Structure and Properties of the San Andreas Fault at Seismogenic Depths: Recent Results from the SAFOD Experiment

Steve Hickman, Mark Zoback, Bill Ellsworth,
Naomi Boness, John Solum, Dave Kirschner,
Sheryl Tembe, Diane Moore, Thomas Wiersberg,
Jörg Erzinger, Steve Roecker, Cliff Thurber, Peter Malin,
Dave Lockner,Carolyn Moore, Teng-fong Wong,
Colin Williams, Judith Chester, Fred Chester

Representing: USGS, Stanford Univ., St. Louis Univ.,
SUNY StonyBrook, GeoForschungZentrum, Rensselaer Polytechnic
Inst., Univ. Wisconsin, Duke Univ., Texas A&M Univ.

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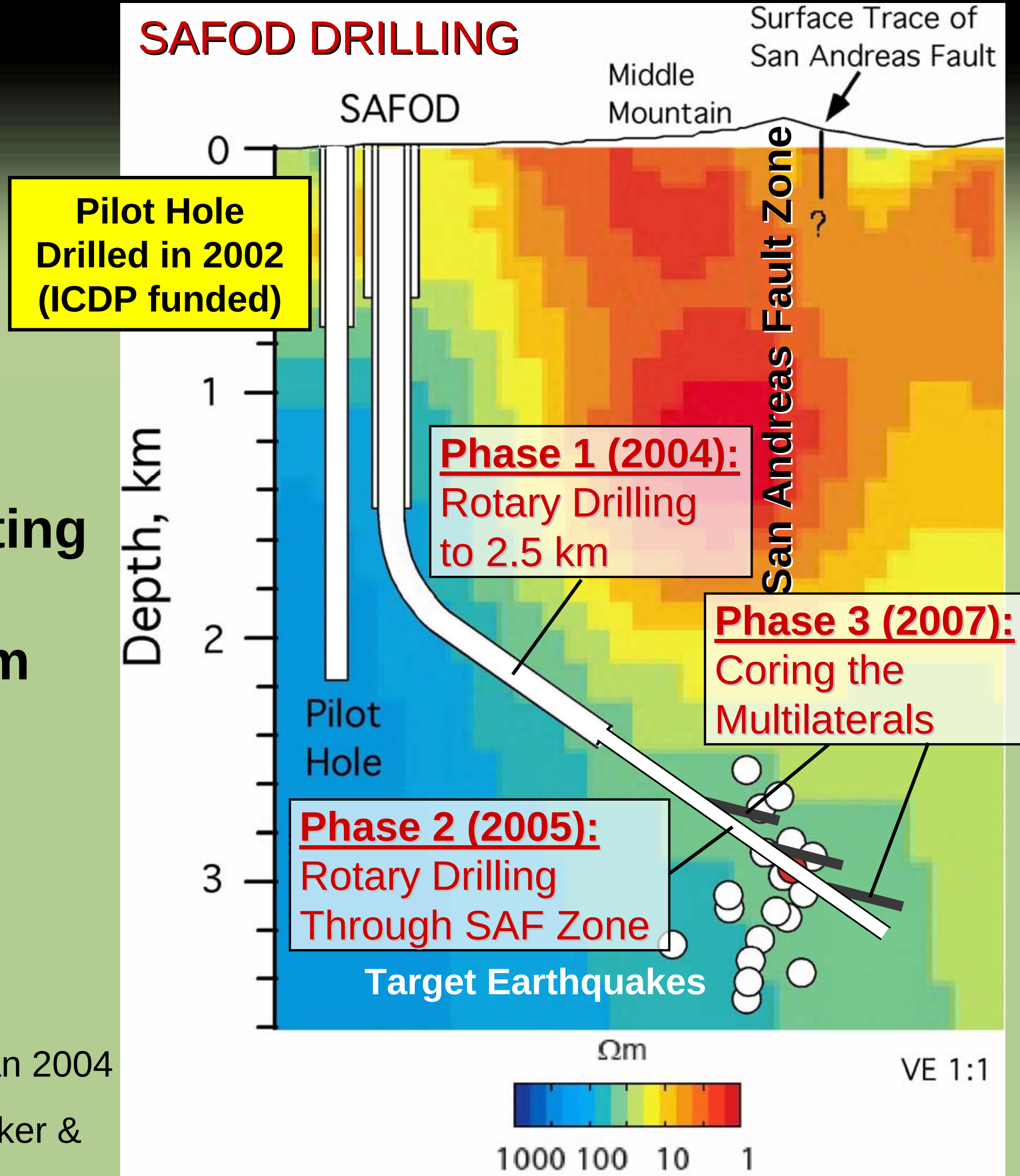
Erice, Sicily, 25-30 September 2007

Talk Outline

1. **Background and seismological setting**

2. **Some Results from Phases 1 and 2**

3. **Phase 3 Coring**



Resistivities: Unsworth & Bedrosian 2004

Earthquake locations: Steve Roecker & Cliff Thurber 2004

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.

Located just north of M6 Parkfield earthquake, where fault fails through creep + microearthquakes.

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

Test fundamental theories of earthquake mechanics:

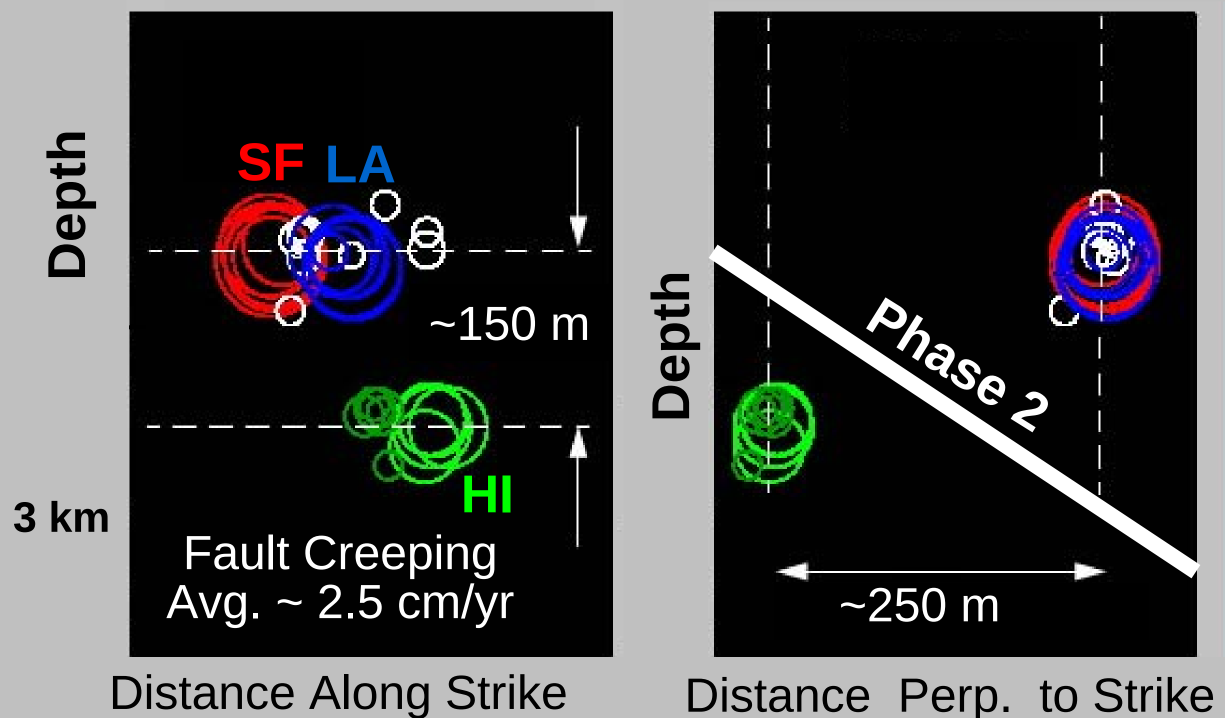
- Determine structure and composition of the fault zone.
- Measure stress, permeability and pore pressure conditions in situ.
- Determine frictional behavior, physical properties and chemical processes controlling faulting through laboratory analyses of fault rocks and fluids.

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.

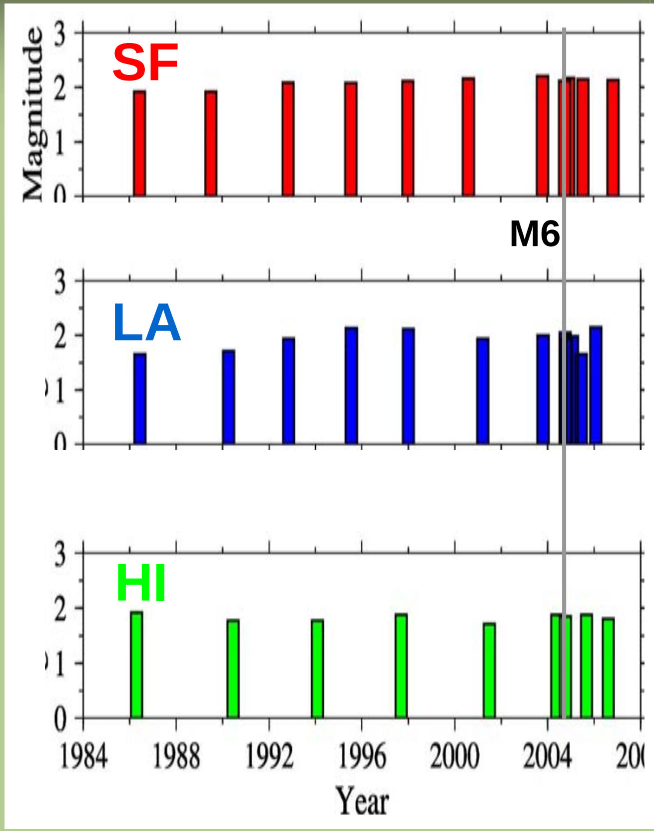

N
San Andreas fault
SAFOD
drill site

Relative Locations of SAFOD Target Earthquakes (Repeaters)



Nadeau et al. 2004, Waldhauser and Ellsworth 2005

circle size = 9 MPa stress drop model



After M6 Parkfield Earthquake on Sept. 28, 2004:

- **Creep rate increased from ~ 2.5 cm/yr to ~ 5 cm/yr**
- **Recurrence interval decreased from ~ 3 yr to ≤ 1 yr**

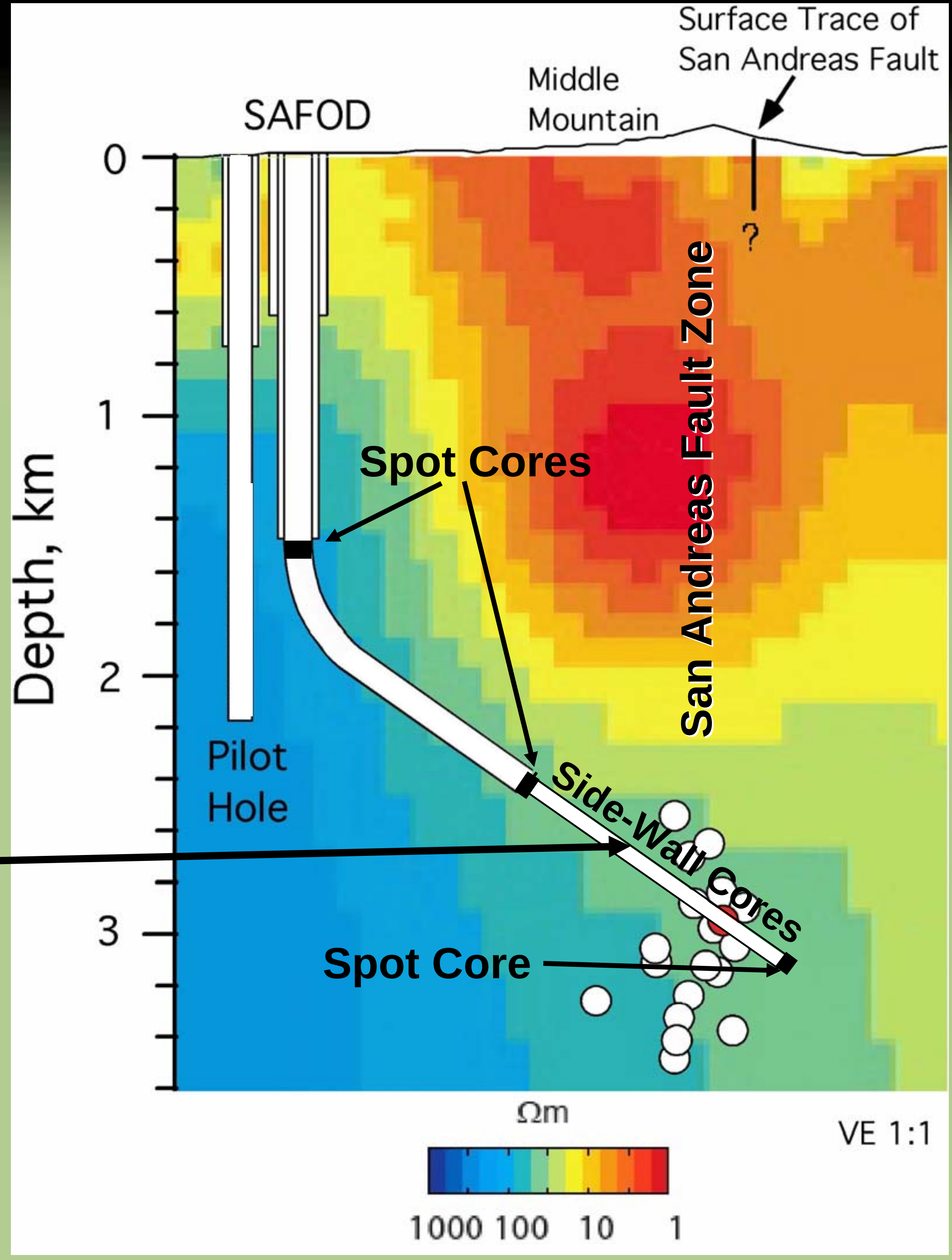
SAFOD Phases 1 and 2

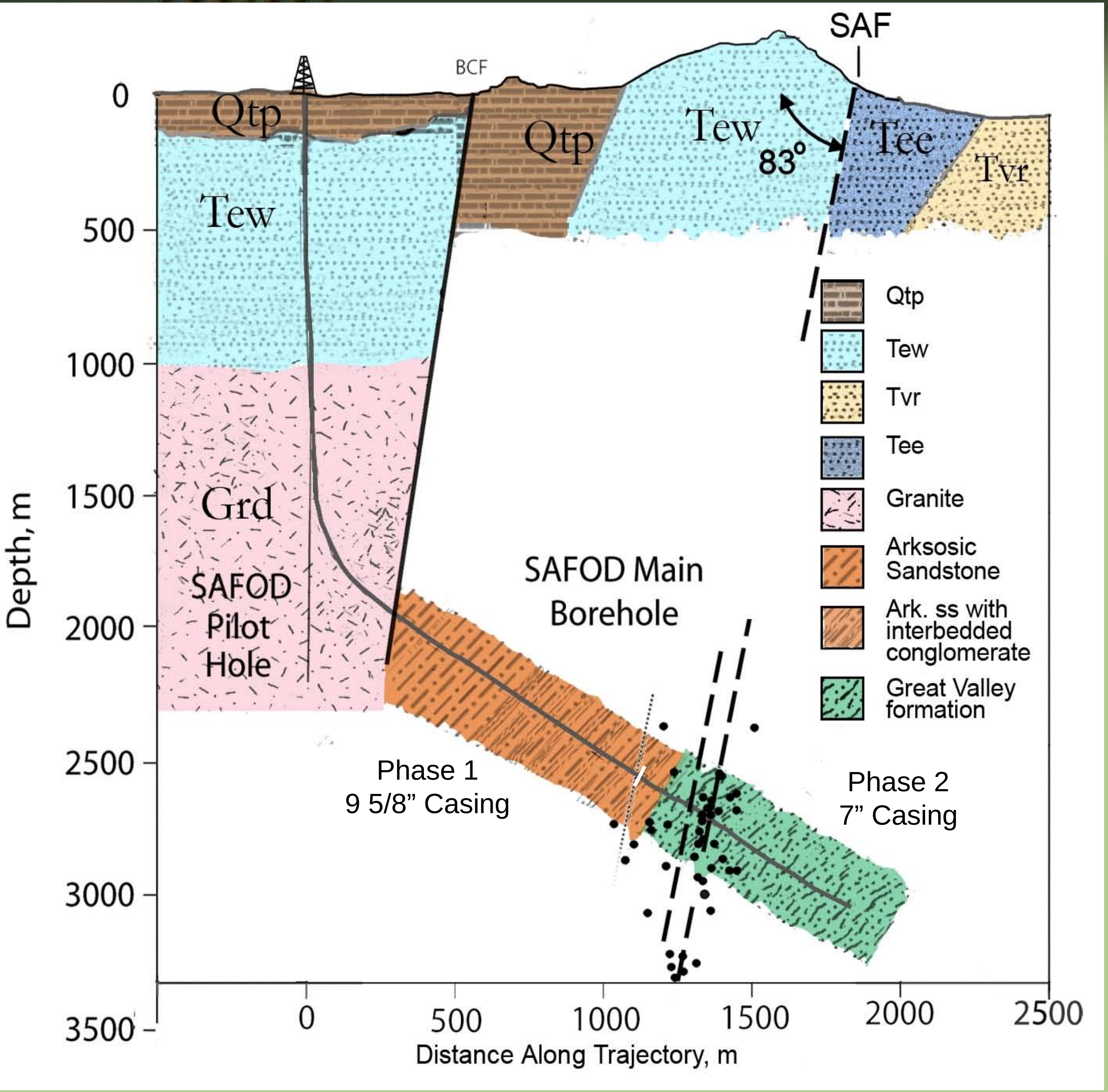
Rotary drilled to 3.1 km vertical depth (4 km measured depth), conducting real-time drill cuttings and mud gas analyses.

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

Collected 52 small (~1.5 cm dia.) side-wall cores from 2.5 to 3.1 km.

After setting casing, collected short spot cores at 1.5, 2.5 and 3.1 km and carried out hydrofracs in core holes.

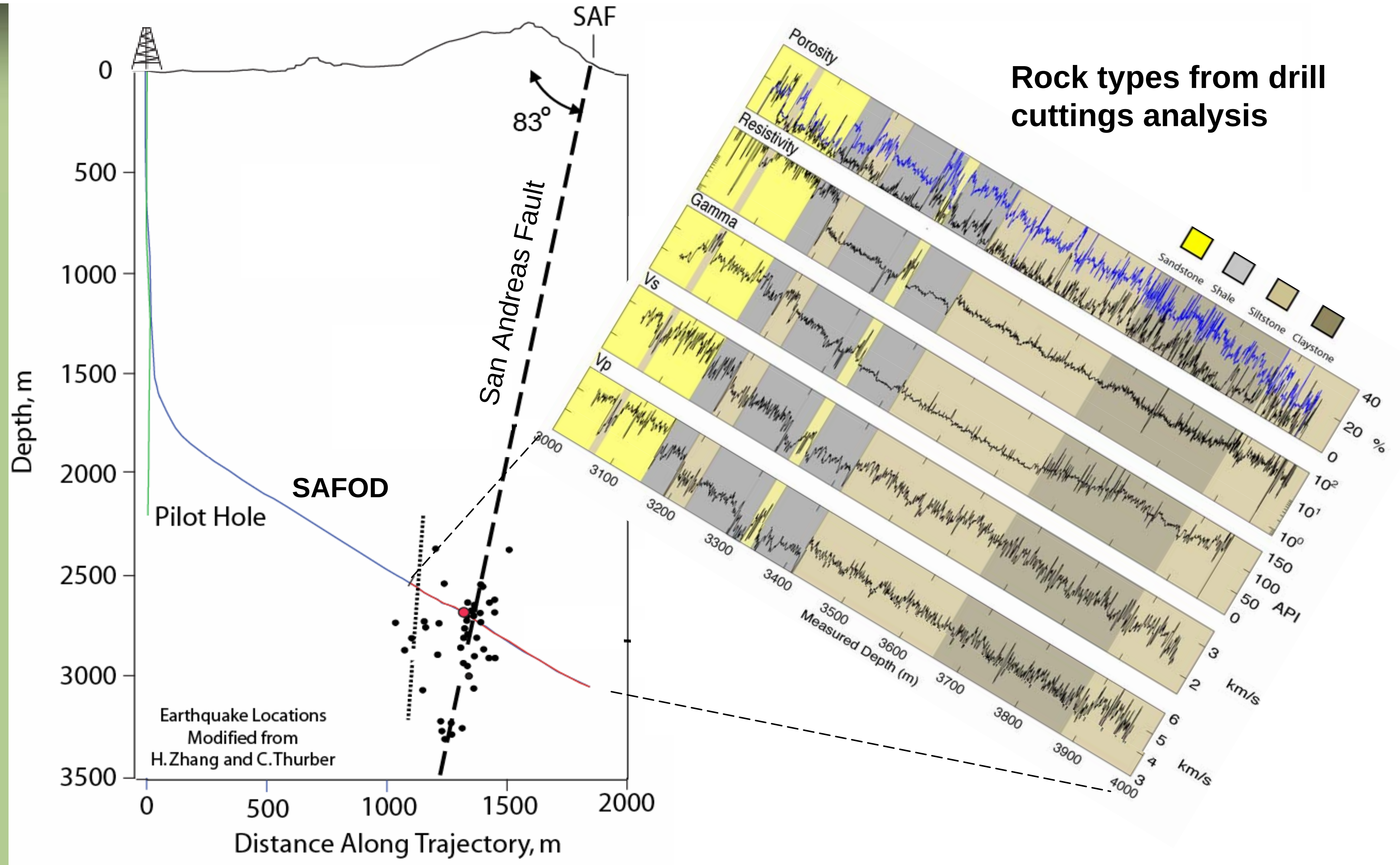




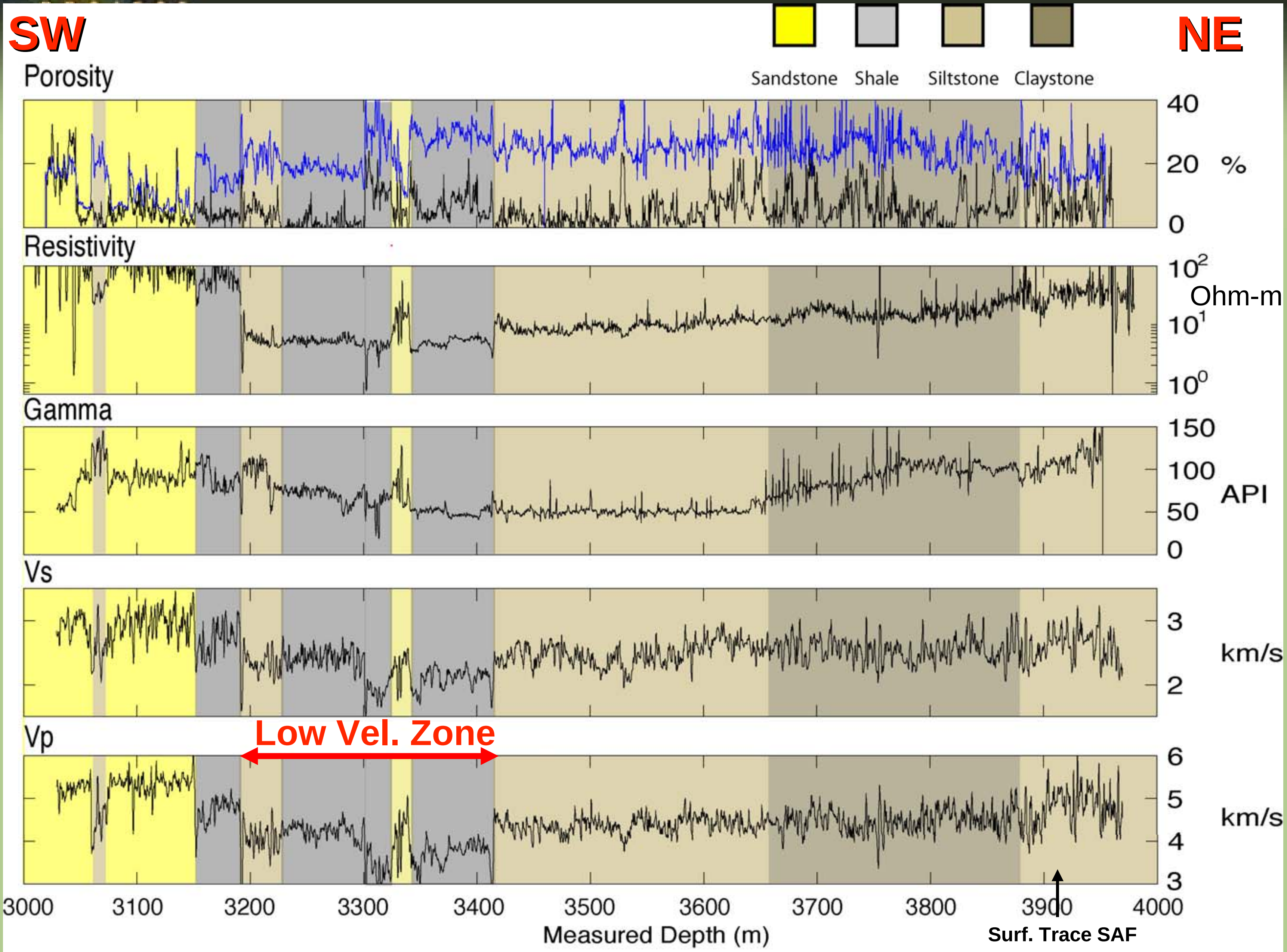
Geology Encountered During Drilling

Crossing the Fault Zone During Phase 2: Wireline Logging and Logging While Drilling

