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Deformation structures associated with the Trachyte Mesa intrusion, Henry Mountains, Utah: Implications for sill and laccolith emplacement mechanisms

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A B S T R A C T

Deformation structures in the wall rocks of igneous intrusions emplaced at shallow crustal depths preserve an important record of how space was created for magma in the host rocks. Trachyte Mesa, a small Oligocene age intrusion in the Henry Mountains, Utah, is composed of a series of stacked tabular, sheet-like intrusions emplaced at 3–3.5 km depth into sandstone-dominated sedimentary sequences of late Palaeozoic–Mesozoic age. New structural analysis of the spatial distribution, geometry, kinematics and relative timings of deformation structures in the host rocks of the intrusion has enabled the recognition of distinct pre-, syn-, and late-stage-emplacement deformation phases. Our observations suggest a two-stage growth mechanism for individual sheets where radial growth of a thin sheet was followed by vertical inflation. Dip-slip faults formed during vertical inflation; they are restricted to the tips of individual sheets due to strain localisation, with magma preferentially exploiting these faults, initiating sill (sheet) climbing. The order in which sheets are stacked impacts on the intrusion geometry and associated deformation of wall rocks. Our results offer new insights into the incremental intrusion geometries of shallow-level magmatic bodies and the potential impact of their emplacement on surrounding host rocks.

1. Introduction

Shallow-level (<5 km depth) sill and laccolith complexes typically consist of a series of sub-horizontal tabular sheet-like intrusions and form an integral part of sub-volcanic plumbing systems (Cruden and McCaffrey, 2001). Understanding the formation of these networks of sub-horizontal intrusions is, therefore, key to assessing volcanic and sub-volcanic processes such as magma supply and storage in the upper crust (Bachmann and Burgantz, 2008). To-date, significant insights into sill and laccolith emplacement have been made through the characterisation of their geometry and internal architecture using field- and seismic-based data (Du Toit, 1920; de Saint Blanquat and Tikoff, 1997; Thomson, 2004; Thomson and Hutton, 2004; Horsman et al., 2005; Stevenson et al., 2007a,b; Thomson and Schofield, 2008; Magee et al., 2012). A number of studies have examined the important role played by active faults and shear zones and pre-existing host rock structures in controlling the emplacement and growth of mid-crustal granitic intrusions (e.g. Hutton et al., 1990; McCaffrey, 1992; Neves et al., 1996; Holdsworth et al., 1999; Passchier et al., 2005). Several studies have examined emplacement-related deformation structures associated with the intrusions of the Henry Mountains (Johnson and Pollard, 1973; Pollard et al., 1975; Morgan et al., 2008), but a complete analysis of the geometry, kinematics and sequential development of the wall rock structures has not yet been published.

The Henry Mountains, located in SE Utah on the Colorado Plateau (Fig. 1a), are a type locality for the study of shallow-level igneous intrusions and their emplacement. It was here that Gilbert (1877) famously first described and named laccoliths (coining the term "laccolite"; Gilbert, 1896). Since then, a number of studies have examined the geometries, geochronology and emplacement of intrusions in the Henry Mountains (e.g., Hunt,

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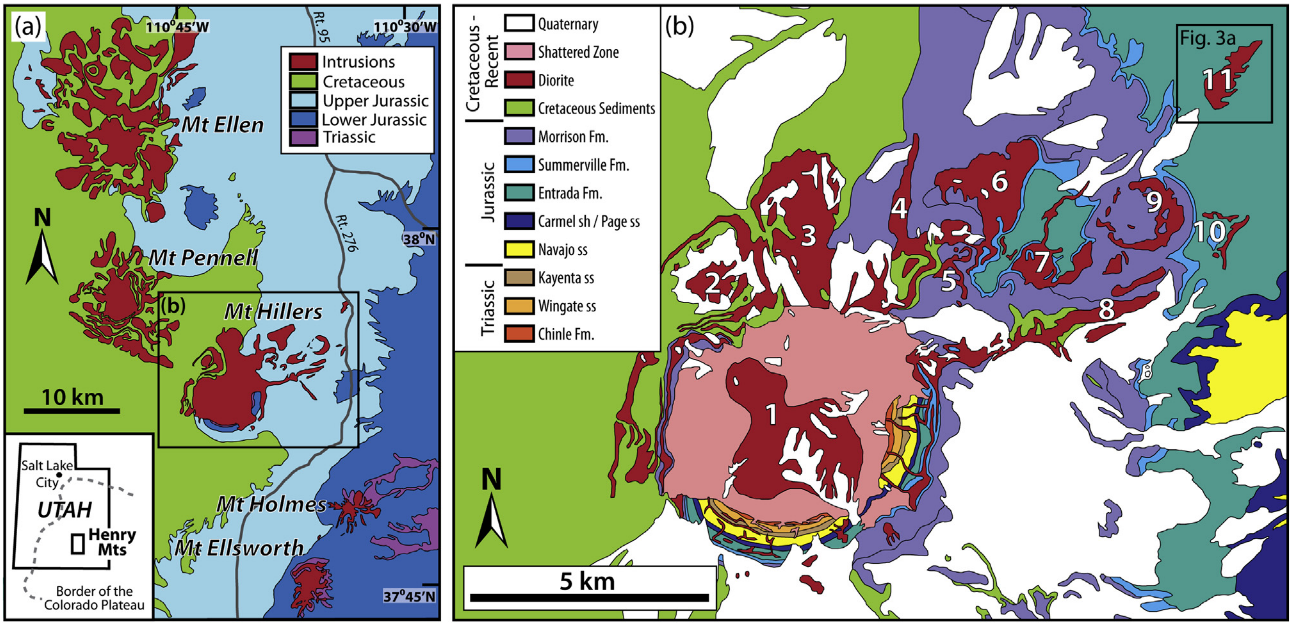

