Repeated Ductile-Brittle-Ductile Flow During the Emplacement of Silicic Lava: Strain Rate-Dependent Deformation, Tephra Production, and Healing

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Abstract

Multiple generations of ductile and brittle deformation recorded in the Obsidian Dome lava, California, inform on the rheological complexities of silicic lava emplacement. Understanding the non-linear rheological evolution of advancing lava is key to improving understanding of the durations, extents, and explosive hazards of future eruptions. Numerous studies of silicic lavas, at Obsidian Dome in particular, have focused on micro-scale textures and features interpreted to record flow within the conduit, primarily. How the lava flowed as a growing mass outside the conduit is largely unconstrained. Field observations at Obsidian Dome identify cycles of ductile flow followed by brittle fracturing, followed by relaxation and continued flow. Mode 1 vertical fractures often served as conduits for tephra venting, presumably following spontaneous exsolution-driven vesiculation and volume expansion deeper in the lava. Tephra, often tack-welded to the fracture surfaces, are preserved in many fractures that clearly closed-up on relaxation of the obsidian. Therefore, crossing the glass transition was likely strain rate driven, rather than cooling- or exsolution-driven that would have inhibited relaxation after the stress was released. The interplay between flow and fracturing is also evident in the ubiquity of crease structures at decimeter to decameter scales over all of Obsidian Dome. Unraveling the complexities of flow and fracturing in obsidian lavas will require and enable improved understanding of similarly non-linear rheological evolutions in ice, salt, the mid crust, and the asthenosphere.

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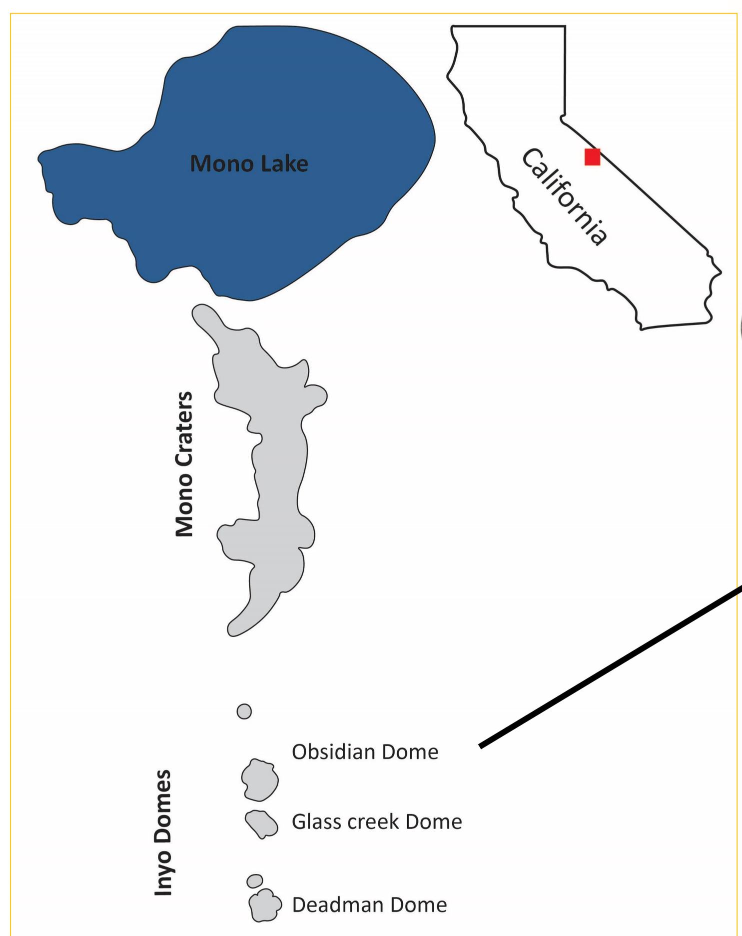
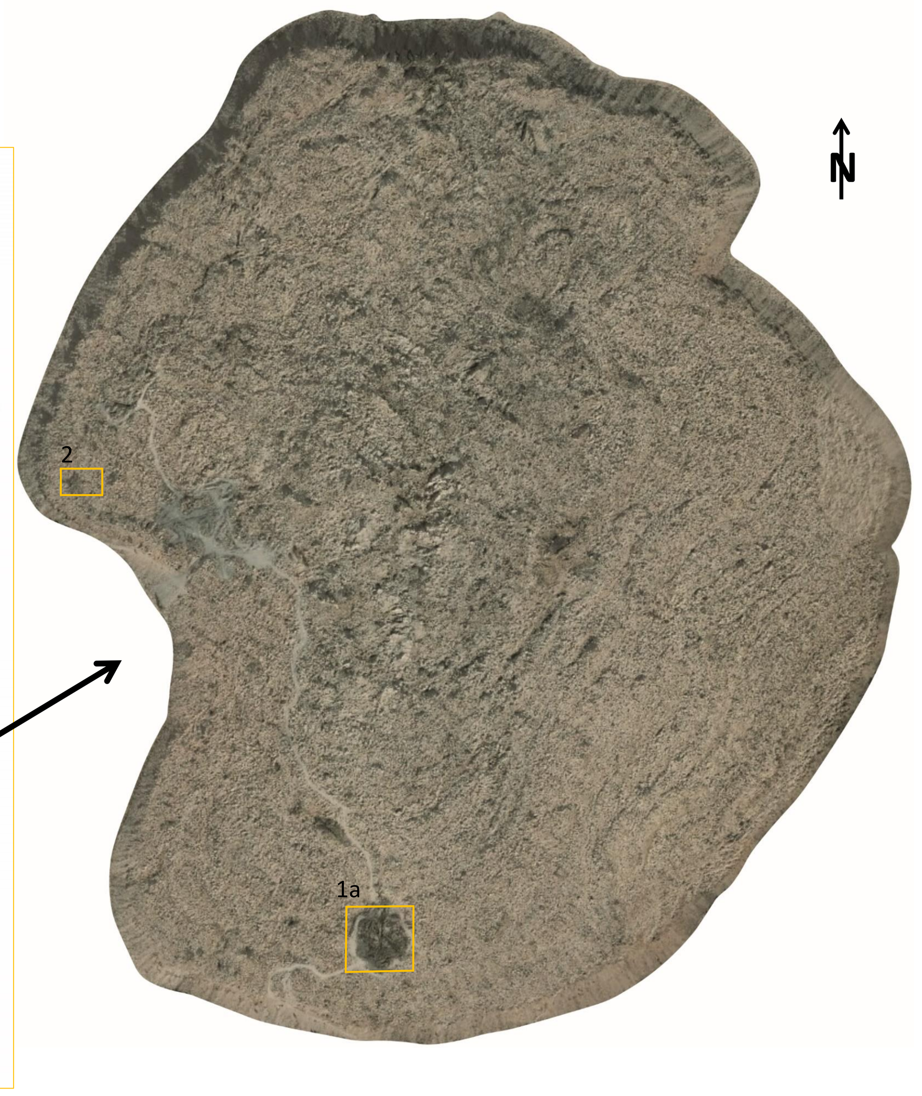
- the interplay between flow and fracturing is also evident in the ubiquity of crease structures at decimeter to decameter scales over all of Obsidian Dome