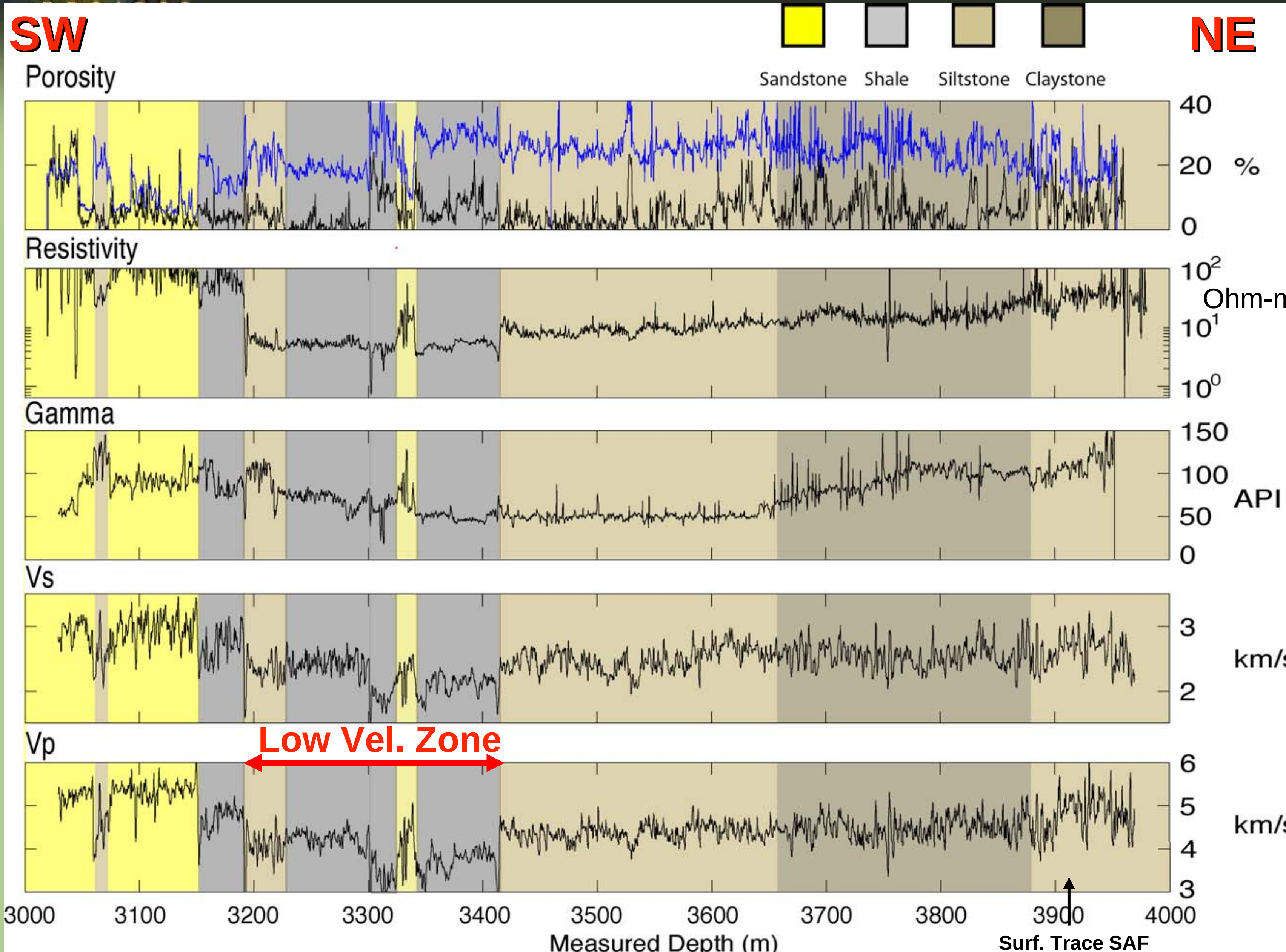
Phase 2 Geophysical Logs

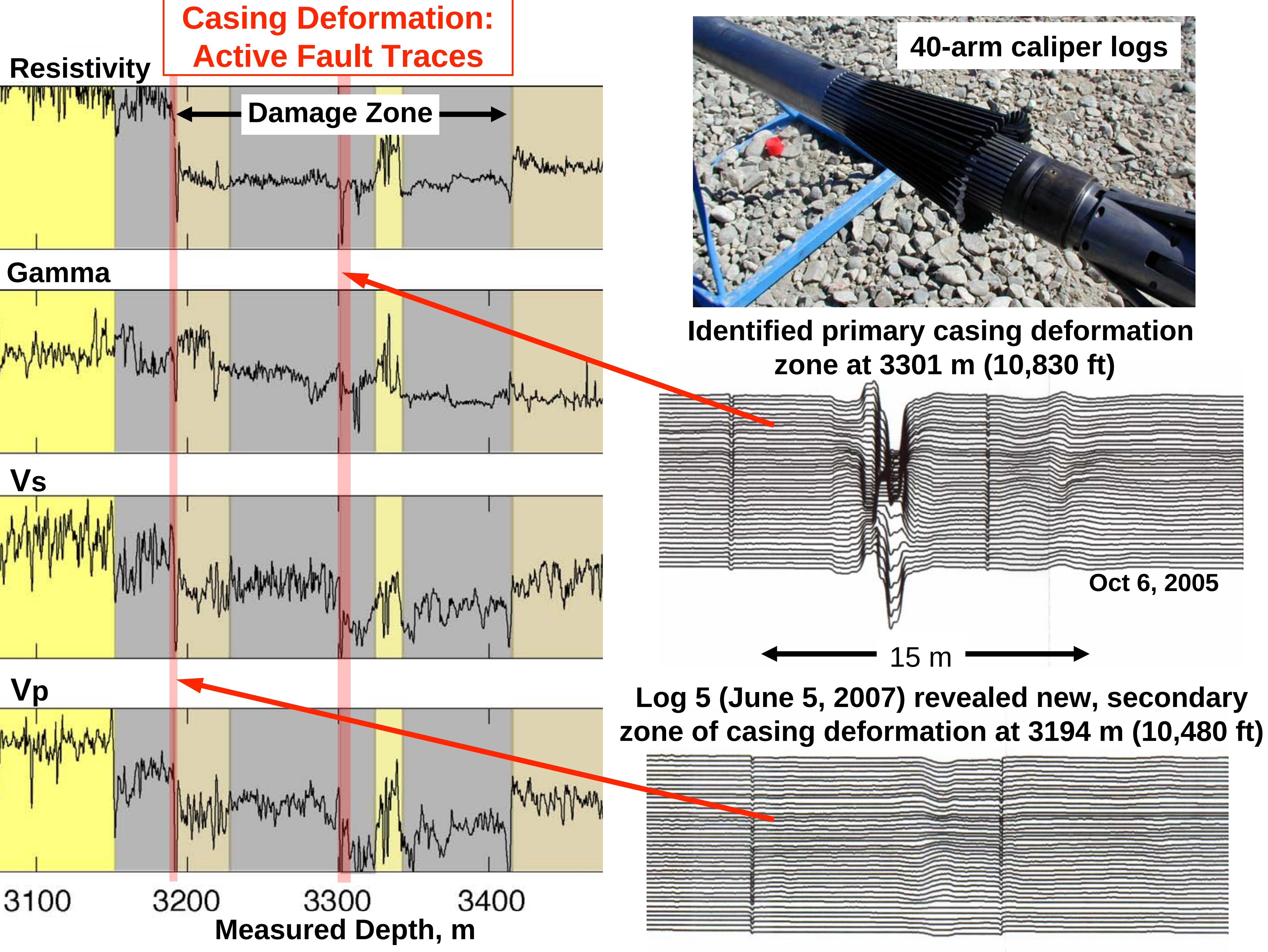


Pronounced Low Velocity/Resistivity Zone ~ 200m Wide



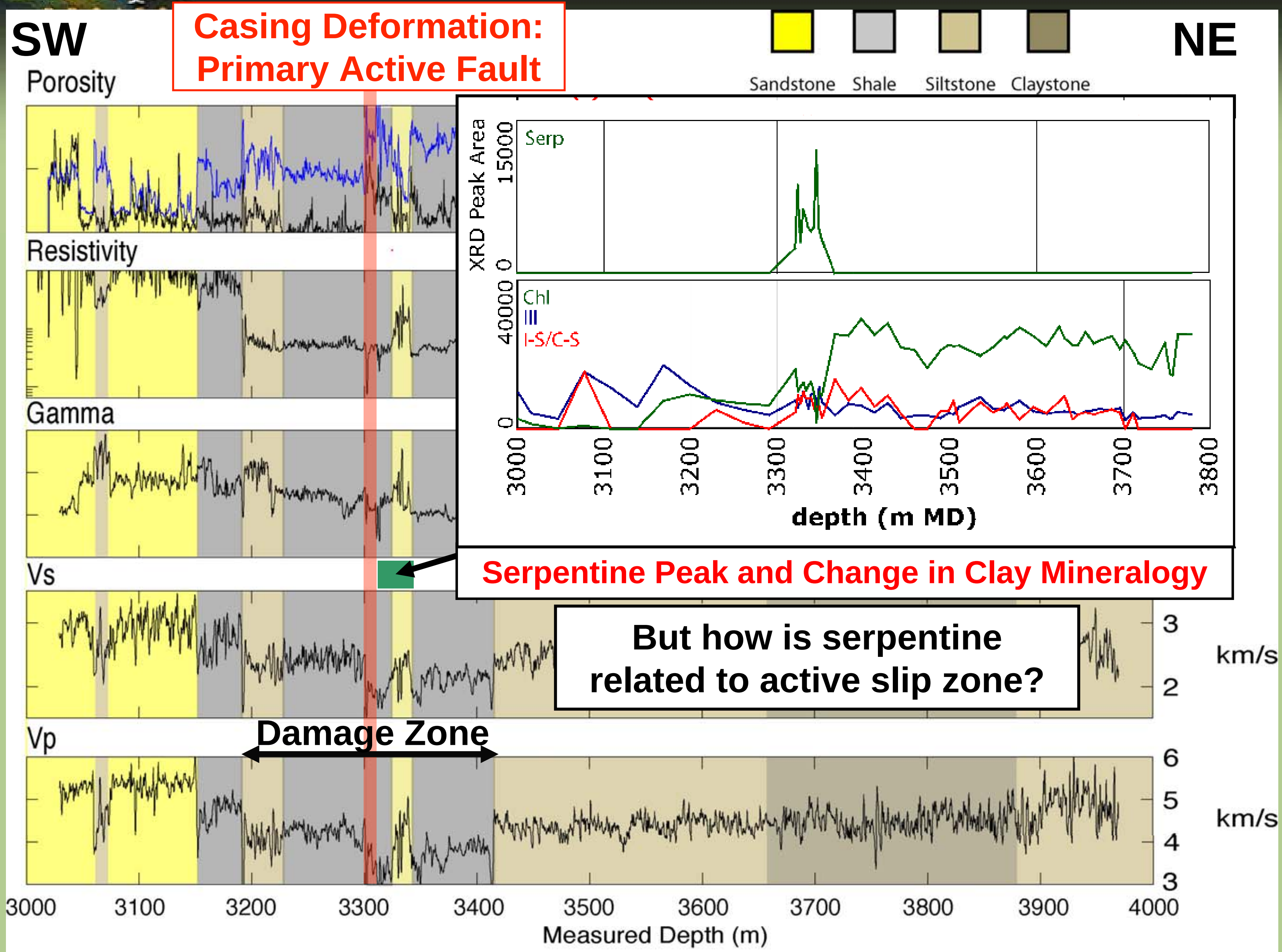
But Where is the San Andreas Fault?



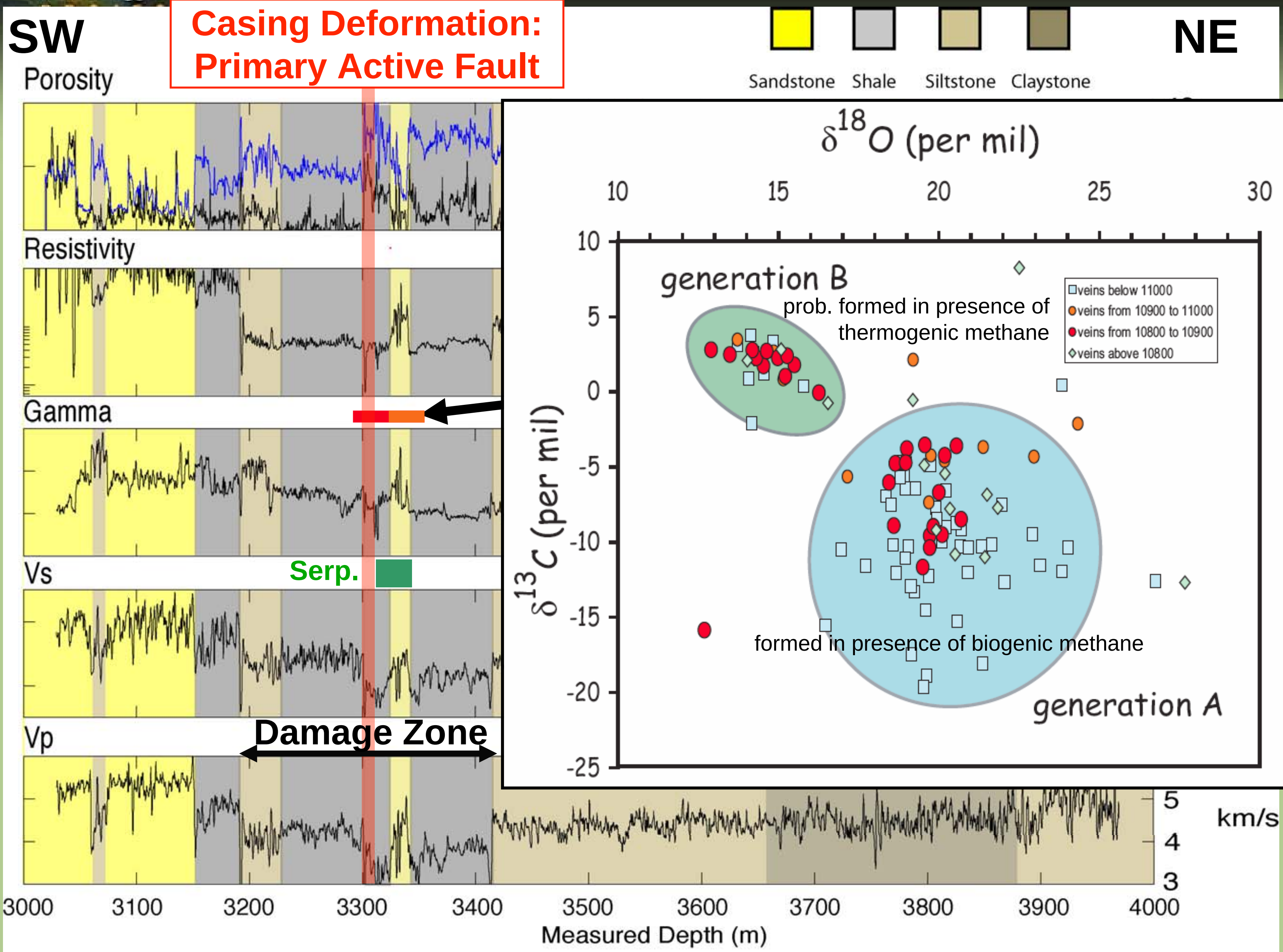

Casing Deformation: Active Fault Traces
Resistivity
Damage Zone
Gamma
Vs
Vp
3100
3200
3300
3400
Measured Depth, m
40-arm caliper logs
Identified primary casing deformation zone at 3301 m (10,830 ft)
Oct 6, 2005
15 m
Log 5 (June 5, 2007) revealed new, secondary zone of casing deformation at 3194 m (10,480 ft)

Mineralogical Anomalies in Phases 1 & 2 Cuttings

(*XRD analysis by Solum et al., 2006*)

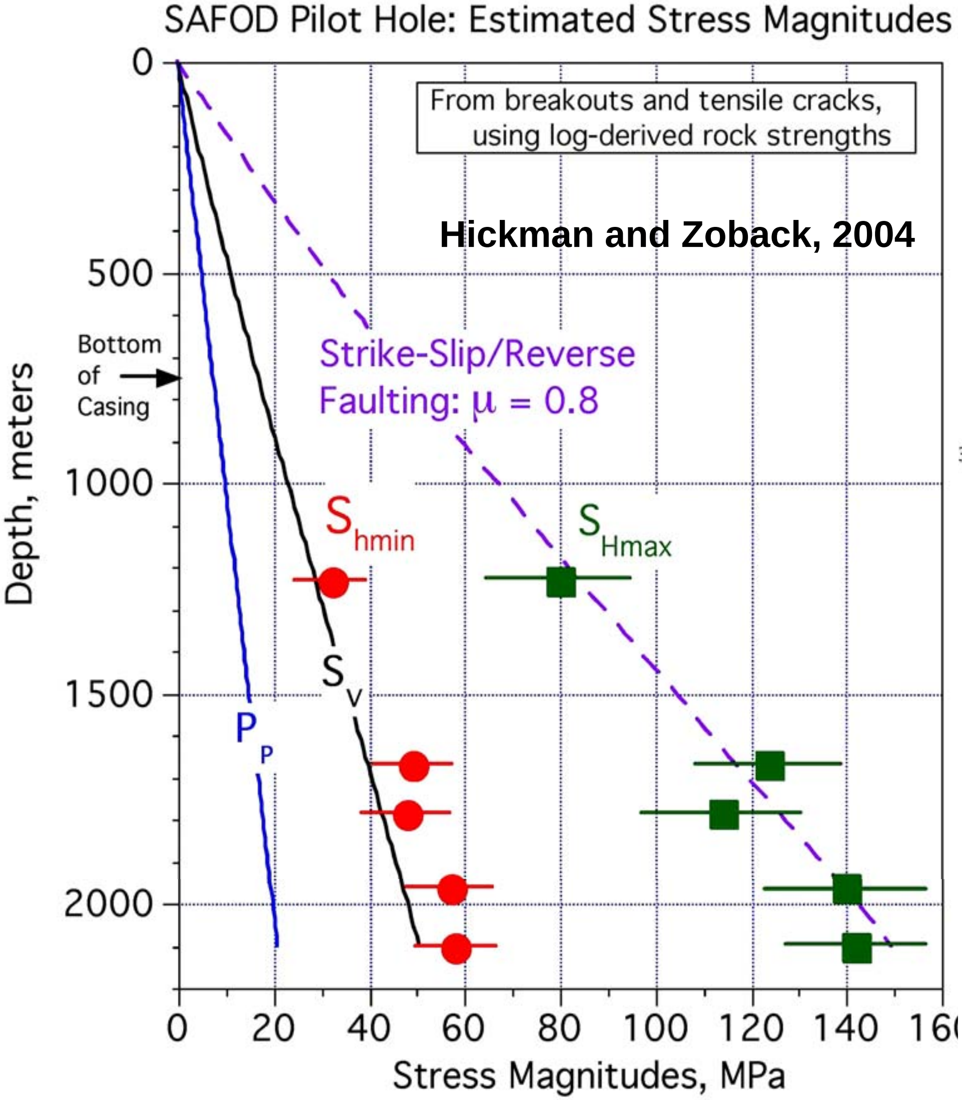


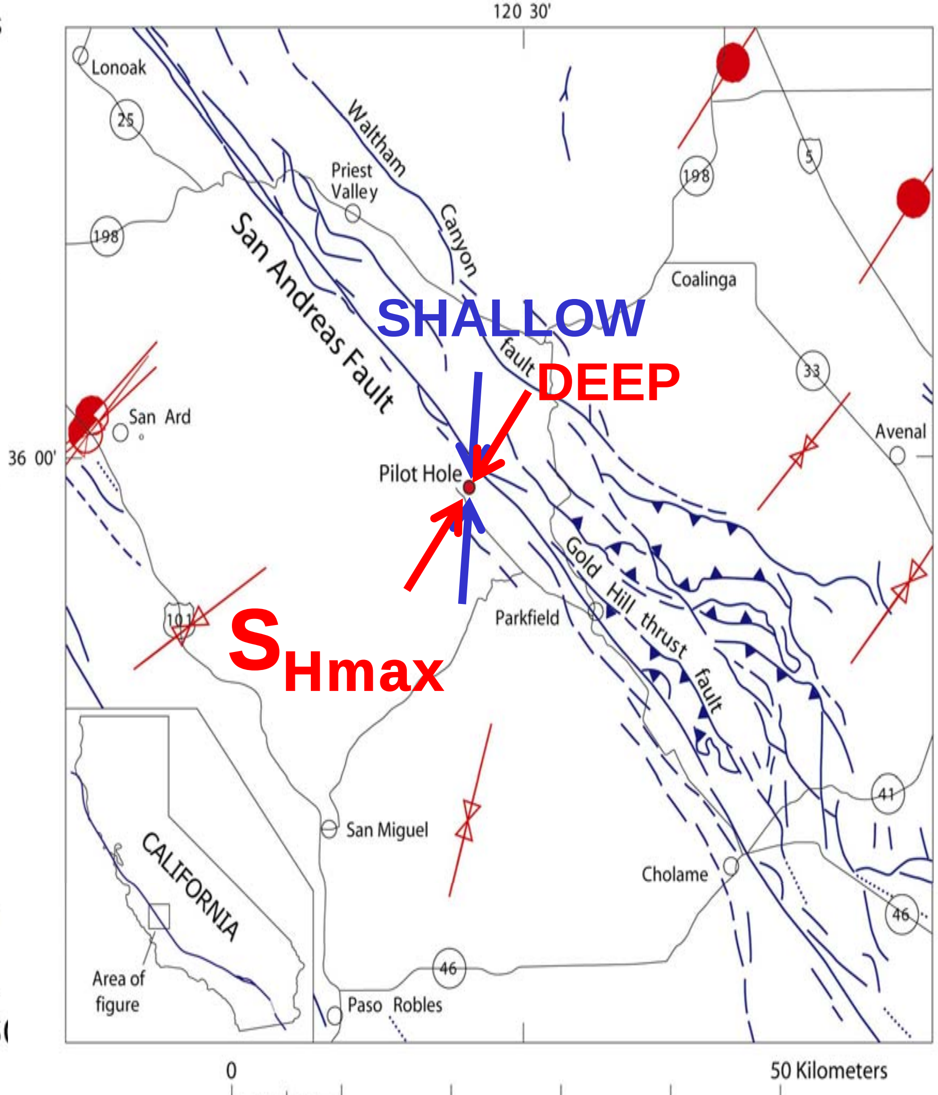
Stable Isotopic Study of Carbonate Veins in Cuttings (*Kirschner et al., 2005*)



High Stress Magnitudes

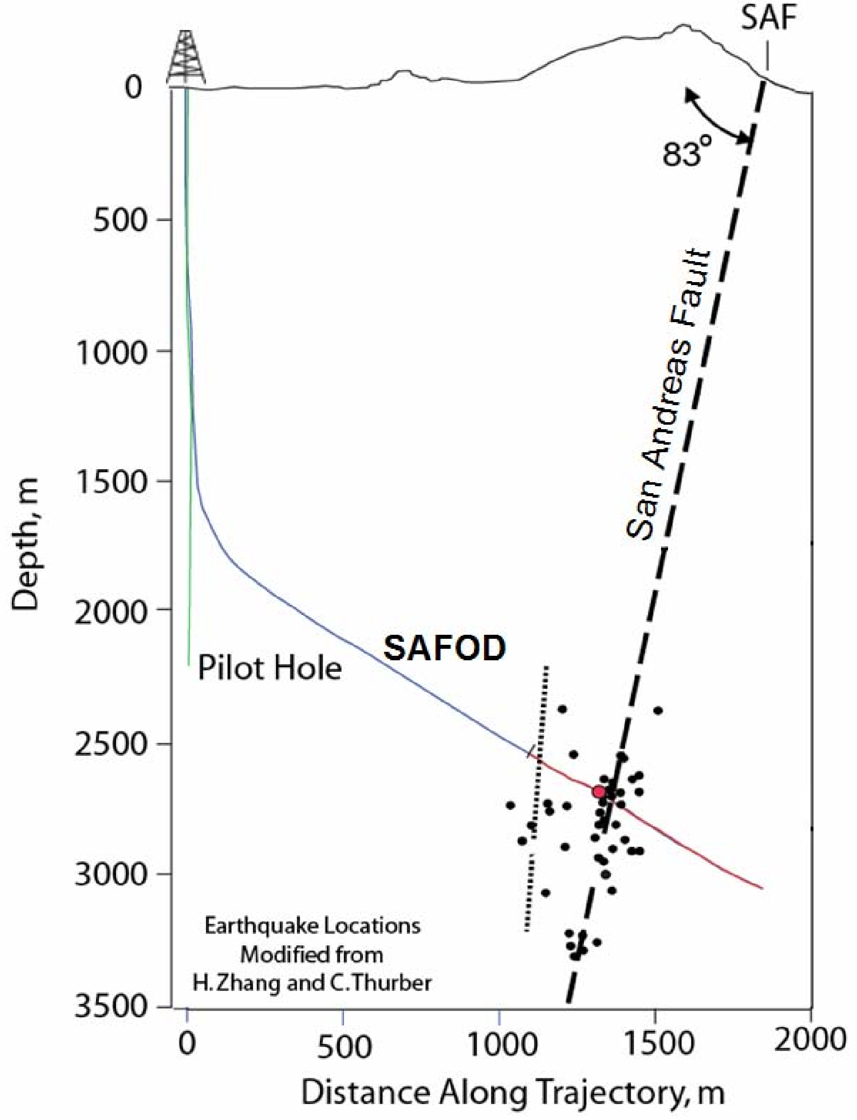
Stress Orientation Consistent With Strong Crust/Weak Fault



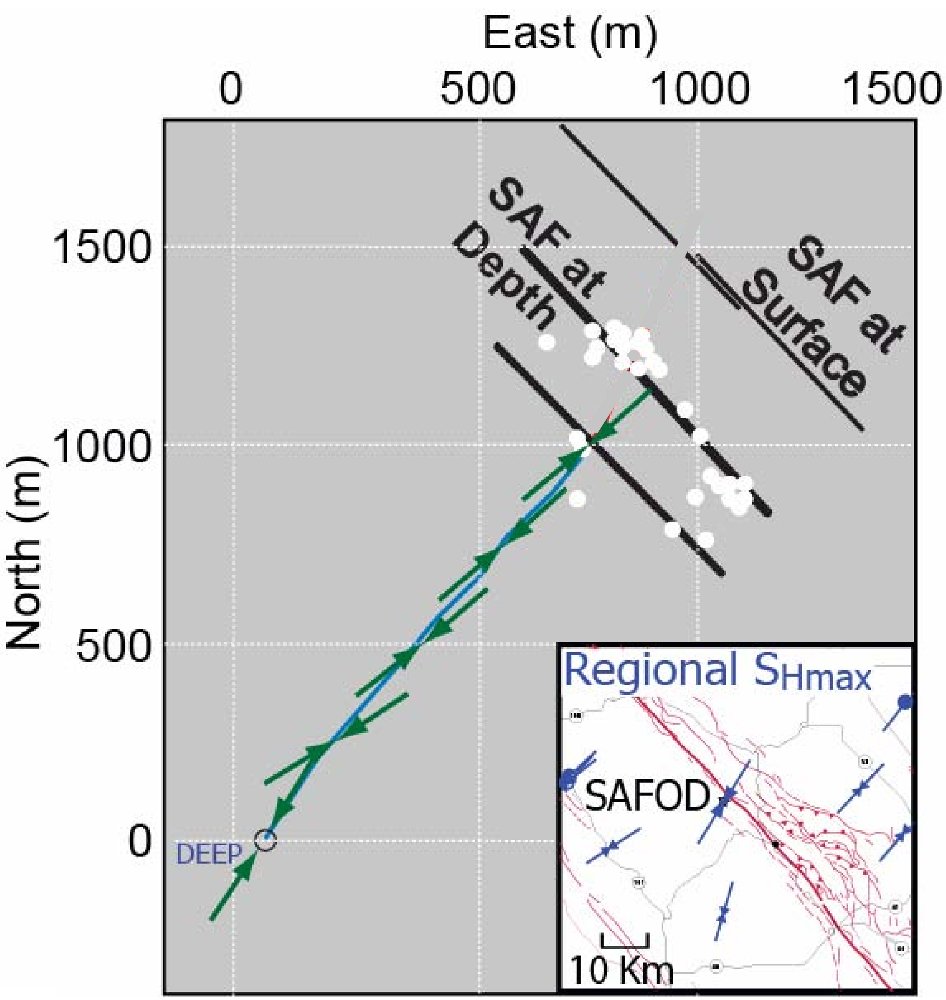


Weak Fault/Strong Crust model confirmed by SAFOD Pilot Hole

But how does direction of S_{Hmax} Change as San Andreas Fault is Approached?



S_{Hmax} Direction in SAFOD from Shear Wave Polarization (Boness and Zoback, 2006)

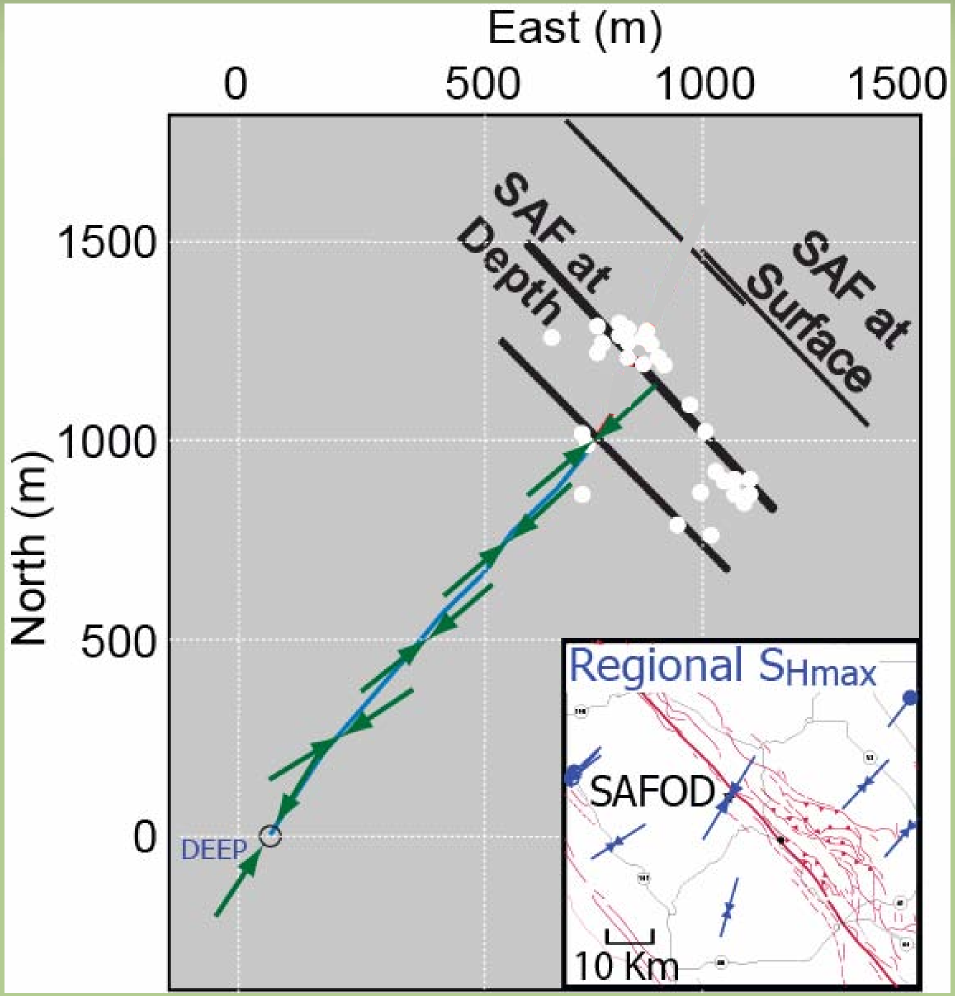


Mechanical Origin of a Weak San Andreas Fault in a Strong Crust (*Creeping segment*)

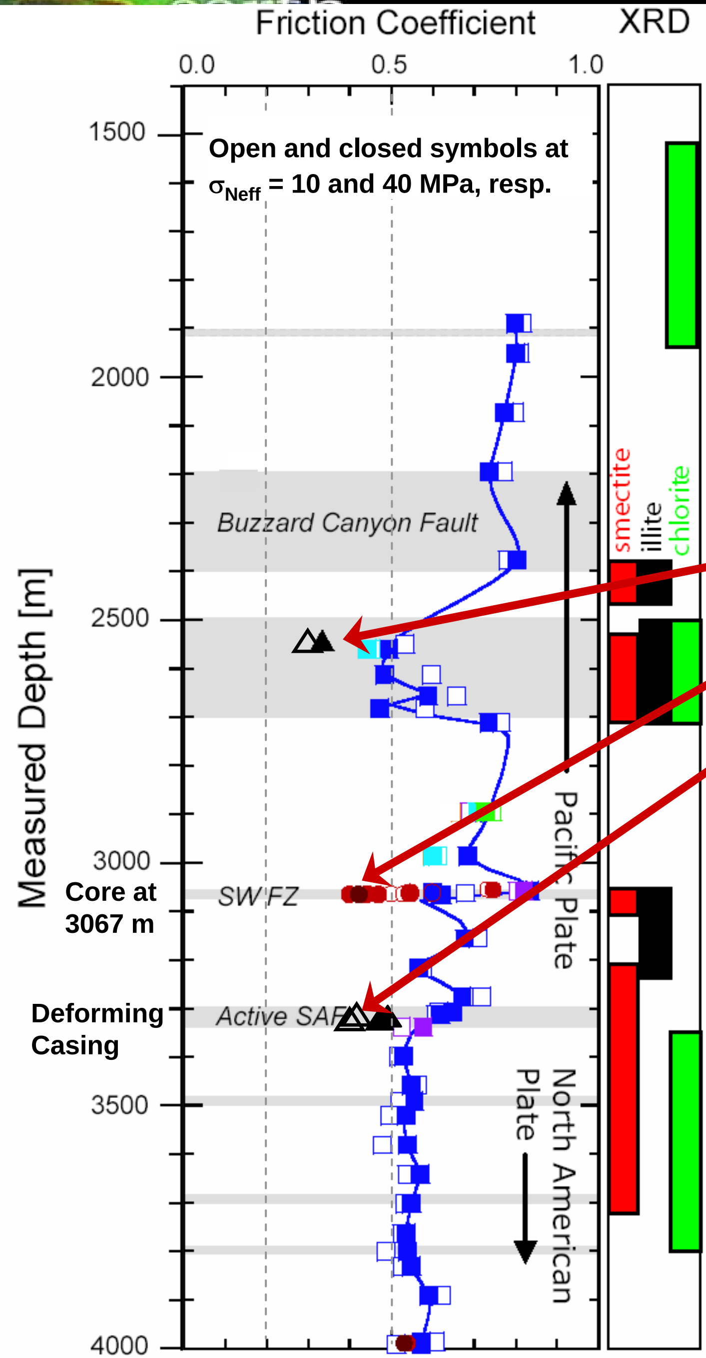
1) Low friction (μ < 0.2) along the fault and high friction elsewhere

