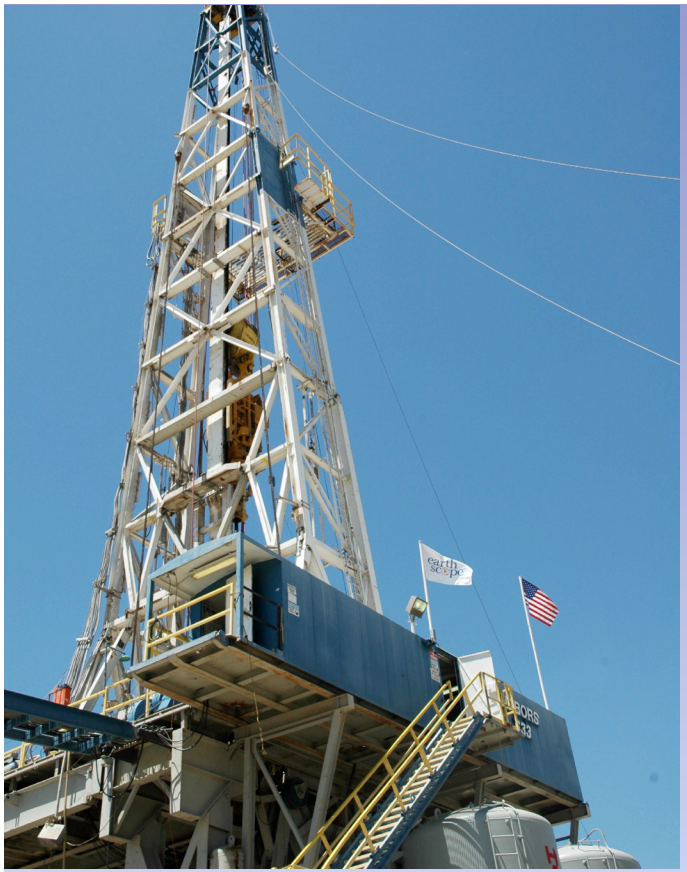

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SAFOD - Phase 1 Status and Looking Ahead to Phases 2 and 3

Mark Zoback, Stephen Hickman and William Ellsworth

UJNR - October 14, 2004

SAFOD Phase 1 Drilling: Summer 2004

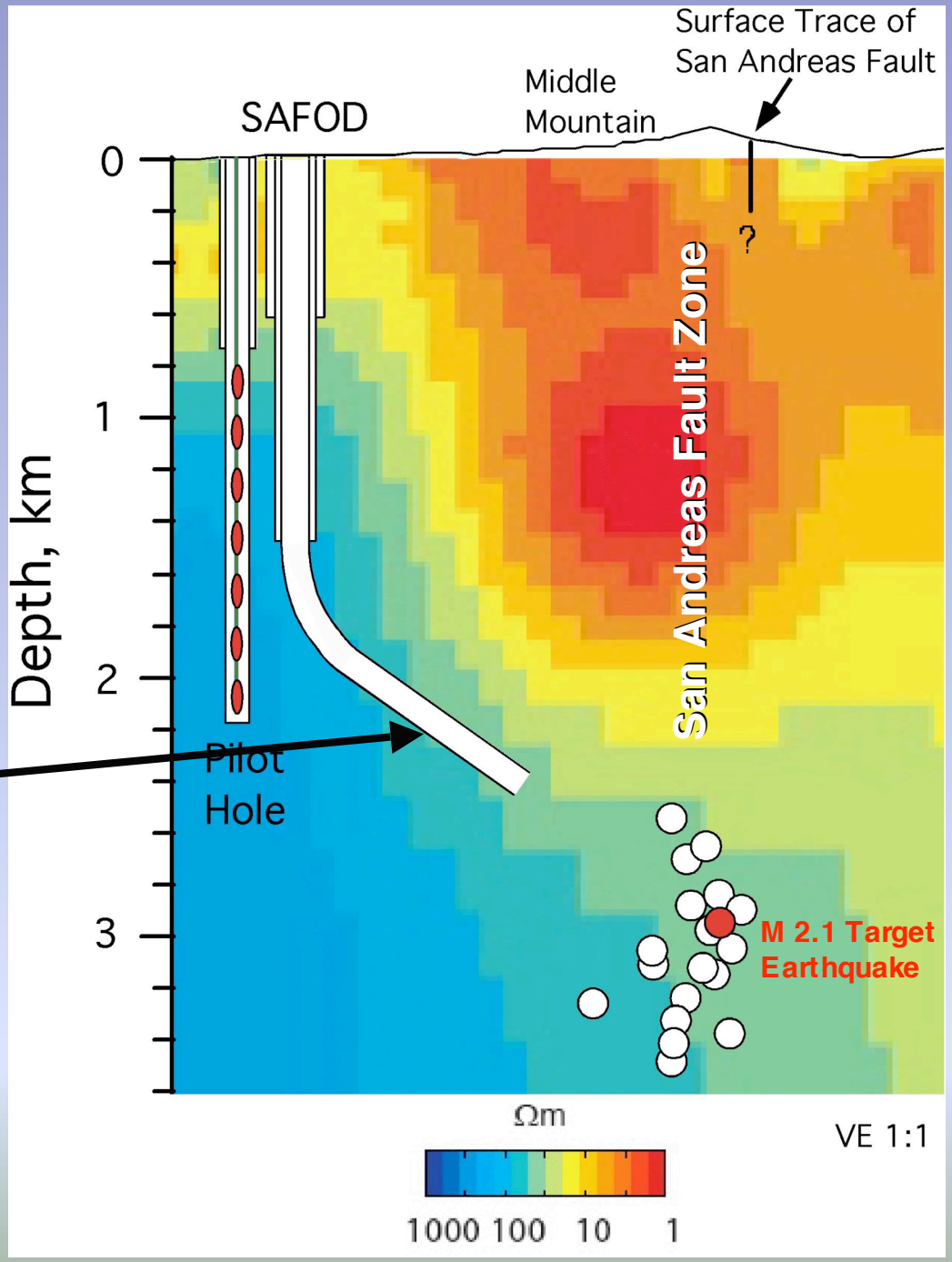
(Pilot Hole drilled summer of 2002)

Phase 1: Rotary Drilling to 2.5 km

Drill 12-1/4" hole to 2.5 km. Below kick-off point (1.5 km), steer hole toward target earthquakes (deviation 55°).

