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Multiple Deformation Mechanisms Operating at Seismogenic Depths: Tectonic Pseudotachylyte and Associated Deformation From the Central Sierra Nevada, California

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Multiple deformation mechanisms operating at seismogenic depths: Tectonic pseudotachylyte and associated deformation from the central Sierra Nevada, California

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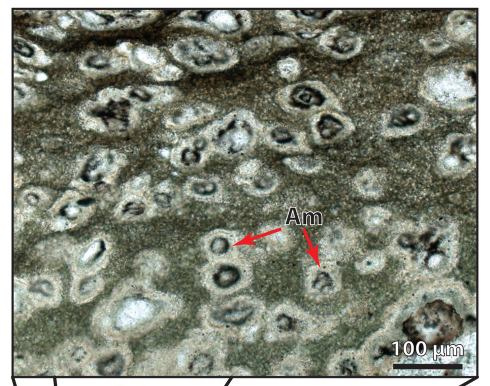
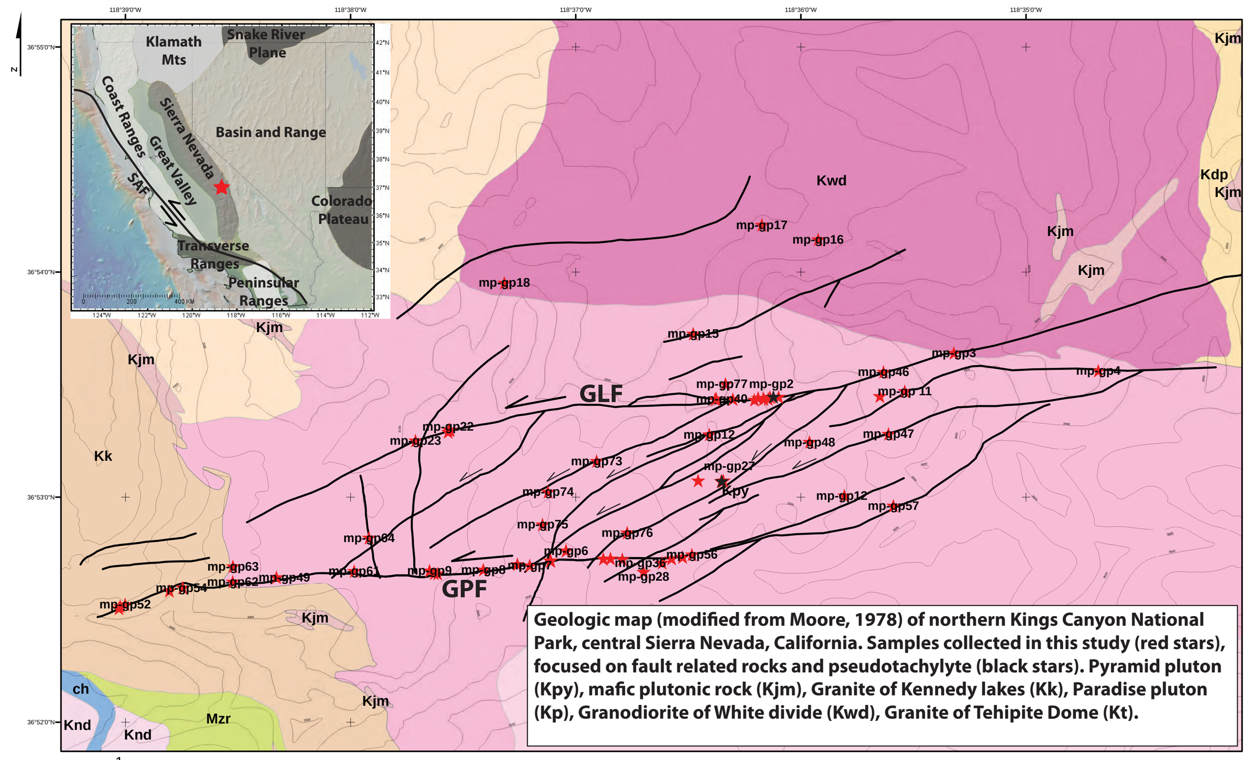
Photomicrograph of ~ 3 mm thick tectonic pseudotachylyte (Pst) vein from the GPF with at least three generations of melt-related pseudotachylyte (1, 2, 3), variable percentages of clasts and reworked pseudotachylyte. Microstructures consistent with a frictional melt origin include:

