Emplacement and propagation mechanisms of magma fingers

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1. Aims and Introduction

Magma transport in large volcanic plumbing systems is often described to occur via networks of channel-like sheet intrusions (i.e., dykes and sills). In many cases, elongate, finger-like geometries emerge from the outer margin of these planar sheet intrusions during magma migration through the Earth's crust. In this study, we aim to:

1) **Map and quantify how host rocks deform to accommodate the emplacement of magma fingers**
2) **Test, whether or not magma finger emplacement can be described with a single end-member emplacement model**

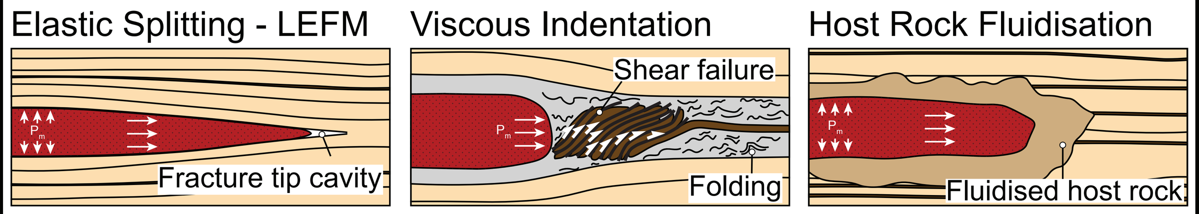
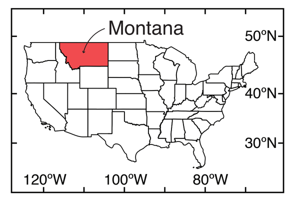


Figure 1. Schematic cross-sectional diagrams of magma emplacement models (modified after Spacapan et al., 2017; Pm indicates magma overpressure). The emplacement of magma fingers is often linked to brittle faulting, folding, cataclastic flow, and non-brittle processes and therefore is not dominated by LEFM. In case of host rock fluidisation, the contact between a relatively low viscous magma and a more viscous fluidised host rock might break-down into elongate magma fingers due to the Saffman-Taylor instability (Pollard et al., 1975; Schofield et al., 2010).

2. Shonkin Sag laccolith revisited

The Shonking Sag laccolith contains the archetypal example of magma fingers.



- The Shonkin Sag laccolith is of Tertiary age
- Mafic composition (Shonkinite)
- Emplaced into Cretaceous Eagle Formation (sandstones with thin shale interlayers) at an estimated emplacement depth of 1.4 km (Barksdale, 1937)

