Testing Fundamental Theories of Earthquakes and Faulting: The San Andreas Fault Observatory at Depth

S an
A ndreas
F ault
O bservatory
at
D epth

Mark Zoback
Dept. of Geophysics
Stanford University

Stephen Hickman and William Ellsworth
U.S. Geological Survey

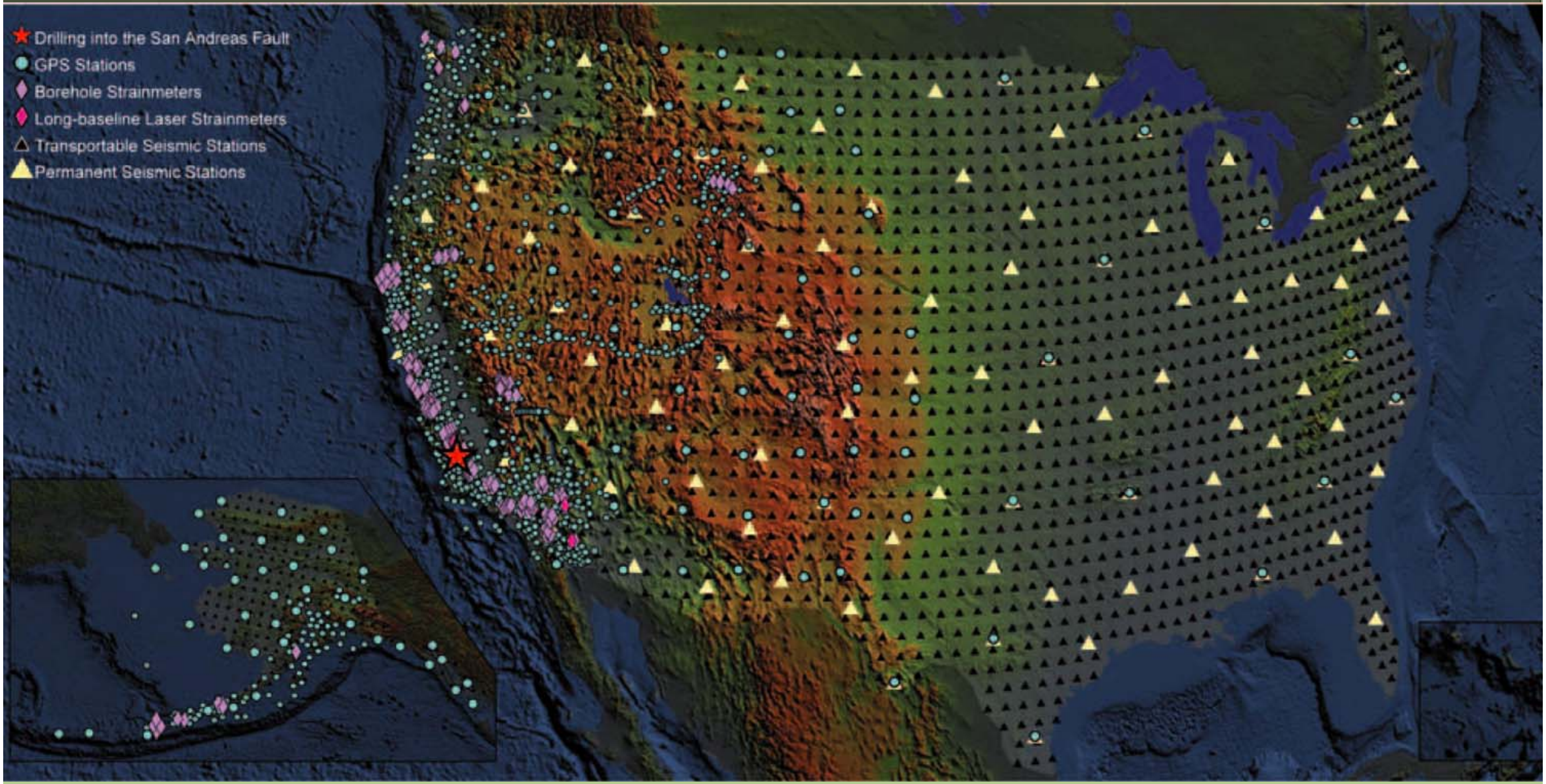
EARTHSCOPE-A New View into the Earth

SAFOD -- A borehole observatory across the San Andreas Fault to directly measure the physical conditions under which earthquakes occur

Plate Boundary Observatory -- A fixed array of GPS receivers and borehole strainmeters to measure real-time deformation on a plate-boundary scale

USArray -- A continental-scale seismic array to provide a coherent 3-D image of the lithosphere and deeper Earth

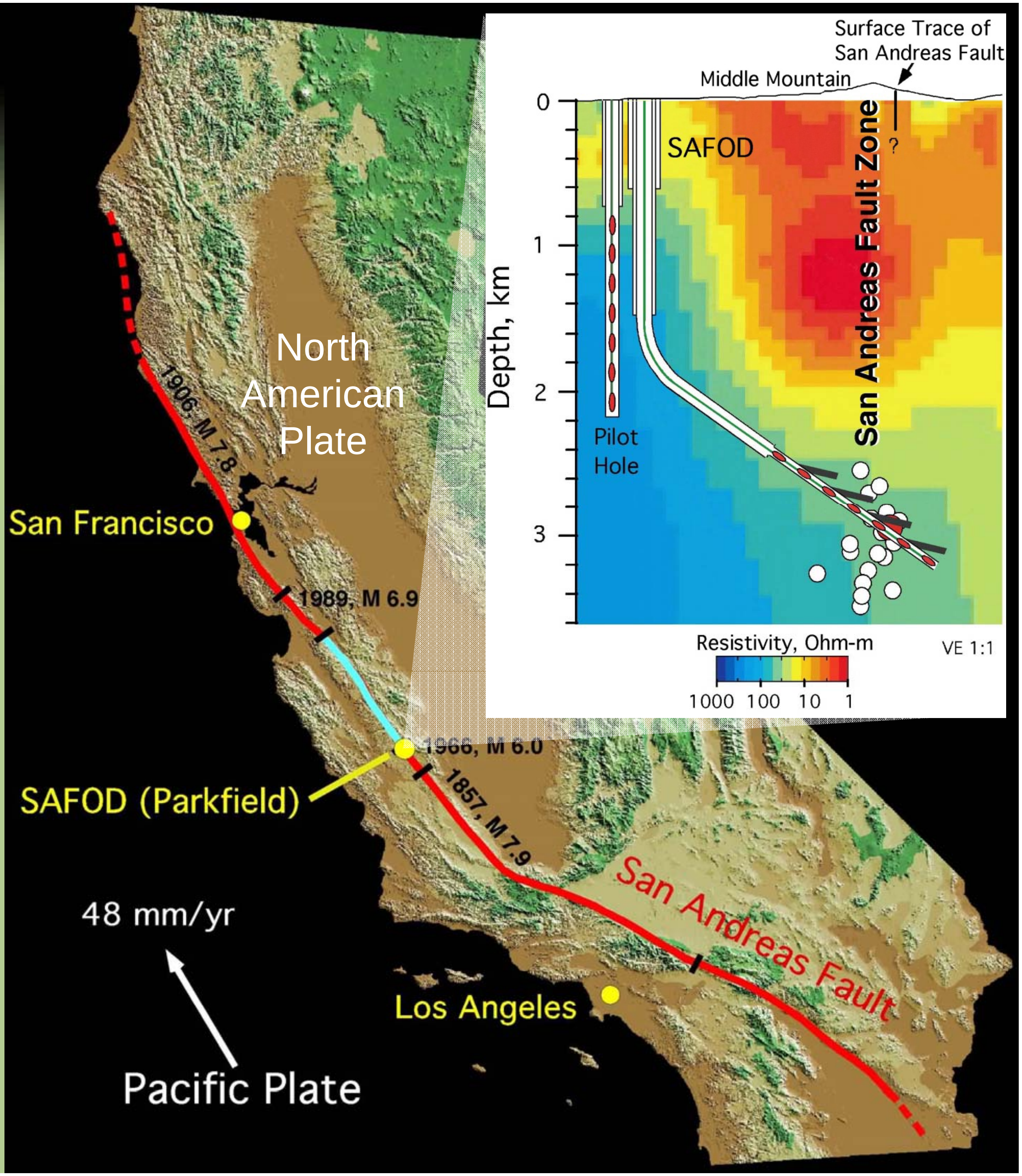
EARTHSCOPE--A New View into the Earth



www.earthscope.org

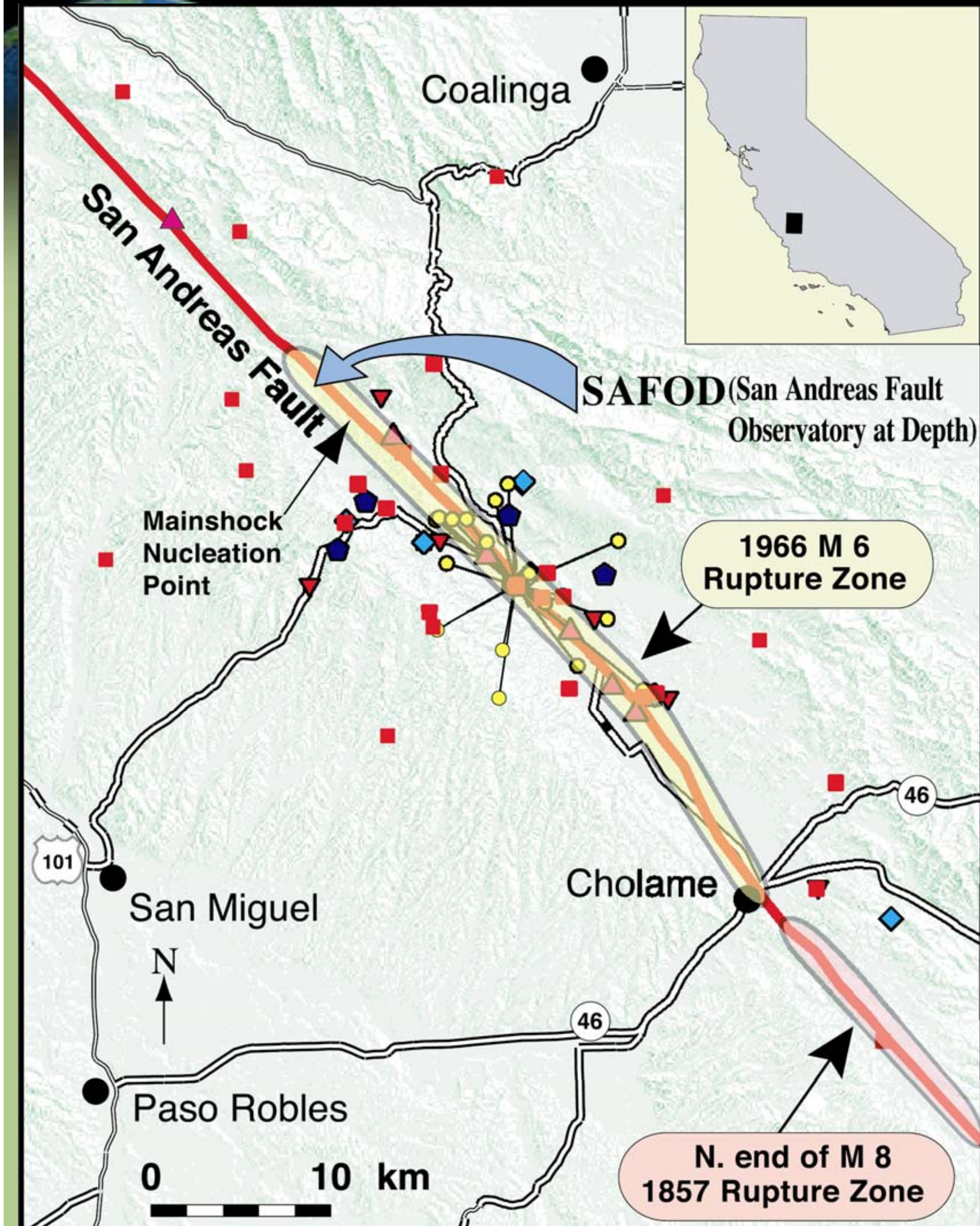
San Andreas Fault Observatory at Depth (SAFOD)

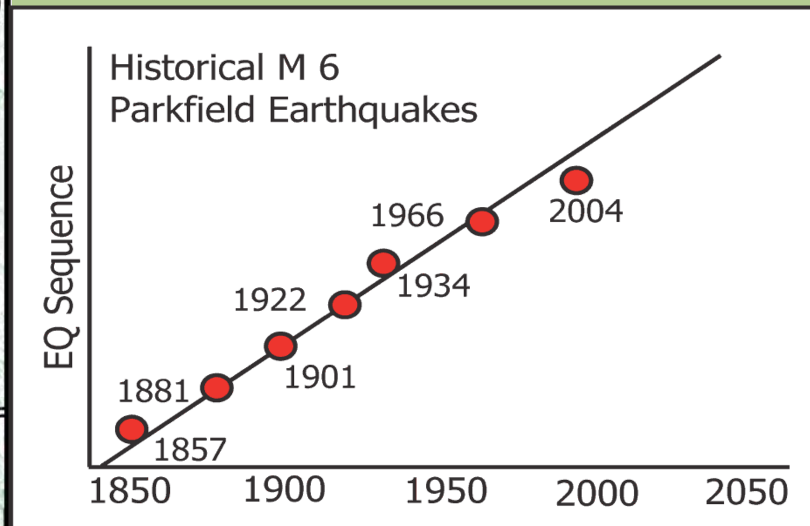
The central scientific objective of SAFOD is to directly measure the physical and chemical processes that control deformation and earthquake generation within an active plate-bounding fault zone.




N
San Andreas fault
SAFOD
drill site

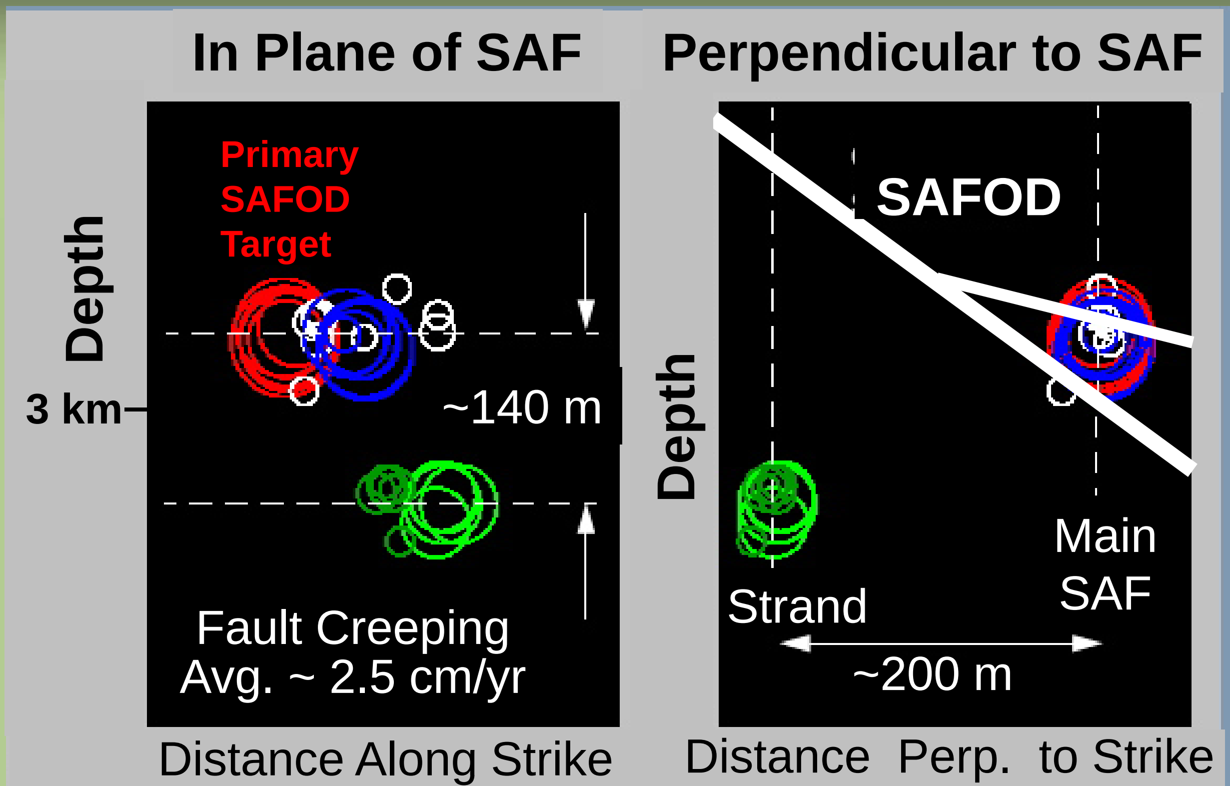
SAFOD Benefits from Knowledge Gained from USGS Parkfield Earthquake Experiment





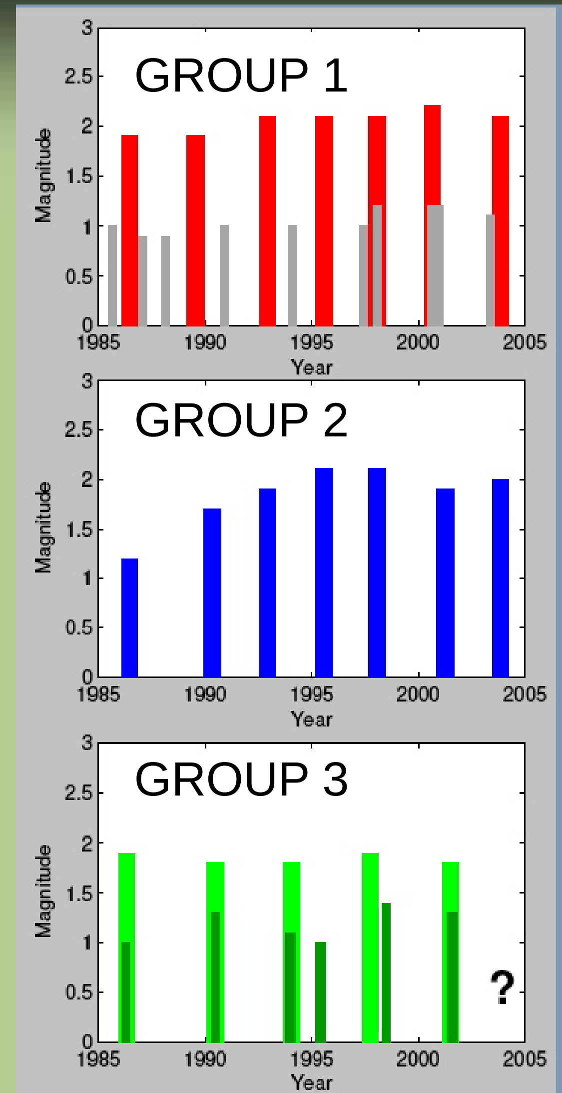
Surface Monitoring Instrumentation
(seismometers, creepmeters, strainmeters, water wells, laser rangefinders, GPS receivers, etc.)

Relative Locations of SAFOD Target Earthquakes (Repeaters)



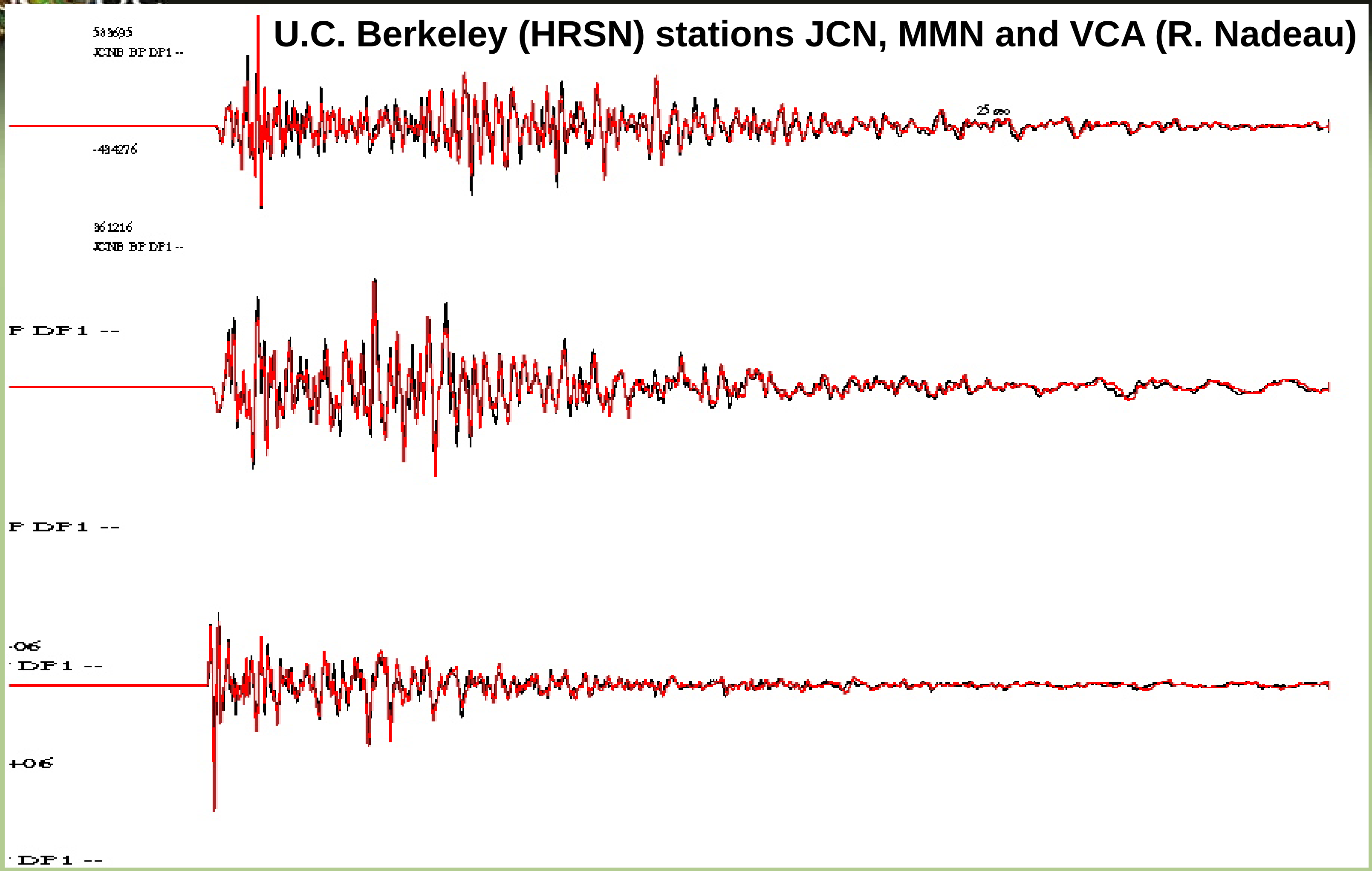
Nadeau et al. 2004, Waldhauser and Ellsworth 2005

circle size = 9 MPa stress drop model



Repeat rate of SAFOD target earthquakes increased in response to M 6 Parkfield Earthquake of Sept. 28, 2004 (surface creep rate also up, now ~ 5 cm/yr)

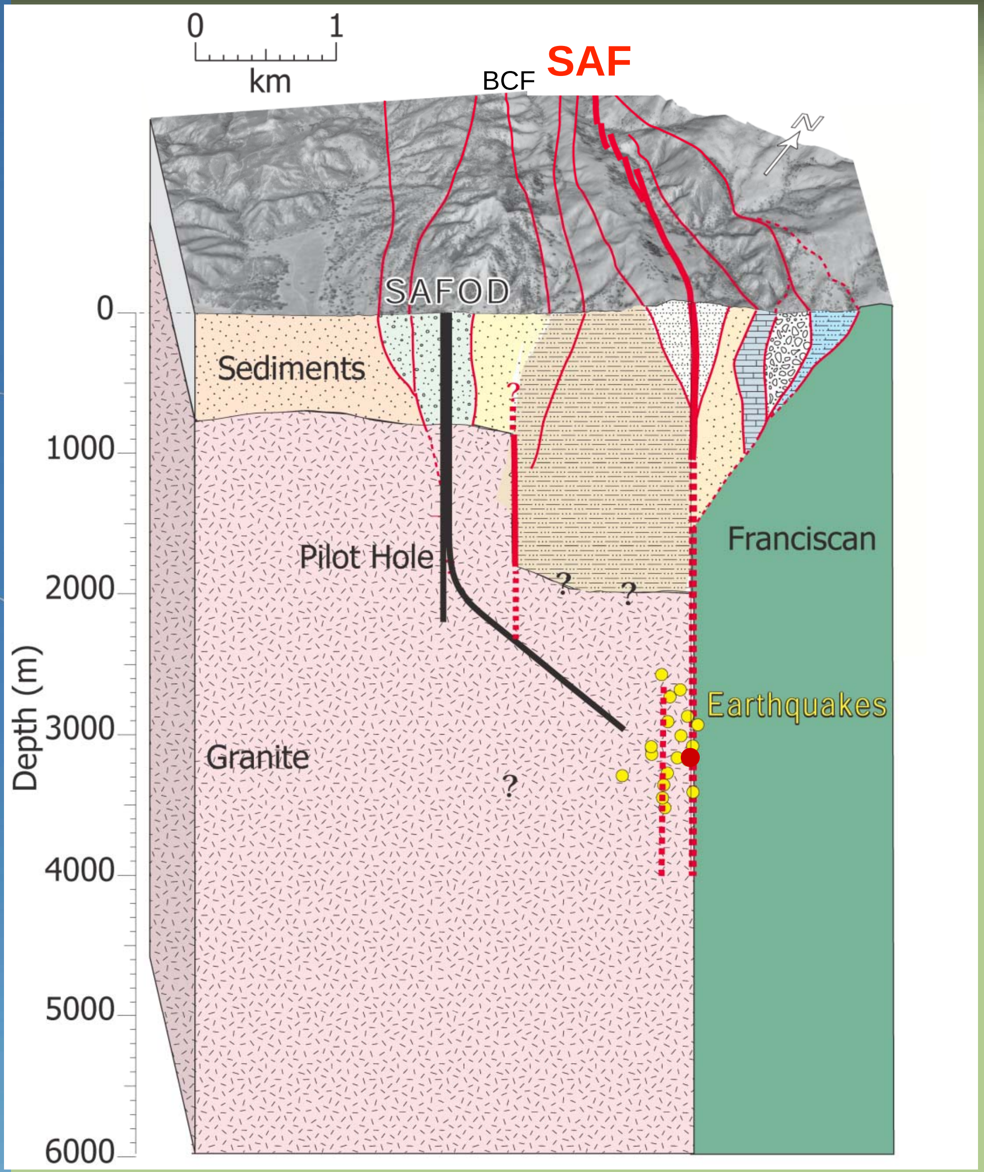
SAFOD Target Earthquake (Group 1) on Oct 1, 2004



Red: Post-M6 repeat of SAFOD Target Earthquake, October 1, 2004
Black: Preceding occurrence of Target Earthquake, October 20, 2003

In both cases, SE earthquake (Group 2) followed within a day of this event.

SAFOD
Preliminary Geological Model



San Andreas Fault Observatory at Depth: Project Overview and Science Goals

Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

SAFOD Phase 1 Drilling: June - October 2004

(Pilot Hole drilled summer of 2002)

Phase 1: Rotary Drilling to 2.5 km

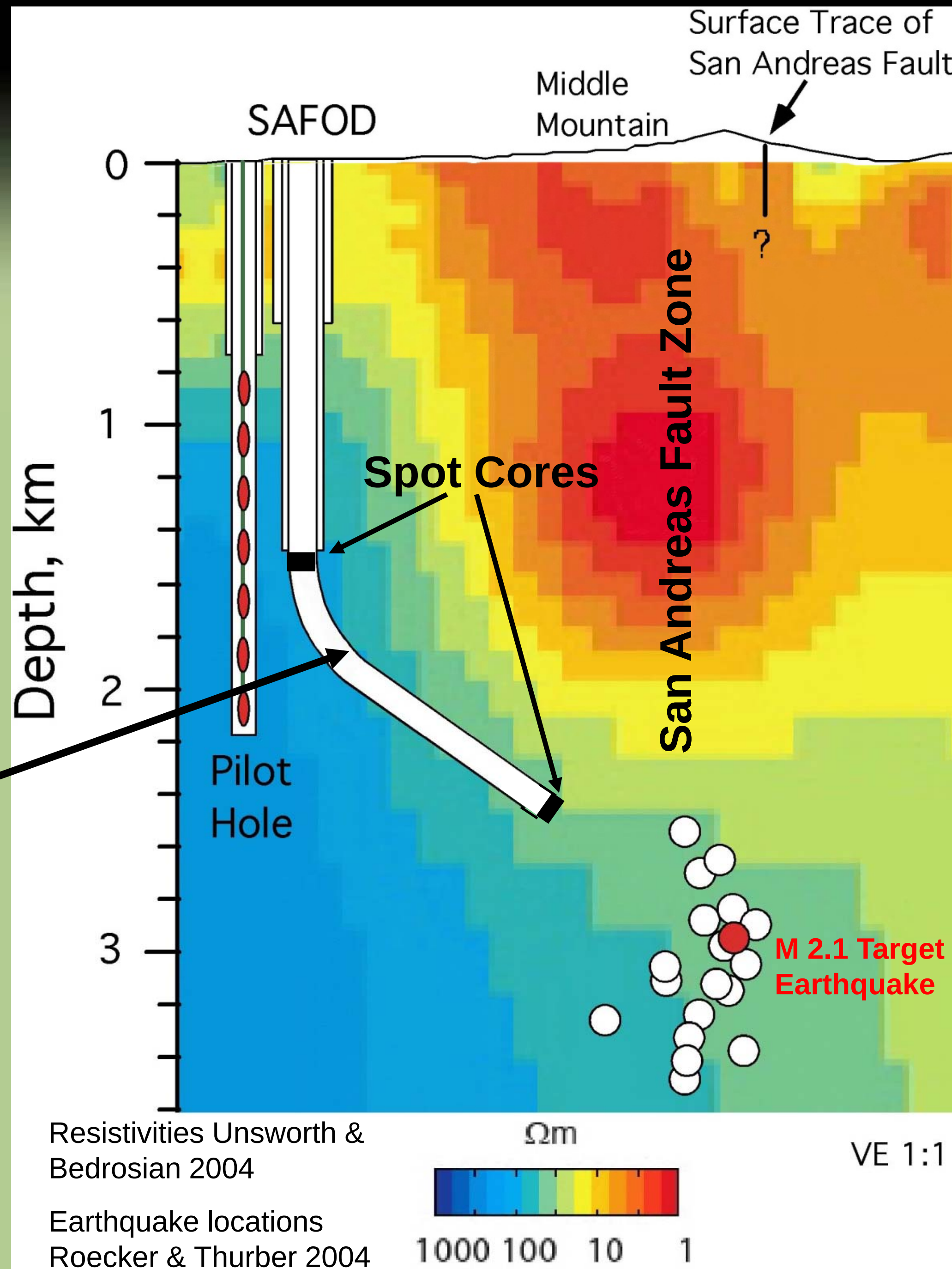
Drilled 12-1/4" hole to 2.5 km, while collecting continuous drill cuttings and carrying out mud gas analyses.

Below 1.5 km, steered hole toward target earthquakes (deviation 55°).

Conducted wireline geophysical logging in open hole.

After setting casing, obtained 20 m of 4" diameter core at 1.5 and 2.5 km. Conducted permeability tests, fluid sampling and hydrofracs in core holes.

Following Phase 1 - Deploy seismometers at bottom of hole for refinement of velocity structure and location of target earthquakes.



SAFOD Phase 2 Drilling: June - September 2005

Phase 2: Drilling Through Fault Zone

Drilled inclined 8-1/2" hole from 2.5 to 3.1 km.

