Mesoscale Fracture Fabric and Paleostress Along the San Andreas Fault at SAFOD

Judith S. Chester
Center for Tectonophysics
Texas A&M University

Collaborators:
R. Almeida, F.M. Chester,
D.L. Kirschner, & J.P. Evans
Science Goals: SAFOD

- Internal fault structure
  - Localized versus distributed shear.
  - Structure of seismic and aseismic creeping segments.
- Mechanics of faulting
  - Weak fault - strong crust?
  - Stress state in fault zone.
- This work:
  Uses spot core to address damage fabric and paleostress along the San Andreas fault zone.

From Hickman et al., 2004
SAFOD Drilling

- Phases of drilling
  - Pilot hole - vertical
  - Phase 1 of main hole - inclined
  - Phase 2 - cut across San Andreas fault zone

- Lithology at San Andreas fault zone

- Rock samples
  - Cuttings
  - Three spot cores
  - Sidewall cores
Where is the Active Trace of the San Andreas Fault?

Petrophysical log data downloaded from SAFOD website
Structural Features of Spot Core from 3056-3067 m MD

- **Lithology**
  - Pebble conglomerate to coarse-grained arkosic sandstone.
  - Fine-grained, well-cemented arkosic sandstone.
  - Fine- to very-fine-grained siltstone.

- **Structures**
  - Small fractures, deformation bands, cataclastic zones throughout.
  - Two faults that juxtapose different lithologies.
  - Bedding contact between sandstone and siltstone preserved in B18-20 section.

- **Three contiguous sections**
  - Box 10-12, Boxes 13-17, Boxes 18-20.
  - Boxes 21-23 too fractured to attempt orientation.
Mapping the Spot Cores from SAFOD

- Mapped (traced) features on transparent plastic wrapped around the core.
- Recorded both lithologic and structural features, sample locations, etc.
- Reference line for orientation.
- Maps of all spot cores are available on the SAFOD web site.
Example of Shear Fractures in 3056-3067 m Spot Core

- Planar features appear as sinusoids on wrap-around maps
- Shear fractures (black) and cataclastic bands (purple)
  - Mutually cross cutting
  - Quasi-conjugate geometry
  - Sense of shear indicates shortening approximately parallel to core axis
Shear Fracture Fabrics in Core

- Fabric in each contiguous section of core similar.
  - Two point maxima
  - Dominant set
- Use best-fit line to each maxima to align the three contiguous sections to each other.
- Aligned cores provide n = 109 measurements and good definition of fracture fabric.
Alignment of Core to Geographic Coordinates

- Bedding orientation in borehole within spot core interval determined from LWD-GVR image logs (Zoback, 2005).
- Core fabrics are rotated about borehole axis to align the bedding observed in the spot core to that in the borehole wall.
Shear Fracture Fabric Bordering the San Andreas Fault Zone

- Contour of poles to shear fractures; bedding and San Andreas Fault planes
- Best-fit planes to conjugate shear fracture sets
  - Shear fractures normal to bedding
  - Strike-slip kinematics
  - Right-lateral set most pronounced
- Principal paleostress axes with $\sigma_1$ at about 80° to plane of San Andreas Fault
Bedding strikes subparallel to San Andreas, and dips slightly towards the fault.

Quasi-conjugate shear fracture and cataclastic zones normal to bedding and consistent with strike-slip kinematics.

Principal stresses approximately perpendicular and parallel to bedding

Maximum principal stress at about 80° to San Andreas.
Minor fault at 3062 m MD

- Cataclastic shear zone
  - Fault contact between coarse and very-fine sandstone
- Largest of several cataclastic shear zones
Minor fault at 3067 m MD

- Hypothesized as the SW trace of SAF
- Progressive increase in fracturing of siltstone toward fault core.
- Fault core contains gouge layers and fault sliver of very-fine-grained sandstone
- Likely largest-displacement fault in all spot core
- Inclined at 22° to core axis
Orientation and Kinematics of the 3062 m and 3067 m Faults

- 3062 m fault
  - Right-lateral shear fracture

- 3067 m fault
  - From inclination to core axis, can determine all possible orientations.
  - Not co-planar with San Andreas
  - If strikes parallel then dip-slip, if strikes oblique then strike-slip.
  - Likely a member of the left-lateral shear fracture set and not candidate for SW trace of the San Andreas Fault.
Comparison of In Situ Stress to Paleostress

- Progressive increase in angle between $S_{H_{\text{max}}}$ and SAF with increasing depth and decreasing distance to fault (Hickman & Zoback, 2003; Boness & Zoback, 2006).