Fig. 1. Simplified regional geological maps of the Henry Mountains. (a) The Henry Mountains region (adapted from Morgan et al., 2008) and its location within Utah (inset map). (b) Mount Hillers and its satellite intrusions (modified from Larson et al., 1985). In (b), the various intrusions that comprise the Mt Hillers intrusive complex are numbered, using the names given by Hunt (1953): 1 – Mt Hillers central complex; 2 – Bulldog Peak intrusion; 3 – Stewart Ridge intrusion; 4 – Specks Ridge intrusion; 5 – Chaparral Hills Laccolith; 6 – Specks Canyon; 7 – speculated feeder system to the Trachyte Mesa intrusion; 8 – Sawtooth Ridge intrusion; 9 –Black Mesa intrusion; 10 – Maiden Creek intrusion; 11 – Trachyte Mesa intrusion.

1953; Johnson and Pollard, 1973; Jackson and Pollard, 1988; Nelson and Davidson, 1993; Habert and de Saint Blanquat, 2004; Horsman et al., 2005; Morgan et al., 2005; de Saint Blanquat et al., 2006; Wetmore et al., 2009; Wilson and McCaffrey, 2013).

Following numerous field studies of the Henry Mountains, Hunt (1953) proposed three general emplacement models for shallow level intrusions (Fig. 2a–c):

(1) Radial growth only, with magma emplaced at a constant thickness, and country rocks displaced both vertically and laterally (i.e. Model I, a “bulldozing” mechanism; Fig. 2a);
(2) Simultaneous vertical and horizontal growth (Model II, Fig. 2b);
(3) Radial growth of a thin sill, followed by dominantly vertical growth and associated vertical uplift of the overlying host rocks (i.e. Model III, a “two-stage growth” mechanism; Fig. 2c).

Increasingly, evidence suggests that shallow-level crustal intrusions are emplaced and grow through the incremental addition of small volumes of magma, with the amalgamation and stacking of sill-like sheets (e.g. Pitcher, 1970; Mahan et al., 2003; Glazner et al., 2004; Menand, 2008; Morgan et al., 2008). Therefore, the two-stage growth model (Hunt, 1953, Model III) appears most applicable for many larger shallow-level intrusions (i.e. vertical inflation with stacking of sill sheets through under- and over-accretion; Annen et al., 2008; Menand, 2008; Menand et al., 2011). However, for the emplacement of individual sills, all three of Hunt's models (1953) may still be viable.

Corry (1988) highlighted that deformation structures associated with emplacement are potentially strongly linked to the mechanism of emplacement (Fig. 2d–f). A number of studies of emplacement-related host rock deformation have focused on intrusions of the Henry Mountains; these include Johnson and Pollard (1973), Jackson and Pollard (1988), and Morgan et al. (2008). However, little consideration has been given to the kinematic pathways and associated strains in the wall rocks that can potentially preserve information concerning emplacement mechanisms of individual sills and magma movement (i.e. flow directions).

In this paper, we present a new structural analysis of the geometry, spatial distribution, kinematics, and relative time sequences of host-rock deformation structures surrounding the Trachyte Mesa intrusion, a small satellite intrusion adjacent to the Mount Hillers intrusive complex, Henry Mountains, Utah, USA (Fig. 1b, intrusion 11). By integrating observations of the host-rock structures with the sequential intrusion history, we have created an improved model for the emplacement of Trachyte Mesa that builds on the pioneering studies of Gilbert (1877), and the more recent work of Johnson and Pollard (1973), Morgan et al. (2008) and Wetmore et al. (2009). The results offer new insights into the incremental evolution of intrusion geometries in shallow-level magmatic bodies and how their emplacement leads to deformation of the surrounding sedimentary host rocks.

2. Geological setting

2.1. Henry Mountains

The Henry Mountains Complex consists of five intrusive centres that form the principal mountain peaks in the area. From north to south these are: Mt Ellen; Mt Pennell; Mt Hillers; Mt Holmes; and Mt Ellsworth (Fig. 1a). Most of the intrusions have an intermediate (dioritic) composition (58–63% SiO_2; Hunt, 1953; Engel, 1959; Nelson et al., 1992) and a porphyritic texture, with dominant feldspar (An20–An60; 20–40%) and hornblende (5–15%) phenocrysts. The intrusions are Oligocene in age (31.2–23.3 Ma K–Ar ages; Nelson et al., 1992), and were emplaced into a 3–6 km thick section of late Palaeozoic–Mesozoic predominantly aeolian to shallow-marine sandstones, siltstones and mudstones that overlie