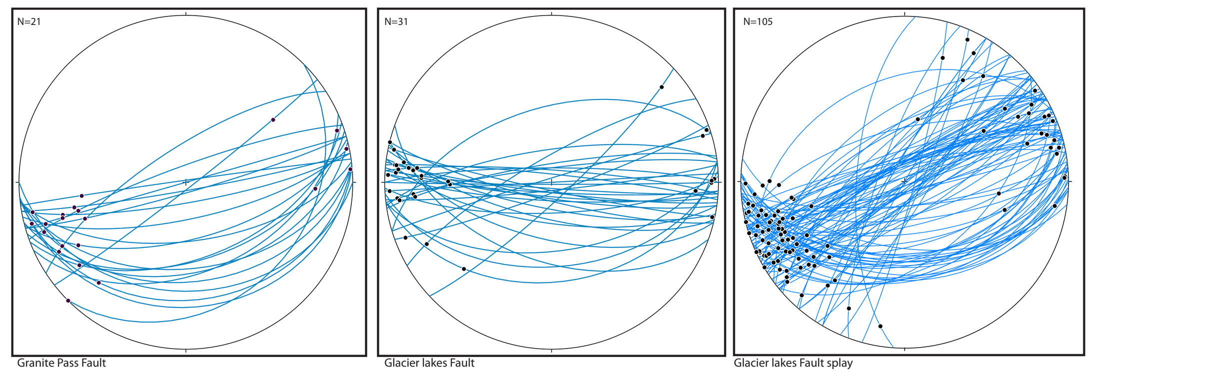
1) Amygdules (Am), filled and hydrothermally altered vesicles, which form during extrusion of gas from a melt,
2) Flow streaks, thin, alternating layers of very fine-grained, contrasting colored bands or streaks, which bend around competent clasts,
3) Isoclinal folds, folding very fine-grained alternating bands of pseudotachylyte matrix, and
4) rounded and embayed quartz and feldspar clasts.



Background and Structure

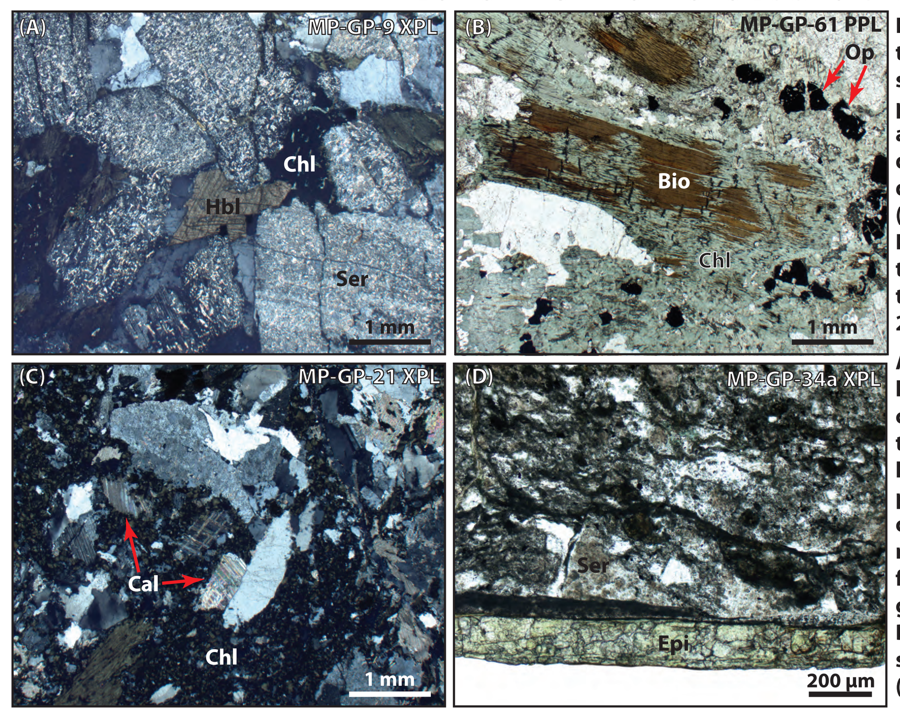


Geologic map (modified from Moore, 1978) of northern Kings Canyon National Park, central Sierra Nevada, California. Samples collected in this study (red stars), focused on fault related rocks and pseudotachylyte (black stars). Pyramid pluton (Kpy), mafic plutonic rock (Kjm), Granite of Kennedy lakes (Kk), Paradise pluton (Kp), Granodiorite of White divide (Kwd), Granite of Tehipite Dome (Kt).