2) Super-lithostatic pore pressure confined to the fault zone (e.g., Rice, 1992)

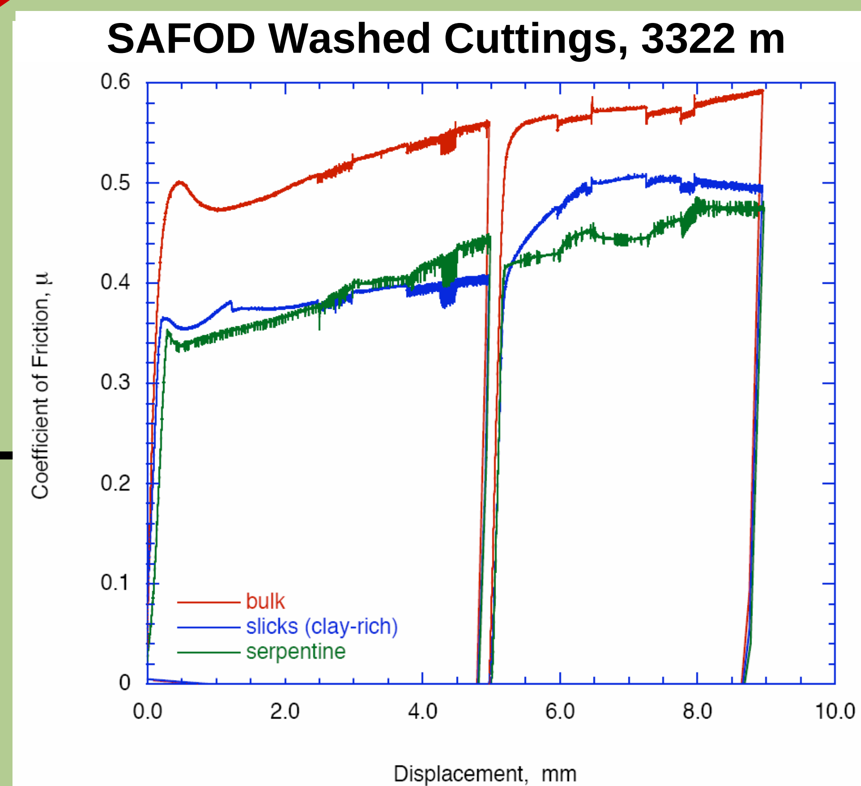
3) Dissolution-precipitation creep (serpentine or other chemically reactive minerals)



Friction of SAFOD Cuttings & Spot Core, Phases 1 & 2 (*Tembe et al., 2006; Morrow et al, 2007*)



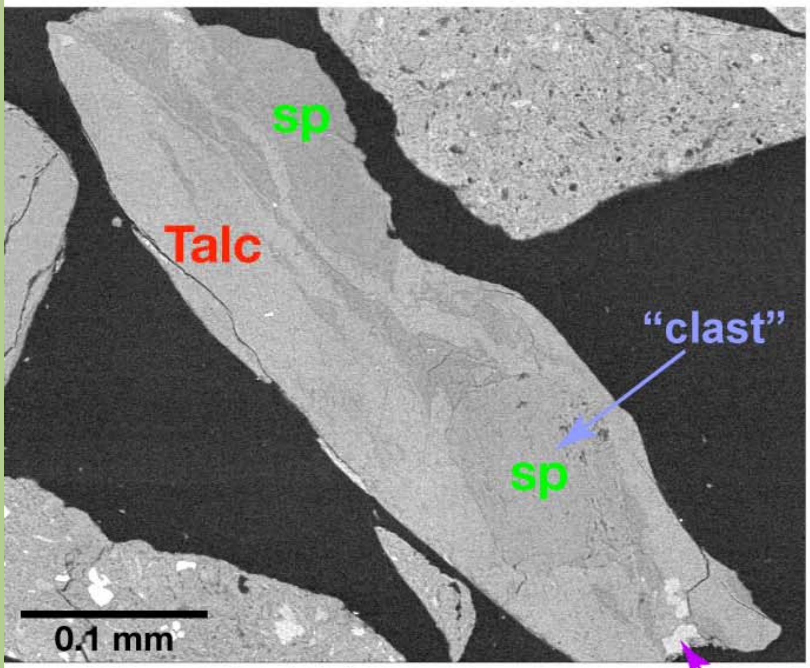
Fault zones are generally weaker than country rock, especially hand-selected cuttings with slickensides (△▲) and spot core of clay-rich fault at 3067 m (○●).



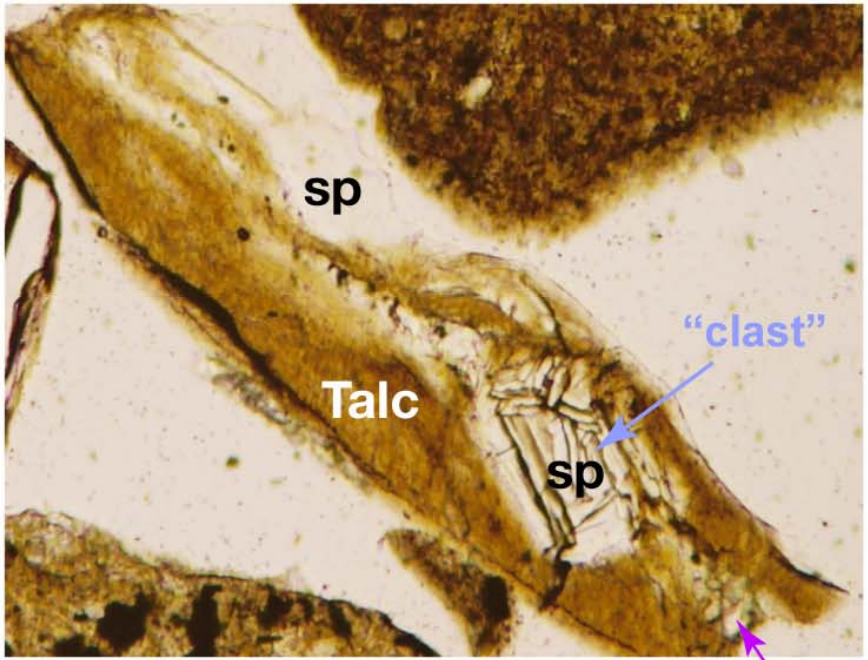
Talc Found in SAFOD Cuttings from Serpentine Zone near Deforming Casing (*Moore et al, 2007*)

3325 m MD

Foliated (sheared?) serpentinite (sp) grain partly replaced by talc. The talc contains ≈5 wt% Fe-oxide, which gives it the brown color.



SEM: Backscattered Electrons

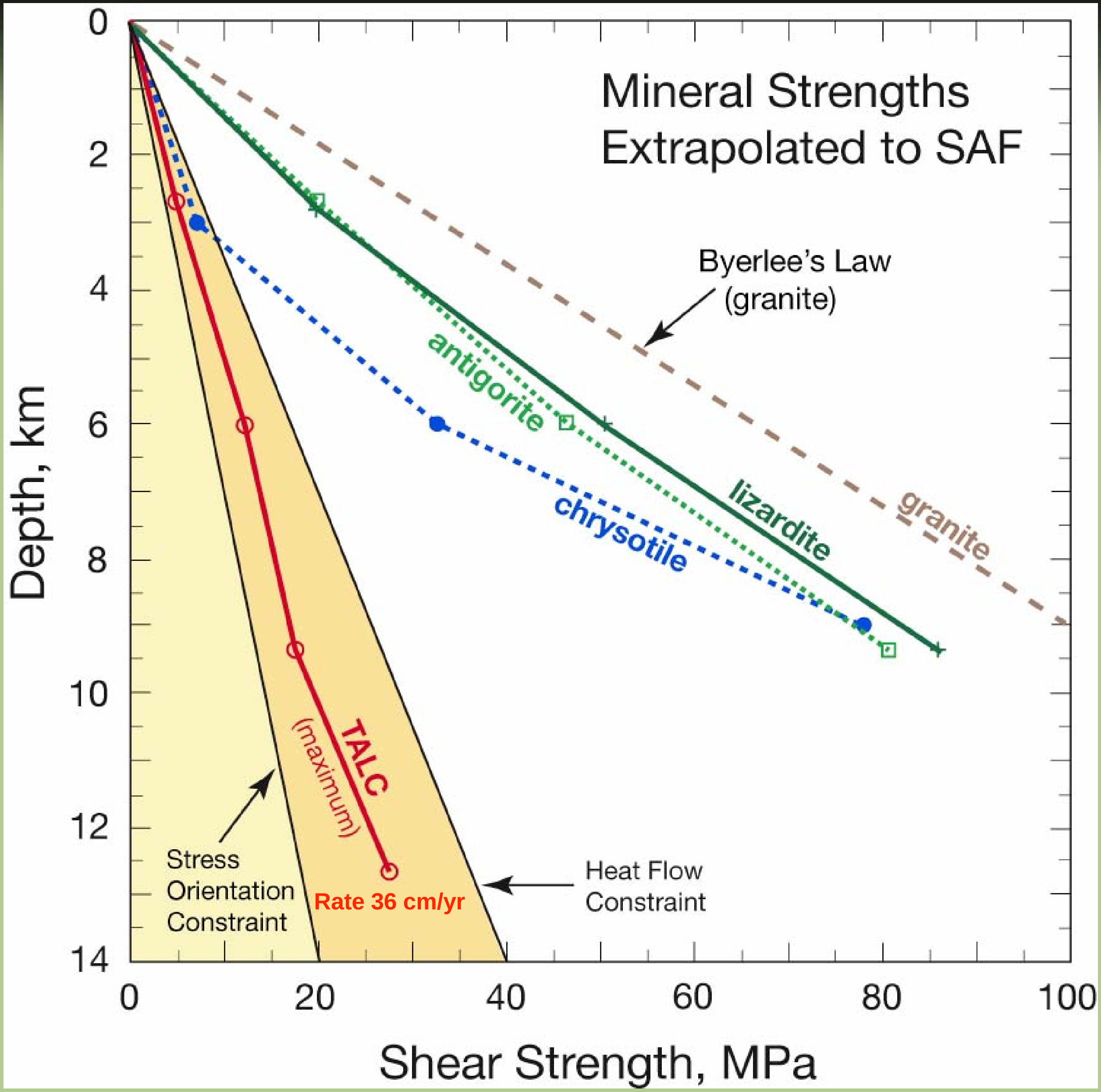


Plane-Polarized Light

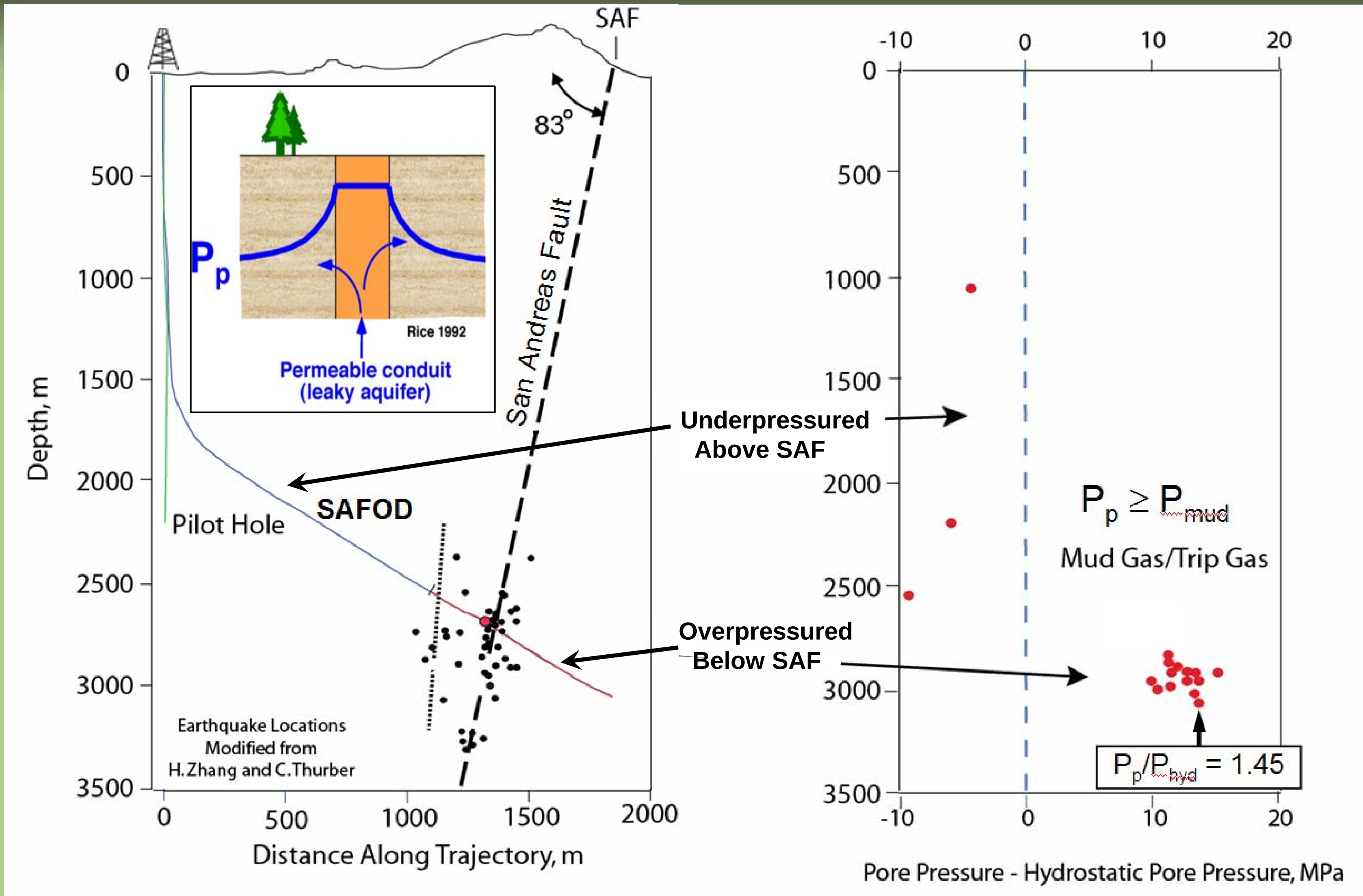
$$\underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + 2\,H_4SiO_{4(aq)} = \underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2} + 5\,H_2O$$

Lab friction tests show that a compositionally similar talc is anomalously weak *and* velocity strengthening (creeping) at seismogenic conditions.

(Moore et el., 2006)

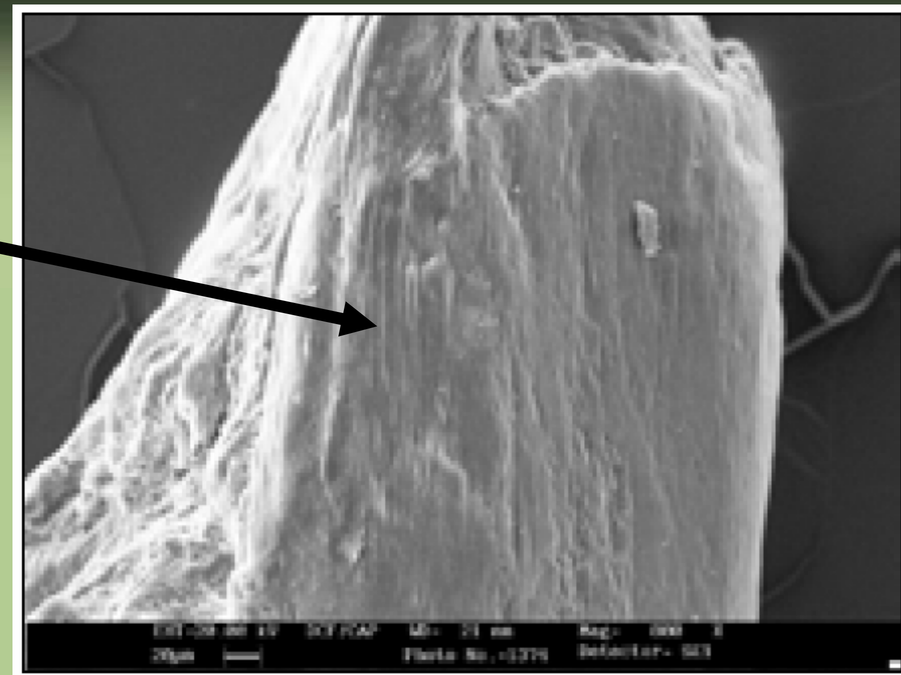


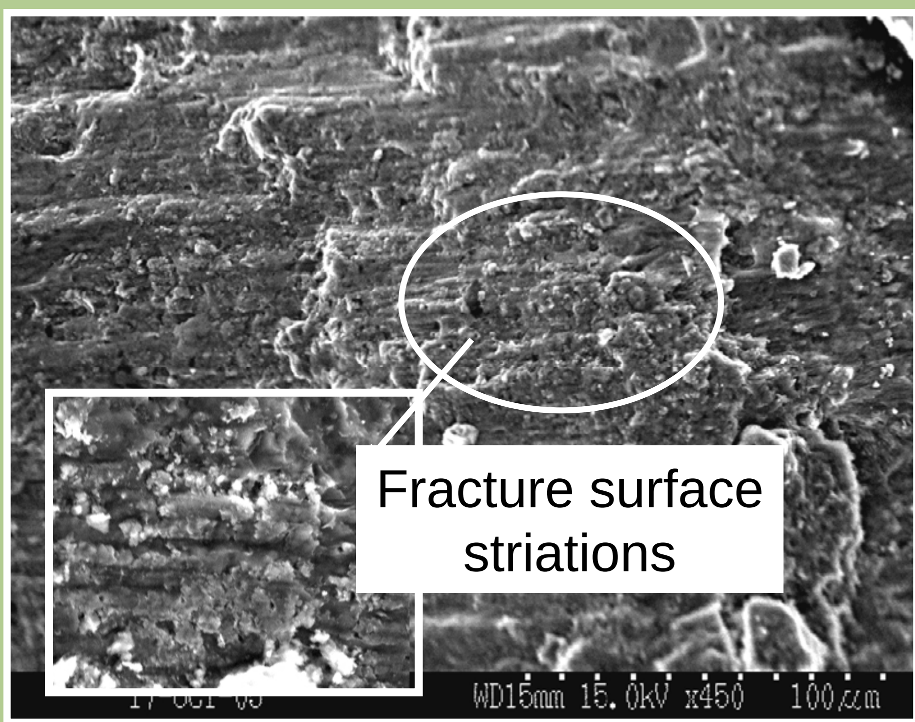
High Pore Pressure in the San Andreas?



Evidence for Dissolution-Precipitation Creep in SAFOD Phase 2 Cuttings

SEM image of serpentinite from 3322 m MD showing aligned chrysotile fibers, similar to those in Santa Ynez Fault in S. Calif. (from Anne-Marie Boullier)





Secondary smectite phase marks polished and striated surfaces (*microfaults*) as an ultra-thin film just nm in thickness.

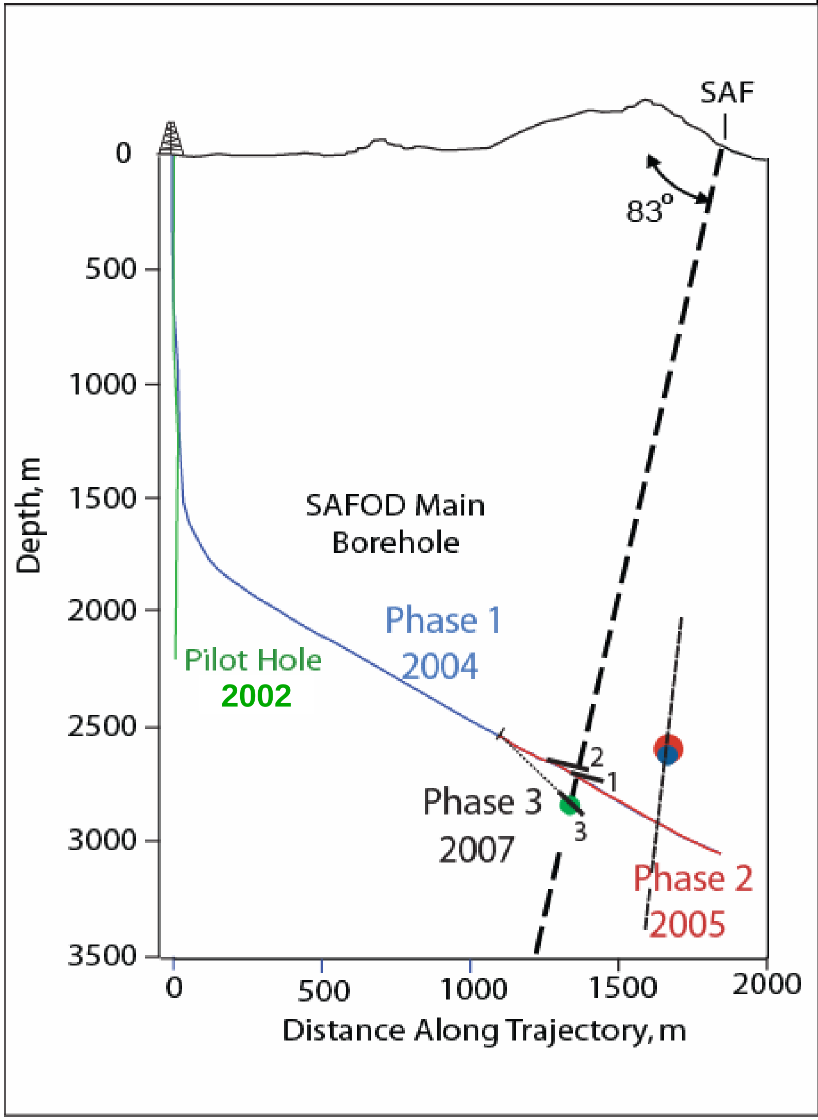
Smectites well oriented and occasionally fibrous in form, creating slickenfibers (Schleicher et al, 2006).

SAFOD Phases 1 and 2: A Few Science Highlights

- Stress orientations and magnitudes are consistent with a weak San Andreas Fault in an otherwise strong crust.
- San Andreas Fault Zone is associated with anomalous physical properties, with actively deforming (creeping) fault core.
- The San Andreas Fault Zone has unique mineralogy, composition and geochemical signature.
- Actively deforming fault core does not appear to be overpressured, although SAF is a barrier to fluid flow (high pressure fluids and distinct gas chemistry on NE side).
- SAFOD fault zone monitoring is operational, with detection of local earthquakes, fault zone guided waves and non-volcanic tremor.

Phase 3 Coring

Phase 3 Plan



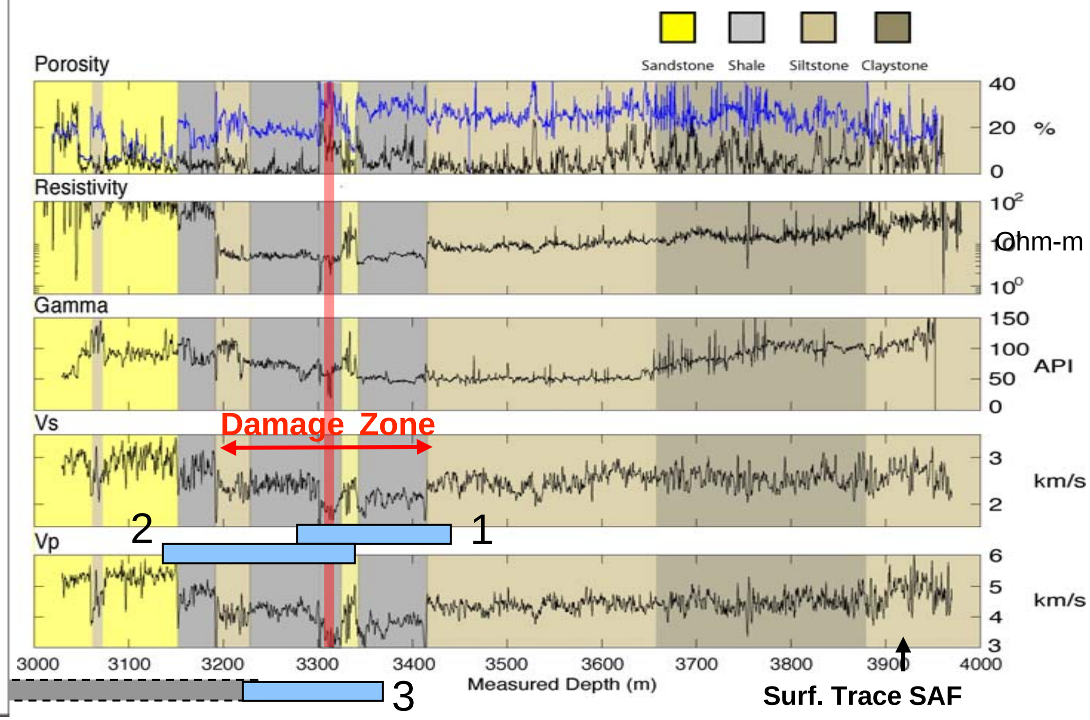
Phase 3: Coring the Multi-Laterals

Continuously core 3 holes off the main hole to intersect actively deforming traces of the SAF *(creeping and seismogenic)*. *Core Hole 3 to intersect target earthquake.*

Determine frictional behavior, physical properties and chemical processes controlling faulting through testing of recovered core.

Conduct wireline geophysical logging in Core Hole 3.

Case and perforate in fault zone for near-field monitoring of seismic radiation, deformation and fluid pressure.



What Actually Happened

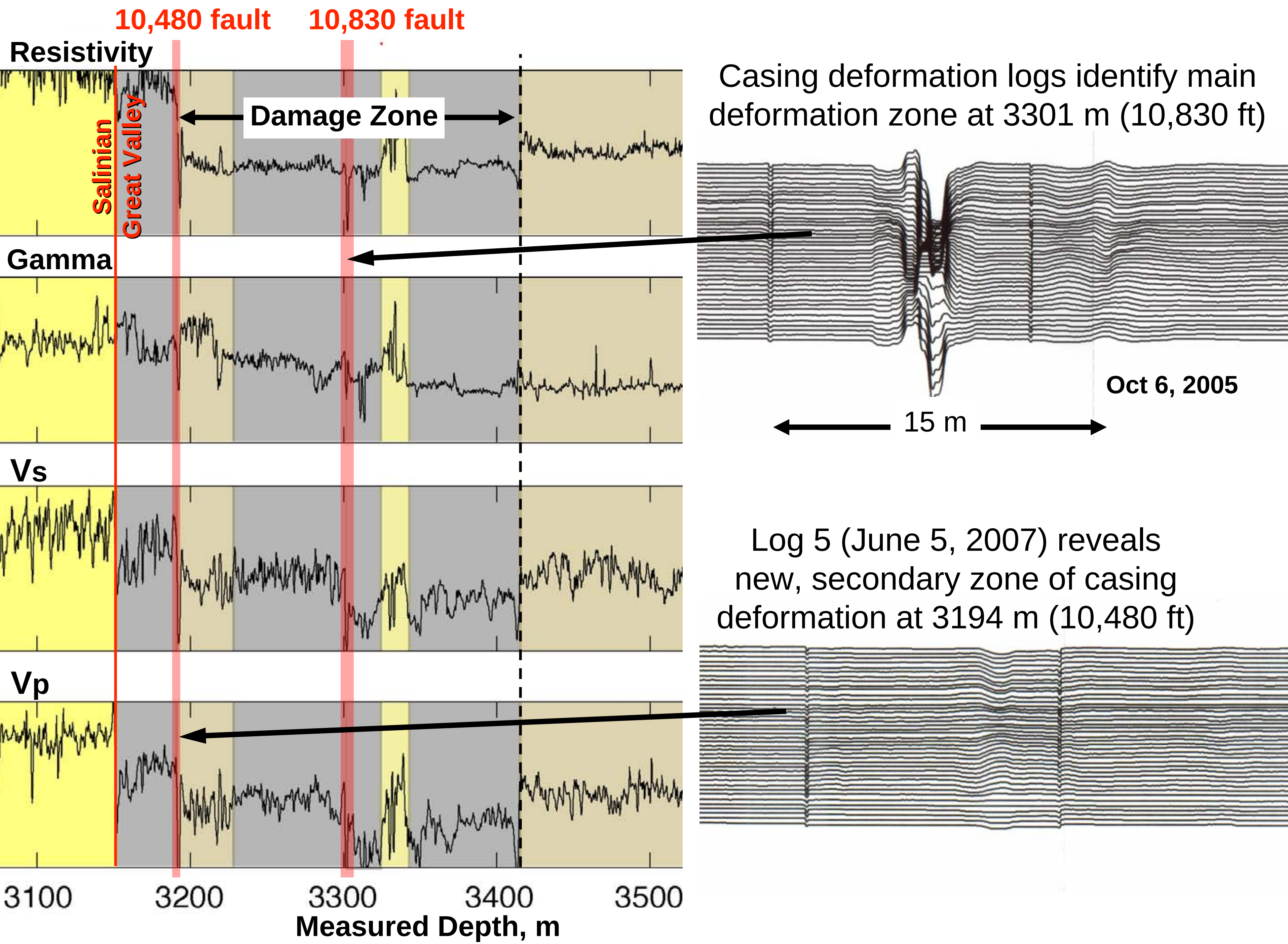
Drilling conditions too difficult to use continuous (wireline) coring as planned:

- Lost Sidetrack #1 (stuck rotary drilling assembly) and conducted bypass drilling to get around lost coring tools in Sidetrack #2.

