Advanced Structural Geology, Fall 2022

State of stress along San Andreas Fault

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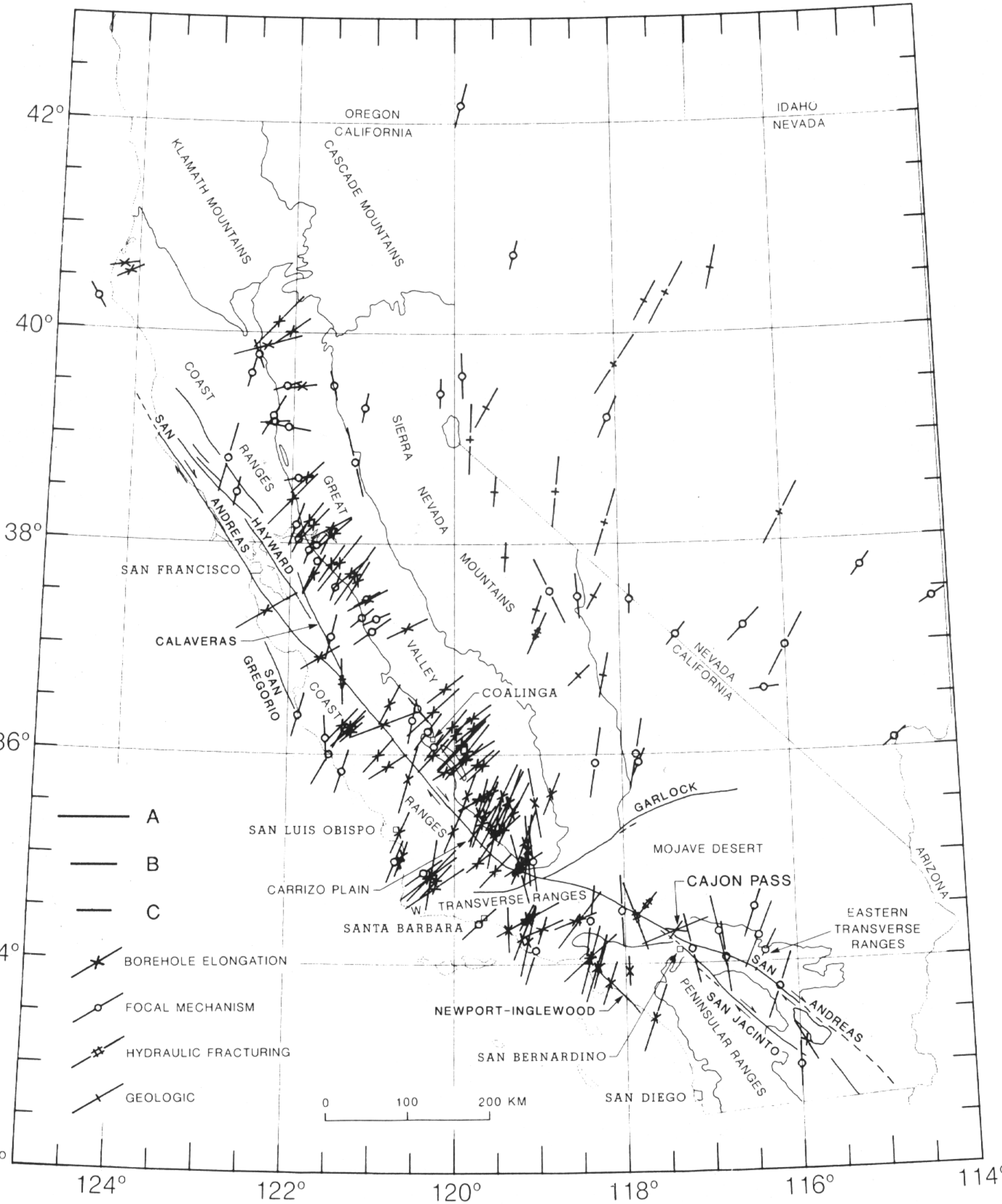
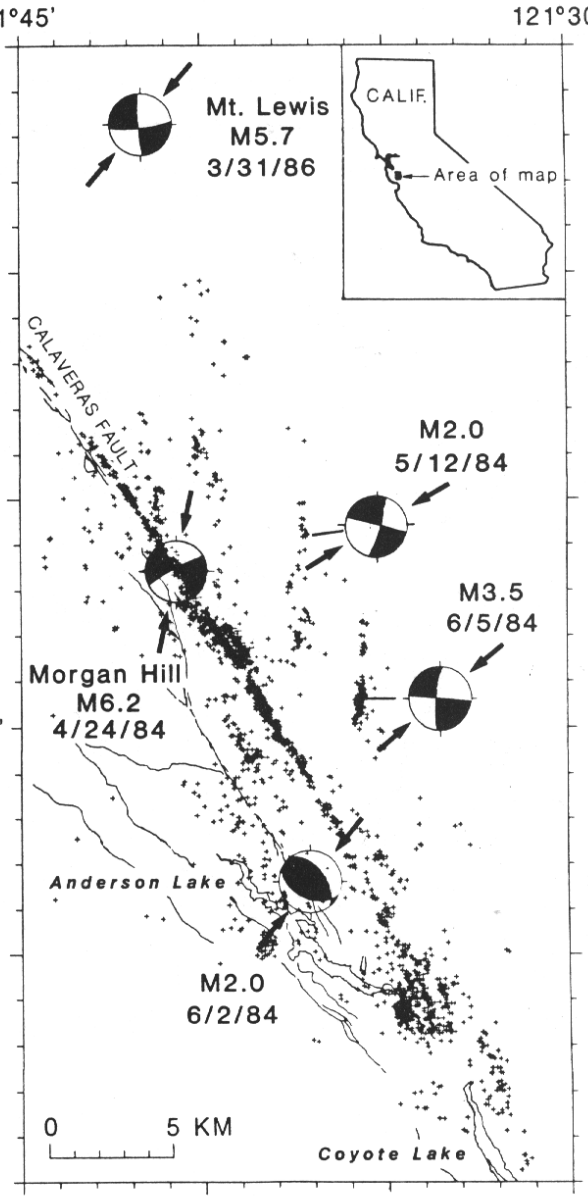
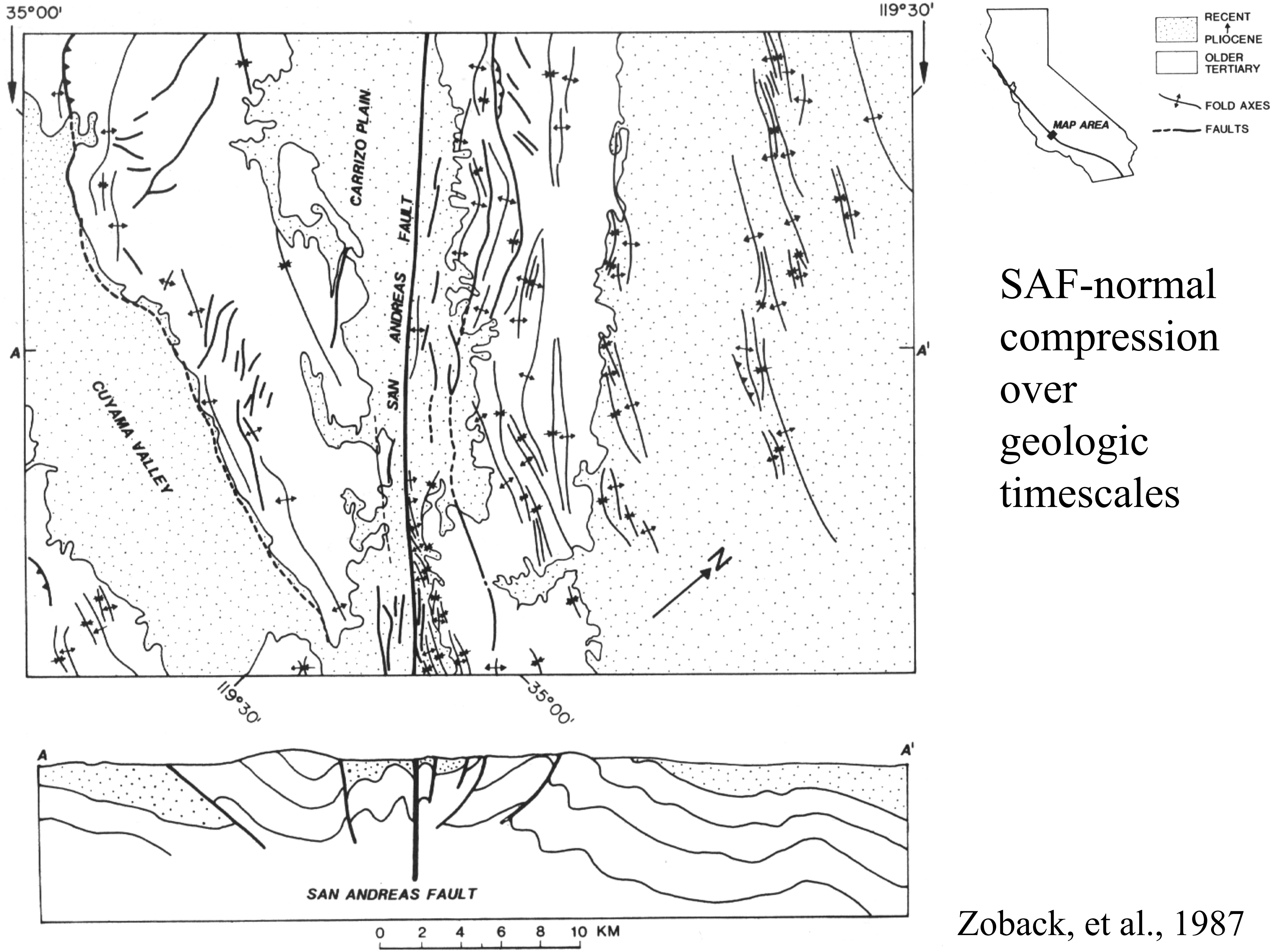




Zoback, et al., 1987



SAF-normal compression over geologic timescales

Zoback, et al., 1987

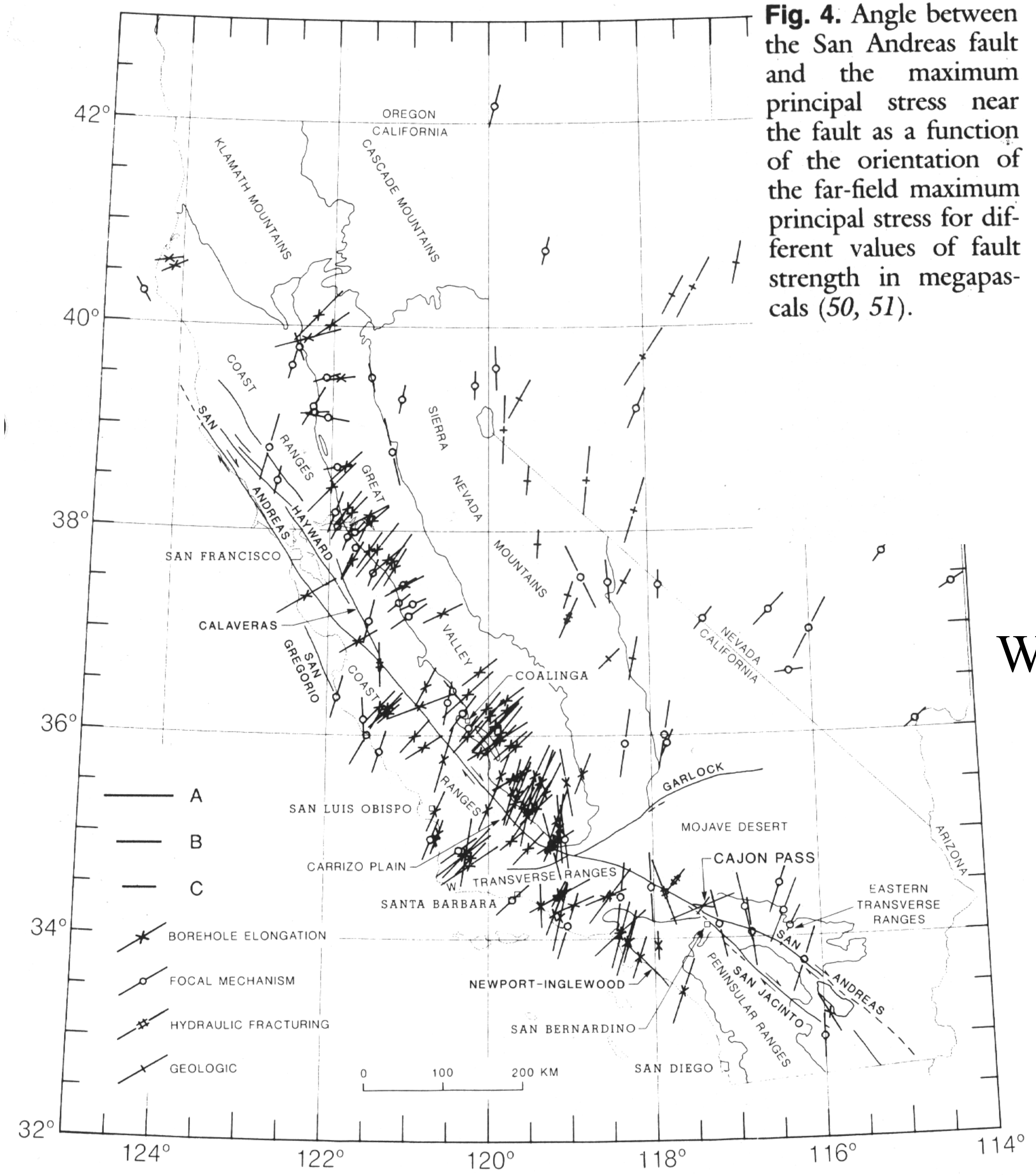
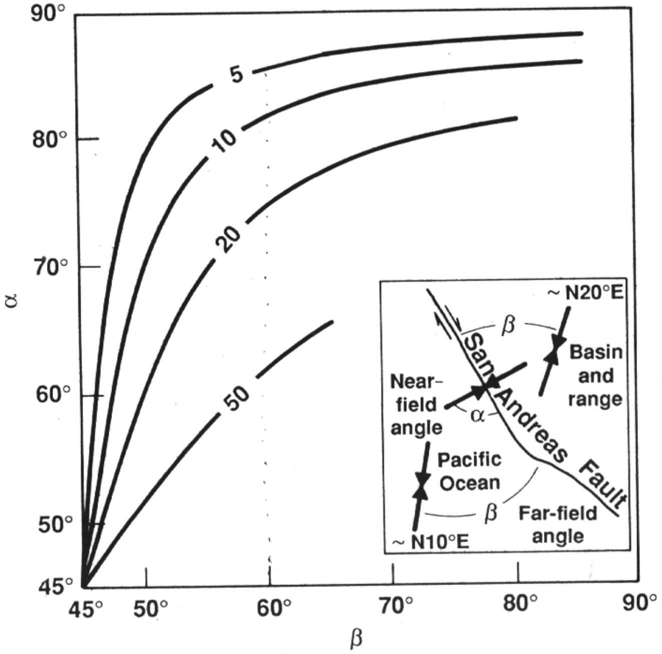
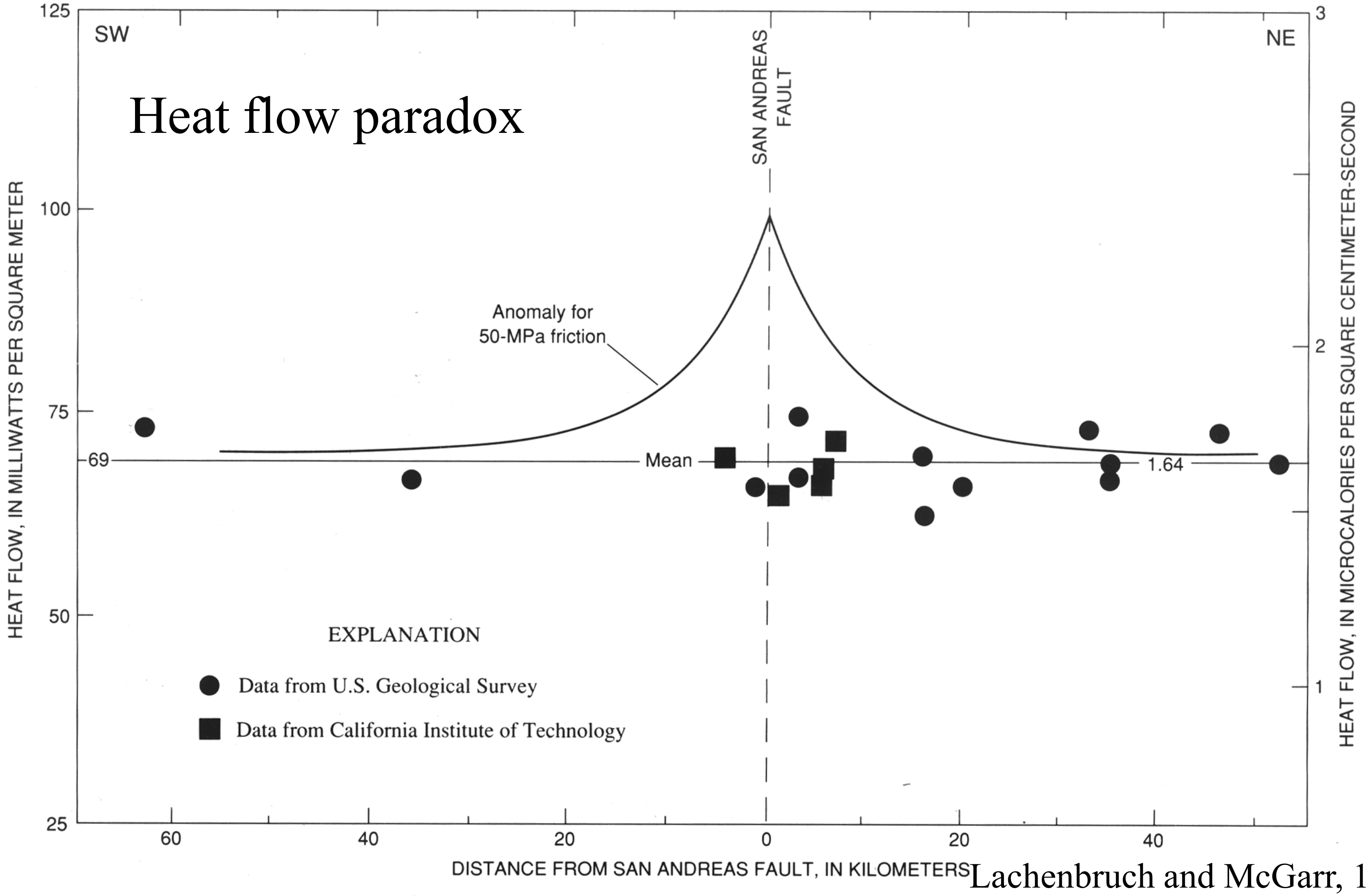


Fig. 4. Angle between the San Andreas fault and the maximum principal stress near the fault as a function of the orientation of the far-field maximum principal stress for different values of fault strength in megapascals (*50, 51*).



