

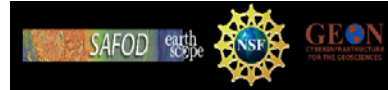
What is the Role of Minor Gouge Zones in the Damage Zone of the SAF System?

Jafar Hadizadeh, University of Louisville, KY USA

Giulio Di Toro, University of Padova, Padova Italy

Karen Mair, University of Oslo, Oslo Norway

Hassan Babaie, Georgia State University, GA USA



EarthScope National Meeting, Monterey, California USA. March 2007. This research was partially supported by the US National Science Foundation EarthScope 0545472.

Summary

We investigated microstructural aspects of one of several minor gouge-bearing shear zones intersected by the SAFOD phase I and II drill holes. Shear zones with similar features, found to exist down to measured depths (MD) of 3100m, have been investigated by others. We hope that this contribution enables us to better understand the relationship between such minor gouge zones and deformation of the SAF damage zone.

The studied gouge shows a sharp contact with fractured and veined granodiorite protolith and appears to have been developed mainly by brittle deformation as indicated by grain-scale deformation features. Elemental and oxide analyses suggest that zeolites are present in the gouge as alteration products. A shape preferred orientation (SPO) foliation is well-developed in the Y-orientation, mainly defined by the apparent flow of alteration products and highly comminuted mineral fragments around relict feldspar and quartz particles. SEM imaging shows that the zone includes lenses of gouge at different stages of comminution with most of the alteration phyllosilicates concentrated in and around the foliated gouge.

The microstructures of the gouge in this study are compared to those of a simulated granite gouge in which the development of similar microstructures had required only a few tens of mm of shear displacement. An interesting microstructural feature is high variability of thickness of the foliated gouge over mm distances in the plane of shearing that resembles those produced in experiments. The observations suggest that the SAFOD gouge might have developed along preexisting suitably-oriented and alteration-softened fracture surfaces. The main difference between the SAFOD and experimental gouge is found in the foliated gouges where the SAFOD gouge seems to have undergone additional processes such as reaction softening by mineral alteration after a certain degree of comminution.

The core sample

The studied core sample from 1465m MD (4806 ft) includes a ~7mm thick hard gouge zone oriented 340° , 35°SW . The zone has sharp contact with fractured and veined Salinian granodiorite protolith. Riedel shear orientations in the gouge indicate a left-lateral sense of shear (Fig. 1).