Instead, we used traditional "spot" coring system to core just outside Salinian/Great Valley contact plus two active traces of SAF at depth:

- Requires coring immediately adjacent to Phase 2 (cased) hole, for accurate targetting of active faults.

Core 4 inches (10 cm) in diameter!


10,480 fault
10,830 fault
Resistivity
Damage Zone
Salinian
Great Valley
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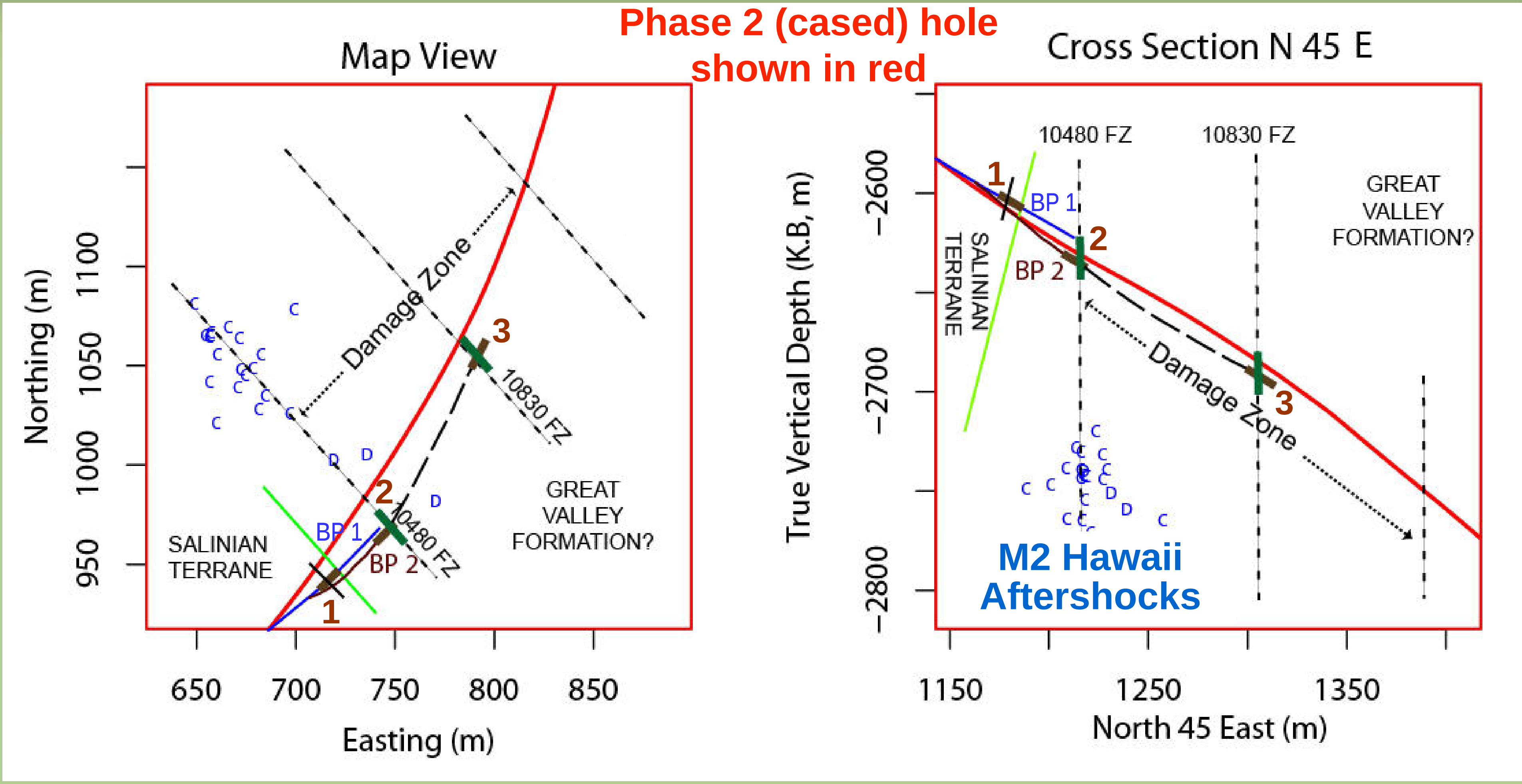
Measured Depth, m
Casing deformation logs identify main deformation zone at 3301 m (10,830 ft)
Oct 6, 2005
15 m
Log 5 (June 5, 2007) reveals new, secondary zone of casing deformation at 3194 m (10,480 ft)

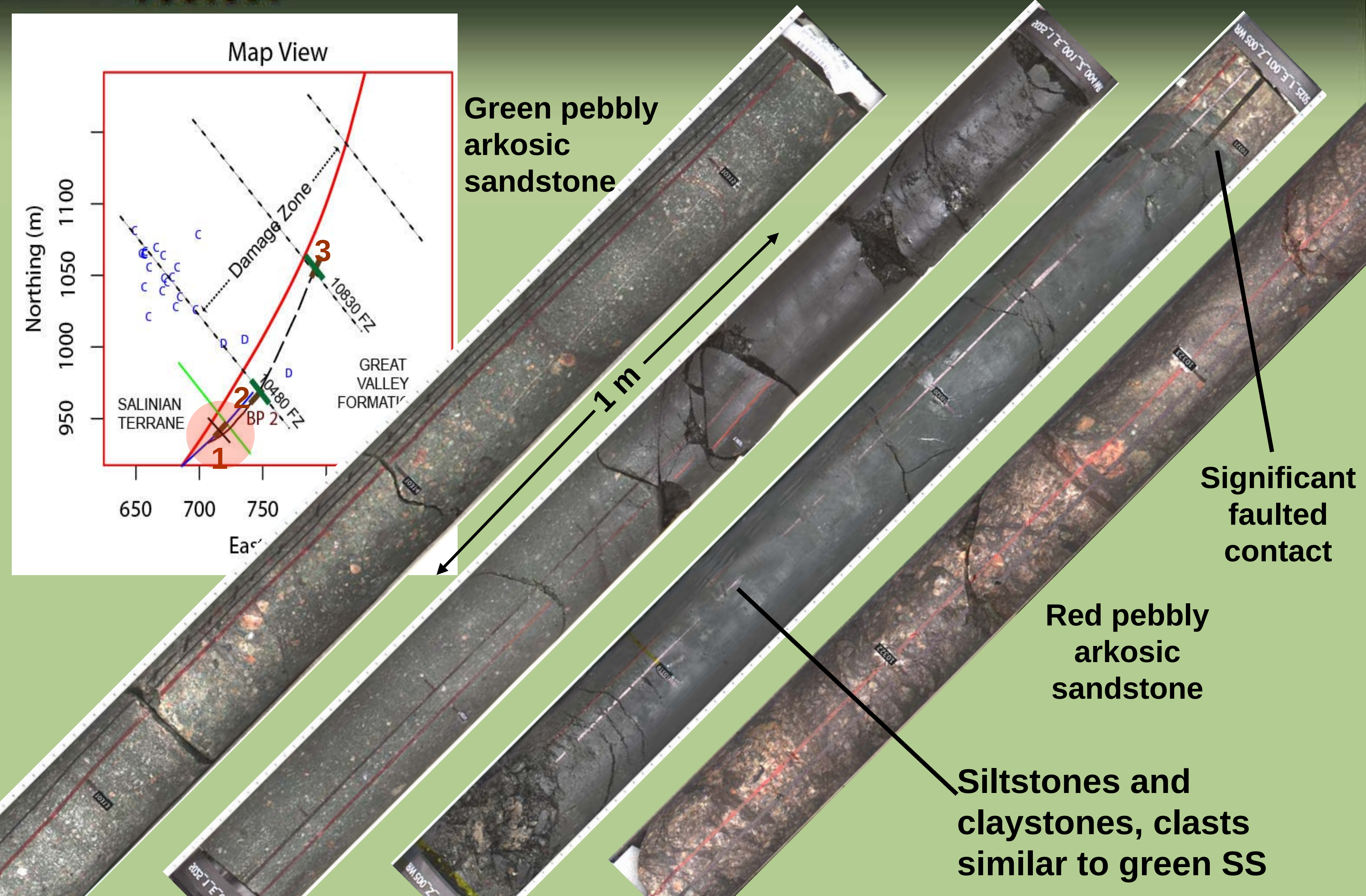
SAFOD Phase 3: Successfully Cored Intervals:
1- Near Salinian/Great Valley (SS/Shale) Contact
2 - Across 10.480' Fault Zone
3 – Across 10,830' Fault Zone



Phase 3 Sidetracks (BP 1 and PB 2) within 10-20 m of Phase 2 cased hole, to allow for targetted coring of casing deformation zones (active faults)

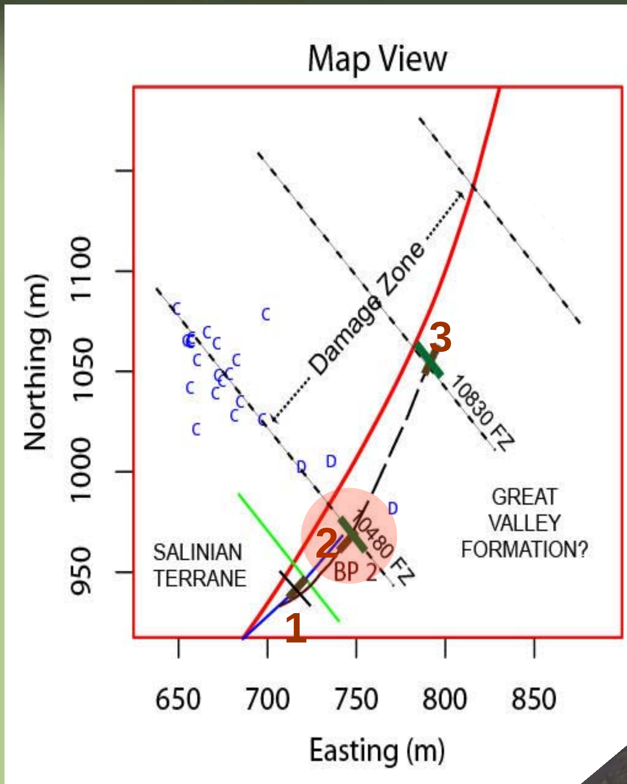
Interval 1- Near Salinian/Great Valley Contact

Cored from 10,306.5-10,346.6 ft



Interval 2 - Across 10,480' Fault Zone

Cored from 10,455.0-10,498.5 ft

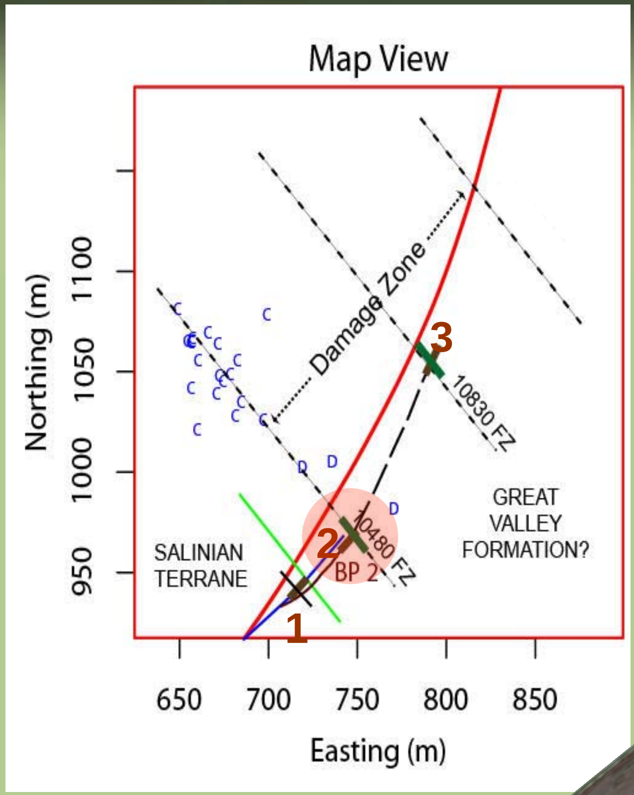


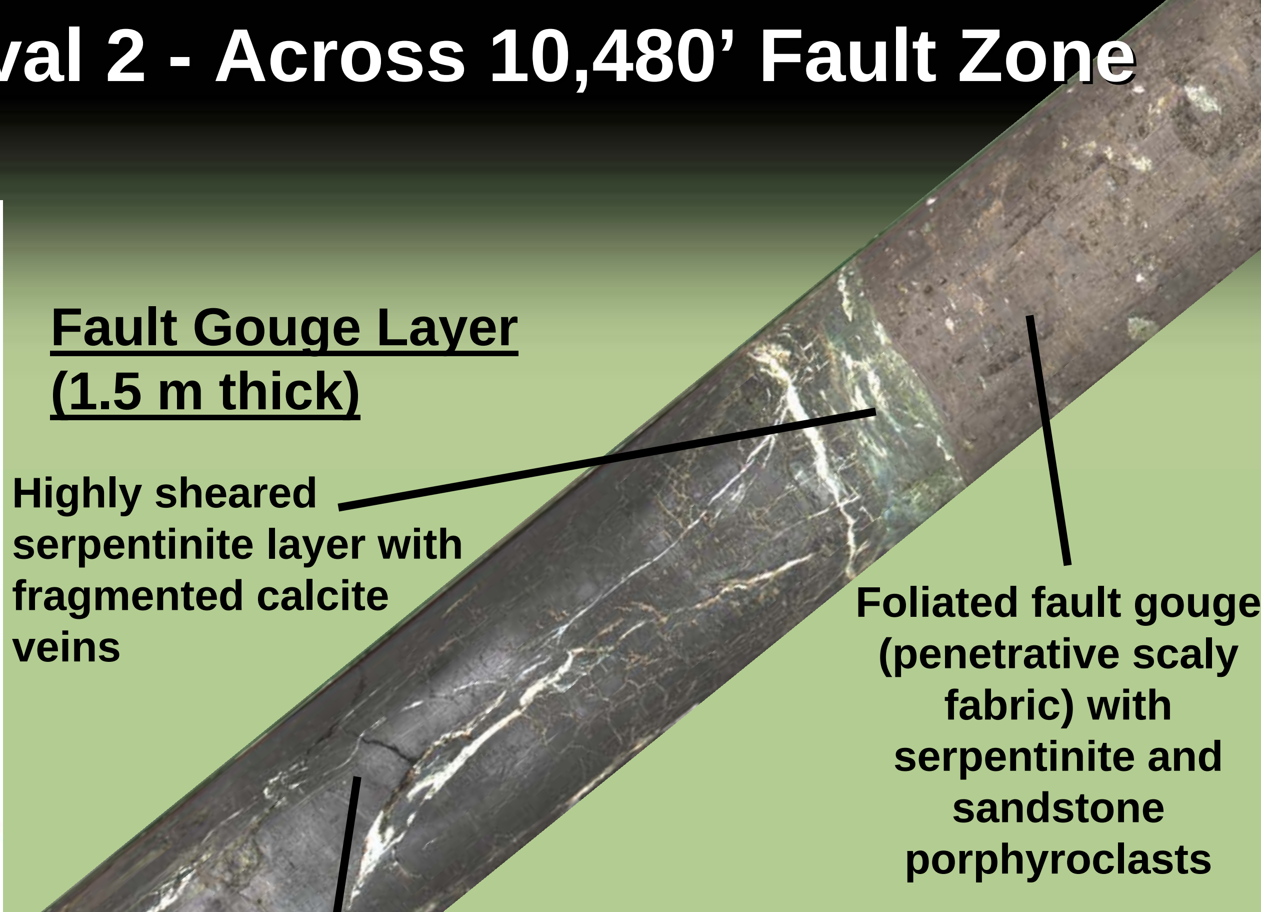
<u>Southwest of Fault Gouge Layer:</u>

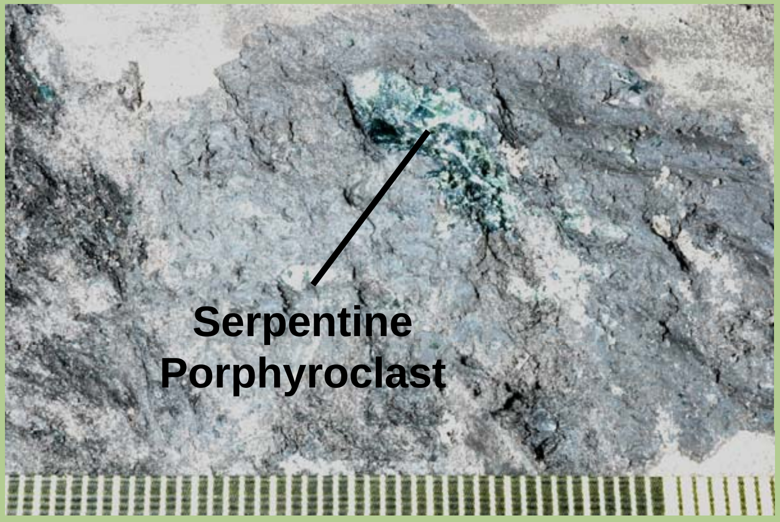
Variably sheared, thinly bedded cataclastic siltstone and shale

Fairly cohesive, with veined porphyroclasts

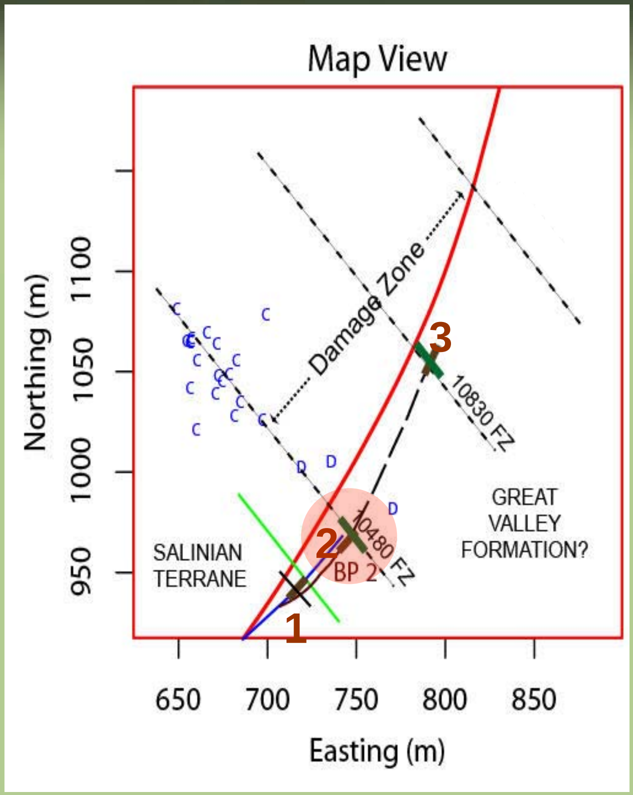
Interval 2 - Across 10,480' Fault Zone

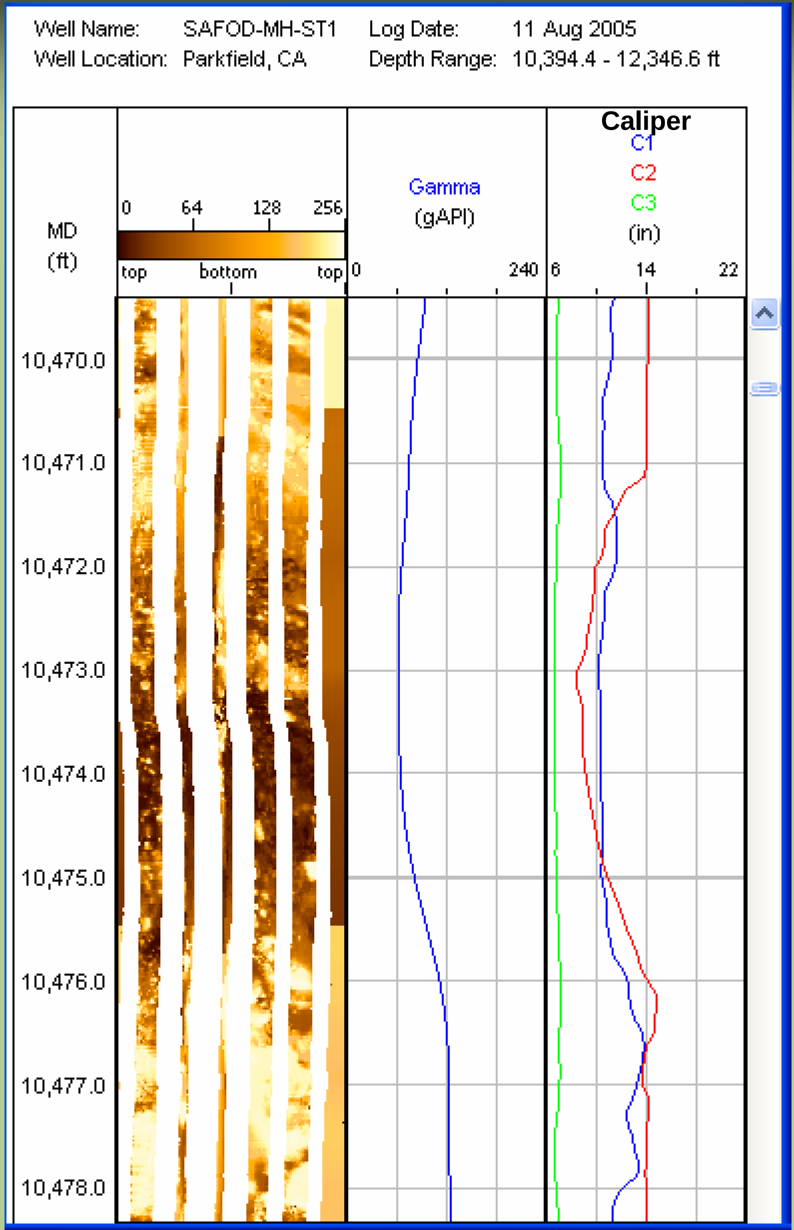






Wellbore Image of 10,480 Fault Zone from Baker Atlas Following 2005 Drilling



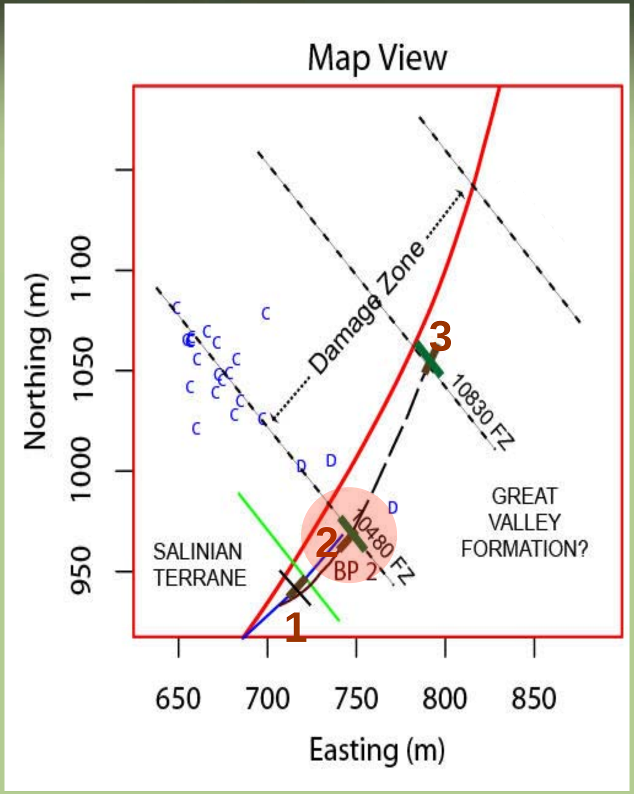


Casing Deformation (6/6/07 PMIT log)

Fault Gouge Layer in Phase 3 Core

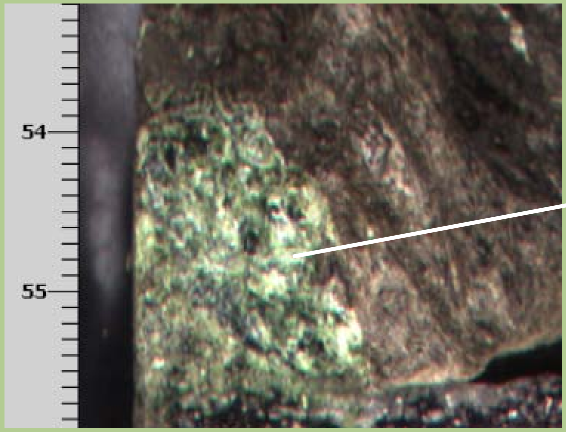
Depth correlations (±1 ft) based on natural gamma logs from Phase 2 hole (PMIT and Baker Atlas) and Phase 3 hole (Schlum. pipe-deployed)

Interval 2 - Across 10,480' Fault Zone



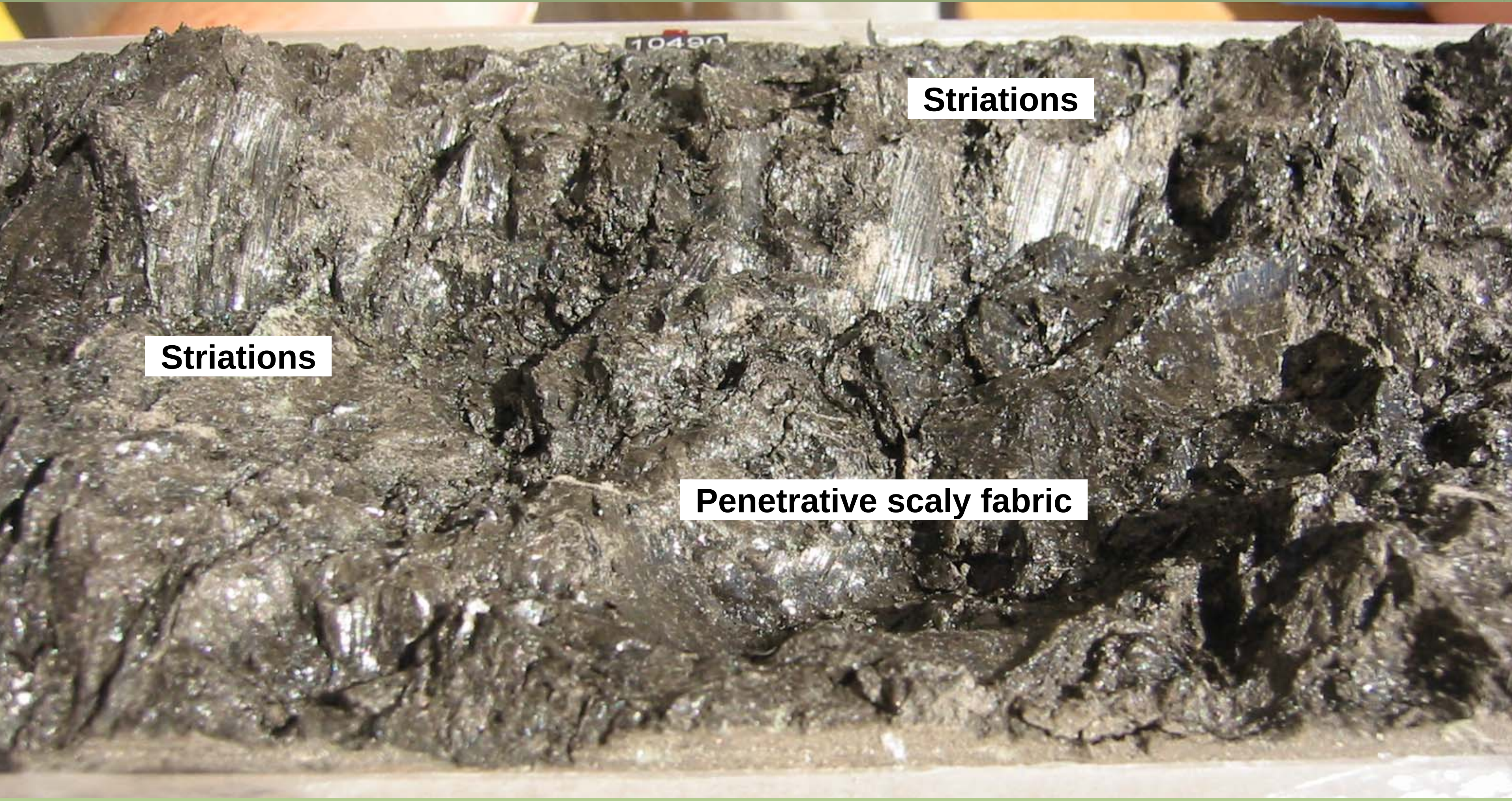
Internal structure of Foliated Fault Gouge revealed by parting of Core Run 2 Section 8 into two equal halves