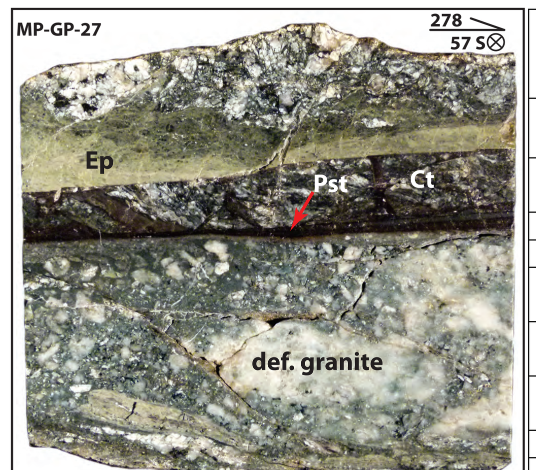
The Volcanic lakes area of Sequoia and Kings Canyon National Park, California, central portion of the Sierra Nevada batholiths, consist of a series of plutons emplaced from 102 to 88 Mya along the western margin of North America (Stern et al., 1981; Bateman, 1992). Faults in the study area are northeast-southwest trending, left-lateral, strike-slip faults up to 8 km in trace length (Kirkpatrick and Shipton, 2009; Kirkpatrick et al., 2008). These faults include the Glacier Lakes (GLF) and Granite Pass (GPF) faults. The GLF and GLF are the principal faults of interest in this study due to excellent exposure and a body of recent work focused on understanding the geometry, textural relationships, temperature, and timing of faulting (Segall et al., 1990; Pachell et al., 2003; Kirkpatrick et al., 2008, 2012; Kirkpatrick and Shipton, 2009). When placed into a thermochronologic framework for the plutonic host rock, 40Ar/39Ar dates of tectonic pseudotachylyte (76.6 ± 0.3 Ma); can be used to infer that pseudotachylyte formed at depths between 2.4-6.0 km with ambient temperatures between 110-160°C (Kirkpatrick et al., 2012). The GLF is an E-W to NE-SW striking, steeply-dipping, left lateral strike-slip fault with a maximum observed displacement of 125 m (Kirkpatrick et al., 2008). The western termination of the GLF is comprised by a series of NE-SW striking, steeply-dipping, left-lateral strike-slip faults that splay from the GLF to the southwest (Kirkpatrick et al., 2008). These splay faults have a highly asymmetric displacement gradient, with the greatest displacement close to the GLF and decreasing to zero to the southwest (Kirkpatrick et al., 2008; and data collected in this study). The E-W striking, steeply-dipping, left-lateral strike-slip GPF is cross-cut by the GLF splays and preserves more pervasive crystal-plastic deformation (Kirkpatrick et al., 2008).

Fluid flow and alteration



Hydrothermal alteration is abundant in the GLF and GPF zones with epidote veins, sericite alteration of plagioclase, calcite precipitation, and chlorite pseudomorphs after biotite. Chloritization of biotitie during hydrothermal alteration has been documented to occur between 200-320 °C (Parry and Downey, 1982; Fiebig and Hoefs, 2002). Thick (type II) calcite twins in the fault zone are consistent with temperatures between 170-200 °C (Ferrill et al., 2004).

A) Fault core composed of fractured and hydrothermally altered granitic rock, including chlorite (Chl), and sericite (Ser) alteration of plagioclase. B) Fault core and highly fractured granitic rock with chlorite pseudomorph after biotite (Bio), and opaque (Op) mineral (hematite and/or magnetite). C) Hydrothermally altered fault core with abundant sericitized plagioclase, and radius-fibrous chlorite (Chl). D) Very-thin (<200 µm) epidote (Epi) fault slip surface and sericitized plagioclase (Ser).

