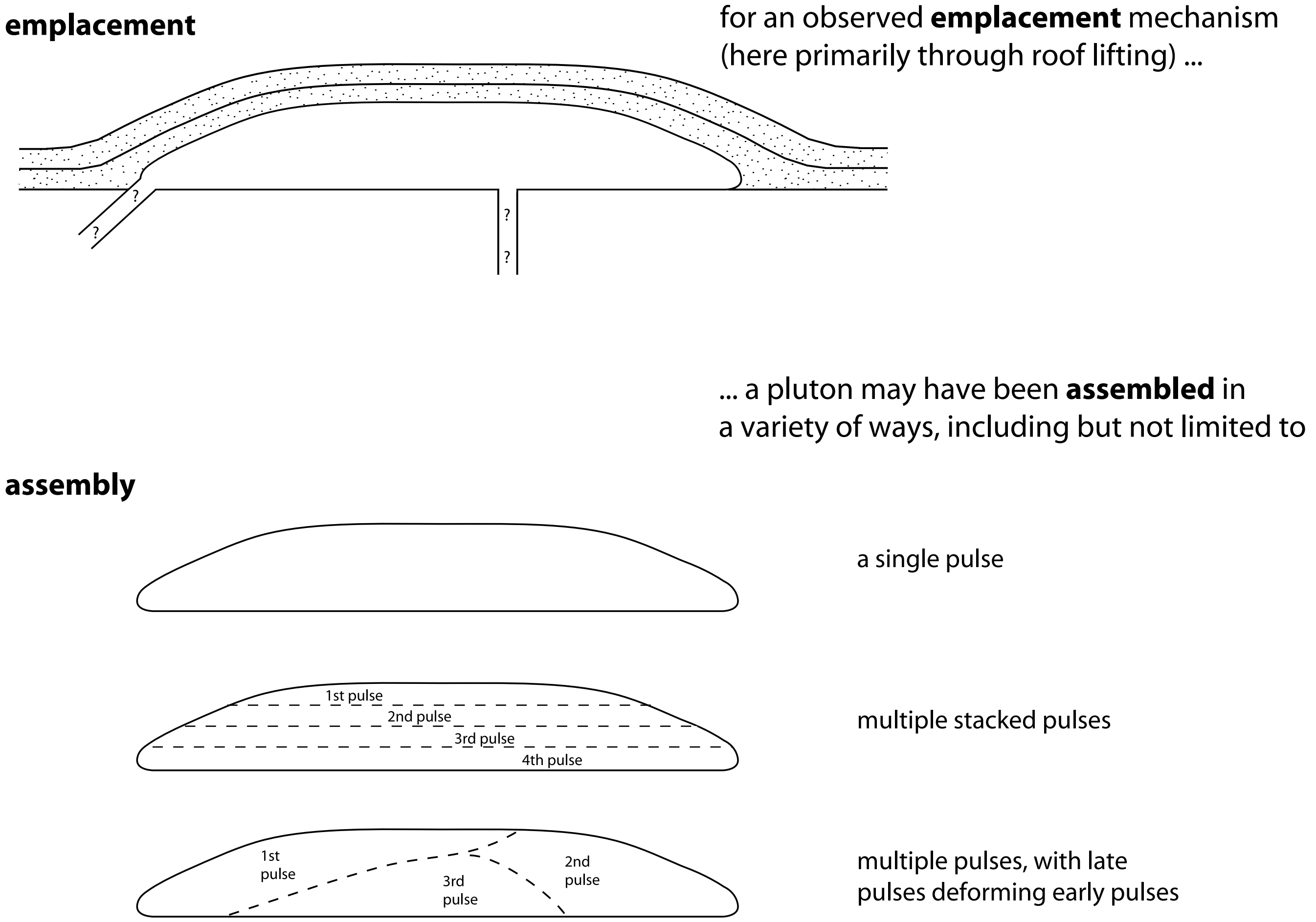

Figure 1 Diagram illustrating the distinction between emplacement and assembly, as used in this paper. For a given observed emplacement geometry, multiple assembly histories are possible.

single, cooling magma body. Consequently, periodic influxes of magma are required to explain the observed trends. However, direct observation of multiple magma pulses is often difficult. For example, recognition of multiple pulses within plutons is only straightforward when a major compositional difference exists (e.g. Wiebe & Collins 1998; Matzal *et al.* 2006). Similarly, primary fabrics within plutons can result from both emplacement-related and assembly-related processes, and separation of these effects is often difficult. Lastly, regional deformation can dramatically influence both pluton geometry and fabric patterns, making inferences of assembly history equivocal (Paterson *et al.* 1998).

Results are presented of a detailed study of intrusions in the Henry Mountains of southern Utah, a location ideally suited for separating emplacement from assembly of igneous bodies. First, the primary emplacement mechanism for these small intrusions is roof lifting, as first proposed by Gilbert (1877) and supported by subsequent workers (e.g. Hunt 1953; Johnson & Pollard 1973; Pollard & Johnson 1973; Jackson & Pollard 1988). Secondly, the intrusions exist at a shallow crustal level where cooling was sufficiently rapid that magmatic fabrics and evidence of multiple magma pulses are preserved. Thirdly, the intrusions are exceptionally well exposed, as the surrounding sedimentary rocks are distinctly more susceptible to erosion than the igneous bodies. Finally, emplacement of the intrusions occurred on the Colorado Plateau during a time of tectonic quiescence, and therefore the fabrics are not affected by regional deformation.

The results demonstrate that assembly occurred by intrusion of a series of sub-horizontal igneous sheets that contain complex internal fabrics. These sheets are locally fed by sub-horizontal tube-shaped conduits, which also exhibit evidence for multiple magmatic pulses. Evidence for magmatic pulses becomes increasingly cryptic as the size of the intrusion increases. Using this evidence, constraints are summarised from numerical modelling on the time scale of the magma intrusion. Finally, the paper discusses how assembly influences emplacement models and provides insights into how intrusions grow in the upper crust.

1. The Henry Mountains

The mid-Tertiary igneous bodies of the Henry Mountains intrude the flat-lying stratigraphy of the Colorado Plateau (Fig. 2). Displacement of the wallrock therefore directly records intrusion geometry. The intrusions post-date the minor Laramide-age deformation that affected this region. Therefore, fabrics within the intrusion reflect emplacement processes and lack a tectonic overprint. The magmas have a geochemical signature typical of volcanic arcs above a subduction zone (Nelson *et al.* 1992; Nelson 1997; Saint Blanquat *et al.* 2006; Bankuti 2007) and are part of a diffuse pattern of simultaneous magmatism throughout the region, which is interpreted to reflect arc-like magmatism above a shallowly dipping slab (Nelson *et al.* 1992) filtered through the thick crust of the Colorado Plateau (Thompson & Zoback 1979). Combined with the 3–4 km original depth of emplacement (Jackson & Pollard 1988), these features make the Henry Mountains an ideal location to study shallow igneous emplacement processes of arc magmas in a relatively simple system. Complications associated with regional tectonism, found in essentially all arcs, are absent.

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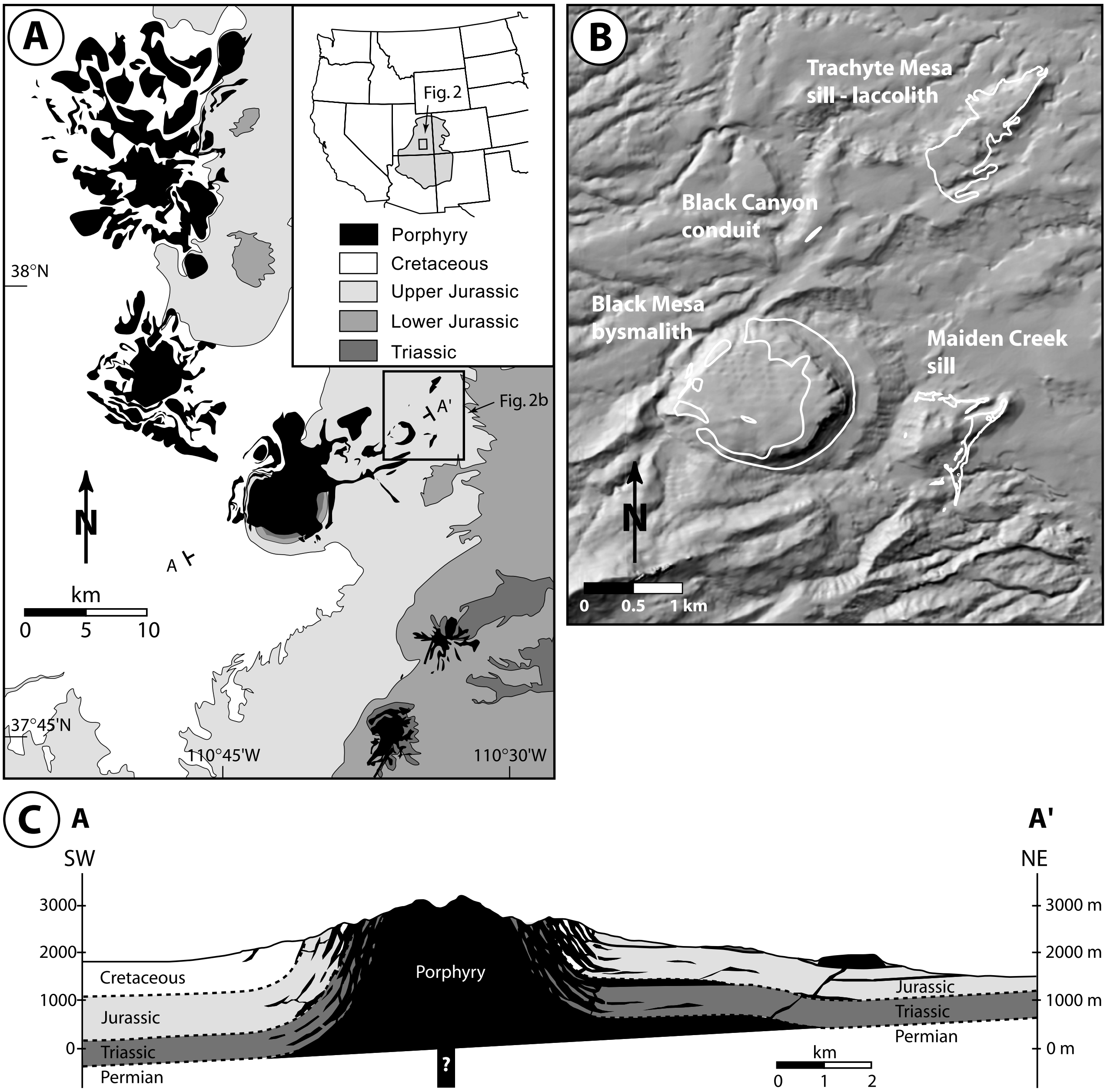

Figure 2 (a) Simplified geologic map of the Henry Mountains region. Box shows the location of (b). Location of cross section shown in (c) is also indicated. Inset shows the location of (a) on the Colorado Plateau in the western United States cordillera. (b) Shaded relief map of the eastern portion of Mt Hillers. Outlines of the three intrusions and the conduit discussed in this paper are shown in white. (c) Schematic cross section through Mt Hillers, oriented NE–SW.

