Variation with Creep Rate in the Mineralogy and Textures of Fault Gouge from the San Andreas Fault Observatory at Depth (SAFOD)

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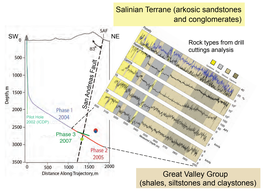
USGS science for a changing world

The SAFOD borehole was drilled to study the physical and chemical processes controlling faulting and earthquake generation along an active, plate-bounding fault at depth. Located near Parkfield, California, the borehole penetrates a section of the fault that is moving through a combination of fault creep and repeating microearthquakes. SAFOD was drilled vertically to a depth of 1.5 km and then deviated across the entire San Andreas Fault Zone to a vertical depth of 3.1 km. After two years of downhole monitoring, cores were acquired from holes branching off the main hole to sample the country rock and actively deforming traces of the fault.

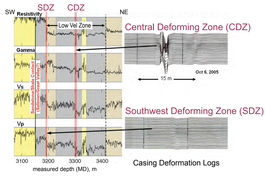
Although very similar overall, the two creeping traces — the CDZ and SDZ — exhibit some differences in texture and mineralogy that are tentatively attributed to significantly higher shearing rate in the CDZ compared to the SDZ. In addition, a ~0.2-m-wide sector of the CDZ located at its northeastern margin is nearly identical in texture and Mg-clay chemistry to the SDZ, possibly due to a gradient in creep rate across the CDZ. These textural and mineralogical features are summarized below.

Drilling Summary

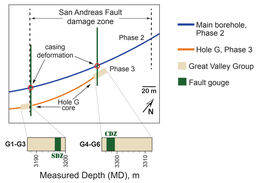
SAFOD Drillhole



Actively Creeping Strands



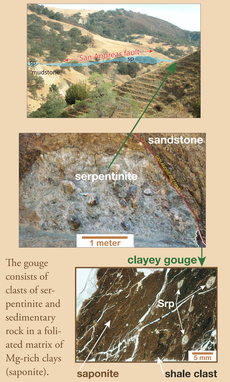
Phase 3 Core Recovery



From geophysical logs, fault width ("damage zone") is ~200 m at this locality; however, creep is highly localized to two narrow strands of foliated gouge within the damage zone, the 2.6-m wide Central Deforming Zone (CDZ), located in the middle of the present-day fault, and the 1.6-m wide Southwest Deforming Zone (SDZ), which marks the SW margin of the fault. The CDZ takes up the majority of the creep, as evidenced by the more pronounced well-casing deformation associated with it. Both creeping strands were successfully cored in 2007.

Fault at Surface near SAFOD

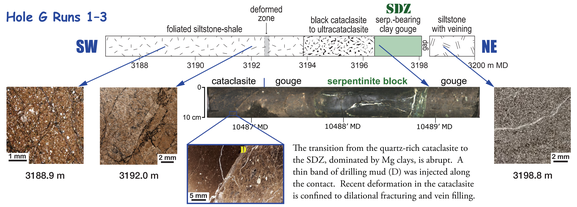
A sheared serpentinite body, mapped by M. Rymer, extends for several kilometers within the fault zone NW of the drillsite. An outcrop of the serpentinite contains fault gouge similar to that in the CDZ and SDZ (*Moore and Rymer, 2012*).



The gouge consists of clasts of serpentinite and sedimentary rock in a foliated matrix of Mg-rich clays (saponite).

Hole G Core

The CDZ and SDZ creeping strands differ markedly from the adjoining rock units, which are variably deformed sedimentary rocks of the Great Valley Group. The CDZ and SDZ consist of porphyroclasts of serpentinite (up to 40-cm diameter) and sedimentary rock dispersed in a matrix of Mg-rich clays. Both gouge zones contain >20 wt% MgO (*Bradbury et al., 2011*), and they are considered to be the product of shearing-enhanced metasomatic reaction of serpentinite that was tectonically entrained in the fault with the adjoining sedimentary wall rocks (*Moore and Rymer*, 2012). Lithologic sections are from *Bradbury et al. (2011)*.



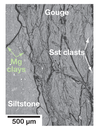
The transition from the quartz-rich cataclasite to the SDZ, dominated by Mg clays, is abrupt. A thin band of drilling mud (D) was injected along the contact. Recent deformation in the cataclasite is confined to dilational fracturing and vein filling.

The red pieces are fossil shell fragments made of Ca-phosphate. They are abundant on the NE side of the CDZ, and minor amounts may be present on the SW side.

Central Deforming Zone (CDZ)

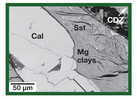
The examined CDZ samples are separated into 4 groups here: 1& 2 represent the sedimentary-rock and gouge portions, respectively, of the sample that straddles the boundary; 3 is the main portion of the 2.6-m-wide gouge zone, and 4 is close to the northeastern boundary.

1 & 2 (SW side)



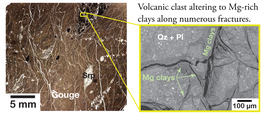
The gouge-wall rock boundary is also sharply defined at the microscopic scale. The siltstone is fragmented at the contact, and small pieces of it are visible in the gouge ~1 mm from the contact.

Fractures extending into the siltstone from the boundary are lined with Mg clays.



Deposits of calcite + Mg clays occur in the siltstone within ~1 mm of the contact. The siltstone in this image also is altering to clays along cracks.

Group 3 (Main)

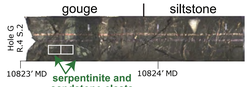


Volcanic clast altering to Mg-rich clays along numerous fractures.