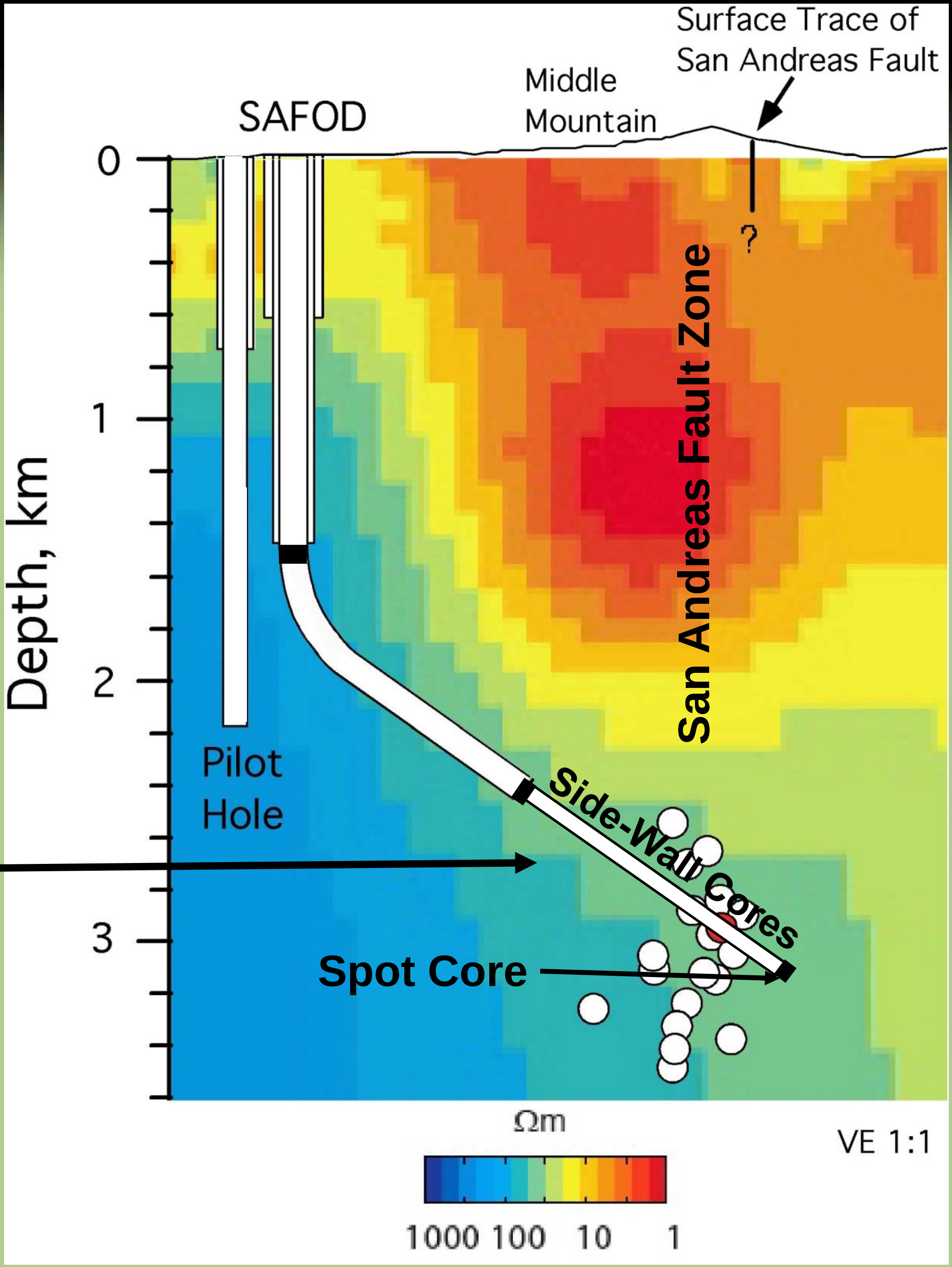
Conducted extensive real-time cuttings and mud gas analyses while drilling across the fault zone.

Conducted comprehensive logging while drilling and wireline geophysical logging in open hole.

Collected 52 small (0.75" dia. x 1") side-wall cores in open hole.

After setting casing, collected 4 m of 2.6" dia. spot core at 3.1 km and carried out hydrofrac in core hole.

Monitoring casing deformation, microseismicity and tremor.



What was it Like Drilling Through the SAF?

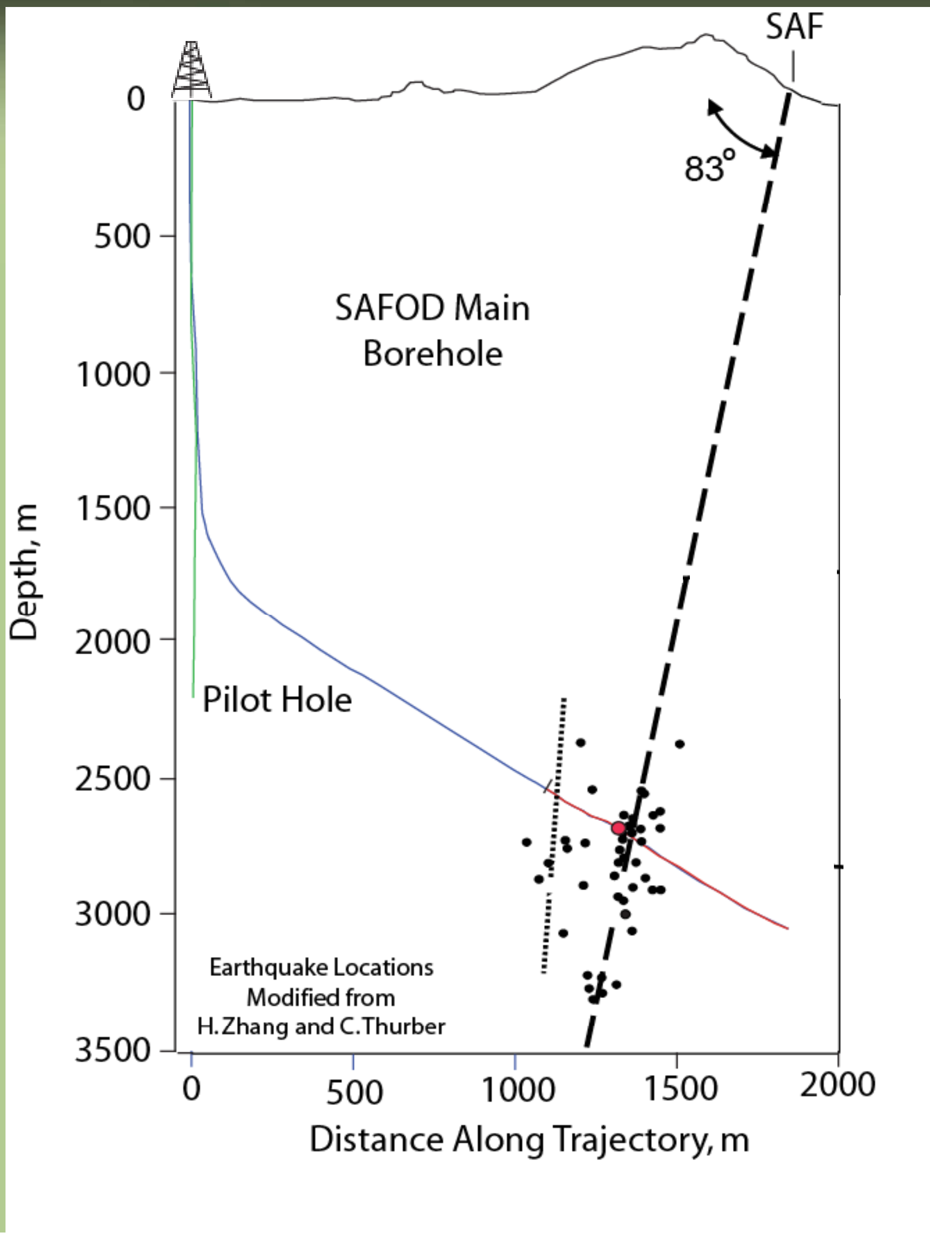
- Frustrating – Top Drive Problems Caused Significant Unexpected Expenses

- Terrifying – Being Stuck for Several Days at 12,300’

- Challenging – Maximizing Scientific Return Within Operational and Budgetary Constraints

- Exhausting – 24/7 Is Not Just an Expression

Success!



SAF
83°
SAFOD Main
Borehole
Pilot Hole
Earthquake Locations
Modified from
H.Zhang and C.Thurber
Depth, m
0
500
1000
1500
2000
2500
3000
3500
0
500
1000
1500
2000
Distance Along Trajectory, m

A remarkable experience for many people

San Andreas Fault Observatory at Depth: Project Overview and Science Goals

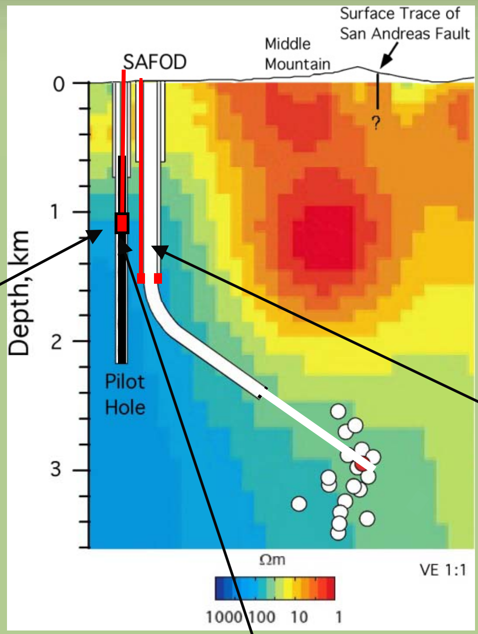
Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

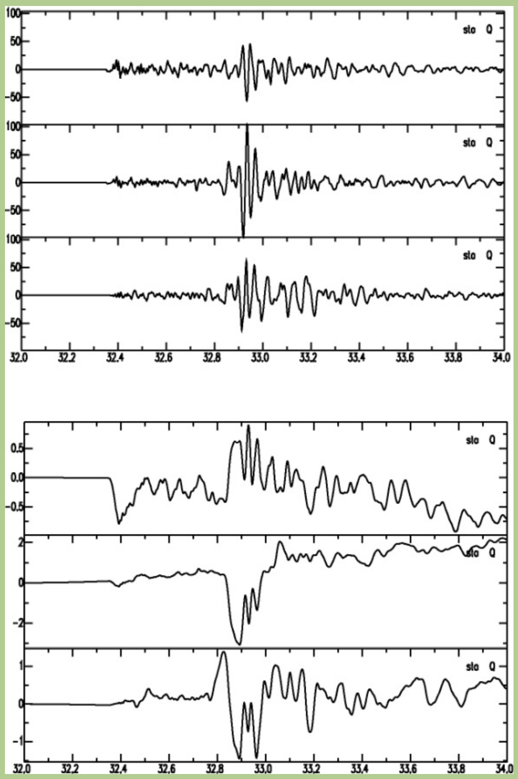
Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

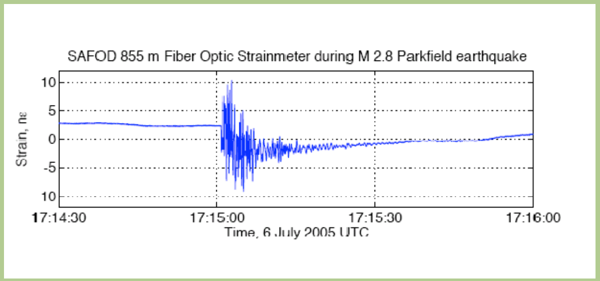
Joint observations of July 6, 2005 M 2.8 earthquake at a distance of 4 km



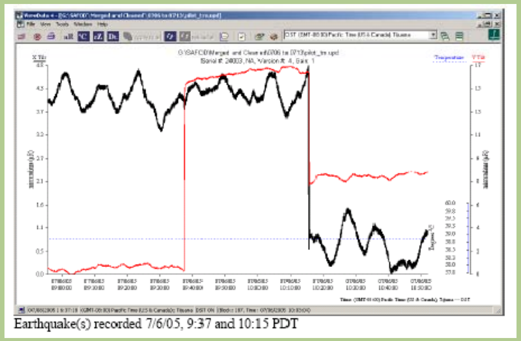
3-Component Seismometer



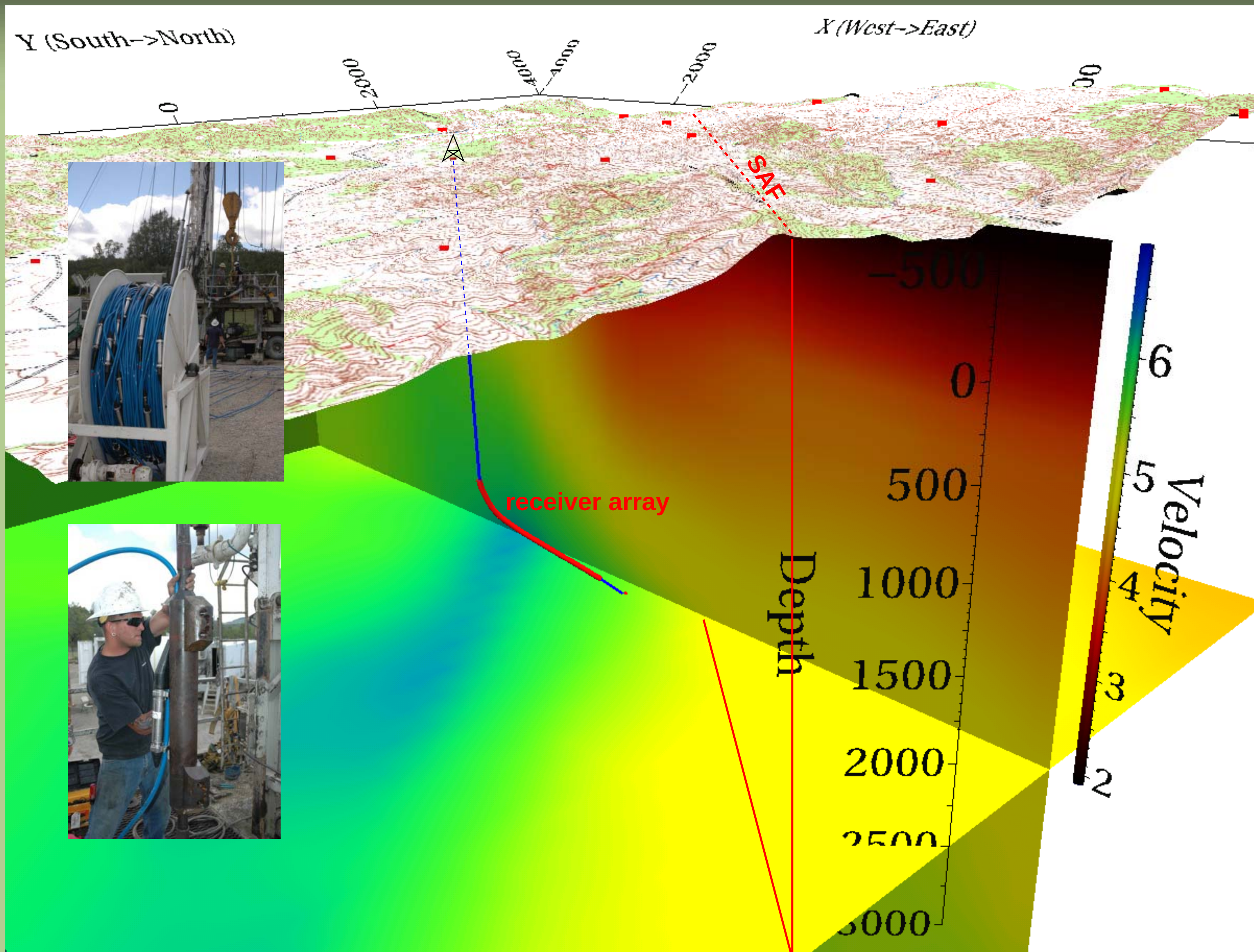
Laser Strainmeter



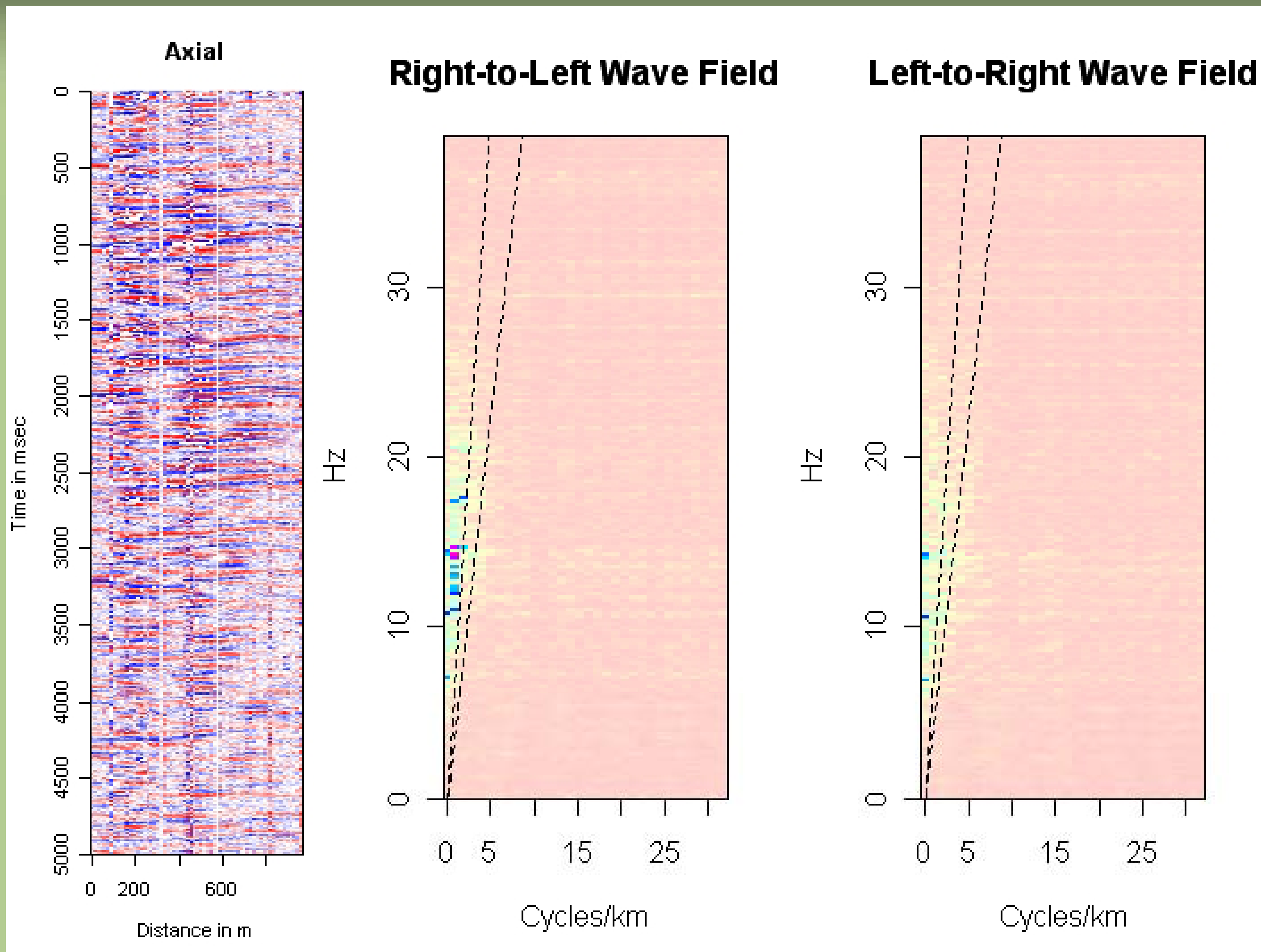
Borehole Tiltmeter

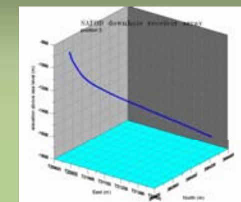


Borehole Seismic Array – May 2005
Paulsson Geophysical Services, Inc.

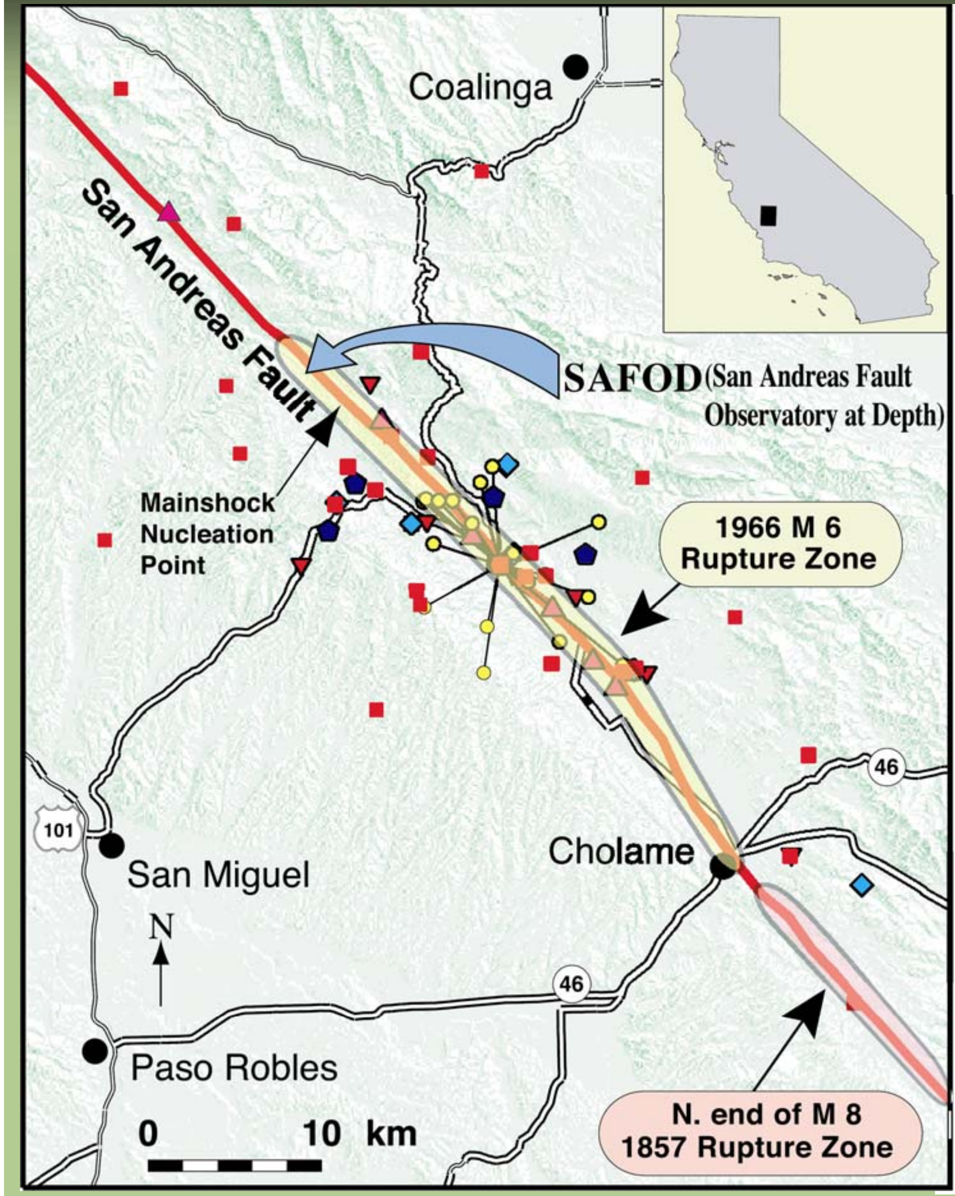


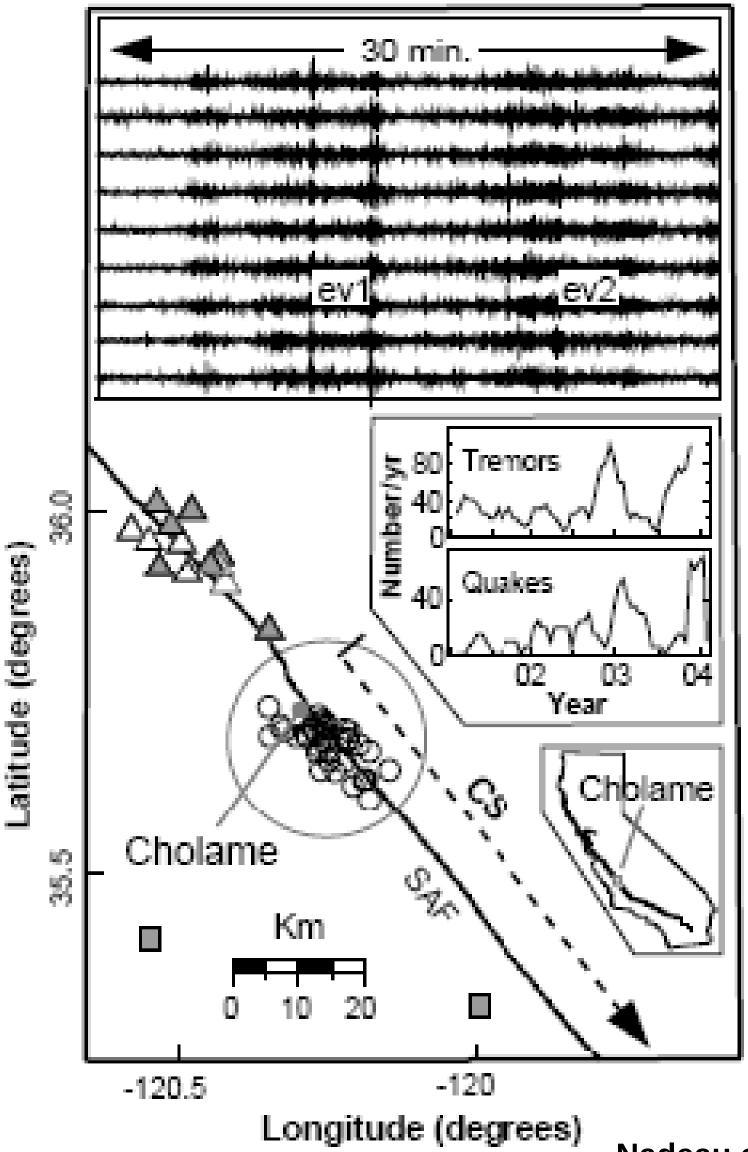
Tremor Wave Field





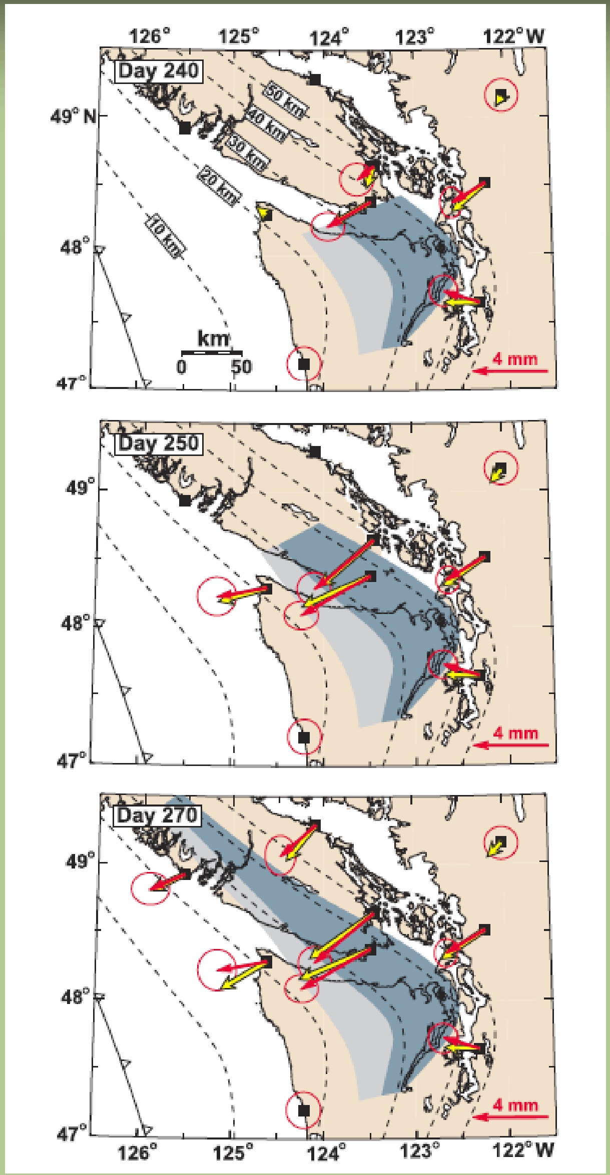
Non-Volcanic Tremor on the San Andreas Fault