Five intrusive centres comprise the Henry Mountains (Fig. 2). Each intrusive centre is a large and complex laccolithic body (Jackson & Pollard 1988, 1990), made of dozens of interconnected component intrusions with a wide range of geometries. All three of the intrusions studied on the eastern margin of the Mt Hillers intrusive centre (Fig. 2b) are in a unique state of erosion. Numerous upper, lower and lateral contacts with the surrounding sedimentary rock are preserved. The level of detail of intrusion geometry preserved helps to illuminate the complex emplacement and assembly processes of the igneous bodies.

1.1. Composition, fabric, and wallrock deformation

The intrusions are composed of plagioclase-hornblende porphyry whose bulk chemistry is consistently similar throughout the range (Nelson *et al.* 1992; Bankuti 2007). Primary phenocryst populations include 30–35% by volume 0·5–1·5 cm-diameter euhedral plagioclase laths, and 5–15% by volume 0·1–0·5 cm-long hornblende needles. Other phenocrysts include <2% euhedral to subhedral oxides (principally magnetite) and <1% euhedral apatite and sphene. The matrix commonly makes up 50% or more of the rock and is composed primarily of very fine-grained plagioclase, hornblende, and oxides.

Field fabric is variably well developed in the intrusions (Morgan *et al.* 2005), as described in more detail for each body below. In general, fabrics are strongest near intrusion margins and decrease in intensity away from the margins. A carapace of solid-state fabric is locally preserved in the outermost few centimetres of each intrusion. Where the carapace is well preserved, it grades smoothly into magmatic fabric away from the wallrock contact. Asymmetry of the solid state and magmatic fabric relative to the contact provides a useful shear sense indicator (e.g. Horsman *et al.* 2005).

Further from contacts, fabric is less well developed. To characterise these weak fabrics, the anisotropy of magnetic

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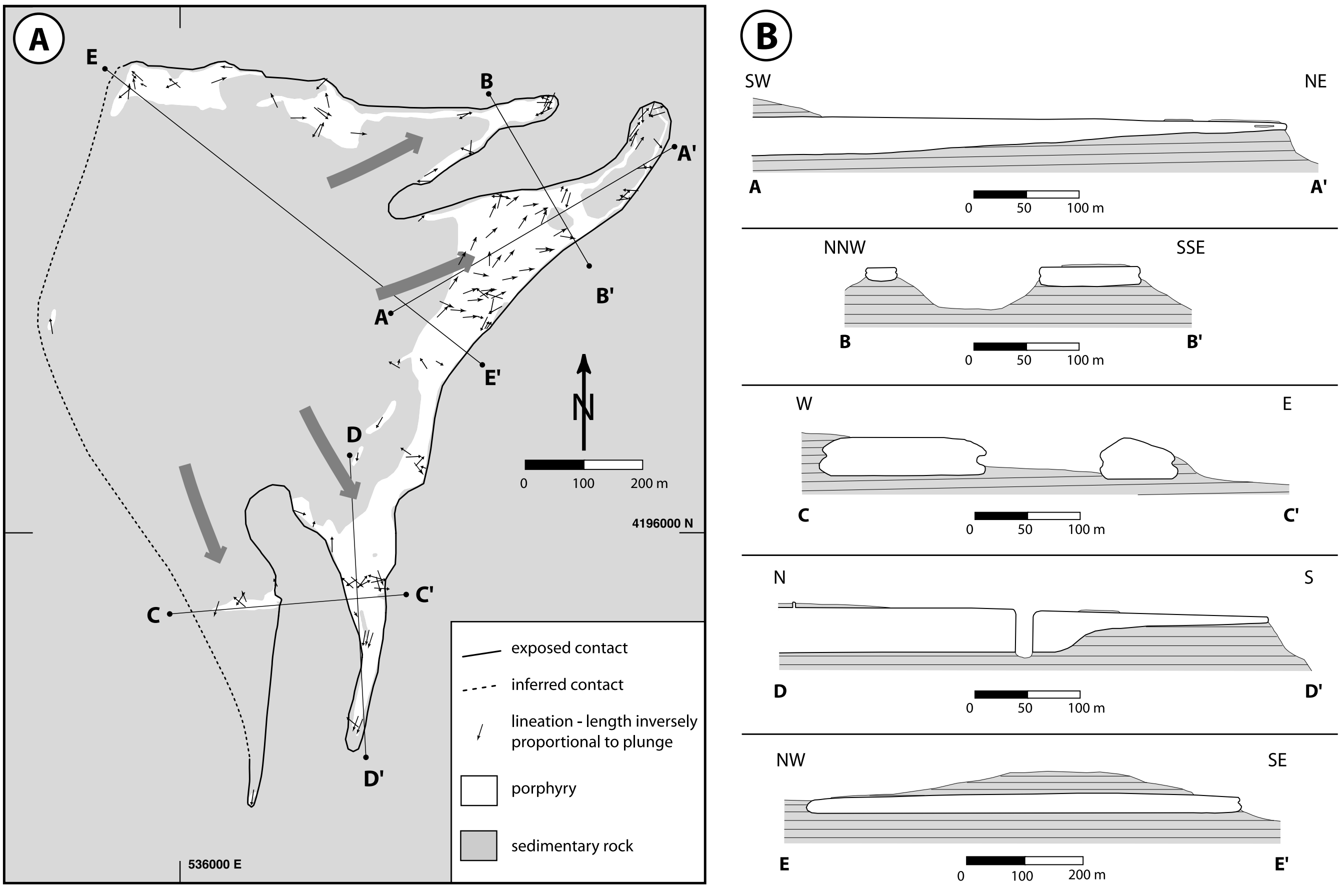

Figure 3 (a) Geologic map of the Maiden Creek sill. Lineations shown with black arrows include field measurements and magnetic fabric results, with arrow length inversely proportional to plunge. Locations of cross-sections shown in (b) are indicated. Large grey arrows indicate inferred primary magma flow directions based on intrusion geometry and fabric patterns. UTM zone 11. (b) Cross-sections through the intrusion. Note that the scale of cross-section E–E′ is different from that of the others.

susceptibility (AMS) was measured at numerous stations in each intrusion. Where detailed comparisons have been made, AMS orientations agree well with both field measurements and three-dimensional laboratory fabric analysis results (Horsman *et al.* 2005). The AMS signal in the porphyry is carried principally by multi-domain and pseudo-single-domain magnetite (Habert & de Saint Blanquat 2004; Horsman *et al.* 2005; Morgan *et al.* 2008), allowing for normal interpretation of results; the maximum eigenvector of the magnetic susceptibility tensor is the magnetic lineation and the minimum eigenvector is the pole to magnetic foliation.

Both field-based measurements and magnetic fabric data provide constraints on magma flow patterns during emplacement. The intrusions are small and occur in an upper crustal setting, suggesting that they cooled quickly and do not record any structural overprinting. In fact, three-dimensional intrusion geometries are so well constrained that the first-order magma flow patterns can be inferred directly from the geometry and then tested against the observed fabrics.

Aside from fabric analysis, wallrock deformation provides information on the emplacement and assembly history of each intrusion. Analysis of fault and fracture orientations and offset sometimes allows for inference of detailed emplacement history (e.g. Pollard & Johnson 1973; Morgan *et al.* 2008). Interpretation of wallrock deformation and igneous fabrics together provides a more complete picture of emplacement and assembly history. Each data set records distinct processes and these data are integrated in the present paper to provide a more complete analysis of emplacement and assembly.

2. Maiden Creek sill

2.1. Three-dimensional geometry

The Maiden Creek sill (Fig. 3) represents the initial stage of igneous emplacement with a relatively small volume of magma (<0·03 km^3). A more thorough description of the intrusion in provided by Horsman *et al.* (2005).

Numerous upper, lower and lateral contacts with wallrock sandstone are preserved. These contacts tightly constrain a complex three-dimensional geometry. In map view, the sill has an elliptical main body from which protrude several finger-like, 100 m-scale lobes. Similar lobate sill geometries have been observed in detailed three-dimensional seismic reflection studies in the North Sea (Thomson & Hutton 2004; Hansen & Cartwright 2006).

In detail, the cross sectional geometry of the intrusion is similarly complex. Whilst the main body has a simple sill-like cross sectional geometry with concordant upper and lower contacts, cross sections along the length of the two best-exposed finger-like lobes (Fig. 3b) show that the base of the intrusion cuts up through the stratigraphic section. Along the easternmost finger this process was gradual (cross section A–A′ on Fig. 3b), while along the SE finger the process was more step-like (cross section D–D′ on Fig. 3b).

2.2. Internal fabric and wallrock deformation

Solid-state fabric exists in the outermost few centimetres of the intrusion near every exposed contact with wallrock, and this carapace is preserved in some locations where the sedimentary rock has eroded, suggesting that the erosion is relatively recent. This solid-state fabric grades smoothly into a similarly oriented magmatic fabric over a few centimetres. Further from the contact magmatic fabric becomes weaker.

Foliation is consistently sub-horizontal and lineation has a fanning radial map pattern in the elliptical main body (Fig. 3). In each finger-like lobe, lineation has a more restricted fanning map pattern generally aligned with the long axis of the lobe. The tightly constrained intrusion geometry requires that magma flowed from the main body into the lobes (Fig. 3).