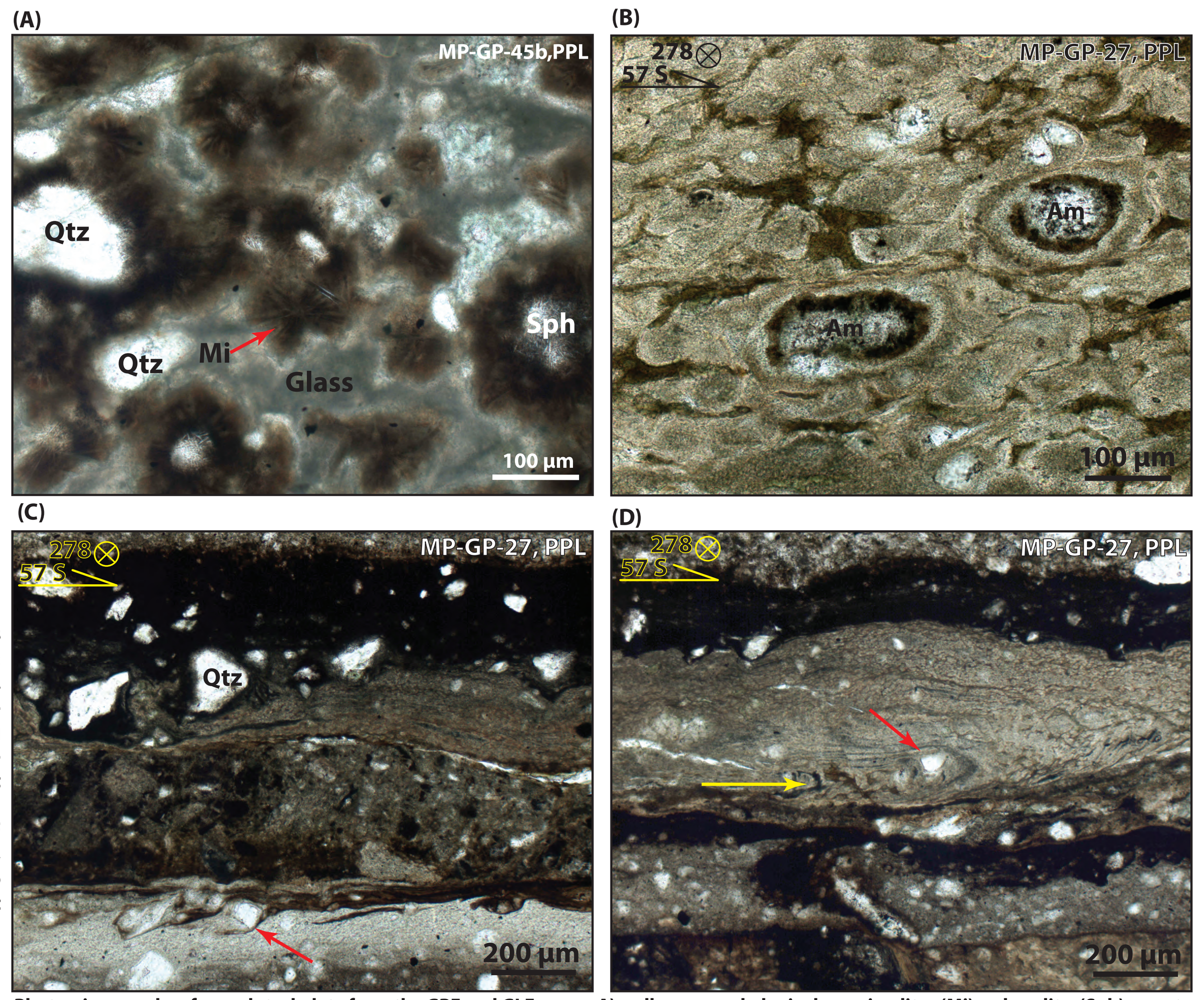


Hand sample of altered granite with epidote (EP) and and chlorite with cross-cutting pseudotachylyte vein (Pst).

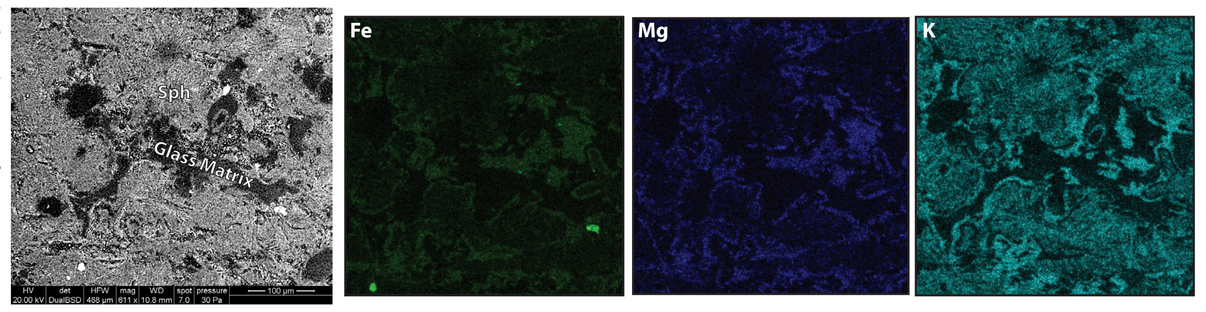
Observations that are consistent with a frictional-melt origin for pseudotachylyte (Magloughlin and Spray, 1992; Lin, 2008; Kirkpatrick et al., 2009).