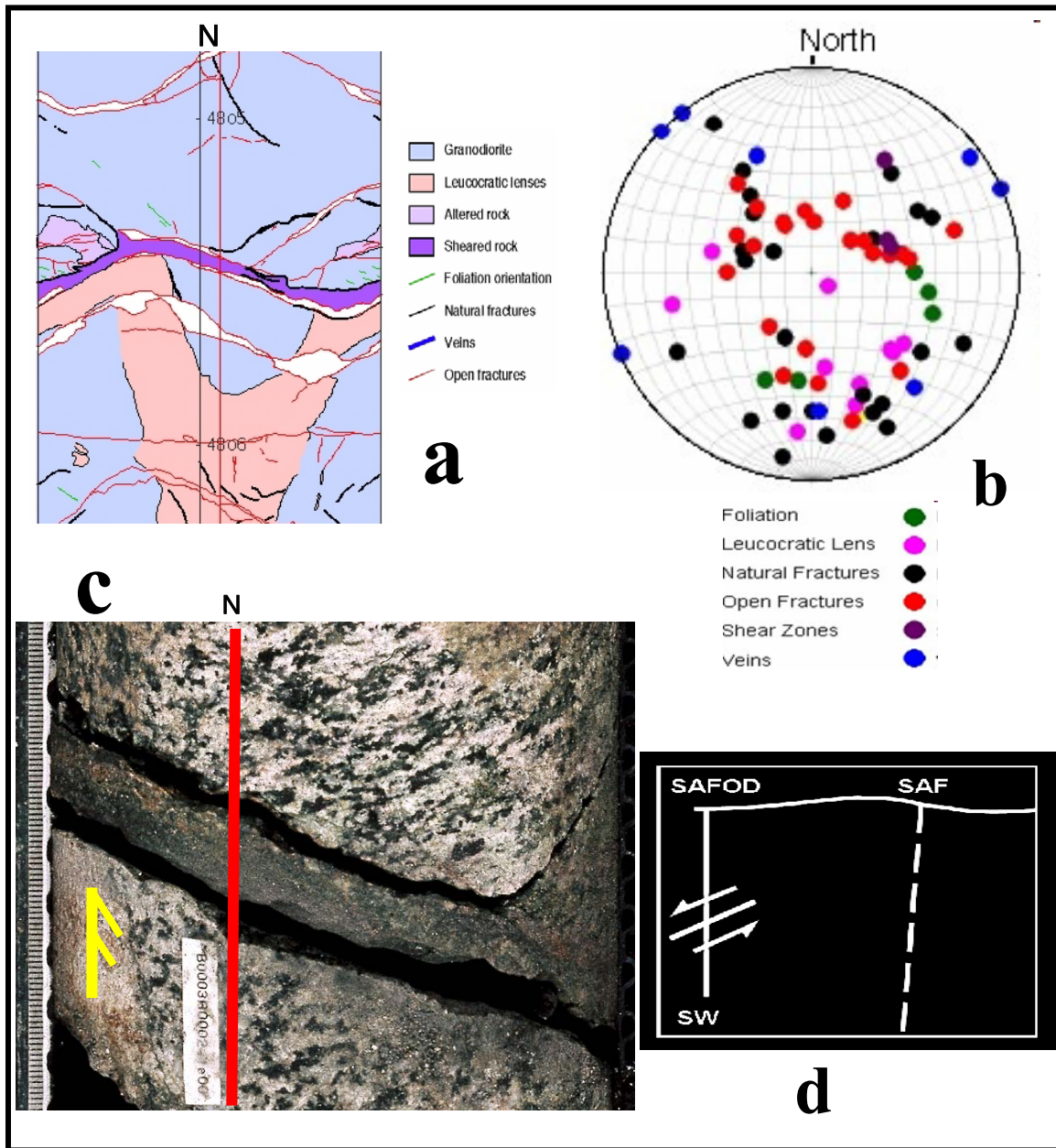


Fig. 1. (a) Core wraparound map. (b) Plot of poles to minor gouge zones in SAFOD Phase I and II cores (Map and plot after Almeida et al. 2005 and 2006). (c) Core sample showing the studied gouge zone in granodiorite protolith prior to sectioning. Note the orientation of foliation in granodiorite. (d) Approximate attitude and sense of shear of the gouge zone with respect to SAF in an un-scaled diagram.

Summary of Findings

1. The studied gouge includes foliated cataclasite domains with highly variable thickness. The non-foliated cataclasites consist of lenses of gouge appearing at different stages of comminution mostly separated by oblique Riedel shears (Fig. 2).

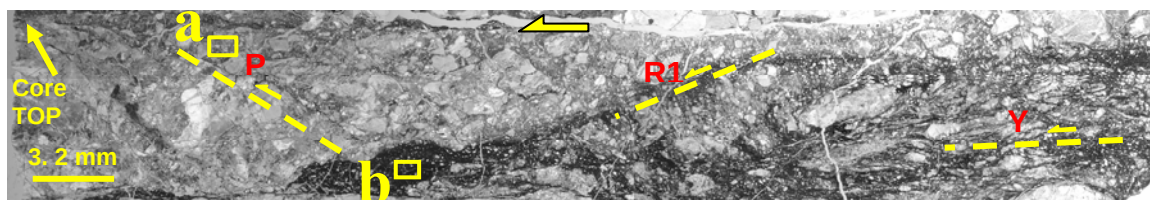


Fig. 2. Optical reflected light mosaic micrograph of the gouge zone in Fig. 1. Note the topside arrow. Insets a and b provide reference locations for close up SEM images in Fig. 3. (sample 2- section 2A2)

The foliation appears to be an SPO in the Y- orientation mostly defined by phyllosilicate flow around quartz and feldspar particles (Fig. 3a). The phyllosilicate, mostly concentrated in the foliated cataclasites, was identified by EDX spot analysis as a zeolite

Fig. 3. Close up view of (a) Foliated, and (b) Non-foliated SAFOD gouge. Note that the scale bars are 1µm in both images. BSD-SEM