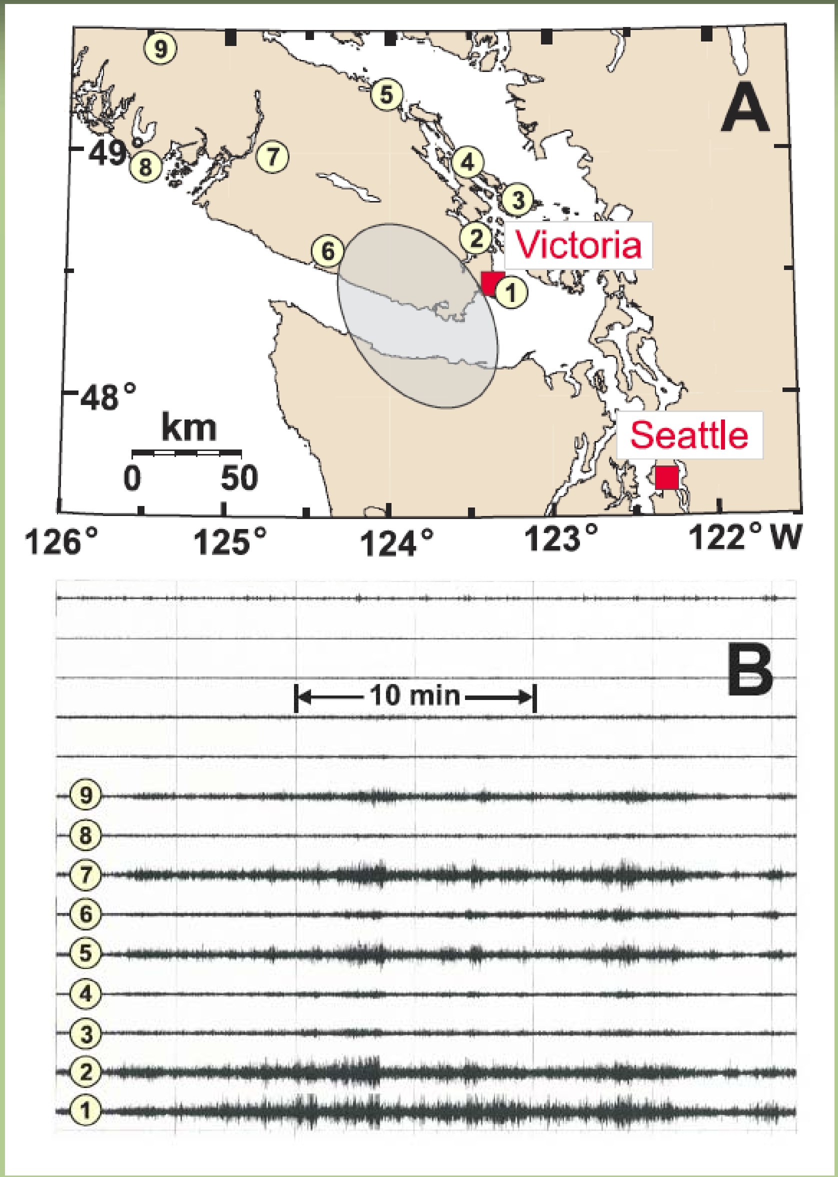




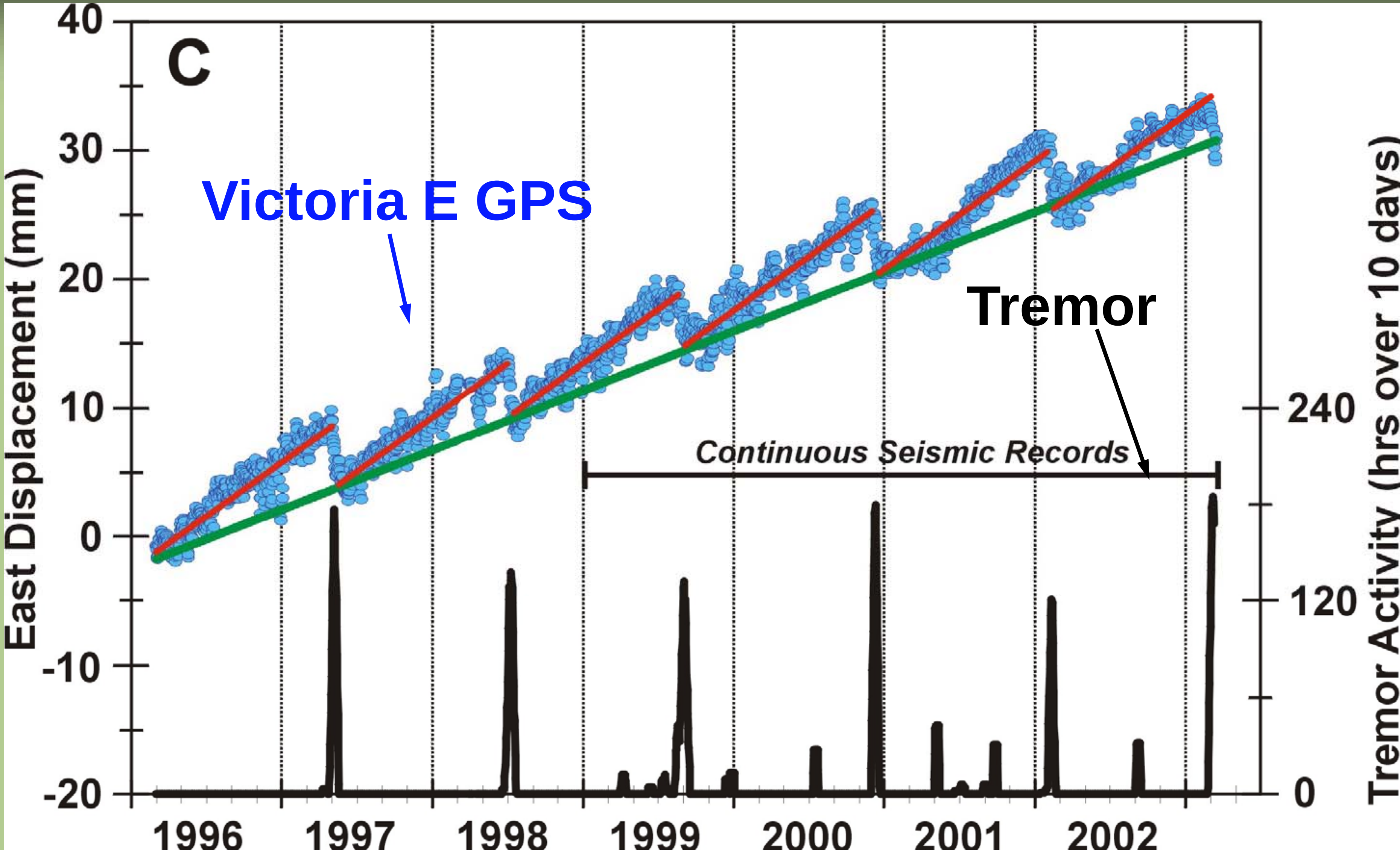
Nadeau et al., 2005

Non-volcanic Tremor with Aseismic Slip Episodes





Cascadia Episodic Tremor & Slip



Rogers & Dragert, 2003

San Andreas Fault Observatory at Depth: Project Overview and Science Goals

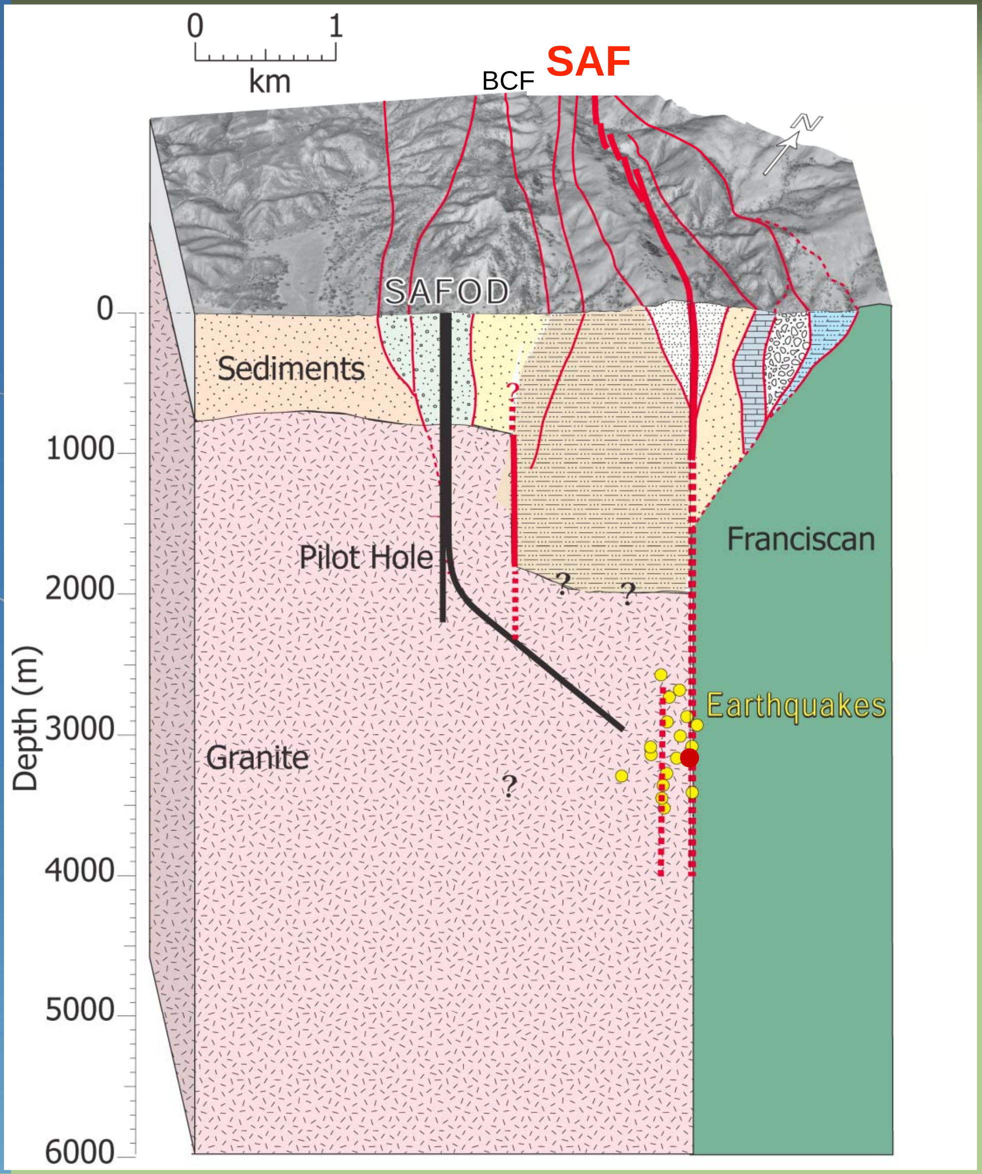
Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

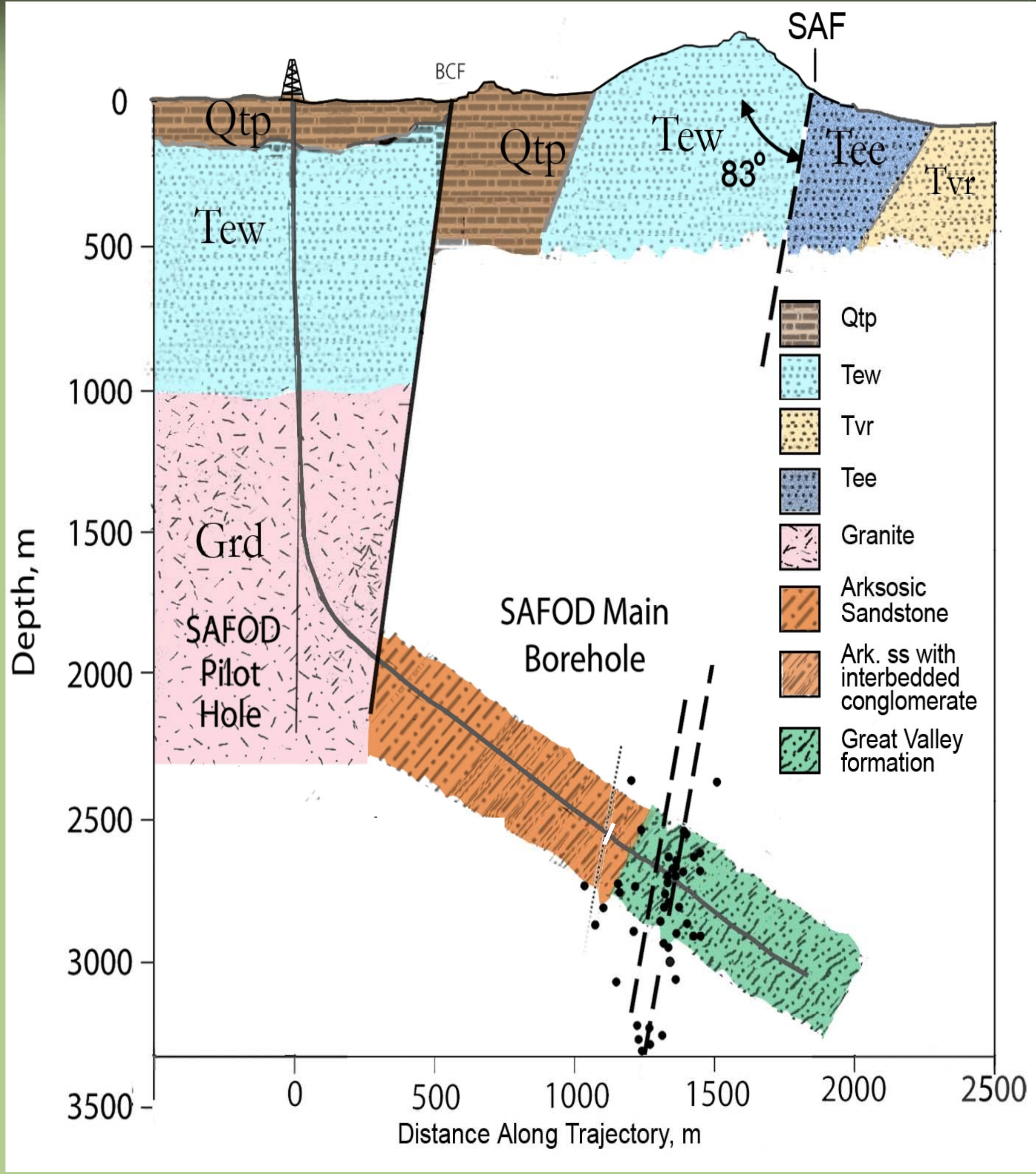
Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

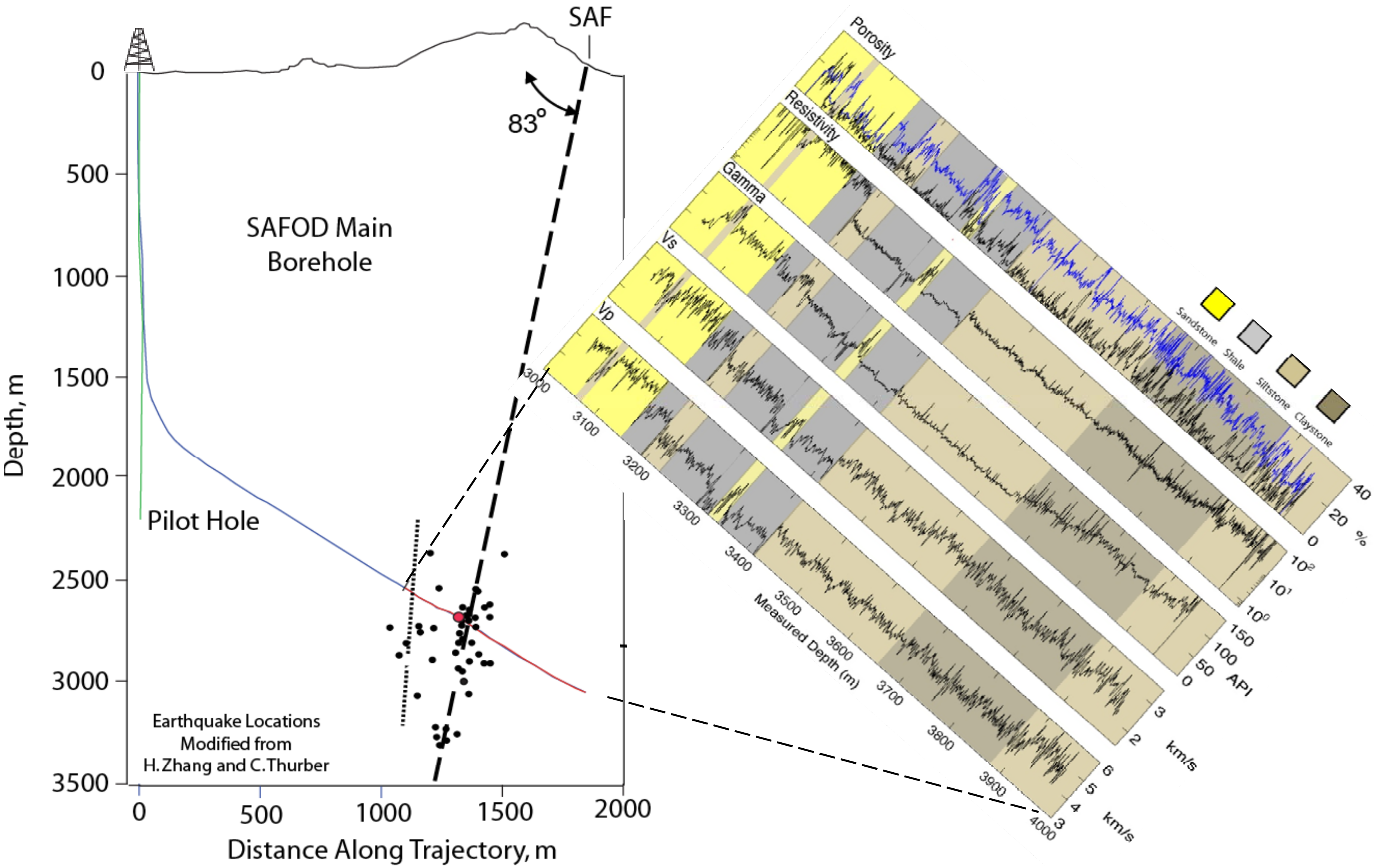
SAFOD
Preliminary Geological Model



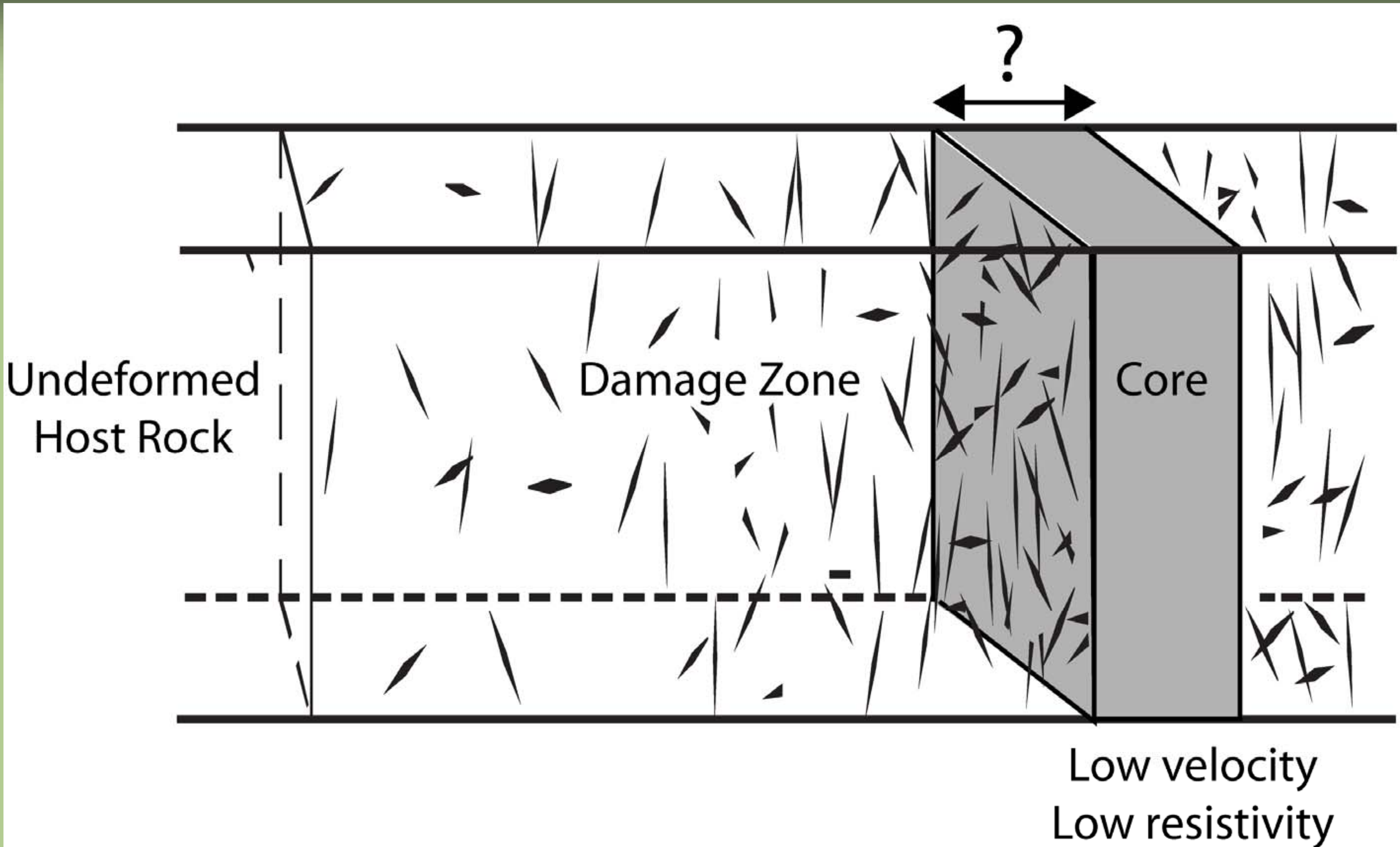
SAFOD
Current Geological Model



Phase 2 Geophysical Logs

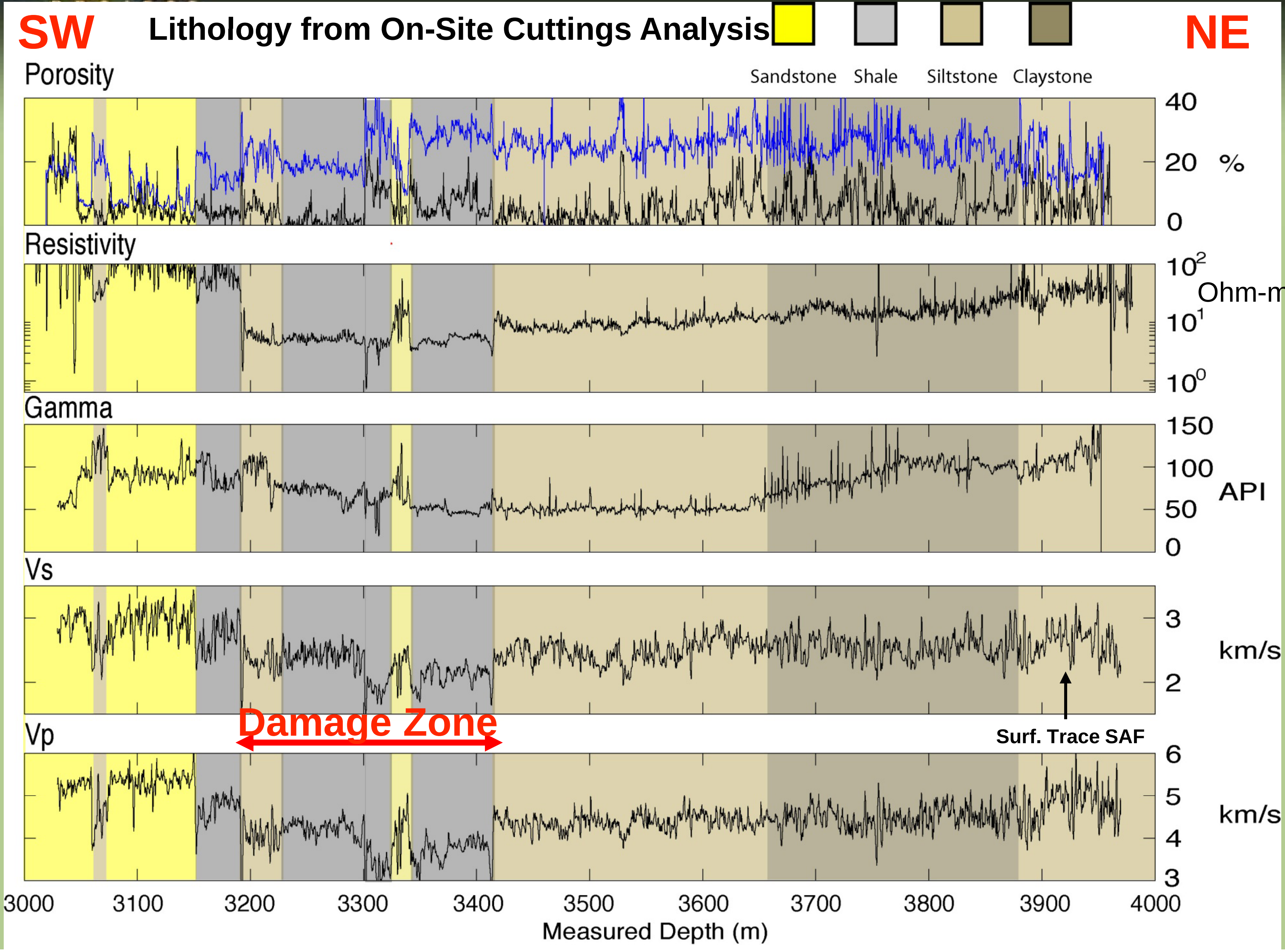


The San Andreas Fault in Outcrop

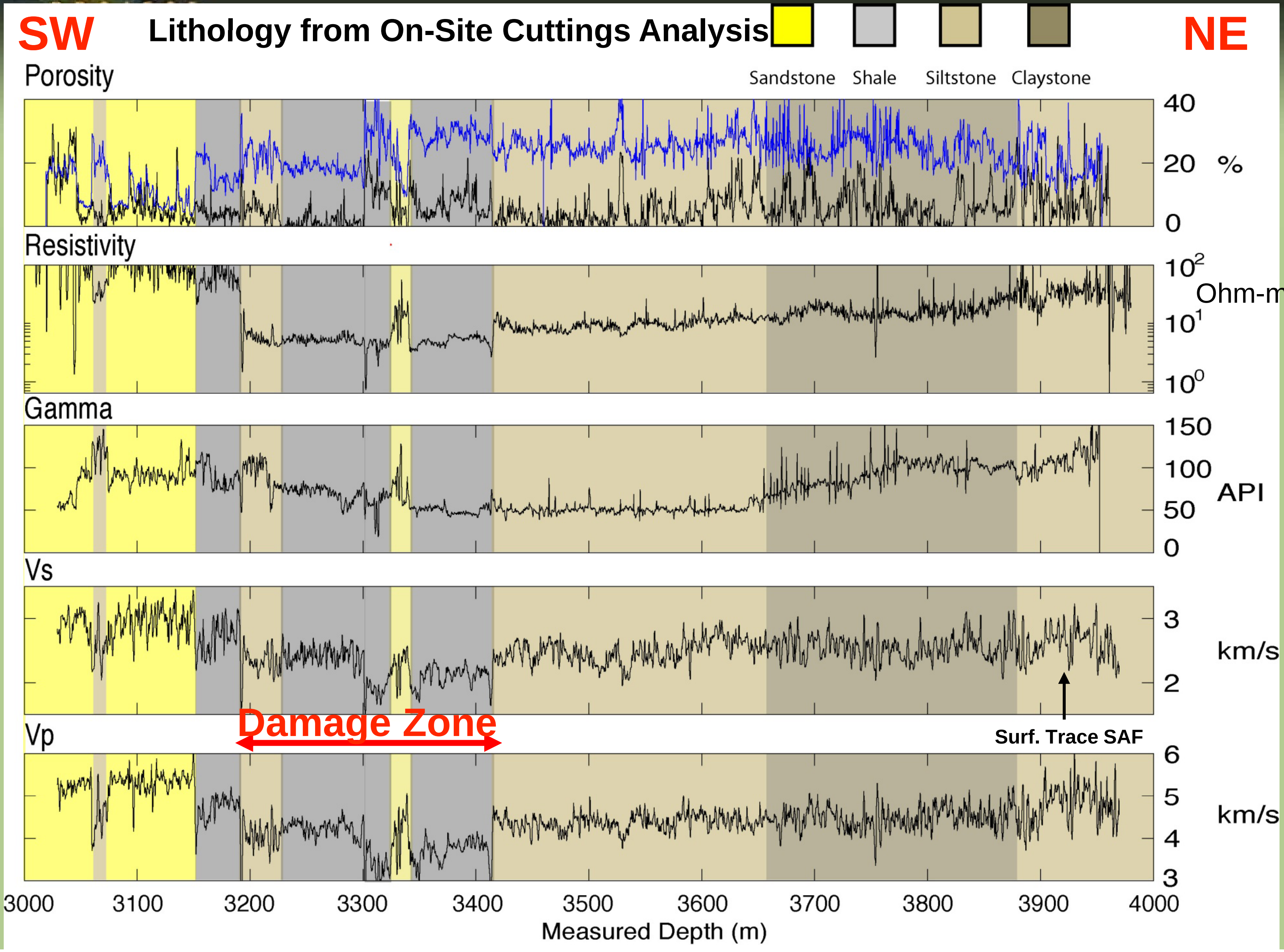


Modified from Chester et al., 2005

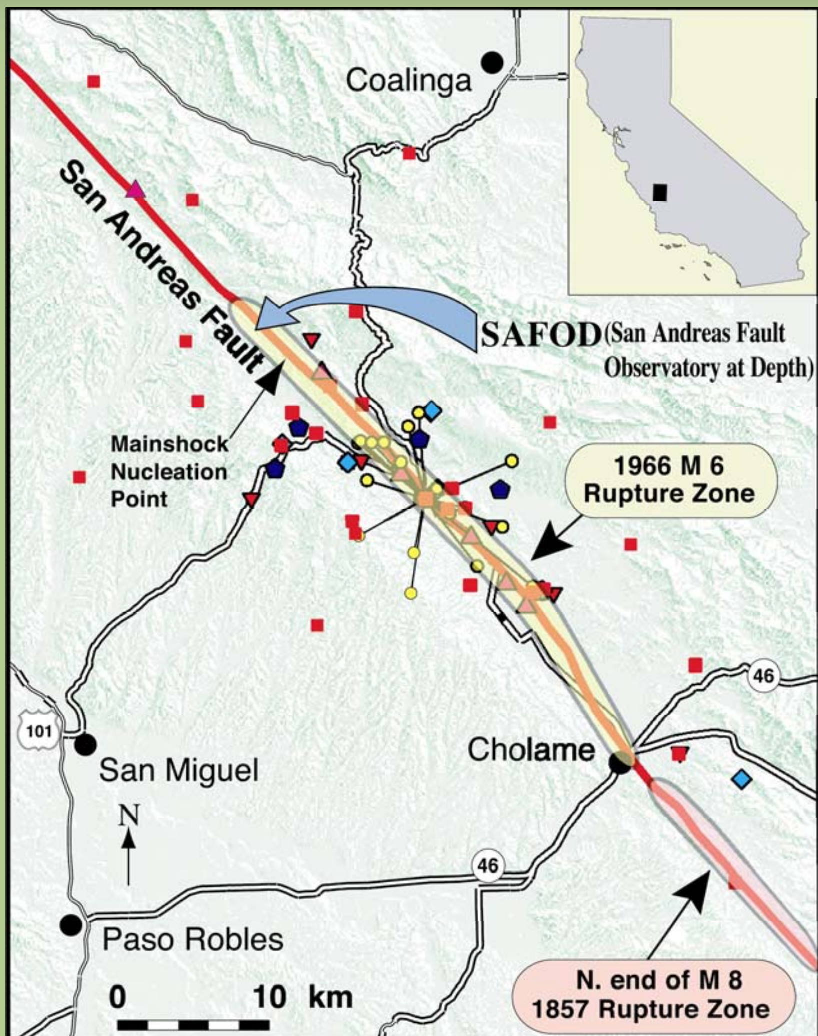
Pronounced Damage Zone ~ 250m Wide

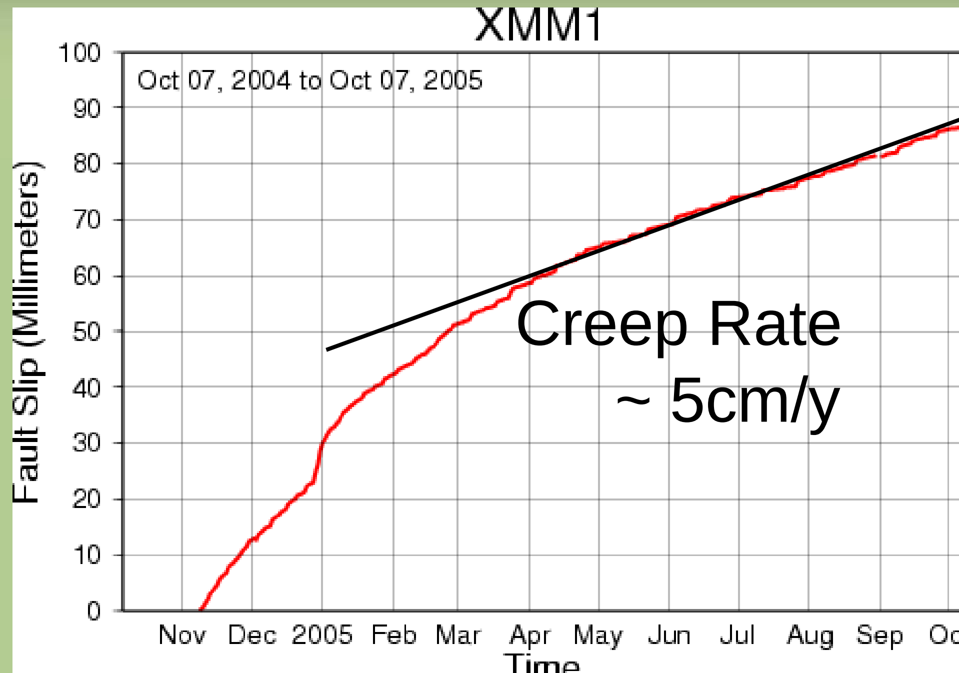


But Where is the San Andreas Fault?