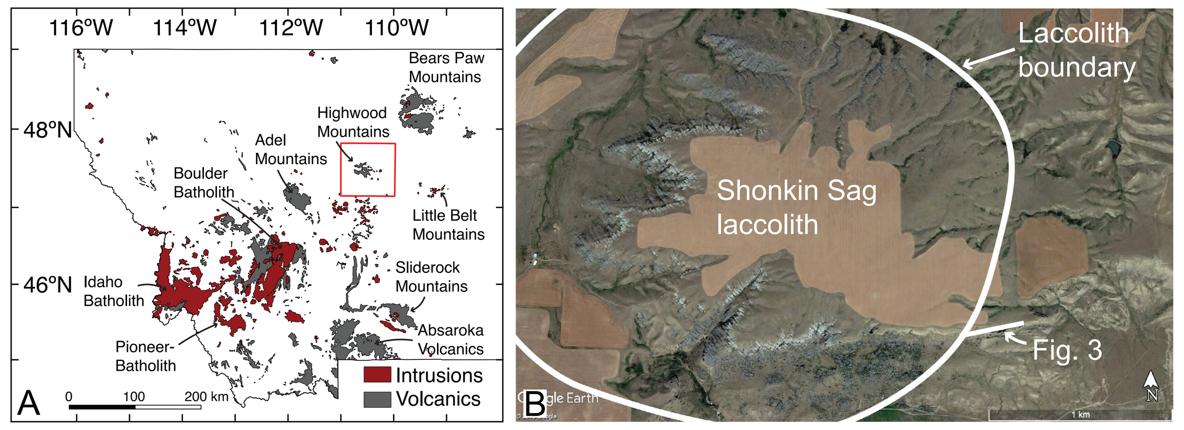


Figure 2. Study location. A) Overview of intrusive and volcanic rocks in Montana highlighted in red and grey, respectively, and B) Satellite image showing the Shonkin Sag laccolith with its boundary indicated. White line at the SE margin of the Shonkin Sag laccolith highlights the studied outcrop location. Satellite image obtained from GoogleEarth. A) is based on the Montana State Geological Map (1:1,000,000 scale) available from MBMG.

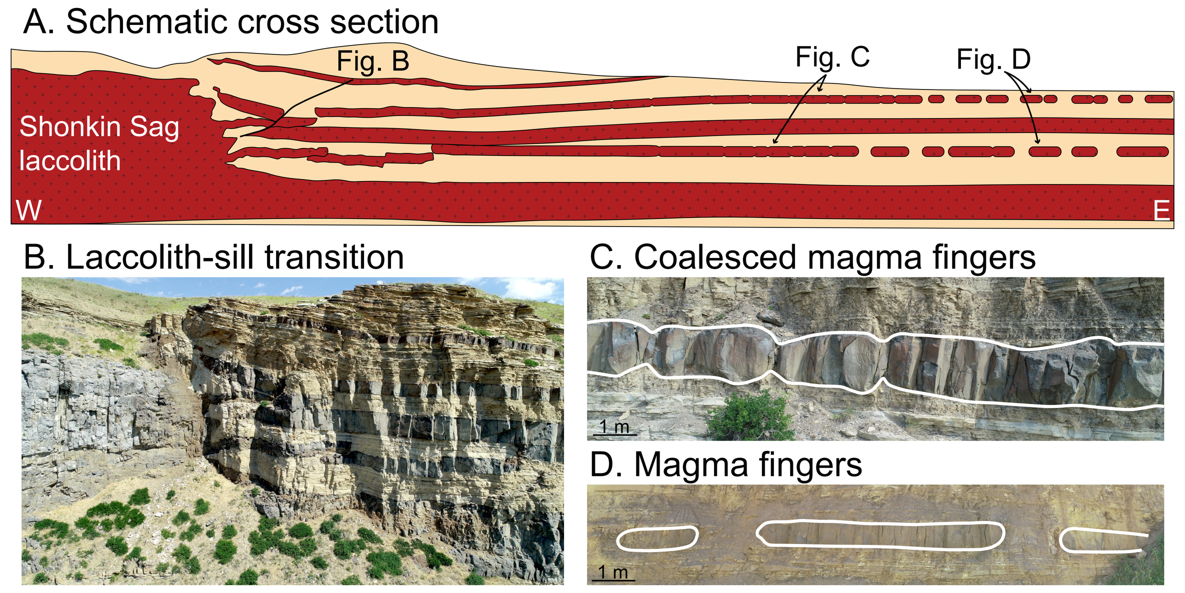


Figure 3. Schematic cross-section (A) of the cliff face, studied at the margin of the Shonkin Sag laccolith, and drone photographs (B-D) to visualise sill geometries observed in the outcrop. Schematic cross-section is not to scale. Please see Fig. 2B for cross-section location.

Previous studies

Pollard et al., (1975) studied the outcrop shown in Figure 3 and described host rock deformation associated with magma finger emplacement as: (i) folding; (ii) shear failure; (iii) wedging. Pollard et al., (1975) suggested viscous fingering as a potential mechanism to initiate magma fingers, however, which deformation mechanism(s) could have led to an unstable contact between the propagating magma and the host rock was unclear.