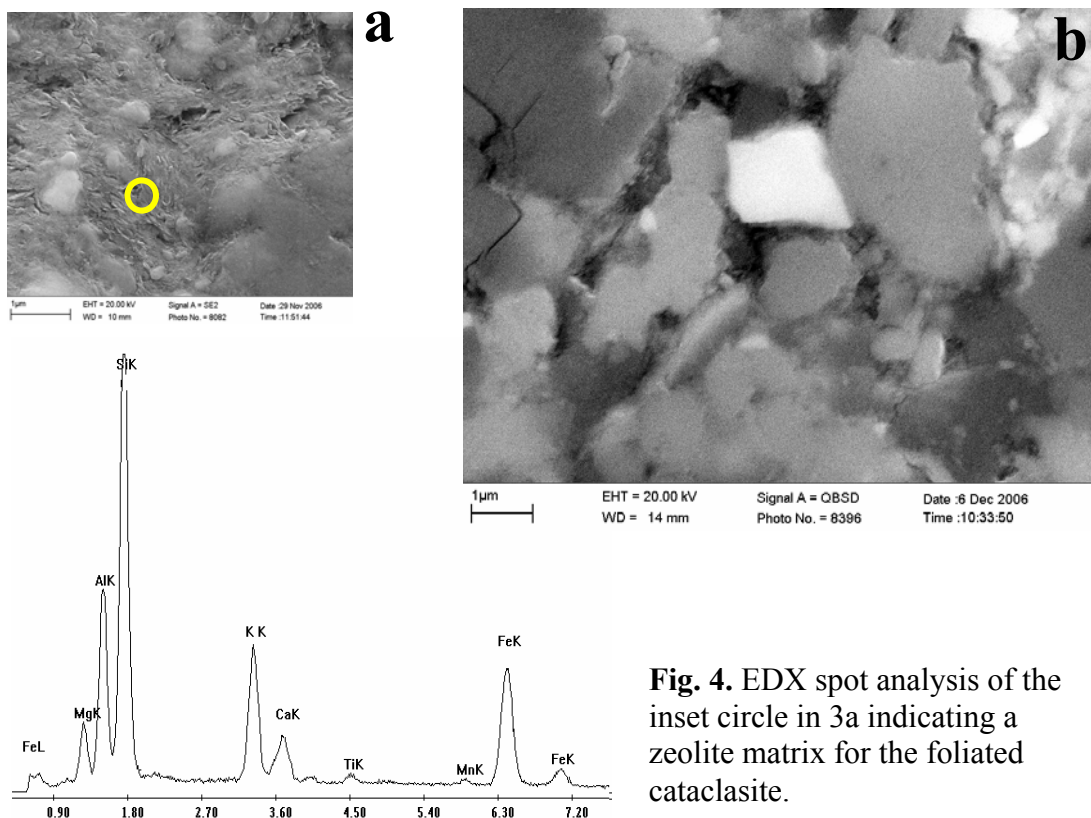
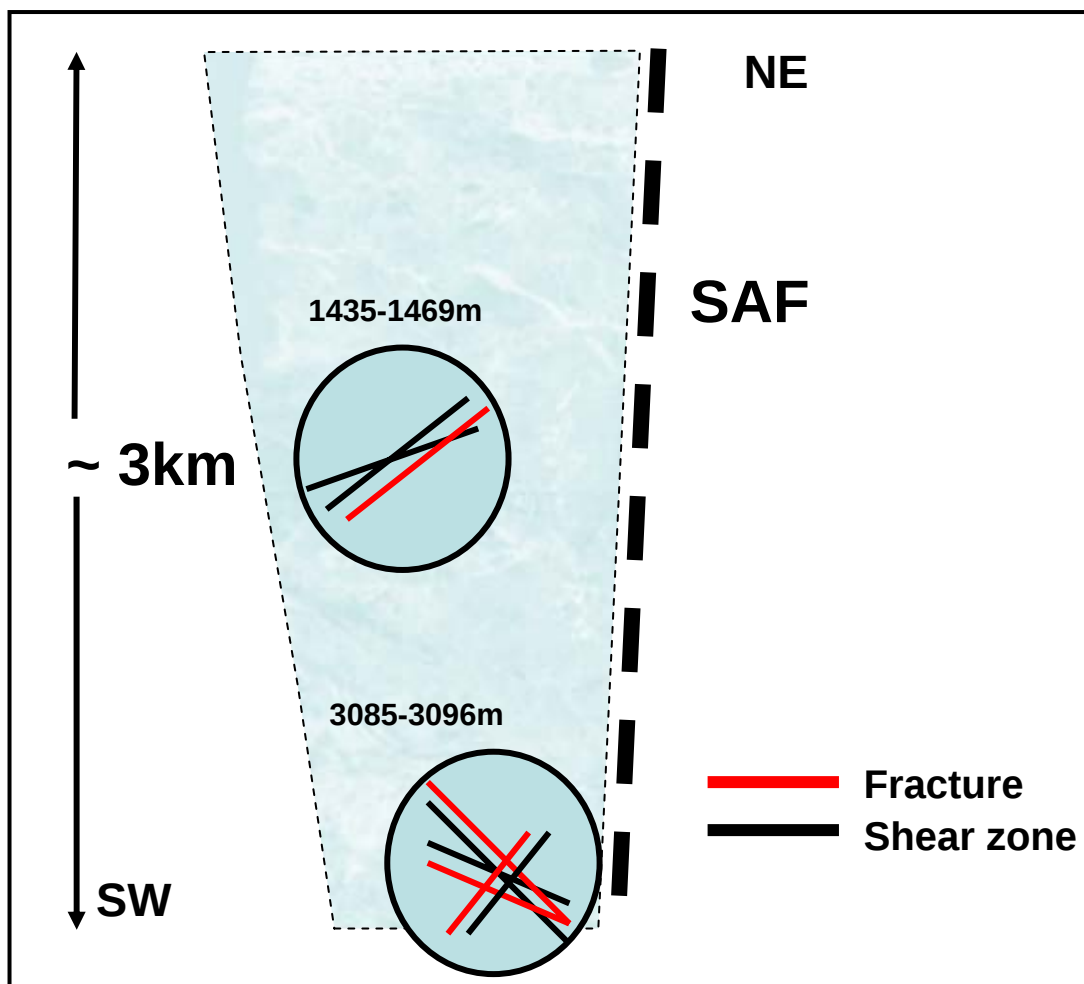