Anastomozing microscale shears



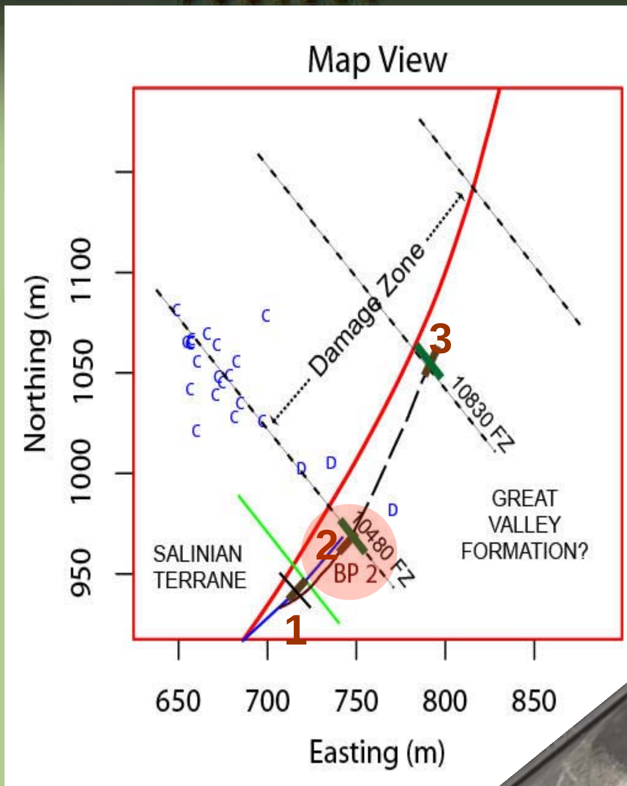
Serpentine clasts

Interval 2 - Across 10,480' Fault Zone

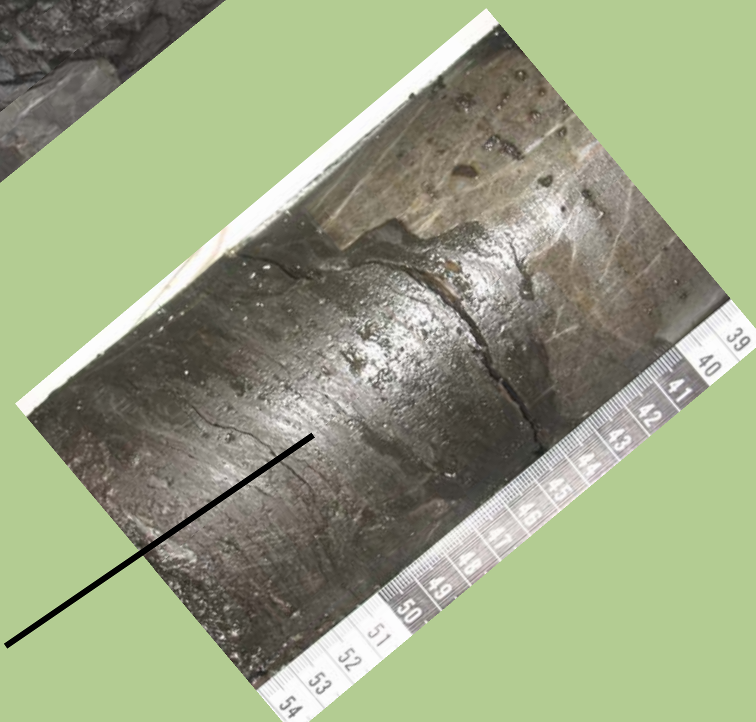


Close up of foliated fault gouge

Interval 2 - Across 10,480’ Fault Zone



Northeast Boundary of Fault gouge Layer



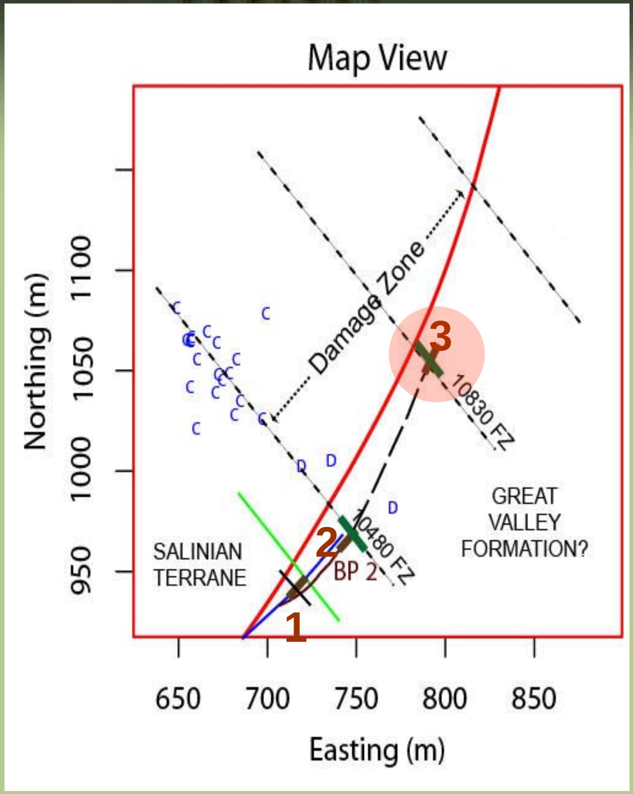
Cataclastic siltstone and shale

Veined quartz sandstone

Highly foliated and sheared shales

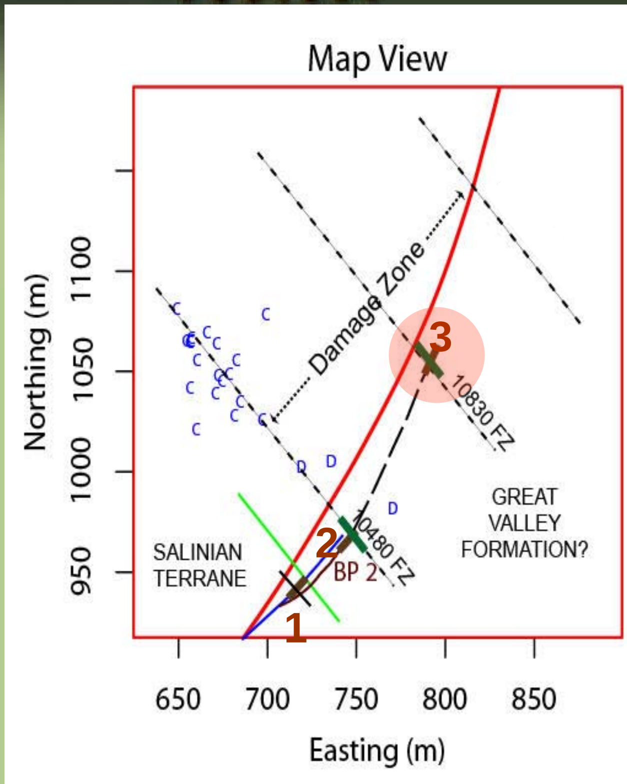
Interval 3 - Across 10,830' Fault Zone

Cored from 10,810.0-10,871.0 ft



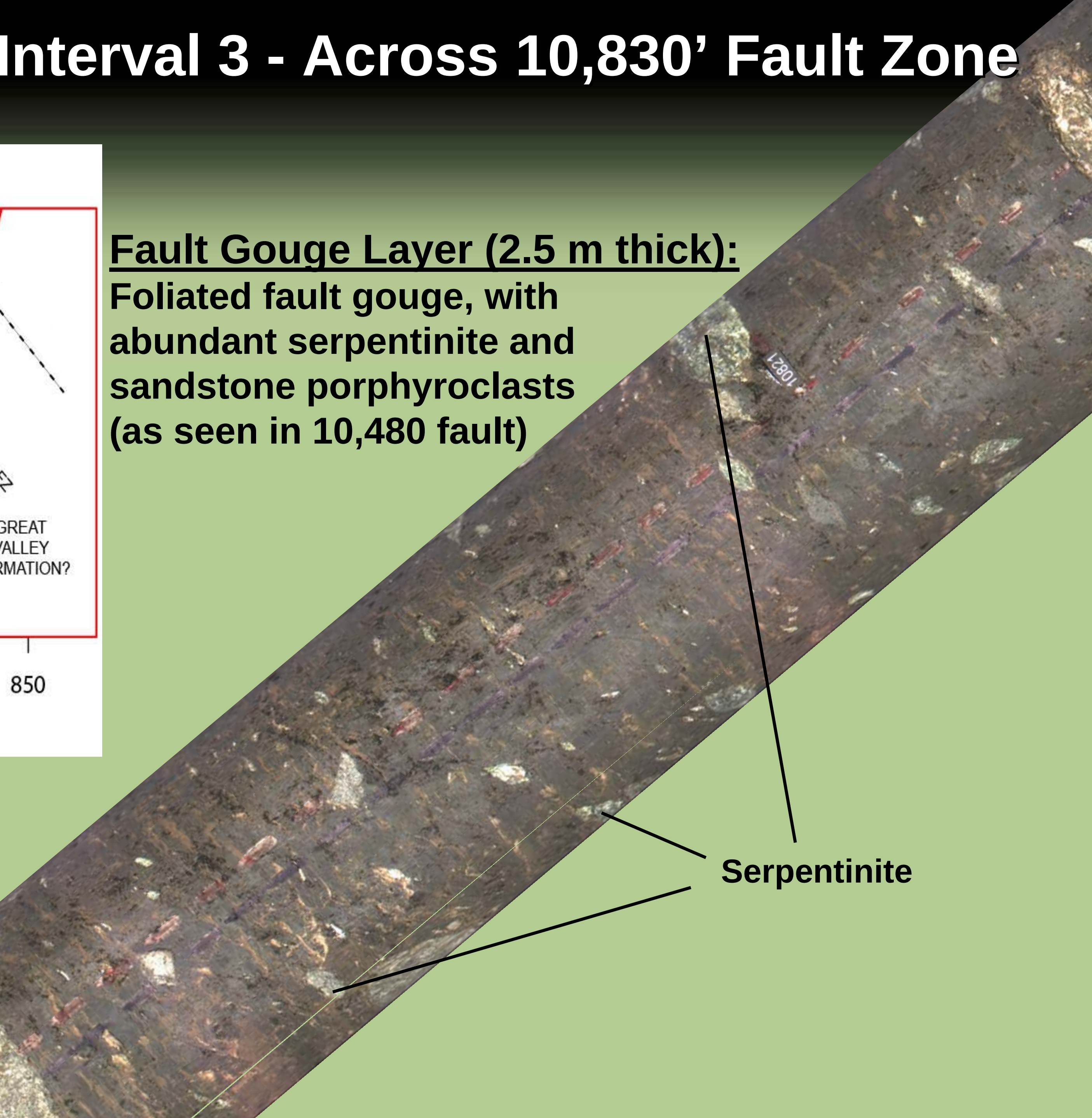
<u>SW of Fault Gouge Layer:</u>
Faulted and variably sheared, thinly bedded siltstones and fine- to medium-grained sandstones

Interval 3 - Across 10,830’ Fault Zone

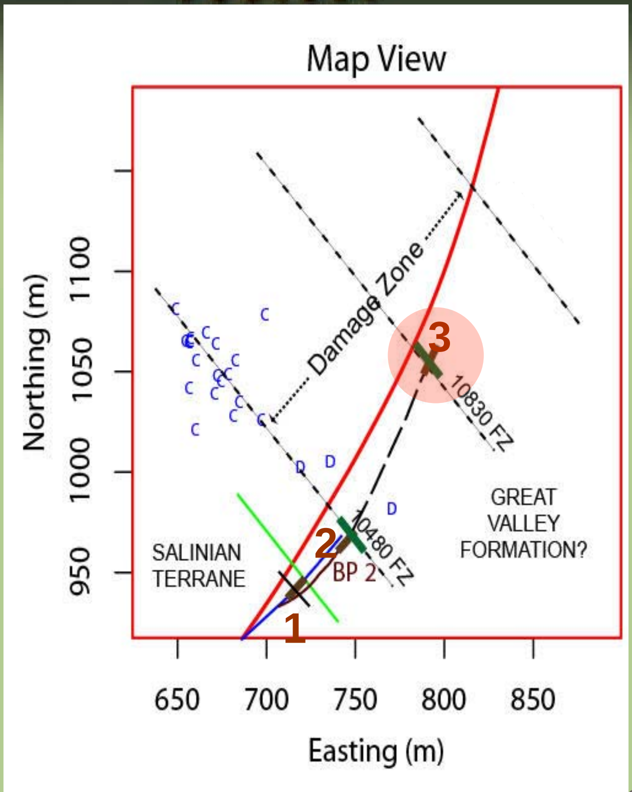


Fault Gouge Layer (2.5 m thick):

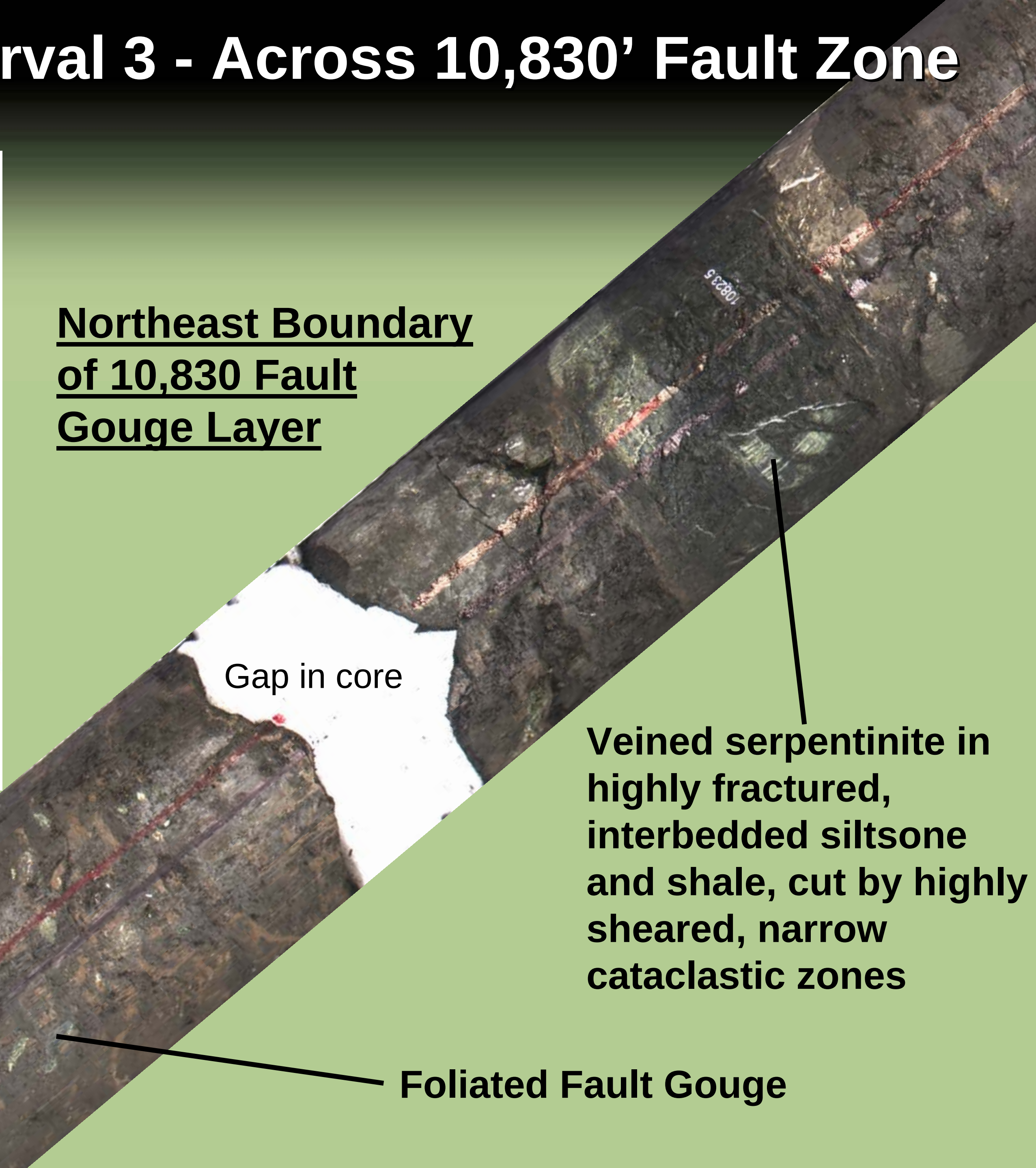
Foliated fault gouge, with abundant serpentinite and sandstone porphyroclasts (as seen in 10,480 fault)



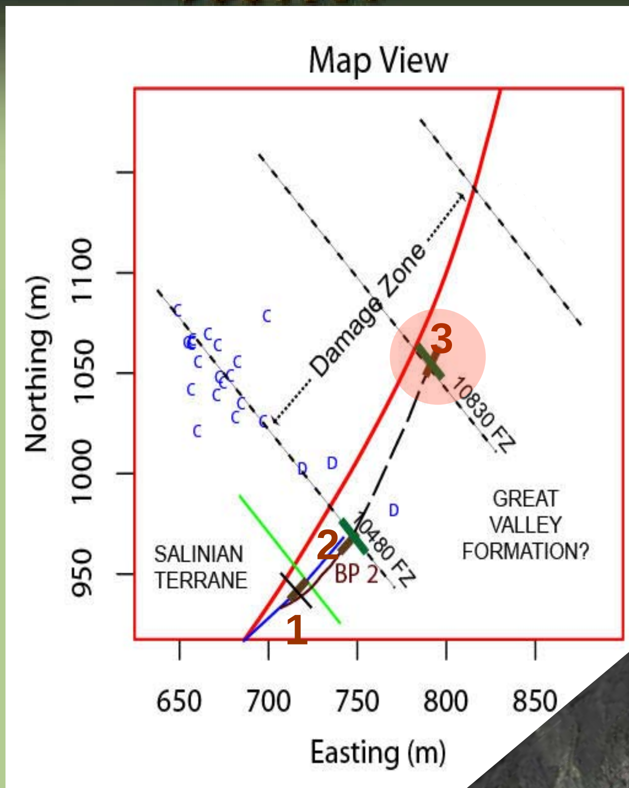
Interval 3 - Across 10,830' Fault Zone



Northeast Boundary of 10,830 Fault Gouge Layer

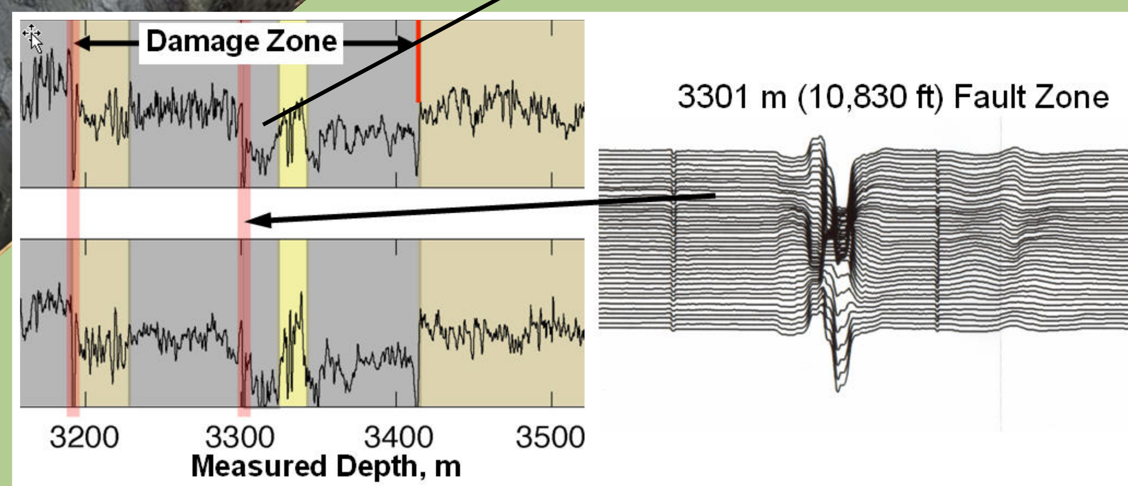


Interval 3 - Across 10,830’ Fault Zone



Northeast of 10,830’ Fault Gouge Layer

Highly Fractured Shales and Very Fine Sandstones (inner low velocity zone)



What Happens Next?

Priorities for Lab Measurements on Phase 3 Core Include (from SAFOD Advisory Panel):

- Mineralogy, elemental composition and isotope geochemistry: whole-rock, veins, and grain-scale.
- Deformation microstructures, particle- and pore-size distribution, and mesostructural analyses.
- Frictional strength and rheological properties (fault and country rock).
- Physical properties (permeability, poroelastic, seismic, thermal, resistivity, etc.).
- Liquid and gas geochemistry, bulk samples and fluid inclusions (major/minor elements and isotopes).
- Thermochronology and dating of host minerals and fault rock (U/Pb, Ar, FT annealing, ESR, TL dating, etc.).

Open Sample Party at USGS in Menlo Park, California, Dec 9, 2007 (Sunday before AGU mtg.):

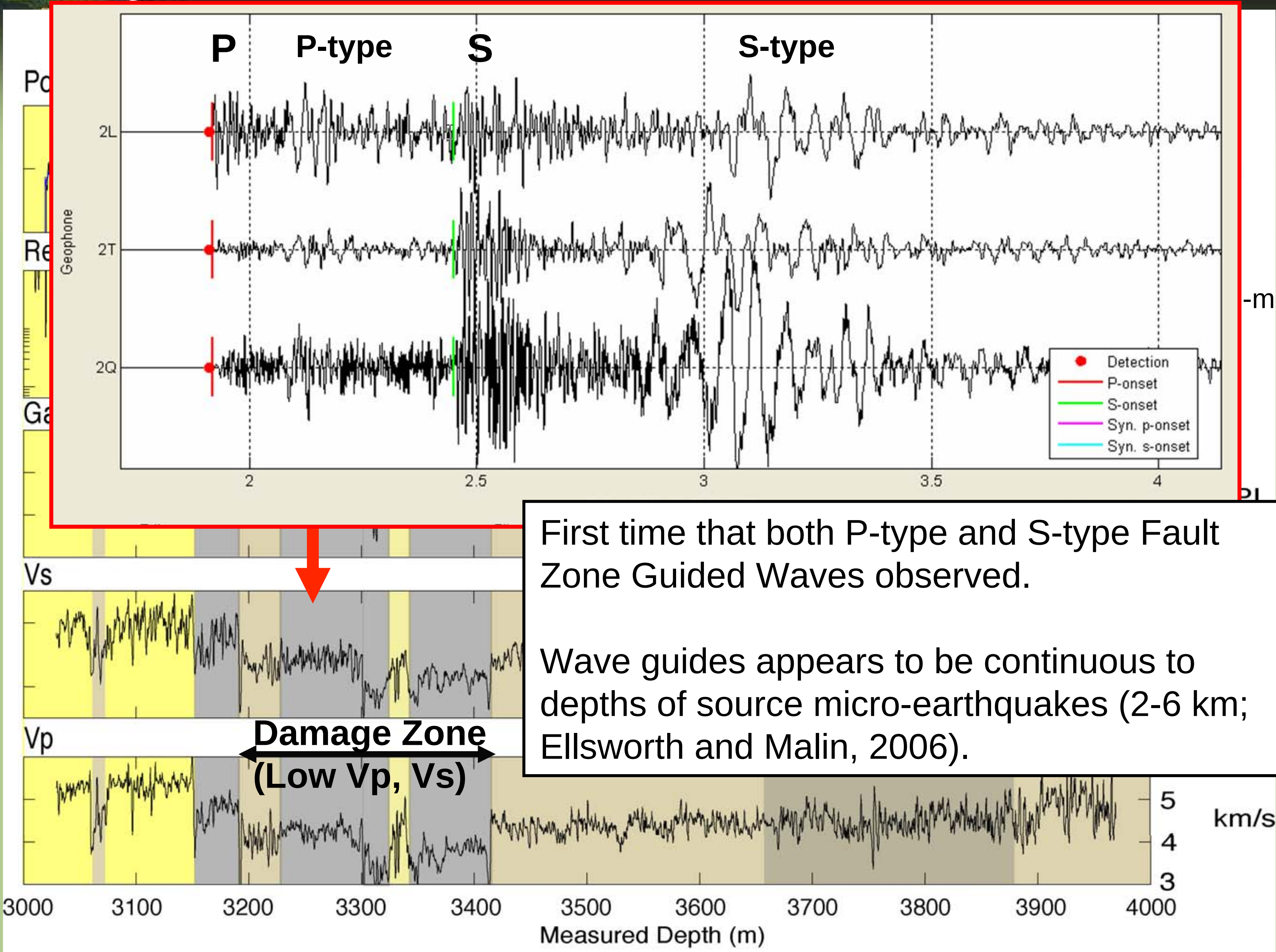
Send email to hickman@usgs.gov

Install downhole monitoring instruments in near field of M2 Hawaii target earthquakes (Spring, 2008):

- Seismometers
- Accelerometers
- Tiltmeters
- Fluid pressure transducer

SAFOD Phase 4 (coring EQs)??

M 1.3 Earthquake in San Andreas Fault Zone Feb 6, 2006
Recorded Downhole at 3260 m (EQ ~4 km below sonde)



First time that both P-type and S-type Fault Zone Guided Waves observed.

Wave guides appears to be continuous to depths of source micro-earthquakes (2-6 km; Ellsworth and Malin, 2006).

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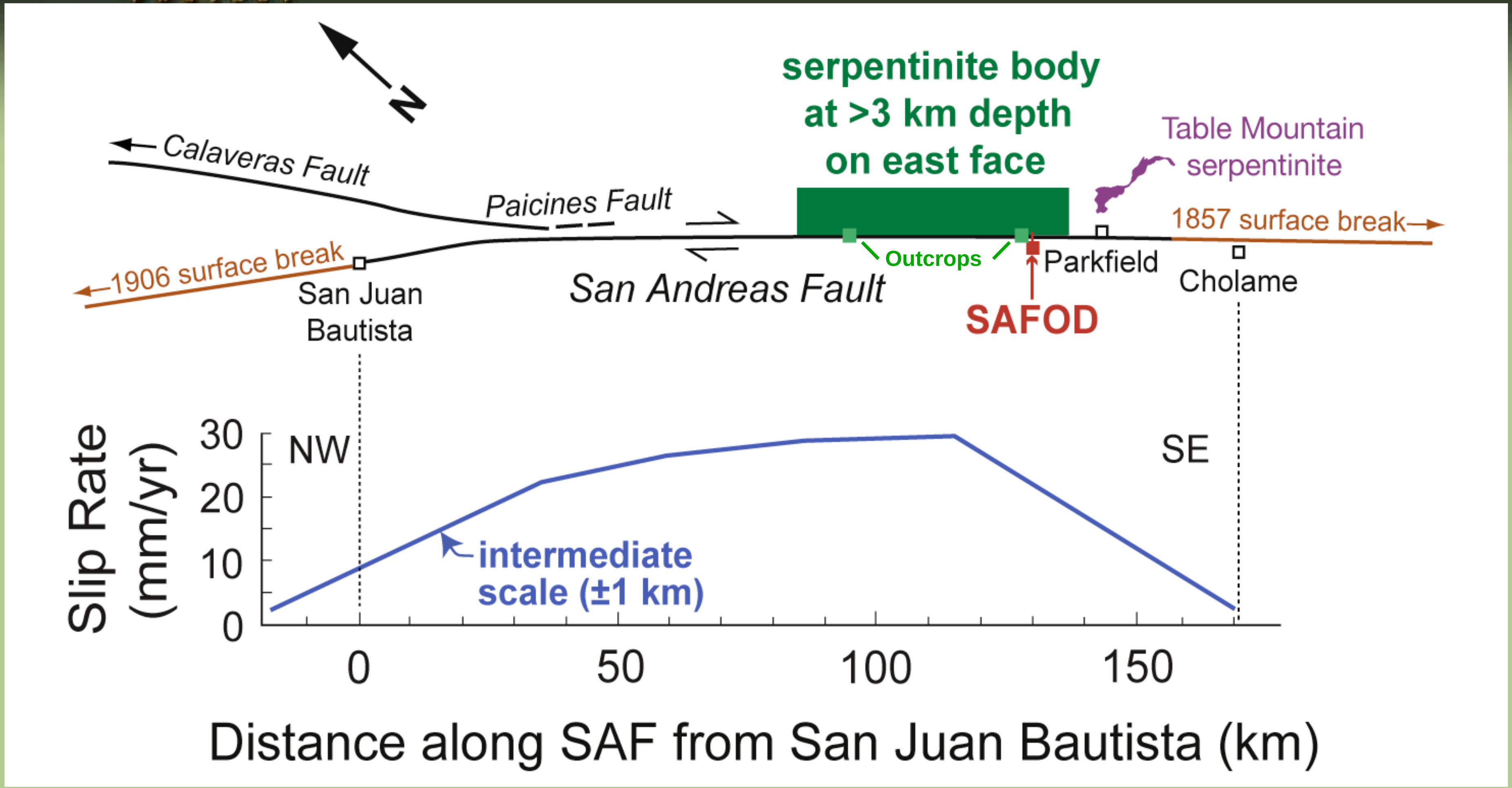
Install downhole monitoring instruments in near field of M2 Hawaii target earthquakes (Spring, 2008):

- **Seismometers**
- **Accelerometers**
- **Tiltmeters**
- **Fluid pressure transducer**

Serpentine in San Andreas Fault:
Is this why it's creeping?