3. Magma emplacement related host rock deformation

(1) Host rock fluidisation

- Mainly observed at the cross-sectional finger tips
- Less commonly at the top and bottom of magma fingers

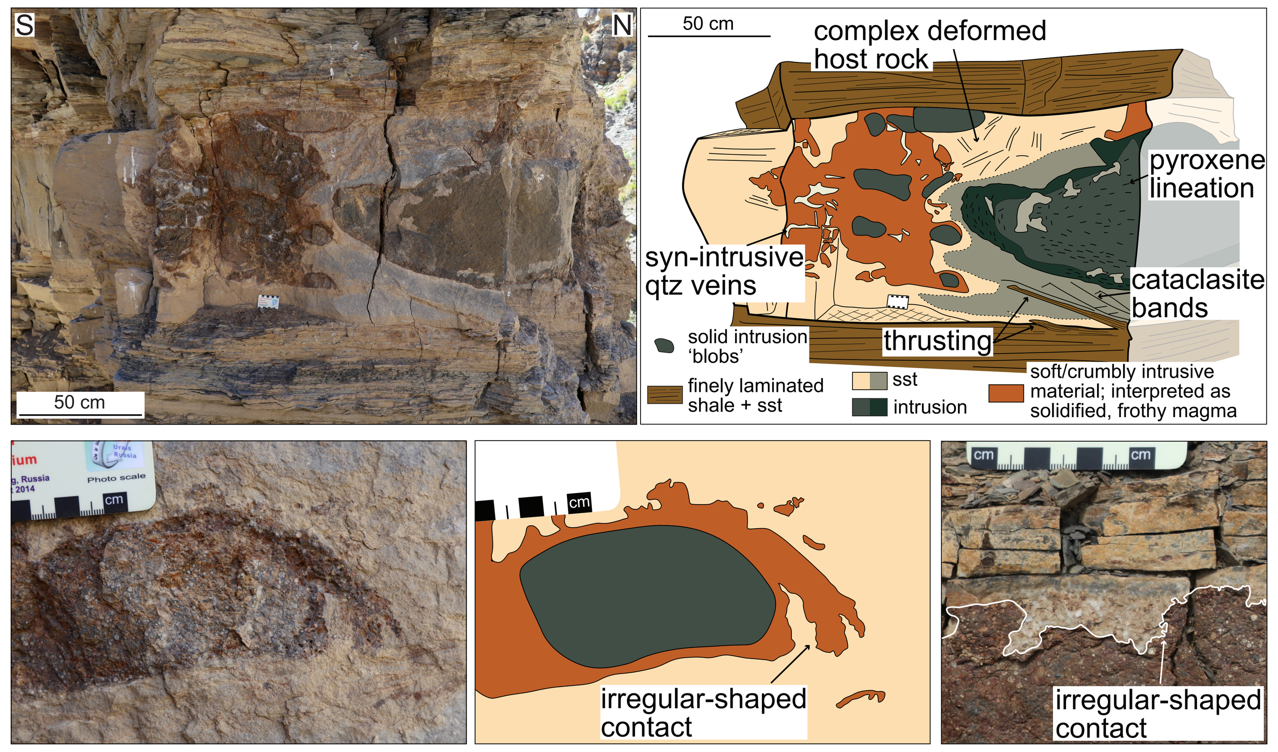
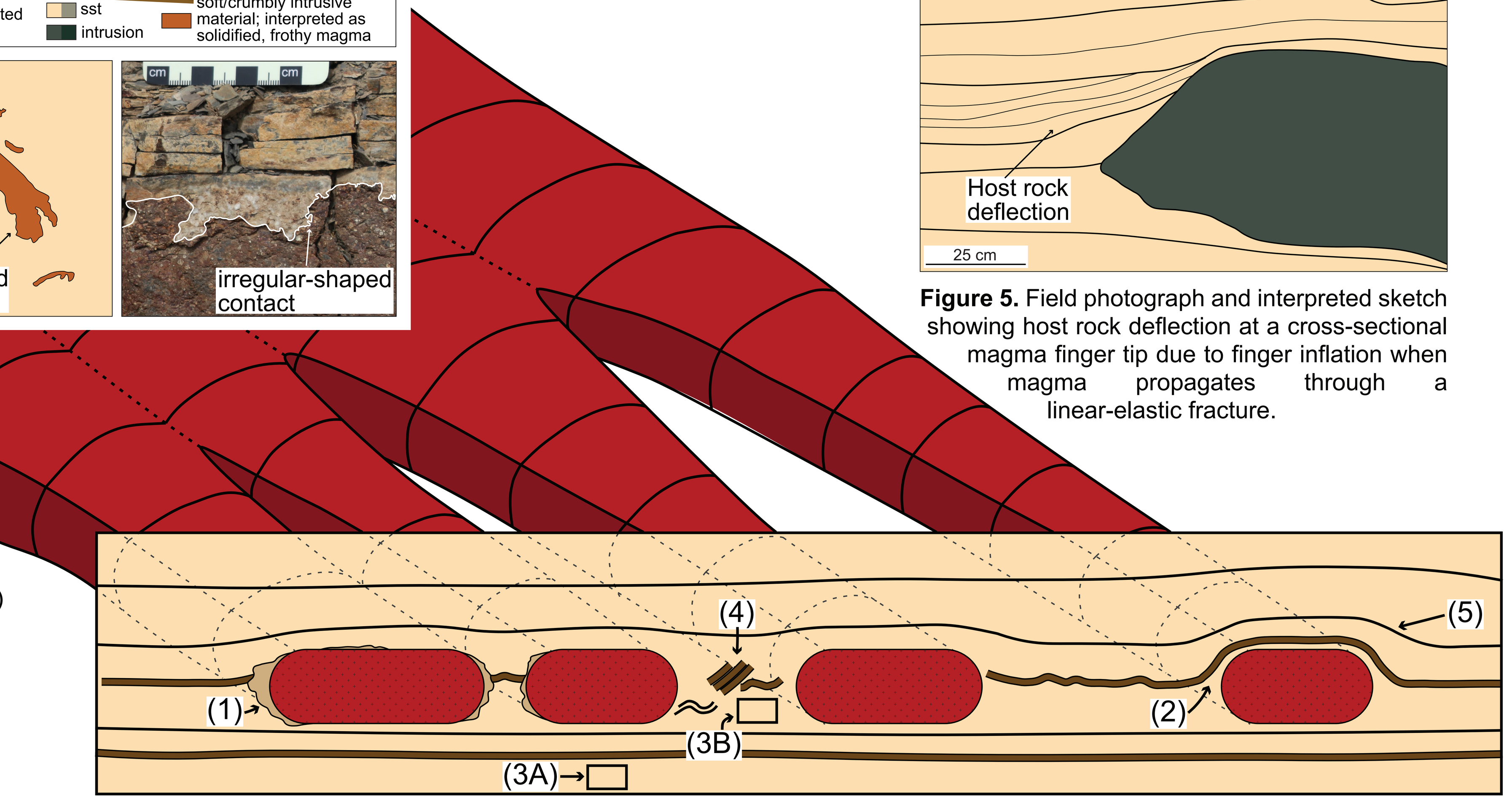