After setting casing, obtain 20 m cores at 1.5 and 2.5 km. Conduct permeability tests, fluid sampling and hydrofracs in core holes.

Collect comprehensive suite of wireline logs from 0.6 - 2.5 km (electrical and ultrasonic imaging, density, porosity, resistivity, dipole sonic, geochemical, temperature, etc.)



Resistivities Unsworth & Bedrosian 2004

Earthquake locations Steve Roecker & Cliff Thurber 2004

SAFOD Phase 1 Status

Drilling – Ended Ahead of Schedule/On Budget

On-Site Activities – 100% Successful

Downhole Measurements – 100% Successful

Coring and Cuttings – 100% Successful

Minifrac – Successful at 4800’

Fluid Sampling – DST not Successful (Long-term test underway)

Observatory – Proceeding Well but some planned activities are behind schedule

SAFOD Phase 2 Drilling: Summer 2005

Phase 2: Drilling Through Fault Zone

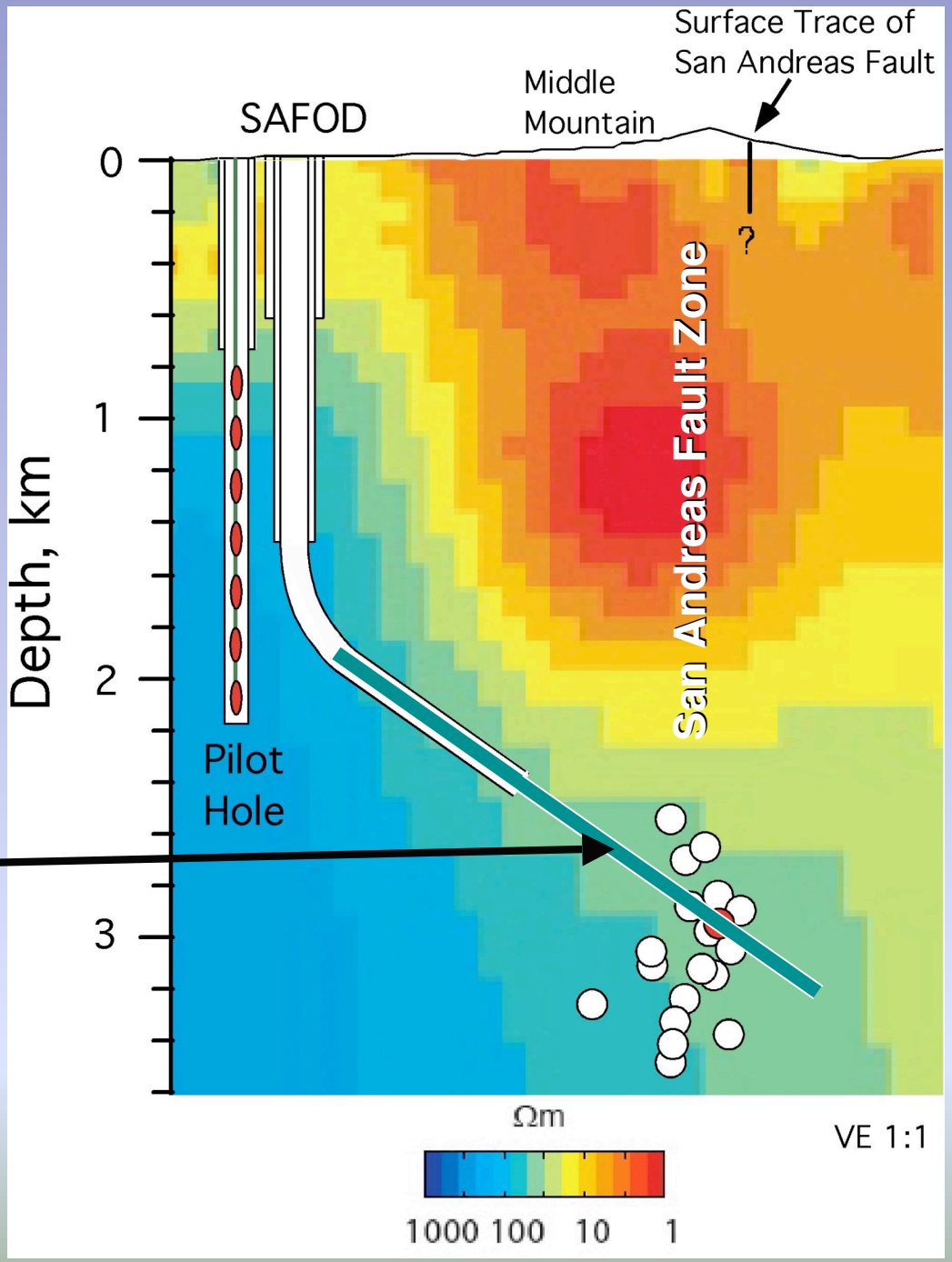
Drill 8-1/2" hole at 55° to 3.2 km

Conduct full Logging While Drilling suite (azimuthal density and resistivity, porosity, fluid pressure, acoustic, gamma).

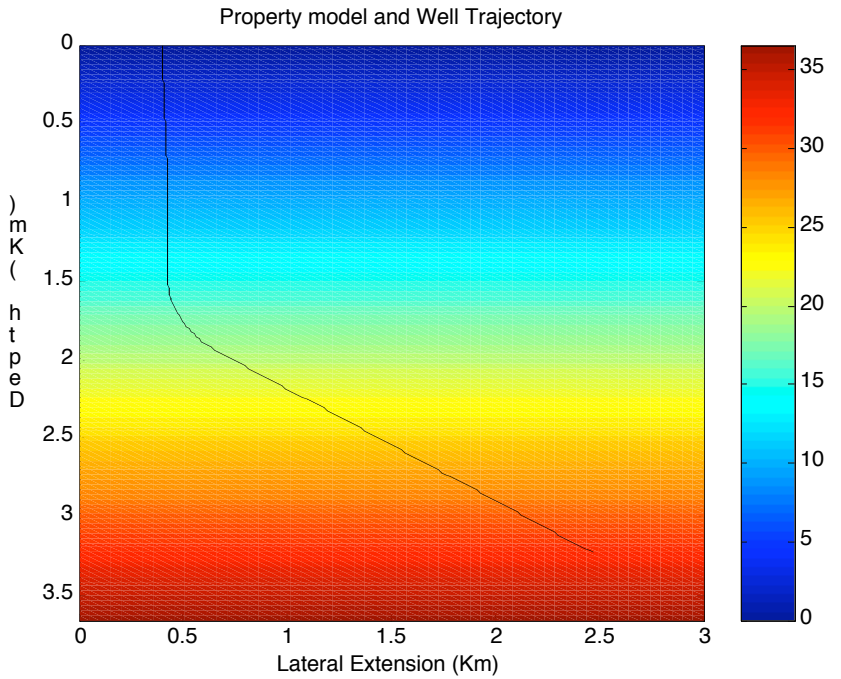
Periodic (up to 4) 10-m spot cores. Side-wall cores if possible.