2.3. Evidence for multiple magma pulses

Several lines of evidence demonstrate that the sill is composed of two stacked horizontal sheets of magma that intruded sequentially. Several cross-sections through the lateral margin of the intrusion are preserved and everywhere show two stacked bulbous terminations (figs 4a and 4b in Horsman *et al.* 2005). Additionally, the sub-horizontal boundary between the two sheets is marked locally by either metre-scale lenses of intercalated sandstone or centimetre-scale zones of solid-state fabric.

The combination of strong fabric at the intrusion margins and weak fabric in the interior suggests that a significant portion of the emplacement-related strain in the intrusion was accommodated in the outer few centimetres of each sheet. This fabric also suggests that emplacement of each sheet occurred rapidly. The two sheets were probably emplaced in rapid succession, because the sheet-sheet contact is commonly difficult to recognise, except where marked by intercalated wallrock. The well-preserved lateral margins of each sheet are bulbous in cross-section, rather than pointed as predicted by many mechanical models of sheet intrusions (e.g. Pollard 1973).

2.4. Summary

The Maiden Creek intrusion is a sill with a complex geometry. It is lobate in map view and the bottom contact cuts upward in cross-section. Both solid-state and magmatic fabrics closely preserve magma flow patterns. These fabric patterns correspond well with the complex intrusion geometry and demonstrate that magma flowed from the main body out into the finger-like lobes to produce fanning lineation and arcuate foliation patterns that reflect progressive growth of the intrusion. The sill is composed of two stacked sheets that were emplaced sequentially as separate magma pulses.

3. Trachyte Mesa laccolith

3.1. Three-dimensional geometry

The Trachyte Mesa laccolith (Fig. 4) has at least twice the volume of magma ($\sim$0·05 km^3) as the Maiden Creek sill. The intrusion is elongate along a line pointing radially away from the main Mt Hillers intrusive centre. Morgan *et al.* (2008) provide a more detailed description of this intrusion. Numerous upper contacts of this intrusion with flat-lying wallrock are well preserved, and lower contacts are locally preserved. These contacts indicate that the intrusion has a broadly sill-like cross-sectional geometry (Fig. 4b).

A well-preserved lateral contact on the NW margin indicates that the intrusion grew in a laccolithic manner. In this location, wallrock layers are bent upward and thinned over the intrusion. Strain analyses of these sandstone layers demonstrate that deformation of the overlying rock was localised at the intrusion margins through vertical growth of the intrusion. There is also evidence for multiple (>10) stacked igneous sheets at this margin, identified by bulbous terminations, solid-state fabrics and intercalated sandstone. Cross-cutting relationships between sheets demonstrate a complex stacking history, but are consistent with a general pattern of emplacement of younger sheets below older sheets. For example, some of these igneous sheets at the margin are rotated with the sedimentary layering, suggesting that they were intruded horizontally and rotated by subsequent emplacement of underlying sheets. However, late horizontal igneous sheets locally intrude the rotated sedimentary beds and earlier igneous sheets.

Although the main body of the intrusion is essentially laccolithic, at several locations on the margins of the intrusion complex, finger-like lobes are preserved (Fig. 4). These 100-m-scale, highly elongate lobes commonly project out from the margin of the main Trachyte Mesa intrusion. These lobes are similar to the finger-like lobes observed within the Maiden Creek intrusion. However, the lobes make up only a small portion of the Trachyte Mesa intrusion volume instead of the majority they make up on the Maiden Creek intrusion.

3.2. Internal fabric and wallrock deformation

Field and magnetic foliation data for the Trachyte Mesa intrusion are consistently sub-horizontal (Fig. 4). Lineation plunges are also consistently sub-horizontal, but trend values have a bilaterally symmetric geometry. Along a central axis, lineation is parallel to the length of the intrusion. Away from that axis, lineation trends perpendicular to the axis and points toward the intrusion margins. Flow patterns with this bilaterally symmetric geometry have traditionally been ascribed to flow away from a central dike-like feeder below the intrusion (e.g. Ferré *et al.* 2002). However, data is presented (see section 5) indicating that the intrusion is fed by a sub-horizontal conduit from the direction of the main Mt Hillers intrusive centre. The average foliation on top of the intrusion also dips approximately 10° to the NE (Fig. 4a), parallel to the long axis of the intrusion, and is used as a bulk magma flow indicator (Morgan *et al.* 2008). Therefore, it is suggested that this pattern represents magma flow out along the length of the intrusion in a sub-horizontal conduit, which then feeds magma out to the lateral margins (see Morgan *et al.* 2008). A similar flow pattern has been inferred for other sills (Thomson & Hutton 2004; Hansen & Cartwright 2006).

Wallrock deformation is documented by Morgan *et al.* (2008). Little deformation is observed on the few outcrops of wallrock on the top of the intrusion, suggesting primarily vertical translation of these rocks. Deformation at the exposed lateral contact on the NW side of the intrusion is consistent with the sedimentary layering being translated upward and over the top of an upward- and outward-propagating hinge. Sedimentary layers immediately above the contact locally show evidence for layer-parallel shortening, which is inferred to result from coupling with the underlying sheets as they moved outward. Further from the contact, sedimentary layers show up to 20% layer-parallel thinning due to bulk roof lifting, accommodated by fracture-induced porosity collapse and faulting. These zones are decoupled from each other by a thin layer of intensely sheared sandstone.

3.3. Evidence for multiple magma pulses

Although cross-cutting relationships clearly demonstrate the importance of pulsed assembly at the margins of the Trachyte Mesa intrusion, exposures of the interior have only equivocal evidence of sheets. In particular, the top of the intrusion has two distinct plateau-like levels, which are thought to

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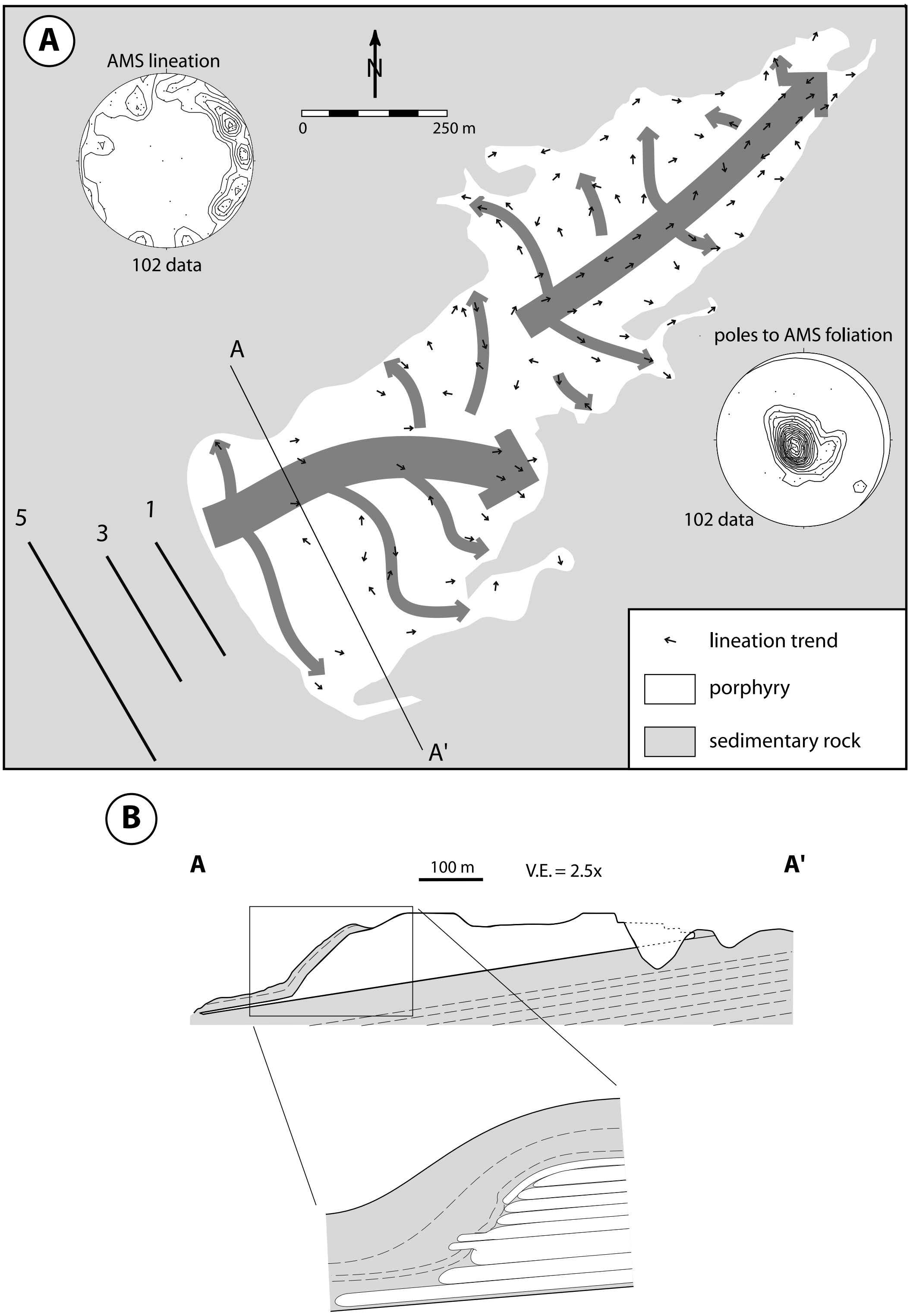

Figure 4 (a) Geologic map of the Trachyte Mesa laccolith. Lineations shown with black arrows are magnetic fabric results and all have sub-horizontal plunges. Equal-area lower hemisphere plots show orientations of magnetic lineation and poles to foliation. Note that foliation dips shallowly to the NE, parallel to the length of the intrusion. Grey arrows indicate inferred primary magma flow directions based on intrusion geometry and fabric patterns. Numbered lines SW of the intrusion indicate locations of magnetic anomaly traverses described in Figure 7. UTM zone 11. (b) Cross-section through the intrusion. 2·5 times vertical exaggeration.

correspond to different sheets. This inference is corroborated by slightly different fabric patterns that occur at those different levels. The lack of distinct sheet–sheet contacts suggests assembly was rapid enough for emplaced pulses to stay above the solidus before the next sheet intruded.

These observations can be interpreted in a variety of ways. First, late-stage magmatic processes may have obscured evidence of earlier pulsed assembly. Alternatively, sheets could form only near the margins of the intrusion while the interior was a single magma body. The latter hypothesis is not consistent with the emplacement, rotation, and pre-intrusion of sheets on the margins or the different flow fields on top of the intrusion. Consequently, it is inferred that late magmatic processes obscured evidence of earlier pulsed assembly.