Figure 4. Field photographs and interpreted sketches indicating host rock fluidisation. (A) Oblique section through a magma finger showing solidified, frothy magma ahead of the lateral finger tip. (B-D) Irregular-shaped fluidal clasts of igneous material indicate intrusion-host-rock-mingling and host rock fluidisation. (D) Irregular-shaped margins of fluidal clasts of igneous material (B, C), as well as irregular-shaped contacts between the coherent intrusion and the host rock (D) indicate host rock-magma mingling and host rock fluidisation.



(2) Wedging

- Indicating magma propagation via LEFM

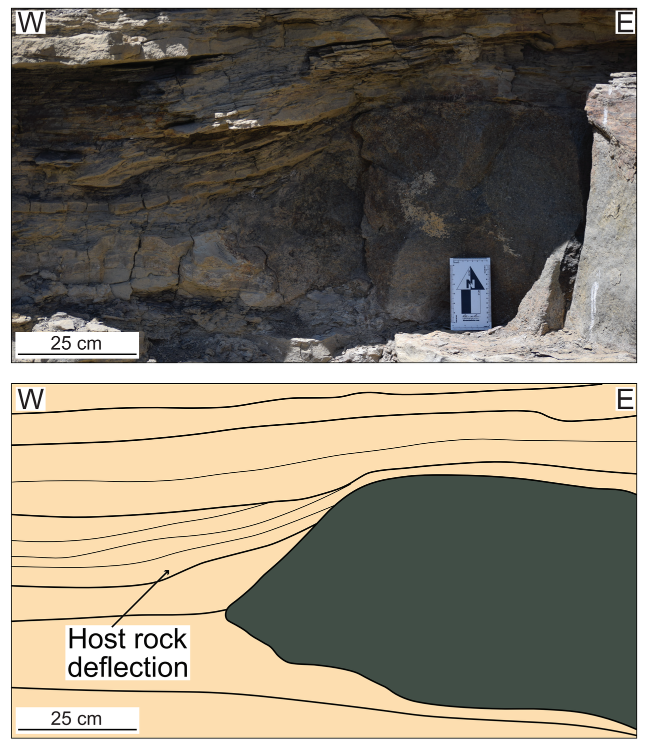


Figure 5. Field photograph and interpreted sketch showing host rock deflection at a cross-sectional magma finger tip due to finger inflation when magma propagates through a linear-elastic fracture.

(3) Compaction

(A) Undeformed host rock
Porosity: ~19%

(B) Deformed host rock
Porosity: ~1-12%

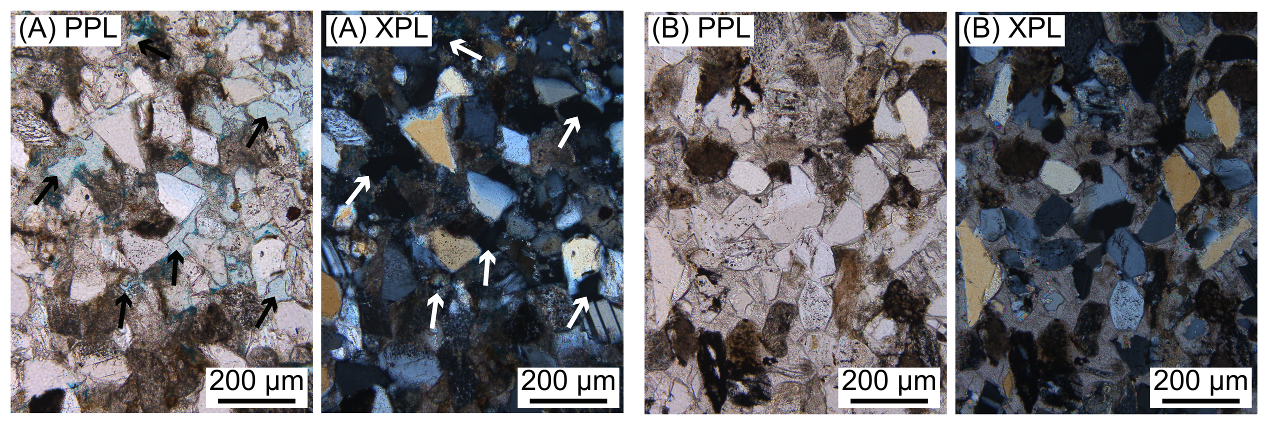


Figure 6. Microphotograph of (A) undeformed and (B) deformed host rock. Arrows indicate open porespace. Samples were collected ~1 m below the intrusion (A) and in the compressional regime between adjacent magma fingers (B).