- At the boundary, in situ $S_{H_{\text{max}}}$ is at 70-80° and in agreement with Paleostress $\sigma_1$ from spot core.

- Similarity suggests current in situ stress represents spatial and temporal average stress bordering San Andreas.

From Boness & Zoback 2006
Fracture Fabric at SAFOD similar to that for Exhumed Faults of the San Andreas System

- North Branch San Gabriel fault (Chester et al. 1993)
  - 16 km right lateral slip, 2-5 km exhumation depth, crystalline rocks
  - Quasi-conjugate shear fracture fabrics
  - Paleo-$\sigma_1$ at 60° to core of fault

- Punchbowl fault (Wilson et al. 2003)
  - 44 km right-lateral slip, 2-4 km exhumation depth, arkosic sediments and crystalline rocks.
  - Quasi-conjugate shear fracture and microfracture fabrics
  - Paleo-$\sigma_1$ at 70-90° to core of fault

- Agreement of current in situ stress and paleostress at SAFOD, and similarity to exhumed faults, suggest finding is generally applicable along San Andreas at several km depth.
Conclusions

- Mesoscale fractures at boundary of SAF define a quasi-conjugate geometry consistent with strike-slip kinematics; $\sigma_1$ oriented at high angle to fault plane.

- Similarity between current- and paleo-stress states suggest that this stress state represents a long-term average state and supports the general applicability of the “weak fault in strong crust” model.

- Orientation of the 3067 m fault indicates that it is not SW trace of the San Andreas Fault, but more likely a member of left-lateral subsidiary fault set.
What Does the Active Trace of the San Andreas Fault Look Like at SAFOD?

*Fault core - damage zone*
*Asymmetric damage*
*Paired cores*
*Multiple, anastamosing cores*

North Branch San Gabriel  
San Andreas, Mojave segment  
Punchbowl  
Carboneras

Modified from Wallace & Morris, 1986
Principal Slip Surface in Ultracataclasite

- Extreme localization of slip
Natural and High-Speed Experimental Slip-surfaces

- Nojima gouge experiment (Mizoguchi & Shimamoto, 2004)
- Punchbowl ultracataclasite

- High speed friction experiment develops slip surface after a few m slip at ~1 m/s at 2 MPa normal stress.
- Friction experiments display dynamic weakening, a temperature increase, but no melt is generated
- Both natural and experimental slip surfaces consist of thin cataclastic zone with uniform birefringence
To select parameters, assume similar to San Fernando ‘71, Imperial Valley ‘79, Morgan Hill ‘84

- $\delta = 33$ mm
- Exponential weakening
- Weak fault
- $(\tau_p - \tau_r) = 0.6 \times \sigma_n^e = 30$ MPa
- $\tau_r = 10$ MPa

Exponential weakening from $\mu_p = 0.6$ to $\mu_r = 0.1$ seen in high-speed friction experiments on Punchbowl ultracataclasite.

$\delta$ and weakening in experiments consistent with model parameters
Stress Cycling Along Rough Frictional Fault Surface

- Slip on rough or wavy fault surfaces generates local stresses in host
  - Local stress varies with far field loading, friction, and roughness
  - Satisfies Coulomb failure locally
  - Damage in host reflects local stress, not far field
- Displacement past many bends explains fabric development?

---

Chester & Chester 2000
Damage Development with Dynamic Rupture

Rupture propagation and dynamic slip
- Nucleation patch
- Propagating slip pulse
- Arrest, jumping, and heterogeneous slip rate and slip

Deformation from passage of earthquake ruptures
- Rupture-tip stress concentration generates fracture in process zone
- Intensification of fabric with repeated rupture
- Damage zone thickness and fabric reflects process zone stress states and dimensions?

Heaton, 1990