Geologic Background: The Mono Craters and Inyo Domes extend from South of Mono Lake to the edge of Long Valley caldera in eastern California. The Inyo Domes consist of 5 magmatic and several phreatic eruptive centers. Obsidian Dome, Glass Creek Dome, and Deadman Dome are the three largest rhyolitic domes, which erupted simultaneously ~660 years ago. The focus of this work was done at Obsidian Dome, the furthest of the three to the North. Obsidian Dome has been the focus of many geochemical and micro-scale textural studies; however our research is focused on large-scale structural features which help constrain how the lava flowed as a mass outside of the conduit.





Introduction: Studies focused on silicic lava emplacement at Obsidian Dome have been constrained to the generation of coarsely vesiculated pumice (CVP) "diapirs" that have breached the finely vesiculated pumice (FVP) surface of the lava flow (**Figures 1 & 2**).

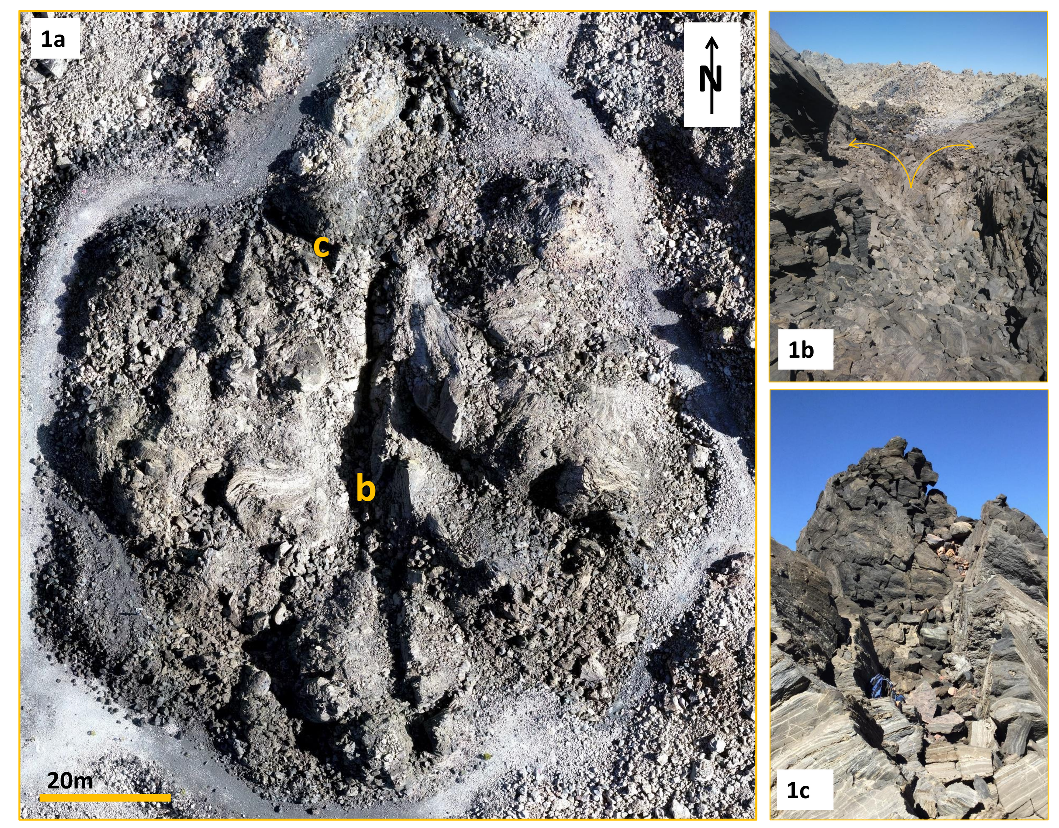


Figure 1a. Drone aerial image (provided by Tyler Leggett) of crease-structure located in the southern part of Obsidian Dome. Structure referred to as "coarse pumice diapir" in Fink, 1983. **1b.** Image of central fracture looking North into the diapir. **1c.** Image of fracture into FVP and extruded CVP dome in background.

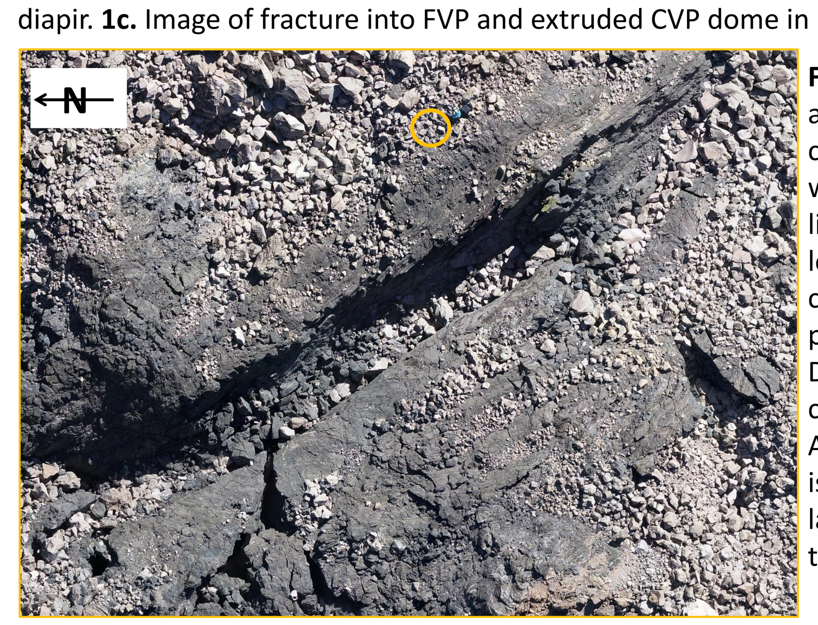


Figure 2. Drone aerial image of CVP crease-structure with FVP boulders littered around it located in the central western part of Obsidian Dome, person circled for scale. Axis of the fracture is parallel to the lava flow front in this area (NW-SE).

Current model for CVP crease-structures at Obsidian Dome: A bottom-up mechanism where a diapir buoyantly rises, due to extension, and a fracture is generated into the upper lava flow, which is dominated by fine vesicular pumice (**Figure 3**).