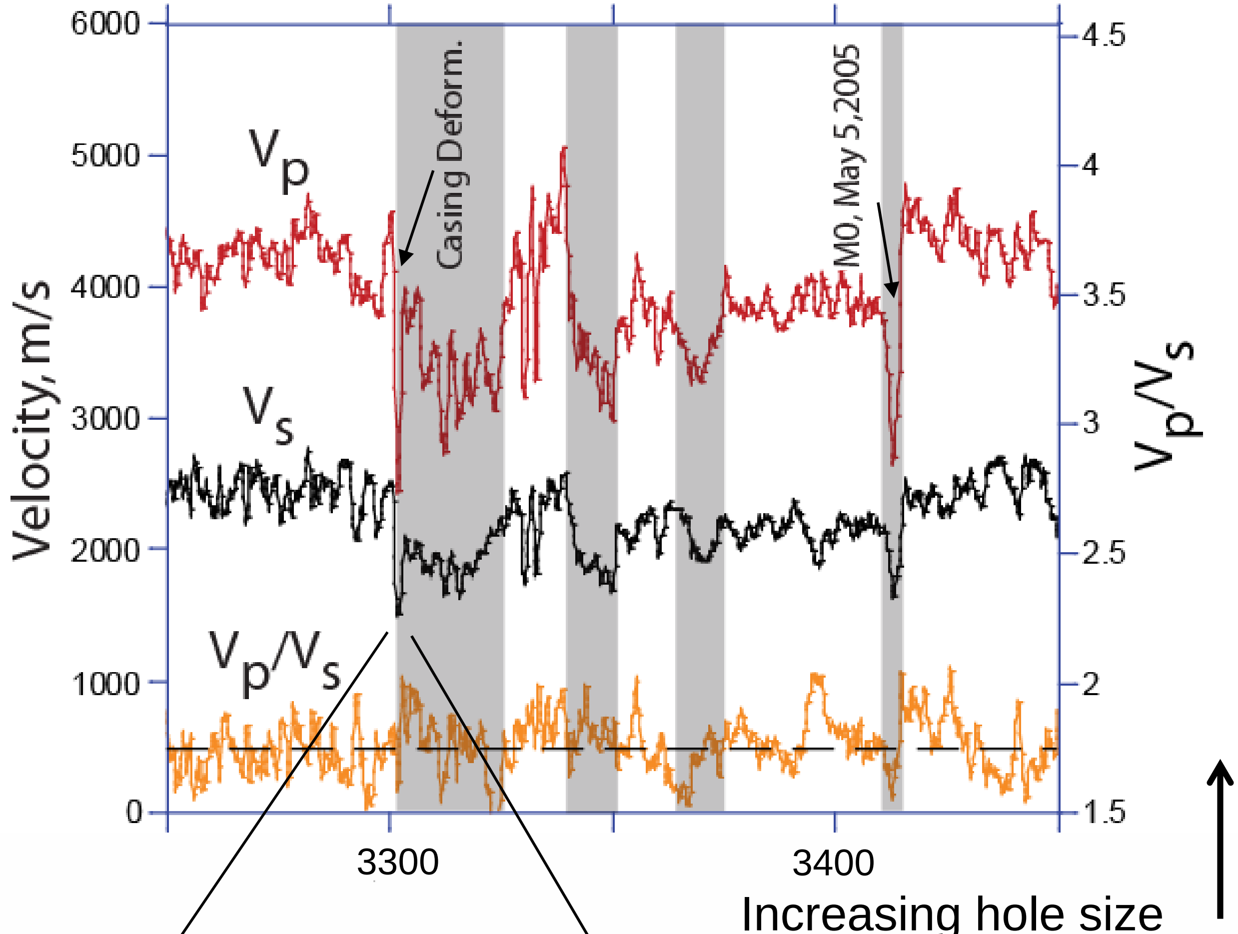


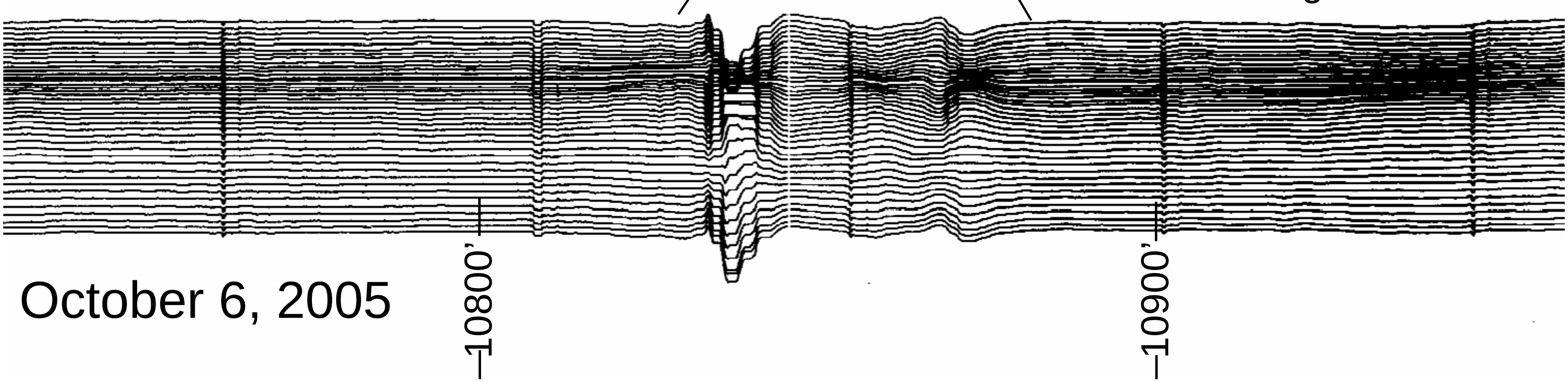
Rapid Fault Creep
Following September 28, 2004 M 6 Event





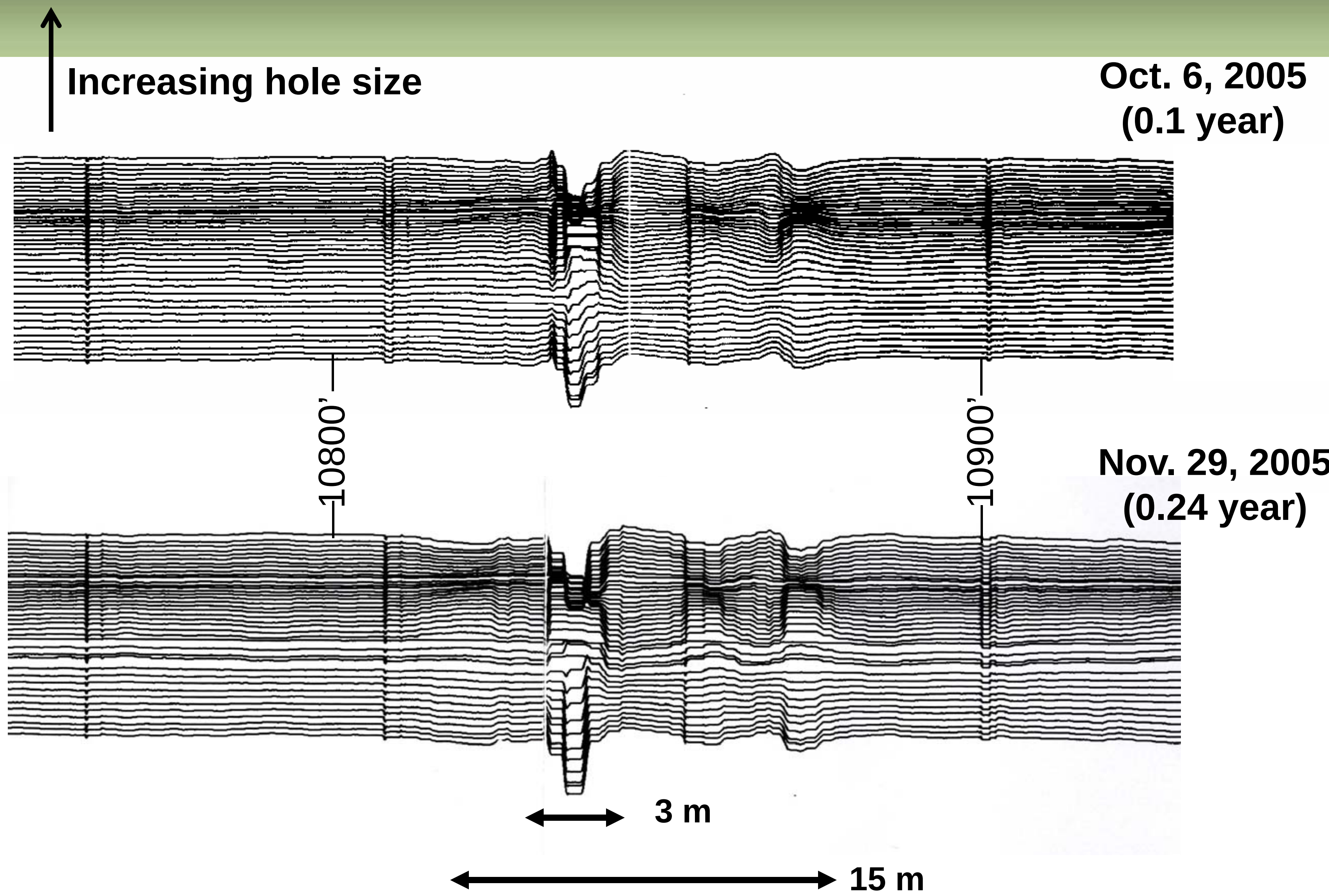
Casing Deformation Log



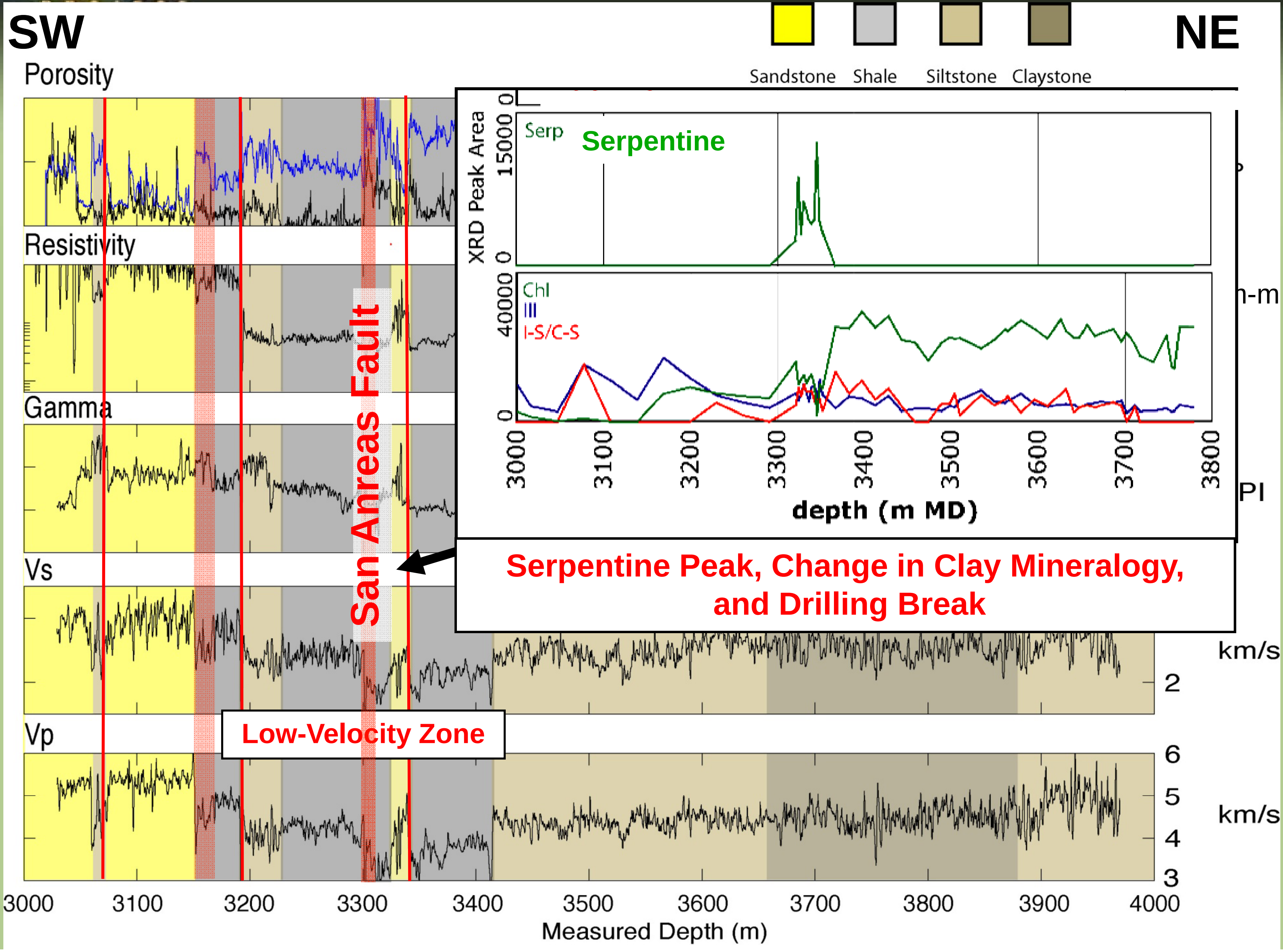


October 6, 2005

Repeat Casing Deformation Measurements

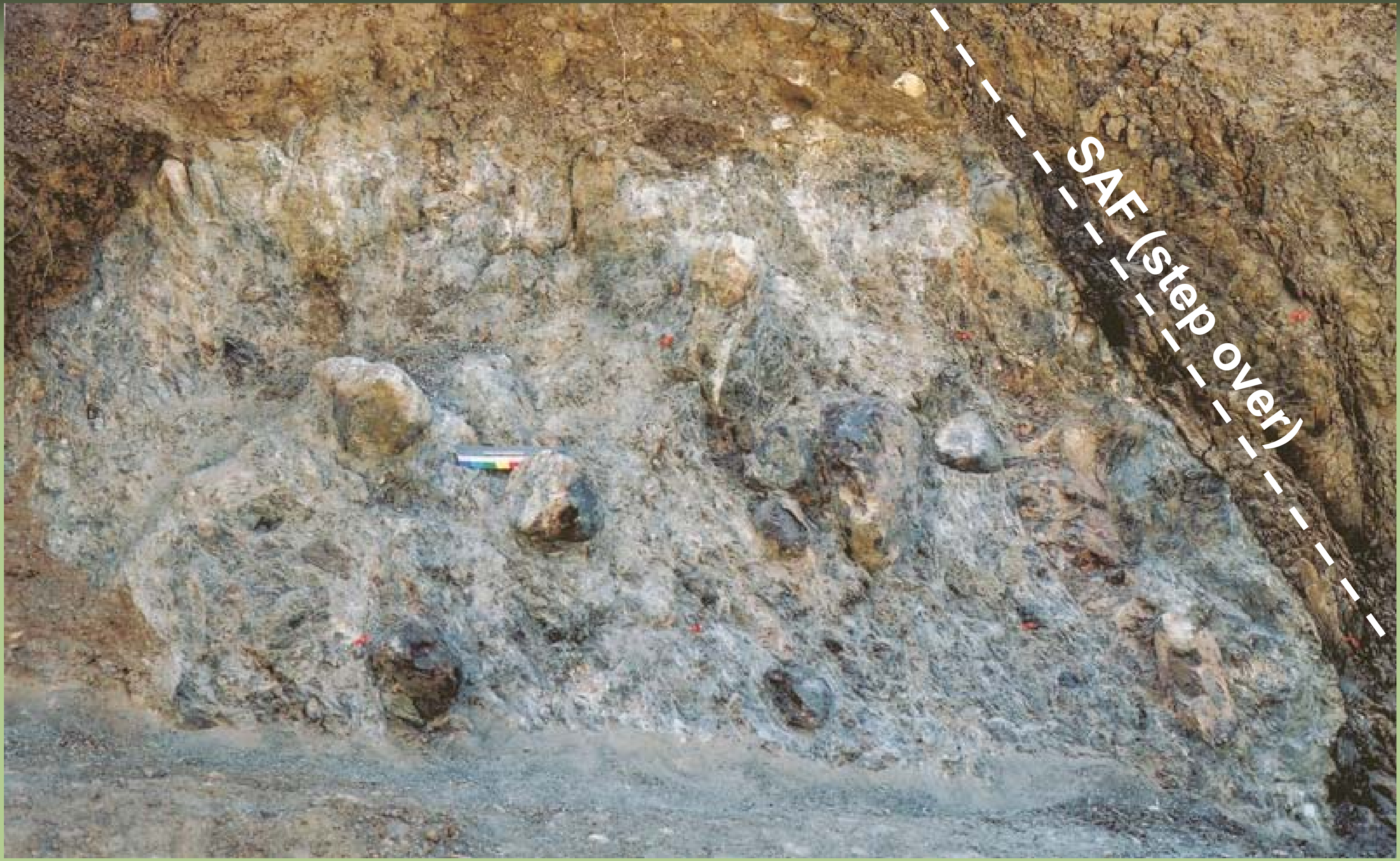


Mineralogical Anomalies in San Andreas Fault Zone



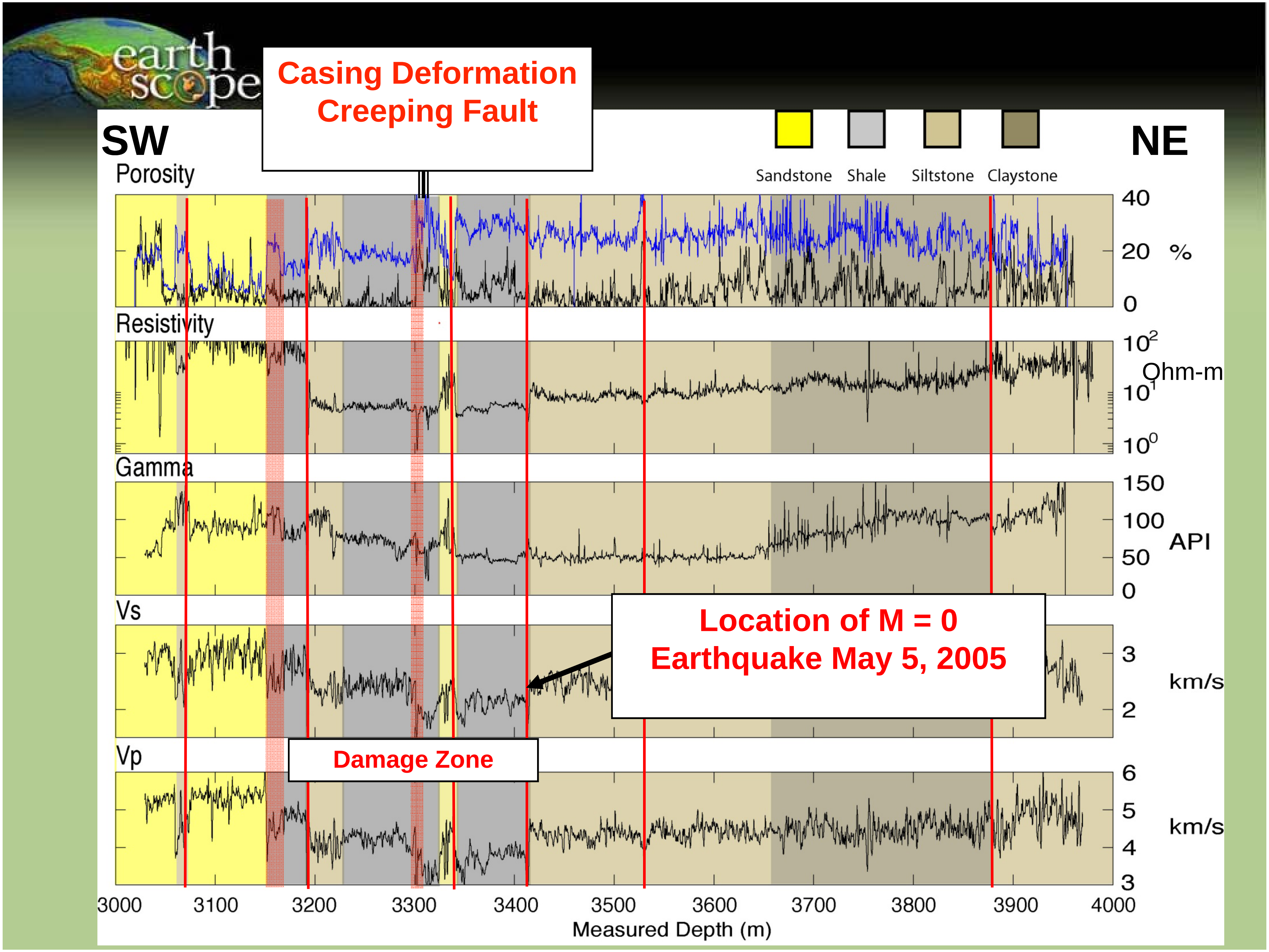
Serpentinite in San Andreas Fault 2 km NE of SAFOD

Is this why it's creeping?

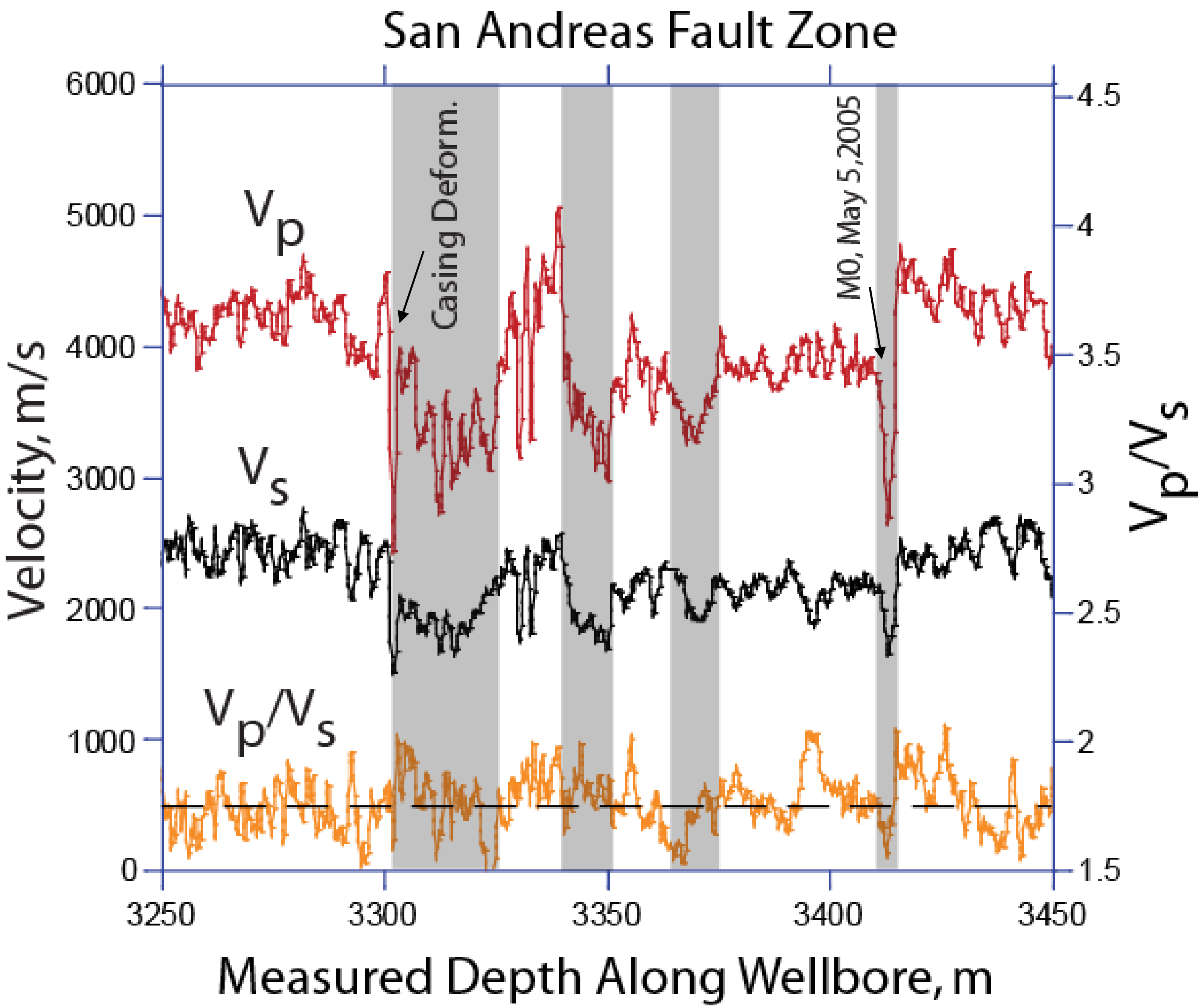


1 m

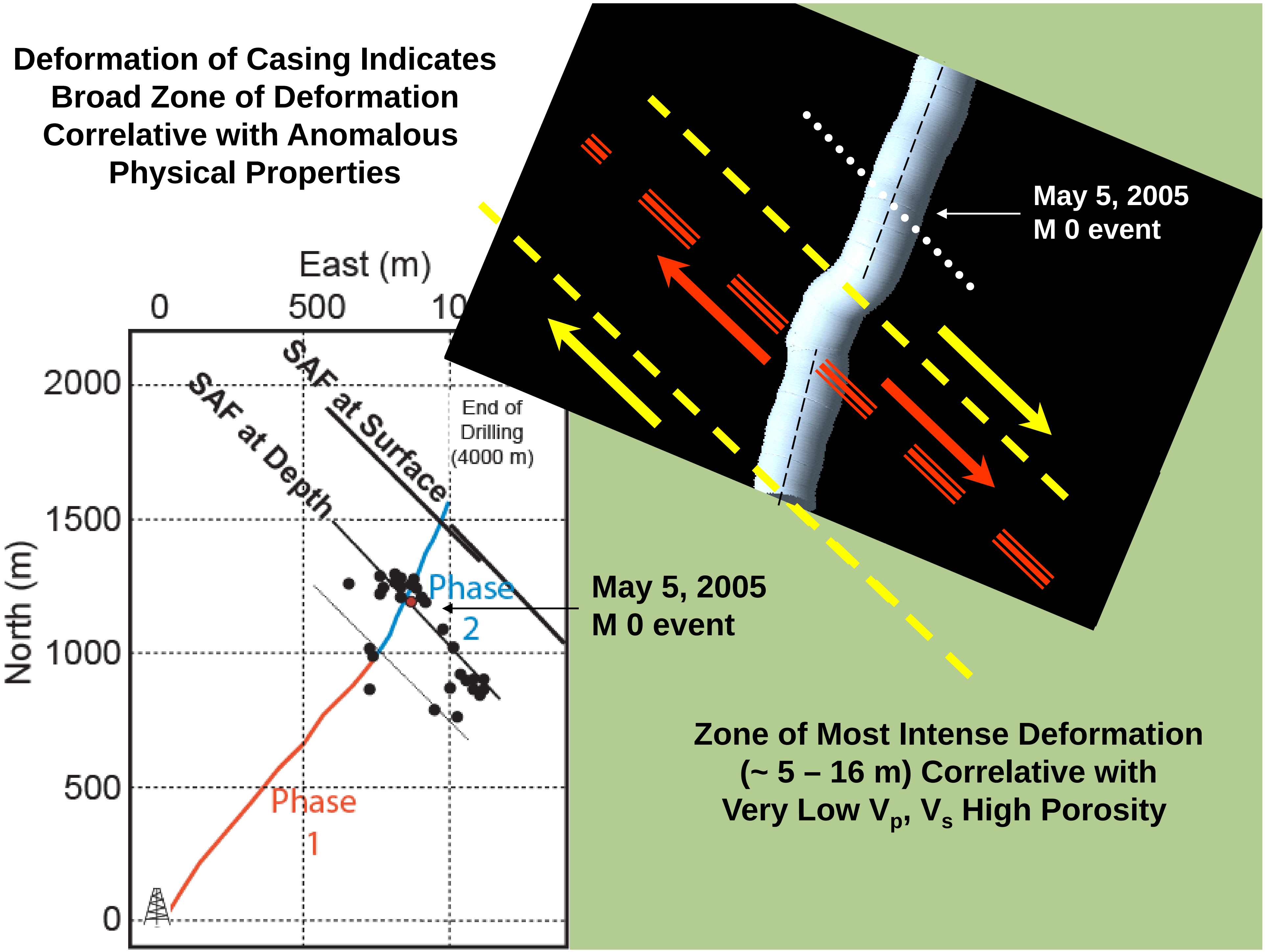
Photo from Mike Rymer



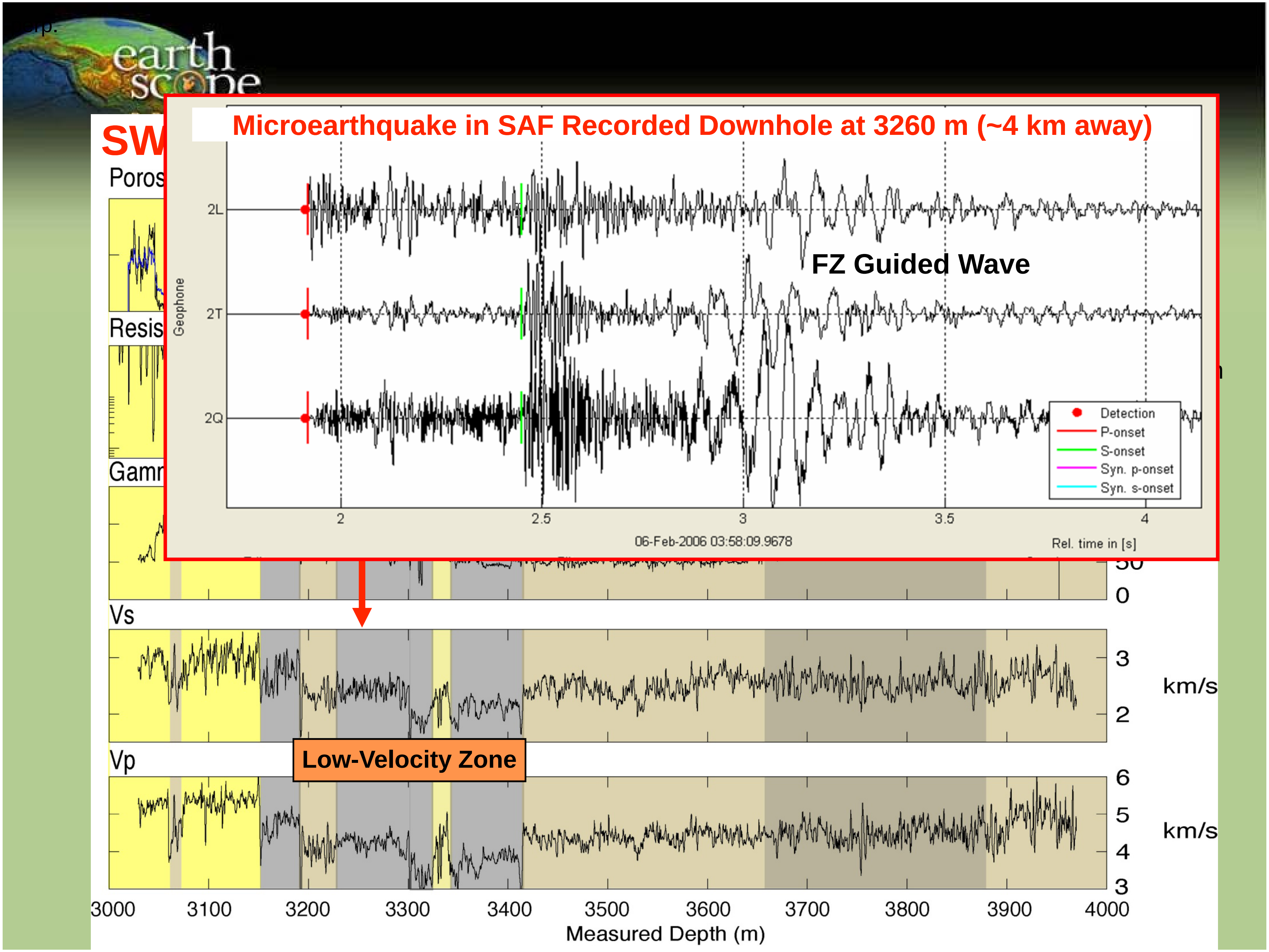
Casing Deformation
Creeping Fault
SW
NE
Sandstone
Shale
Siltstone
Claystone
Porosity
40
20
%
0
Resistivity
10^2
Ohm-m
10^1
10^0
Gamma
150
100
API
50
0
Vs
3
km/s
2
Location of M = 0
Earthquake May 5, 2005
Vp
Damage Zone
6
5
km/s
4
3
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
Measured Depth (m)


San Andreas Fault Zone
Velocity, m/s
6000
5000
4000
3000
2000
1000
0
Vp
Vs
Vp/Vs
Casing Deform.
M0, May 5,2005
4.5
4
3.5
3
2.5
2
1.5
Vp/Vs
3250
3300
3350
3400
3450
Measured Depth Along Wellbore, m

Deformation of Casing Indicates Broad Zone of Deformation Correlative with Anomalous Physical Properties