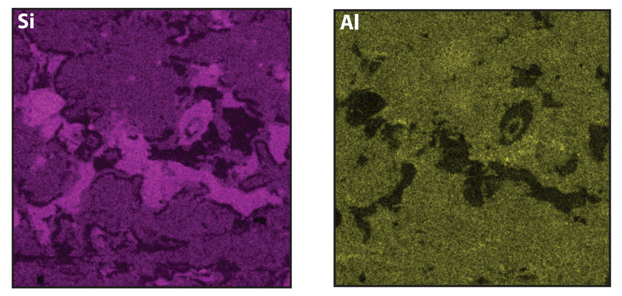
Feature	Quality of evidence*	Outcrop	Optical Microscopy	SEM
Sherulites and Microlites	e.		X	X
Amygdules	e.		X	X
Flow structures	v.g.		X	X
Quartz and Feldspar clasts	g.		X	X
Rounded/Embayed clasts	g.		X	X
Injection vein morphology	g.	X	X	X
Aphanitic matrix	g.	X	X	X

*Quality of evidence assessments: good (g.), very good (v.g.), and excellent (e.) are ranked on qualitative usefulness of a feature as an indicator of rapidly-quenched melt.



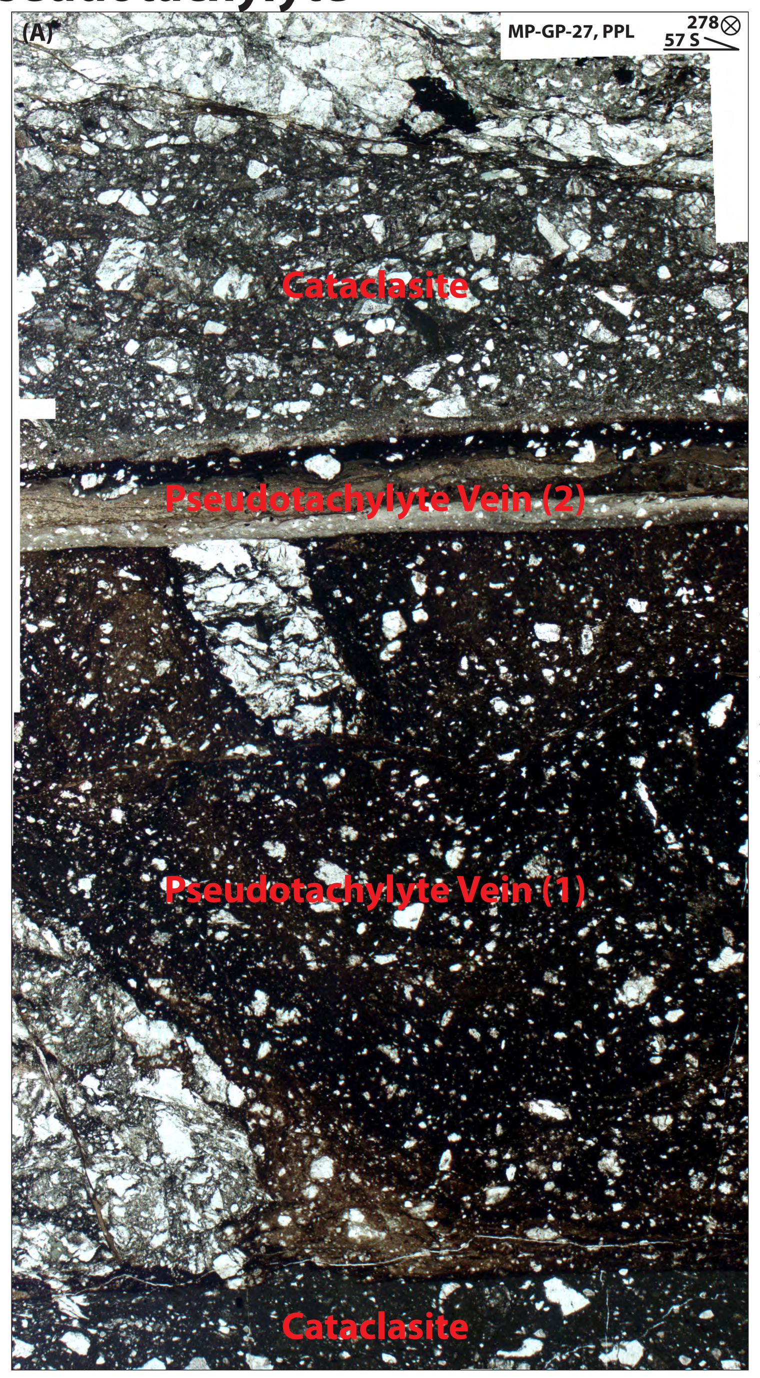
Photomicrographs of pseudotachylyte from the GPF and GLF zones. A) well preserved plagioclase microlites (Mi), spherulites(Sph), quartz (Qtz) and feldspar clasts, and isotropic glass. B) very fine-grained matrix and quartz filled amygdules (Am), interpreted to be consistent with a melt-related origin. C) embayed clasts and flow structures (red arrow). Consistent with viscous flow. D) isoclinal fold in very fine-grained matrix (red arrow), this is consistent with transport direction from left to right in the photo and viscous flow.