Fig. 4. EDX spot analysis of the inset circle in 3a indicating a zeolite matrix for the foliated cataclasite.

mineral alteration (most likely Stilpnomelane-see peaks in Fig. 4). A comparison of foliated and non-foliated cataclasites (Fig.3a and Fig.3b-shown at the same scale) suggests that apart from the zeolite matrix the sizes of feldspar and quartz particles in each case are not very different. This latter similarity has important implications for mechanism of particle size reduction and foliation and needs to be quantitatively ascertained. The use of the term ultracataclasites (Sibson 1977) to describe the foliated gouge in this sample is also dependent upon the establishment of particle size and the clast-matrix ratio.

2. Projection of the fracture sets and minor shear zone attitudes in phase I and II cores (Almeida et al. 2005 & 2006) indicates that these structural features generally coincide (Fig. 5). The same study indicates that the shear zones do not coincide with the gneissic foliation and/or the leucocratic lenses in the granodiorite Protolith. The co-orientation of fracture sets with shear zones appears to be more extensive closer to the main trace of SAF.

Fig. 5. Minor shear zone attitude data (Fig. 1b-Almeida et al. 2005) plotted schematically with respect to SAFOD drillhole and the trace of the San Andreas Fault.



Discussion

A microstructural comparison was carried out between the gouge in this study and deformed simulated westerly granite gouge from a previous experimental study (Fig 6). A contrast is noted in how cataclastic foliation might have developed in each case. The

Fig. 6. Westerly granite simulated gouge after 387mm of sliding at 25MPa, and 25°C (Hadizadeh et al. 2004). Optical cross polarized light image.