Weak fault in strong crust

"Weak" faults?
-San Andreas example



Lachenbruch and McGarr, 1990

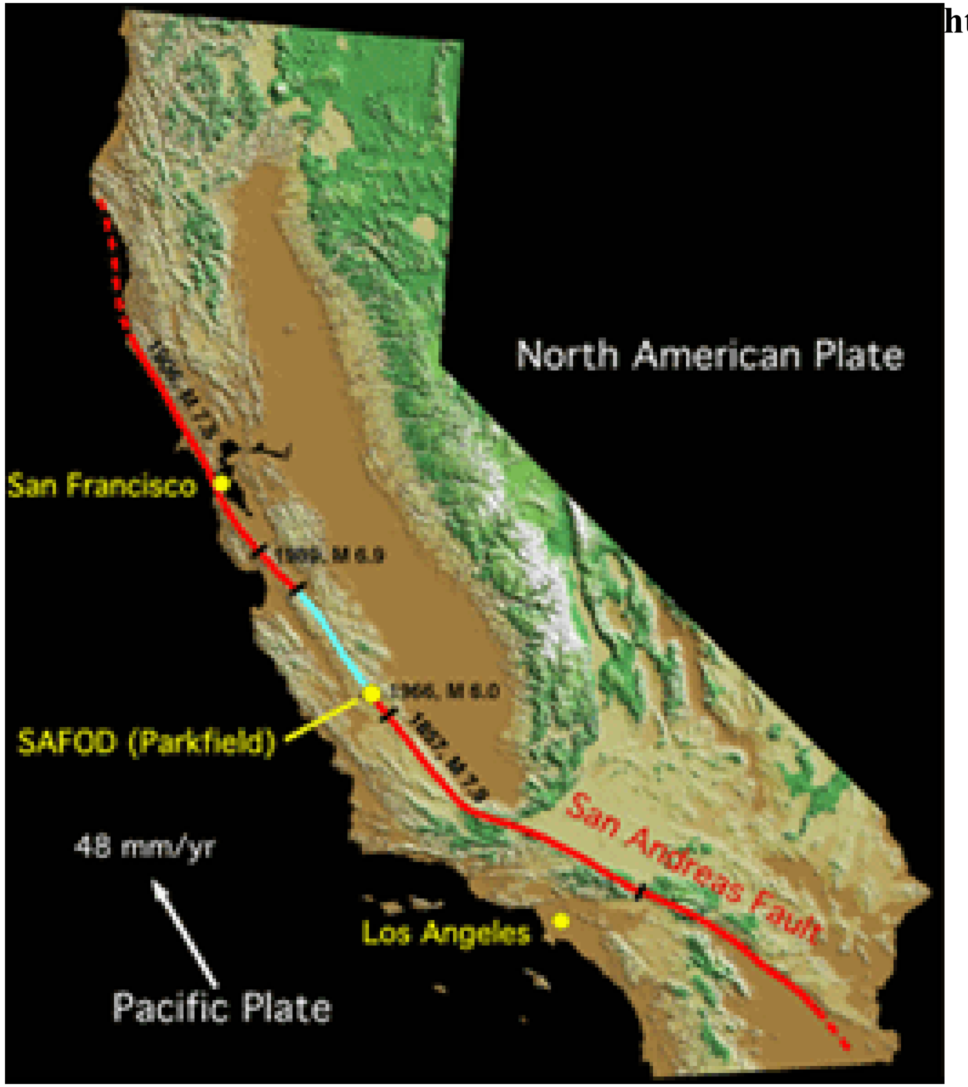
FIGURE 10.5.—Heat flow as a function of distance from the San Andreas fault in the Mojave segment (region 7, fig. 10.6). Theoretical anomaly is for a slip velocity of 25 mm/yr and average friction of 50 MPa (Lachenbruch and Sass, 1988).

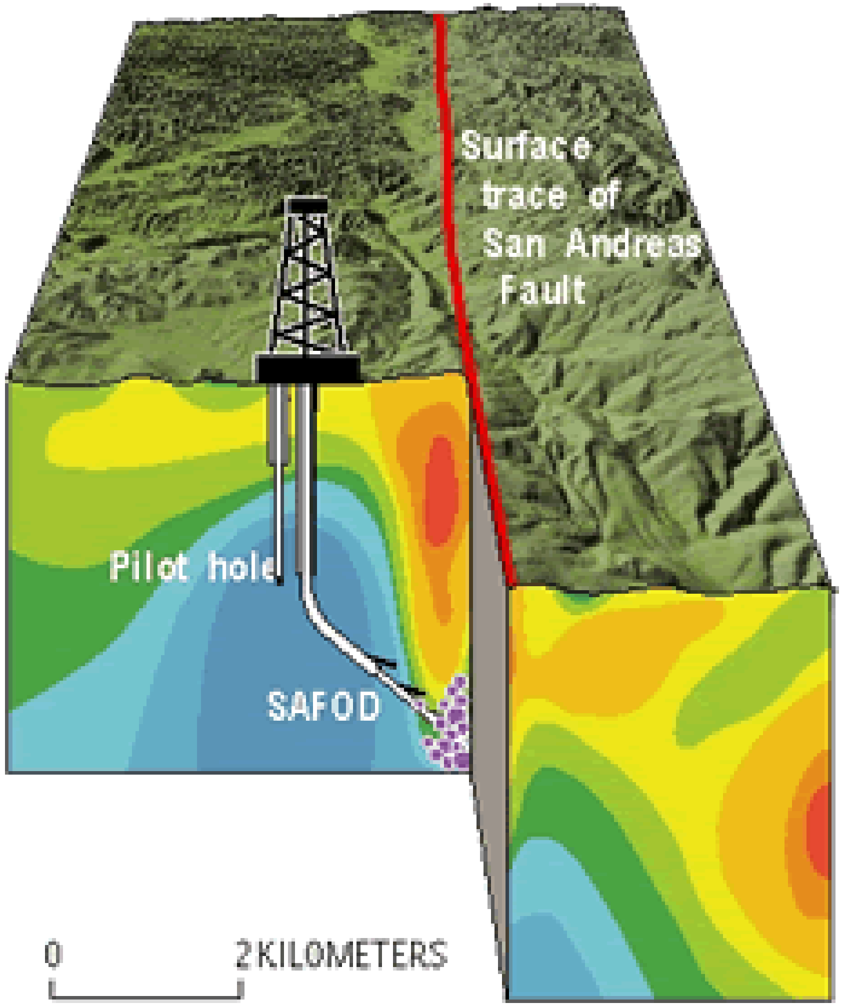
Weakening mechanisms

- High fluid pressure
- Dynamic weakening during earthquakes
- Ultra low friction fault gouge

How to test: SAFOD!

http://www.icdp-online.de/sites/sanandreas/index/index.html





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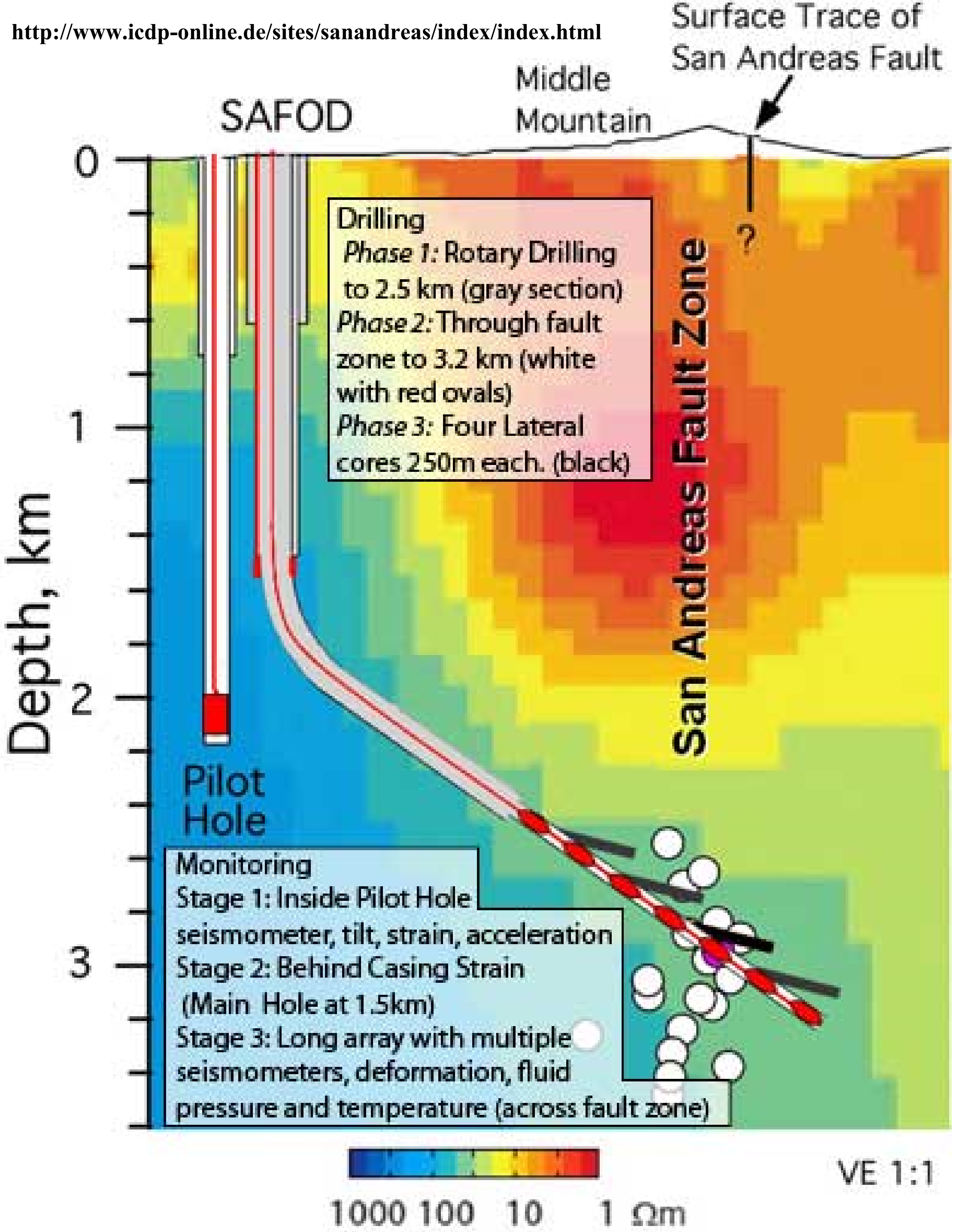
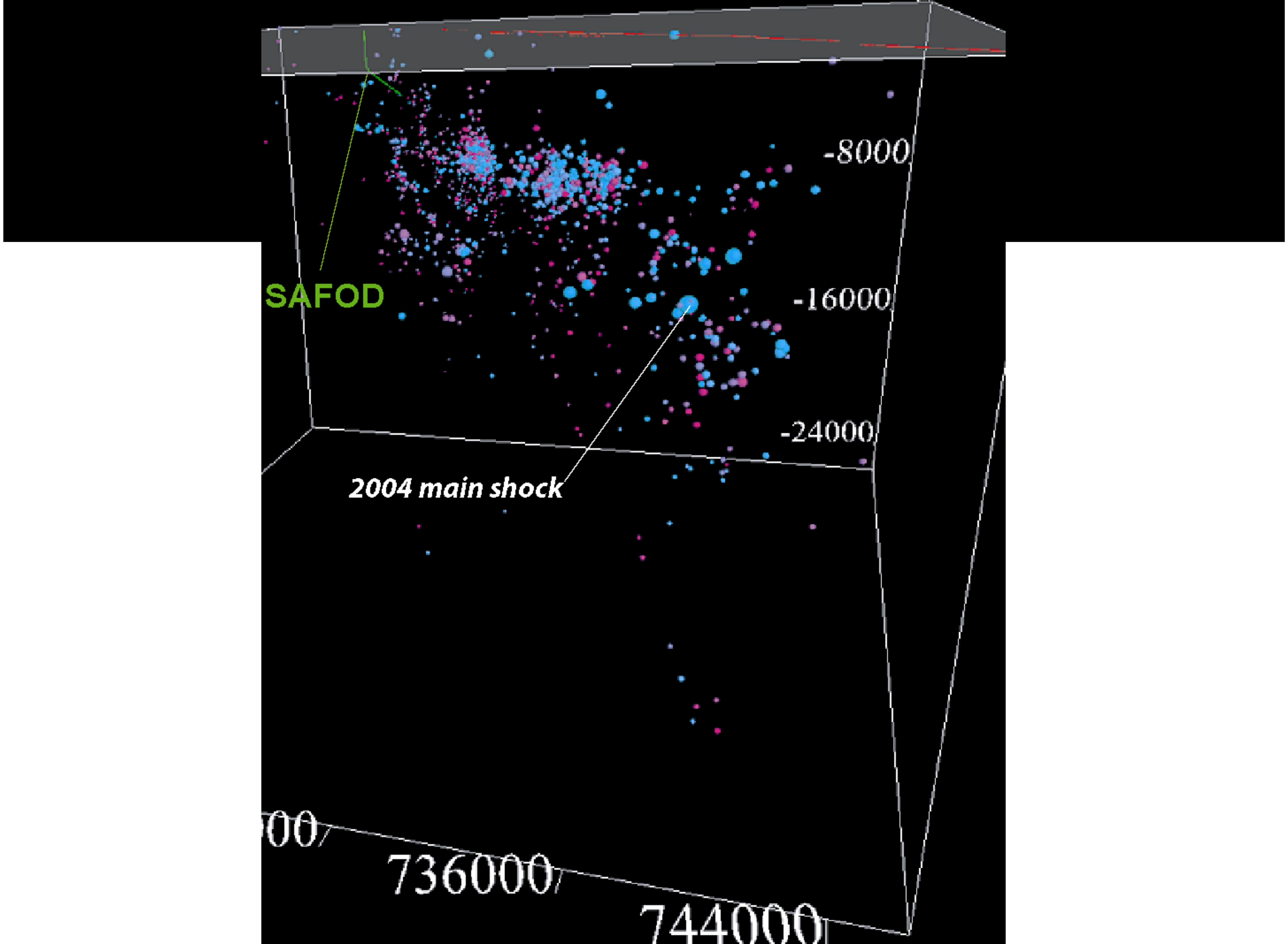


SAFOD should help us learn about:

- composition of fault zone materials and determine the constitutive laws that govern their behavior
- measure the stresses that initiate earthquakes and control their propagation
- test hypotheses on the roles of high pore fluid pressure and chemical reactions in controlling fault strength and earthquake recurrence
- observe the strain and radiated wave fields in the near field of microearthquakes.