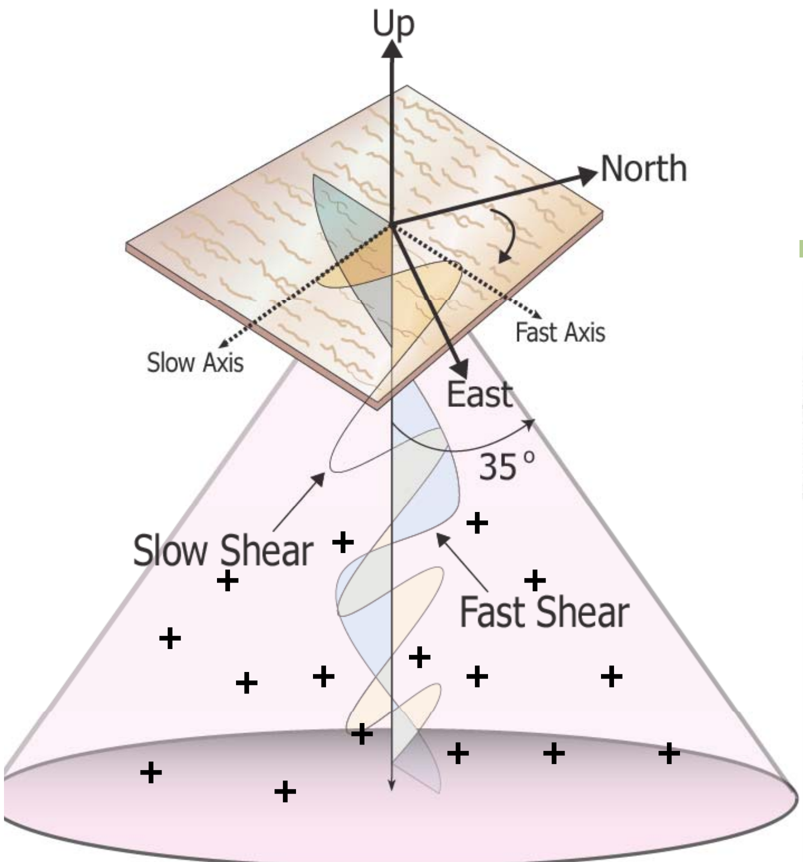


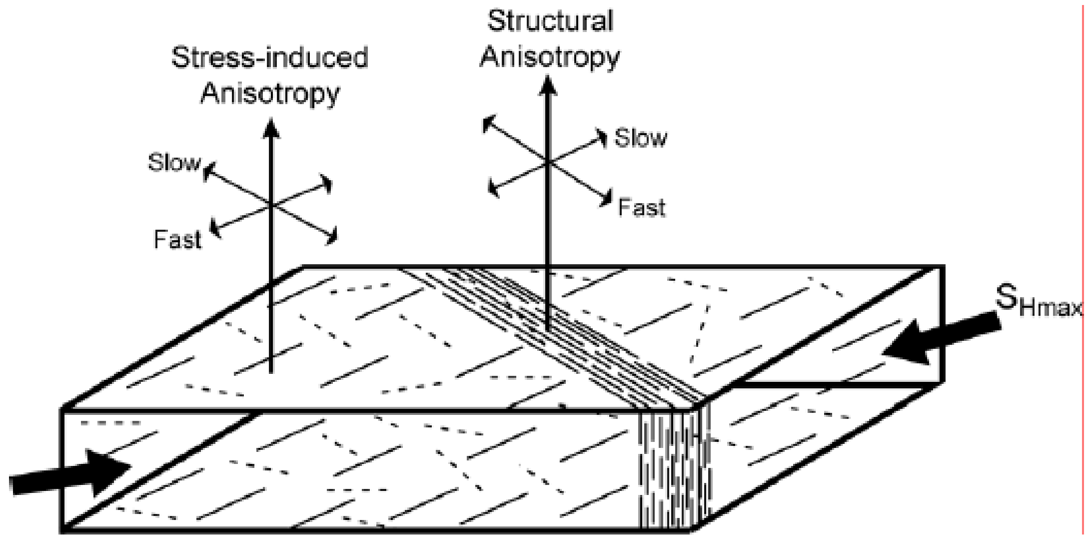
Zone of Most Intense Deformation (~ 5 – 16 m) Correlative with Very Low V_p, V_s High Porosity

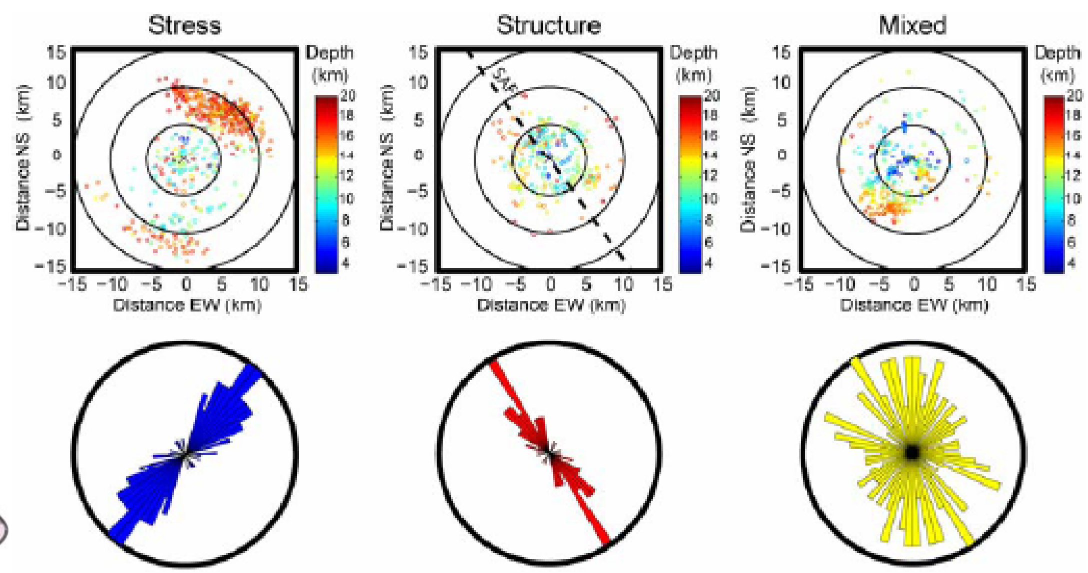


earth scope
SW
Poros
Resis
Gamm
Microearthquake in SAF Recorded Downhole at 3260 m (~4 km away)
FZ Guided Wave
Geophone
2L
2T
2Q
Detection
P-onset
S-onset
Syn. p-onset
Syn. s-onset
2
2.5
3
3.5
4
06-Feb-2006 03:58:09.9678
Rel. time in [s]
Vs
3
2
km/s
Vp
Low-Velocity Zone
6
5
4
3
km/s
0
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
Measured Depth (m)

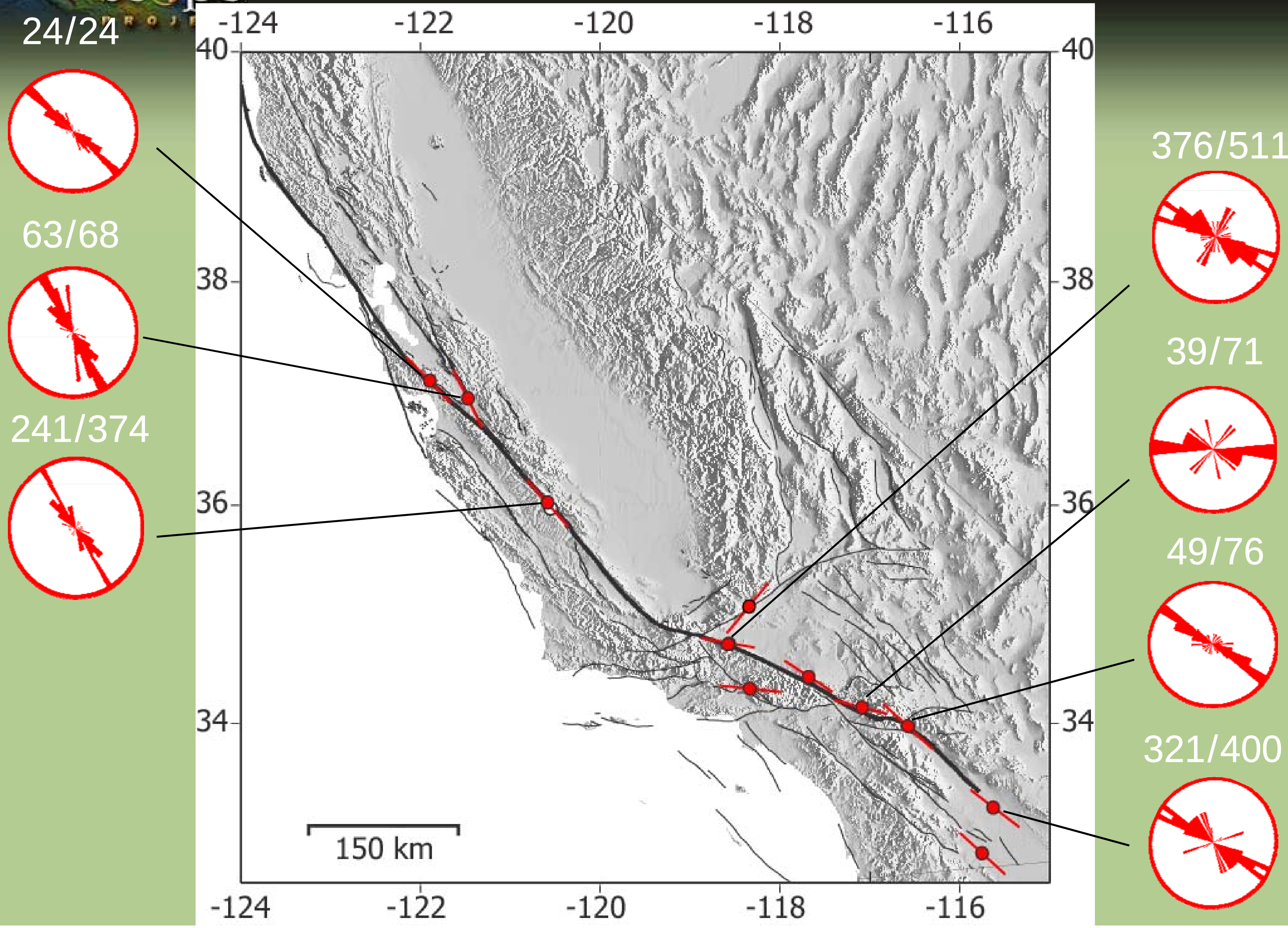
Crustal
Shear Velocity Anisotropy:
Stress or Structure







Shear Velocity Anisotropy: Structure



San Andreas Fault Observatory at Depth: Project Overview and Science Goals

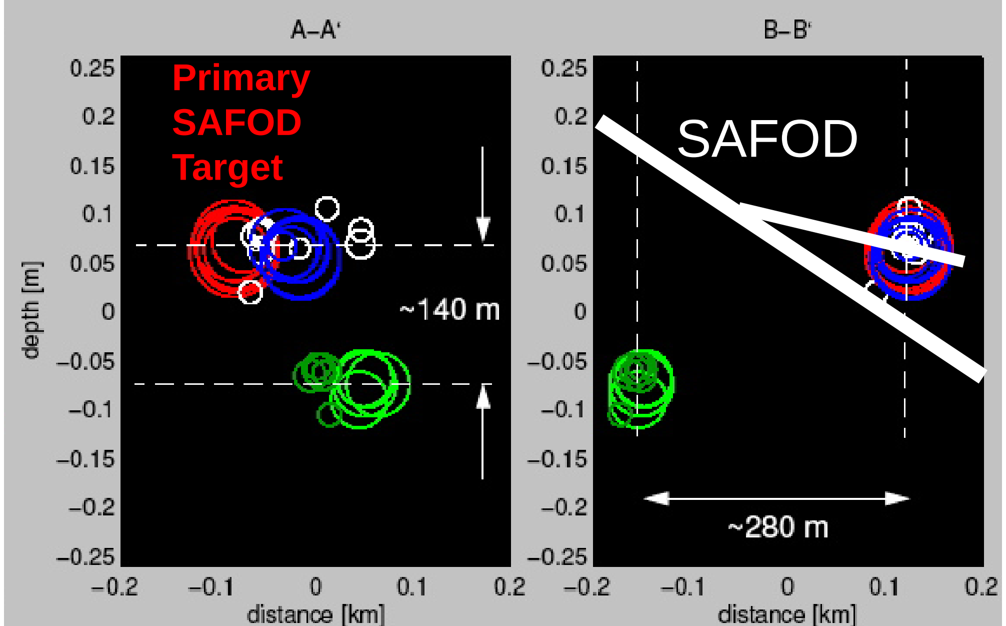
Test fundamental theories of earthquake mechanics:

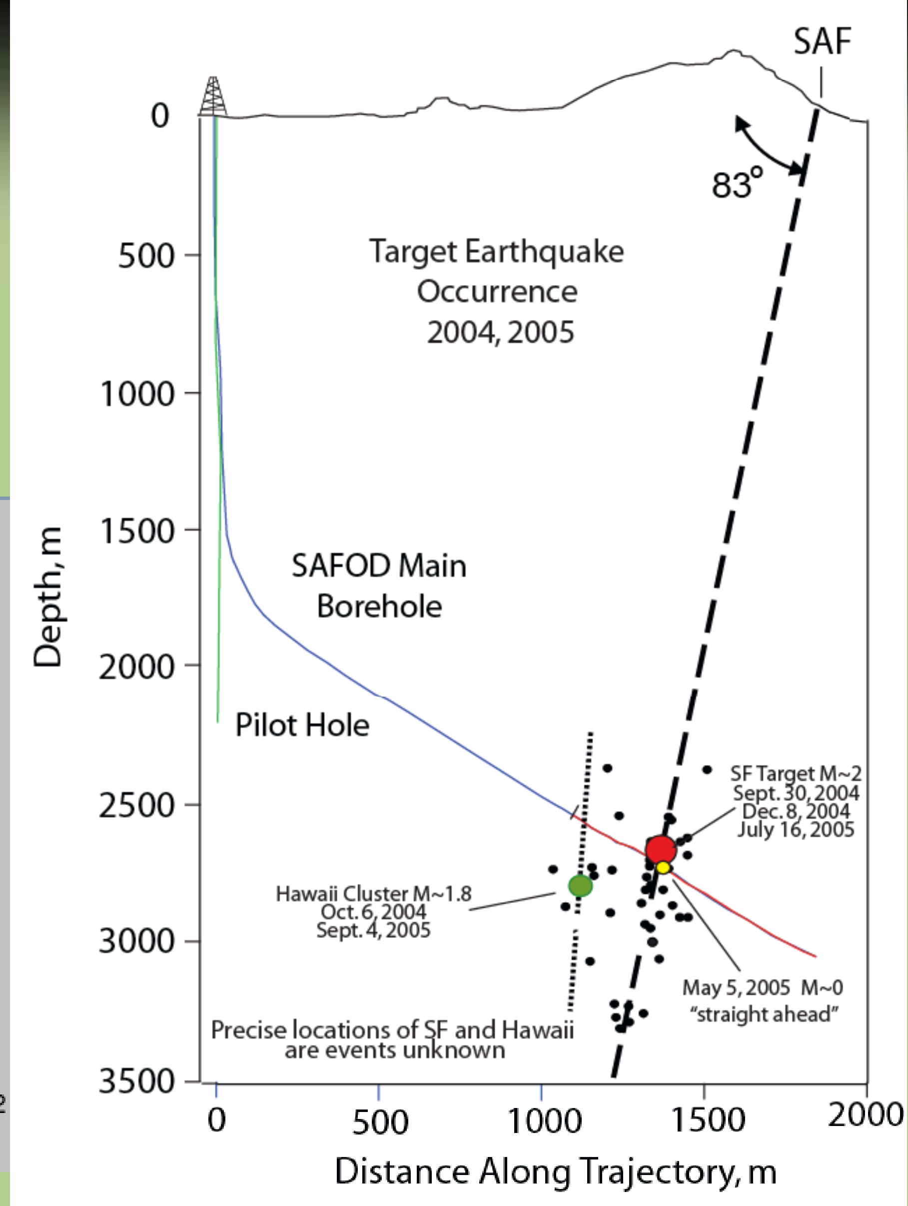
- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

Measurement of the State of Stress and Pore Pressure Within an Active Plate-Bounding Fault Zone



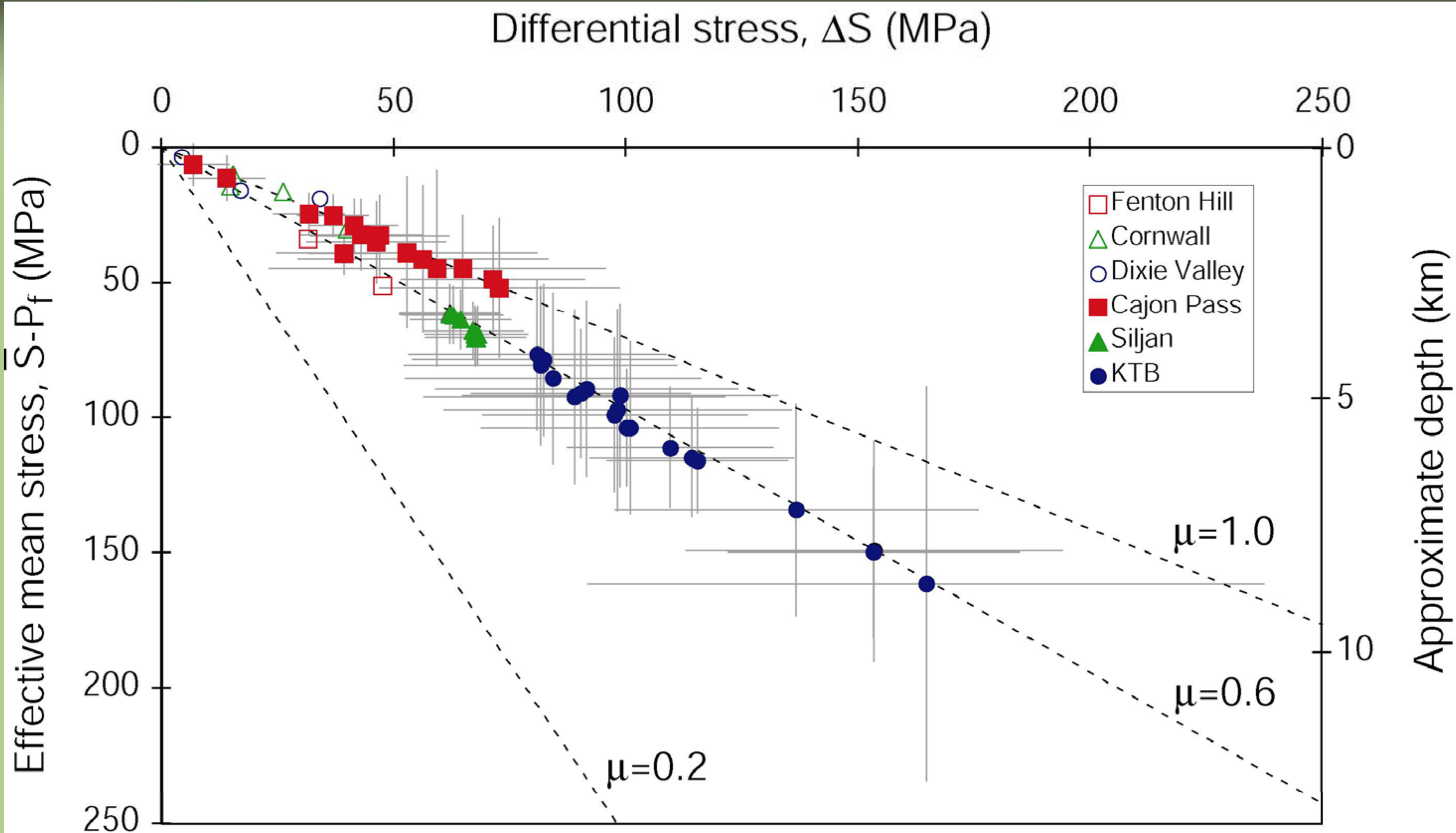


Nadeau et al. 2004, Waldhauser and Ellsworth 2005

Developing a Comprehensive Geomechanical Model

Parameter		Data
Vertical stress	→	$S_v(z_0) = \int_0^{z_0} \rho g \, dz$
Least principal stress	→	$S_{hmin} \Leftarrow$ LOT, XLOT, minifrac
Max. Horizontal Stress	→	S_{Hmax} magnitude $\Leftarrow$ modeling wellbore failures
Stress Orientation	→	Orientation of Wellbore failures
Pore pressure	→	$P_p \Leftarrow$ Measure, sonic, seismic
Rock Strength	→	Lab, Logs, Modeling well failure
Faults/Bedding Planes	→	Wellbore Imaging

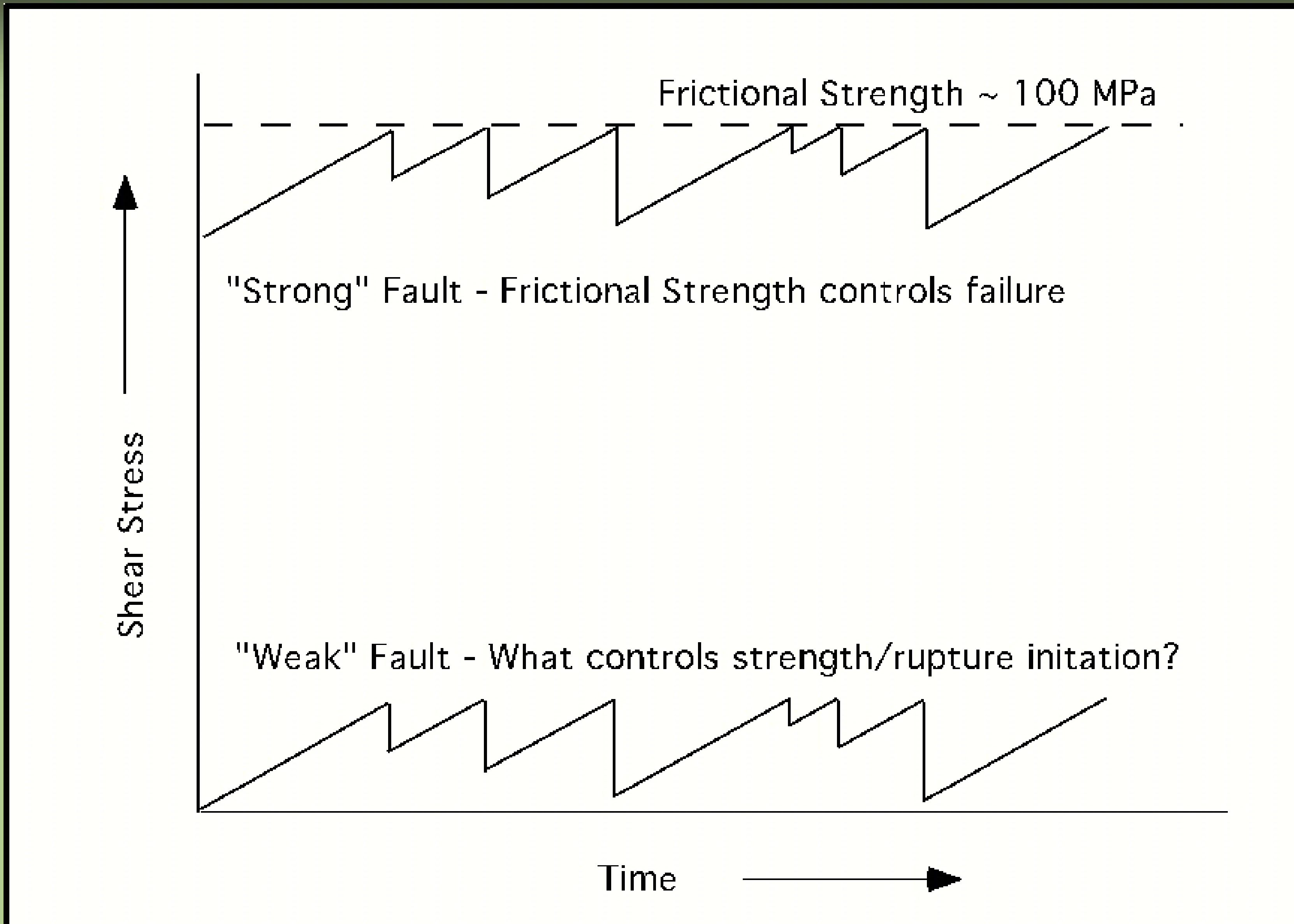
Strong Crust in Intraplate Areas
Hydrostatic Pore Pressure

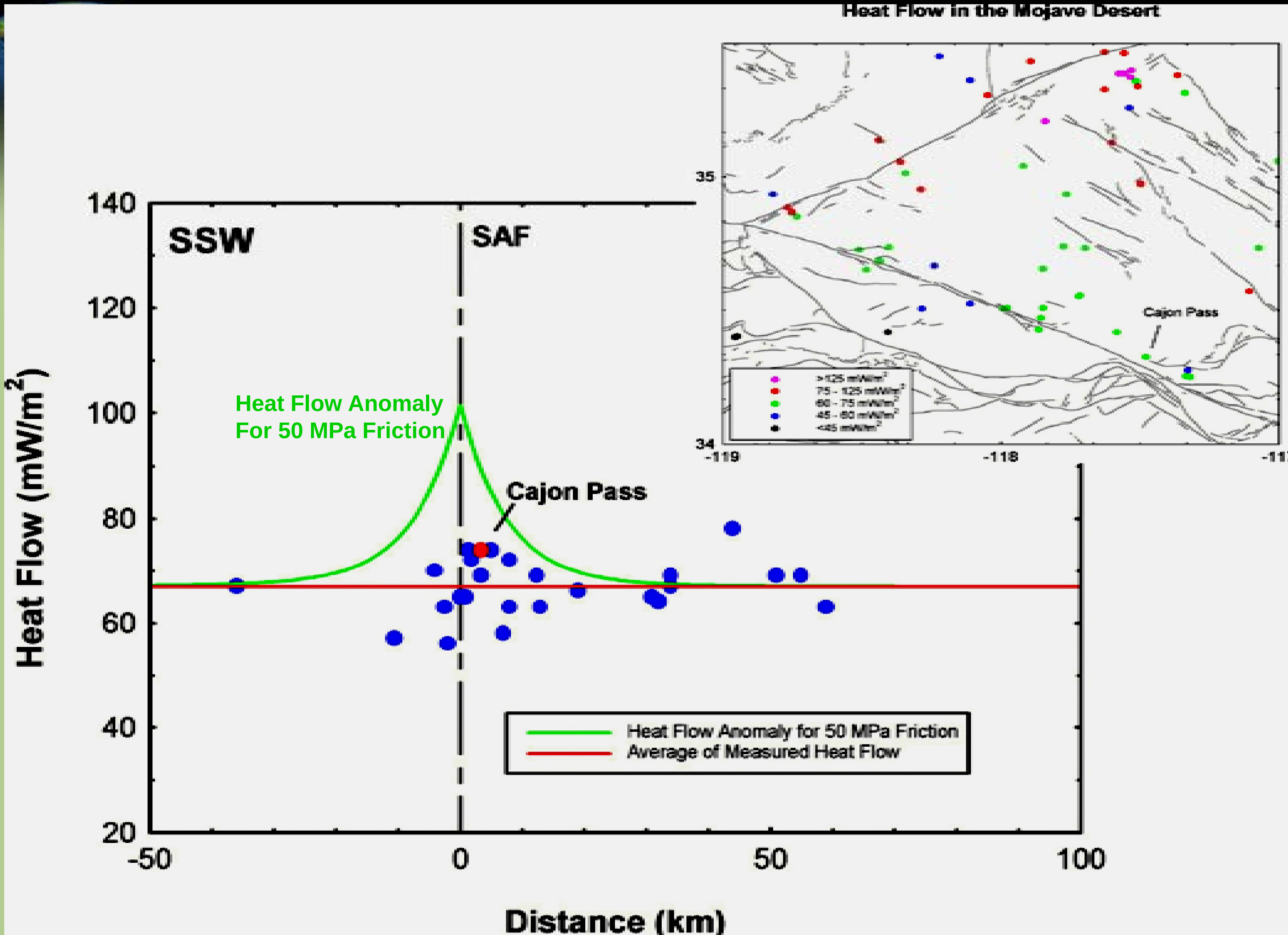


Townend and Zoback (2001)

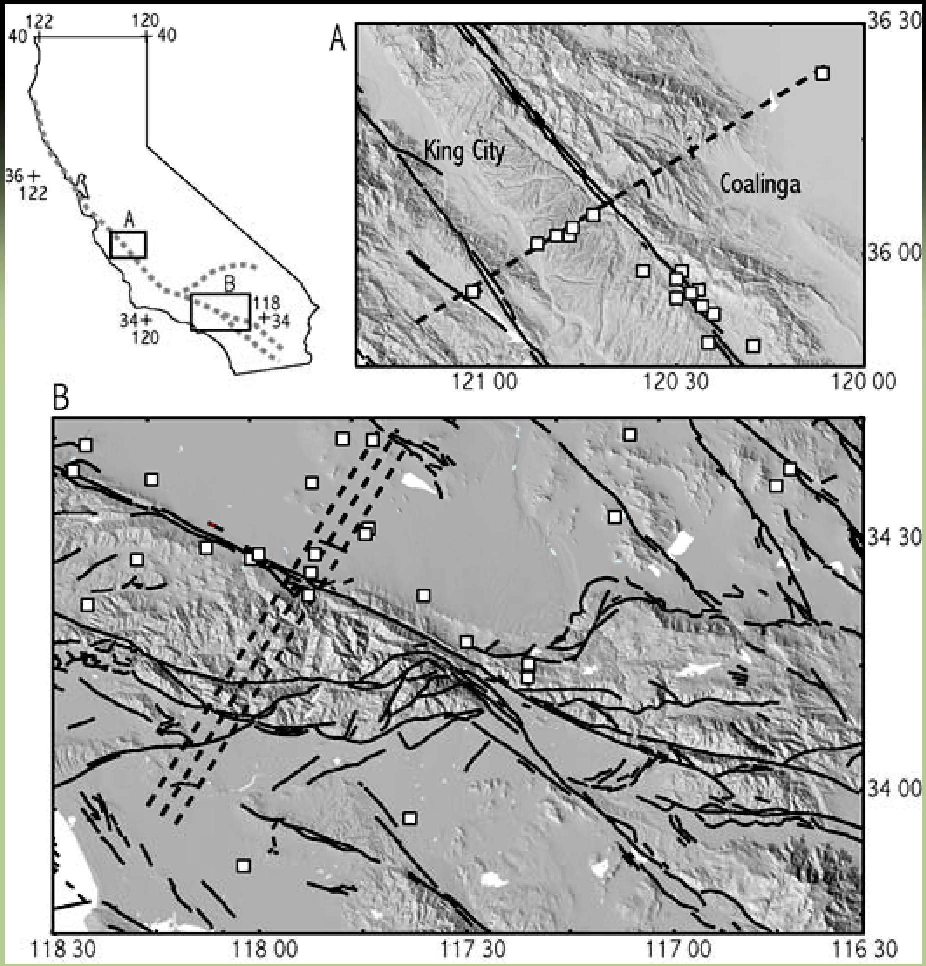
How Faulting Keeps the Crust Strong

Why are major plate-boundary faults like the San Andreas weak?