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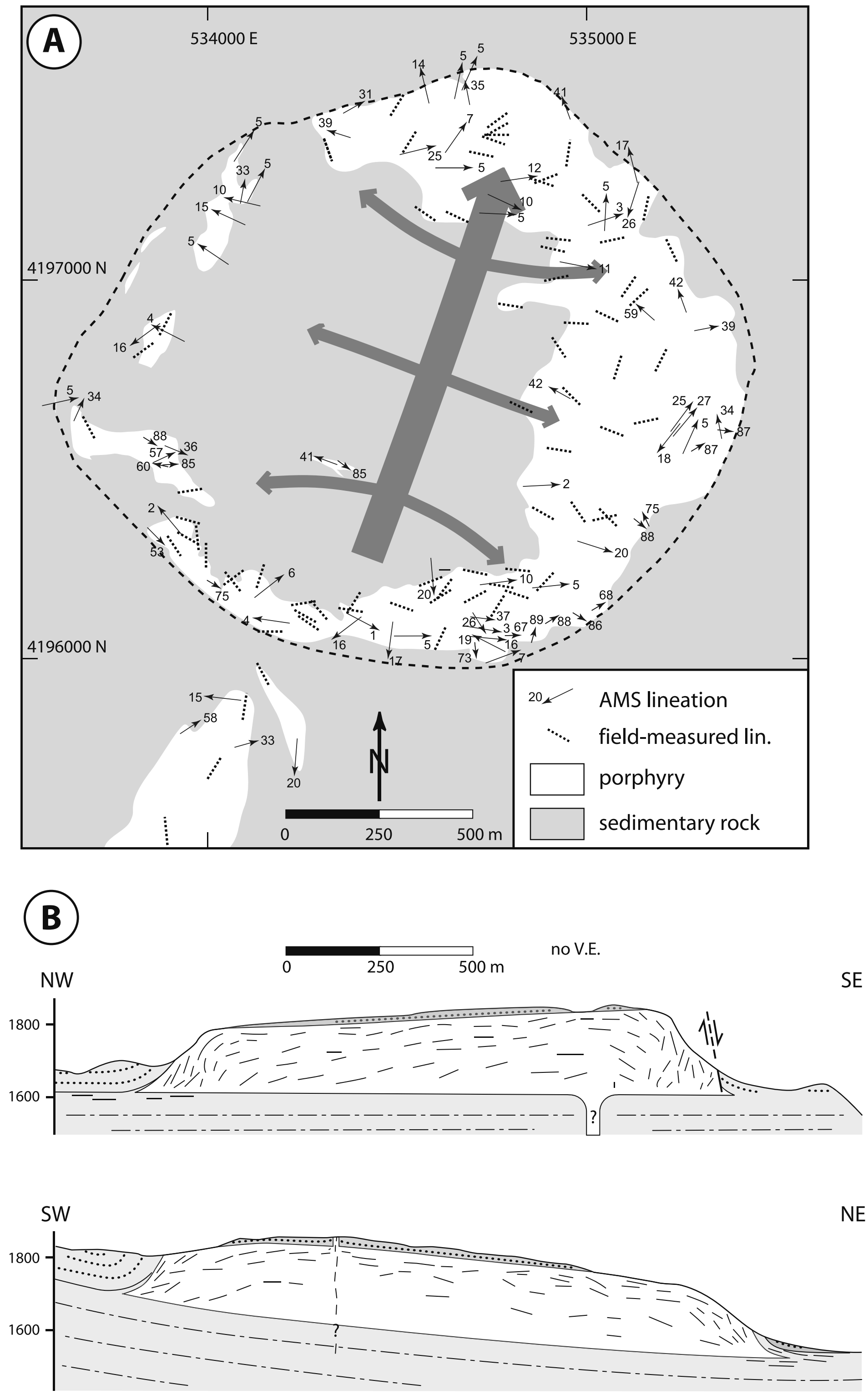

Figure 5 (a) Geologic map of the Black Mesa intrusion. Lineations shown with black arrows are magnetic fabric results, with plunge indicated. Lineations shown with black lines are field measurements of lineation trend. Grey arrows indicate primary magma flow directions based on intrusion geometry and fabric patterns. UTM zone 11. (b) Cross-sections through the intrusion, with schematic trace of foliation indicated.

3.4. Summary

The Trachyte Mesa laccolith is an elongate body in map-view. In cross-section it exhibits sub-horizontal, sill-like upper and lower contacts, along with laccolithic margins. Magma in the intrusion flowed out along a central axial conduit that fed flow to the lateral margins. Numerous magma pulses contributed to assembly of the intrusion. Evidence of these pulses as distinct sheets is clear at the lateral margins of the intrusion, but cryptic in the centre of the body.

4. Black Mesa bysmalith

4.1. Three-dimensional geometry

The relatively voluminous (~0·4 km^3) Black Mesa bysmalith (Fig. 5) is the largest of the studied intrusions. Habert & Saint Blanquat (2004) and Saint Blanquat *et al.* (2006) provide more detailed descriptions of this intrusion. As with the other two intrusions studied, numerous preserved top and lateral contacts allow the geometry of the intrusion, which is ~1·7 km in

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diameter and roughly circular in map view, to be clearly constrained. The eastern margin is a sub-vertical fault along which the sub-horizontal wallrock is displaced upward ~200 m. This vertical offset is determined from stratigraphic relationships between sub-horizontal shale and sandstone on the top of the intrusion and similar wallrock exposed at the base of the intrusion. This type of relation occurs on the margin of a bysmalith, which is defined as an intrusion with a flat floor and flat roof that lifts the overburden in a piston-like manner along a curved, steeply dipping fault. In contrast, the western margin of the intrusion is a monocline. Taken together, the intrusion resembles a trapdoor, with a hinge along the western side and a discrete, faulted offset along the eastern side. Consequently, the Black Mesa intrusion represents a transitional stage of development between a laccolith and a bysmalith.

4.2. Internal fabric and wallrock deformation

There is little information available about the internal fabric of the Black Mesa intrusion, because the current exposures record almost exclusively the outermost margins of the body. Along the steep, faulted eastern margin of the intrusion, solid-state and magmatic lineations are both steeply plunging. Immediately adjacent to wallrock contacts, the fabric is solid-state and defined by cataclastically deformed phenocrysts. Further from this contact, the fabric is magmatic and defined by phenocryst shape-preferred orientation. The observed fabrics are consistent with syn-magmatic shearing on the sub-vertical bounding fault along the eastern margin of the intrusion.

Where exposure exists, the top of the intrusion is also characterised by both solid-state and magmatic fabrics. Solid-state fabrics occur in the outer few centimetres and grade inward to magmatic fabrics, similar to the other intrusions. Foliation is sub-horizontal in both the solid-state and magmatic fabrics. Lineation orientation changes with distance from the top contact. The solid-state and magmatic lineations at the upper contact are oriented WNW, while the magmatic lineations are oriented NNE several centimetres below the contact. Saint Blanquat *et al.* (2006) interpret this fabric to indicate NNW stretching during divergent ENE-oriented magma flow. They attribute the pattern to intrusion from below, perhaps by a dike-like feeder striking approximately NNE. The similarity of this fabric pattern to that observed in Trachyte Mesa intrusion suggests that a lateral pipe-like feeder at the base of the intrusion is also possible. However, no feeder conduit, is exposed.

Outcrops of wallrock on the top of the intrusion are relatively undeformed. Minor fracturing exists as conjugate sets, with orientations generally consistent with regional trends away from the Henry Mountains. This observation is similar to overburden rocks atop both the Maiden Creek and Trachyte Mesa intrusions.

4.3. Evidence for multiple magma pulses

Several observations provide indirect evidence of multiple pulses. In the upper portion of the intrusion, sub-horizontal textural layering and cataclastic zones can be traced for tens of metres. The remainder of the intrusion displays no internal contacts, although exposures of the interior are very rare. Additionally, petrologic and geochemical zonation exists along vertical profiles through the intrusion (Bankuti 2007). None of these observations provides unequivocal evidence of multiple magma pulses. However, together they strongly suggest that the intrusion was amalgamated from multiple magma pulses.

4.4. Summary

The Black Mesa intrusion has an approximately cylindrical geometry. The western margin of the intrusion is monoclinal, while the eastern margin is a vertical fault with a displacement of ~200 m. Magma in the intrusion flowed out along a central axial conduit before flowing laterally out to the margins. Multiple pulses of magma likely contributed to the assembly of the intrusion, but evidence for these pulses is more cryptic than in the two smaller intrusions studied.

5. Magma conduits

Dikes are rare in the Henry Mountains. Instead, isolated sub-horizontal igneous bodies with approximately elliptical cross sections are observed, similar to the elongate lobes of the Maiden Creek body. Following Hunt (1953), it is suspected these were pipe-like feeders that locally provided magma for the separate intrusive bodies. Two examples are described below: (1) an exposed example of one of these feeders (section 5.1); and (2) geophysically imaged conduits that act as feeders to the Trachyte Mesa intrusion (section 5.2). In the absence of a purely descriptive geometric name defined in the literature, these igneous bodies are referred to as conduits. These conduits presumably feed magma from the main Mt Hillers intrusive centre to the satellite bodies and represent the final stage of a longer ascent process that principally involves vertical movement.

5.1. Black Canyon conduit

Approximately 5 km SW of the Trachyte Mesa intrusion, a highly elongate igneous body is exposed for ~150 m as a series of isolated outcrops in Black Canyon (Fig. 6). The composition and texture are similar to the larger igneous bodies in the area. This intrusion was originally reported by Hunt (1953), and is herein referred to as the Black Canyon conduit.

For several of the individual outcrops, both the top and side contacts of the Black Canyon conduit are well exposed (Fig. 6). In general, the top contact is sub-horizontal, while the lateral contacts are sub-vertical. These observations constrain the width of the intrusion to less than ~5–10 m along the length of the exposure. The absence of continuous outcrop indicates that the intrusion cannot be a continuous tabular body (e.g. a dike or sill). Rather, the intersection of the topography and the igneous body is most consistent with a pipe-like conduit, with the base of the intrusion oriented near the current exposure level of the body. Consequently, the Black Canyon conduit likely represents a pipe-like feeder transporting magma radially away from the main Mt Hillers intrusive centre.