(4) Folding and brittle deformation

- Predominantly in the compressional regime between adjacent magma fingers

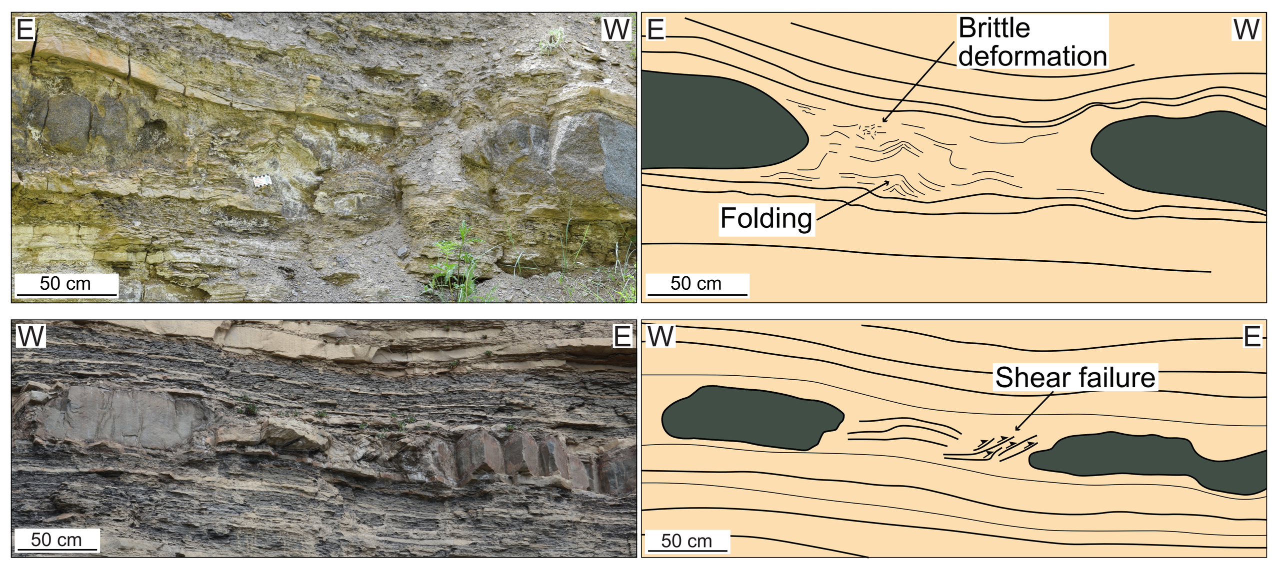


Figure 7. Field photograph and interpreted sketches of (A) folded and faulted host rock strata, and (B) thrusted and stacked sandstone beds between two magma fingers.

(5) Host rock uplift

- Caused by elastic deformation during magma finger inflation
- ~20% of finger thickness accommodated by host rock uplift