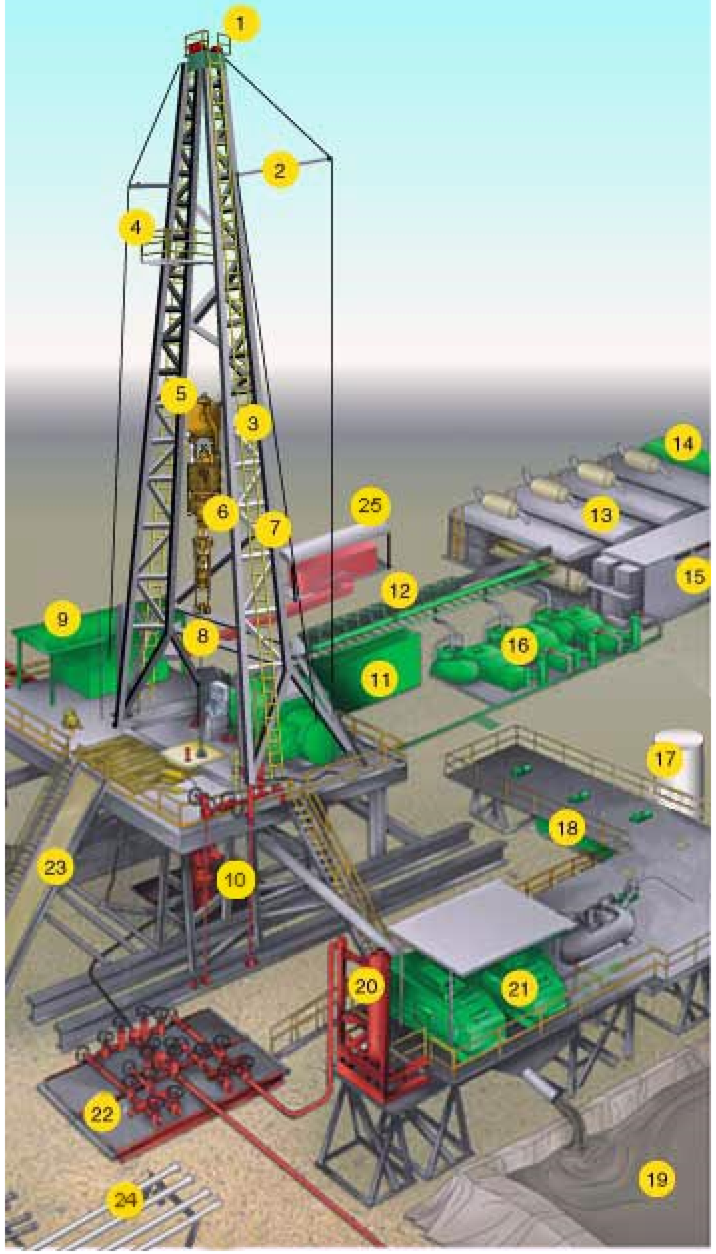


SAFOD
-8000
-16000
-24000
2004 main shock
736000
744000

Drilling Rig Components

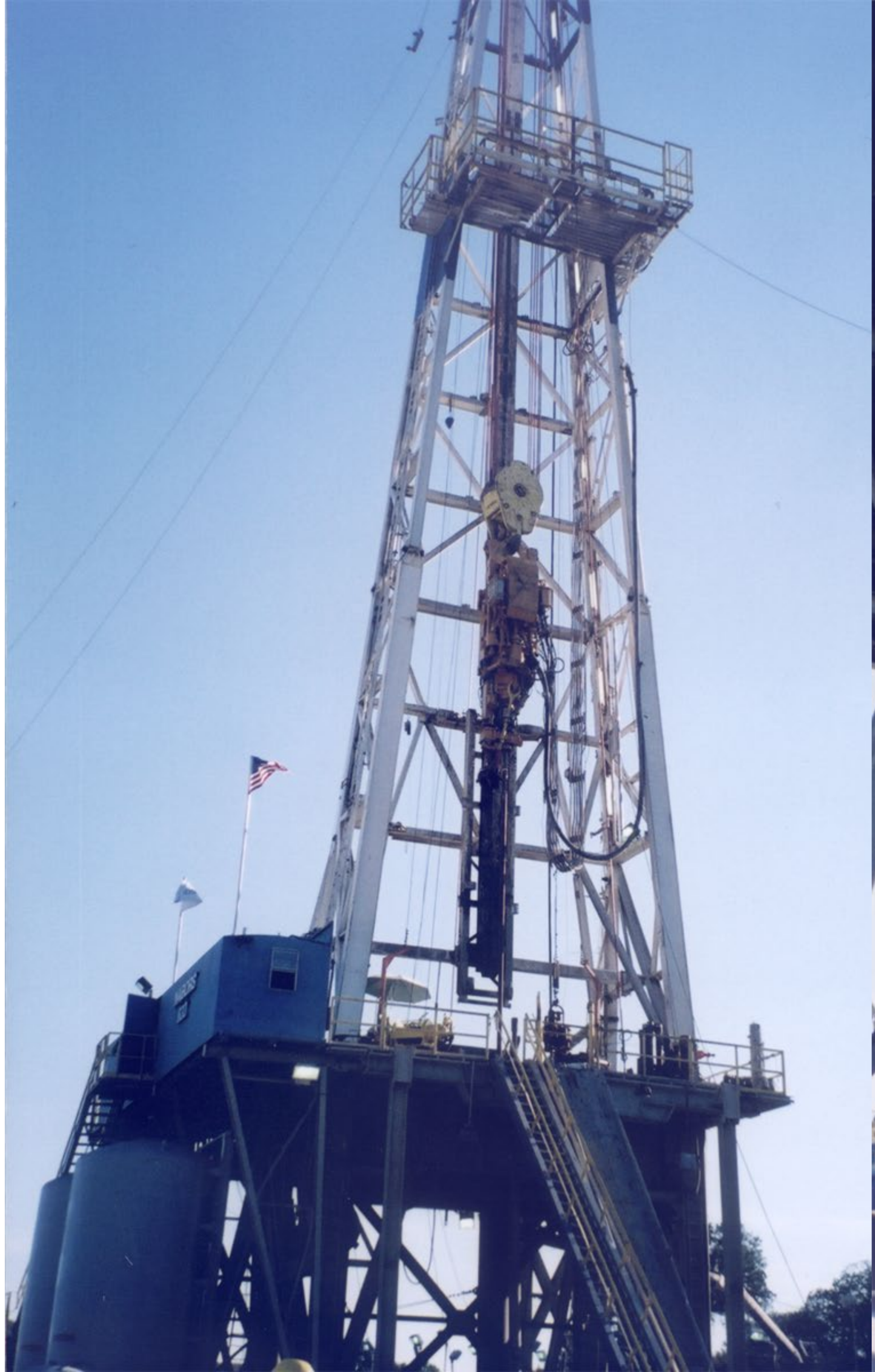
Click on the name below or a number on the graphic to see a definition and a more detailed photo of the object.

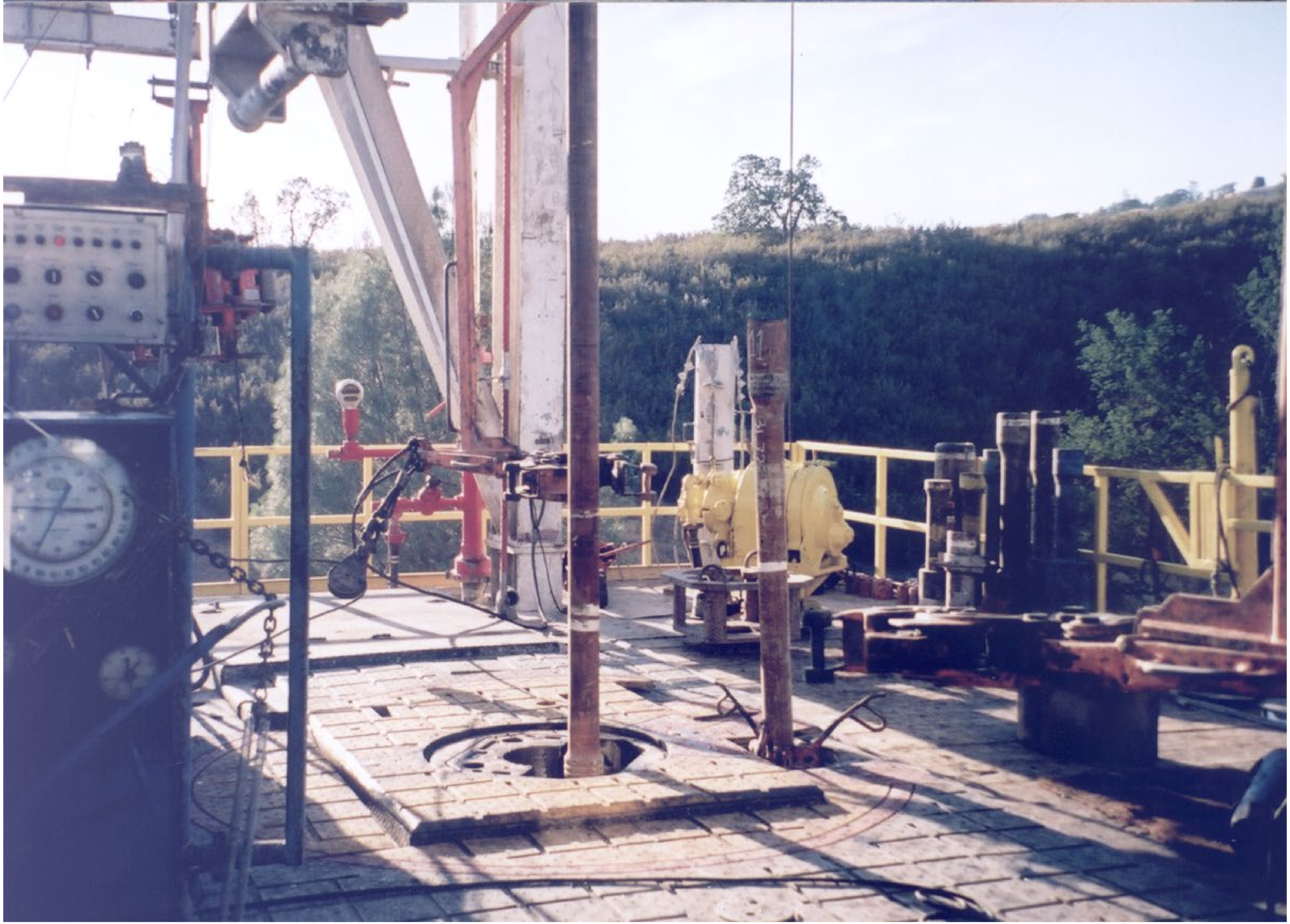
1. Crown Block and Water Table
2. Catline Boom and Hoist Line
3. Drilling Line
4. Monkeyboard
5. Traveling Block
6. Top Drive
7. Mast
8. Drill Pipe
9. Doghouse
10. Blowout Preventer
11. Water Tank
12. Electric Cable Tray
13. Engine Generator Sets
14. Fuel Tank
15. Electrical Control House
16. Mud Pumps
17. Bulk Mud Component Tanks
18. Mud Tanks (Pits)
19. Reserve Pit
20. Mud-Gas Separator
21. Shale Shakers
22. Choke Manifold
23. Pipe Ramp
24. Pipe Racks
25. Accumulator



Equipment used in drilling

http://www.osha.gov/SLTC/etools/oilandgas/illustrated_glossary.html

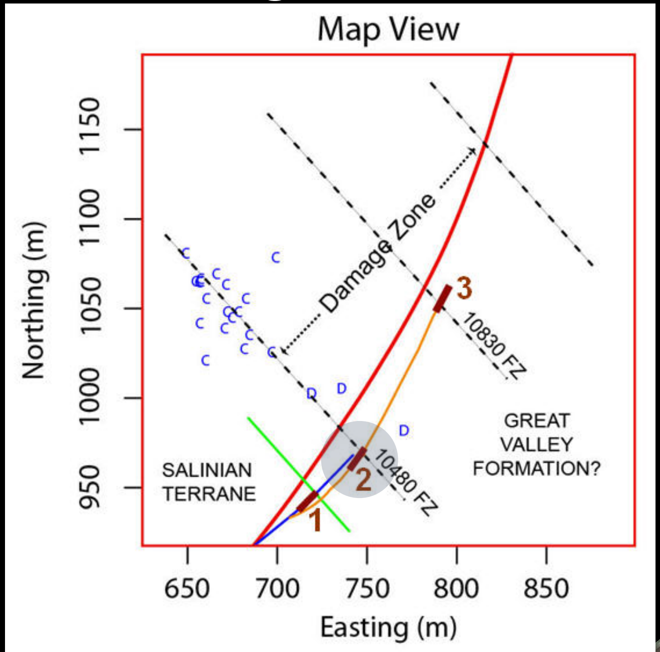





earth
scope

Phase 3 Coring: Interval 2 - Across 10,480’ Fault

Talc + Serpentine Found in Cuttings from 10,480 and 10,830 faults (see Solum et al, 2006; *Moore and Rymer, 2007*) →Mineralogical control on fault strength?



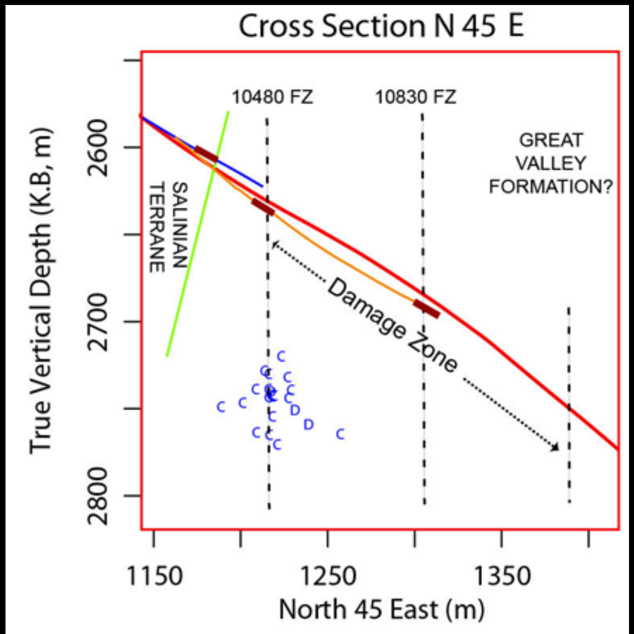
Casing Deformation Zone: Fault Gouge Layer (1.5 m thick)

Highly sheared serpentinite layer with fragmented calcite veins

Foliated fault gouge with serpentinite and sandstone porphyroclasts

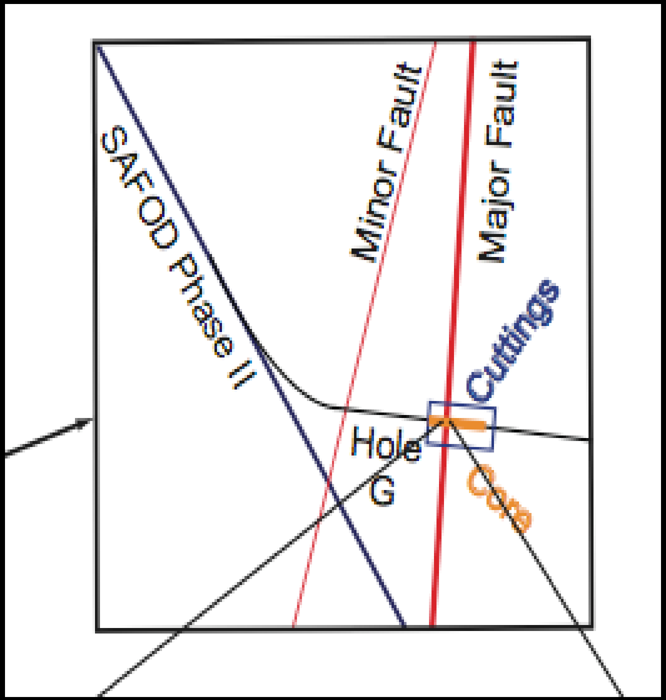
Foliated gouge with serpentinite and sandstone porphyroclasts

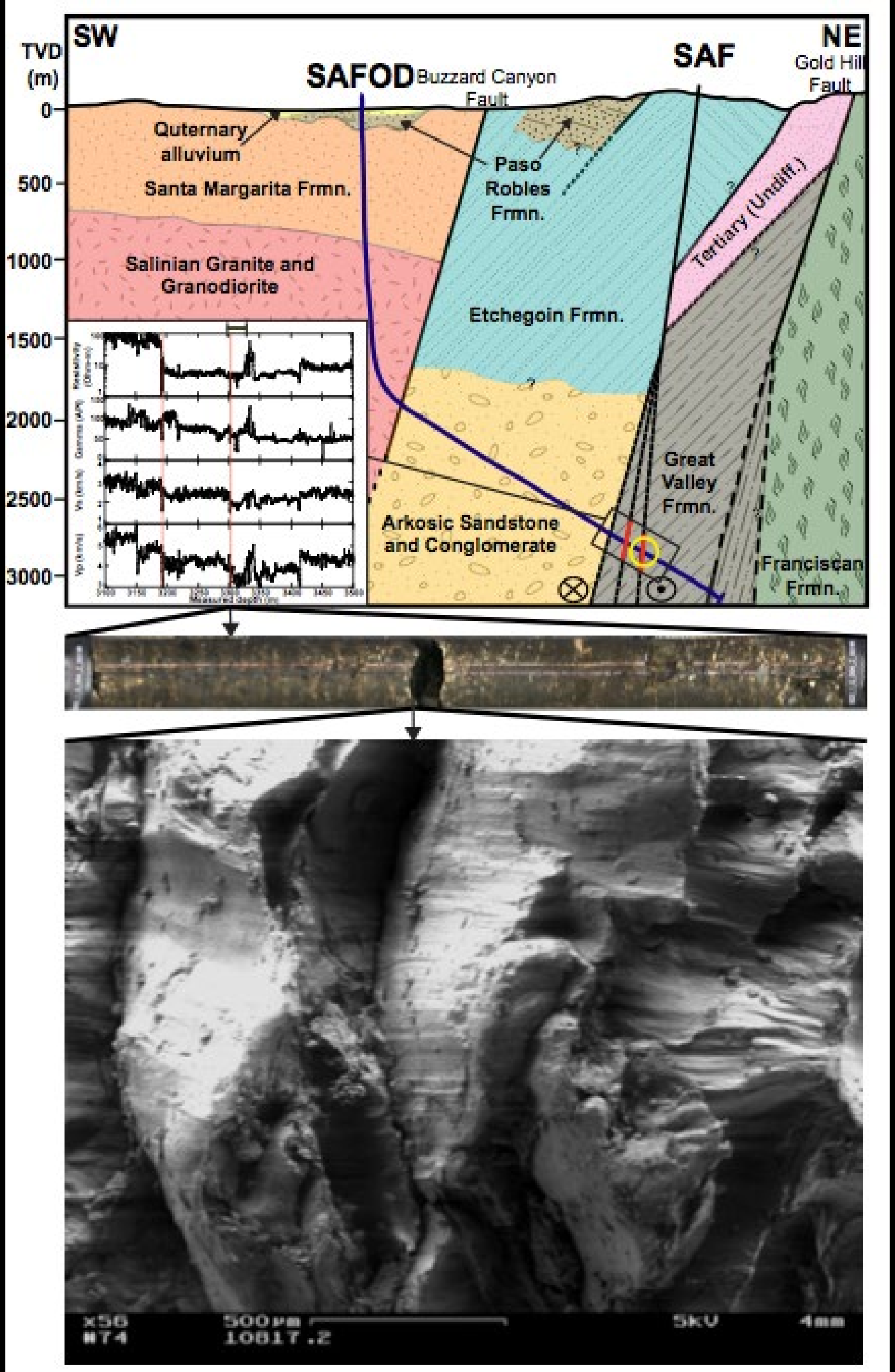
Serpentinite cut by white (calcite) veins



Hickman, et al.

