The intrusion space problem: a comparative study of accommodation and deformation structures associated with the emplacement of the Maiden Creek and Trachyte Mesa satellite intrusions, Henry Mountains, Utah.

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This presentation covered the work done by the speaker for a PHD at Durham University, which was published in *Geoscientist*, July 2013, in a paper jointly authored by the speaker, Ken McCaffrey, Bob Holdsworth, Ian Jarvis and Jon Davidson.

Introduction

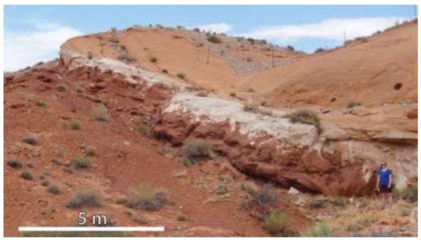
In 1869, John Wesley Powell travelled 1,000 miles down the Green River and Colorado River and discovered the Henry Mountains, the final mountain range in the USA to be named in 1872. The mountains look like volcanoes from a distance and they were believed to be structural domes associated with lavas. G>K. Gilbert, twice President of the Geological Society of America visited them in the summers of 1876 and 1877 and identified them as intrusions exposed as the cover was eroded away and coined the term laccolites. The Henry Mountains are subduction-related, with the magma ascending through the crust and frequently ponding at depth. The intrusions can be discordant or concordant resulting in sills, laccoliths and loppoliths. Corrie (1988) identified the end-members as punched laccoliths and Christmas-tree laccoliths. They are essentially saucer-shaped sills with individual sheets transgressing strata boundaries. The magmatic fringes propagate forward and laterally and may coalesce as a larger body. Plutons in Yosemite may be multiple magma pulses rather than one big event. Hunt (1953) proposed 3 models for intrusion, a bulldozer mechanism, simultaneous growth and 2-stage growth with the intrusion reaching its radial extent then inflating upwards. Models 1 and 2 would create remnant hinge zones, while the third model would have hinge zones only at the end.

The speaker's aims in her research were to determine:

- What is the effect of emplacement of shallow-crustal intrusions on the surrounding country rock?
- How is the additional volume of magma accommodated within the crust, i.e. the so called "space problem"?
- Can we use style of deformation to infer sub-surface intrusion geometries?
- What can the style of deformation tell us about emplacement mechanism?
- What controls the emplacement mechanism?

Geological setting

The Henry Mountains are on the Colorado Plateau, which was quiescent during the whole of the Phanerozoic. There are 10 or more mountain ranges formed by igneous intrusions, which were emplaced over about 20 million years in the Tertiary. Extending 50km north to south, they rise to Mount Ellen and 4 other peaks and comprise a central complex with satellite intrusions. The rocks are plagioclase-hornblende porphyries emplaced at >3 and probably 5km depth into the Entrada Sandstone, quite porous sandstone with stress leading to deformation bands.



The speaker used terrestrial laser scanning, which gives great detail, using regional 360^{o} panoramas and a high-resolution laser scanner, enabling the capture of fractures and bedding geometries from inaccessible outcrops. This technique allows quantification of fracture attributes and their spatial distribution, enabling the identification of 3-dimensional fault surfaces and obtaining azimuth and dip data.

Trachyte Mesa

The Trachyte Mesa intrusion at Mt Hillers is 1.5-2.0km long and comprises multiple sill sheets. Phase 1, the pre-emplacement structure has normal faults and discrete deformation banding 5.0m and closer. Deformation banding increases ion a centimetre to decimetre scale in phase 2 with slickensided faults parallel to the intrusion margins. Phase 3, late emplacement has Mode 1 joints with calcite crystals on the joint surfaces in 2 sets, paralle to and normal to the margins – cooling joints. The phase 2 faults line up with the edges of sill sheets and there is evidence of the sills climbing up these step faults, showing the magma comes in to its radial extent then inflates with more magma leading to faults at the outer margin then complex sill climbing.

In summary, Trachyte Mesa is a satellite intrusion about 1.5km^2, 12.5km from the Mt Hillers intrusive centre. The principle magma flow direction was north-east to south-west to produce an elongate body composed of multiple stacked sills/sheets (over-accretion) with roof-faulting sill-climbin,g and some 'out-of-sequence' stacking (under- or mid-accretion). Deformation structures include conjugate deformation bands (sub-horizontal extension); dip-slip faults (down to NW extension movement); and relaxation (cooling) 'mode 1' fractures with calcite infill. The defomation style is extension-dominated and emplacement was by Sill stacking and 'two-stage' (1. radial; 2. vertical) growth.

Maiden Creek

This 200m thick intrusion is right next to Black Mesa and Sawtooth Ridge. There is an elliptical main body with 2 sets of finger-like lobes to north and south up to 100m thick. Beds are truncated against the magma and there is a zone of intense deformation in the sandstones adjacent to the lateral margins of intrusions. There is a wedge of highly faulted deformed rocks with deformation bands leading to pencil cleavage. The faults go from the sandstone into the intrusion

In the southern part of the Maiden Creek intrusion is the Maiden Creek shear zone, with bedding above being flat-lying while those beneath are intensely deformed. Beds are folded over flanking each of the intrusions with movement to the north-north-west and dominantly brittle deformation.

In summary, Maiden Creek is a satellite intrusion about 1 km^2, 10.5 km from the Mt Hillers intrusive centre. The principle magma flow direction was north-east to south-west to east-north-east to west-south-west to produce a body with complex geometry, for which 2 models are proposed. *Model 1* has a central ellipsoid body with 4 finger-like lobes (Horsman et al., 2005) while *Model 2* has multiple inclined (saucer-shaped?) sheets radiating outwards from an elongate central body (lobe/feeder dyke - this study). Deformation structures include conjugate deformation bands (sub-horizontal compression), low-angle reverse faults at intrusion margins, zones of intense deformation and pencil cleavage with sub-horizontal shear zones separating zones of intense deformation from less deformed rocks above, styolites on top contact of intrusions and relaxation (cooling), 'mode 1' fractures**.** Deformation style is compression-dominated at the margins and the emplacement mechanism is variable and poorly understood.

Conclusions and the future

Deformation structures commonly parallel intrusion margins and in some cases flow directions and kinematic analysis can give a strong indication of likely magma flow directions. Deformation styles (e.g. compressional, extensional, strike-slip) vary according to the local intrusion geometry, being dominantly compressional between intrusive bodies and more extensional around steps and corrugations on intrusion top surfaces. In stacked sill-sheet systems, insights into the order of stacking (i.e. over-, mid- and under-accretion; Menand, 2008) may be determined through analysis of associated deformation structures. Deformation structures can be used to understand the growth mechanism of sill sheets, eg dip-slip faults at sill sheet terminations imply a "two-stage" growth model. In areas where intrusion outcrop is not available, these findings can be applied to infer underlying intrusion geometries.

As for the future, it is expected that there will be a geophysical survey of the Maiden Creek intrusion, crystal size distribution (CSD) studies and the publication of papers.