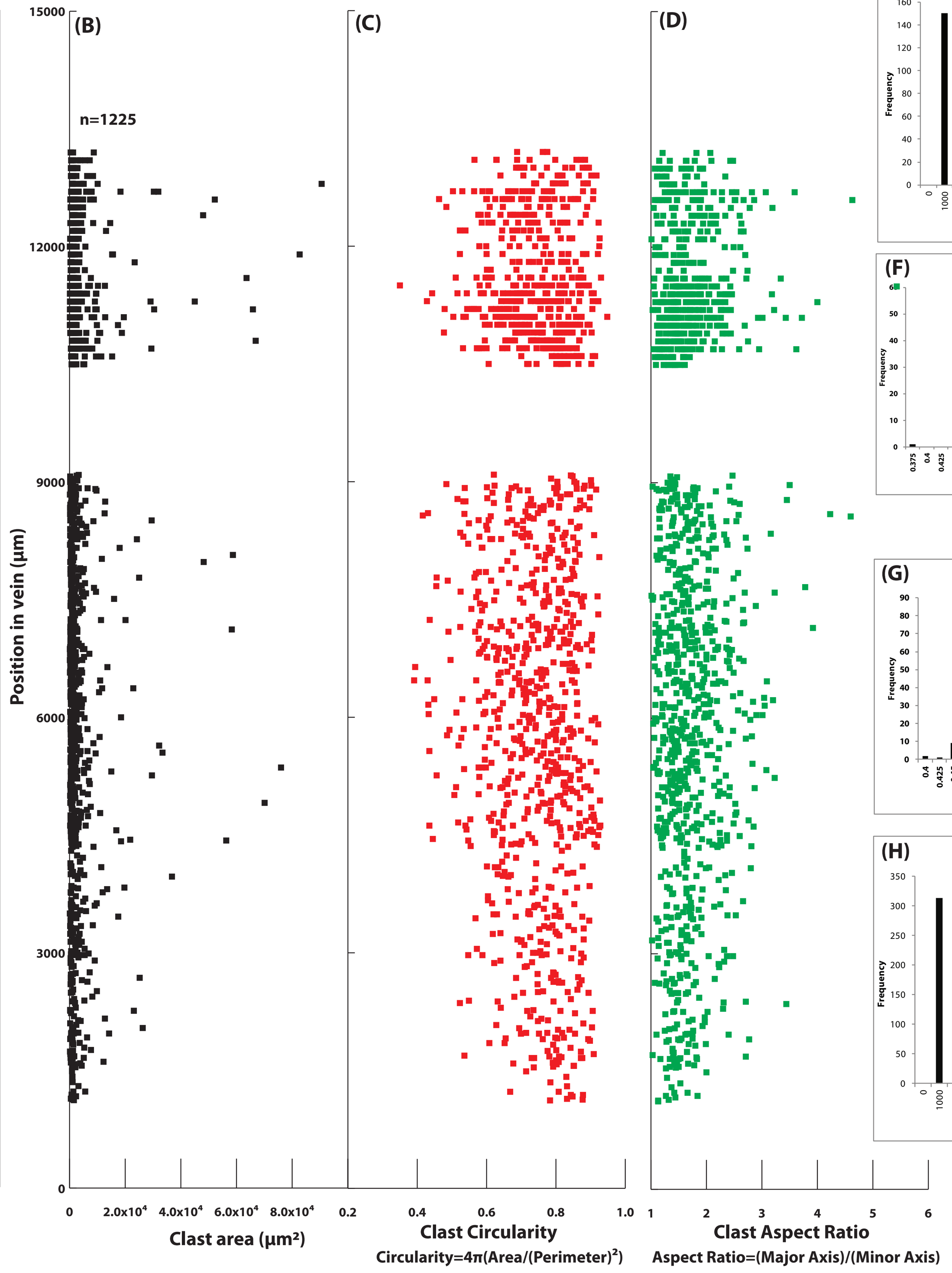


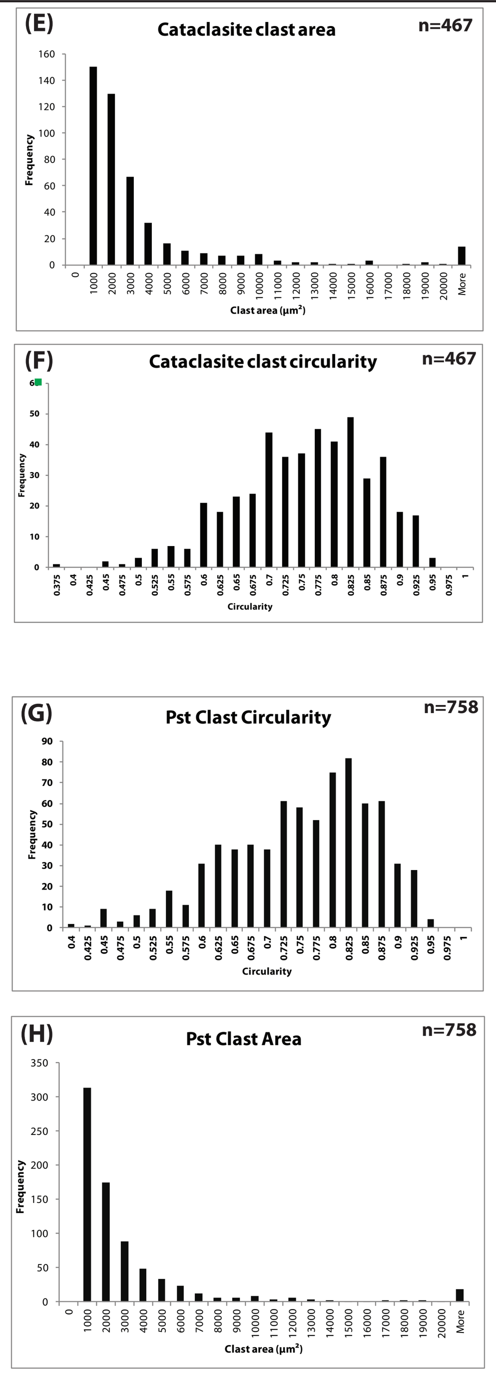


SEM-BSE image of pseudotachylyte matrix and EDS element maps, note concentration of Fe, Mg, and K at the margin of glassy matrix. This observed changes in Fe, Mg, and K concentrations at the margin of the glassy (Si-rich) matrix has been interpreted to represent primary crystal fractionation during rapid crystallization.