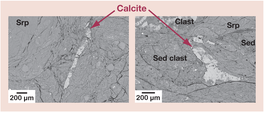
Throughout most of the CDZ the gouge is rich in matrix clays, the average porphyroclast size is relatively small, and the larger porphyroclasts are dispersed in the clays (matrix supported).

The photo at right is a typical view of the foliated gouge matrix across most of the CDZ. The foliation is phacoidal, and the gouge tends to separate along the usually slickensided surfaces. The gouge is clay-rich, at ~60-65 volume percent. *Sills et al. (2009)* found a marked shape-preferred orientation of porphyroclasts, with their long axes oriented subparallel to the strike of the fault.

Group 4 (NE side)



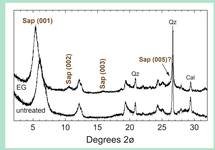
The ~0.2-m-wide sector of the CDZ at its northeastern boundary contains a concentration of porphyroclasts that are clearly visible on the surface of the core. The white boxes are thin-section locations.



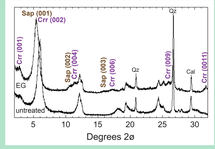
This is also the only portion of the CDZ that contains calcite deposited along the foliation (above, left) or in pressure shadows adjacent to porphyroclasts (above, right). The clast-rich character of this sector is also obvious at the microscopic scale of these SEM images.

Minerals: Saponite, a trioctahedral, Mg-rich smectite clay; Corrensite, a 1:1 ordered, interstratified saponite-chlorite.

XRD

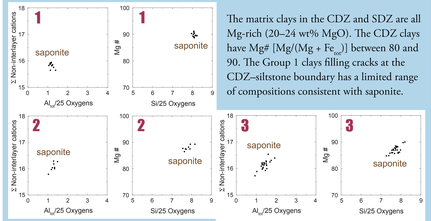


Throughout most of the CDZ,untreated and glycolated XRD patterns indicate that saponite is the only swelling clay present.



The Group 4 samples show the presence of two swelling, Mg-rich clays: corrensite and saponite.

Mineral Chemistry



The matrix clays in the CDZ and SDZ are all Mg-rich (20–24 wt% MgO). The CDZ clays have Mg# [Mg/(Mg + Fe_{tot})] between 80 and 90. The Group 1 clays filling cracks at the CDZ–siltstone boundary has a limited range of compositions consistent with saponite.

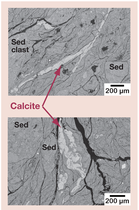
Clays with the same composition as the Group 1 clays are found throughout the CDZ in the gouge matrix and also lining cracks in porphyroclasts. However, the range of compositions increases from SW to NE, to include clays with progressively higher Al and lower Si contents, larger concentrations of interlayer cations (Ca, Na, K), and lower Mg#.

The dashed line represents a saponite-corrensite boundary consistent with the occurrence of corrensite only in Group 4.

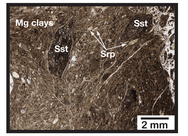
Southwest Deforming Zone (SDZ)

The examined SDZ samples are divided into 3 groups, representing the southwestern, the central or main, and the northeastern portions of the gouge layer. Differences among these groups are not as pronounced as they are across the CDZ. The textures and mineralogy are similar to those of the NE side of the CDZ.

Groups 1 & 2



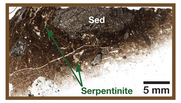
Calcite veinlets up to 5 mm in length occur throughout the SDZ. One relatively straight vein terminates against another one in the upper photo. The contorted calcite deposit in the lower photo also is surrounded by clayey gouges; it may be a somewhat older vein-let that is being deformed by shear in the gouge.



Portion of thin section scan of Group 2 gouge.

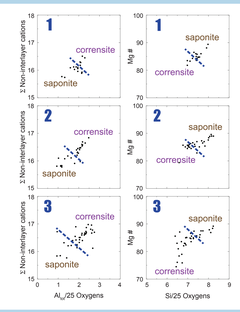
Group 3 (NE side)

This piece of core is the NE end of recovered core from the SDZ. The large green clast is serpentinite with an alteration halo surrounding it. The three white boxes are thin section locations.



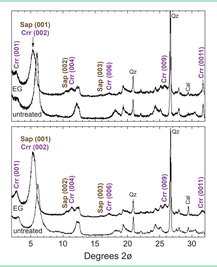
Although the SDZ as a whole is rich in porphyroclasts, the clast-to-matrix ratio and average clast size appear to be somewhat higher here than in the rest of the SDZ. This photo shows the gouge in the leftmost box marked on the core sample above. The pale greenish-brown porphyroclasts are serpentinite; the larger clasts here are of sedimentary rock.

Mineral Chemistry



SDZ clay chemistry is consistent with the identification of both corrensite and saponite in all XRD patterns. Some Group 3 clays have higher Al and lower Si contents than Group 1 & 2 clays.

XRD



Both corrensite and saponite appear in all of the XRD patterns from the SDZ. The remaining ~7Å peaks in the glycolated CDZ and SDZ samples are predominantly serpentine, probably with some chlorite derived largely from clasts of sedimentary rock.

Interpretation

- Saponite is the stable Mg clay forming at the depths of core recovery (~2.7 km vertical depth, 112°C), and where age relations can be determined, it is always younger than corrensite. Corrensite is stable at higher temperatures than saponite and may represent crystallization at greater depths. Its presence in the core samples may reflect upwelling of the weak gouge under fault-normal compression.

- Larger amounts and sizes of porphyroclasts, along with calcite deposition in the gouge matrix, in the SDZ and NE-CDZ are consistent with a lesser degree of shearing-enhanced reaction to form Mg-rich clays. In addition, the greater abundance of corrensite compared to saponite reflects a lesser degree of equilibration of the gouge at the present P-T conditions in these areas compared to the more actively creeping portions of the CDZ.