Hunt (1953) noted the Black Canyon conduit was located between the Trachyte Mesa intrusion and the Mt Hillers intrusive centre, with an orientation toward Trachyte Mesa. Hunt consequently suggested that the conduit might be an exposure of the feeder for the Trachyte Mesa intrusion. The present authors disagree with this interpretation for two principal reasons. First, the conduit is located higher in the stratigraphic section than the Trachyte Mesa intrusion. It is unlikely that a magma conduit would cut downsection, particularly given our observation of the upward-sloping bottom contact in the finger-like lobes of the Maiden Creek intrusion. Secondly, as described below (see section 5.2), geophysical studies suggest that multiple tube-like conduits feed the Trachyte Mesa intrusion below the current level of exposure.

Fabric in the conduit is magmatic in the middle of the body and solid-state on the edges (Fig. 6). Magmatic fabrics farther from the wallrock contact are dominated by lineation, with

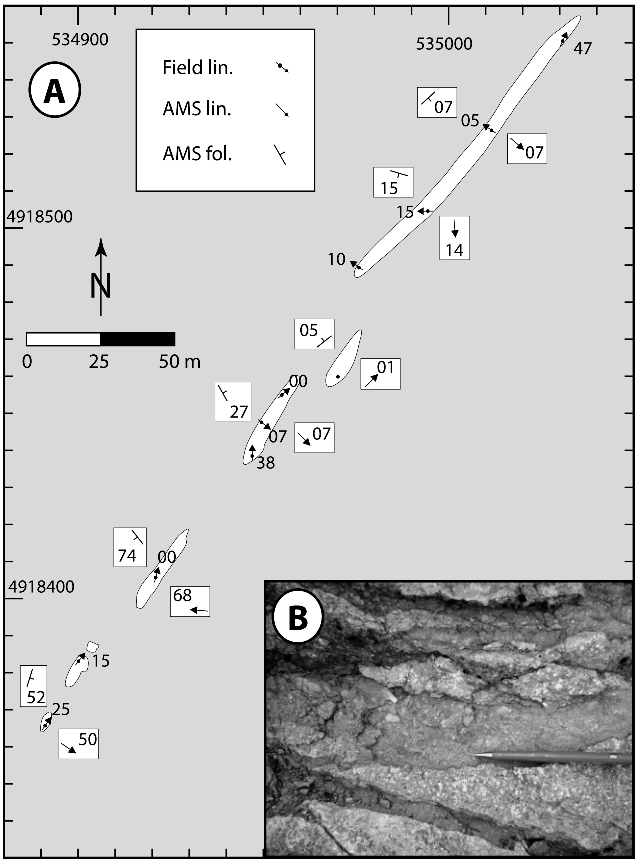

Figure 6 (a) Simplified geological map of the Black Canyon conduit. Field-measured lineation shown at the station locations. AMS lineation and foliation results, plotted nearby in white boxes, are from the same stations. UTM zone 11. (b) Field photograph of several generations of breccia veins. Composition of clasts in the breccia include porphyry, sandstone, and older breccia.

local, poorly developed foliation. In general, solid-state and magmatic lineations near wallrock contacts trends perpendicular to the length of the intrusion, while magmatic lineation further from contacts trends roughly parallel to the length of the intrusion. The first lineation, oriented NS–SE and subparallel to the long axis of the intrusion, is interpreted as recording flow along the length of the conduit. Magmatic flow presumably went from the SW to the NE, away from the Mt Hillers intrusive centre. The second lineation is interpreted as recording the radial expansion of the conduit during pulsed growth of the body.

Six oriented samples were collected for AMS analysis. Samples were taken from rocks containing only magmatic fabrics and were processed similarly to those from the other intrusions (e.g. Horsman *et al.* 2005). Similar to the field lineation, AMS results display an irregular lineation in the magnetic fabric that varies in both trend and plunge along the length of the intrusion (Fig. 6a), although the field and magnetic lineation locally disagree. Magnetic foliation is generally flat-lying, consistent with the one observed field foliation. Magnetic fabrics are dominantly plane strain, which appears inconsistent with the strong field-based linear fabric.

Veins of fine-grained, green breccia are locally preserved along the outcrop (Fig. 6b). These roughly planar veins generally strike sub-parallel to the trend of the intrusion and contain clasts of both porphyry and sandstone. Evidence of multiple cross-cutting diking events suggests multiple episodes of brecciation. The presence of these zones suggests multiple injections of magmas, with either very high strain rates or sufficient cooling of the intrusion to cause fracturing. Kinematic indicators present within the breccia zones potentially indicate oblique slip, but this inferred shear sense varies from vein to vein. These structures are interpreted as recording the relative displacement between individual magma pulses.

In summary, the Black Canyon conduit records dominantly linear fabrics in a tube-like body, suggesting outward magma flow from the Mt. Hillers intrusive centre. The observed breccia veins, field fabrics, and AMS results are consistent with the intrusion of multiple magma pulses through the conduit. The complicated lineation pattern likely records simultaneous magma flow and intrusion growth within this small, geometrically complex body.

5.2. Trachyte Mesa feeder

Magnetic anomaly data were collected along five traverses on the alluvial plateau SW of the Trachyte Mesa intrusion to provide constraints on the feeder system for the body. Data are presented from three of these traverses (1, 3, 5) in Figure 7 and locations are shown on Figure 4. Data from the two traverses not presented (2, 4) show patterns similar to the discussed traverses. The length and placement of the traverses were governed by the size of the accessible plateau area, eliminating any changes in the magnetic field that might occur due to changes in elevation. The traverses were oriented NW–SE, perpendicular to an axis connecting Mt Hillers to the intrusion. The closest traverse is 110 m SW from the nearest exposure of the intrusion (Fig. 4). The first and third traverses are 170 m long. The fifth traverse, which is furthest from the intrusion, is 290 m long and is ~320 m from the SW edge of the intrusion. Magnetic data were collected every three metres along each traverse using two magnetometers separated on a pole in the gradiometer mode. The data from each traverse were smoothed.

Traverses one and three each reveal two to four anomalies, two of which can be traced between the traverses. Each of these two traverses has a relatively large anomaly near the NW end (Fig. 7). Traverse five, the most distant from the exposed intrusion, has numerous smaller anomalies. The magnitude of the anomalies varies considerably between the five traverses. Traverse one has anomalies that vary between positive and negative 10 γ/m, whereas traverse three has a positive anomaly close to 100 γ/m and traverse five has negative anomalies of similar magnitude.

To test possible intrusion geometries, the observed anomaly profiles were forward modelled as dikes, sills, and finger-like bodies using GM-SYS software. Each 2·5-dimensional model simulates a block of country rock Entrada Sandstone that was intruded by various shapes of porphyry. The susceptibility and remanence of samples from the porphyry and from the country rock Entrada Sandstone were determined using rock magnetic facilities at Lake Superior State University and the University of Michigan. The sills and finger-like bodies were modelled to be at a depth of 12 m below the surface, based on the elevation of the observed base to the intrusion 300 m to the NE. Shapes of the modelled finger-like bodies were modified in order to have the greatest correspondence between the observed and calculated (model) magnetic intensities. Dikes were placed at various positions and with various dips for the best fit. Dike widths and sill thicknesses were also modified for the best fit.

The models illustrate that along each traverse, a series of finger-like bodies more accurately matches the observed anomalies than one sill or a set of dikes. The models also show that a thick finger-like shape of porphyry, somewhat similar to the projected cross-sectional shape of the Black Canyon conduit, may exist on the NW end of the closest two traverses.

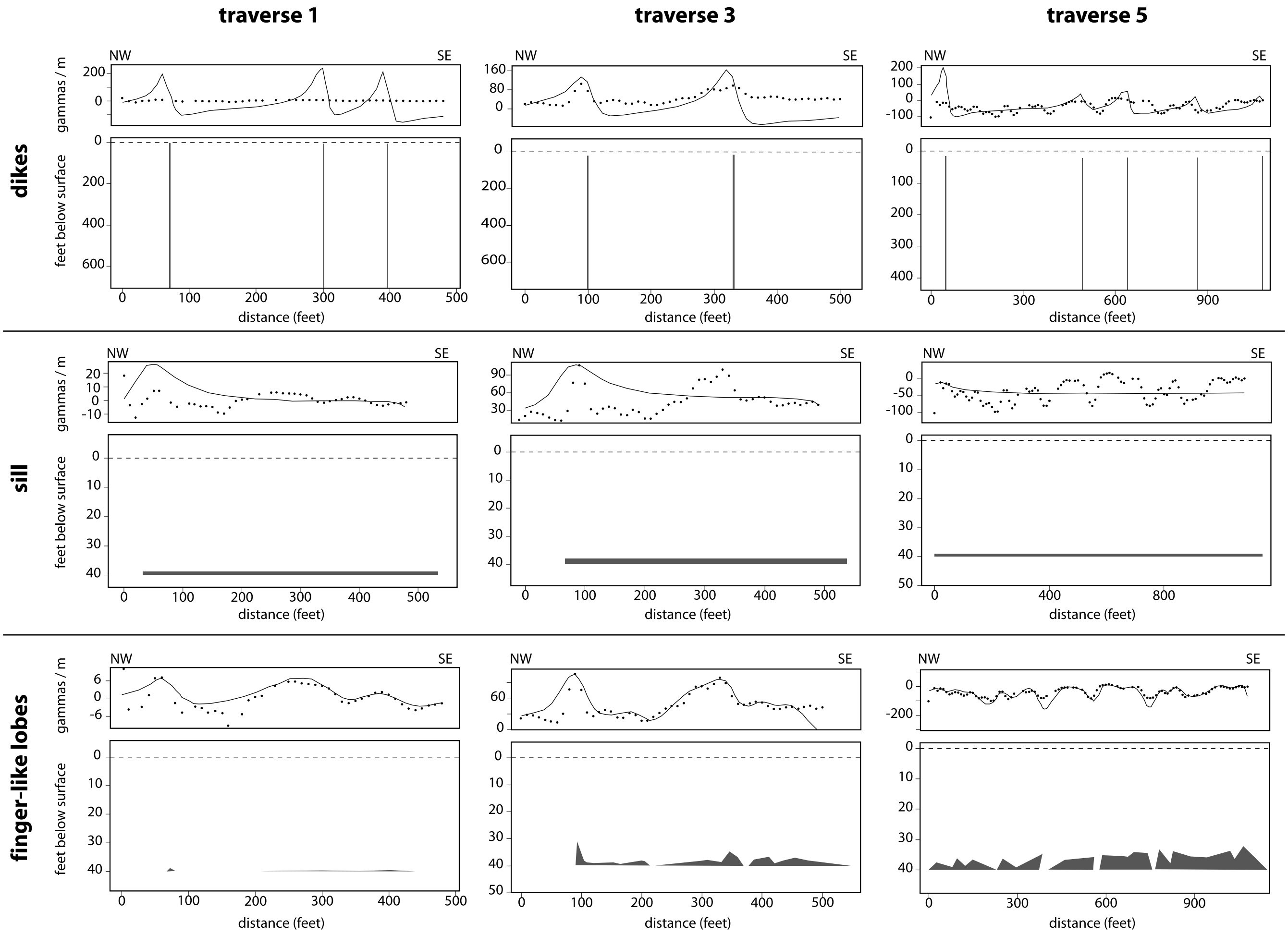

Figure 7 Magnetic anomaly data from traverses SW of the Trachyte Mesa laccolith. Forward models of the data test possible feeder geometries for each magnetic anomaly traverse. Tested feeder geometries include dikes, sills and finger-like bodies. Finger-like feeder bodies best match the observed anomaly data. Note that scales and vertical exaggeration differ for each plot. Locations of the traverses are shown on Figure 4.