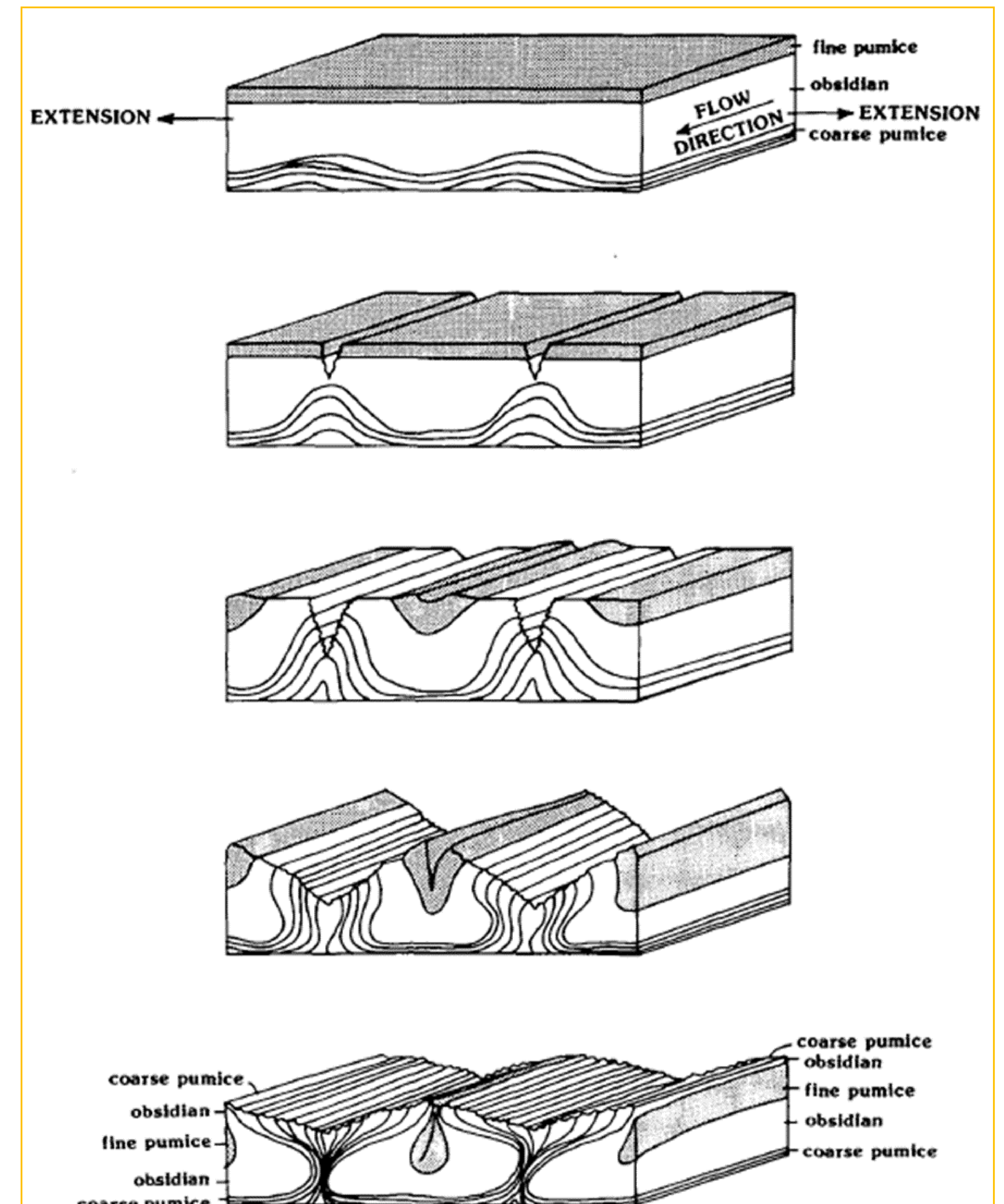


Figure 3. Extension allows a coarse vesicular pumice diapir to buoyantly rise to the surface causing a fracture in the lava's fine pumice layer at the surface. Further extension and rise of the multiple parallel diapirs may generate compression and result in uplifting between the two crease-structures. From Fink, 1983.

Alternative model for crease-structures at Obsidian Dome: A top-down mechanism where extension and thermal contraction generates a fracture in the lava surface which propagates down into the saturated ductile lava beneath, which froths and vesiculates on its way to the surface (**Figure 4**).