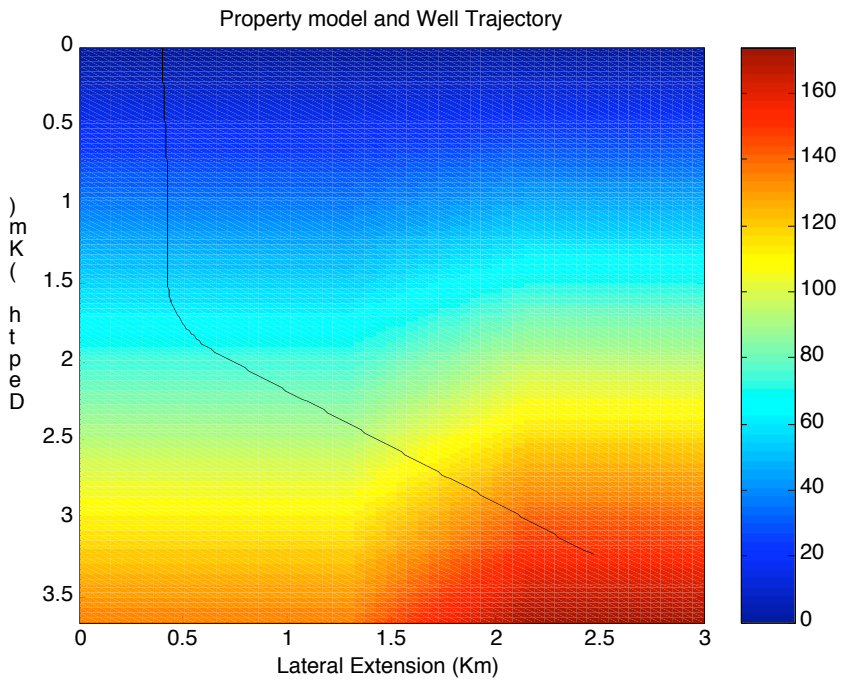
Following open-hole wireline logging (perhaps with drill-pipe deployment), case and cement hole.

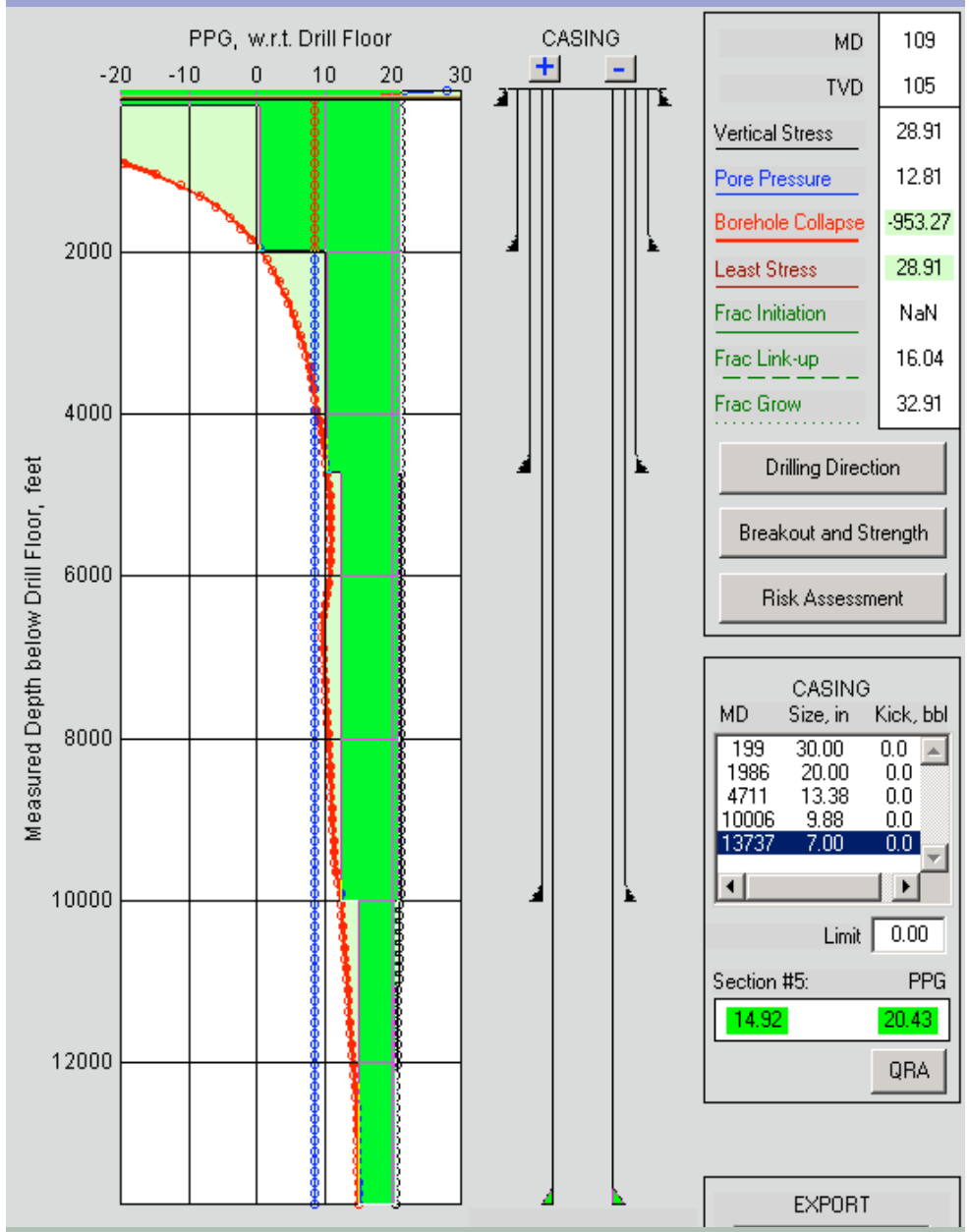
Conduct permeability tests, fluid sampling and hydrofracs through perforations in cemented casing (10 tests).