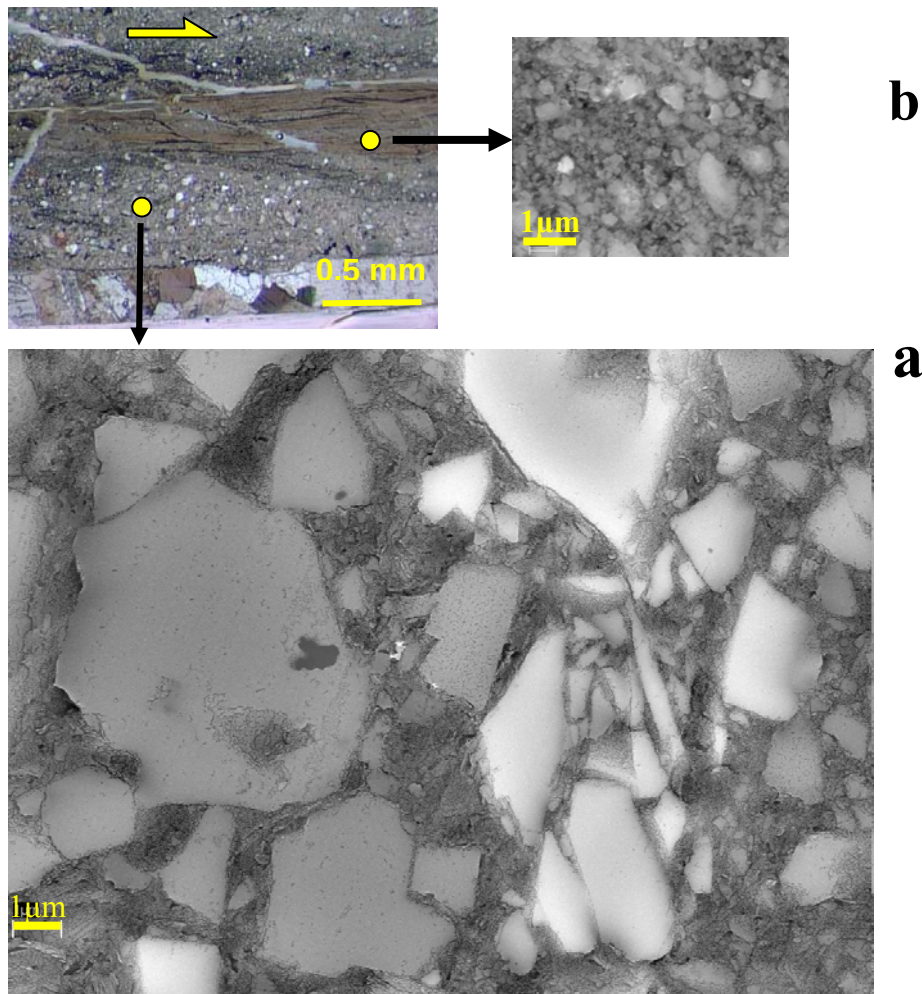


Fig. 7. Close-up view from spots on Fig. 6. (a) non-foliated, and (b) foliated simulated Westerly granite gouge. Note that scale bars have been equalized. BSD-SEM image.

experimental foliation is entirely particle size-driven, while the foliated cataclasites in the SAFOD gouge seems to have undergone additional processes such as reaction softening by mineral alteration after a certain degree of comminution. This conclusion may be reached by observing that feldspar and quartz particles in the SAFOD foliated and

non-foliated gouge have similar size distributions (see Figs. 3a and 3b). The experimental foliated and non-foliated gouge on the other hand has different particle size distributions (see Figs. 7a and 7b). A study of core samples from Cajon Pass drillhole in California (Blenkinsop and Sibson 1992) suggested that both cataclasis and reaction softening had contributed to particle size reduction. It is consistently shown that mesoscale fracture systems in fault damage zones act as fluid flow pathways and therefore are affected most by mineral alterations.

As indicated in Fig. 5, the gouge in minor shear zones might have developed along preexisting suitably-oriented and alteration-softened fracture surfaces. A pervasive network of such minor gouge zones could lower the overall frictional strength of the damage zone because of the lower friction coefficient of the phyllosilicate content of the foliated ultracataclasites (Paterson and Wong 2005). The combination of fractures and a system of low friction gouge zones within the flower structure of the SAF at shallow depths could give the entire damage zone a beanbag-like deformability. Further studies regarding the effects and significance of limited lateral extent, thickness variability, and particle size distribution of the gouge in SAFOD minor shear zones is recommended.

Conclusions

1. Despite apparent limited shear displacement minor shear zones in the damage zone of the SAF include foliated ultracataclasites.
2. The microstructures of the studied gouge indicate that mineral alterations and possible alteration softening mechanisms might have played a significant role.
3. The damage zone distribution of minor shear zones and their average shear displacement requires further investigation

References Cited

- Almeida R., Chester J. S., Chester F. M., Waller T. J., Kirschner D. L., and Moore D. 'Lithology and structure of SAFOD phase I core samples', EOS Trans. AGU, 86(52), T21A-0454, 2005.
- Almeida R., Chester J. S., Chester F. M., et al. 'Lithology and mesoscale structure of SAFOD phase I and phase II cores', Unpublished manuscript displayed at <http://geoweb.tamu.edu/faculty/chesterj/safod> 2006.
- Blenkinsop T. G. and Sibson R. H. 'Aseismic fracturing and cataclasis involving reaction softening within core material from the Cajon Pass drill hole' JGR 97, 5135-5144, 1992.
- Hadizadeh J., Goldsby D., Konkachbaev, A. I., Yazdanpanah M., Tullis T. E., Beeler 'Some mechanical implications of the development and evolution of Y shears in simulated granite gouge'. EOS Trans. AGU 85, 47, 1669, 2004.
- Paterson, M.S. and Wong, T.-f., Experimental Rock Deformation - The Brittle Field, 2nd Edition. Springer-Verlag, New York, 348 pp., 2005.
- Sibson R. H. 'Fault rocks and fault mechanics', J. Geol. Soc. London 133, 191-213, 1977.