San Andreas Fault, Structure and Frictional Strength



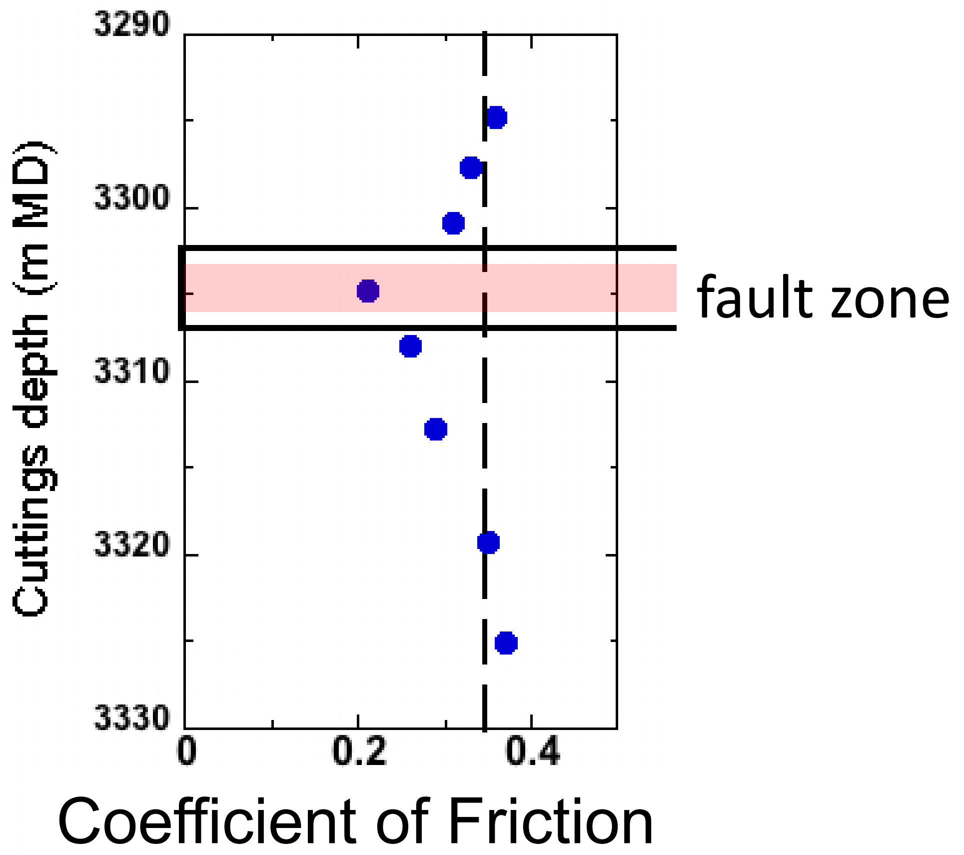


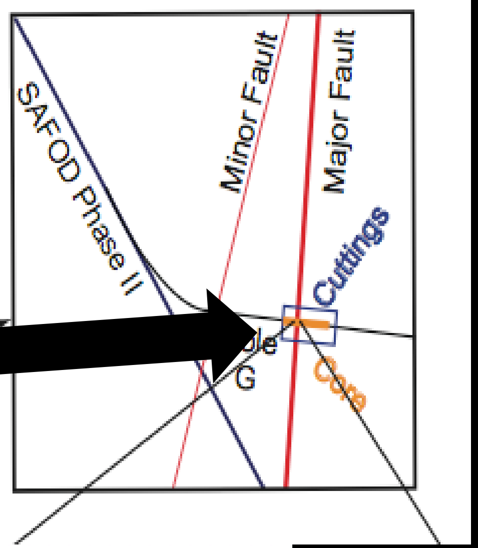
Zoback, Hickman & Ellsworth, 2011

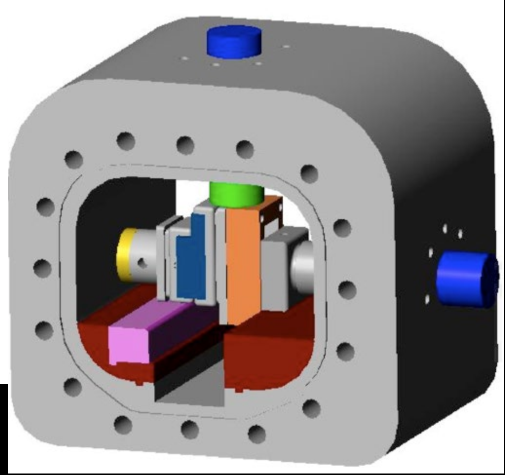
-C. Marone

Frictional strength is low in the fault zone

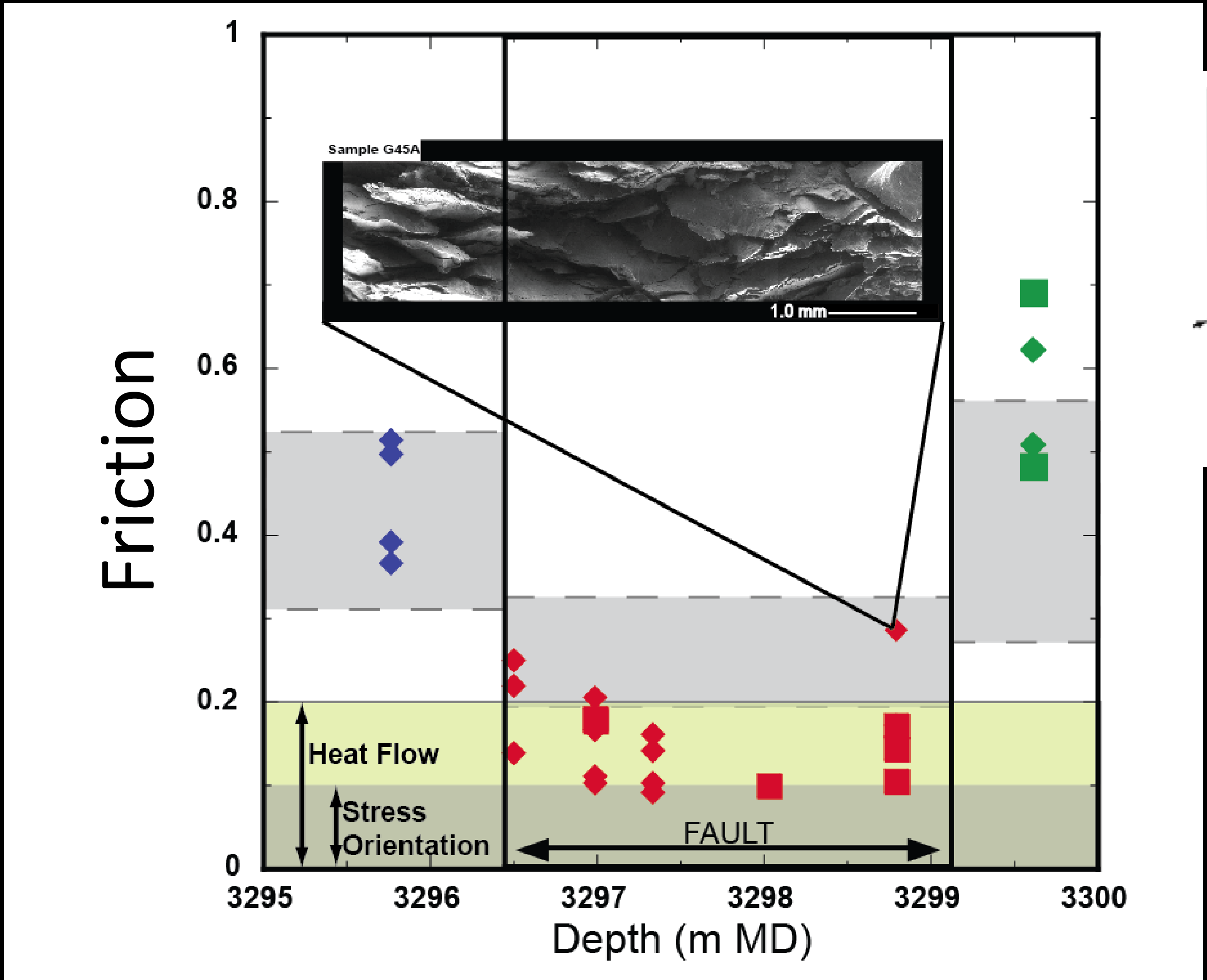
SAFOD Phase III Drill Cuttings

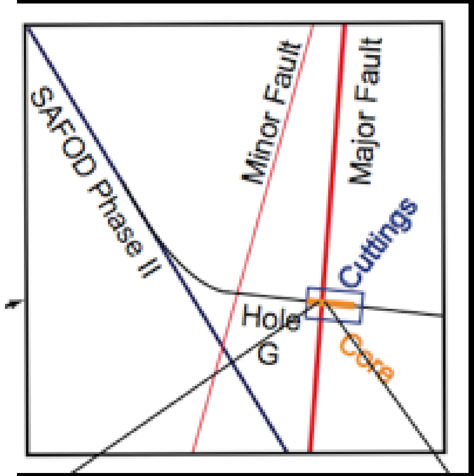






Frictional Strength, SAFOD Phase III Core

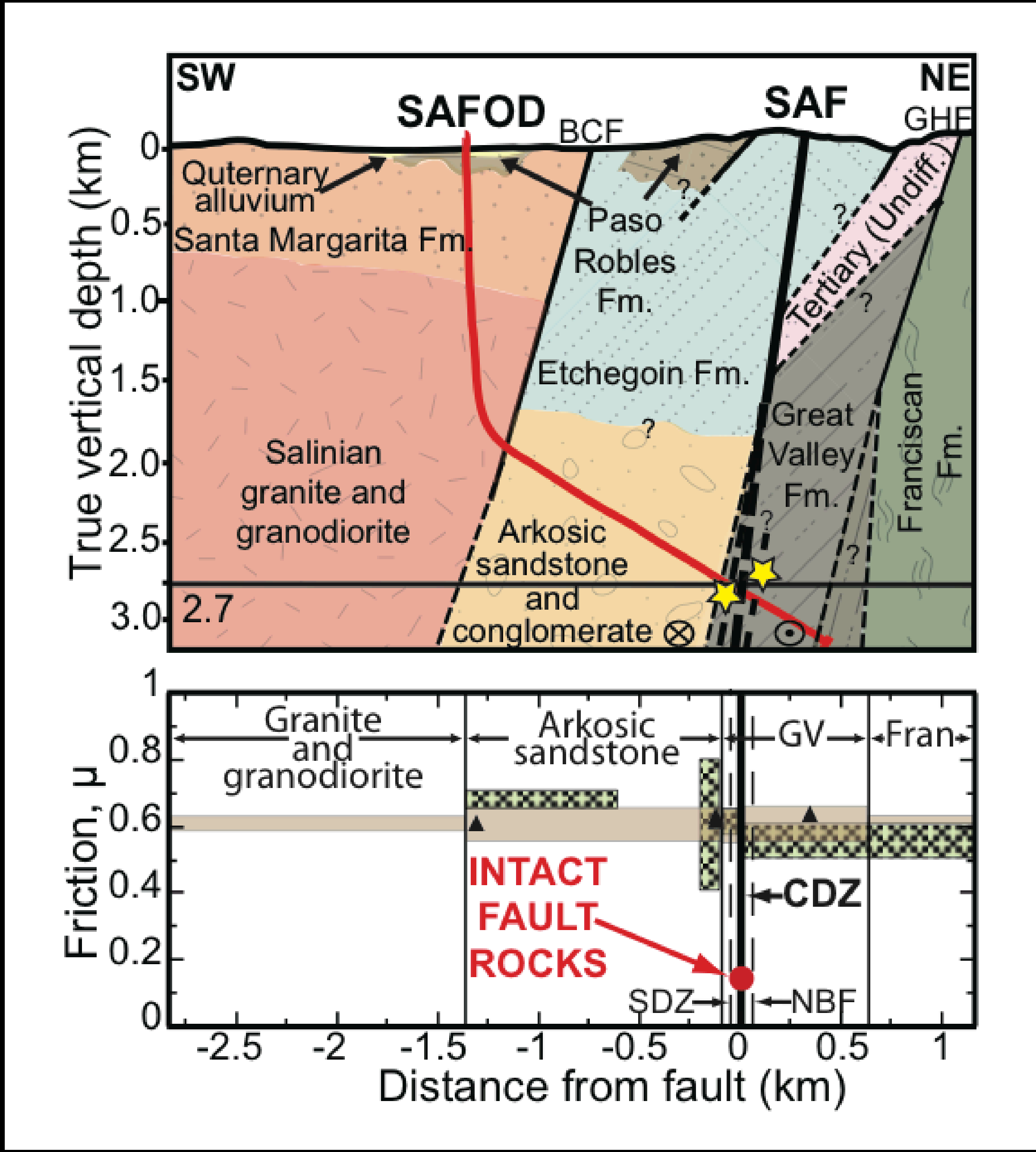




Carpenter, Marone, and Saffer, *Nature Geoscience*, 2011

Carpenter, Saffer and Marone, *Geology*, 2012

-C. Marone



Results from Scientific Drilling

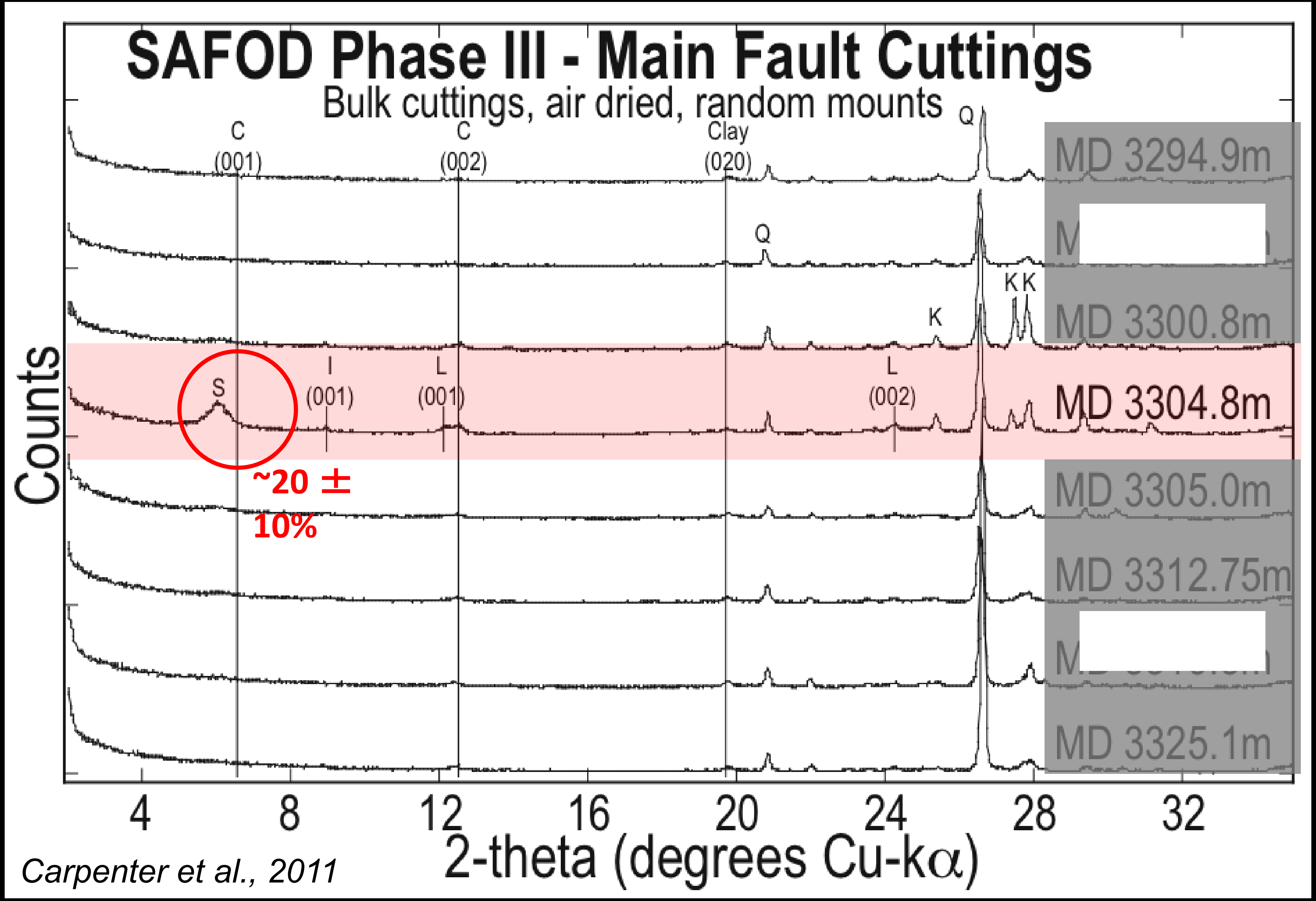
San Andreas in Central CA: Weak Fault in a Strong Crust

Carpenter, Saffer, and Marone.
Geology, 2012

-C. Marone

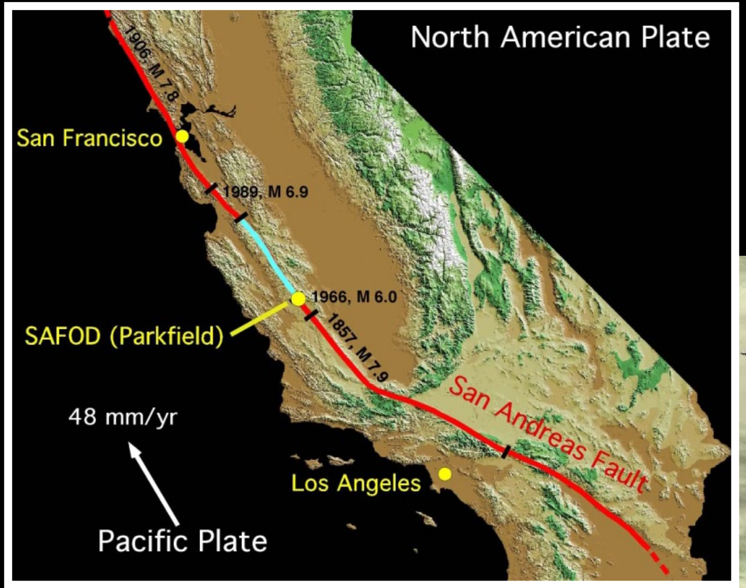
Why is the Main Strand of the San Andreas Fault Weak?

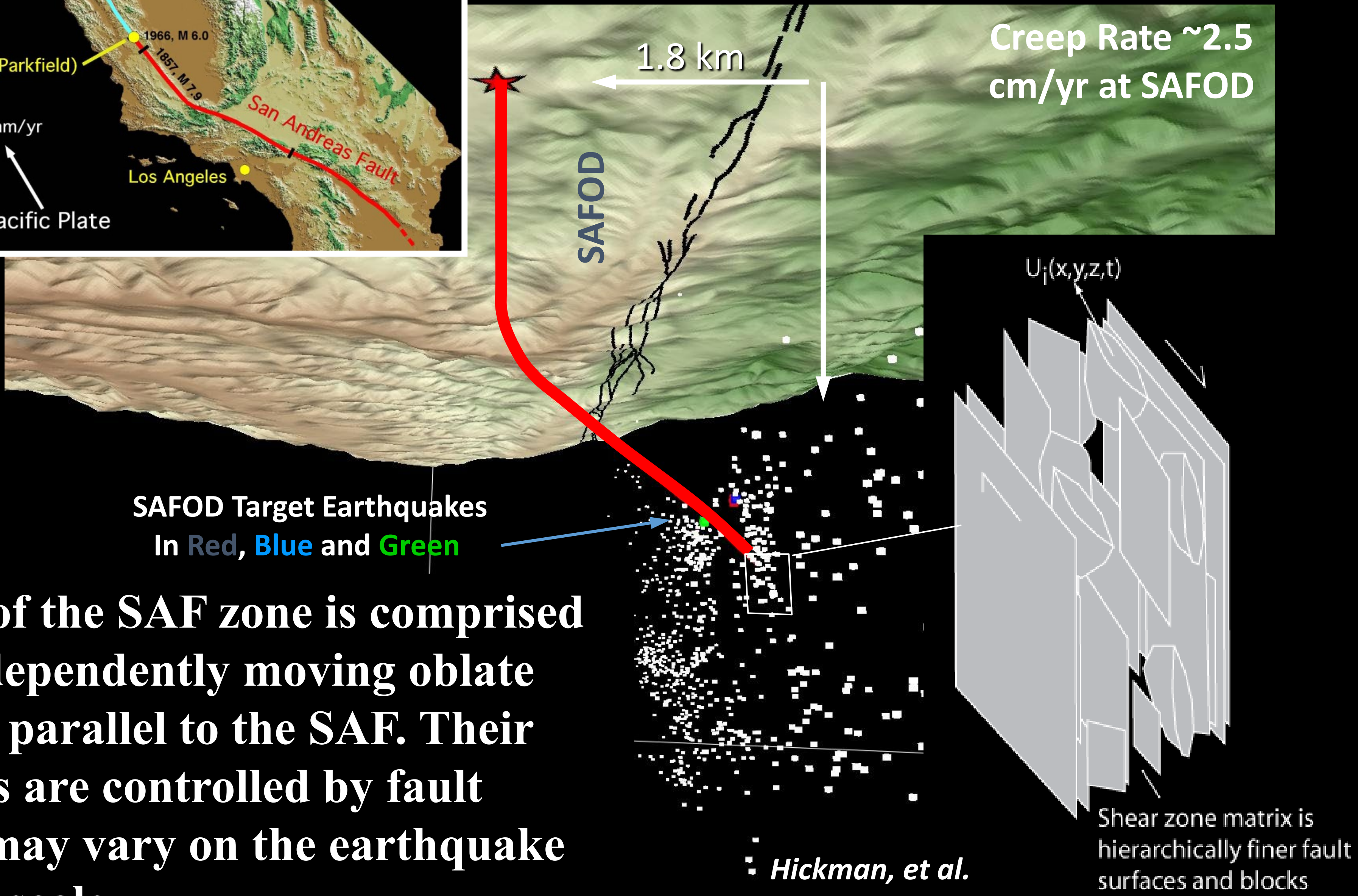
Hydrous Clay (Saponite, Smectite) and Fabric