Low Friction Model





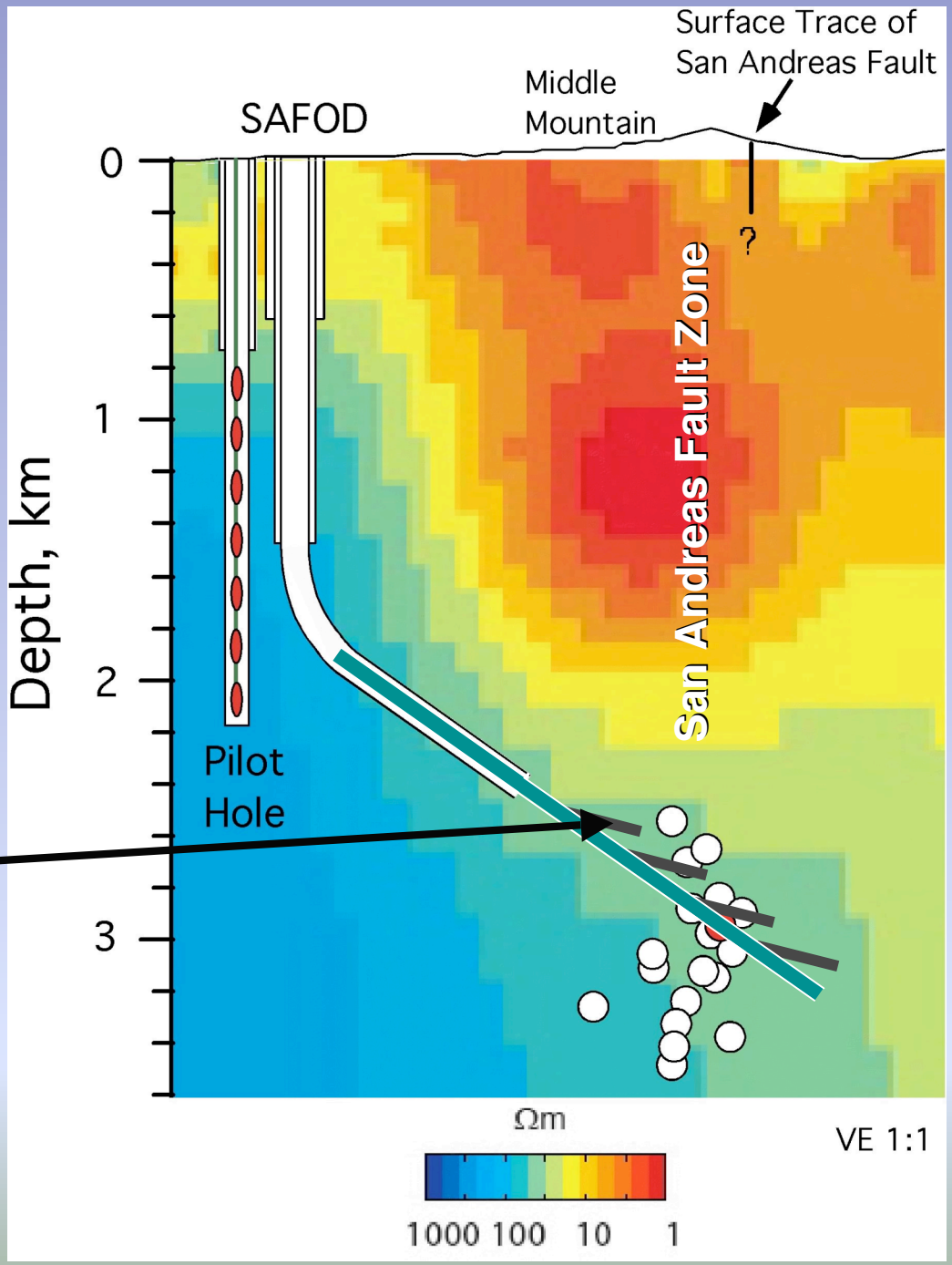


SAFOD Phase 3 Drilling: Summer 2007

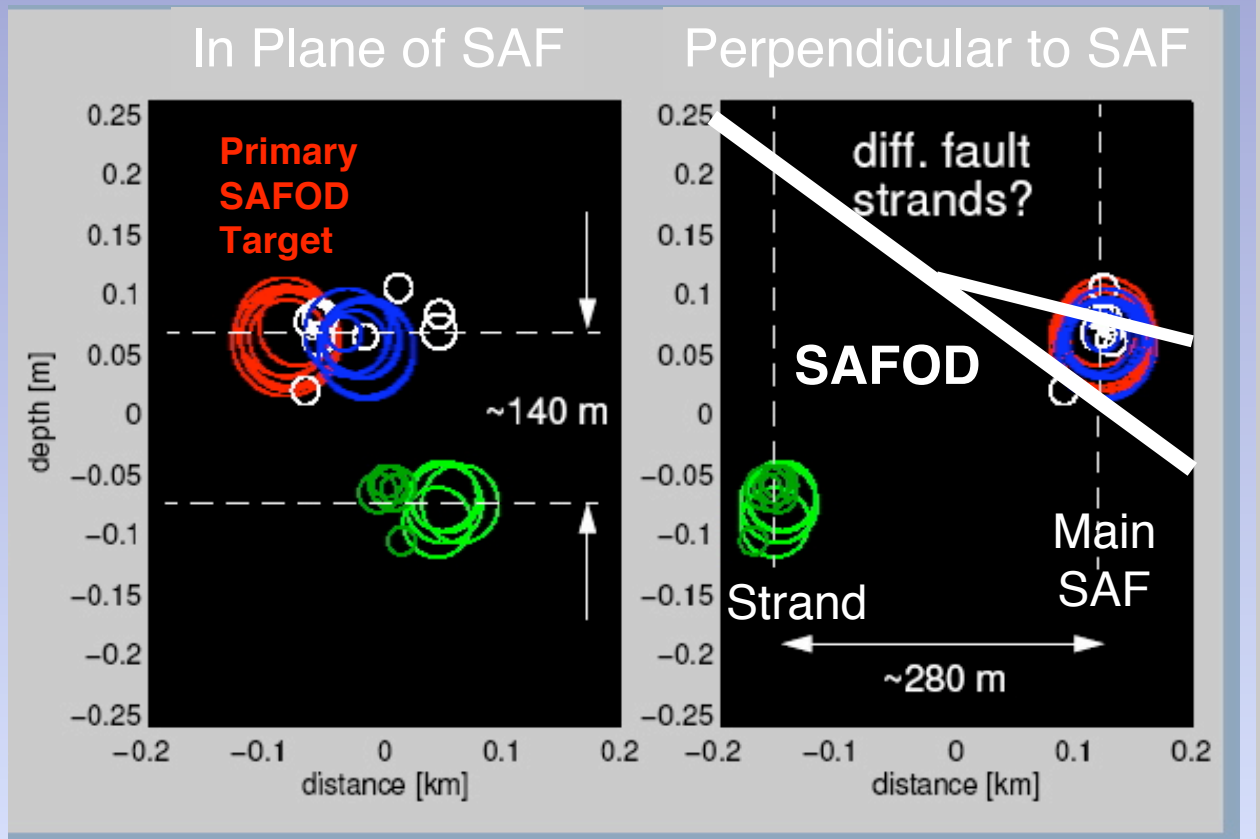
Phase 3: Coring the Multi-Laterals

Drill 4 multilateral core holes extending 250 m from main hole.