Pseudotachylyte

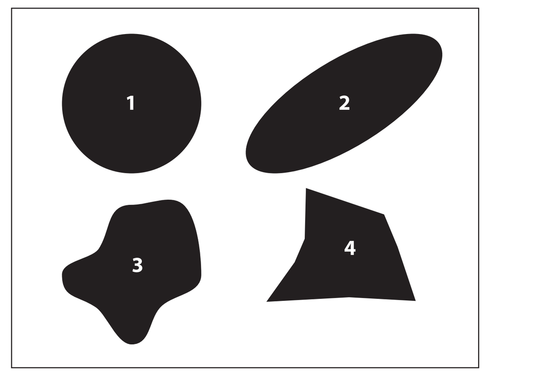




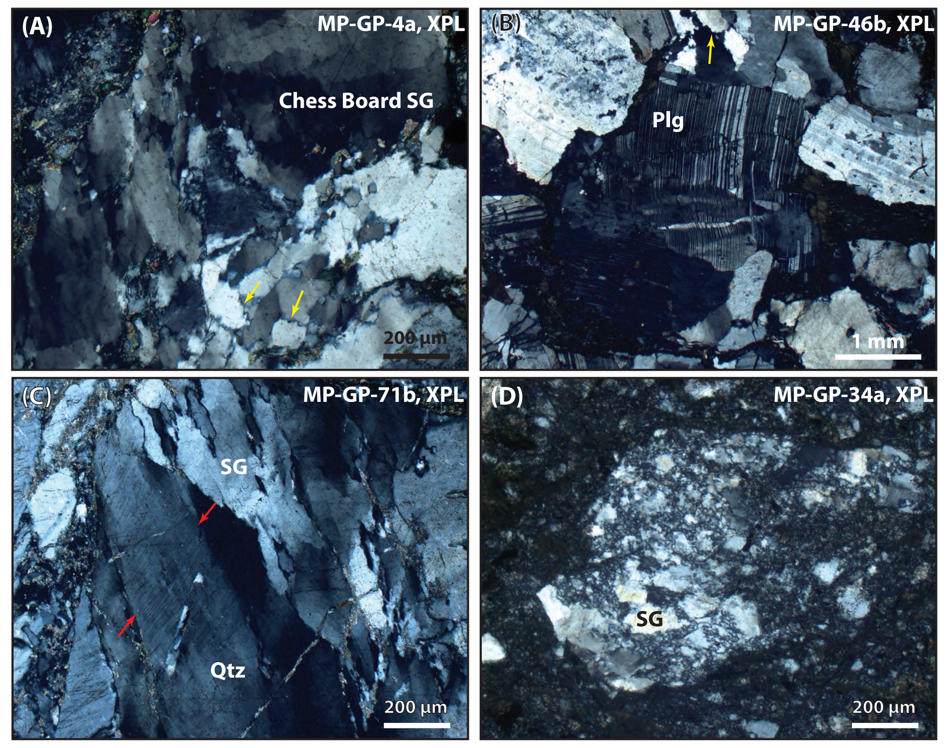


Pseudotachylyte and cataclasite from the GPF used for clast size and shape analyses. A) photomicrograph of multiple generations of pseudotachylyte (11.6% clast) (1 and 2) and cataclasite (25.0% clast), used to measure clast area, position, and shape data, multiple generations of pseudotachylyte suggest multiple earthquakes along the same section of the fault. B) clast size as a function of position, 2 dimensional clast area varies from <200 μm^2 up to 90,000 μm^2, with the largest clasts concentrated in the center of the vein. C) clast circularity ($4\pi(Area/Perimeter^2)$) as a function of position, note that both the cataclasite and pseudotachylyte contain a wide range in circularity and no clear pattern is observed. D) clast aspect ratio (major axis/minor axis) as a function of position, the majority of clasts have aspect ratios between 1 and 3 in both the pseudotachylyte and cataclasite. Histograms of clast area for the cataclasite and pseudotachylyte are similar for both size and circularity of clasts (E, F, G, H); however, pseudotachylyte clasts tend to be more circular than clasts in the cataclasite (E, G).

Clasts were measured using NIH ImageJ. The area, perimeter, and the major and minor axes of clasts were measured and circularity and aspect ratios were calculated. The aspect ratio of clasts could theoretically vary from 1 (circle) to ∞ (an infinitely elongate ellipsoid). Similarly the circularity of a clast can theoretically vary from 1 (circle) approaching 0.0 (infinitely elongate polygon). 1) circularity=1, aspect ratio=1.0. 2) circularity=0.65, aspect ratio=2.58. 3) circularity=0.71. aspect ratio=1.34. 4) circularity=0.57, aspect ratio=1.13.



Plastic deformation



Evidence for plastic deformation associated with the GLF and GPF zones includes undulose extinction, grain boundary bulging (GBL), deformation lamellae, subgrain formation and rotation (SG) in quartz, and kinking and folding in plagioclase. These deformation mechanisms are consistent with deformation temperatures between 300-500 °C (Passchier and Trouw, 2005).