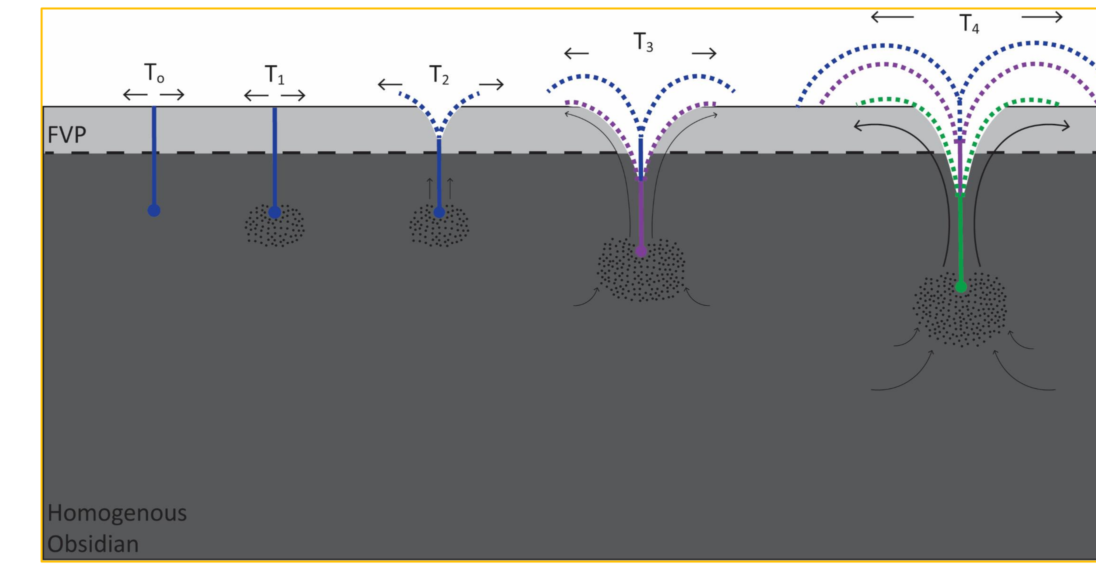


Figure 4. Schematic for top-down mechanism generating crease-structures.

- **T_o** a fracture (blue) forms in the FVP lava surface, with the fracture tip propagating into the ductile obsidian below
- **T_1** decompression facilitates exsolution of volatiles and volume expansion
- **T_2** extension facilitates lateral spreading and upward movement of vesiculated buoyant obsidian at depth
- **T_3** another fracture (purple) initiates deeper into the ductile melt causing a strain-rate driven cross from the ductile to brittle field of the obsidian. Further exsolution drives material to the surface
- **T_4** (green) fracturing propagates even deeper, generating more exsolution and the material at the surface is moved out of the way as buoyant magma is pushed to the surface from depth. Apposing limbs of the structure begin to bend away from the fracture axis and mimic a "flower-opening" behavior

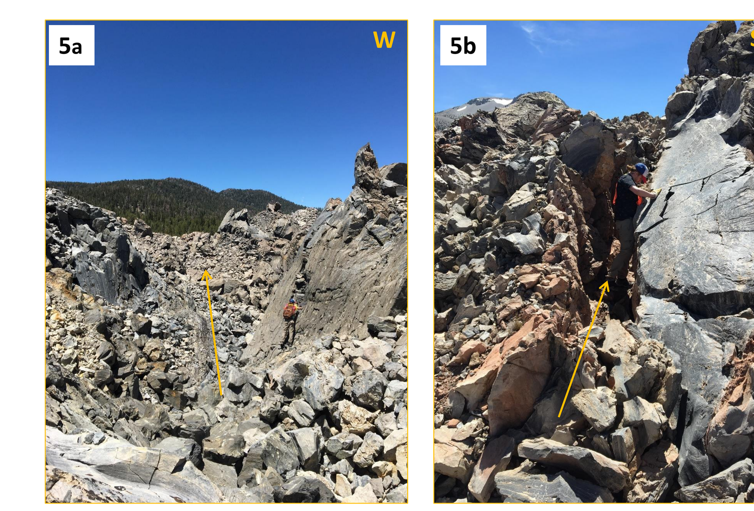


Figure 5a. Large east-west crease-structure with banded obsidian fracture surfaces. **Figure 5b.** Small SW-NE trending crease-structure with obsidian curviplanar fracture surfaces. The upper portion of the structure grades from obsidian into FVP. Arrows indicate axis of fracture.

Tephra Venting

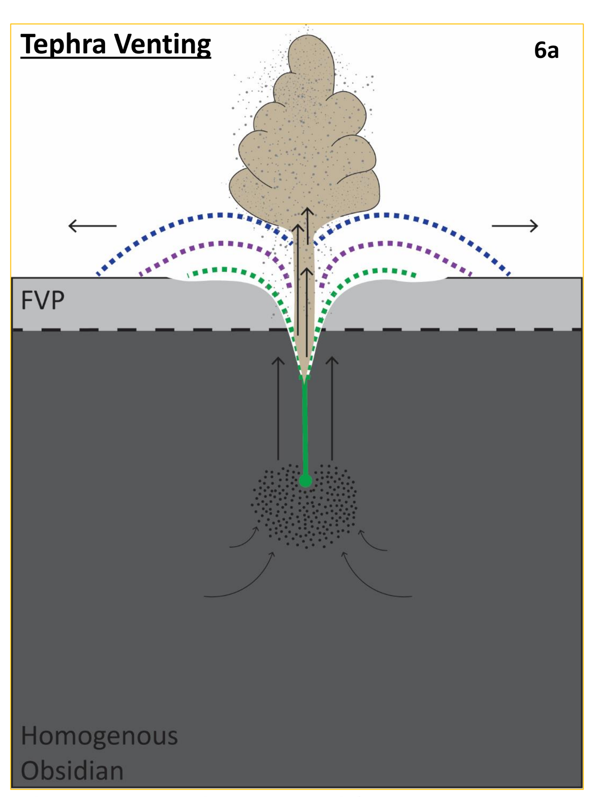
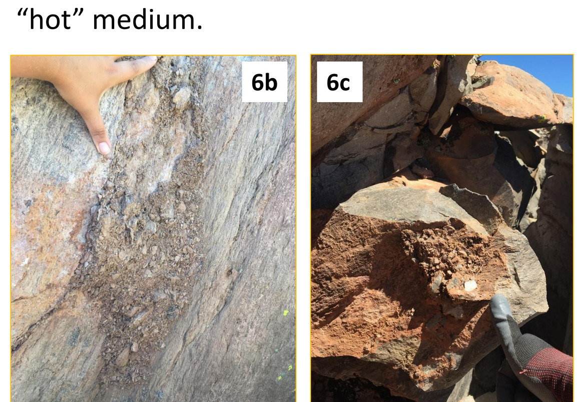