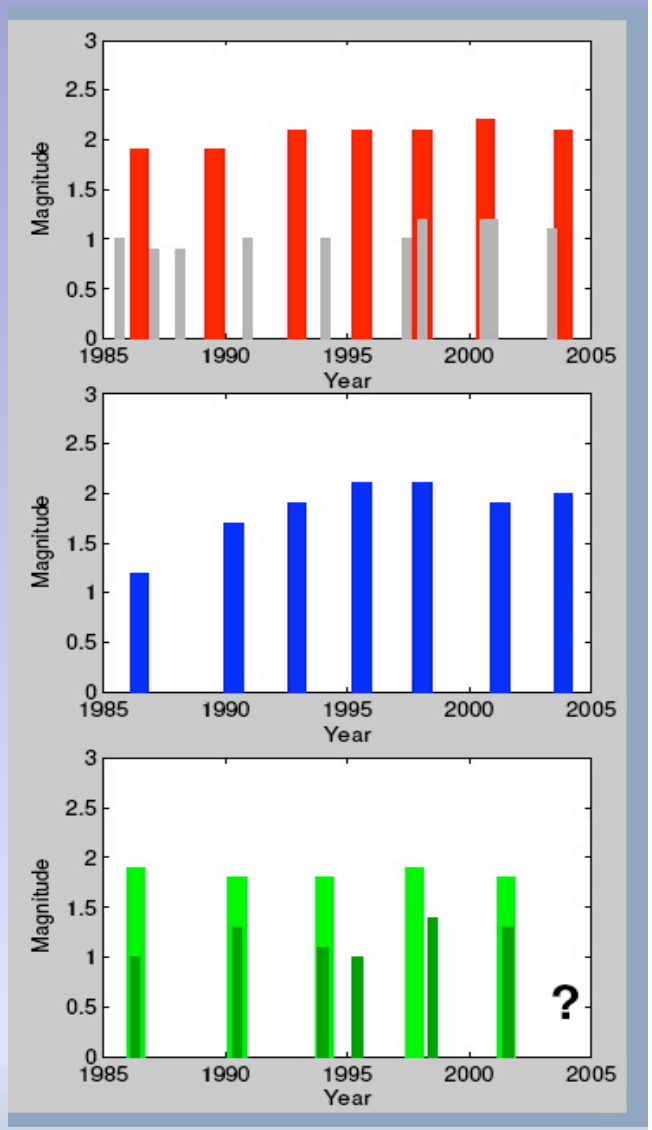
Depths to be determined from data obtained in Phase 2, plus repeat logging for casing shear and downhole seismic monitoring (2005-2007).



Relative Locations of SAFOD Target Earthquakes (Repeaters)