Correlation from traverse to traverse suggests that a network of finger-like lobes may anastomose at a particular bedding horizon and finally converge near the SW exposure of the Trachyte Mesa intrusion.

6. Discussion

The geometries of the three intrusions studied lie along the hypothesised evolution of an upper crustal intrusion from sill to laccolith to bysmalith. Individually, each intrusion provides insight into different aspects of shallow magma emplacement. Together, the intrusions provide a framework to consider several aspects of emplacement and assembly, including: (1) evolution of pluton geometry; (2) fabric patterns and magma flow evolution; (3) times scales of emplacement and assembly; and (4) heterogeneity of magma pulses in space and time.

6.1. Evolution of pluton geometry

The exceptional preservation of intrusion geometry in the Henry Mountains provides an informative view of the geometries of the three igneous bodies. Using observations of the intrusions as a guide, a hypothetical history of pluton assembly is presented during growth from sill to laccolith to bysmalith. Figure 8 shows idealised intrusion geometries for a sill, laccolith, and bysmalith with pulsed assembly histories. Figure 9 schematically shows both the primary emplacement mechanism (vertical displacement of the wallrock) and the preferred assembly histories for the three intrusions studied.

The Maiden Creek intrusion demonstrates the early stages of sill formation, which presumably involved a relatively small magma pulse spreading away from a pipe-like feeder in the form of finger-like lobes. In the immediate vicinity of the feeder, these lobes coalesced to form a sill-like body with a roughly elliptical shape in map view. A second magma pulse of approximately the same volume followed the same emplacement path, so that two stacked sheets comprise the intrusion.

The Trachyte Mesa intrusion demonstrates how a pluton can evolve into a sill-like body and begin to inflate into a laccolith. Further magma pulses (or larger initial pulses) spread beyond the nascent sill observed at the Maiden Creek intrusion to produce a larger and more mature sill. This more developed intrusion maintains the tabular cross-sectional geometry, but exhibits a more simple map-view geometry, in which finger-like lobes constitute a small portion of the total volume. Late magma pulses followed emplacement paths similar to early pulses. Additionally, the pulses thickened the intrusion a few metres at a time. Eventually, earlier emplaced sheets were rotated upward and sometimes intruded by subsequent sheets to form a laccolithic margin. Assembly of the Trachyte Mesa intrusion ceased at this stage with characteristics of both sill and laccolith geometries.

The Black Mesa intrusion illustrates further development of an igneous body with increased magma supply. As the number of emplaced sheets grew, the margins of the laccolith steepened. Eventually, a fault formed along the E margin of the

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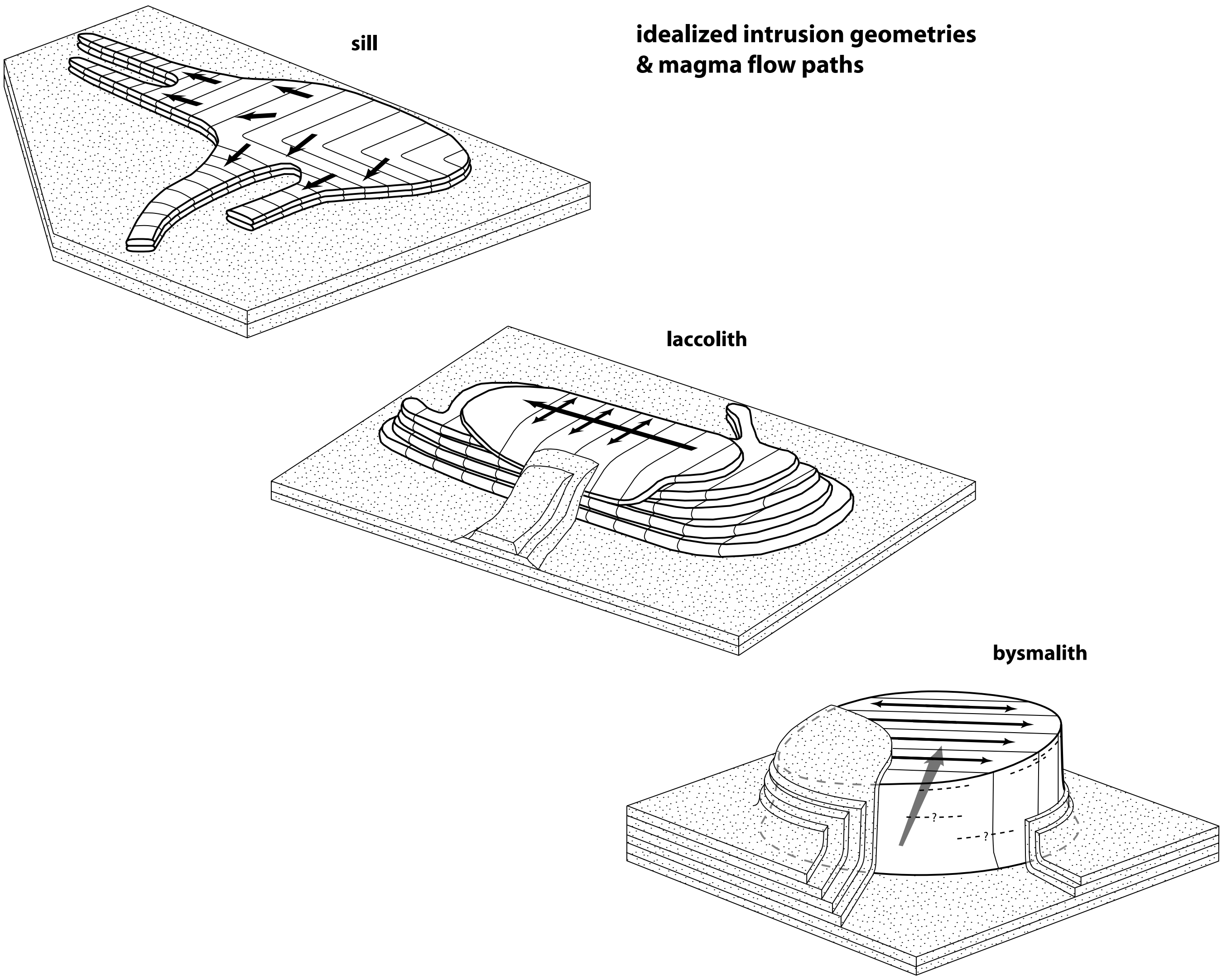

Figure 8 Schematic block diagrams of idealised intrusions, including magma sheets, inferred primary magma flow directions and relationships with sedimentary wallrock. These diagrams show characteristic features of intrusions with sill, laccolith and bysmalith geometries assembled from multiple pulses. Although the sketches are somewhat similar to the observed intrusions in the Henry Mountains, they do not accurately reflect those observations.

laccolith and the overburden was lifted in a piston-like manner to produce a bysmalith. The circular map pattern minimises the area of the intrusion-bounding fault, maximising the efficiency of overburden uplift. Additionally, the different geometries on the eastern and western margins of the Black Mesa intrusion provide clear evidence of the transitional nature of the change from laccolith to bysmalith. Emplacement of additional magma pulses would presumably have produced further roof uplift and eventually a fault around the entire pluton margin. Examples of well-developed bysmaliths are seen elsewhere in the Henry Mountains (e.g. Bull Mountain and Table Mountain on the Mt Ellen intrusive centre; Hunt 1953).

The main distinctions between the different types of intrusion appear to be (1) the amount of magma that is emplaced and (2) the manner in which the wallrock accommodates emplacement. The amount of magma appears to correspond to the specific number of magma pulses, recognisable as horizontal sheets at the periphery of the intrusion where cooling is rapid. The magma pulses must have similar volumes, within an order of magnitude, as they have similar thicknesses over approximately the same map area. The Maiden Creek intrusion consists of two magma pulses, the Trachyte Mesa intrusion consists of at least ten magma pulses, and thermal modelling suggests the Black Mesa consists of at least ten pulses (Saint Blanquat *et al.* 2006).

The Black Mesa intrusion also demonstrates the importance of the evolution of emplacement mechanisms as pluton volume grows. In fact, this intrusion preserves the transition of primary emplacement mechanism from wallrock rotation and distortion seen on the laccolithic western margin to wallrock uplift through faulting, as seen at the bysmalithic eastern margin. This transition is likely related to mechanical limits on the amount of strain the wallrock can accommodate, and perhaps to rates of deformation, with both high strain and high strain rates leading to localisation and faulting.