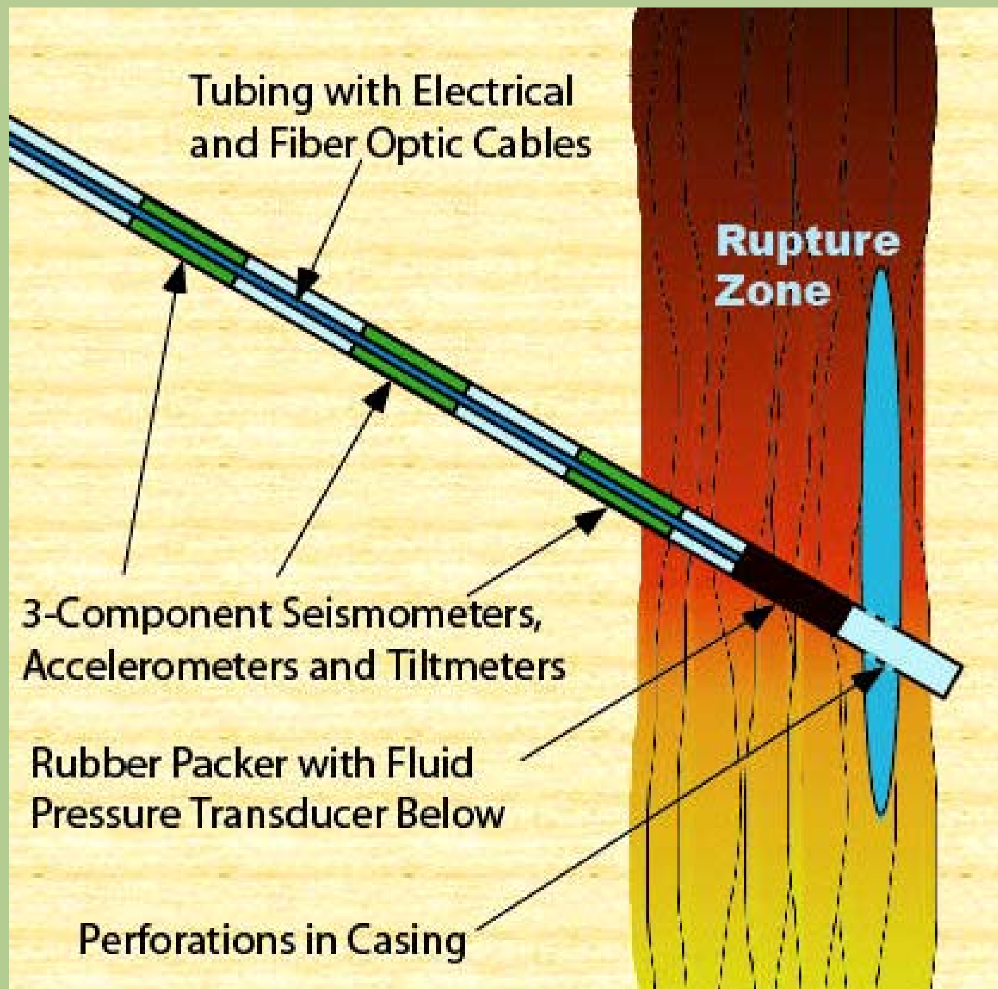


Creep in serpentinites can result from:

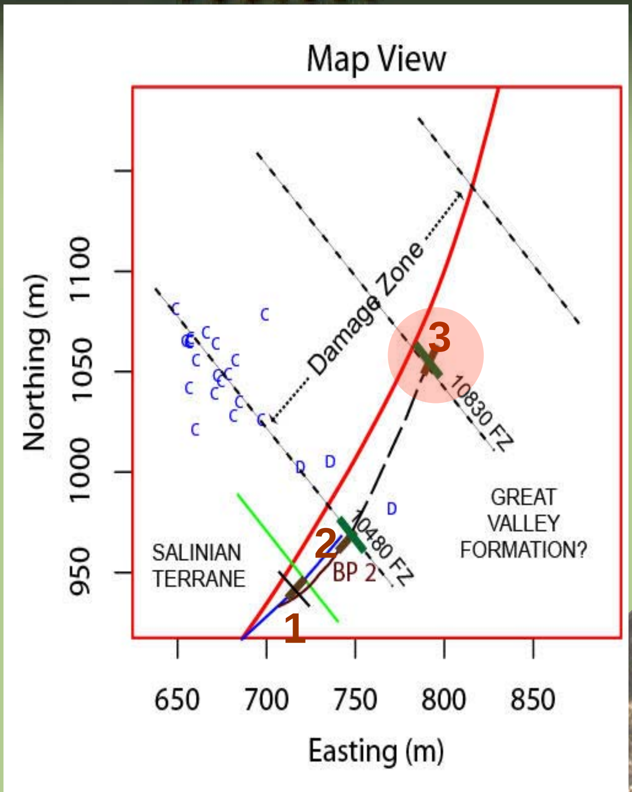
- **Velocity-strengthening friction (e.g., Reinen et al., 1991; Moore et al, 1998).**
- **Syntectonic dissolution-diffusion-crystallization, as inferred for Santa Ynez Fault in S. Calif. (Andreani et al, 2005).**

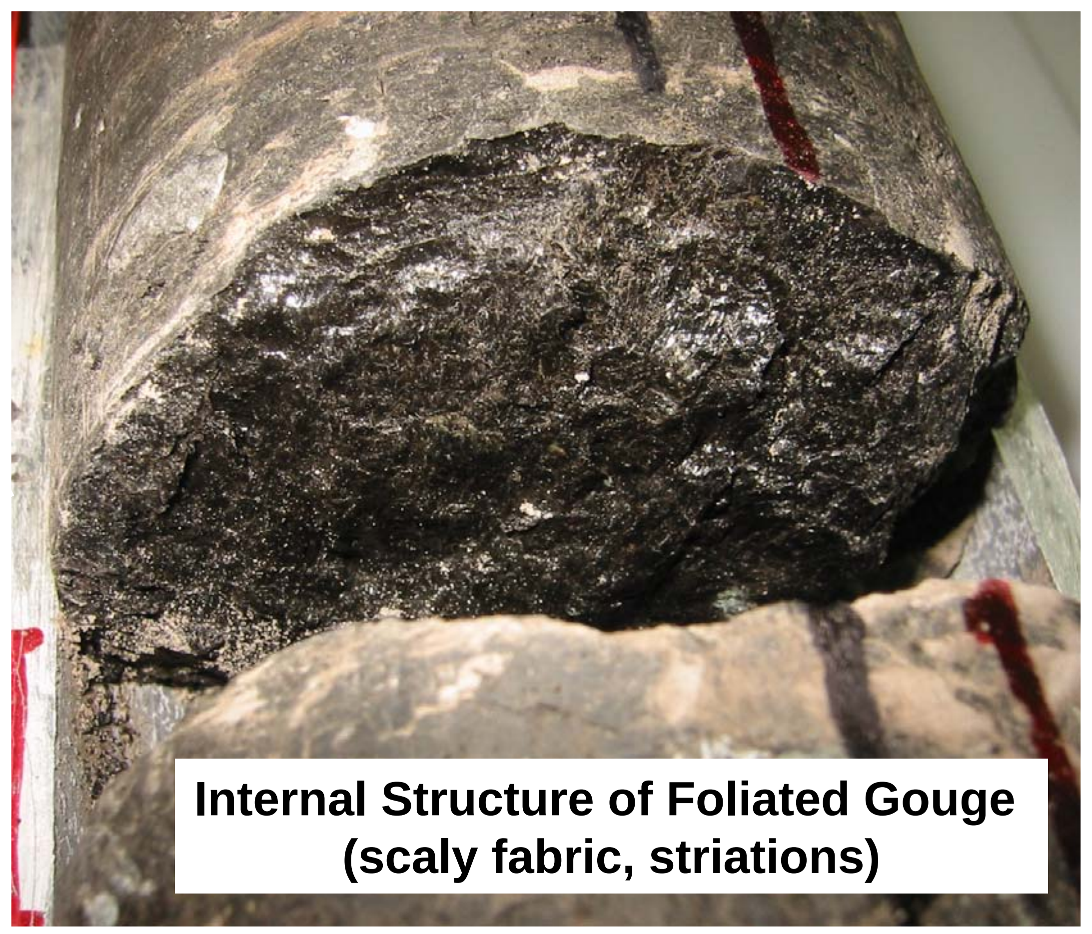
Stage 3 Monitoring Array

Spring 2008: Install retrievable monitoring array directly inside the fault zone (*Core Hole 2*)



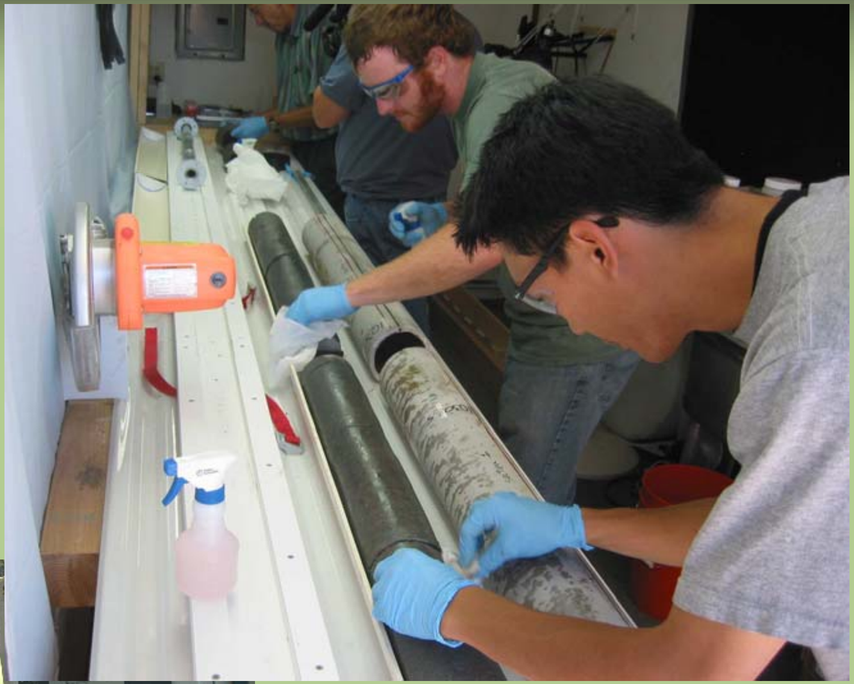
Interval 3 - Across 10,830' Fault Zone





Internal Structure of Foliated Gouge (scaly fabric, striations)

First core Out of the Barrel!



Recommended Priorities for Measurements on SAFOD Core, *SAFOD Advisory Board, Jan 2006*

(1: critical, 2: very important, 3: desirable)

On-site characterization and sub-sampling:

- **Reconnaissance mesostructural descriptions (lithology; core condition and contiguity; orientation, distribution and cross-cutting relationships of fractures and veins) – 1**
- **High resolution photography, including 360° scans if conditions permit – 1**
- **Multi-sensor track physical property logging on core (resistivity, density, magnetic susceptibility, natural gamma) – 2**
- **Liquid and gas extraction from core for geochemistry (major and minor elements, stable isotopes, noble gasses) – 2**
- **On-site core sub-sampling for microbiology and organic geochemistry – 2**

Recommended Priorities for Measurements on SAFOD Core (cont.)

(1: critical, 2: very important, 3: desirable)

Studies to be conducted later – Fault and country rocks:

- **Frictional, dilatational and rheological (e.g., creep) properties – 1**
- **Permeability, resistivity, porosity and poroelastic properties – 1**
- **Microstructural analyses (particle-size distribution, deformation microstructures, grain-scale mineral redistribution) – 1**
- **Mineralogy (XRD) and petrography (optical) – 1**
- **Detailed mesostructural core descriptions – 1**
- **Core reorientation for selected intervals (using image log correlation or paleomagnetic techniques) – 1**
- **Geochemical analyses of veins, fluid inclusions and bulk fluid samples (major and minor elements, stable isotopes, gases) – 1**

Recommended Priorities for Measurements on SAFOD Core (cont.)

(1: critical, 2: very important, 3: desirable)

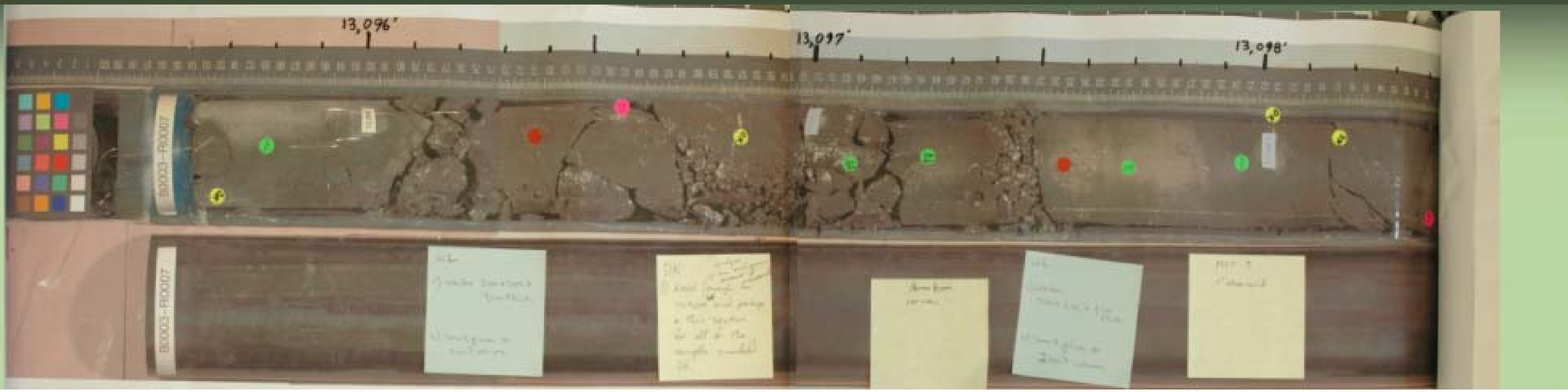
Studies to be conducted later – Fault and country rocks (cont.):

- **Seismic properties (velocities, anisotropy, attenuation) – 1**
- **Physical property measurements on representative core materials, for correlation with geophysical logs and tomographic surveys – 1**
- **Bulk elemental composition, for nature and extent of fluid-rock interaction – 2**
- **Thermochronology and dating, especially fault rocks and veins – 2**
- **Thermal conductivity, specific heat and radiogentic heat production – 2**
- **Magnetic properties (anisotropy of susceptibility, magnetic mineralogy) – 3**
- **X-Ray Tomography on selected cores – 3**
- **Microbial activity and organic analysis – 3**

Sample Request Process: How it Worked for SAFOD Phases 1 and 2

- Requests for samples using SAFOD Sample Request Form (available on EarthScope and SAFOD ICDP web sites).
- After NSF approves of request, it is forwarded to staff of GCR who:
  - Prepare subsamples, usually in consultation with requesting scientist.
  - Send information on subsamples to SAFOD Data Manager, for entry into SAFOD ICDP data base.
  - Send samples to requesting scientist.
- In cases where multiple researchers requested samples in close proximity to each other, several iterations were needed before final sample dispensation was arrived at.
- In all cases consensus agreement was reached that met everybody’s needs (i.e., process worked quite well).

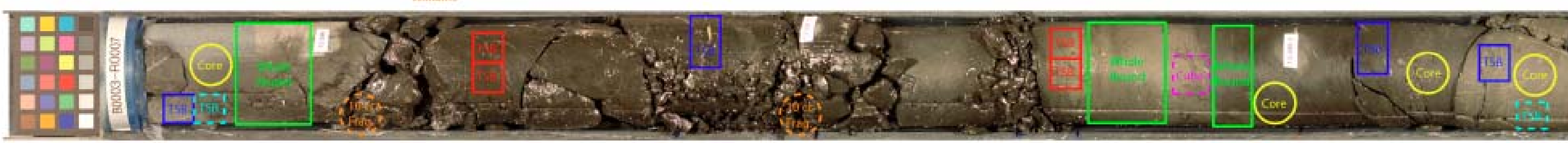
Phase 2 Spot Core: Initial Sample Requests from Sample Party (7 research groups)



Phase 2 Spot Core: Final Consensus on Sample Distribution

SAFOD Run 0007 Box 0003 Front

Chester (pending)
Kirschner
Lockner
Marone
[illegible]
Schleicher
Williams



SAFOD Run 0007 Box 0003 Back

Sample Request Process: How Will It Work for SAFOD Phase 3?

- Greater likelihood of conflicting requests for Phase 3 core, when we recover core from active traces of San Andreas Fault.
- Thus, following approval of initial proposals by NSF, all requests for Phase 3 core will be passed on to independent SAFOD Sample Committee (SSC).
- SSC decides how core is to be used, who gets the samples, and in what order (i.e., for sequential measurements on same samples).
- Following approval by SAFOD Advisory Board and NSF, SSC was populated with experts in microstructures, mineralogy/geochemistry, rock mechanics and core handling/curation who are not involved in SAFOD.
- SSC Members: Co-Chairs - Brian Evans (MIT) and Jan Tullis (Brown Univ.); Dave Olgaard (ExxonMobil), John Firth (IODP Gulf Coast Repository), Emi Ito (Univ. Minnesota), Andy Kronenberg (TAMU), John Logan (Univ. Oregon), Peter Vrolijk (ExxonMobil)

SAFOD Core Archiving Procedure

Following procedure recommended unanimously by participants in 2004 SAFOD Samples Workshop and approved by SAFOD Advisory Board:

- SAFOD core left intact wherever possible and subsamples obtained from intact piece (I.e., core *not* routinely cut into working and archive halves).
- When large volumes of sample required (e.g., for preparing oriented minicores), a minimum 1.5-cm-thick chord is cut lengthwise off of the main SAFOD core and set aside as an archive.

Advantages of this procedure are:

1. Guarantees that some SAFOD core retained from all depths.
2. Leaves large enough piece of core intact to allow for rock physics investigations.
3. Avoids problems associated with trying to uniformly split SAFOD core lengthwise when it is highly fractured and disaggregated.

How is SAFOD core being preserved?

SAFOD core is being preserved at the IODP Gulf Coast Repository (GCR) following standard IODP core curation protocol:

1. Core placed in half-round PVC tubes; cleaned, aligned and labeled; preliminary petrographic descriptions prepared, and core photographed.
2. Core hermetically sealed in shrink wrap plastic to prevent desiccation and chemical interaction with the atmosphere and placed in core storage boxes.
3. Sealed and boxed cores stored under constant refrigeration at 4º C at the GCR until needed for examination or subsampling by the GCR staff or members of the SAFOD science team.
4. All subsampling performed in GCR core handling labs by experienced GCR staff or under the direction of these staff, after which the core is resealed in shrink-wrap plastic and returned to the refrigerated core storage lockers.
5. GCR maintains records on sample dispensation, which are regularly forwarded to SAFOD Data Manager for posting on SAFOD web site.

The CoreWall Suite

(Morin, Ito et al., LACCore, University of Minnesota)

Corelyzer

- The primary user interface for visual core description
- Cross platform
  - Windows, OSX, Linux
- Displays:
  - Core images
  - Multi-sensor core-logger data
  - Smear slides and other images from microscopes
  - Interpretation and comments from all users
  - Links to related data, papers, websites
- Can display more data/images than can be held in main memory
- Can be extended by users with plug-ins

earth scope PROJECT

Attended by 48 scientists from U.S. Universities, USGS and DOE labs, and foreign institutions.

SAFOD Phase 2 Sample Party: 4 December 2005

Scientific and Operational Background

12:00 *Introduction*, Steve Hickman

12:15 *Geophysical Logging Results from Phases 1 and 2,* Mark Zoback and Naomi Boness

12:30 *Locations of the Target Earthquakes*, Bill Ellsworth

12:45 *SAFOD Sampling and Sample Policy*, Steve Hickman

Synoptic Mineralogy and Physical Properties (mostly from cuttings)

1:00 *Geologic and Lithologic Overview of Phases 1 and 2*, Jim Evans, Sarah Draper and Diane Moore

1:20 *XRD Mineralogy and Rock Strength from Phases 1 and 2*, John Solum and Sheryl Tembe

SAFOD Core and Fluid Samples

1:40 *Textural and Mineralogical Evaluation of Phase 2 Side-Wall Cores*, John Solum, Diane Moore and Judi Chester

2:00 *Structure and Lithology of Large-Diameter (“Spot”) Cores from Phases 1 and 2*, Judi Chester, Fred Chester and Diane Moore

2:20 *Status of Core Orientation from Phase 1*, Ben van der Pluijim (for Josep Pares) and Fred Chester

2:35 *Phase 2 Miscellaneous Rock Samples and Paleontology*, Diane Moore

2:50 *Mud Gas Logging and Fluid Sampling from Phases 1 and 2,* Thomas Wiersberg and Jim Thordsen

Open Sample Party (Coffee and Refreshments Served)

3:05 - Examination of core, miscellaneous rock samples, cuttings and thin sections
- Informal discussions of research plans and sampling needs (aided by previews of AGU posters from SAFOD Special Session)
- Submission of sample requests

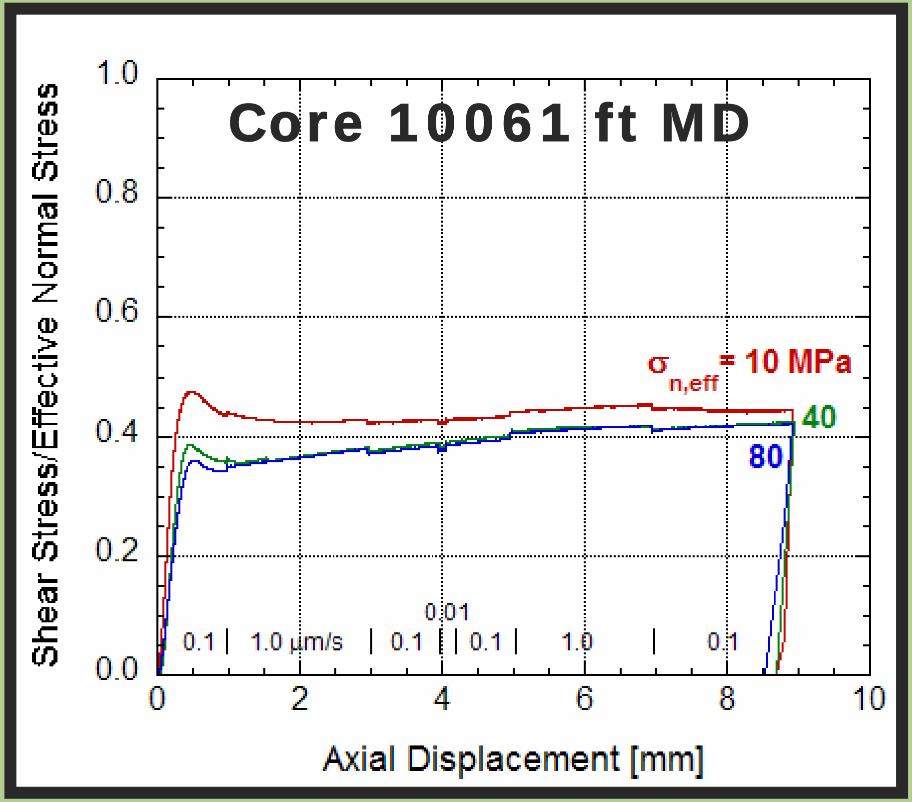
6:00 Tour of USGS Rock Mechanics Lab and Discussion of Sample Preparation Techniques (***Optional***), Dave Lockner and Diane Moore

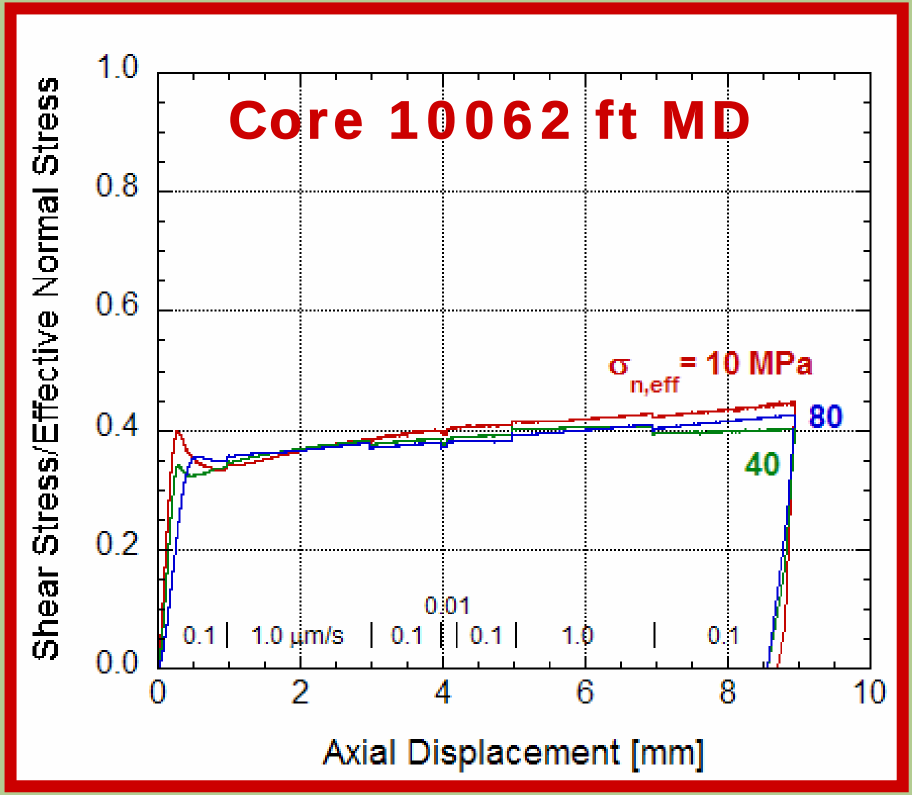
Testing of Shear Zone Cored at 3067 m MD

Clay-rich, heavily sheared

Velocity strengthening (creeping)

Weakest SAFOD samples tested so far



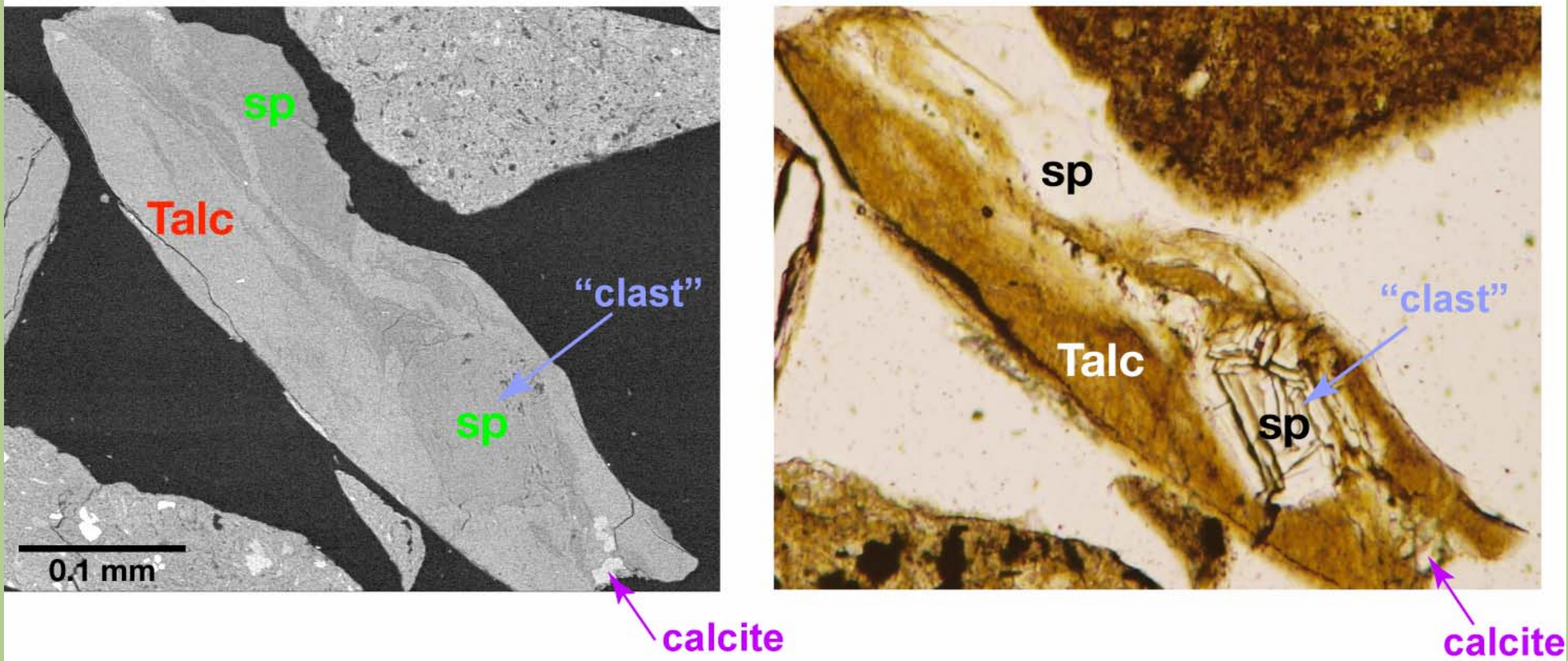


Tembe et al., 2006

Talc Found in SAFOD Cuttings near Primary Deformation Zone (*Moore et al, 2007*)

3325 m MD

Foliated (sheared?) serpentinite (sp) grain partly replaced by talc. The talc contains ≈5 wt% Fe-oxide, which gives it the brown color.