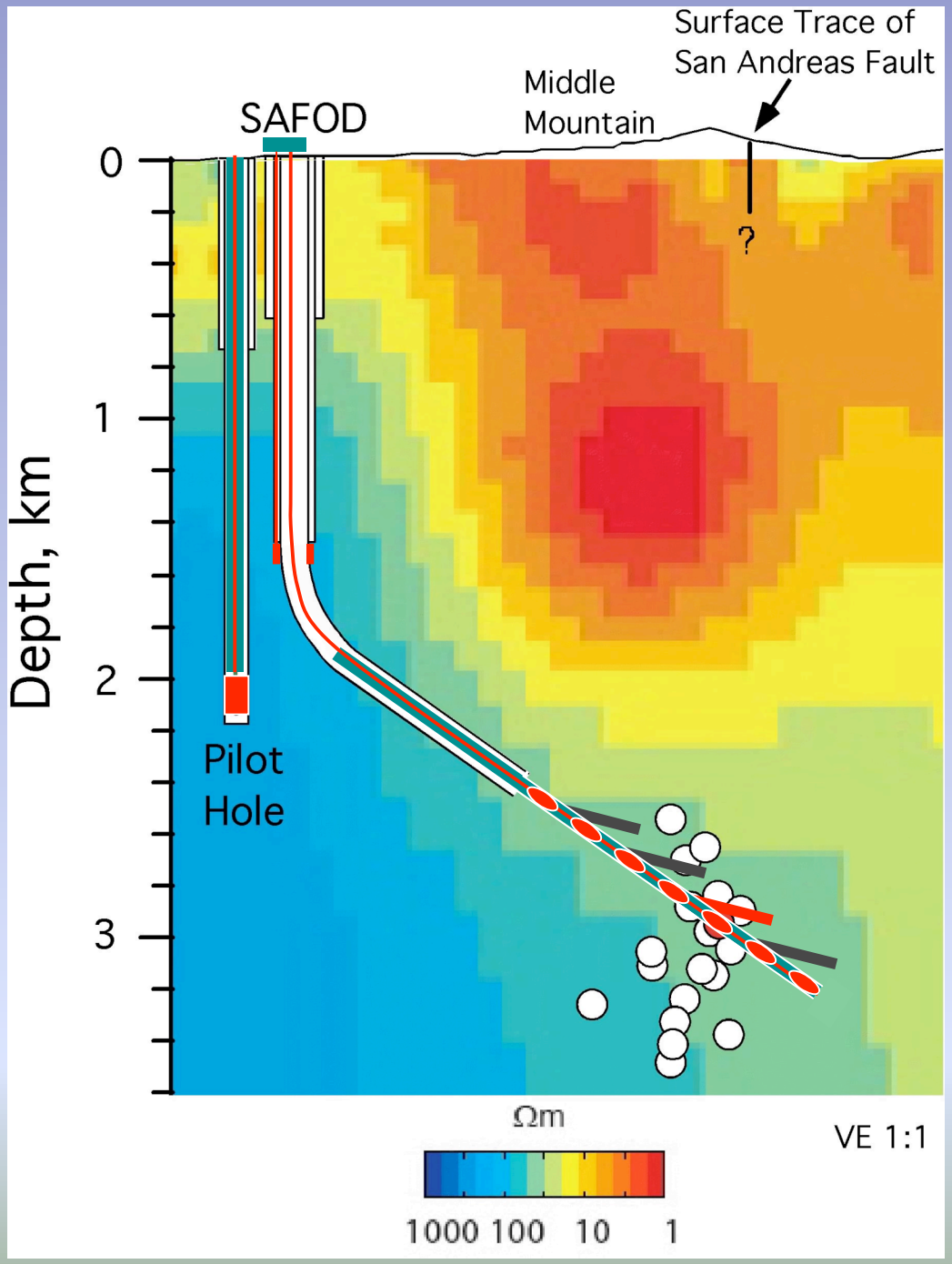
circle size = 9 MPa stress drop model



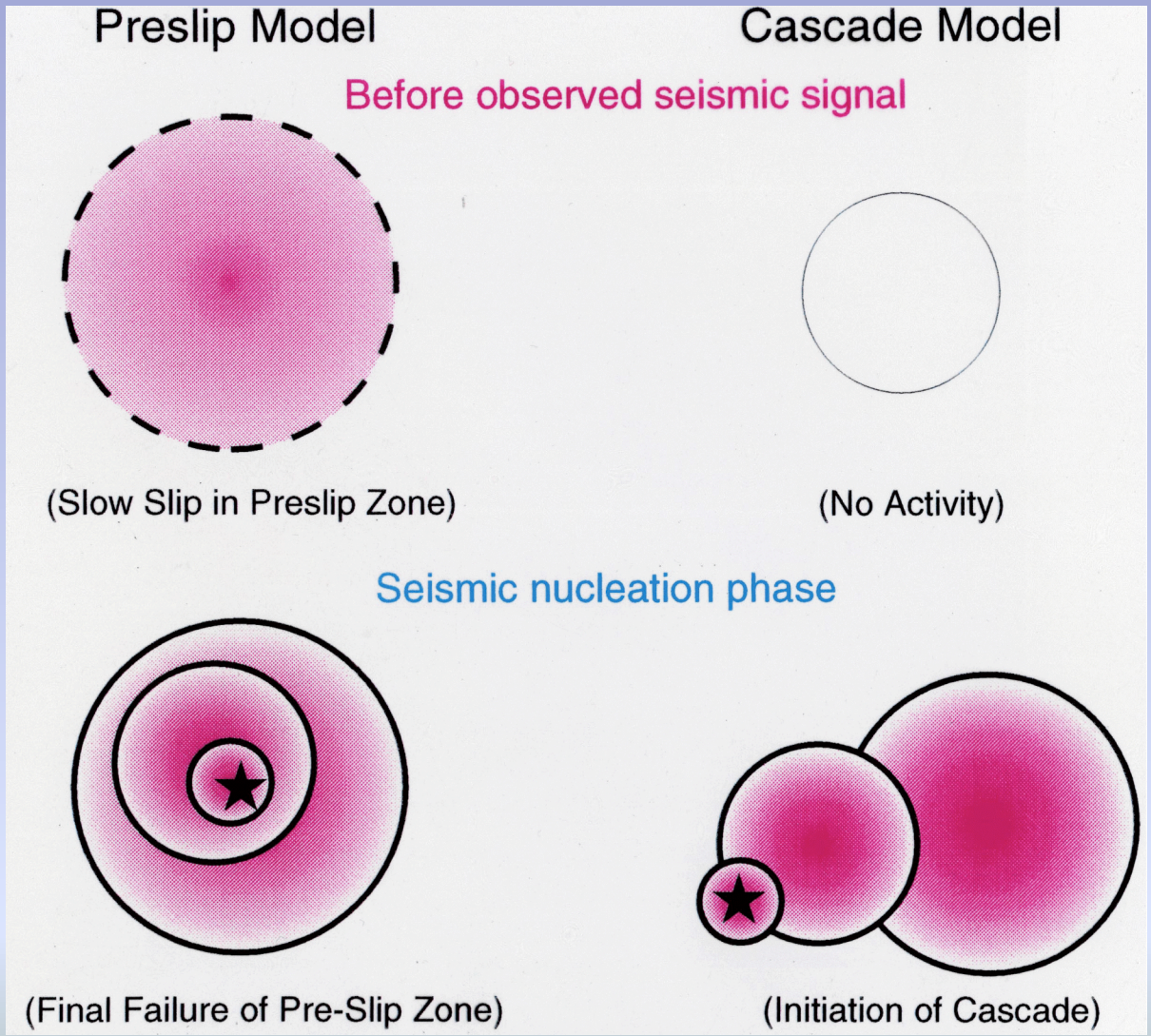
Felix Waldhauser 2004

SAFOD Observatory

Monitoring Instrumentation Deployment in 3 Distinct Stages

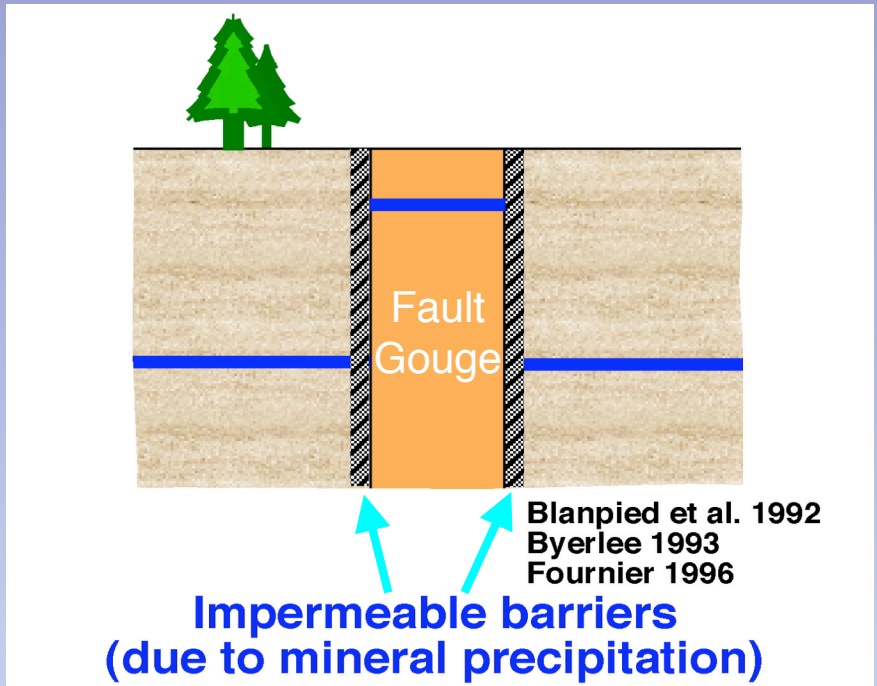


What factors control the nucleation, propagation and arrest of earthquake ruptures?