Figure 6a. Mode 1 vertical fracture propagates into hot, ductile obsidian creating exsolution-driven vesiculation, volume expansion of the deeper lava, and subsequent tephra venting at the surface of the lava flow. **Figure 6b & 6c.** Evidence of tephra venting. Tack-welded lapilli-sized clasts of obsidian and rhyolite annealed to fracture surfaces. Red leathery surfaces indicate fractures were propagating into a "hot" medium.



Secondary Fracture Formation and Relaxation

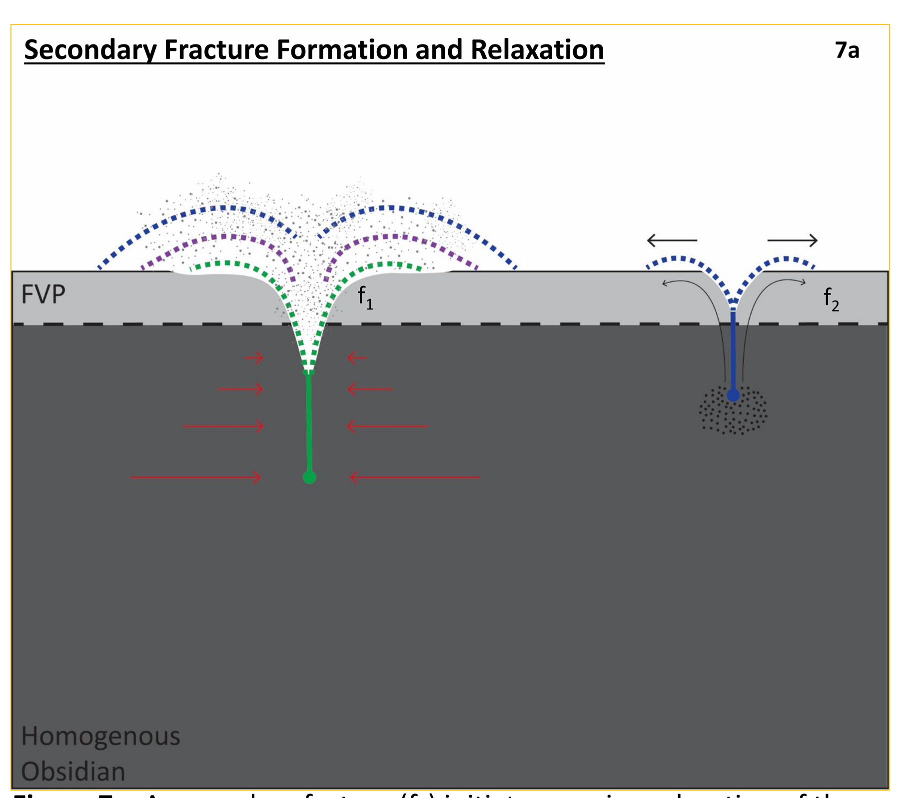
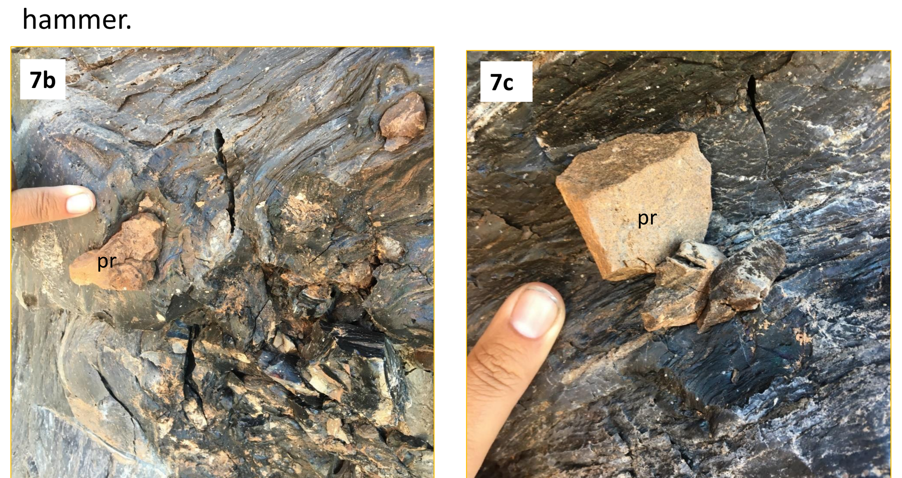