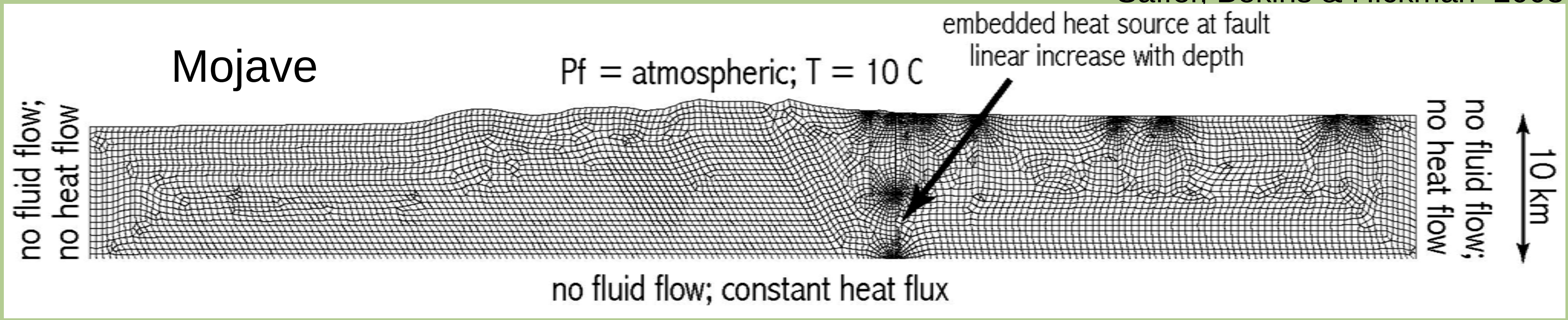




Lachenbruch & Sass, 1980, 1992

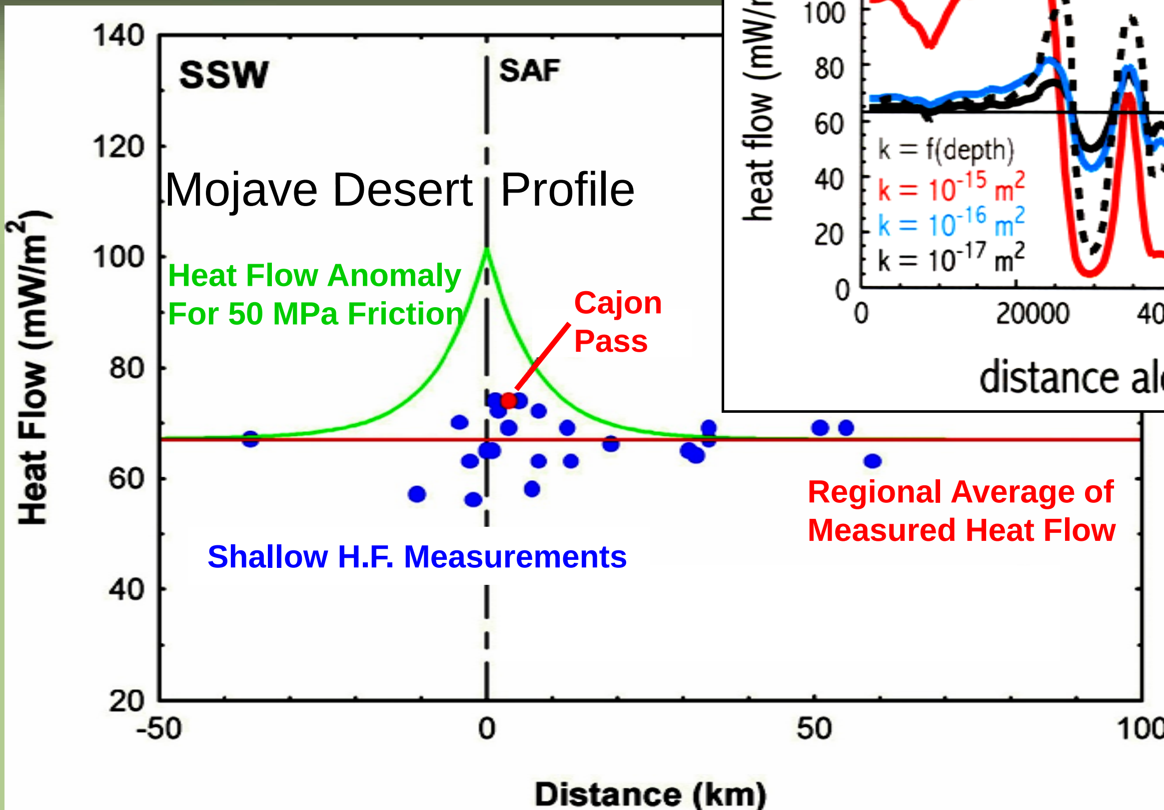


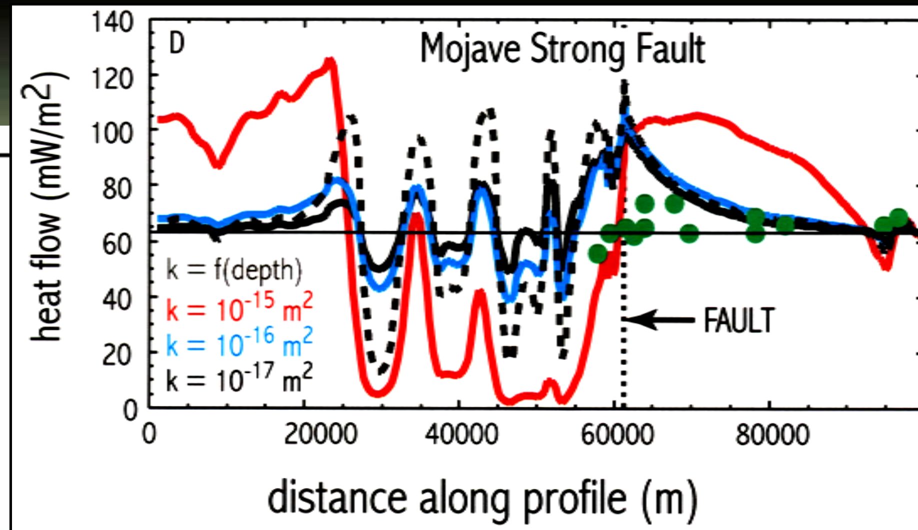
Saffer, Bekins & Hickman 2003



The San Andreas Stress/Heat Flow Paradox

Lachenbruch & Sass 1980, 1992



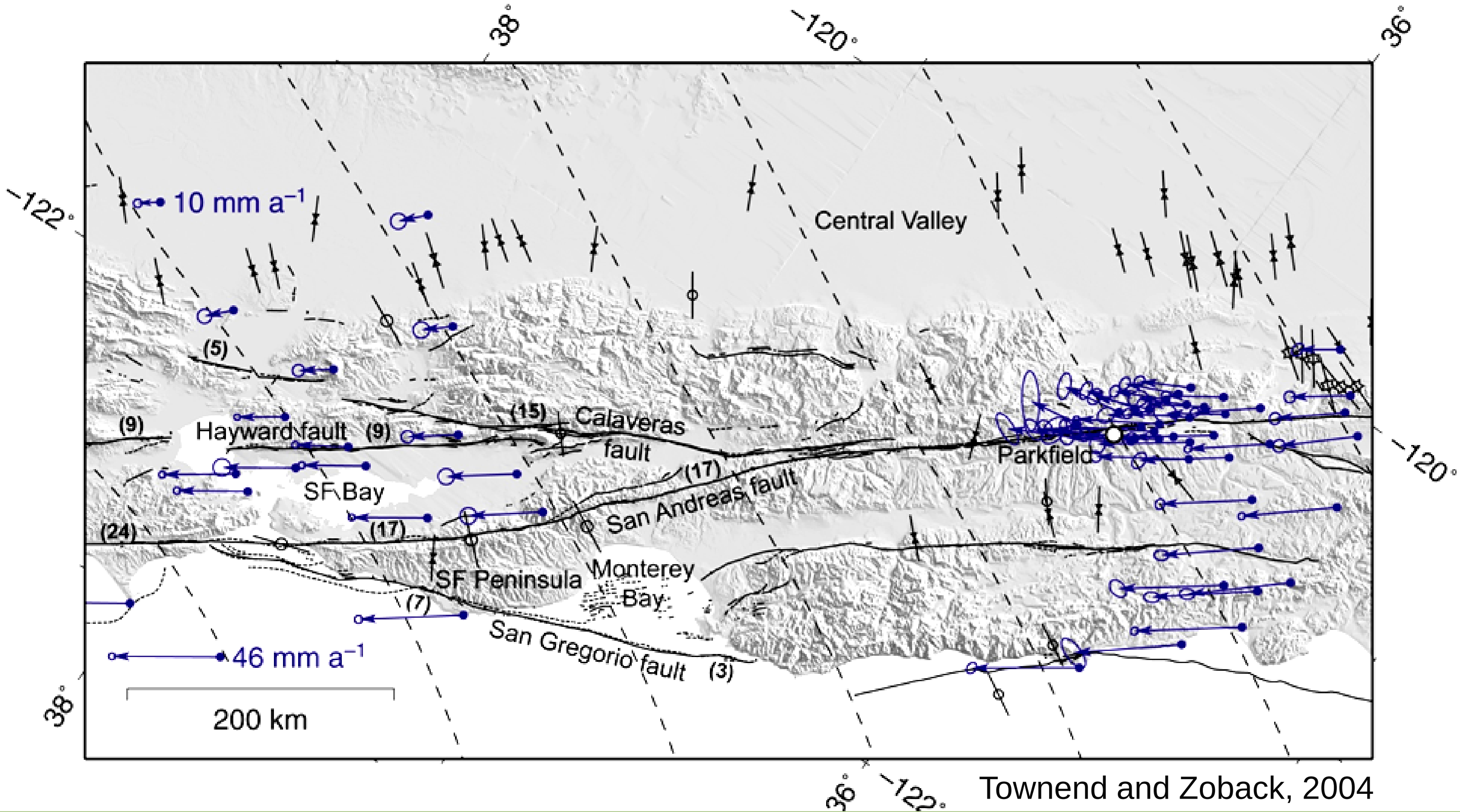


Saffer, Bekins and Hickman 2003

Modeling shows groundwater flow cannot erase thermal signature of strong SAF, even for wide range of assumed permeabilities.

In fact, high permeability (red line) would actually ***accentuate*** near-surface heat flow NE of fault, contrary to what is observed.

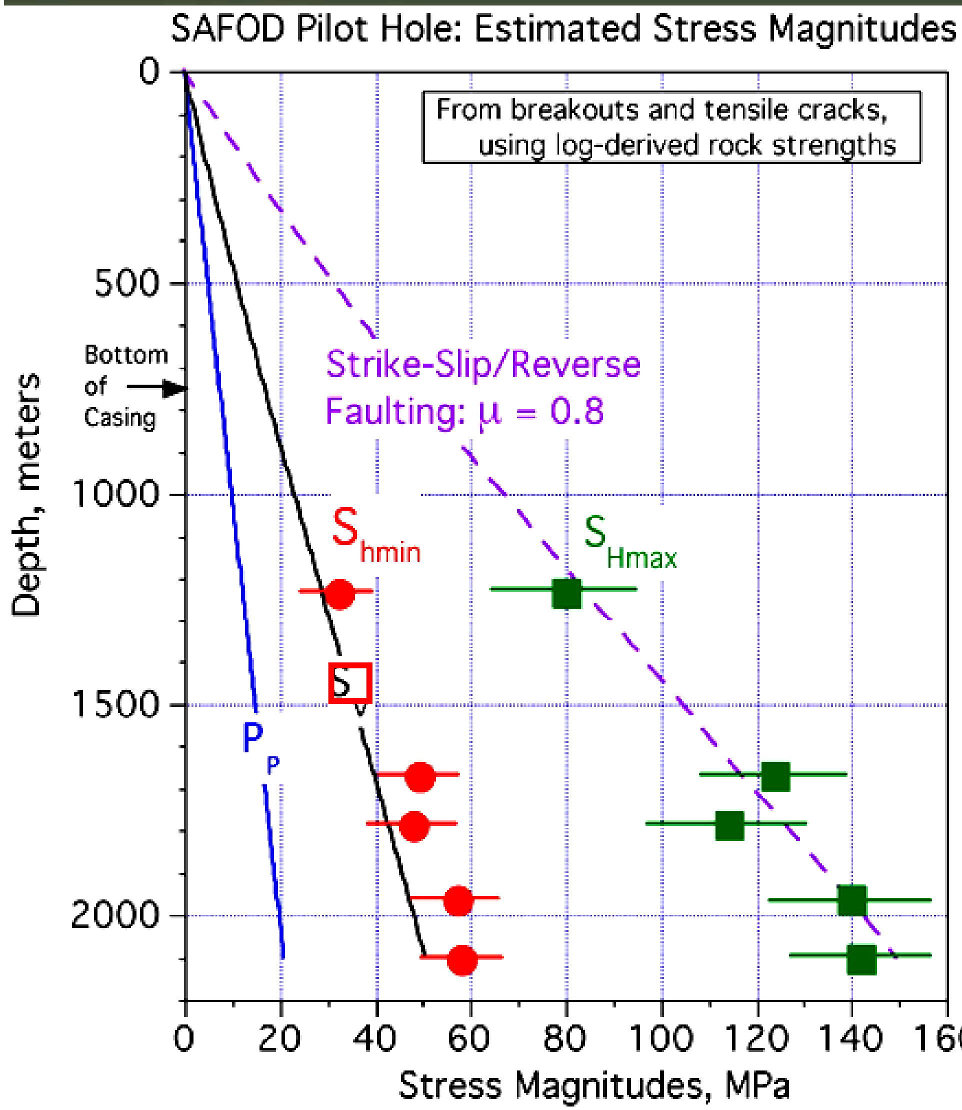
Is There Fault Normal Compression Near the Fault as Well as in the Coast Ranges?

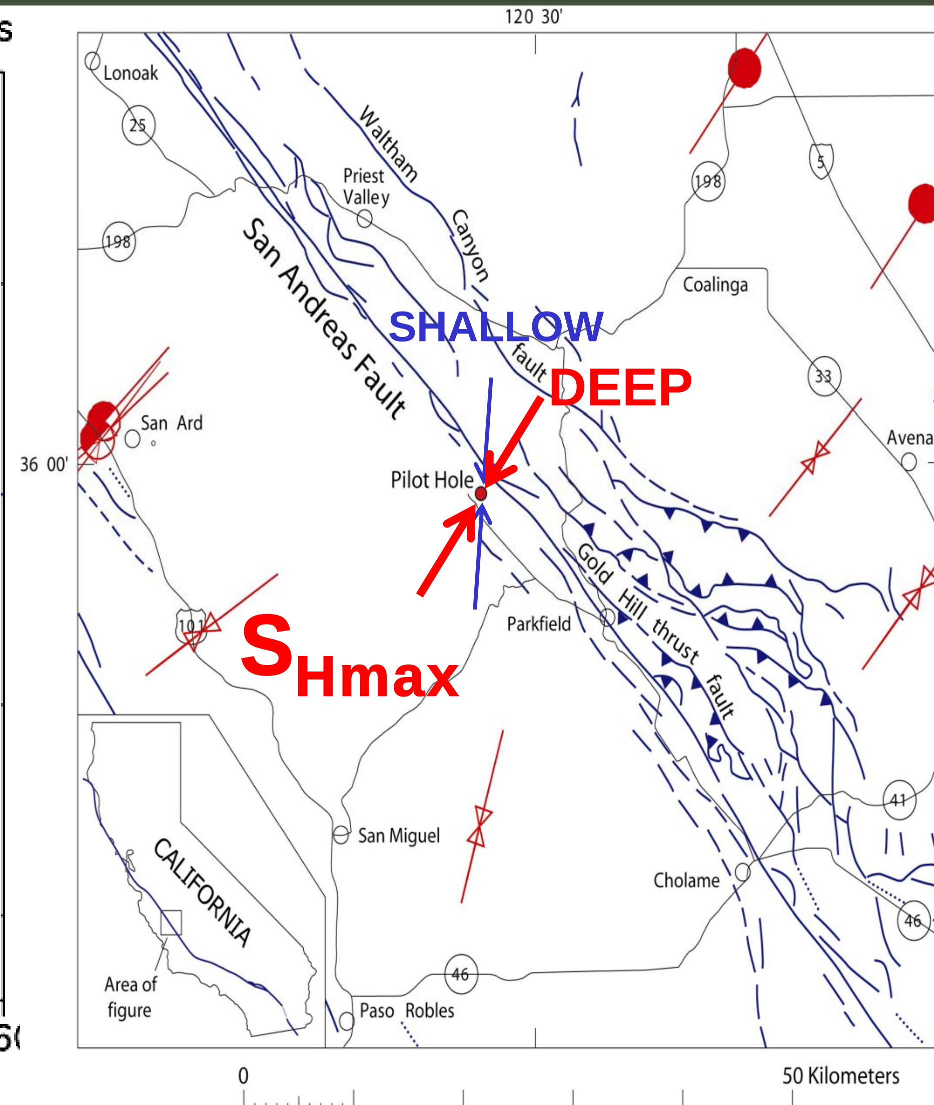


Townend and Zoback, 2004

High Stress Magnitudes

Stress Orientation Consistent With Strong Crust/Weak Fault



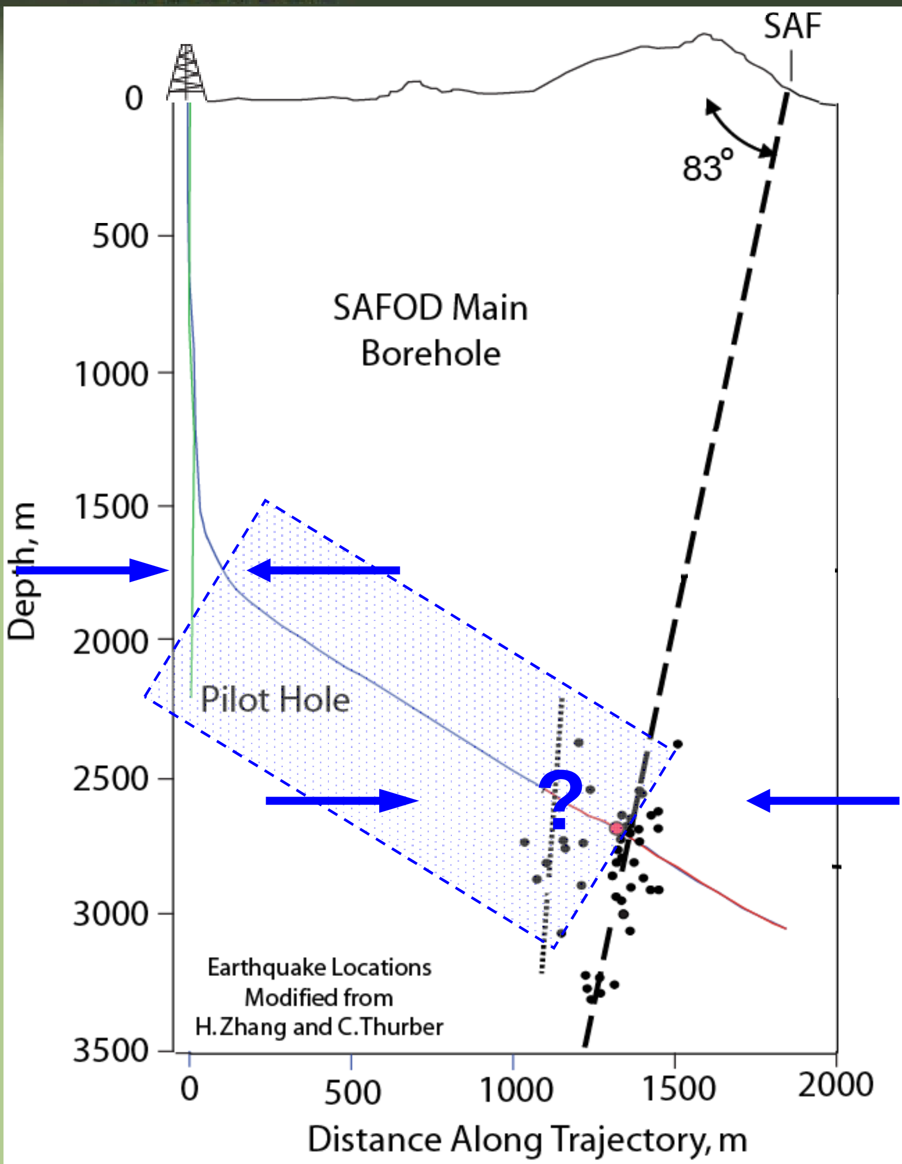


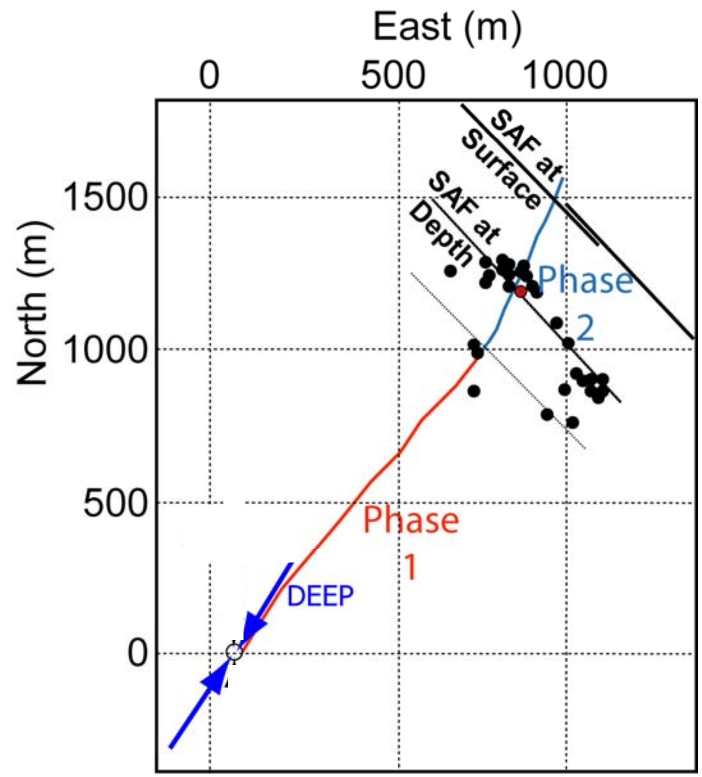
Hickman and Zoback (2004)

Boness and Zoback (2004)

Weak Fault/Strong Crust model confirmed by SAFOD pilot hole

Maximum Principal Stress at High Angle to the San Andreas Fault

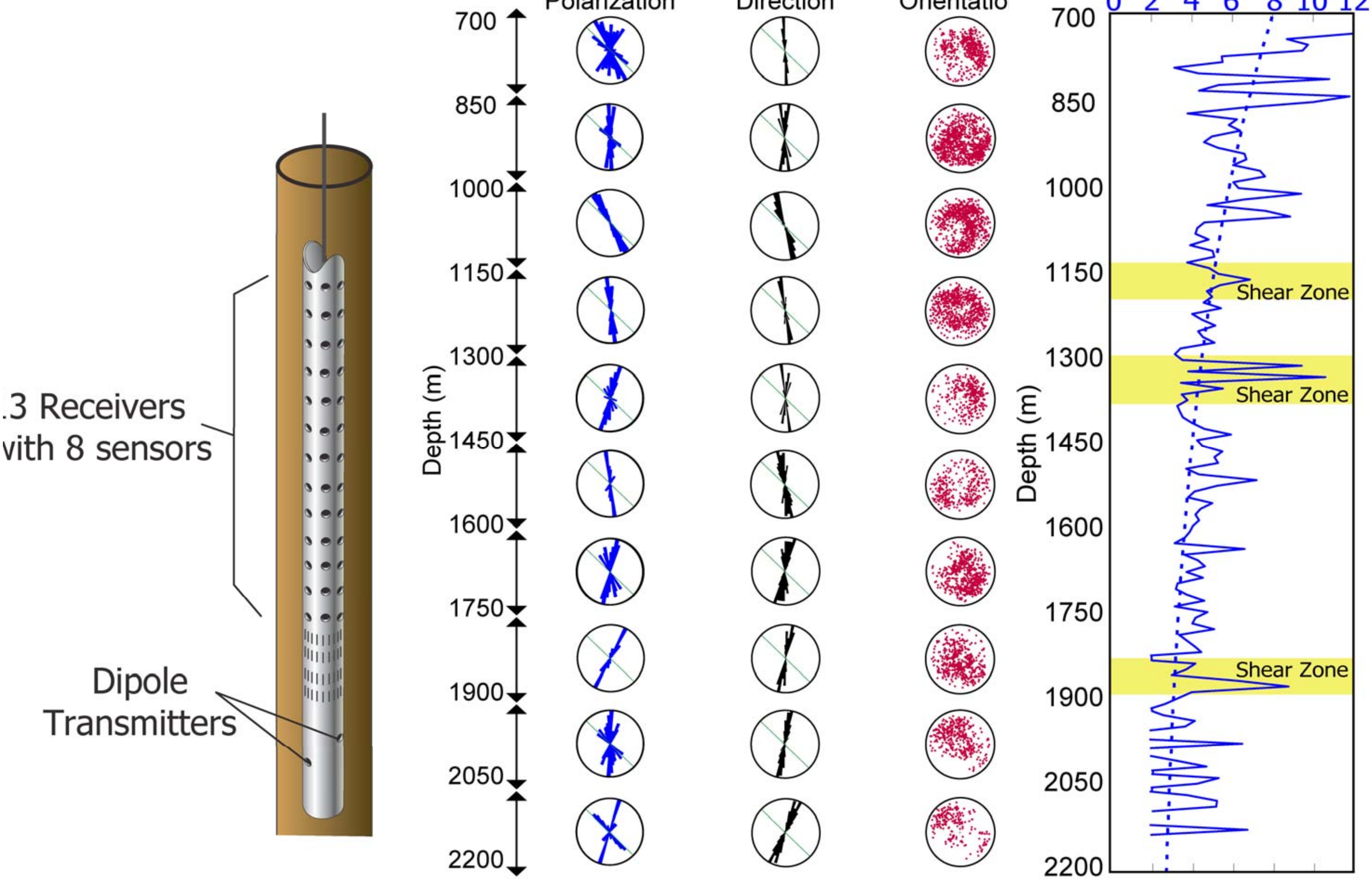




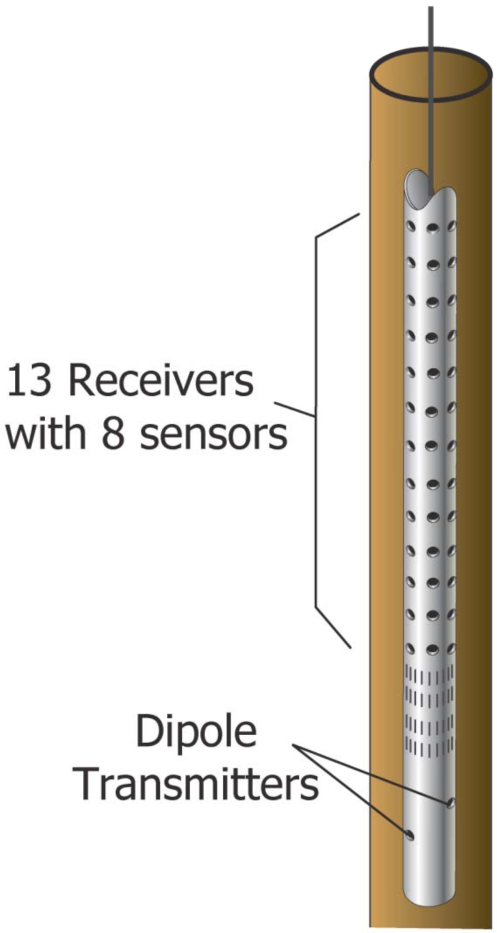
But what will happens to the maximum stress direction as we enter the fault zone?

SAFOD Shear Velocity and Stress in Pilot Hole

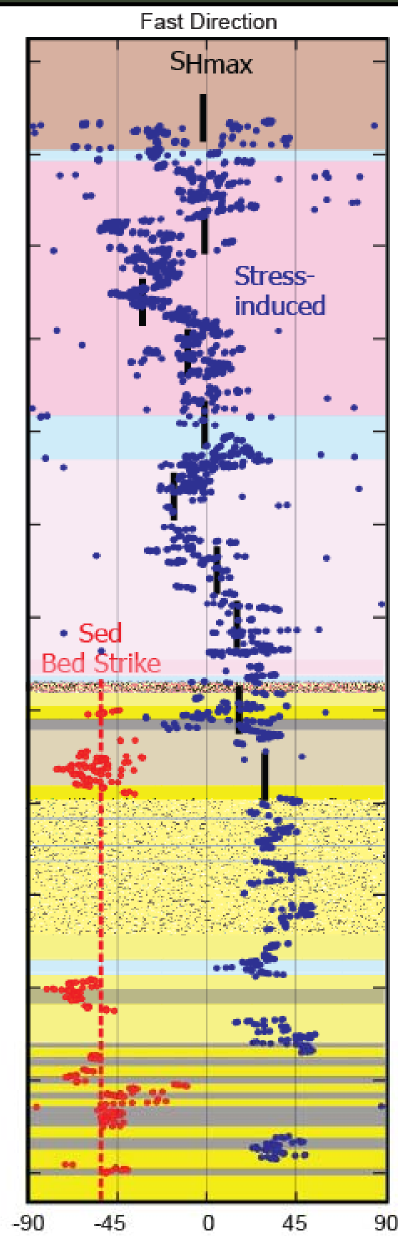
(Boness & Zoback, GRL, 2004)



Direction of Maximum Horizontal Stress

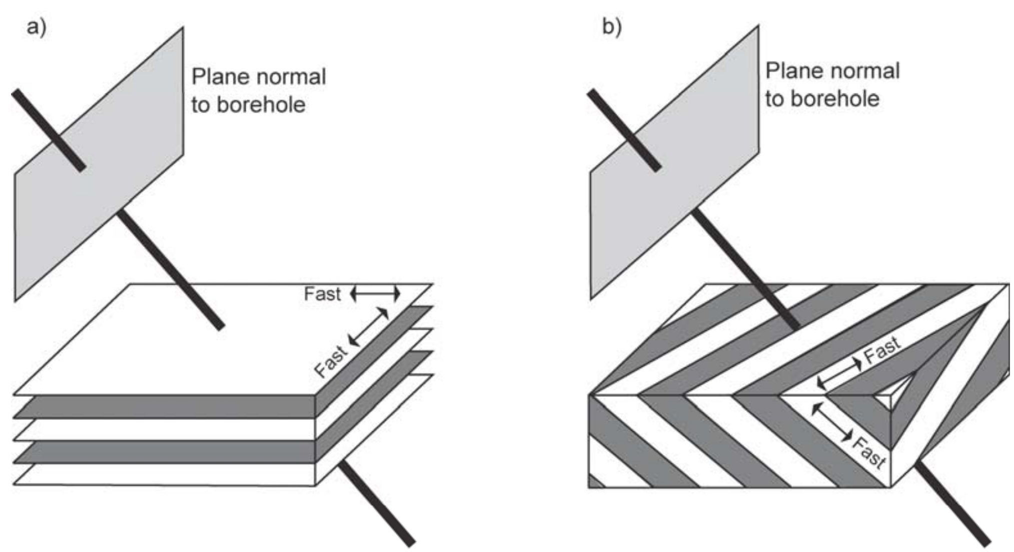


Dipole Sonic Shear Logs

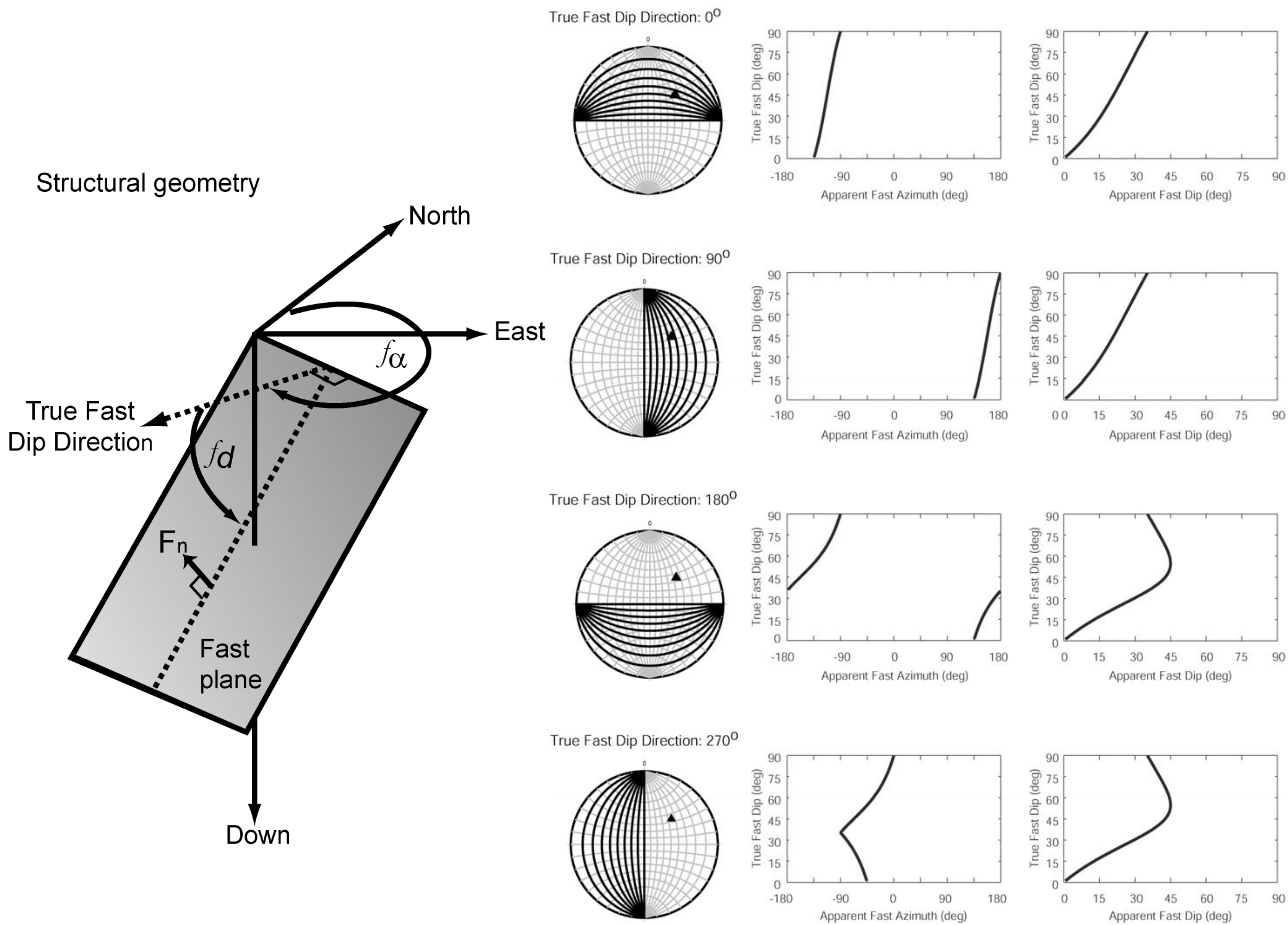


Using Shear Velocity Anisotropy to Determine Stress Direction

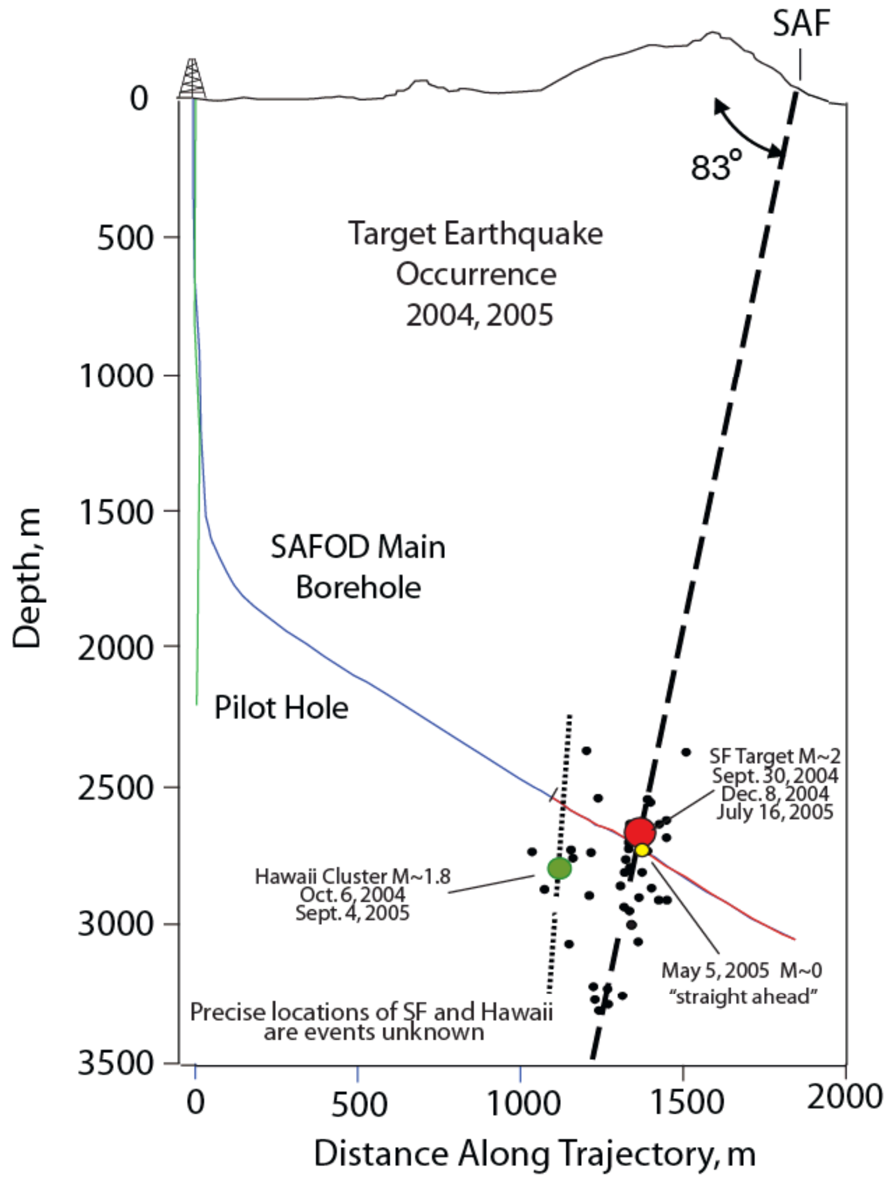
Must Correcting for the Effects of Bedding on Cross-Dipole Data