During the progression from sill to laccolith to bysmalith, the volumetric importance of peripheral lobes decreases as total pluton volume increases. For example, a large portion of the intrusive volume of the Maiden Creek sill occurs as lobes radiating away from a relatively small central main body. The Trachyte Mesa laccolith, finger-like lobes exist only at the margin of the relatively large main body of the intrusion. No such lobes are exposed as part of the approximately cylindrical Black Mesa intrusion. This decrease in the volumetric importance of finger-like lobes may reflect increasing stability of pluton geometry; emplacement of additional magma produces vertical pluton growth rather than lateral growth. Similarly,

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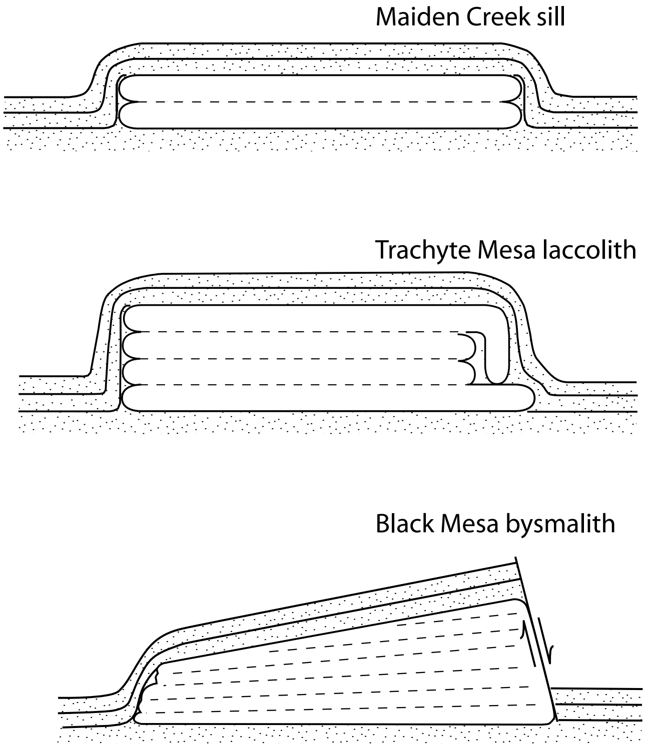

Figure 9 Schematic cross-sections through the Maiden Creek, Trachyte Mesa, and Black Mesa intrusions to illustrate idealised emplacement mechanisms and our preferred assembly histories. Intrusions are not drawn to scale. The number of pulses shown is intended to demonstrate relationships between successive pulses rather than actual number.

the cylindrical shape of the Black Mesa intrusion may have evolved from a less volumetrically efficient elongate laccolith, similar to the Trachyte Mesa intrusion, at an earlier stage.

6.1.1. Comparison with previous models. Pollard & Johnson (1973) developed a model of the evolution of pluton geometry that was mainly based on wallrock geometry. This model involves the following three stages: (1) Intrusion of an initial sill and growth by lateral propagation; (2) When a critical length/thickness ratio is achieved, the sill begins to inflate vertically by overburden bending to produce a laccolith, which is also still growing laterally; (3) Finally, fracturing of wallrocks over the periphery of the intrusion permits the uplift of both the wallrock and older igneous sheets. This fault-controlled roof uplift results in vertical growth and transforms the laccolith into a bysmalith.

The observations of the present authors are in general agreement with this succession of events (sill to laccolith to bysmalith), but not in agreement with the proposed mechanisms. First, no clear evidence is found for a true laccolithic stage of growth, for the three following reasons: (1) Each intrusion has a tabular, nearly flat roof, not a dome-like shape predicted by laccolithic growth; (2) Profiles of the contacts on the margins of all three intrusions (including the W side of Black Mesa) have a staircase-like shape rather than a smooth progressive bending predicted by classic laccolith models; and (3) The existence of simultaneous vertical and lateral propagation is not supported by the data. The initial sill of the Trachyte Mesa laccolith, for example, had a size similar to the final horizontal size of the pluton.

The idea of the achievement of the maximum horizontal size before the beginning of vertical growth is also supported by structural data from the wallrock. First, the absence of faults (i.e. ‘remnant’ hinges) in wallrock above all the intrusions shows that deformation remained localised more or less at the same place (along the margins) during growth. Thus, the vertical growth began after lateral growth, and consequently vertical growth was not accompanied by significant lateral growth. Secondly, in the marginal wallrock around the Black Mesa intrusion, not only sub-vertical, but also sub-horizontal and shallowly dipping fractures and faults have been measured, with normal and reverse slip sense (Saint Blanquat *et al.* 2006). These can be interpreted as remnants of flexural hinges developed during the beginning of the vertical growth, before the loss of continuity of the bedding (see fig. 16 of Corry 1988).

The question remains as to what factors control the change from sill-like emplacement to bysmalith-like emplacement during the growth of a large intrusion. As stated above, the present authors’ observations contradict Pollard & Johnson’s (1973) suggestion that the switch occurs once a laccolith reaches a particular radius relative to its thickness. Another possible controlling factor may be wallrock lithology, as suggested by the emplacement of the Black Mesa intrusion within relatively compliant shale (the Summerville formation), whereas the two smaller intrusions both formed within relatively stiff sandstone (the Entrada formation). Additional possibilities include an increase in magma emplacement rate, or variations in feeder position and geometry.

6.2. Fabric and magma flow patterns

The rapid cooling of the intrusions due to their small size and shallow depth ensures that the fabrics preserved in the plutons reflect magma flow patterns. Thus, by combining detailed knowledge of intrusion geometry with fabric data from the intrusions, the evolution of magma flow during emplacement and assembly can be considered. Additionally, the observations of feeder conduit geometry allow the examination of relationships between magma flow patterns and the magma supply.

Bulk magma flow patterns evolve as intrusion geometry progresses from sill to laccolith to bysmalith. In the Maiden Creek sill, a direct correlation is observed between the complex, lobate intrusion geometry and fabric patterns. Magma flowed radially out from an unexposed feeder into the main body and then was channelised into the lobate finger-like regions. The observed correspondence between geometry and fabric pattern thus provides a useful test of the utility of fabric analysis in these rocks. These complex, lobate geometries are not confined to the upper crust; Stevenson *et al.* (2007) inferred assembly of a mid-crustal pluton through emplacement of numerous finger-like magma pulses.

Magma flow patterns in the Trachyte Mesa intrusion reflect more organisation of the magma distribution system than developed in the Maiden Creek intrusion. Rather than flowing radially away from the feeder source in numerous sinuous lobes, magma flowed from the several sub-horizontal feeder pipes and, once in the intrusion, out along the central axial magma channel. From this channel, magma flowed out laterally to supply the margins of the intrusion. This bilaterally symmetric magma flow pattern bears a striking resemblance to inferred magma flow patterns in large, complex sills analysed in detailed three-dimensional seismic reflection studies (Thomson & Hutton 2004; Hansen & Cartwright 2006) and to physical models of magma flow by Kratinová *et al.* (2006). Although these patterns are commonly interpreted as resulting from flow away from a steeply dipping feeder dike (e.g. Ferré *et al.* 2002), these examples demonstrate that feeder geometry cannot be inferred from fabric data alone.

Magma flow patterns in the Black Mesa intrusion have a bilateral symmetry similar to that observed in the Trachyte Mesa intrusion. Both intrusions have central axial conduits

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trending radially away from the main Mt Hillers intrusive centre. Additionally, the lateral margins of the both intrusions were presumably fed by flow away from an axial conduit. This similarity suggests that the magma distribution system may be similar in both the laccolith and the bysmalith. However, little fabric data from the interior of the Black Mesa intrusion is available, so this hypothesis is not well constrained. Nonetheless, the similarity suggests that early in its assembly history (i.e. preserved in fabrics near the roof) the Black Mesa intrusion went through a stage similar to that observed on the Trachyte Mesa intrusion. By extension, if the transition from laccolith to bysmalith involved vertical inflation and progression toward a cylindrical shape, it is consistent with the magma distribution system remaining stable throughout that geometric evolution. Thus, it appears that with increasing maturity of the magma distribution system, flow patterns evolve and become progressively more stable and efficient.

This analysis of correspondence between evolving intrusion geometry and magma flow patterns was possible only because the conditions were ideal for preservation of fabric in these small intrusions.

6.3. Pulsed assembly

Evidence of pulsed assembly exists in each of the three intrusions. This evidence is unequivocal in the Maiden Creek and Trachyte Mesa intrusions. In the Black Mesa intrusion, the sub-horizontal textural layering and cataclastic zones near the top of the intrusion suggest that early stages of assembly involved multiple magma pulses. The importance of magma pulses during the late stages of assembly of the Black Mesa intrusion is less clear, but vertical variation in geochemistry suggests that pulses existed throughout assembly (Bankuti 2007). Assuming that pulsed assembly continued throughout the growth of the intrusion, a threshold governing sheet contact preservation was crossed at some point. This threshold is of considerable interest because of the ongoing debate regarding possible pulsed assembly of large intrusions.

Several factors govern the preservation of evidence for pulses. Differences in composition of juxtaposed pulses result in the most easily recognisable contacts. A large temperature contrast between the pulse and the host rock (i.e. wallrock or a previous magma pulse) favours the development of solid-state fabric and makes pulse contacts more easily recognisable. The strain rate in the intruding magma must however be sufficiently high to produce solid-state fabric. A long time-lag between pulses allows the previous pulse to cool and favours strong fabric development. These several factors are interdependent and govern processes like annealing of emplacement-related fabric and reworking of pulse margins, both of which can destroy evidence of pulses.

For example, Tuffen & Dingwell (2005) demonstrate how early cataclastic fabrics in shallow volcanic conduits were modified and eventually destroyed by subsequent annealing and ductile deformation. They note that in some cases it is possible to recognise multiple generations of such overprinting structures. This cyclical brittle–ductile deformation may be a consequence of temperature variations moving the melt across liquid–glass transition. Thus, a new pulse of magma may reheat older solidified magma, including solid-state fabric, resulting in annealing and renewed flow deformation of the older magma. Matzal *et al.* (2006) present further evidence of reworking of pulse margins deeper in the crust. In their model, as a magma pulse is emplaced and begins to cool, the volumetric crystal percentage increases, and the remaining melt is largely trapped inside a crystal-rich carapace. Subsequent pulse emplacement reheats the margin of the previous sheet, partially incorporating some of the other material, and blurring the transition between the pulses both chemically and texturally.