SEM: Backscattered Electrons | **Plane-Polarized Light**

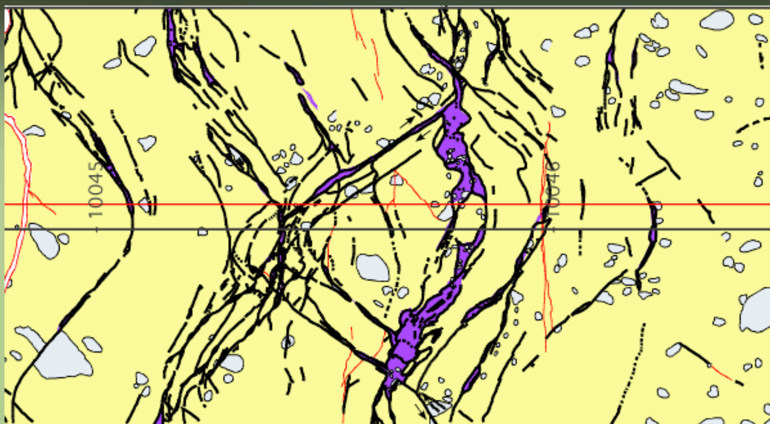
Talc is very weak *and* velocity strengthening (creeping) at seismogenic conditions

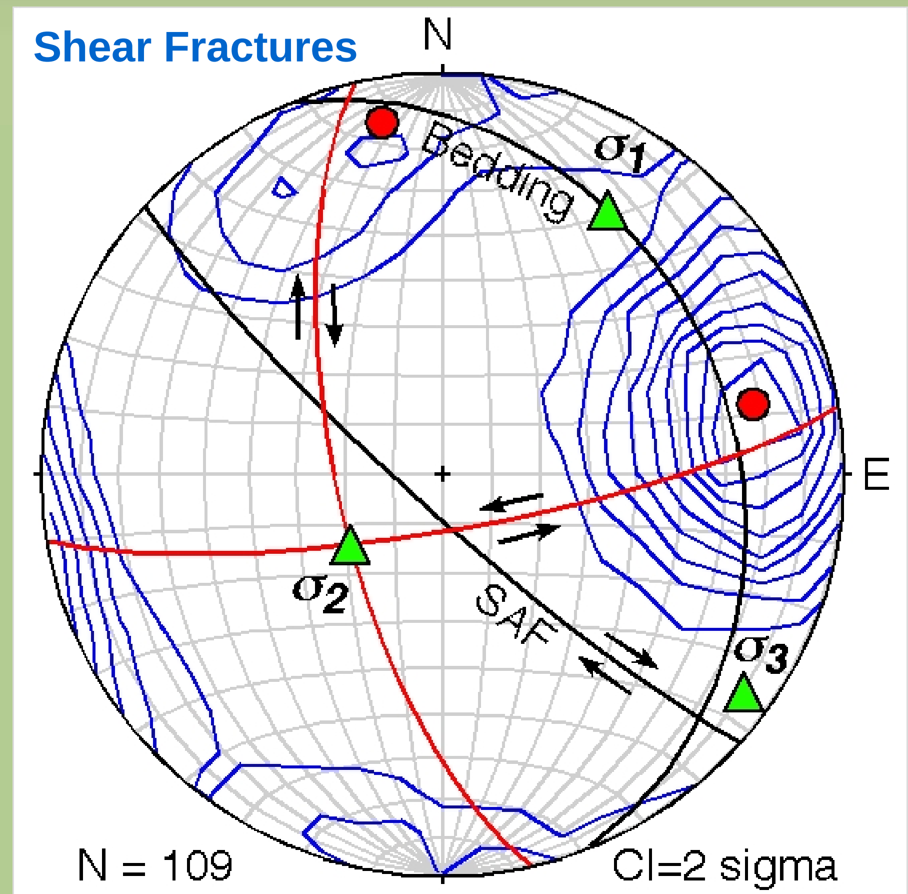
Spot Coring: Phases 1 and 2

Diamond Coring Bit

Shear Fracture Fabric in SAFOD Phase 1 Spot Core (3067 m MD)

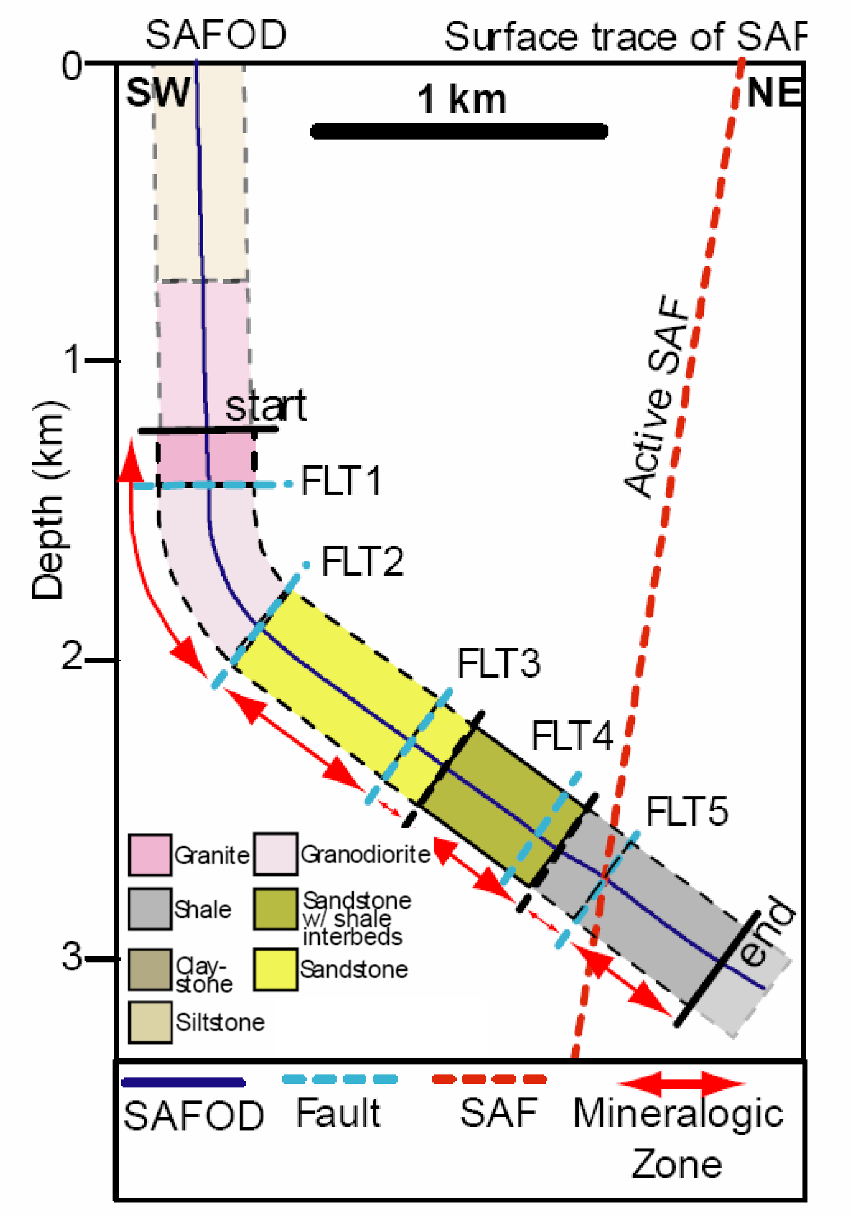
Almeida et al., 2007

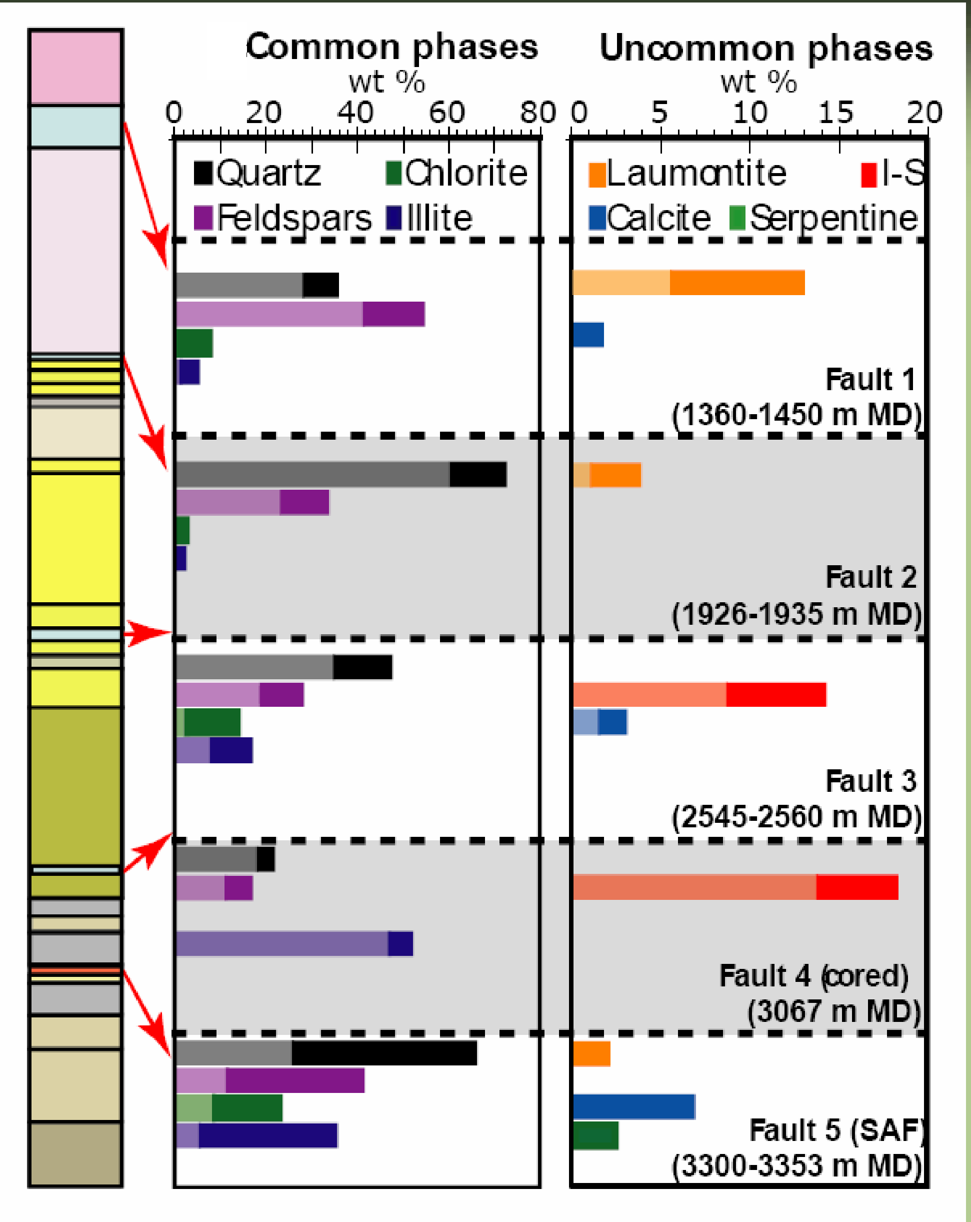




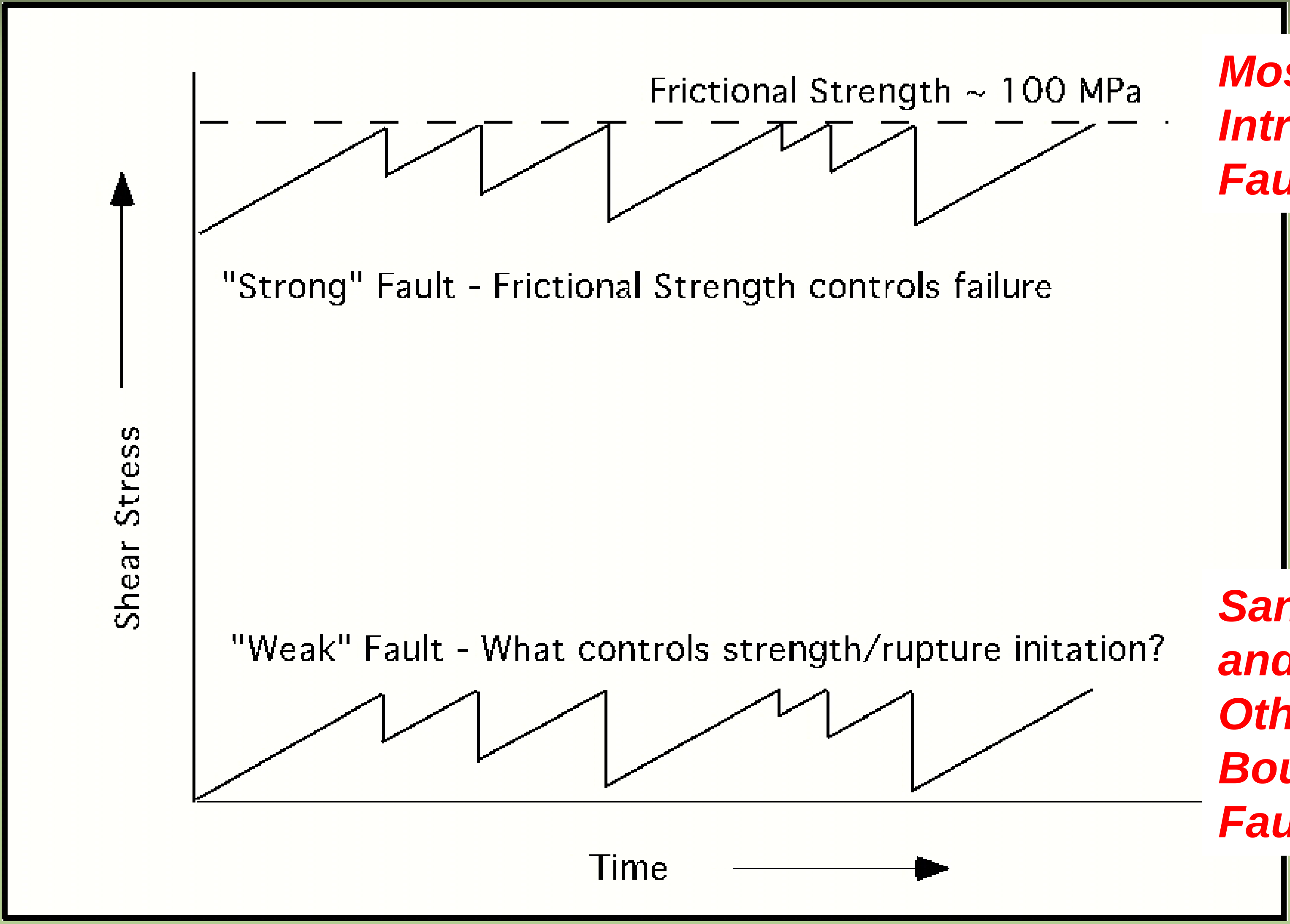
- Contour of poles to shear fractures, bedding and San Andreas Fault.
- Bedding strikes subparallel to San Andreas and dips slightly toward fault.
- **Red dots** are best-fit planes to conjugate shear fracture sets.
- Principal paleostress axis: σ_1 at ~ 80° to plane of San Andreas Fault

Mineralogy of Fault Zones Crossed by SAFOD
(XRD analyses on cuttings by Solum et al, 2006)





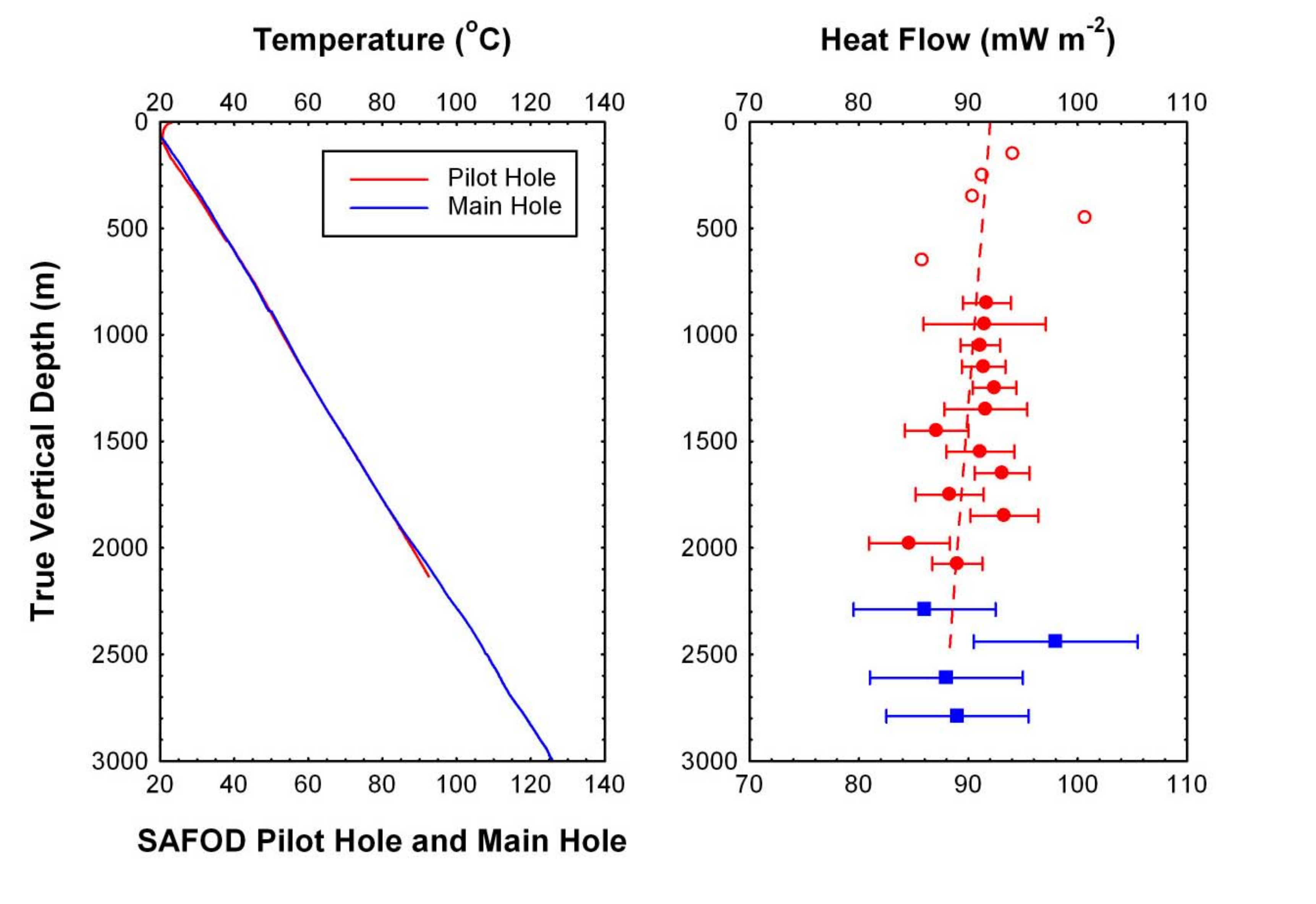
Previous Heat Flow and Stress Results Suggest SAF is Weak Fault in an Otherwise Strong Crust



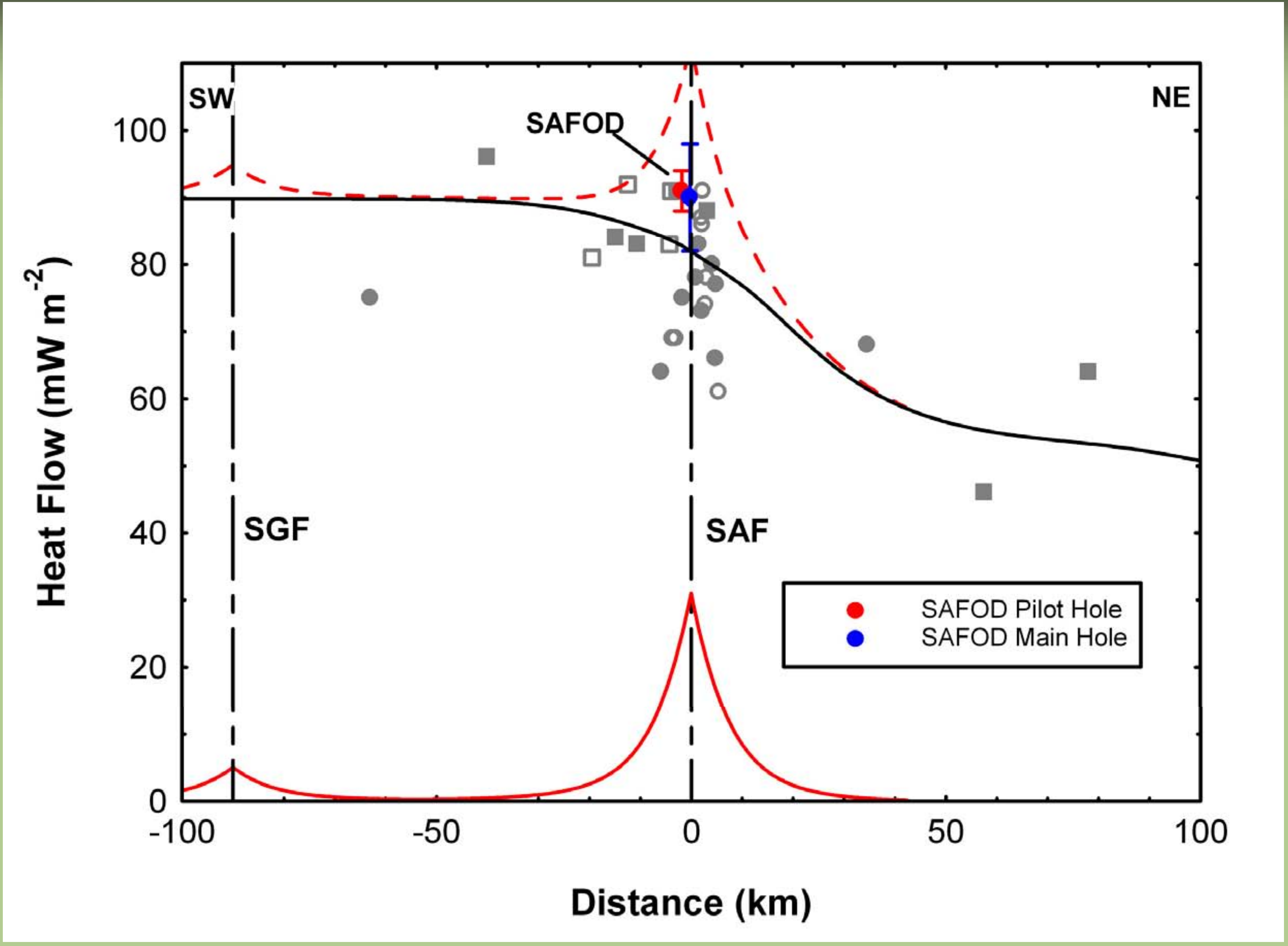
Most Intraplate Faults

San Andreas and Many Other Plate Boundary Faults

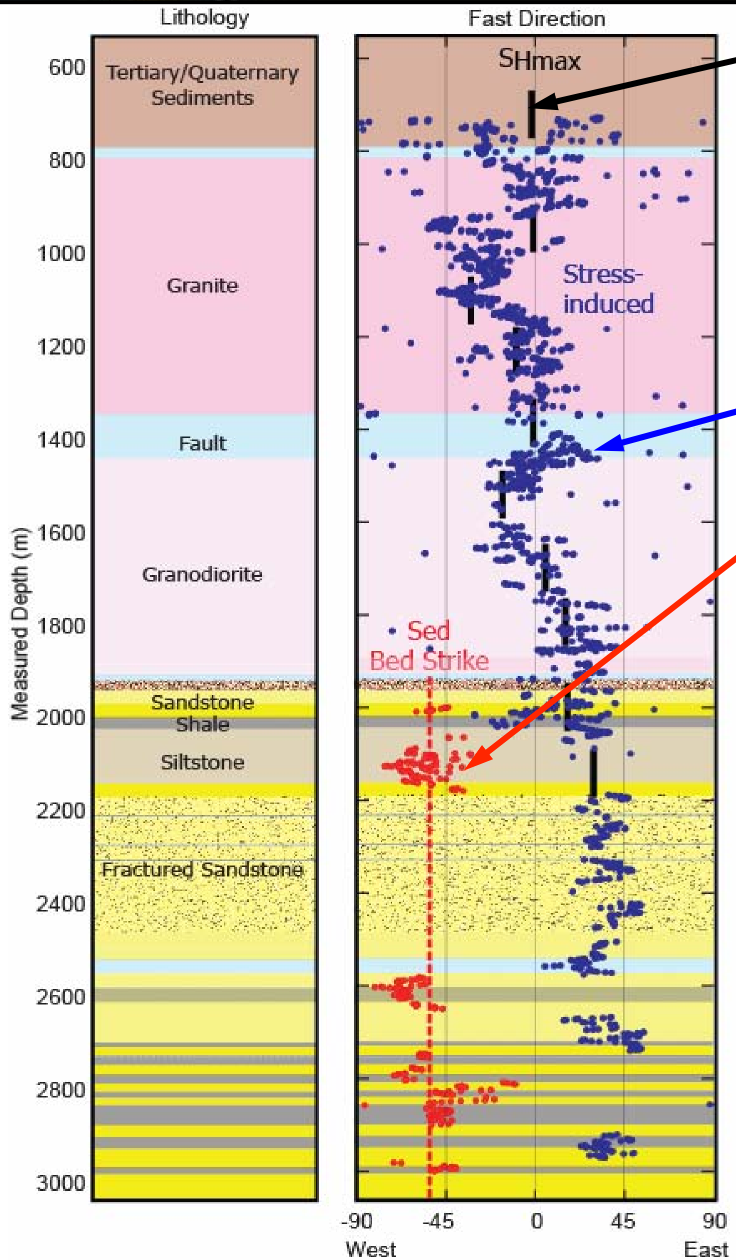
Heat Flow in SAFOD Main Hole and Pilot Hole
(*Williams et al., 2004, 2006*)



Heat Flow in SAFOD Main Hole and Pilot Hole
(*Williams et al., 2007*)

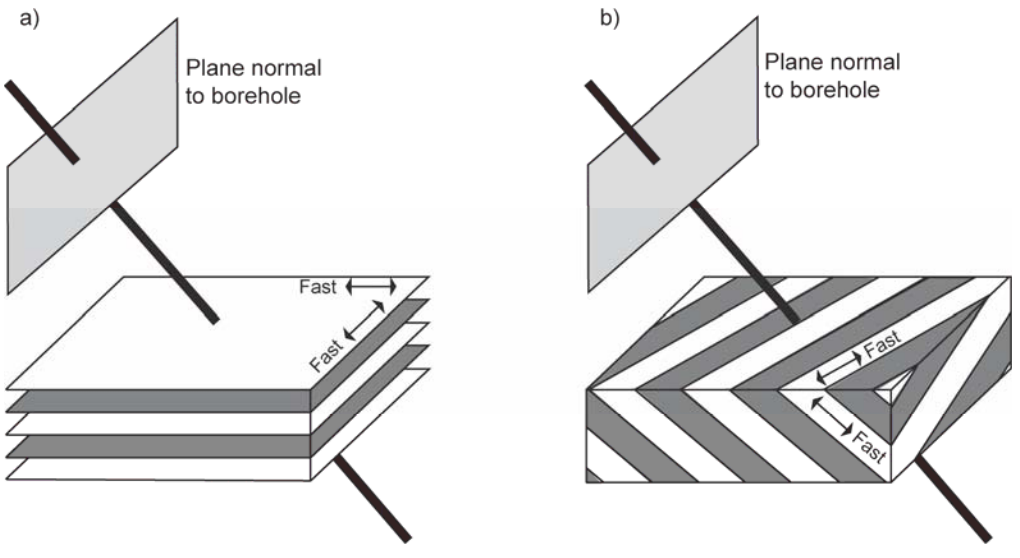


But What is S_{HMax} Direction Close to SAF at Depth?