San Andreas Fault Observatory at Depth:

Test fundamental theories of earthquake mechanics
Establish a long-term observatory in the fault zone





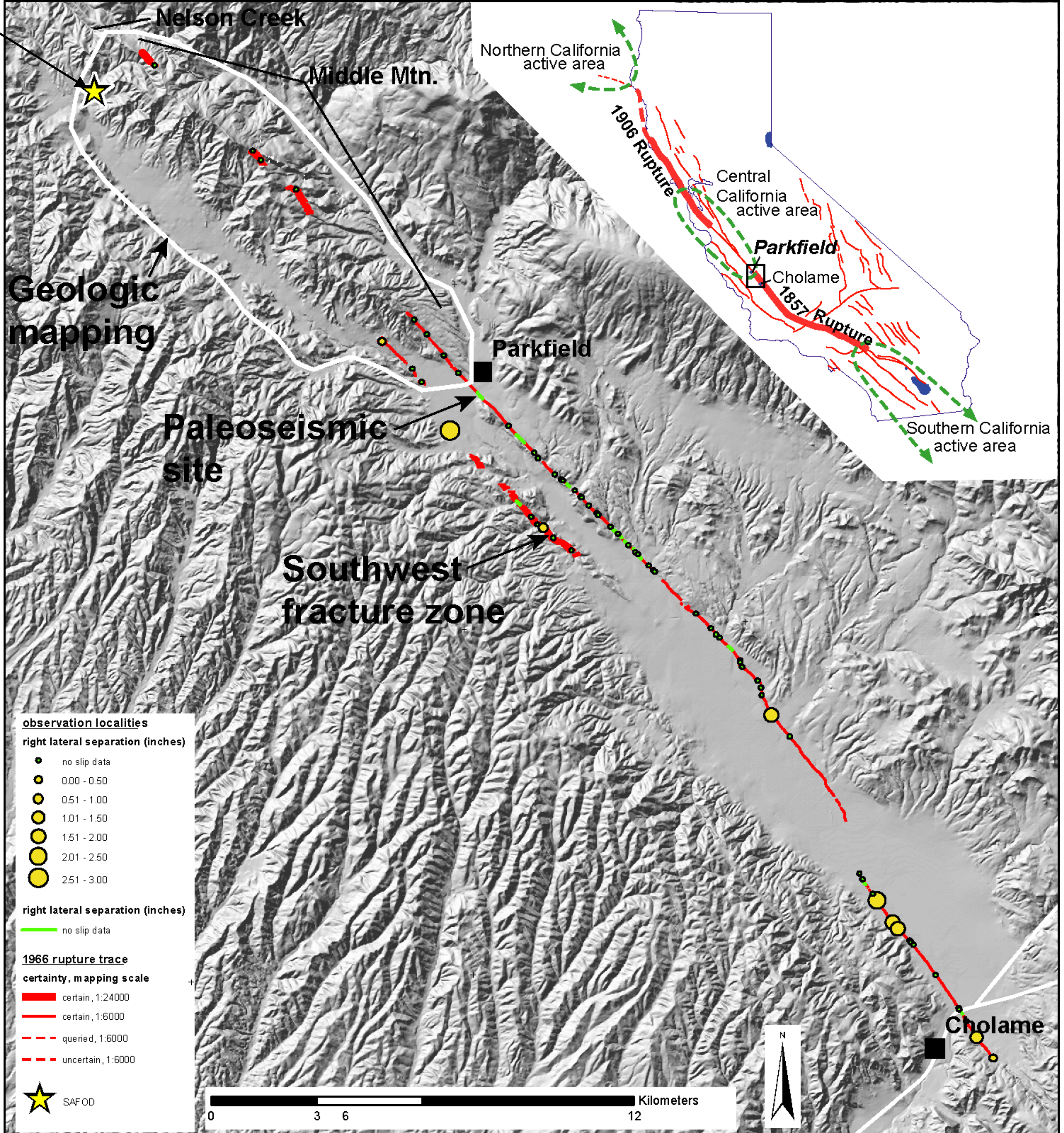
Upper few km of the SAF zone is comprised of relatively independently moving oblate blocks elongate parallel to the SAF. Their relative motions are controlled by fault activity which may vary on the earthquake recurrence timescale

Problems
- •Fault zone structure (blocks and motions)
- •Material properties (geologic descriptions and history)
- •Strain release history
- •Landscape development

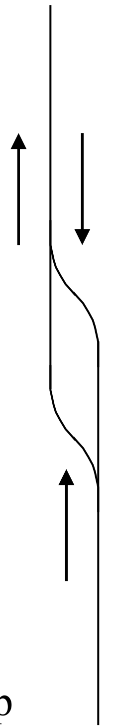
Tools
- •Large scale geologic mapping
- •Tectonic geomorphology
- •Earthquake geology
- •Visualization

PRELIMINARY Results
- •Geologic map/cross sections->block model
- •Moderate earthquakes and creep->paleoseismology

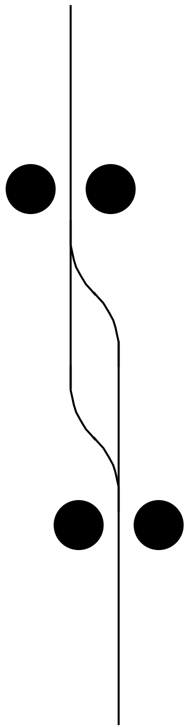
SAFOD



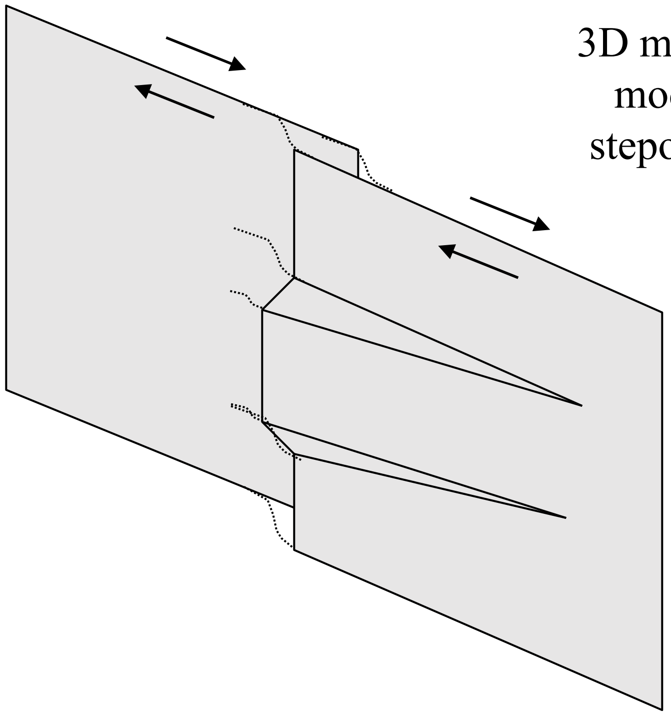
Fault zone is comprised of heterogeneous non coplanar fault surfaces bounding oblate blocks whose geometry and activity varies in time and space



Map view
mode II step
(bend)



Cross-section
view mode
III step
(bend)

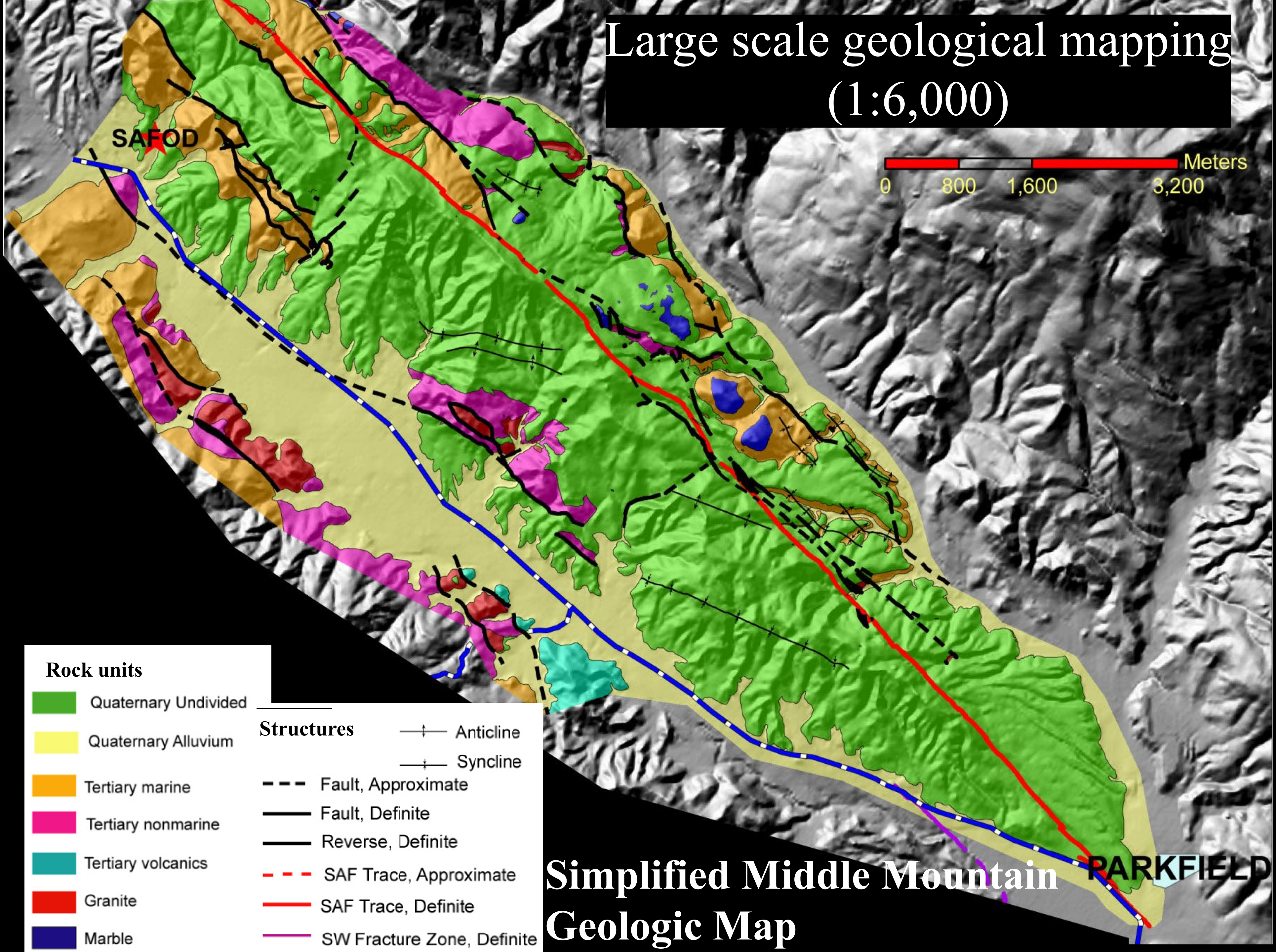


3D mixed
mode
stepover

Strong influences on
- **Stress and displacement fields around the fault surfaces**
- **Further development and linkage**
- **Fluid flow**
- **Rupture dynamics**
- **Fault zone strength**

Questions:
Geometric—Fault surface and block shapes and sizes
Time—How long are they active? What is slip history? Block motion history?
Development—Linkage and evolution of roughness

Large scale geological mapping (1:6,000)



Simplified Middle Mountain Geologic Map

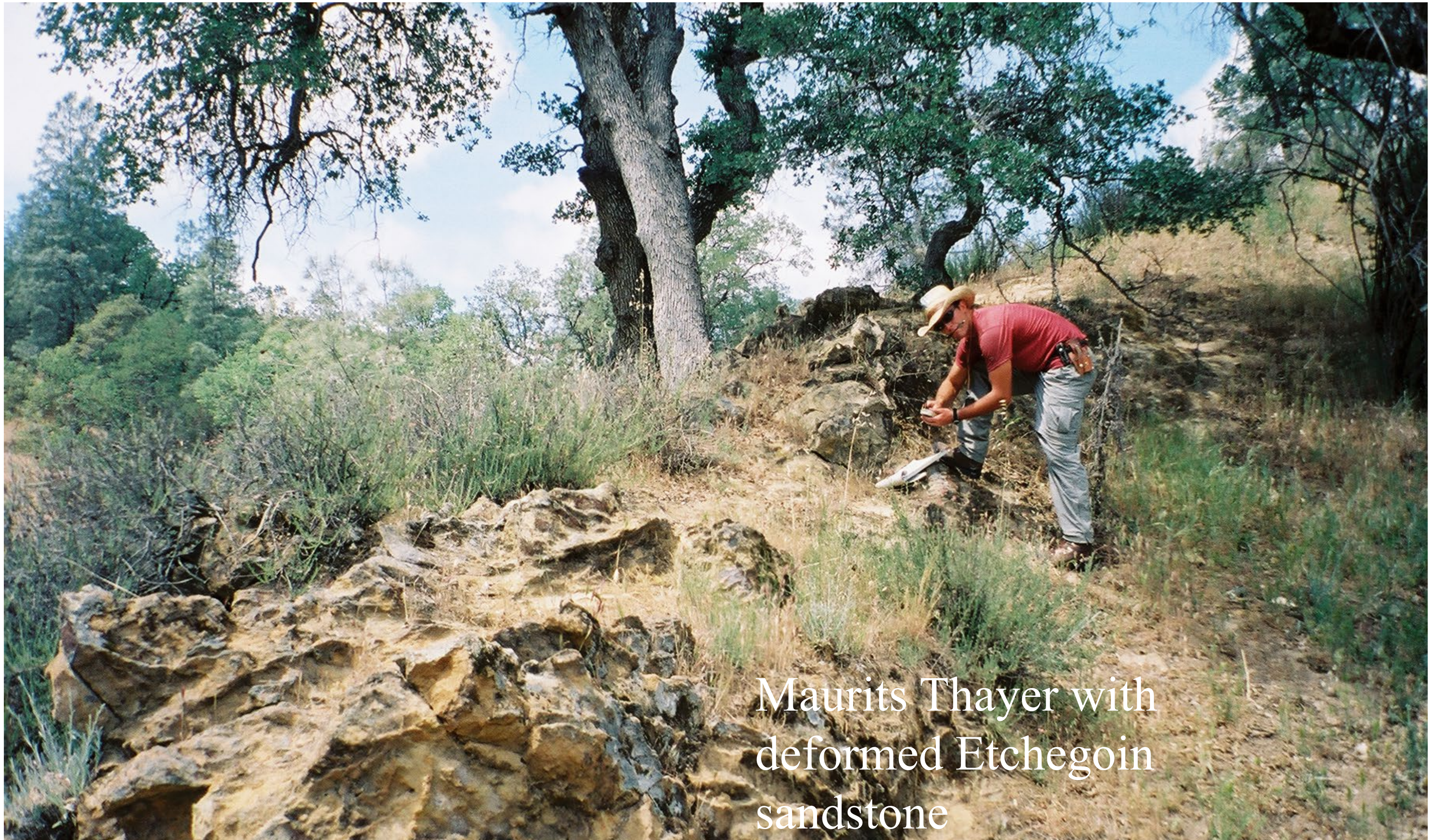
Large scale geological mapping (1:6,000)

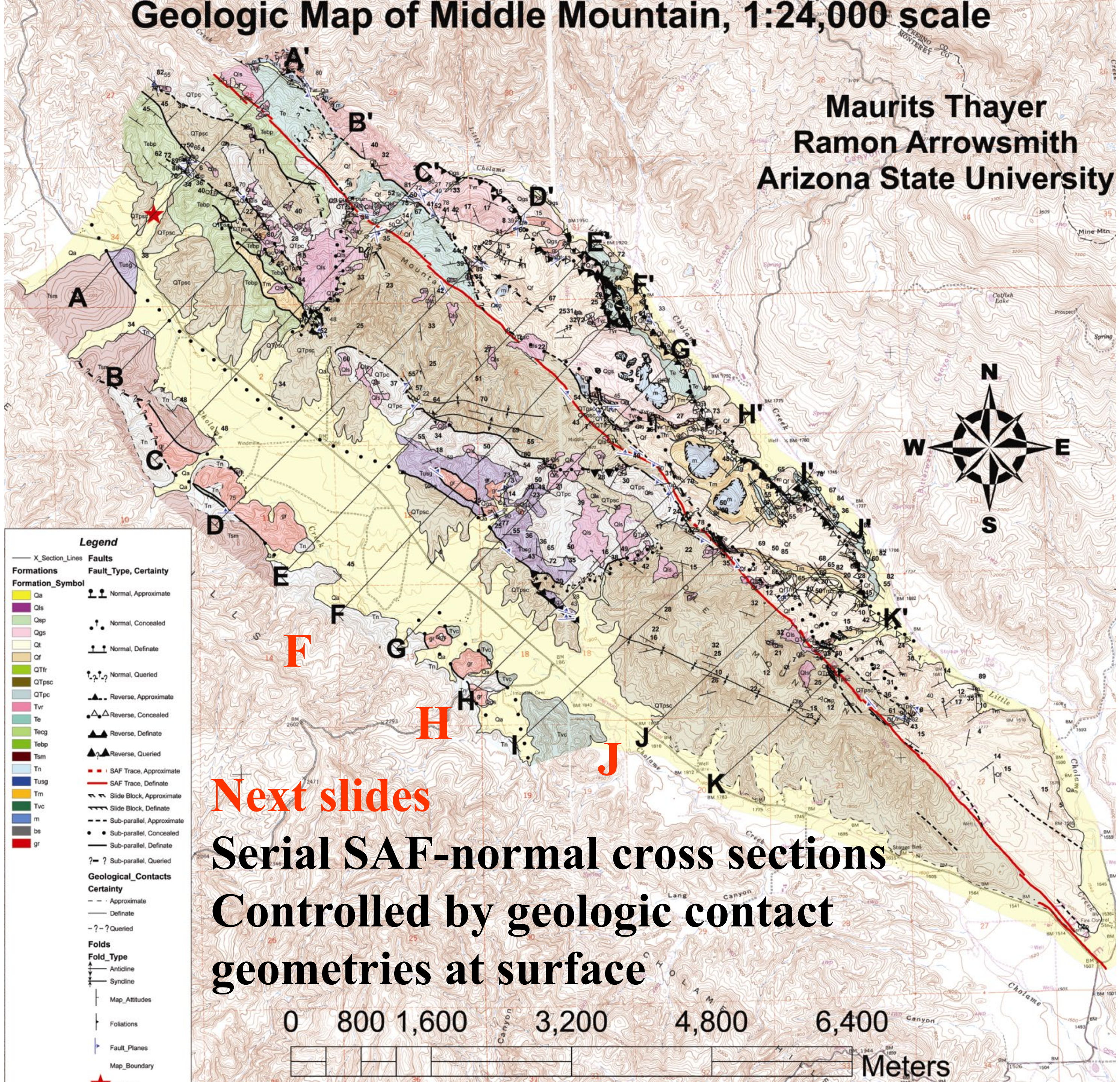
- **Previous mapping was 1:62,500 (Dibblee), or 1:24,000 (Sims)**
- **Rugged topography with complex contact relationships.**