Figure 7a. A secondary facture (f_2) initiates causing relaxation of the first fracture (f_1) and tephra venting to cease. Lapilli settles and slightly anneals to the ductile surfaces within the first fracture (green and purple dashed lines). Red arrows show ductile flow, acting to close the fracture. **Figure 7b & 7c.** Evidence of tephra annealing. Lapilli sized clasts of pink rhyolite (pr) annealed to fracture surfaces that are composed of ductile deformed obsidian, which is overprinted by vertical cracks. Clasts can be easily knocked off with a hammer.



Relaxation and Tephra Annealing

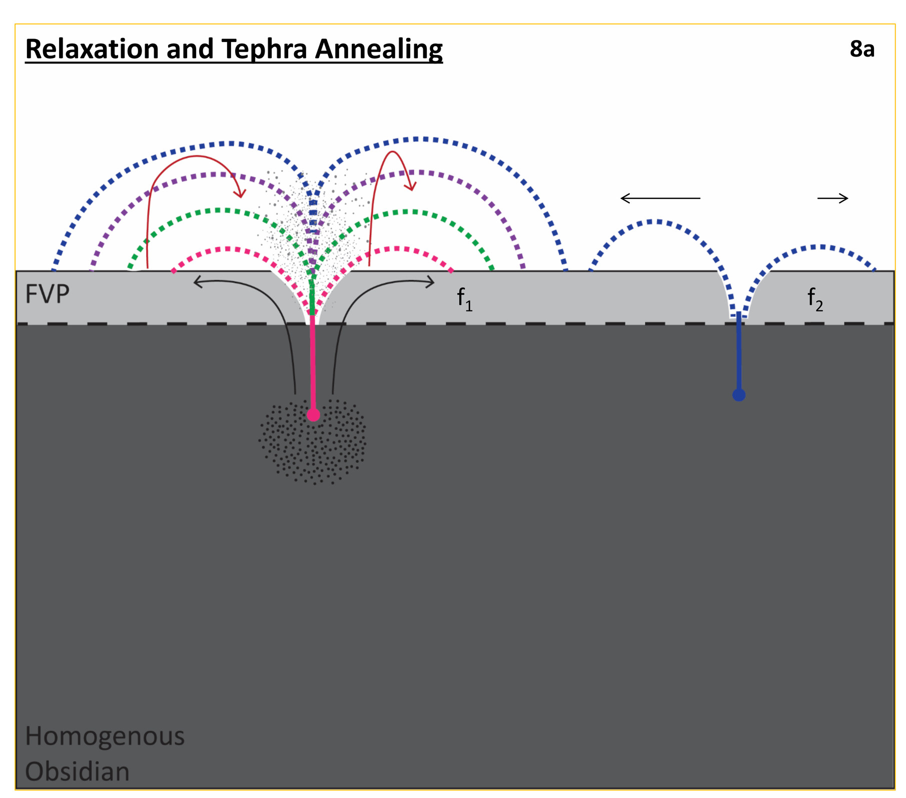


Figure 8a. Further extension of the secondary fracture (f_2) causes localized compression at the first fracture (red arrows, f_1). Hot fracture surfaces and annealed lapilli compress and weld. Vesiculated pumice compresses back to obsidian in thin bands around masses of lapillisite, lapilli-sized juvenile ejecta that anneal to fracture surfaces. Refocused extension at the first fracture generates another fracture (pink) into the ductile obsidian at depth re-initiating vesiculation and buoyant rise of the obsidian thrusting the welded lapillisite covered surfaces out of the way and creating brittle deformation. Extension of both crease-structures can cause impingement of the curviplanar surfaces, causing steepened limbs (red arrows). **Figure 8b.** Evidence of obsidian (compressed CVP) bands forming around a mass of lapillisite, note banding of coarsely vesiculated pumice and obsidian. **Figure 8c.** Annealed angular lapilli clasts of rhyolite surrounded by stringers of obsidian. **Figure 8d.** Evidence of brittle deformation cutting across previously ductile deformed lapillisite covered fracture surfaces **Figure 8e.** Ropey textures of obsidian and coarsely vesicular pumice filling in areas around red surfaces. Lapilli-sized clasts are annealed to the red surfaces, which also show brittle deformation in the form of vertical cracks.