A) Recrystallized quartz with "chess board" subgrains, GBL (yellow arrows), and undulose extinction. This deformation is consistent with dislocation glide and creep, and temperatures between 300-500 °C (Passchier and Trouw, 2005). B) Microfractured, kinked and folded plagioclase feldspar (Plg), consistent with dislocation glide and temperatures between 400-500 °C; and GBL in quartz (yellow arrow) consistent with temperatures between 300-400 °C (Passchier and Trouw, 2005). C) Plastically deformed quartz grain (Qtz), with well developed deformation lamellae (red arrows) and subgrains (SG), consistent with dislocation glide and creep and temperatures between 300-400 °C (Passchier and Trouw, 2005). D) Recrystallized quartz grain with abundant, very fine-grained subgrains (SG), consistent with dislocation glide and creep, and temperatures between 300-400 °C (Passchier and Trouw, 2005).

Conclusions

1) Well preserved tectonic pseudotachylyte from the GLF and GPF provide convincing evidence for ancient seismicity (Kirkpatrick et al., 2008, 2012), and multiple generations of psudotachylyte in a single sample suggest multiple earthquakes along the same section of the fault.
2) Clasts in cataclasite and pseudotachylyte have similar ranges in size and shape characteristics.
3) Pseudotachylyte tends to have a lower clast to matrix ratio than cataclasite from the fault zones.
4) Alteration and precipitation of hydrothermal minerals is consistent with temperature conditions between 170-320 °C.
5) Cross-cutting relationships suggest that some pseudotachylyte formation occurred post- hydrothermal alteration, suggesting the possibility that some H_2O was present during pseudotachylyte formation.
6) Crystal-plastic deformation suggests deformation temperatures between 300-500 °C; however, it is not clear if the plastic deformation occurred, pre-, syn-, or post pseudotachylyte formation.