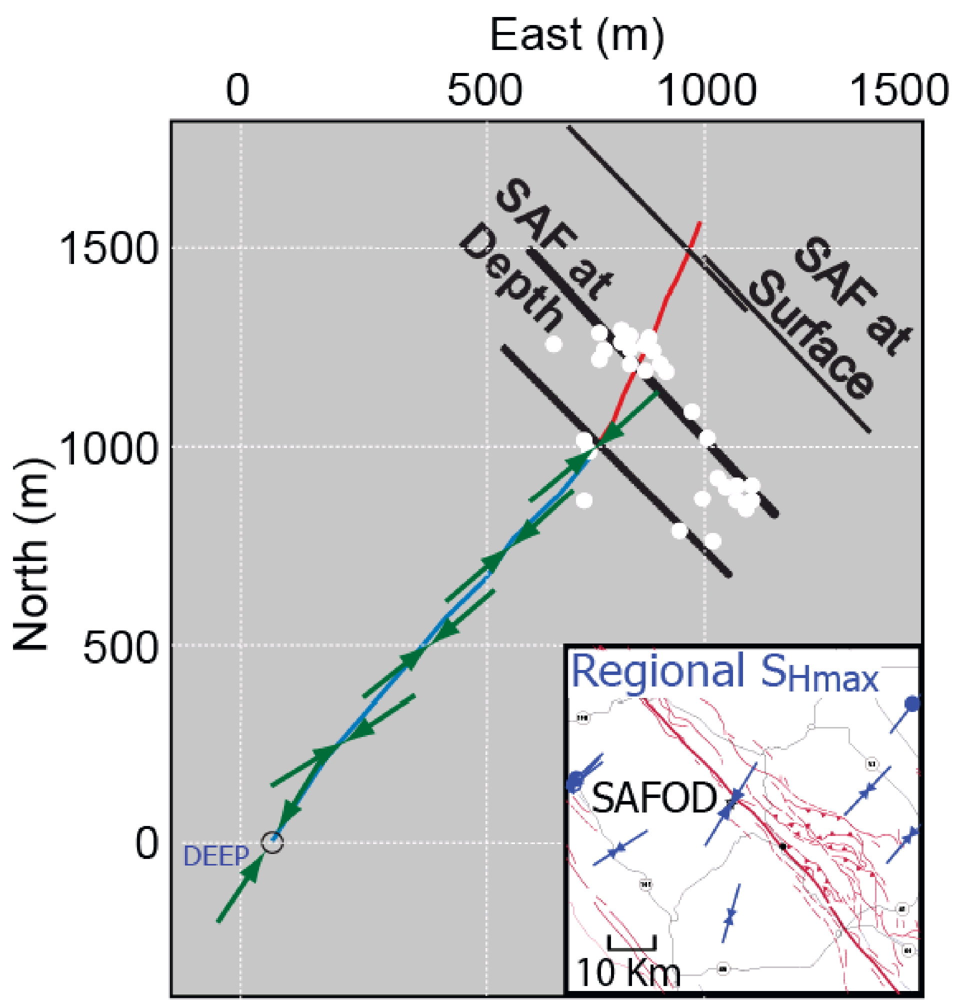


Boness and Zoback (Geophysics, 2006)

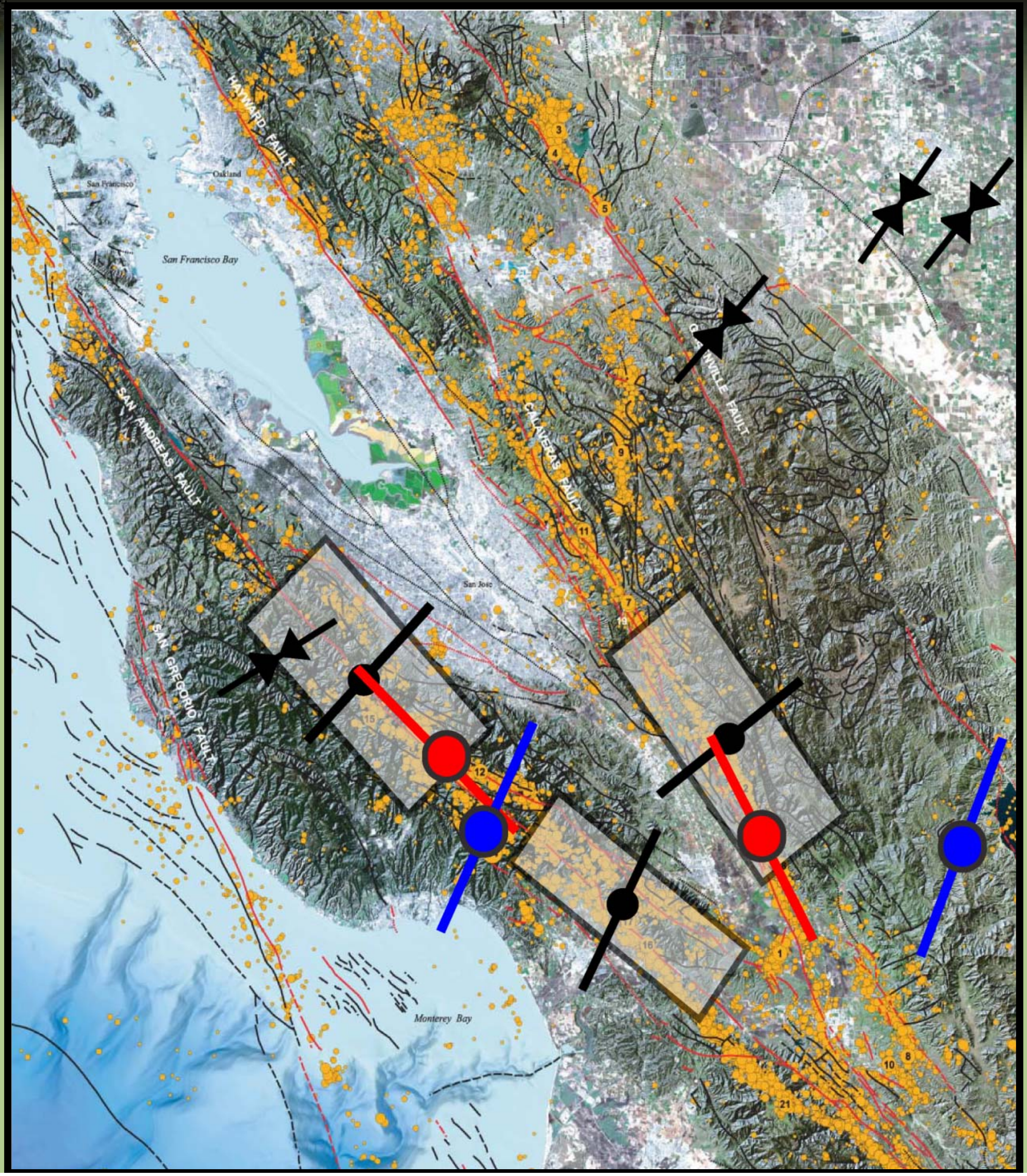

Structural geometry
North
East
True Fast
Dip Direction
fα
fd
Fn
Fast
plane
Down
True Fast Dip Direction: 0°
True Fast Dip Direction: 90°
True Fast Dip Direction: 180°
True Fast Dip Direction: 270°
True Fast Dip (deg)
Apparent Fast Azimuth (deg)
Apparent Fast Dip (deg)

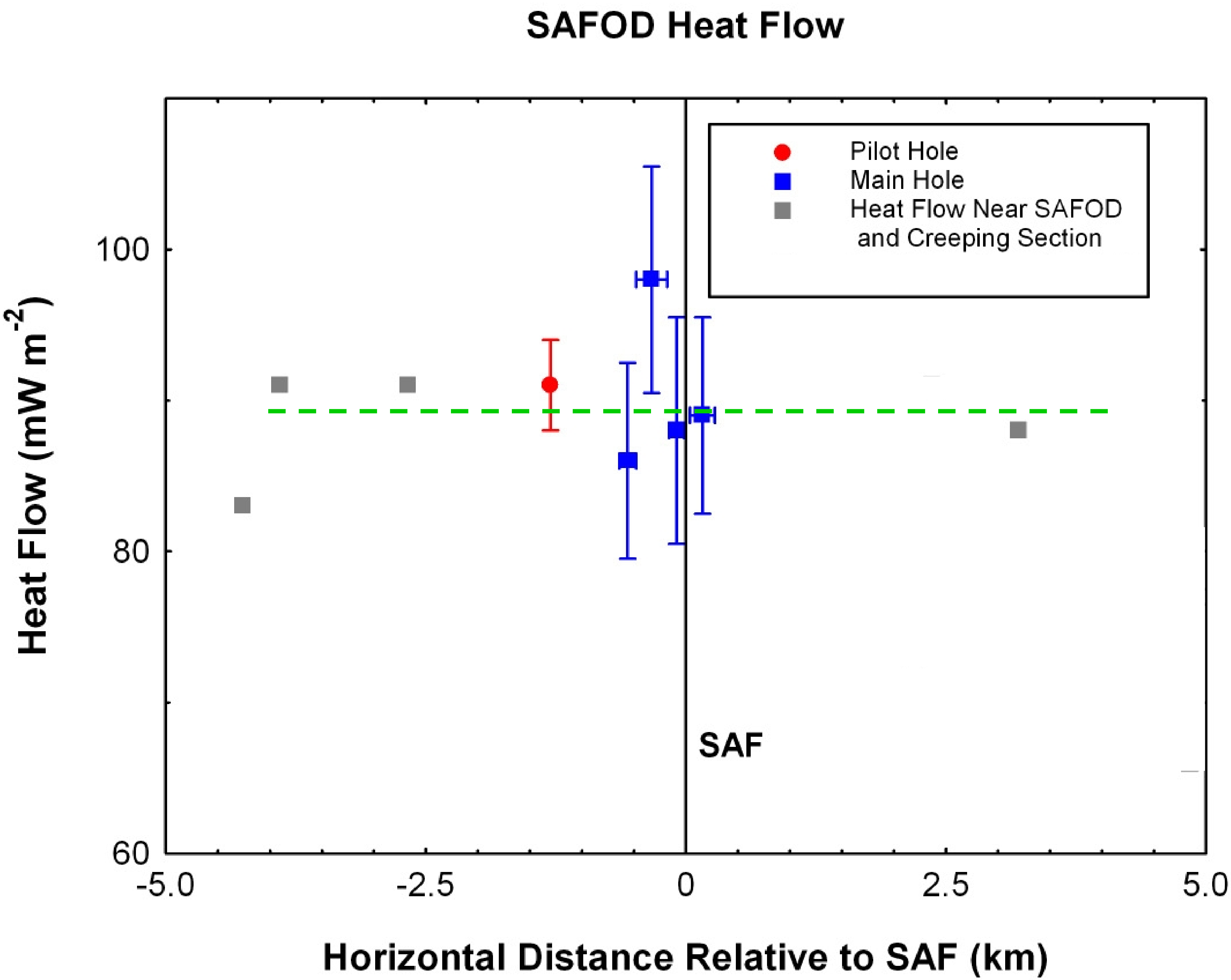
Direction of Maximum Horizontal Stress



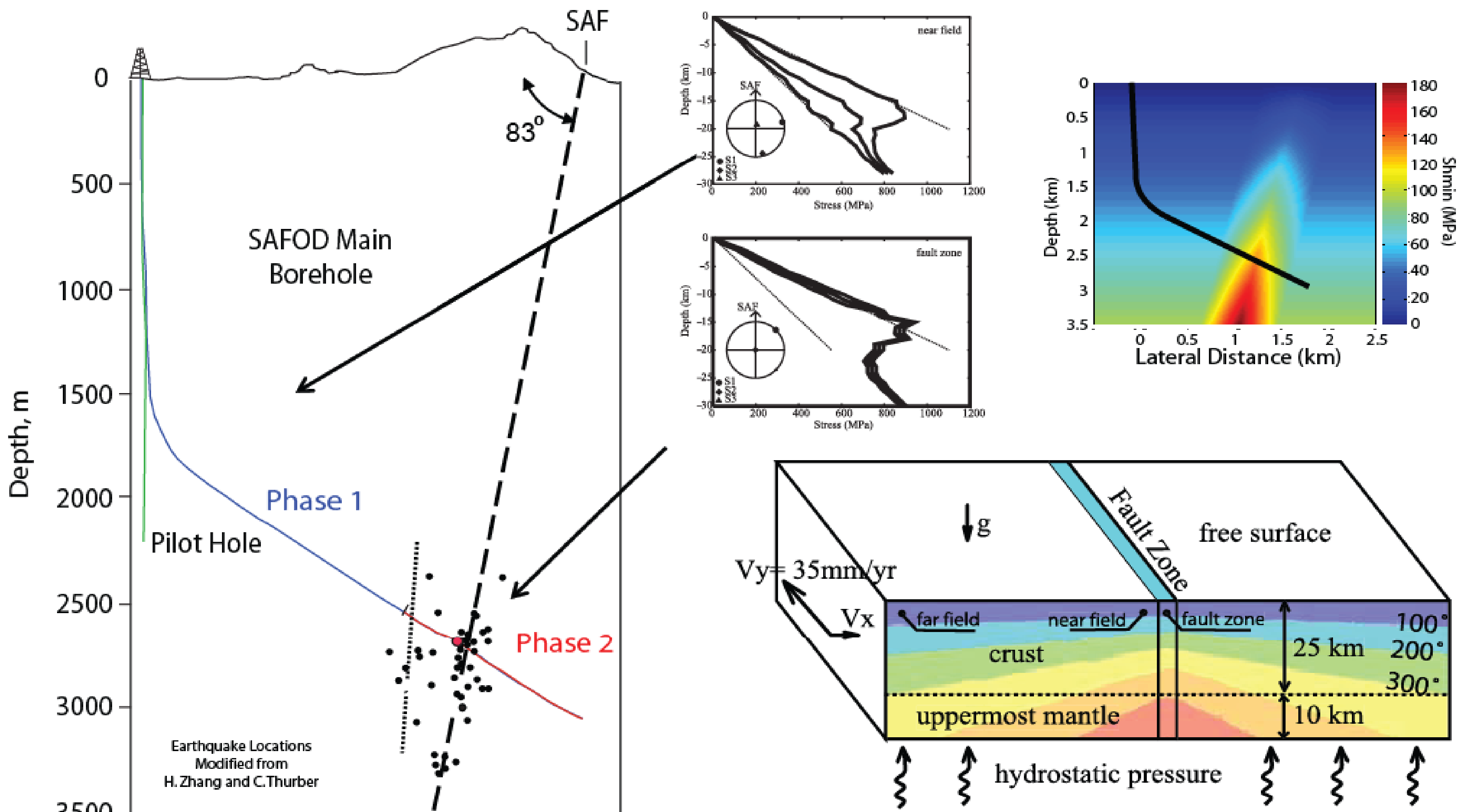


Bay Area Stress Mapping




SAFOD Heat Flow
Pilot Hole
Main Hole
Heat Flow Near SAFOD
and Creeping Section
100
80
60
Heat Flow (mW m-2)
SAF
-5.0
-2.5
0
2.5
5.0
Horizontal Distance Relative to SAF (km)

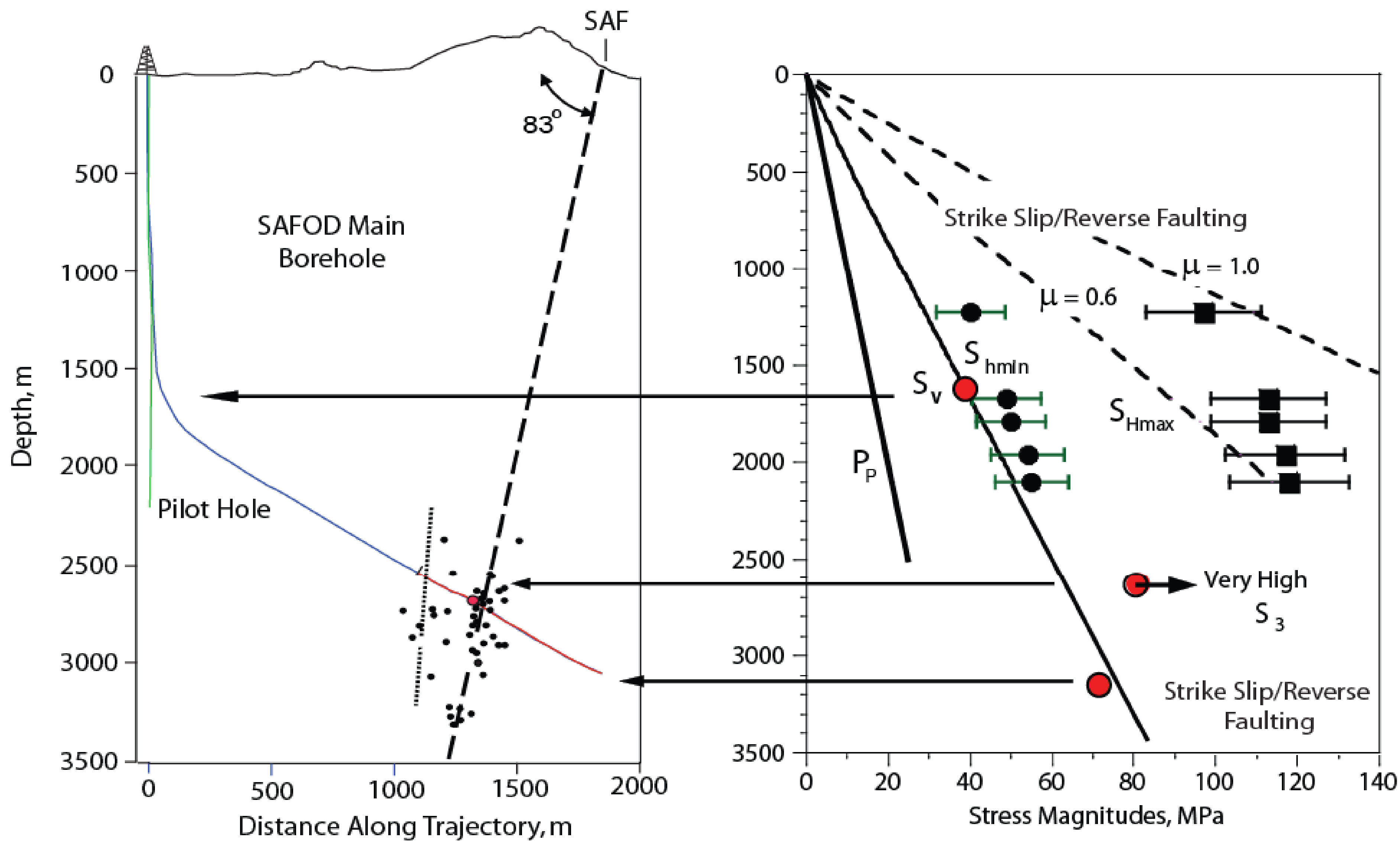
Weak Ductile Fault Zone Model
(also predicts high stress within fault zone)



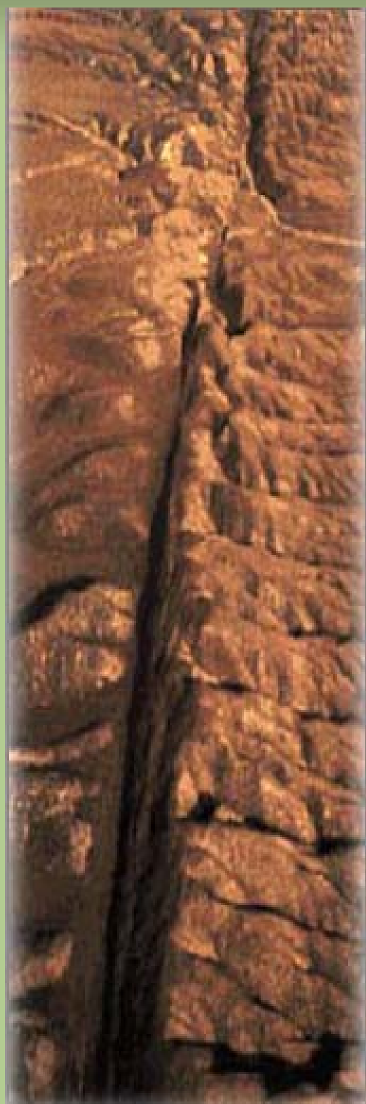
Weak Fault in a Strong Crust

Chery , Zoback and Hickman (2004)

Increase in Least Principal Stress Observed in the San Andreas Fault Zone



San Andreas Fault Observatory at Depth: Project Overview and Science Goals



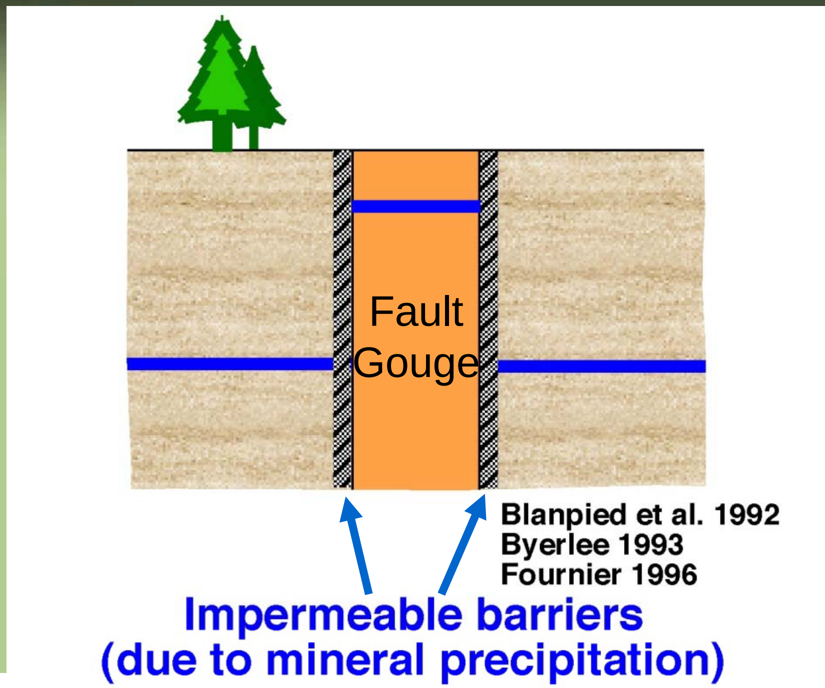
Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

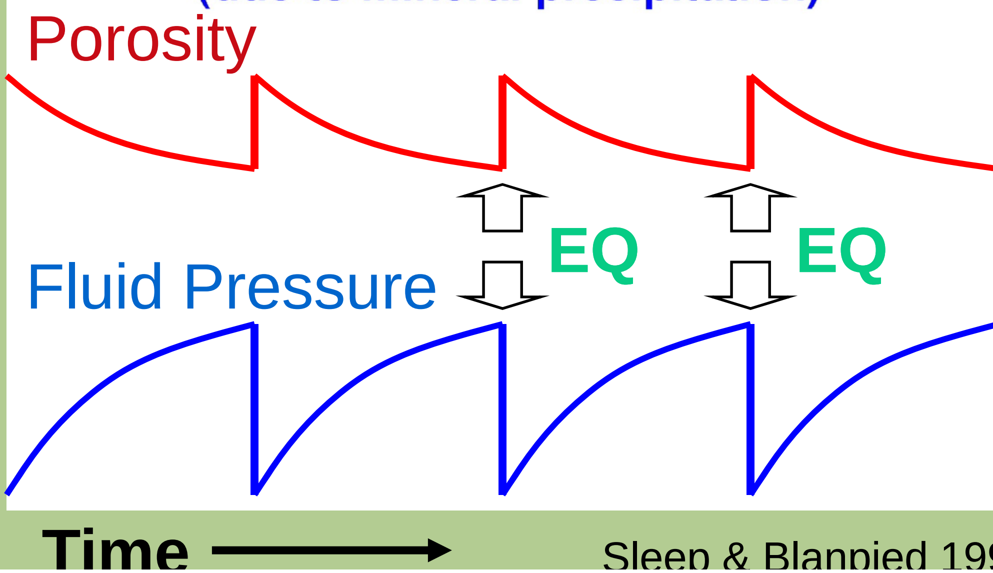
Does fluid pressure vary during the earthquake cycle?



Fault Sealing Models Motivated by:

Geologic studies of exhumed faults:

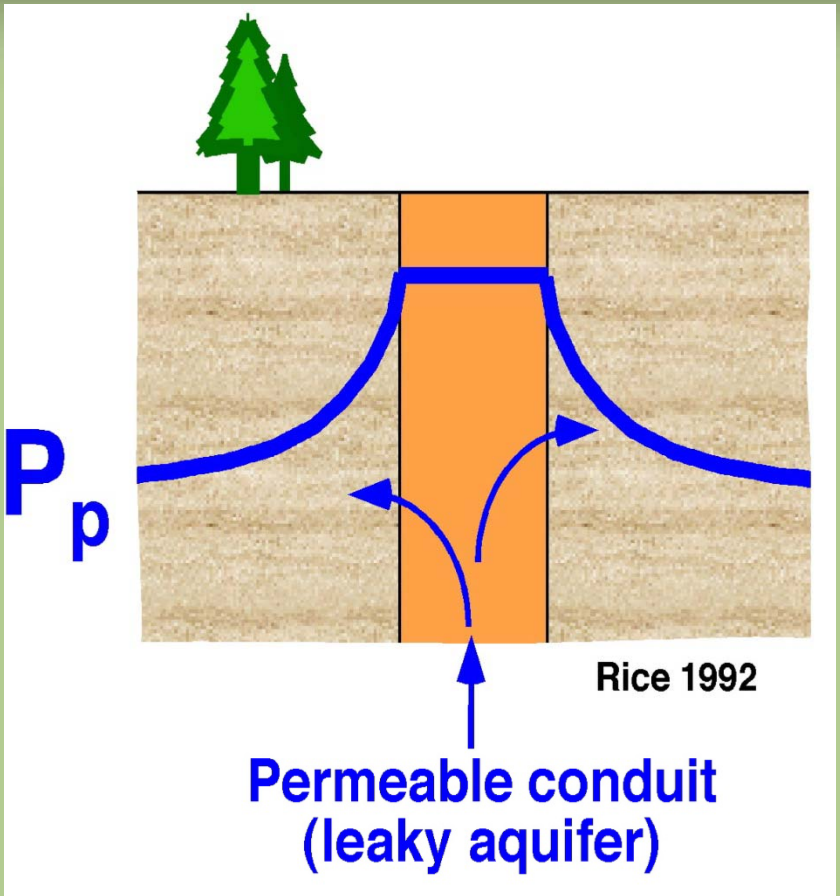
- Repeating cycles of mineral precipitation (crack sealing) and refracturing, even at depths as shallow as 2 - 3 km

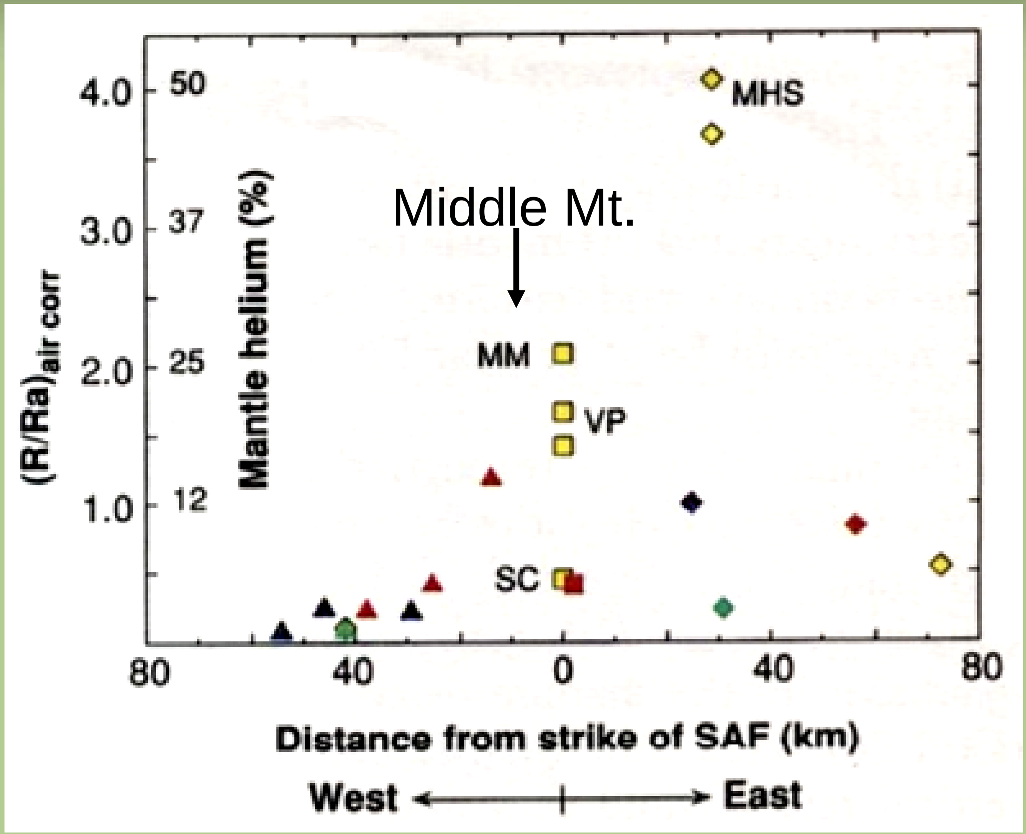


Sleep & Blanpied 1992, 1995

Viscous compaction of fault gouge after earthquakes could lead to fluid pressure fluctuations that are intimately related to the earthquake cycle.