3 months of effort: ~40 km^2

~1000 miles of linear coverage

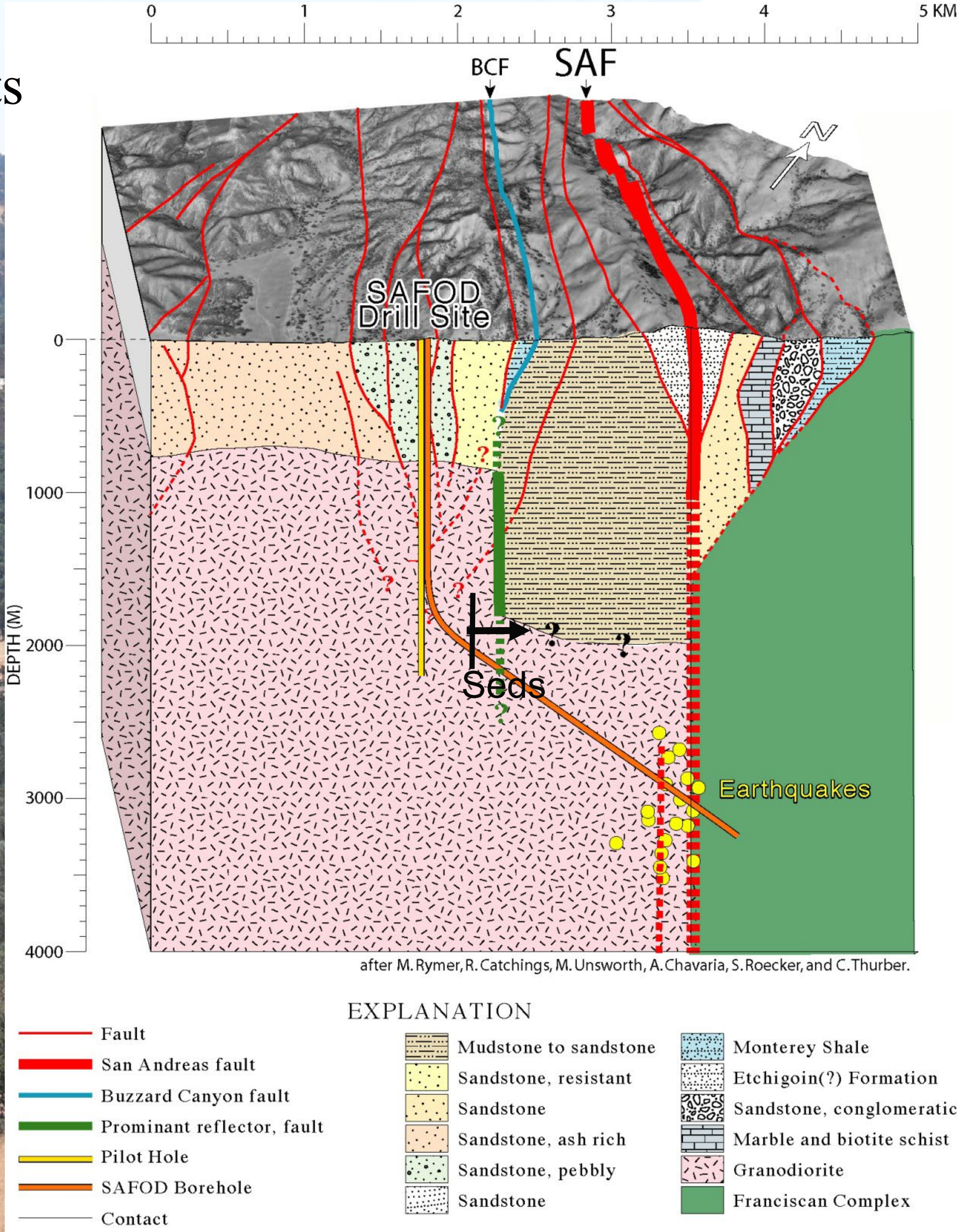
90 person days x 10+ miles/day





Geologic Map of Middle Mountain, 1:24,000 scale
Maurits Thayer
Ramon Arrowsmith
Arizona State University
A A'
B B'
C C'
D D'
E E'
F F'
G G'
H H'
I I'
J J'
K K'
N
S
E
W
F
H
J
Legend
X_Section_Lines
Formations
Formation_Symbol
Qa
Qls
Qsp
Qgs
Qt
Qf
QTfr
QTpsc
QTpc
Tvr
Te
Tecg
Tebp
Tsm
Tn
Tusg
Tm
Tvc
m
bs
gr
Faults
Fault_Type, Certainty
Normal, Approximate
Normal, Concealed
Normal, Definate
Normal, Queried
Reverse, Approximate
Reverse, Concealed
Reverse, Definate
Reverse, Queried
SAF Trace, Approximate
SAF Trace, Definate
Slide Block, Approximate
Slide Block, Definate
Sub-parallel, Approximate
Sub-parallel, Concealed
Sub-parallel, Definate
Sub-parallel, Queried
Geological_Contacts
Certainty
Approximate
Definate
Queried
Folds
Fold_Type
Anticline
Syncline
Map_Attitudes
Foliations
Fault_Planes
Map_Boundary
Next slides
Serial SAF-normal cross sections
Controlled by geologic contact
geometries at surface
0 800 1,600 3,200 4,800 6,400
Meters

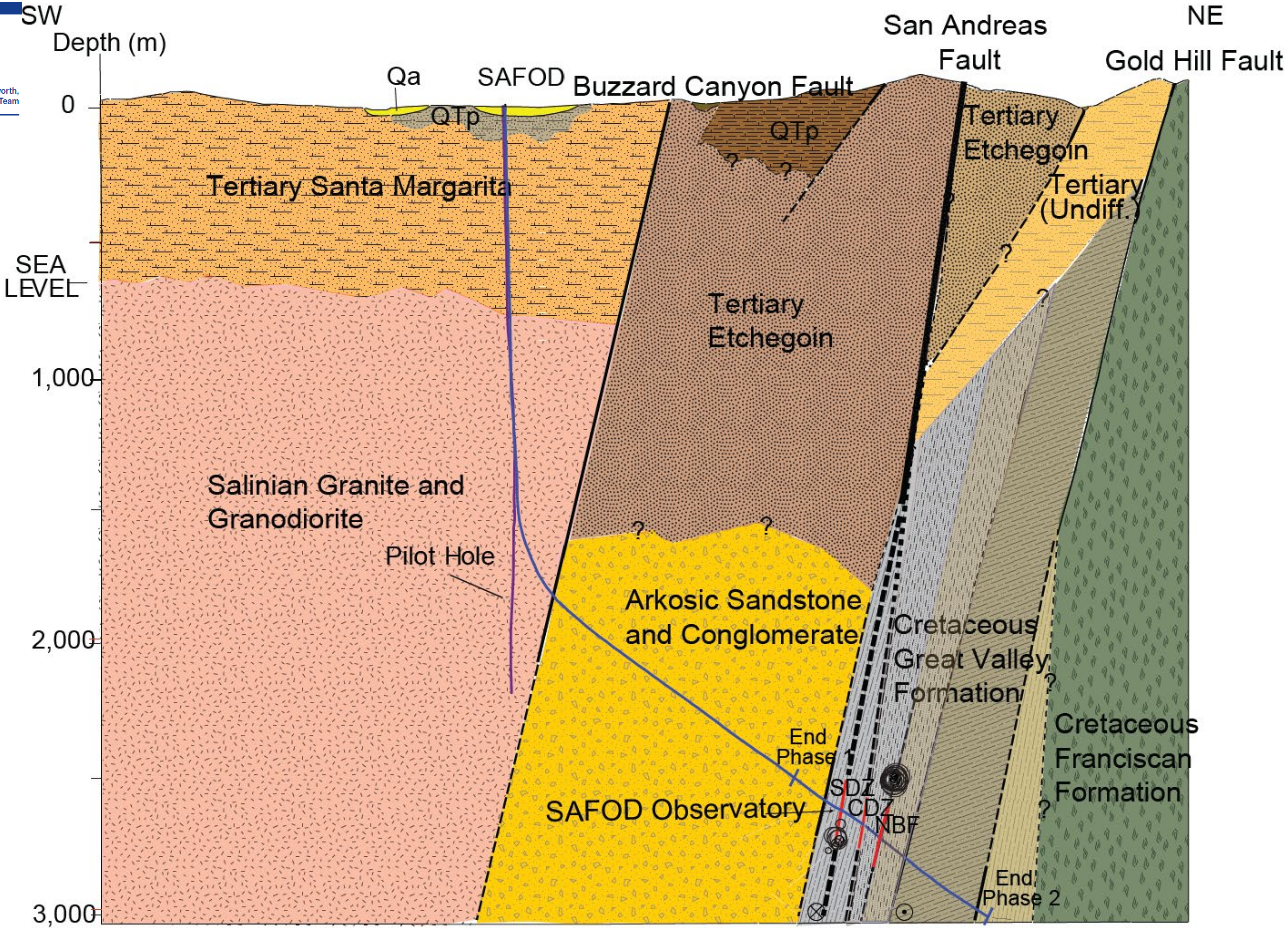
Original geological model inconsistent with drilling results



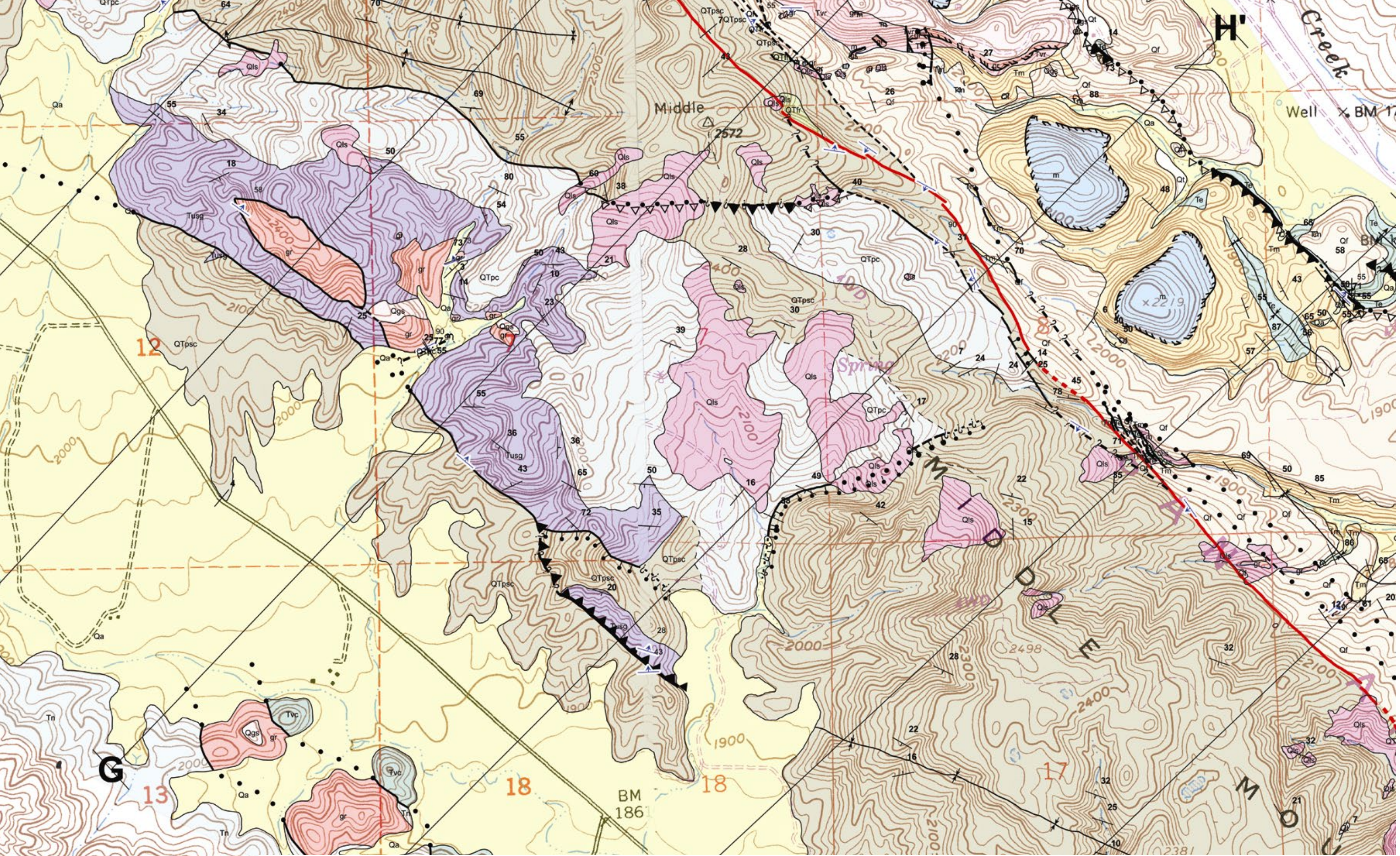
Scientific Drilling Into the San Andreas Fault Zone —An Overview of SAFOD's First Five Years

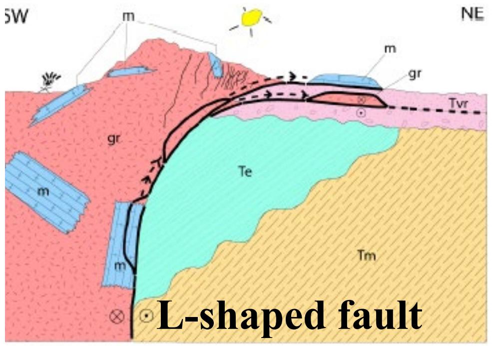
by Mark Zoback, Stephen Hickman, William Ellsworth, and the SAFOD Science Team

doi:10.2204/iodp.sd.11.02.2011

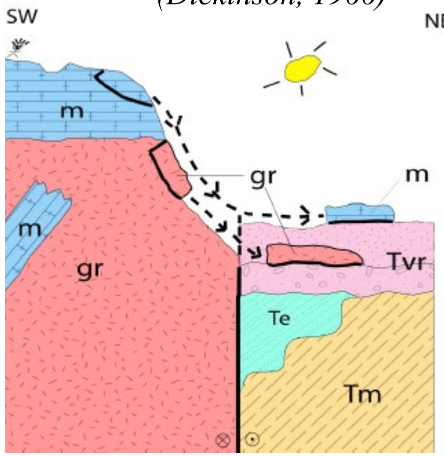


Incorporation of blocks into shear zone

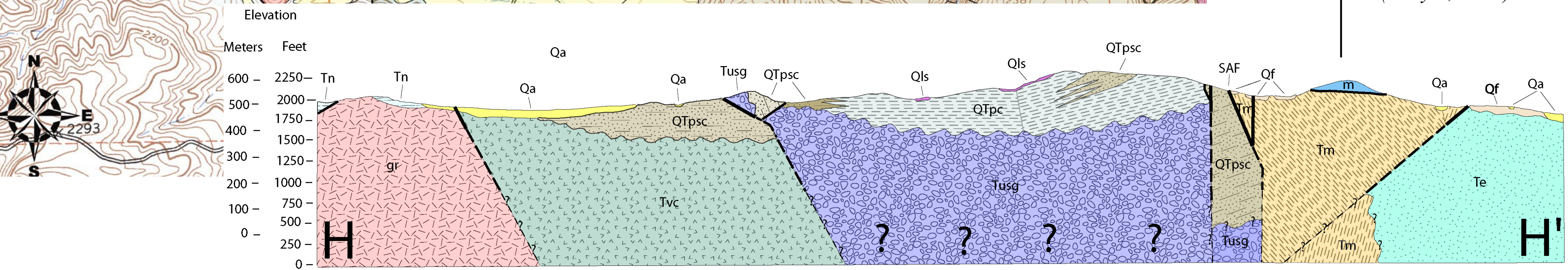


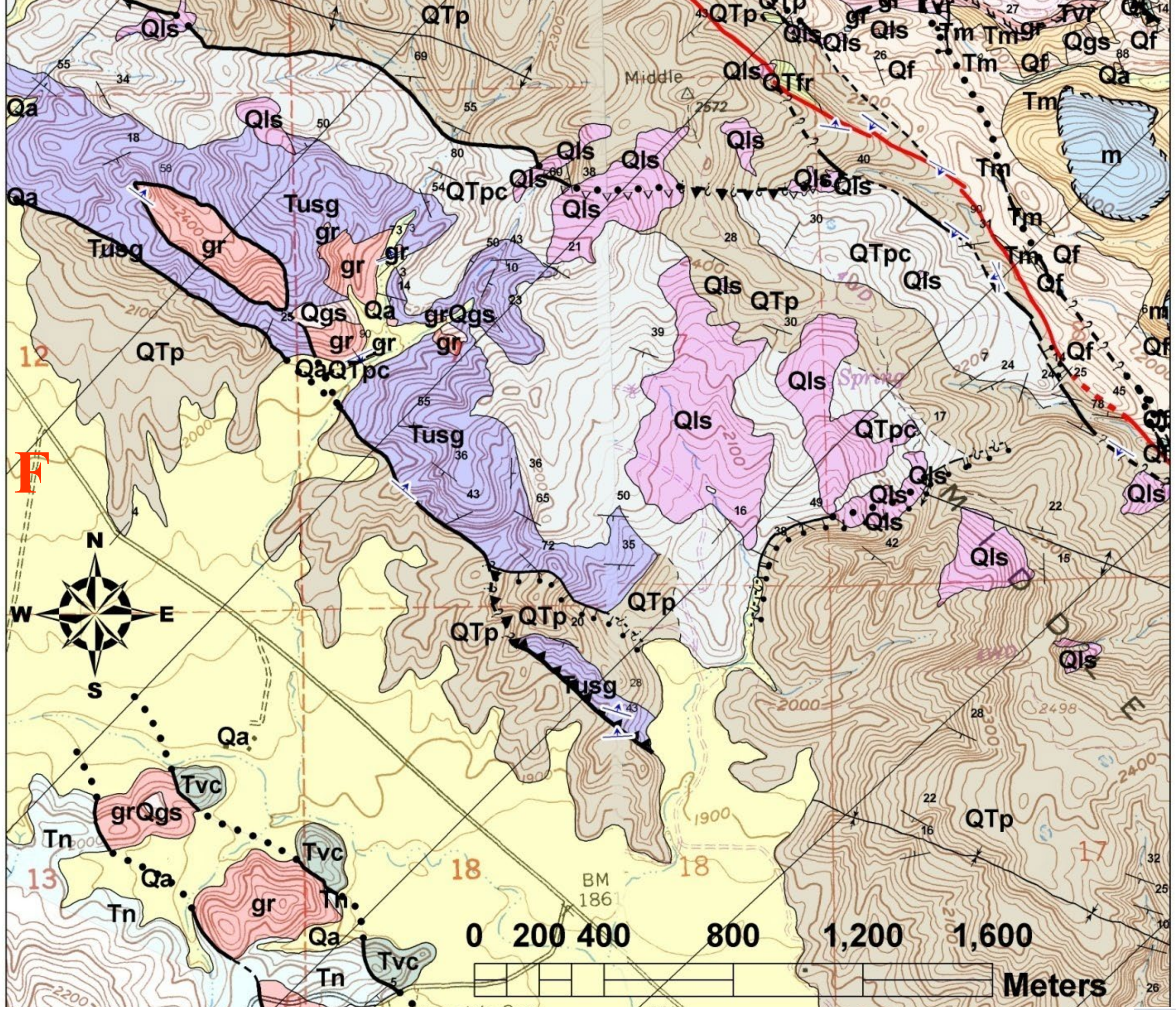


L-shaped fault
(Dickinson, 1966)