The question remains at to why sheeting is clearly preserved in the Maiden Creek and Trachyte Mesa intrusions, but cryptic in the Black Mesa intrusion. Both the shallow depth of emplacement and the relatively small volume of all three intrusions contribute to rapid cooling. The lack of preservation in the Black Mesa intrusion demonstrates the ephemeral nature of such features, even with rapid cooling. The lack of field evidence of pulsed assembly in some deeper, larger intrusions (e.g. Glazner *et al.* 2004) is therefore not surprising. Pulsed assembly is, however, apparent in some plutons, despite the factors working against preservation of evidence. Most examples of large intrusions with pulsed assembly are composite plutons where pulses of different composition make recognition straightforward (Wiebe 1993, 1994; Wiebe & Collins 1998; Wiebe *et al.* 2002; Matzal *et al.* 2006; Michel *et al.* 2008), although evidence can be cryptic even in composite plutons (Mahan *et al.* 2003).

Host rock deformation can provide indirect evidence of magma pulses. Albertz *et al.* (2005) suggest that moderate background strain rates in pluton aureoles may be punctuated by high strain rate excursions associated with emplacement of magma pulses. Fernández & Castro (1999) called upon similar processes. These pulses of intense deformation can produce localisation of strain as shear zones or faults in the vicinity of plutons. This intense deformation is superposed upon the background deformation of host rock associated with pluton emplacement.

Several hypotheses exist for the formation of magma pulses and can be broadly divided into mechanisms due to: (1) ascent processes; (2) emplacement processes; or (3) source region processes. Ascent-related mechanisms suggest that interaction between magma ascending in sub-vertical dike-like or pipe-like channels results in formation of magma pulses (e.g. Denlinger & Hoblitt 1999). Emplacement-related mechanisms attribute magma pulses to similar interactions during pluton assembly rather than in the feeder conduit. The processes of magma generation and segregation in the source region operate an order of magnitude more slowly than the processes of ascent and emplacement (Petford *et al.* 2000). Thus, even minor cyclical processes in the source region can result in more dramatic cyclicity in the upper crust.

Regardless of the mechanisms leading to pulse formation, the existence of pulses may largely invalidate existing mechanical models of the growth of shallow intrusions (e.g. Pollard & Johnson 1973; Kerr & Pollard 1998; Zenzri & Keer 2001), which rely on entire igneous bodies acting as a single mechanical entity throughout assembly. Future theoretical models should account for empirical evidence for pulsed assembly and actual geometric shapes (e.g. flat rather than domed tops) of the intrusions. Further field-based work needs to concentrate on how magma flows during a single pulse, which can in turn constrain mechanical models of emplacement and assembly.

6.4. Time scales of emplacement and assembly

Recognition of the pulsed nature of the assembly of many upper-crustal plutons leads to the question of the time scales on which these processes operate. Few timing constraints exist for the Henry Mountains, but radiometric ages constrain timing at the scale of the entire range and, to a lesser extent, in individual intrusive centres (Nelson *et al.* 1992). For example, ages throughout the Henry Mountains span ~9 Myr from 30 Ma to 21 Ma. Individual intrusive centres have age ranges restricted to ~3 Myr or less. Other data provide evidence of the relative ages of component intrusions in intrusive centres. For example, Jackson & Pollard (1988) used palaeomagnetism

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to demonstrate that early sills on Mt Hillers were rotated and uplifted by later magmatism that formed the underlying main laccolithic body.

Thermal modelling can provide additional constraints on assembly times for individual plutons (e.g. Annen *et al*. 2006). The present authors use one-dimensional thermal modelling of the Black Mesa intrusion by Habert & Saint Blanquat (2004) and Saint Blanquat *et al*. (2006) to provide a conservative maximum duration of pulsed assembly. Several assumptions and observations ensure that this thermal modelling provides a maximum estimate of the duration of assembly. First, the assumption of cooling solely through conduction provides a maximum estimate of the time necessary to cool through the solidus, because the advection of heat due to interaction with groundwater, or to the release of intrusion-related fluids, would cool the intrusion more rapidly than conduction alone. Secondly, the lack of evidence of clear contacts between separate magma pulses in the pluton constrains the time between pulses to be no longer than the time for the margin of last pulse to cool through the solidus. Results of the thermal model suggest that the lack of internal contacts can be explained if the intrusion formed in less than 100 years through the amalgamation of numerous sheets. This result implies that the roof lifted at least 2 m/yr during assembly. The less voluminous Maiden Creek and Trachyte Mesa intrusions were likely assembled in much shorter periods of time.

The time scales of the emplacement of individual component magma pulses are difficult to assess directly. However, individual pulses in each intrusion must be short lived, particularly if individual plutons are emplaced within 100 years (e.g. the Black Mesa intrusion). The magma supply clearly persisted for a lengthy period of time relative to the lifespan of a single pluton, or even a single intrusive centre. At the scale of the Mt Hillers intrusive centre, magma may have ascended in a few relatively large batches. However, the satellite intrusions studied in the present paper were likely assembled in myriad small, laterally fed pulses from the adjacent larger body.

Evidence from other studies reinforces the observations made in the Henry Mountains. Examples of the pulsed nature of assembly come from studies of both modern and ancient upper-crustal magmatism. Interferometric synthetic aperture radar studies demonstrate that sub-volcanic magma chambers inflate and deflate on time scales of weeks to months (e.g. Voight *et al*. 1998; Pritchard & Simons 2004). Henry *et al*. (1997) note that the Solitario laccolith-caldera is composed of three distinct episodes of magmatism, and demonstrate that these episodes are each composed of numerous magma pulses. Evans *et al*. (1993) used seismic reflection to recognise that the Lake District batholith is composed of numerous sub-horizontal sheets. Similarly, radiometric dating of such intrusions suggests that magmatism feeding a single intrusion can last a million years or even a few million years (Harrison *et al*. 1999; Glazner *et al*. 2004; Matzal *et al*. 2006). Such time spans are considerably longer (often by an order of magnitude) than it takes a shallow pluton assembled as a single large pulse to solidify.

Thus, several independent lines of evidence suggest that pluton assembly in the upper crust is not a continuous and gradual process. Rather, many plutons grow through the amalgamation of numerous pulses of magma. These pulses tend to be obscured even under conditions ideal for preserving evidence of magma pulses: high crustal levels, fast cooling rates, and no regional deformation. The characterisation of pulses likely depends on both the temporal and the spatial scales of observation.

6.5. Emplacement versus assembly

The exceptional exposure and ideal conditions for preserving evidence of magma pulses in the Henry Mountains allow us to make some statements about emplacement and assembly of plutons that are generally applicable to intrusions. The first concerns the difference between emplacement and assembly. The intrusions of the Henry Mountains inspired Gilbert (1877) to coin the term *laccolite*, which he used to describe a pluton that made space for itself by uplifting the overlying rocks. For the last 100 years, there has been no argument about the *emplacement* of the small intrusions in the Henry Mountains. The *assembly* of these plutons, in contrast, has not been understood. Although previously inferred to have formed from a single pulse of magma, the present work demonstrates that they occurred in multiple magma pulses. Thus, emplacement and assembly can be distinguished. The process of assembly by multiple pulses opens new fields of research. For instance, how does an individual magma pulse flow either into a pre-existing chamber or into wall rock? How do these patterns and processes evolve as subsequent pulses are emplaced? At present, these processes are largely unstudied.

Another unique aspect of the Henry Mountains is the well-exposed intrusion geometries, which allow the present authors to recognise that none of the three intrusions studied fits neatly into a common idealised geometry category. The Maiden Creek sill has a highly complex map-view geometry, despite its simple cross-sectional geometry. The Trachyte Mesa laccolith is largely tabular, similar to a sill, only bending the wallrocks on the margins of the intrusion. This pattern is consistent with most laccoliths, which commonly have flat rather than domed tops (Corry 1988). The Black Mesa intrusion is clearly transitional between a laccolith (on the west side) and a bysmalith (on the east side). These details of true intrusion geometry provide essential information about emplacement and assembly history. While idealised models provide a useful reference frame, they can lead to oversimplification of the mechanisms of emplacement, assembly, and magma flow.

Finally, there is the historical aspect of pluton emplacement and assembly. Many plutons assembled from multiple pulses change geometry considerably over time, as emplacement mechanisms accommodating sequential pulses evolve (e.g. McNulty *et al*. 2000; Belcher & Kisters 2006). The complexities inherent in analysing plutons in tectonically active regions (e.g. overprinting of fabrics, incomplete data sets, unknown three-dimensional geometries, etc.) make it difficult to directly compare them with the Henry Mountains intrusions. However, many of the same features are found in both cases, suggesting that similar processes operate during emplacement and assembly, regardless of differences in scale or the presence of tectonic activity (e.g. McCaffrey & Petford 1997; Saint Blanquat *et al*. in press).

7. Conclusions

The three intrusions studied in the Henry Mountains represent successive snapshots of the emplacement of an upper crustal pluton during geometric evolution from sill to laccolith to a piston-like bysmalith. Assembly of each of these intrusive bodies occurred through a series of magma pulses, manifested locally as distinct magma sheets. The exceptionally well-preserved intrusion geometries demonstrate that idealised models of intrusion shape are overly simplistic. These bodies appear to be fed by sub-horizontal, pipe-like conduits emanating from the main intrusive centre, located several kilometres away.

Magma flow patterns are well preserved because of rapid cooling due to the small intrusion volumes, rapid assembly, and shallow depth of emplacement. These magma flow patterns correspond well with observed complex intrusion geometries. Early magma flow in the sill involved radial flow away from a pipe-like feeder and into several finger-like lobes. As intrusion volume grew, the magma distribution system stabilised through the formation of a central axial conduit that fed magma laterally out to the pluton margins. During further growth this magma distribution system remained stable, and consistent magma flow patterns reflect this stability. Increasing intrusion volume also resulted in the evolution of the primary emplacement mechanism: from wallrock uplift; through rotation; to distortion at intrusion margins; to wallrock uplift through faulting.

Evidence of the magma pulses comprising each body becomes more cryptic as intrusion volume grows. Many processes can obscure evidence of pulses and these processes typically become more effective at deeper crustal levels. Thus, a lack of evidence does not necessarily imply a lack of pulsed assembly.

It is concluded that assembly of these igneous intrusions occurs through the amalgamation of numerous pulses of magma, which may be a common occurrence in upper crustal intrusions. These pulsed emplacement and assembly processes operate at many spatial and temporal scales. The conditions in the Henry Mountains – shallow crustal levels, fast cooling rates, and no regional deformation – were ideal for the preservation of internal structures. As the conditions of emplacement and assembly for most plutons are considerably more complex, preservation of primary internal structures is less likely.

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