What is the pore pressure in the fault zone and the origin and composition of fault zone fluids?



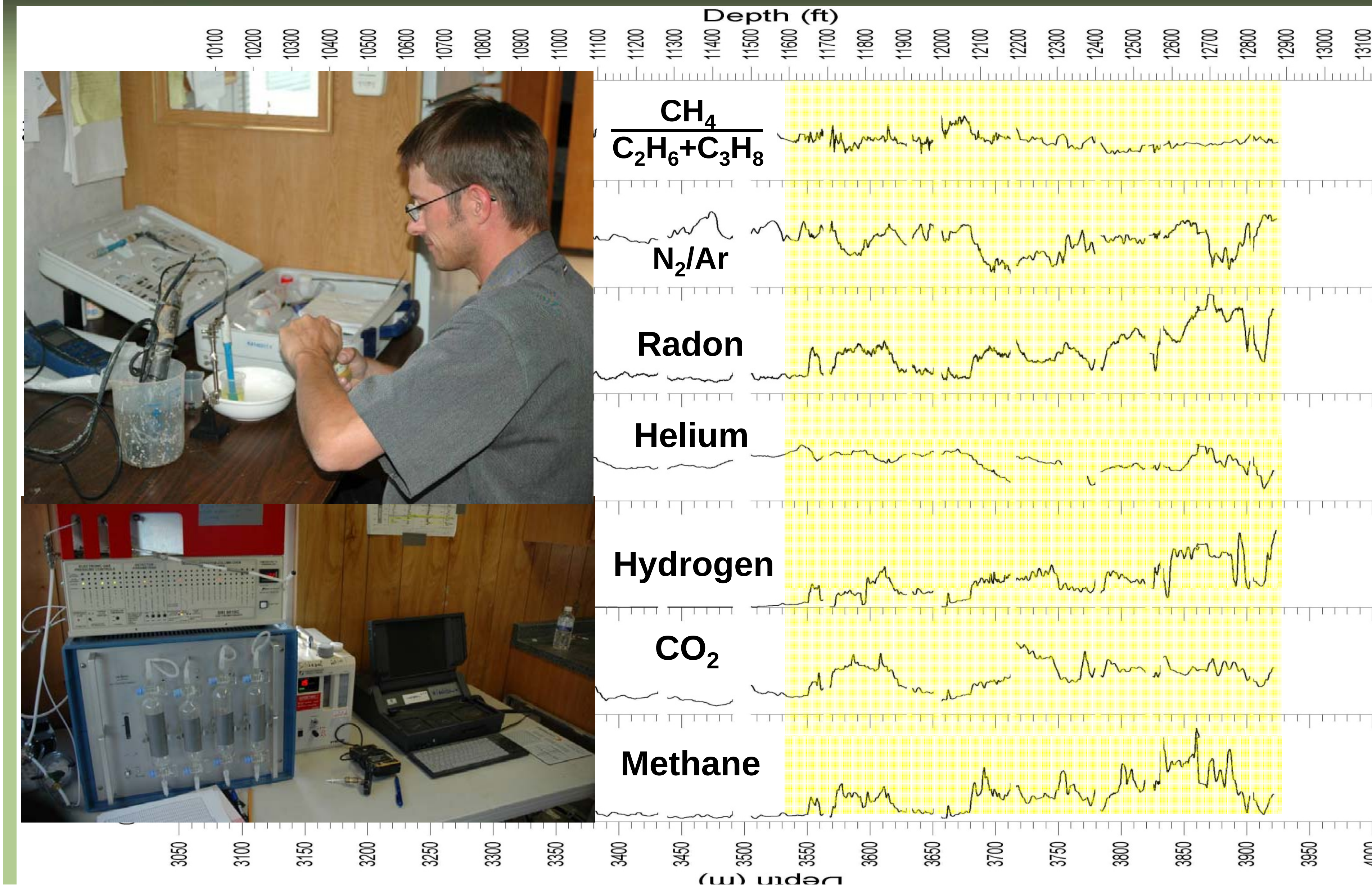


Kennedy et al. 1997

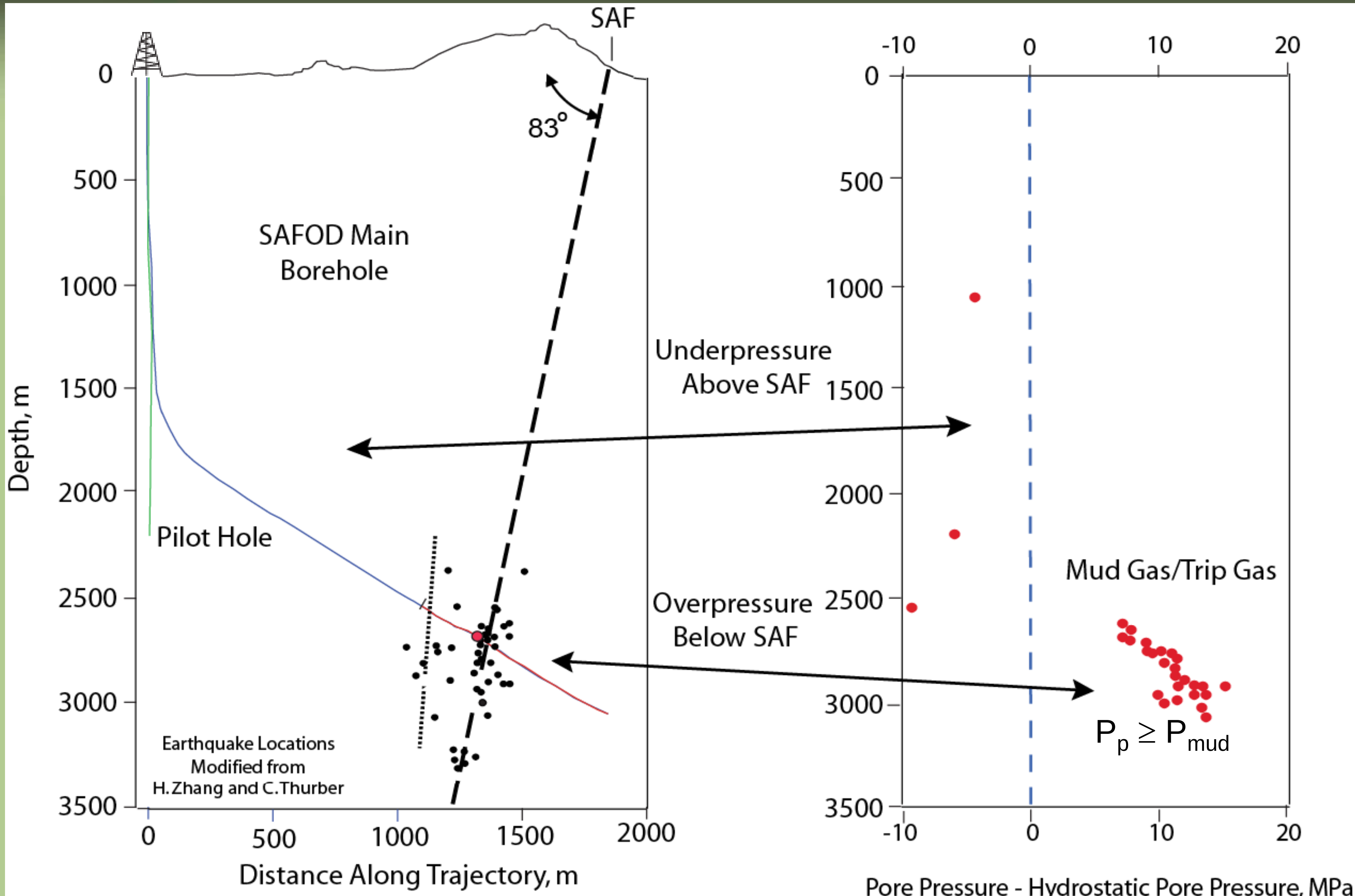
Permeable conduit model requires continual fluid input from deep crustal fault zone "root".

There is some support for this "leaky" fault zone model from geochemical observations along the San Andreas Fault.

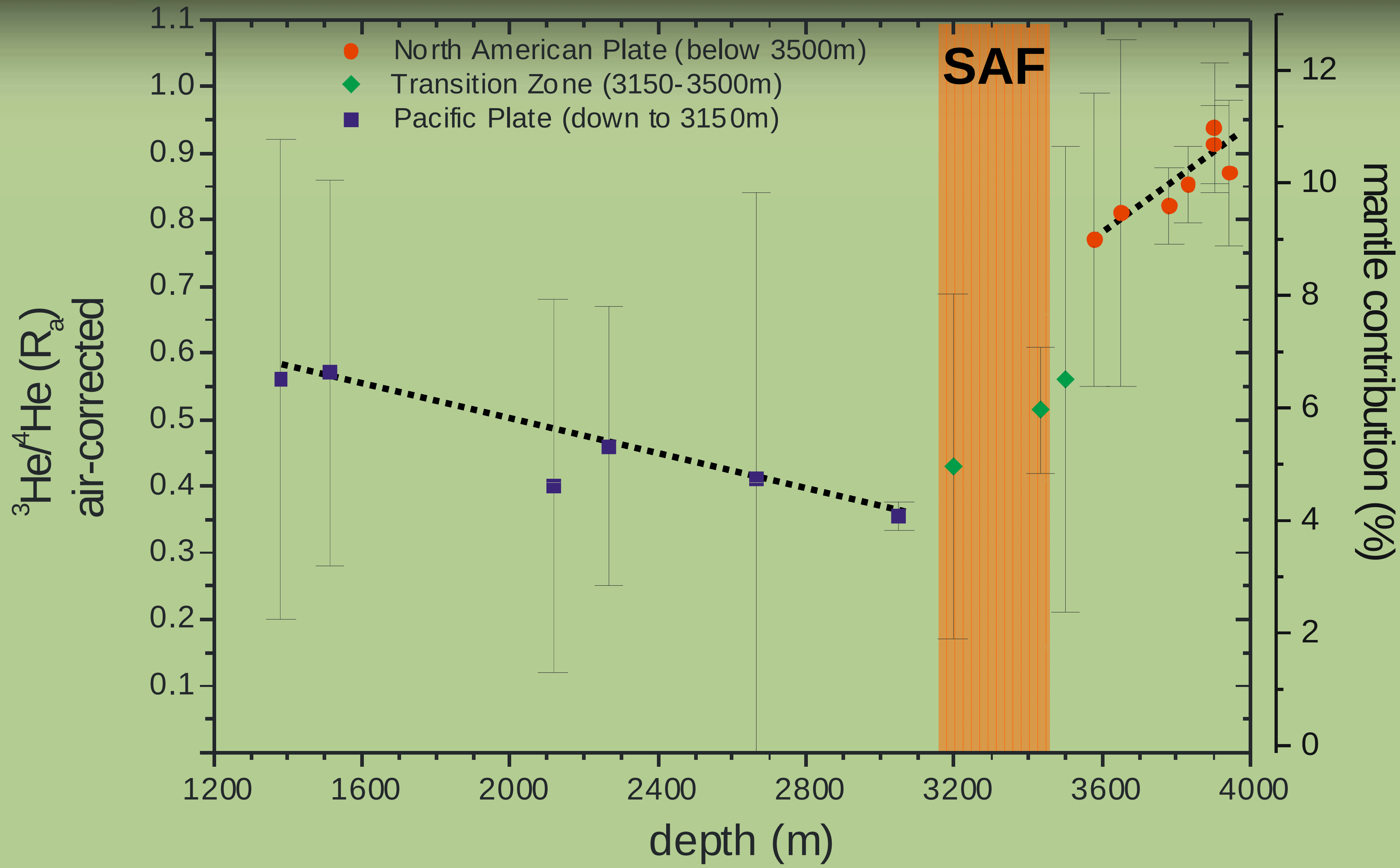
Gases in Drilling Mud



No Evidence of High Pore Pressure

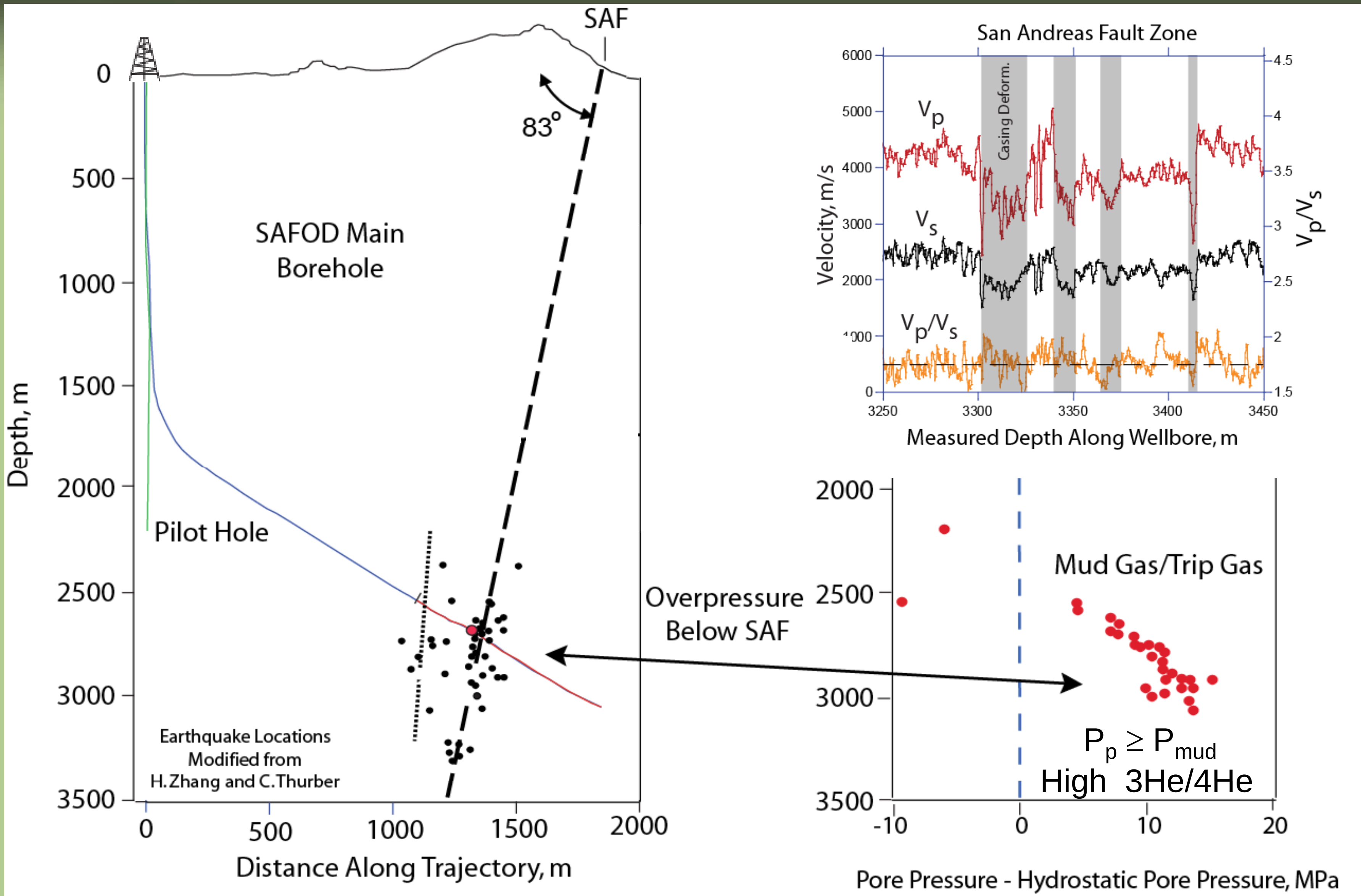


Mantle-Derived Fluids on East Side of Fault



Wiersberg and Erzinger (in press)

No V_p/V_s Anomalies Associated with Fault Zones (No Localized Pore Pressure?)



Science Highlights

- Observatory and Fault Zone Monitoring is Operational - Detection of Non-Volcanic Tremor
- San Andreas Fault is a Broad Zone with Distinct Composition and Anomalous Physical Properties
- Evidence for Multiple Active Traces at Depth
- Pore Pressure – The San Andreas is a Barrier to Fluid Flow (mantle helium on NE side of fault) But it Does Not Appear to be Overpressured
- The San Andreas is a Weak Fault in a Strong Crust

Science Highlights

- Observatory and Fault Zone Monitoring is Operational - Detection of Non-Volcanic Tremor
- San Andreas Fault is a Broad Zone with Distinct Composition and Anomalous Physical Properties
- Evidence for Multiple Active Traces at Depth.
- Pore Pressure – The San Andreas is a Barrier to Fluid Flow (mantle helium on NE side of fault) But it Does Not Appear to be Overpressured
- The San Andreas is a Weak Fault in a Strong Crust – But Why?

MECHANICAL IMPLICATIONS OF A WEAK SAN ANDREAS:

Heat-flow constraint and fault-normal compression (S_{Hmax} at 75°or more to SAF) require either:

1) Low friction ($\mu \leq 0.1$) along the fault and high friction elsewhere

or

2) Super-lithostatic pore pressure confined to the fault zone

and/or

3) Dynamic weakening mechanisms

MECHANICAL IMPLICATIONS OF A WEAK SAN ANDREAS:

Heat-flow constraint and fault-normal compression (S_{Hmax} at 75°or more to SAF) require either:

1) Low friction ($\mu \leq 0.1$) along the fault and high friction elsewhere

or

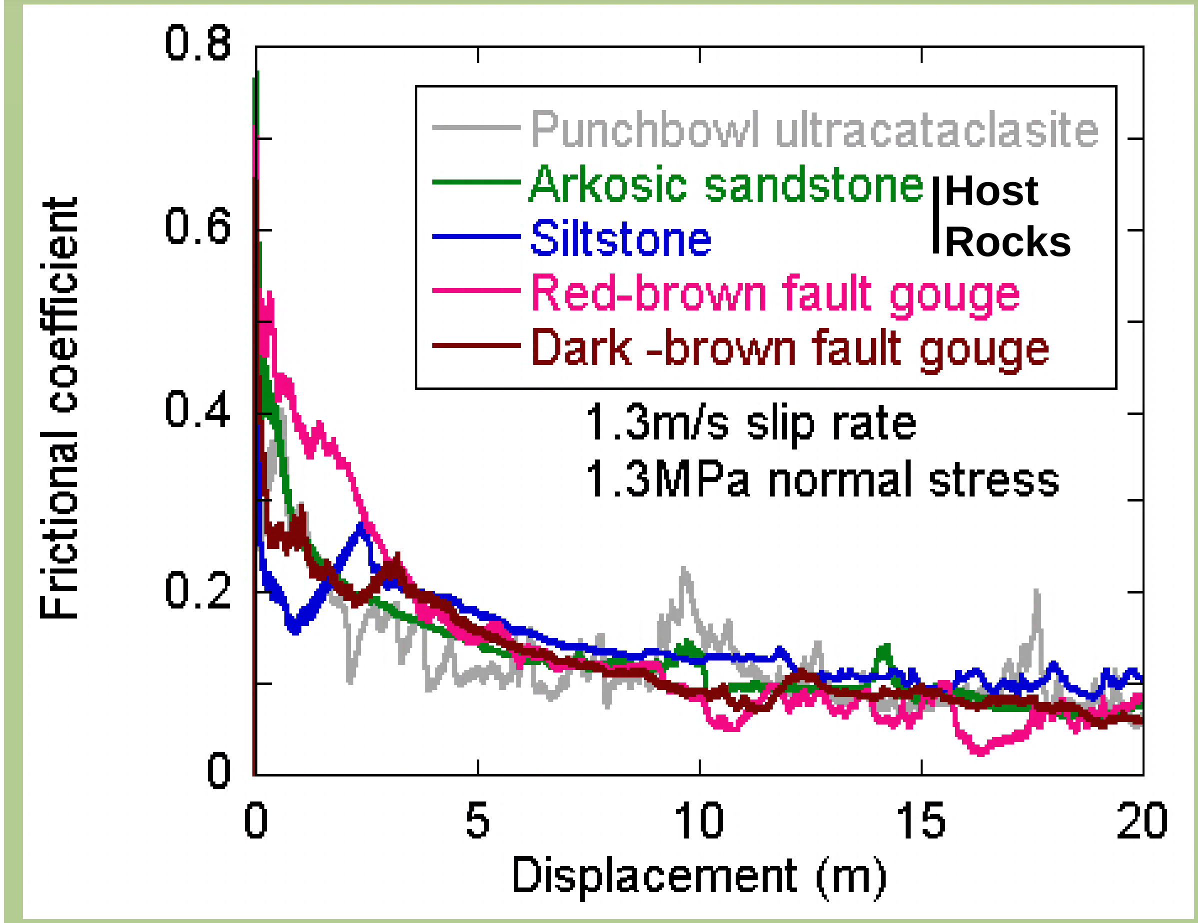
2) ~~Super-lithostatic pore pressure confined to the fault zone~~

and/or

3) Dynamic weakening mechanisms

High-Speed Friction of Fault-Rocks from SAFOD

(*H. Kitajima, J.Chester, T. Shimamoto, F.M. Chester - Texas A&M University and Kyoto University*)



Fault-rock samples from the shear zone at 3067 m, deformed wet.

Dramatic reduction of friction at coseismic slip rates.

Initial friction and critical slip distance varies with rock type

Behavior similar to Punchbowl ultracataclasite.

May be due to cataclasis and shear localization, with flash heating at asperity contacts and/or thermal pore fluid pressurization with increasing displacement.

TEM and optical examination of materials before and after shearing underway.

San Andreas Fault Observatory at Depth: Project Overview and Science Goals

Test fundamental theories of earthquake mechanics:

- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

Establish a long-term observatory in the fault zone:

- Characterize 3-D volume of crust containing the fault.
- Monitor strain, pore pressure and temperature during the cycle of repeating microearthquakes.
- Observe earthquake nucleation and rupture processes in the near field. Are earthquakes predictable?

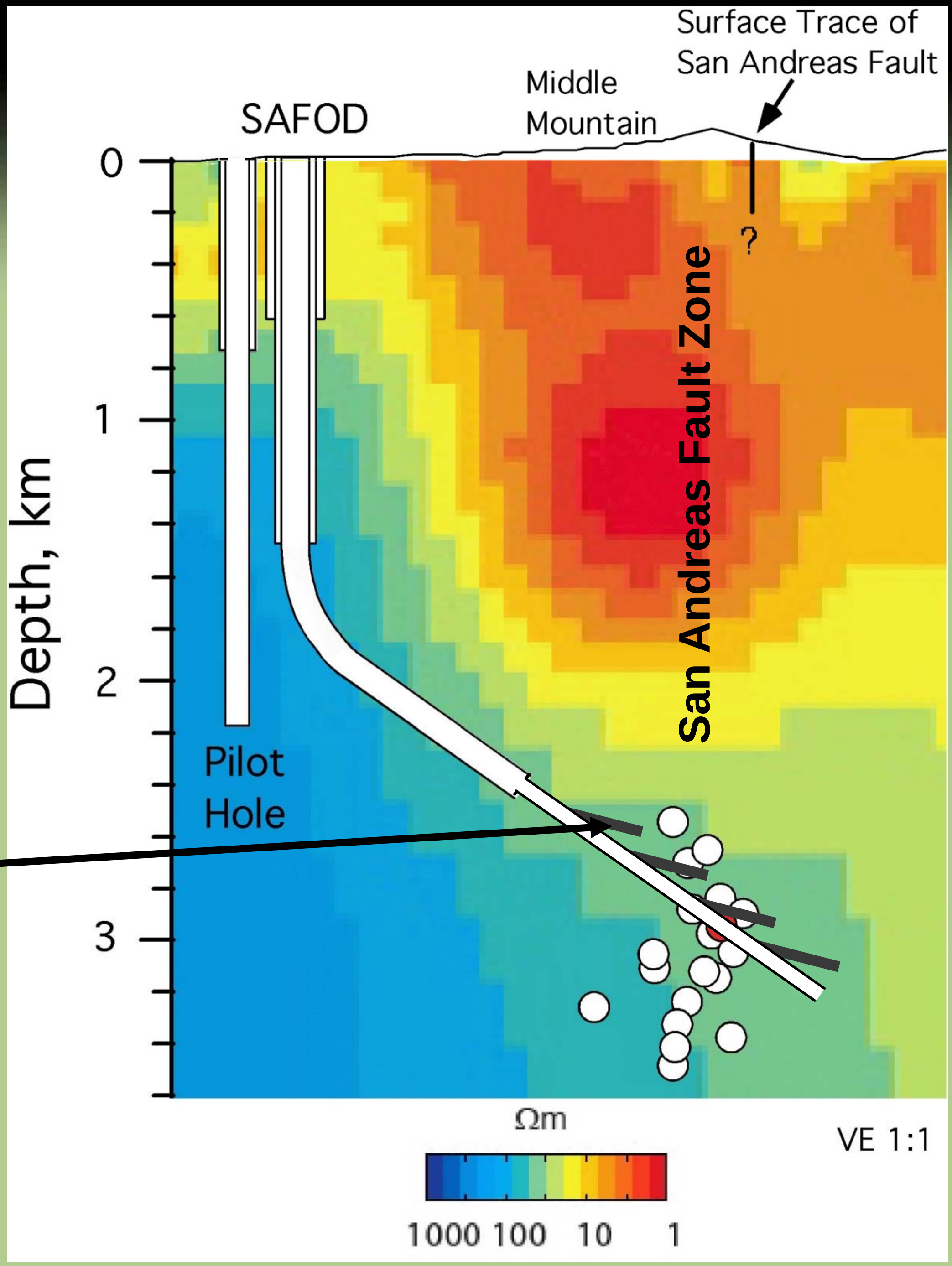
More to come
SAFOD Phase 3 Drilling:
June - August 2007

Phase 3: Coring the Multi-Laterals

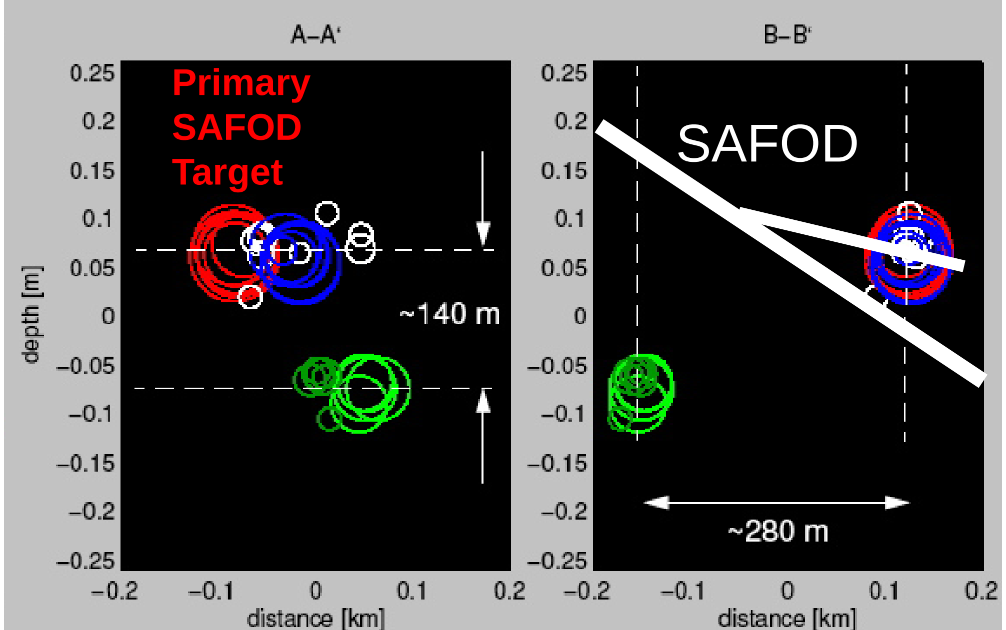
Mill through casing and continuously core 4 holes extending 250 m from main hole *to intersect actively deforming traces of San Andreas Fault.*

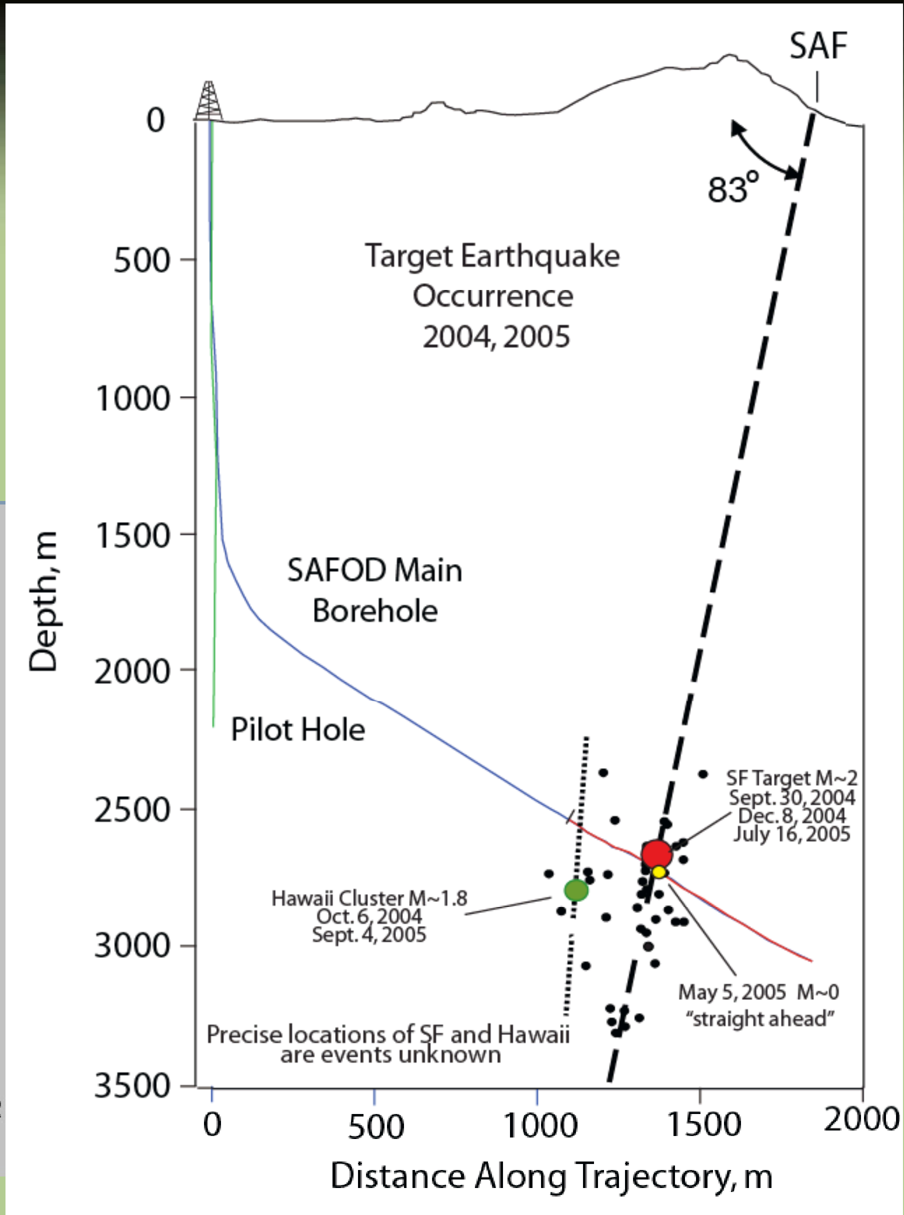
Conduct fluid pressure, permeability and hydrofrac tests in core holes.

Leave one core hole open for long-term fluid pressure monitoring in the fault zone.



Core Holes to Sample Seismic and Creeping Segments





Nadeau et al. 2004, Waldhauser and Ellsworth 2005

Wrap-Up SAFOD Phases 1 and 2

- Drilling, Sampling, Downhole Measurements Carried Out Within the San Andreas Fault Zone
- We Have Established Access to the San Andreas Fault at Seismogenic Depth
- Many Aspects of Earthquake Research Being Impacted
  - Earthquake Physics
  - Fault Rock Geology
  - Rock Mechanics
  - Role of Fluids and Gases

Looking Forward - Phase 3 in 2007