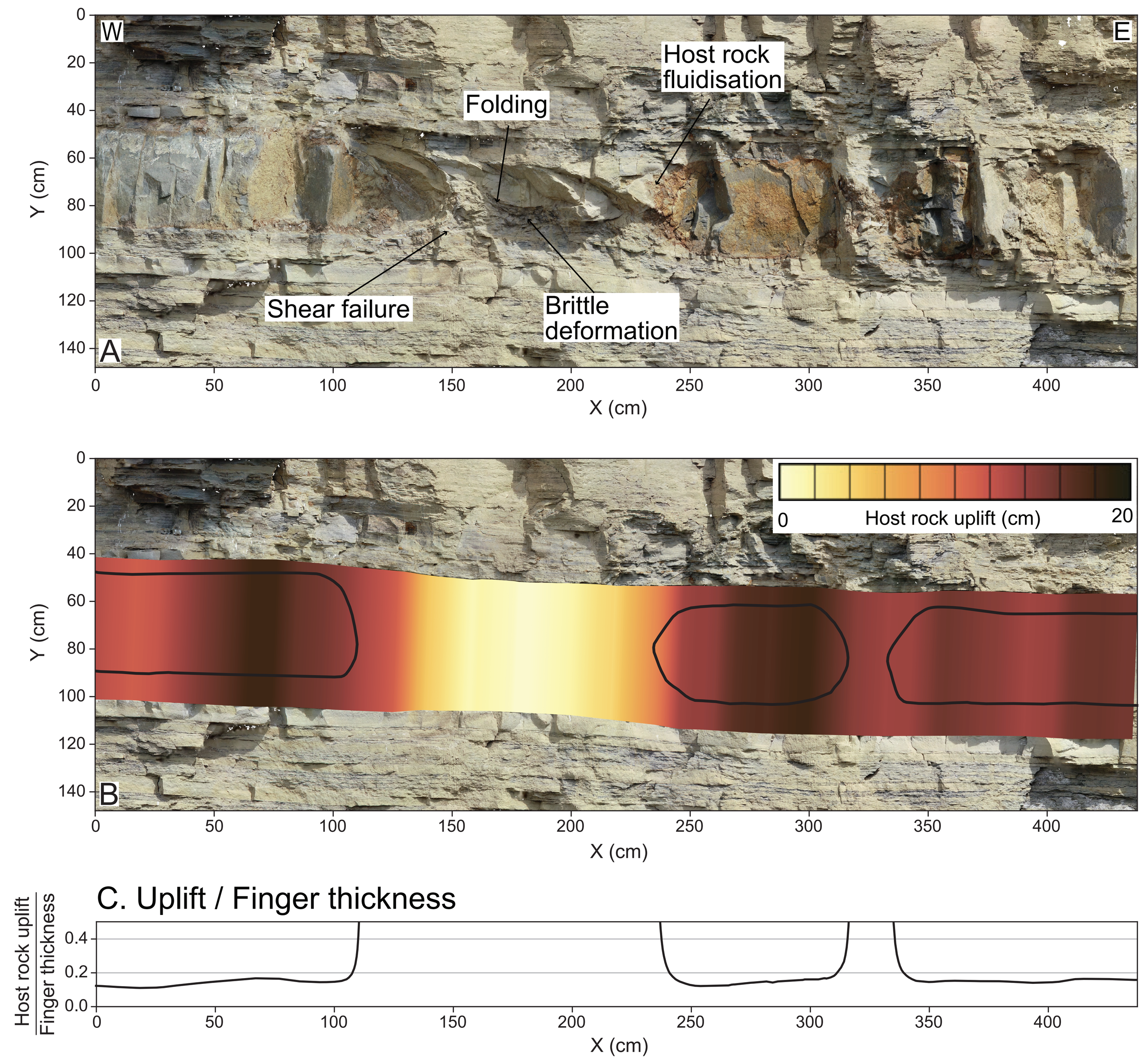


Figure 8. Orthorectified photomosaic made from drone footage with (A) host rock deformation indicated and (B) host rock uplift color-coded. (C) Amount of host rock uplift plotted in relation with the magma finger thickness.

4. Emplacement model for magma fingers at the Shonkin Sag laccolith

1) Finger initiation

- Potentially due to thermal host rock fluidisation at the propagating sill tip
- Contact between magma and fluidisved host rock breaks down into elongate magma fingers; $\eta_{magma} < \eta_{host\ rock}$ → viscous fingering

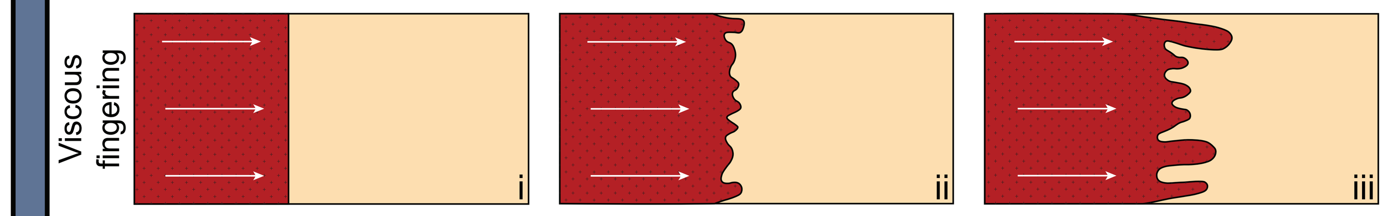


Figure 9. Schematic diagrams (map view) showing the growth of finger-like geometries due to viscous fingering (redrawn from Pollard et al., 1975). White arrows indicate the magma flow direction.