Slide blocks
(Thayer, 2006)





Example of fault block form

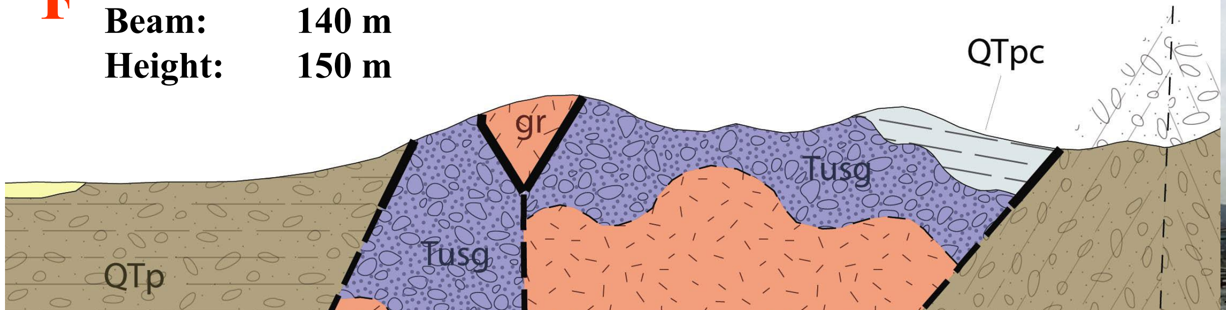
Hull shaped block ~5:1 aspect ratio

Preliminary apatite Fission track ages on granite blocks such as these are 40-50 Ma (Fayon and Arrowsmith, unpublished)

F

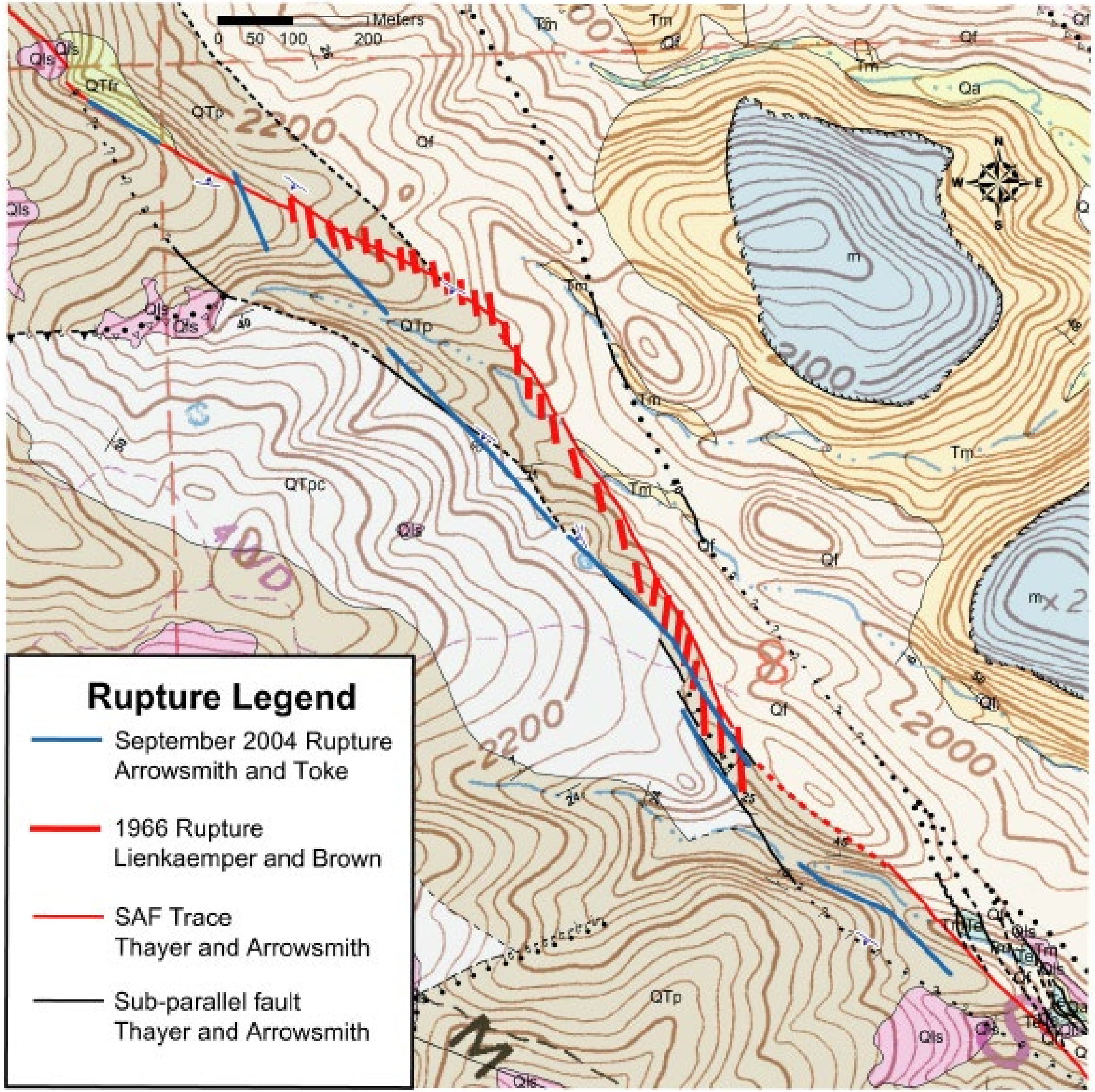
Length:	640 m
Beam:	140 m
Height:	150 m

=~25x



RMS QEII

Length:	293 m
Beam:	32 m
Height:	50 m

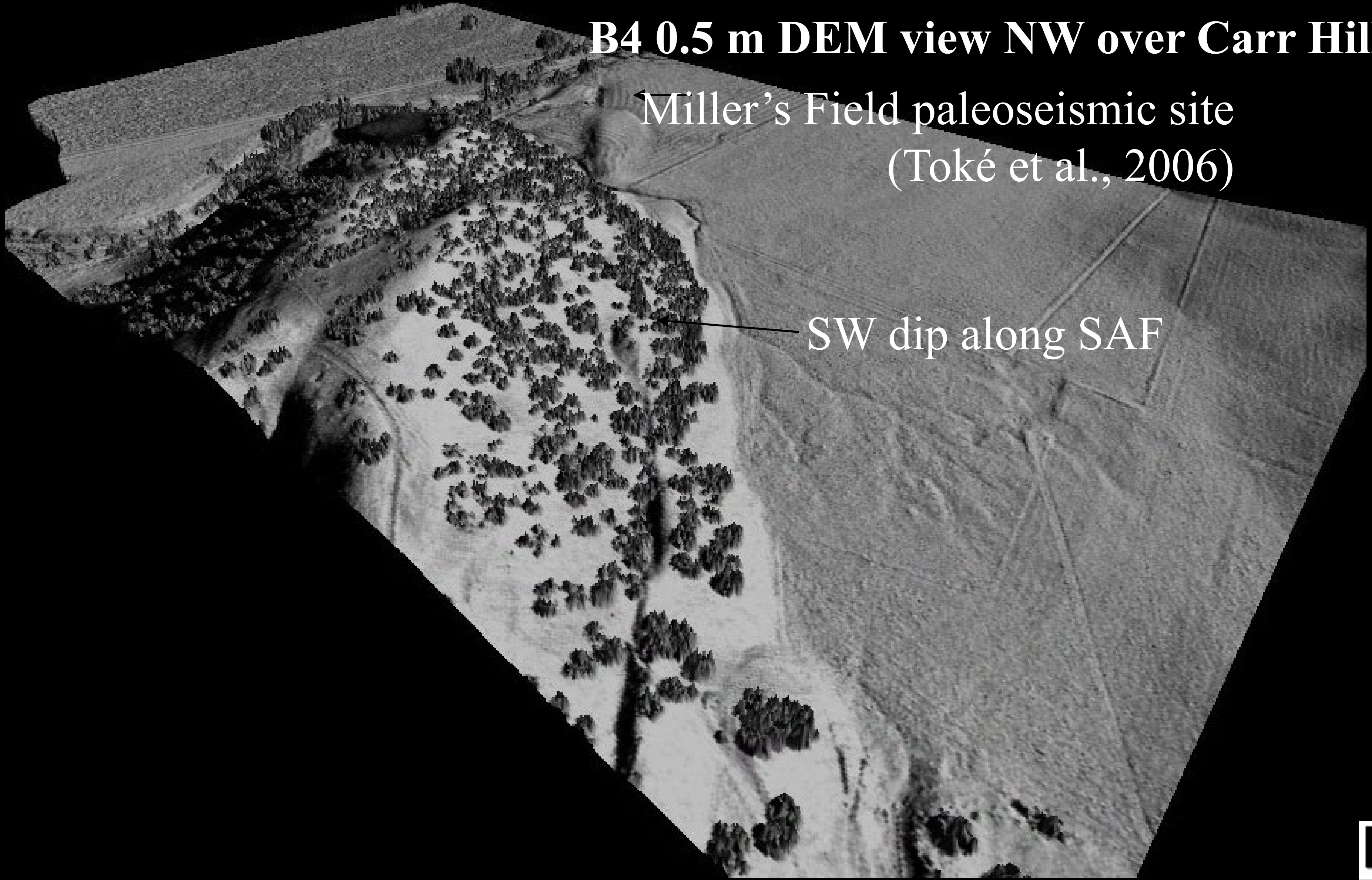


Variation in slip location in 1966 and 2004 earthquakes suggests process of formation

SE-directed rupture (1966) in red on NE and NW-directed rupture (2004) in blue bound 100 m wide and 800 m long zone