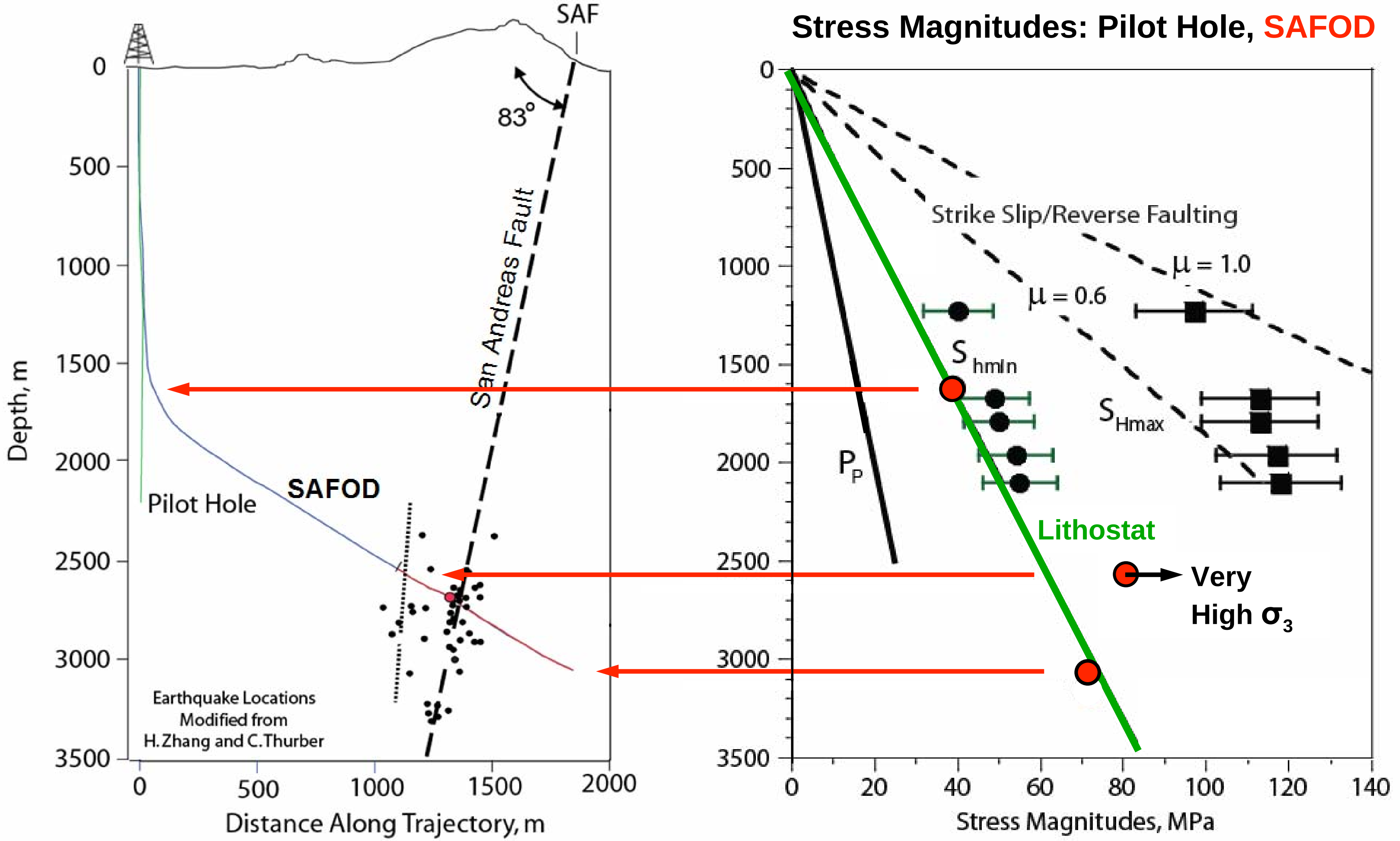


S_{Hmax} Direction in Pilot Hole from Breakouts and Tensile Cracks
(Hickman and Zoback, 2004)

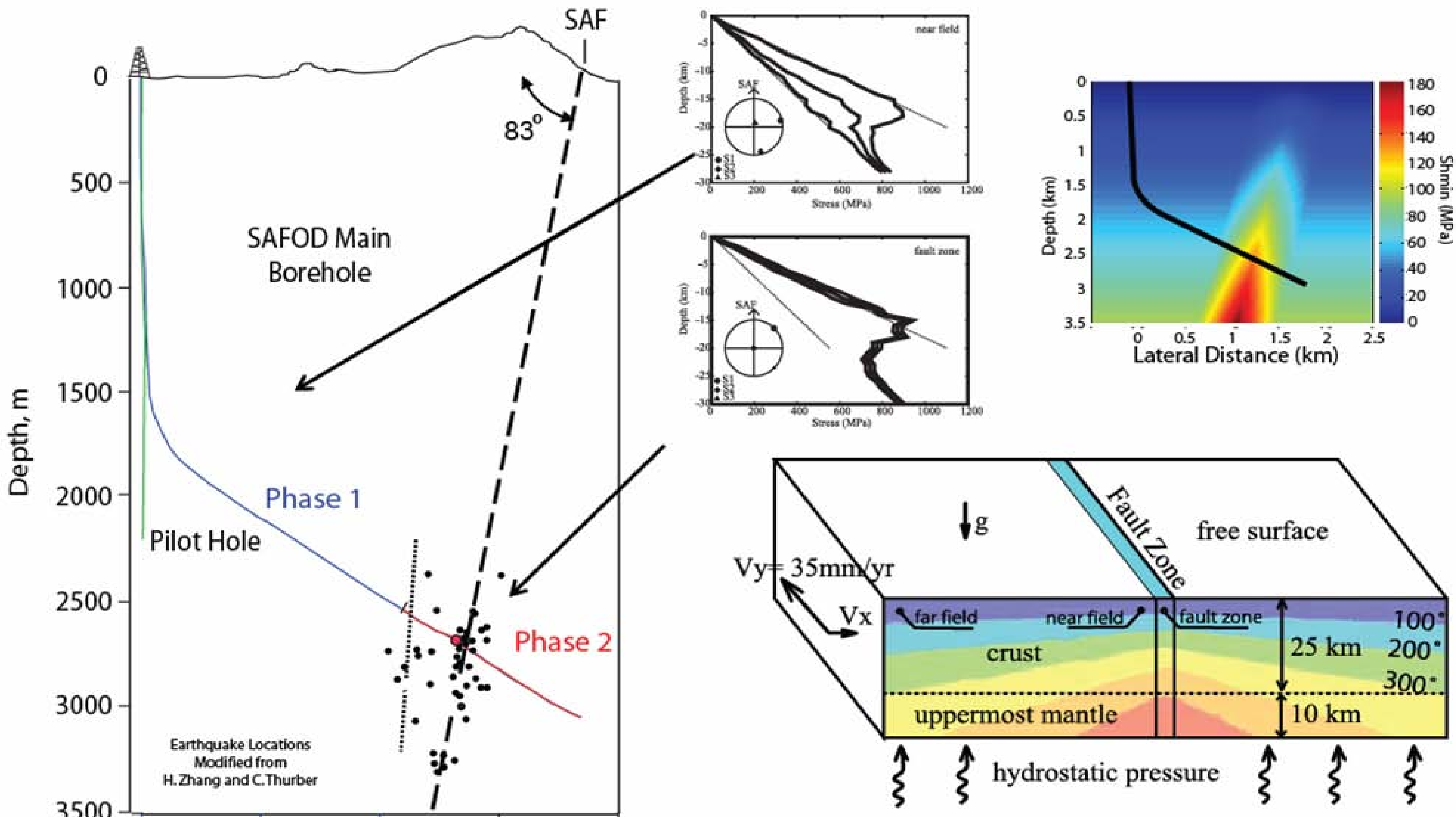
Fast Shear Wave Polarization Direction in SAFOD Main Hole from Cross-Dipole Sonic Logs
(Boness and Zoback, 2006)



Increase in Least Principal Stress Observed In Proximity to San Andreas Fault Zone



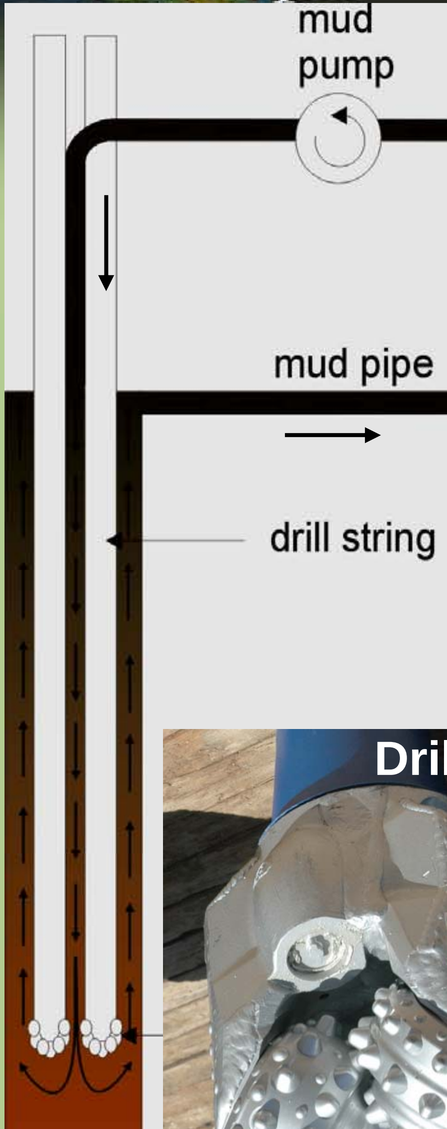
Weak Ductile Fault Zone Model



Weak Fault in a Strong Crust

Chery , Zoback and Hickman (2004)

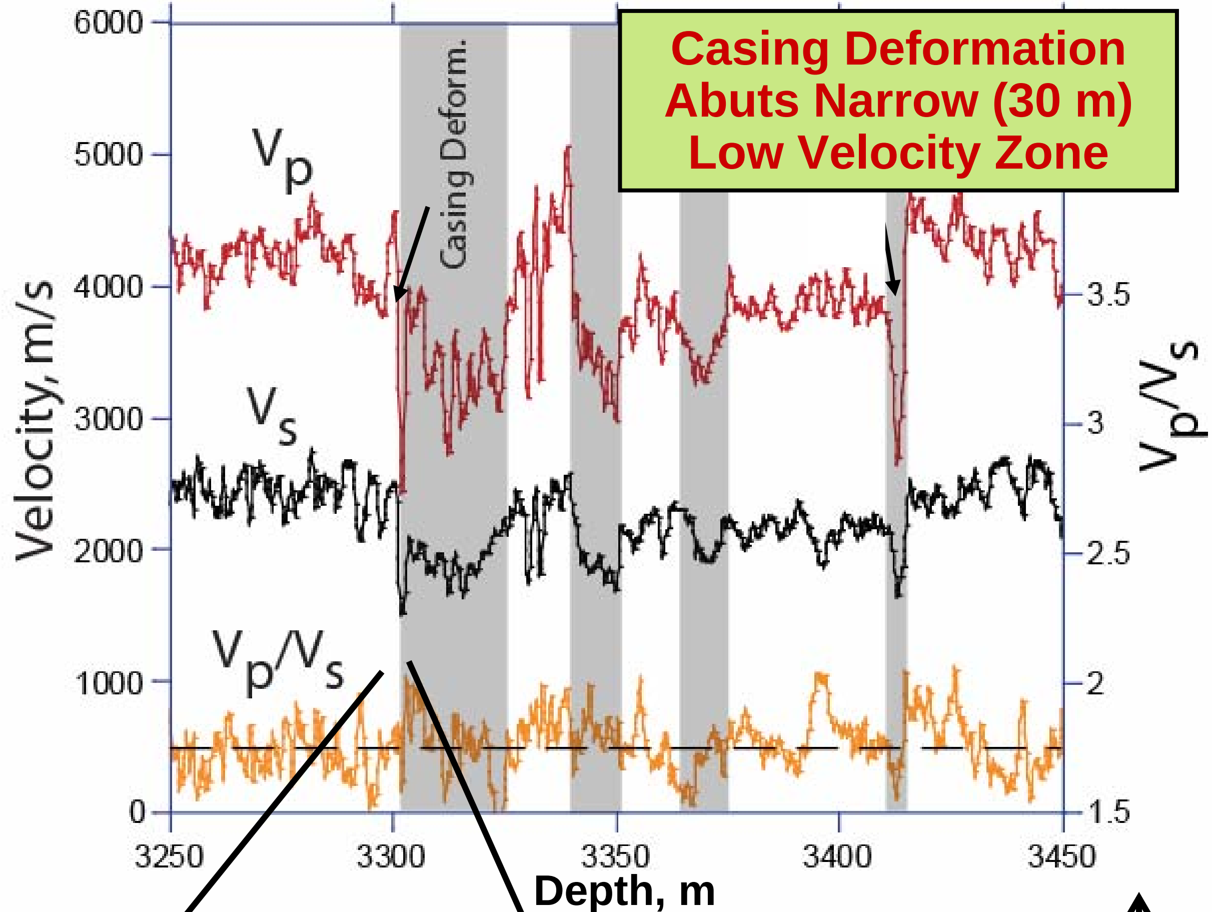
SAFOD Drill Cuttings Analyses



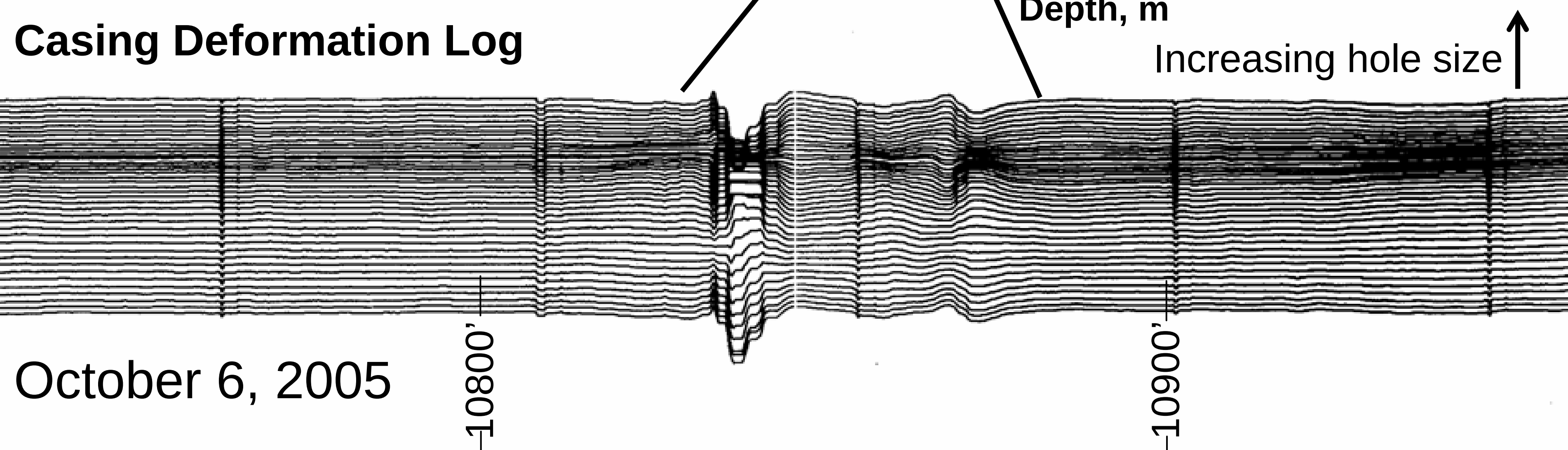
Carefully washed and dried; also preserved without washing and in drilling mud

<u>On-Site and Laboratory Analyses:</u>

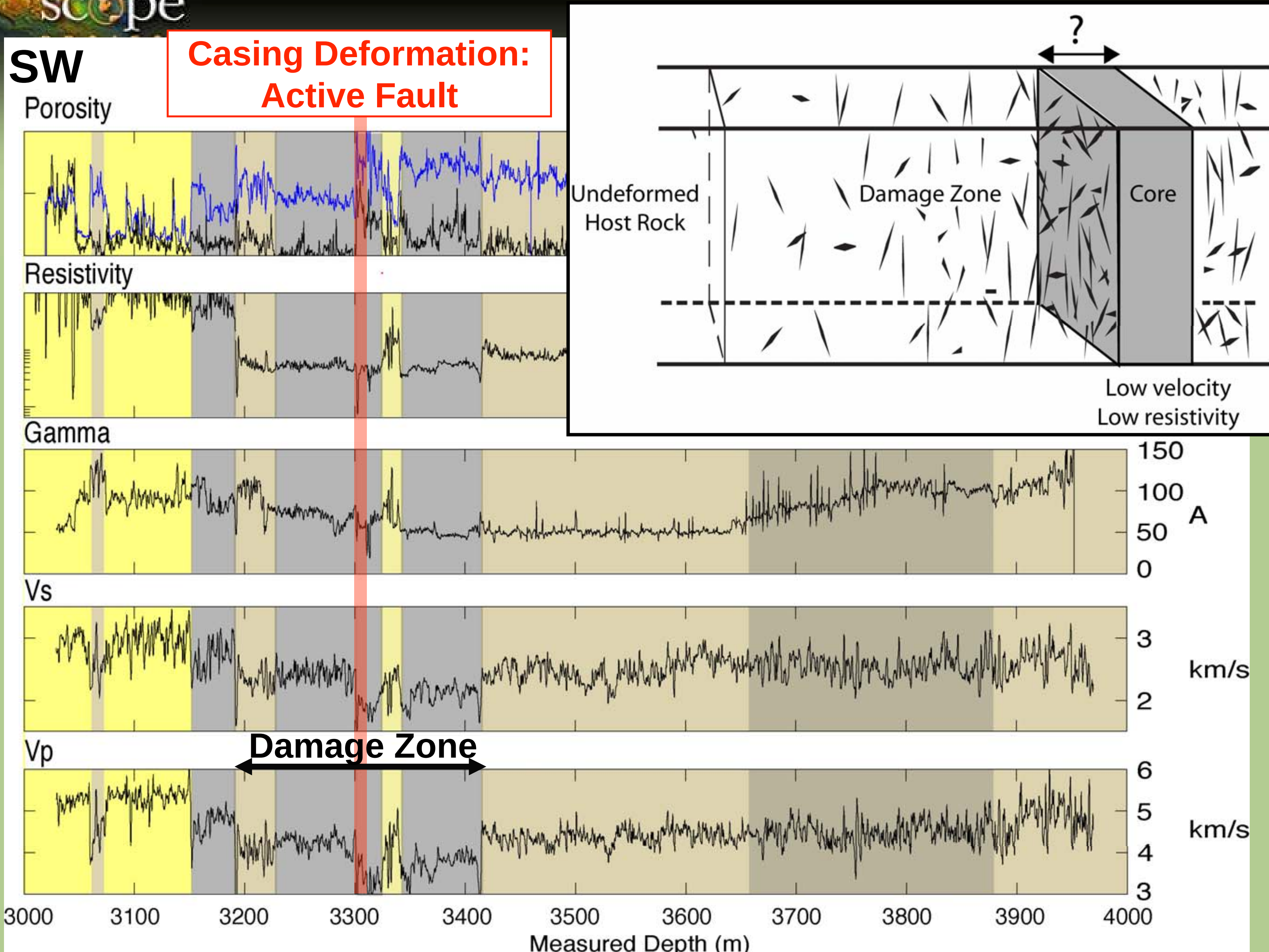
Optical, XRD, XRF, TEM, SEM, IR, friction tests, fission track annealing, isotopic studies, magnetic properties, fluid inclusion volatiles, thermal maturation, conductivity, and real-time mud gas analysis.



Casing Deformation Log

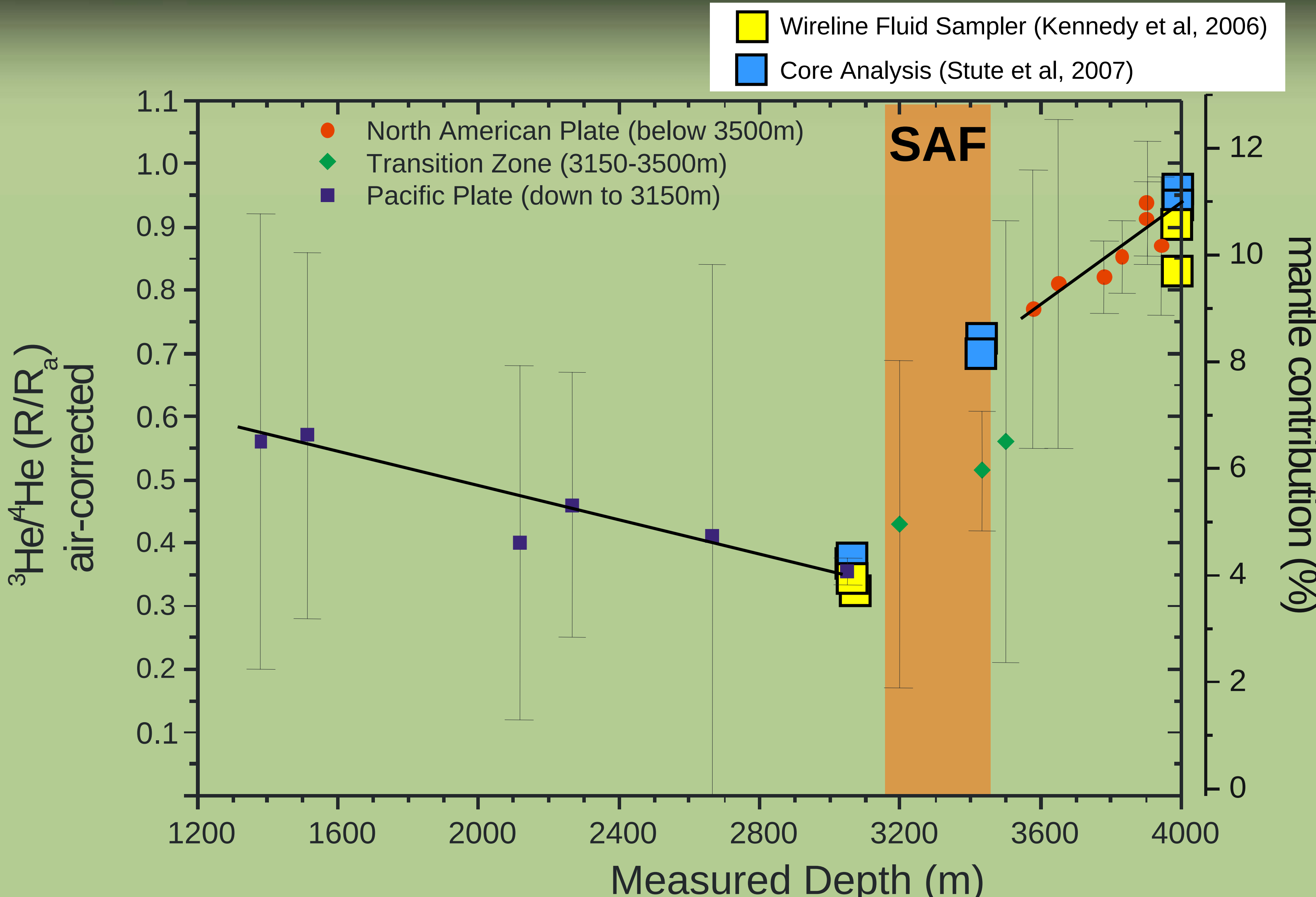


October 6, 2005



SW
Casing Deformation:
Active Fault
Porosity
Resistivity
Gamma
Vs
Vp
Damage Zone
150
100
A
50
0
3
km/s
2
6
5
km/s
4
3
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
Measured Depth (m)
?
Undeformed
Host Rock
Damage Zone
Core
Low velocity
Low resistivity

Helium from SAFOD Mud-Gas Analysis Shows San Andreas Fault is a Barrier to Cross-Fault Fluid Flow (*Wiersburg and Erzinger, 2006*)

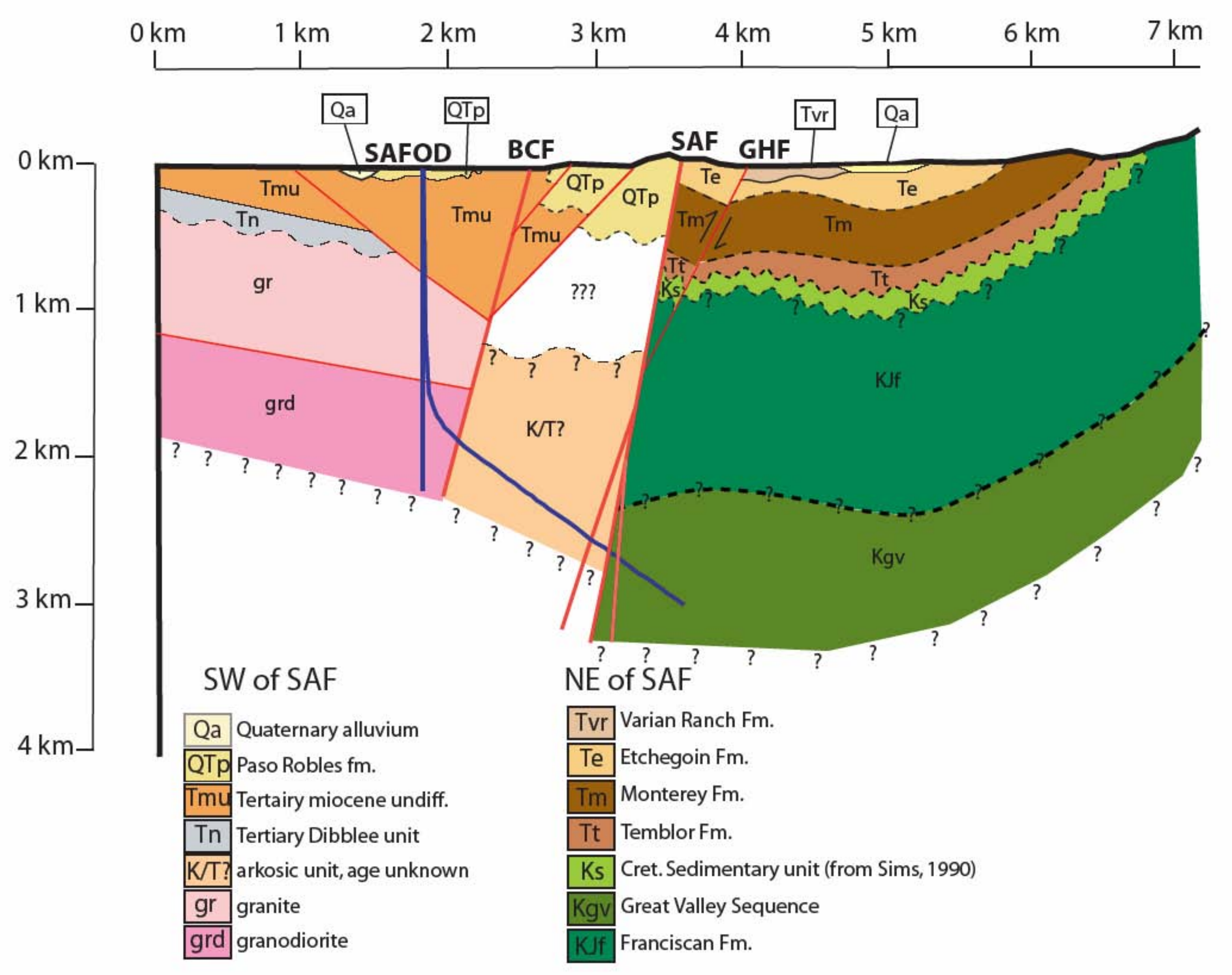


Post-Drilling Geologic Model: Phases 1 and 2
(*Draper et al. , 2006; Barton et al, 2006; Solum et al., 2006*)

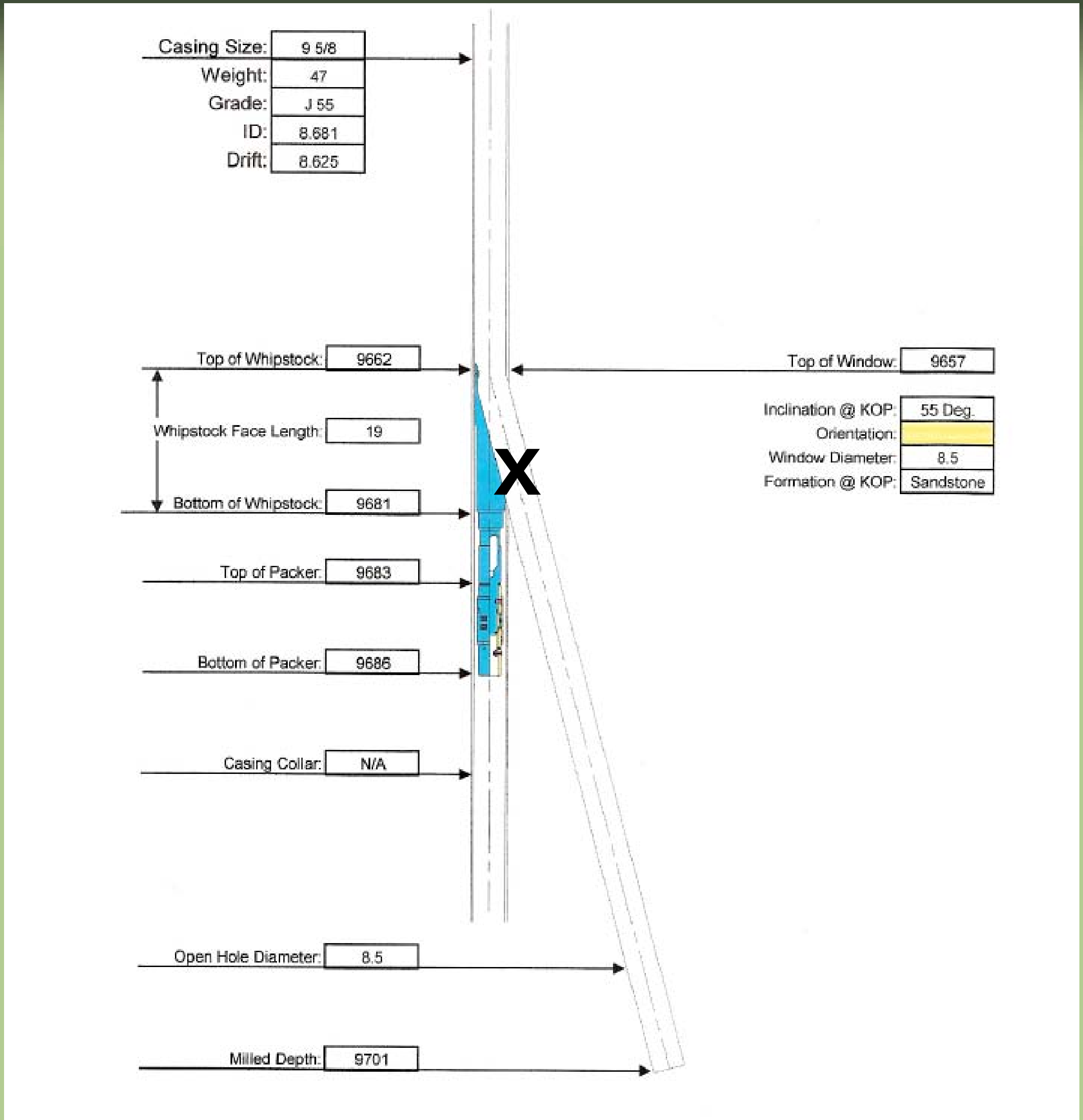
Simplified version of model based on optical and XRD analyses of drill cuttings and borehole geophysical logs.

Surface geology from Mike Rymer, Maurtis Thayer & Ramon Arrowsmith.

Identification of Great Valley at TD from micropaleo analyses of Kris McDougall.



Bit Stuck in Window Caused Sidetrack



Interval 2 - Across 10,480' Fault Zone

The short lithologic
descriptions from top to bottom of section 7 are as follows (and shown in the attached jpg).

Cataclastic siltstone and shale with local banding and foliation

Foliated gouge (penetrative scaly fabric) with 5% mesoscale serpentinite and sandstone porphyroclasts

Serpentinite cut by white (calcite) veins

Foliated serpentinite gouge with sheared, fragmented veins

Foliated gouge (penetrative scaly fabric) with 5% mesoscale serpentinite and sandstone porphyroclasts

Mesostructural Sketch Map (courtesy of Judith and Fred Chester, 2007)