2) Finger propagation

- Growth in length accommodated by:
  → Host rock fluidisation
  → Viscous indentation
  → Elastic splitting (LEFM)

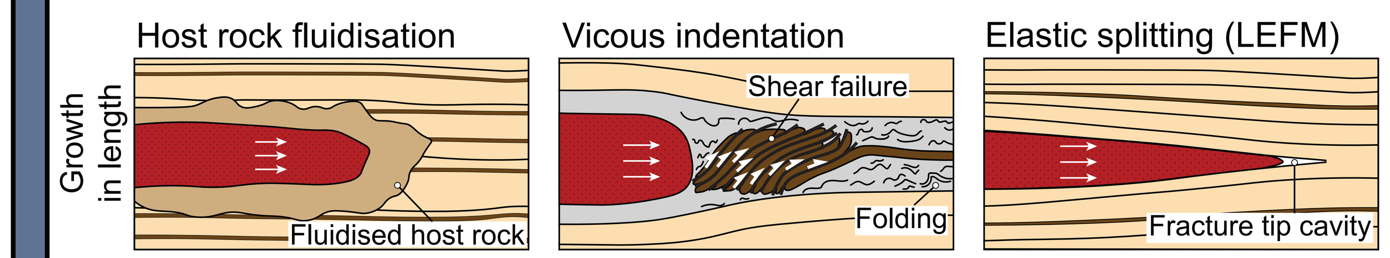


Figure 10. Schematic cross-sectional diagrams parallel to the magma flow direction of magma fingers indicating the propagation mechanisms observed at the outer margin of the Shonkin Sag laccolith. White arrows indicate the magma flow direction. Diagrams modified after Spacapan et al., 2017.

3) Finger inflation

- Folding and shear failure in the compressional regime between adjacent magma fingers → host rock shortening and thickening
- Presented host rock uplift data should be considered minimums, since we cannot quantify the exact pre-intrusion host rock thickness between adjacent fingers

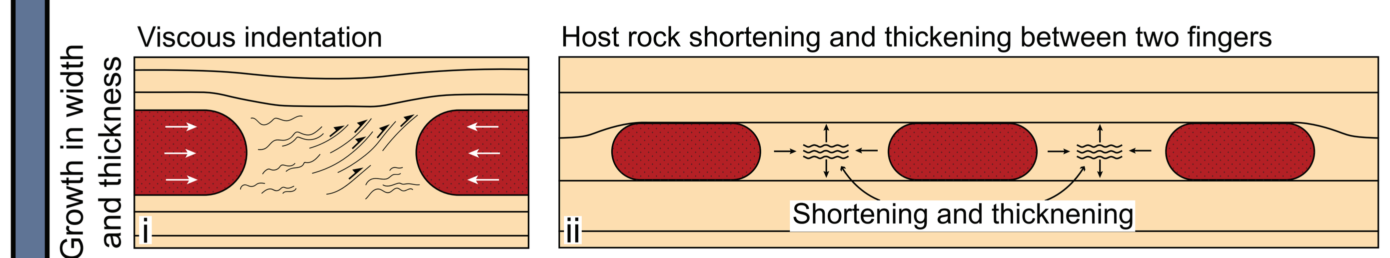


Figure 11. Schematic cross-sectional diagrams perpendicular to the magma flow direction highlighting the host rock deformation in the compressional regime between adjacent fingers. White arrows indicate magma finger growth in width.

5. Conclusions

Emplacement of magma fingers is more complex than a single end-member model

- Host rock fluidisation, folding, brittle deformation, and wedging observed in the same outcrop at meter scale and in some cases even associated with a single finger
- Host rock uplift accommodates up to 20% of the magma finger thickness

Magma emplacement mechanism(s) can change over time

- Mechanism(s) that initiates magma fingers might be different to their propagation mechanism(s)
- Host rock fluidisation potentially more likely to occur during the early stage of magma emplacement due to availability of pore-fluids

References

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