Fracture and Annealing with respect to glass transition (Tg)

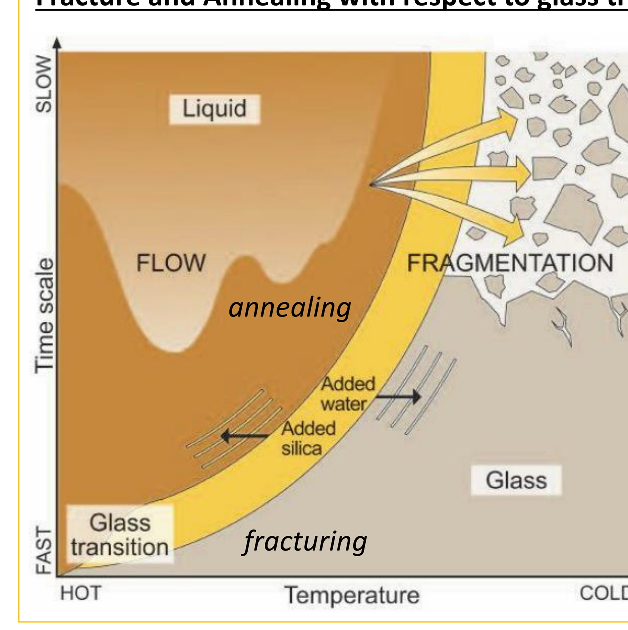
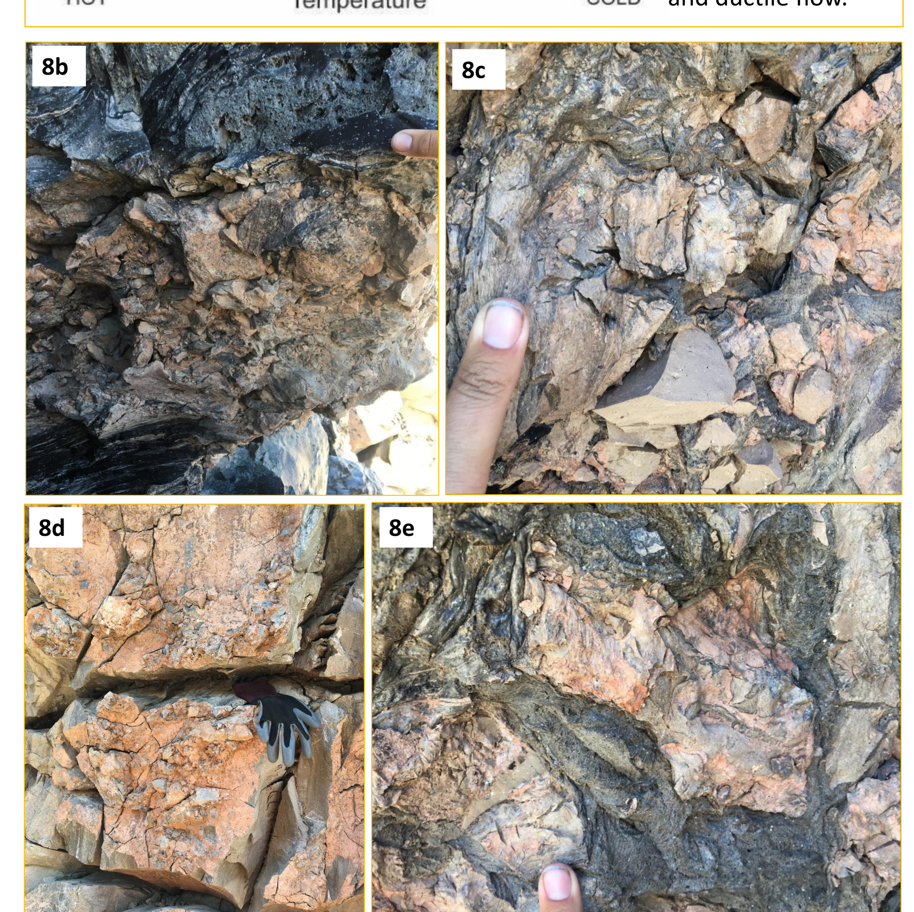


Figure 9. Schematic of glass transition for volcanic silicic melt. From Dingwell, 2006. Crossing the glass transition (Tg) during crease-structure formation is strain rate driven, rather than cooling- or exsolution-driven, generating *fracturing*. Relaxation back across Tg allows *annealing* of tephra to fracture surfaces and ductile flow.



Implications

Curviplanar facture surfaces created during crease-structure formation are ubiquitous throughout the surface morphology at Obsidian Dome

- crease-structure formation is independent of diapir formation
- there are no surface folds at Obsidian Dome
- cycles of fracturing, tephra venting, relaxation, and annealing are hypothesized to occur during crease-structure formation across the surface of the advancing lava

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