Thayer, 2006

B4 0.5 m DEM view NW over Carr Hill

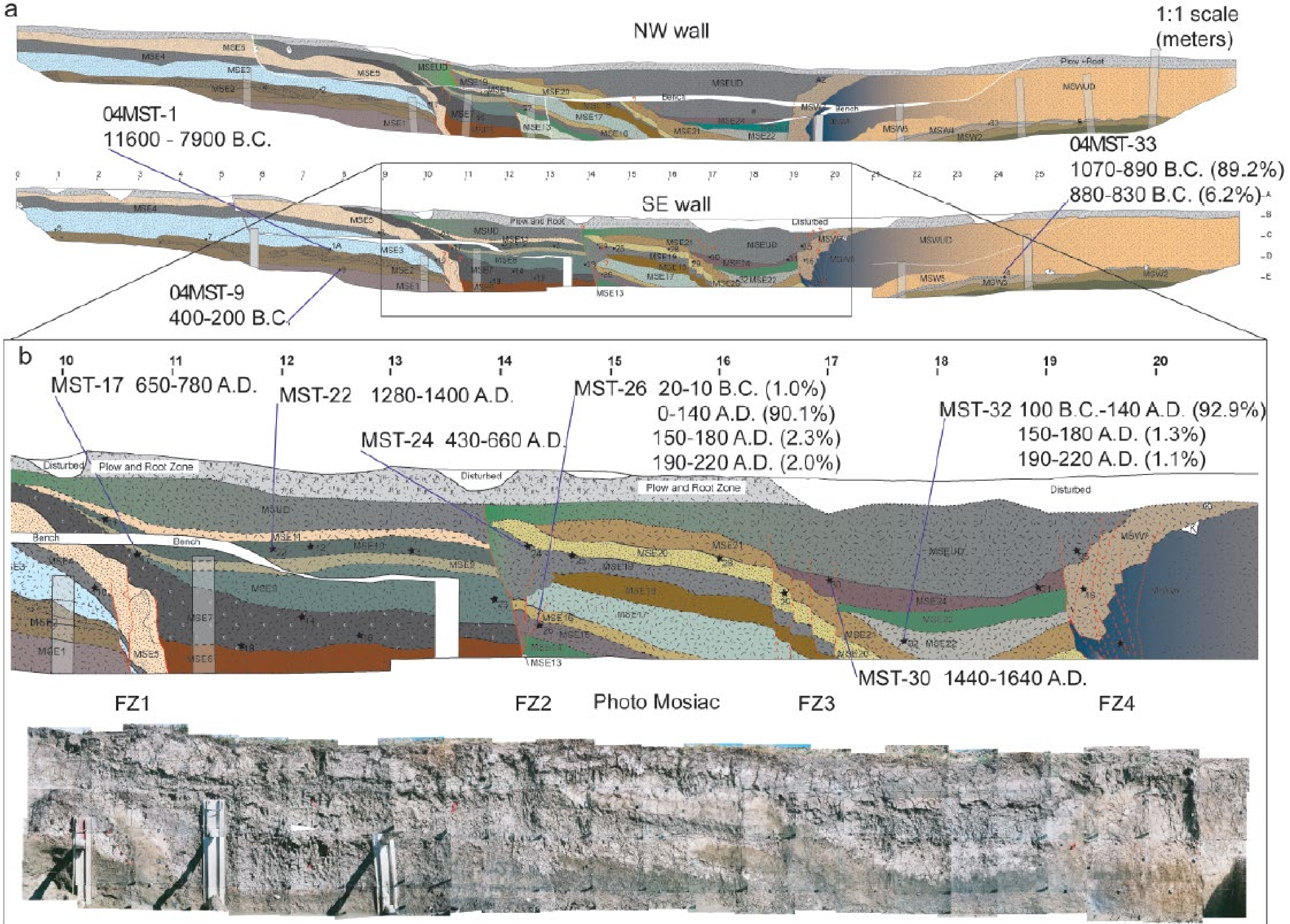


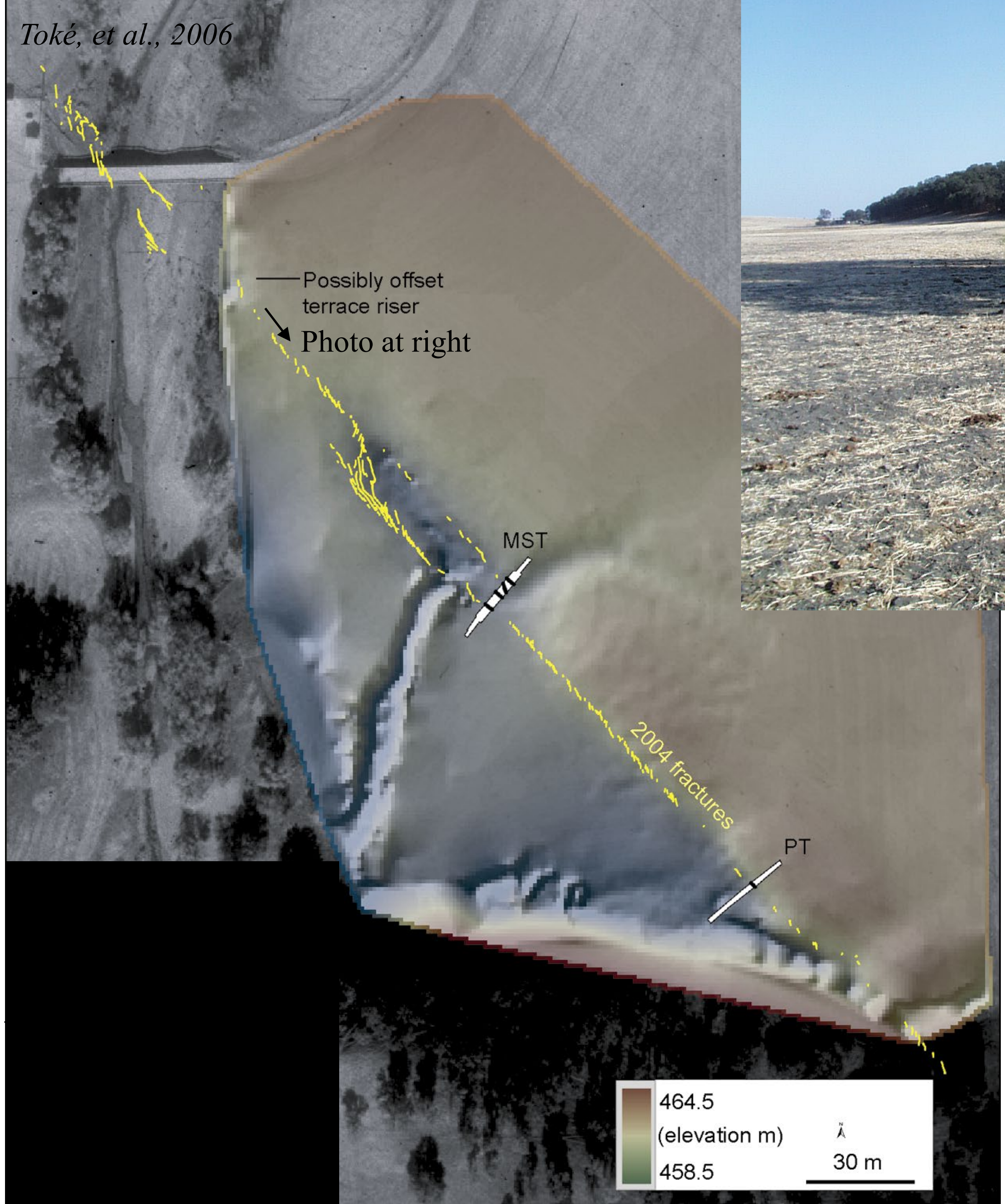
B4

Paleoseismological trench excavation

Toké, et al., 2006

Miller's Sag Paleoseismic Investigation

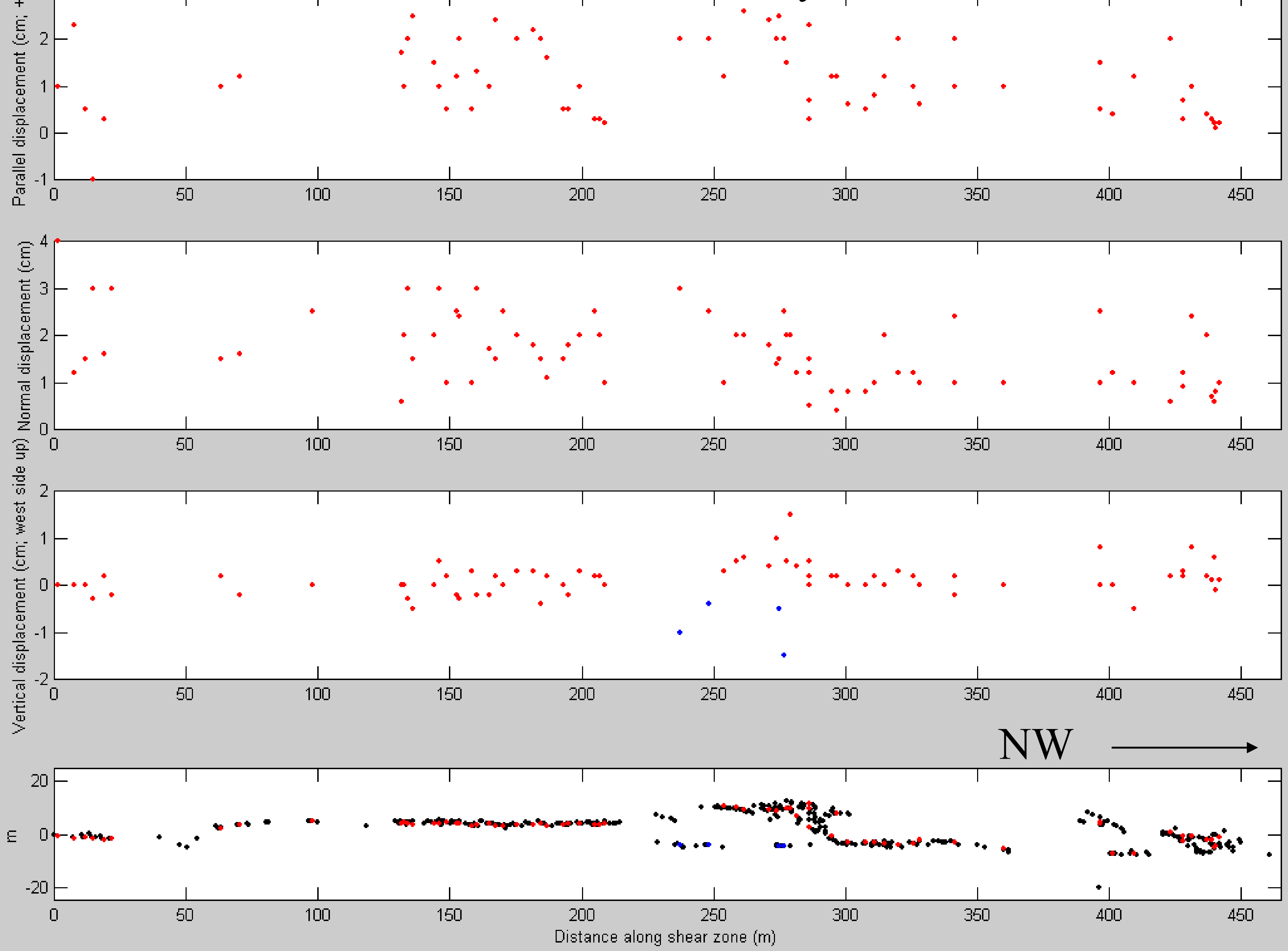


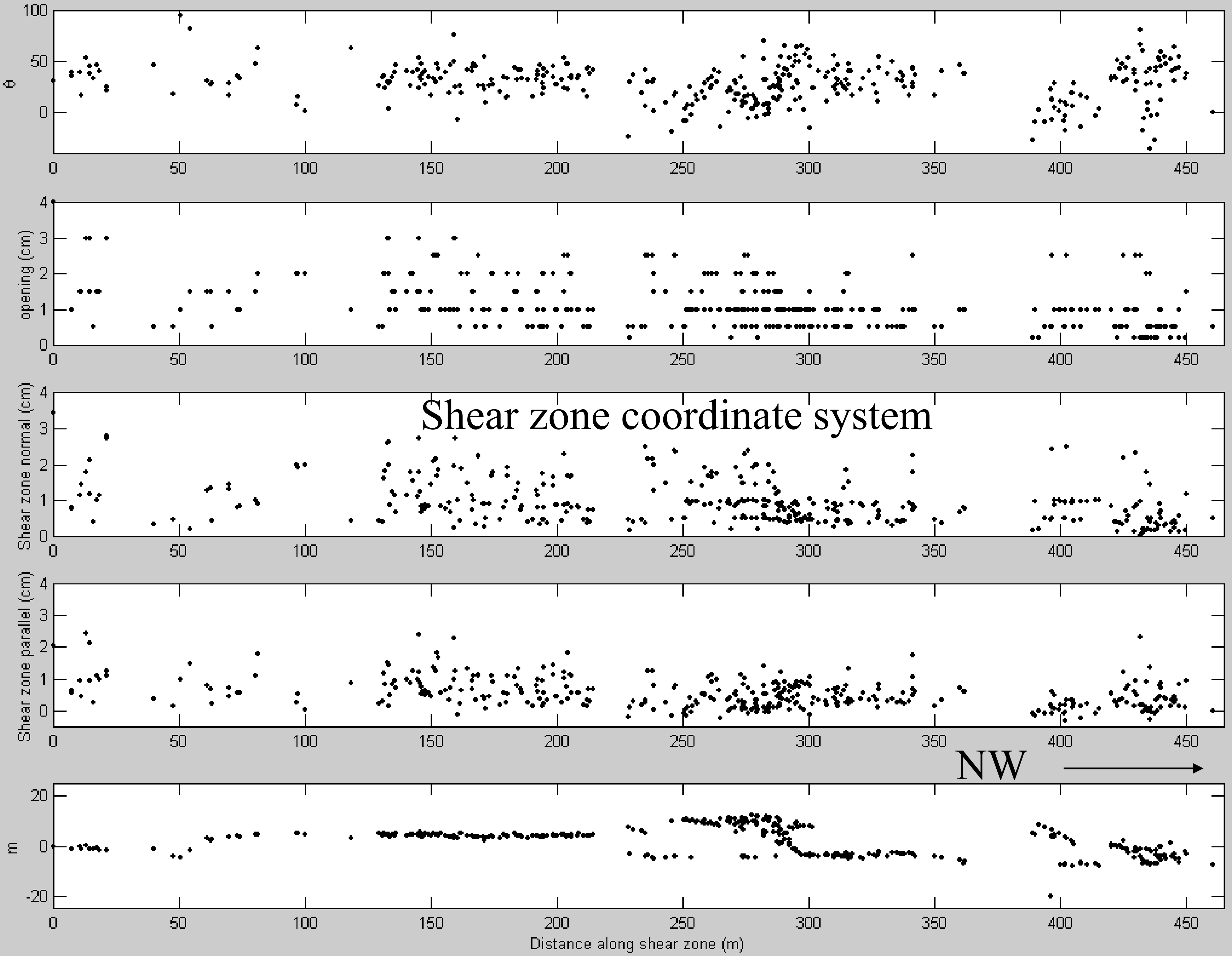


Survey of 369 earthquake fractures in Miller's field 2 days after the 2004 earthquake:

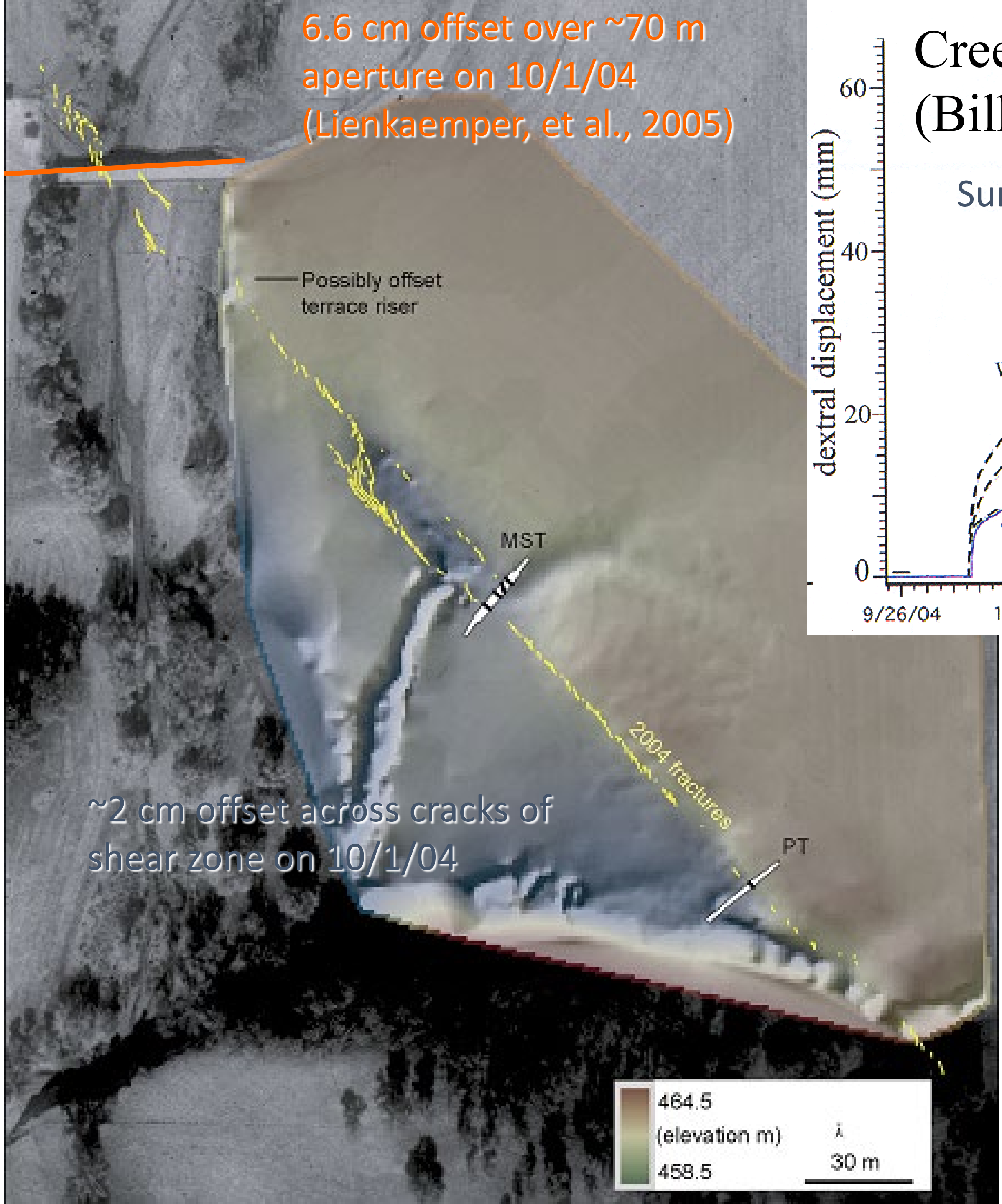
Spectacular pattern of shearing and association with pre-existing tectonic landforms

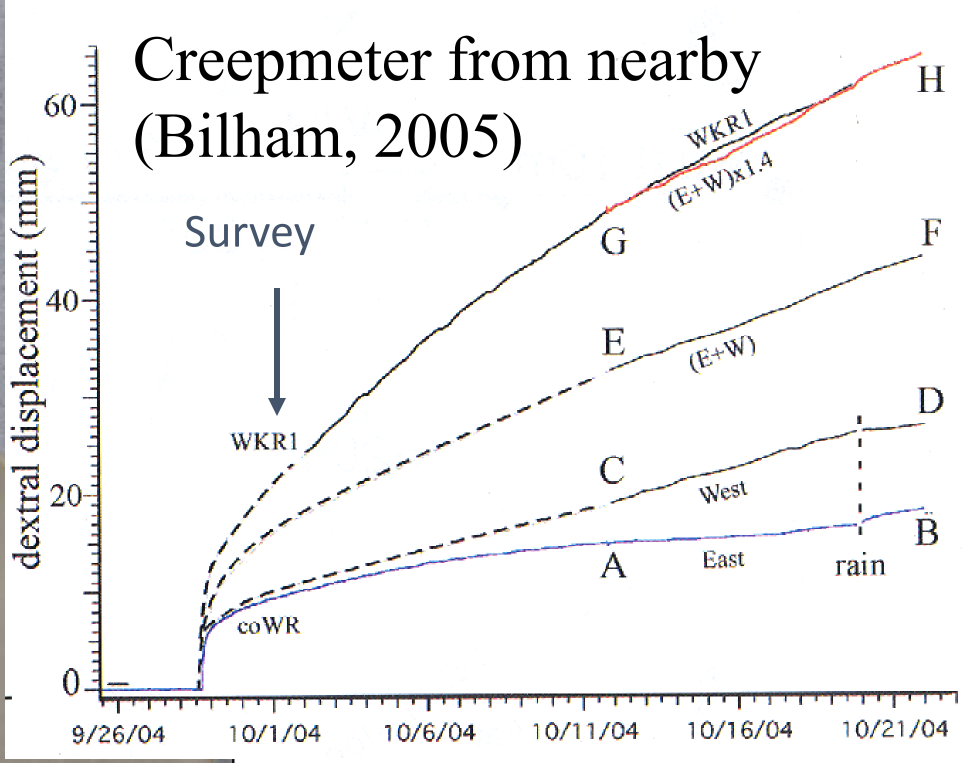
Crack coordinate system





Shear zone coordinate system
NW
θ
opening (cm)
Shear zone normal (cm)
Shear zone parallel (cm)
m
Distance along shear zone (m)

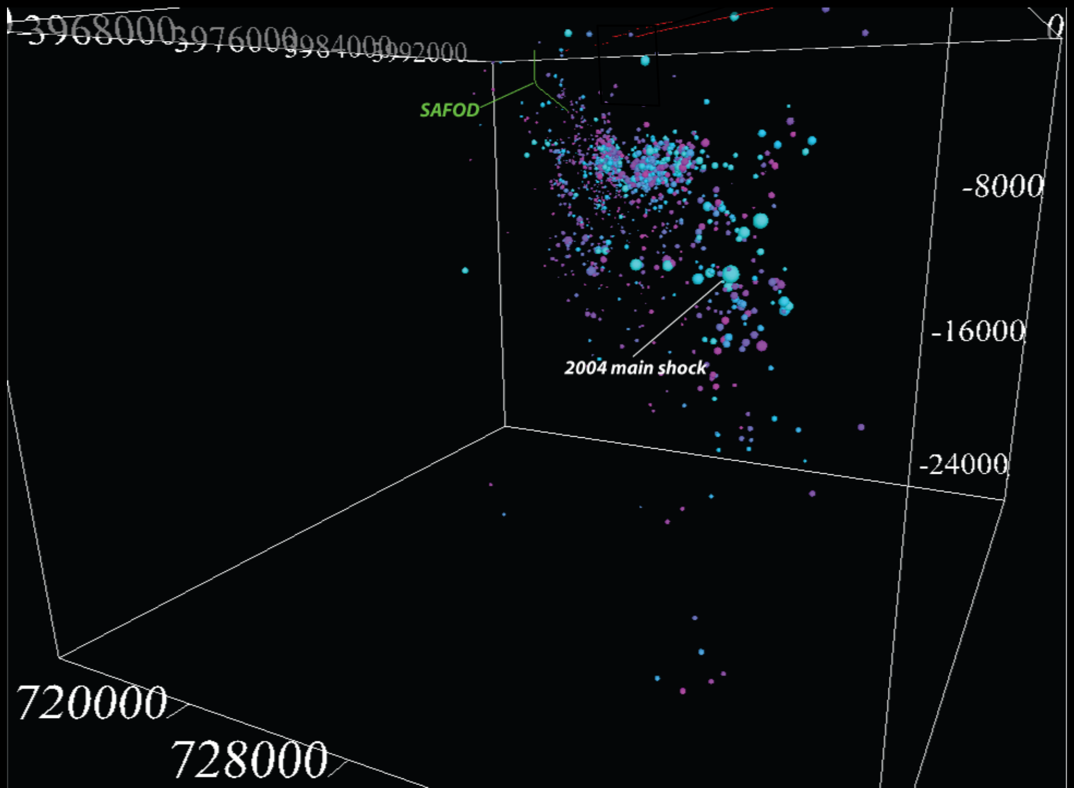


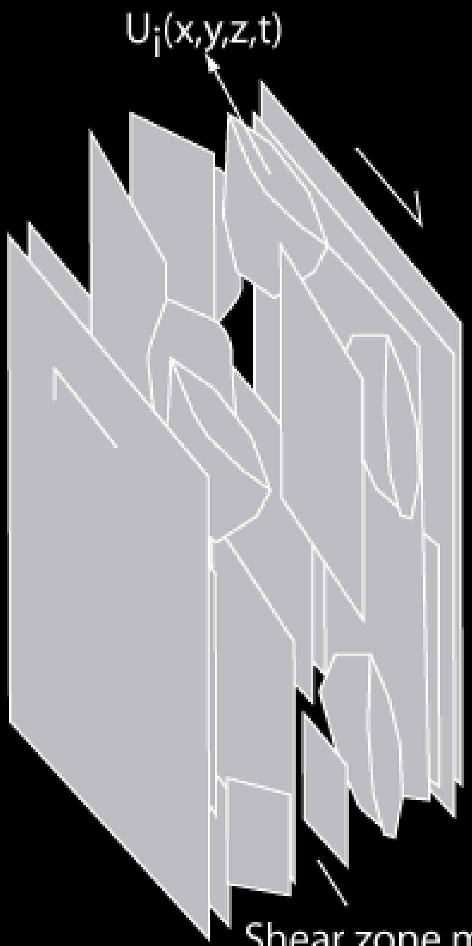


Significant afterslip (~2x) since these observations no doubt caused further crack growth and linkage

Up dip decrease in slip

These observations and inferences suggest a model in which the upper few km of the SAF zone is comprised of relatively independently moving oblate blocks elongate parallel to the SAF. Their relative motions are controlled by fault activity which may vary on the earthquake recurrence timescale.





Shear zone matrix is hierarchically finer fault surfaces and blocks