Can earthquakes be predicted and, if so, how?

How does fluid pressure vary during the earthquake cycle?



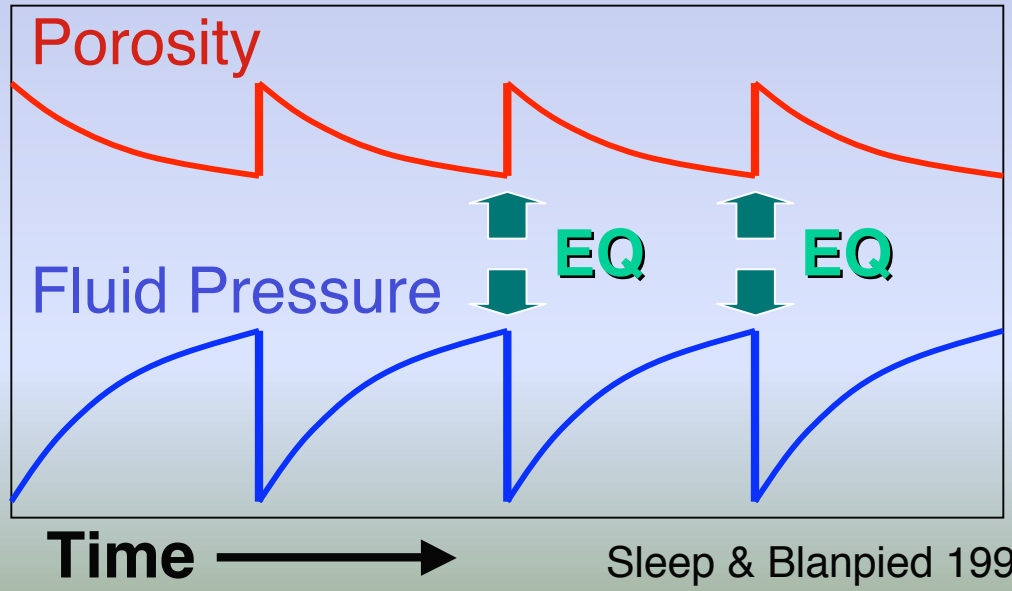
Fault Sealing Models Motivated by:

High temperature lab experiments:

- Permeability short-lived at hydrothermal conditions (T $\geq$ 150° C)

Geologic studies of exhumed faults:

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

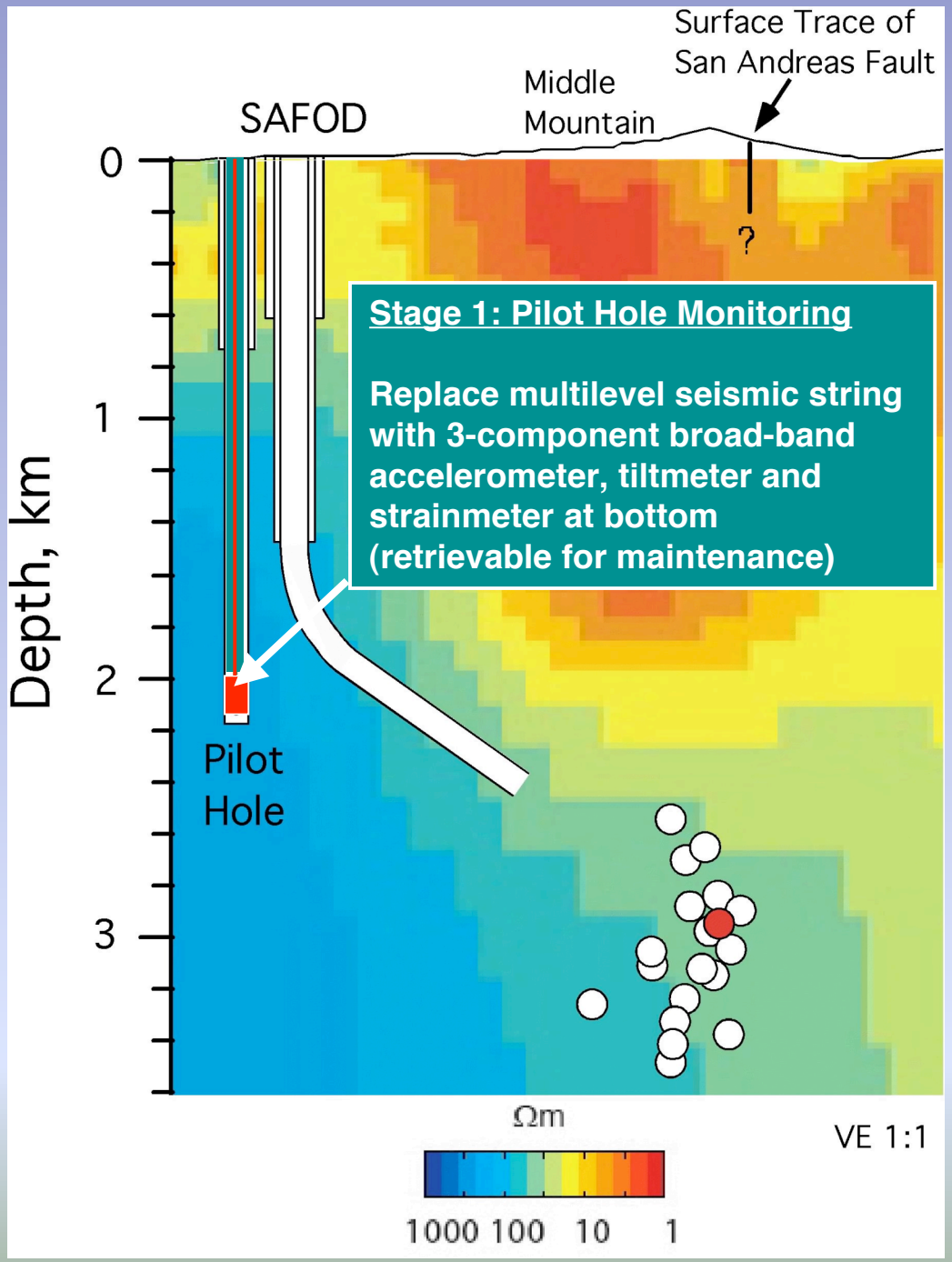


Sleep & Blanpied 1992, 1995

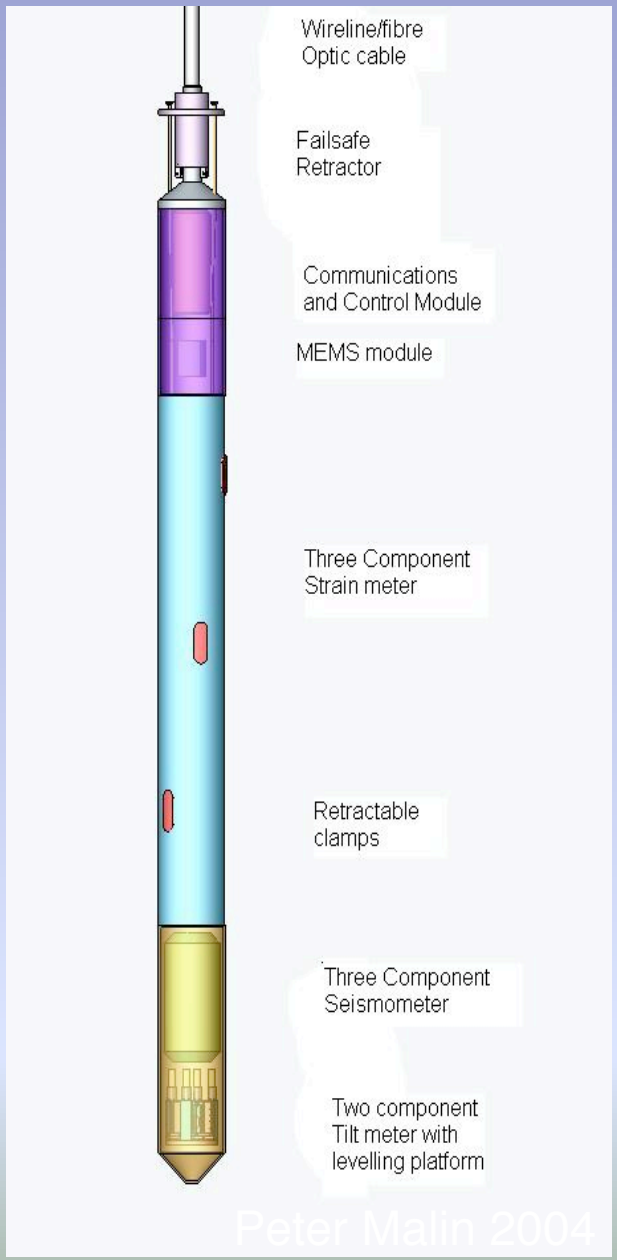
Viscous compaction of fault gouge after earthquakes could lead to fluid pressure fluctuations that are intimately related to the earthquake cycle.

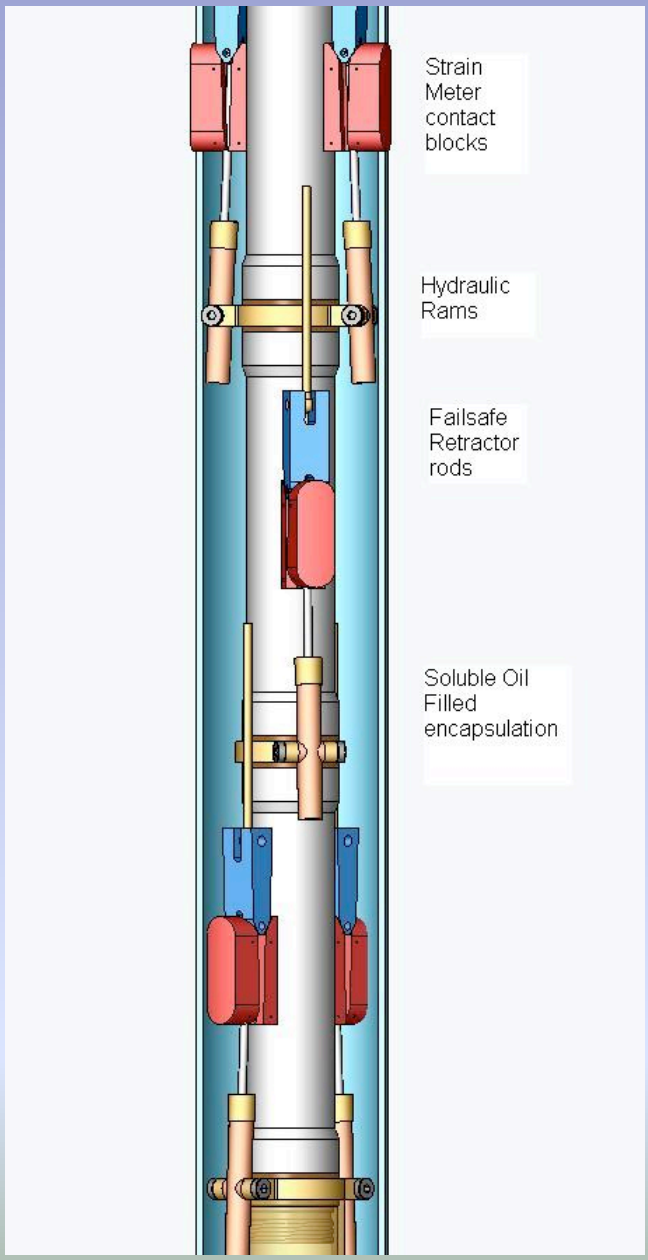
Monitoring Instrumentation Deployment

Stage 1 - Pilot Hole Monitoring: Spring 2005



Prototype Removable Borehole Monitoring System (Stage 1)

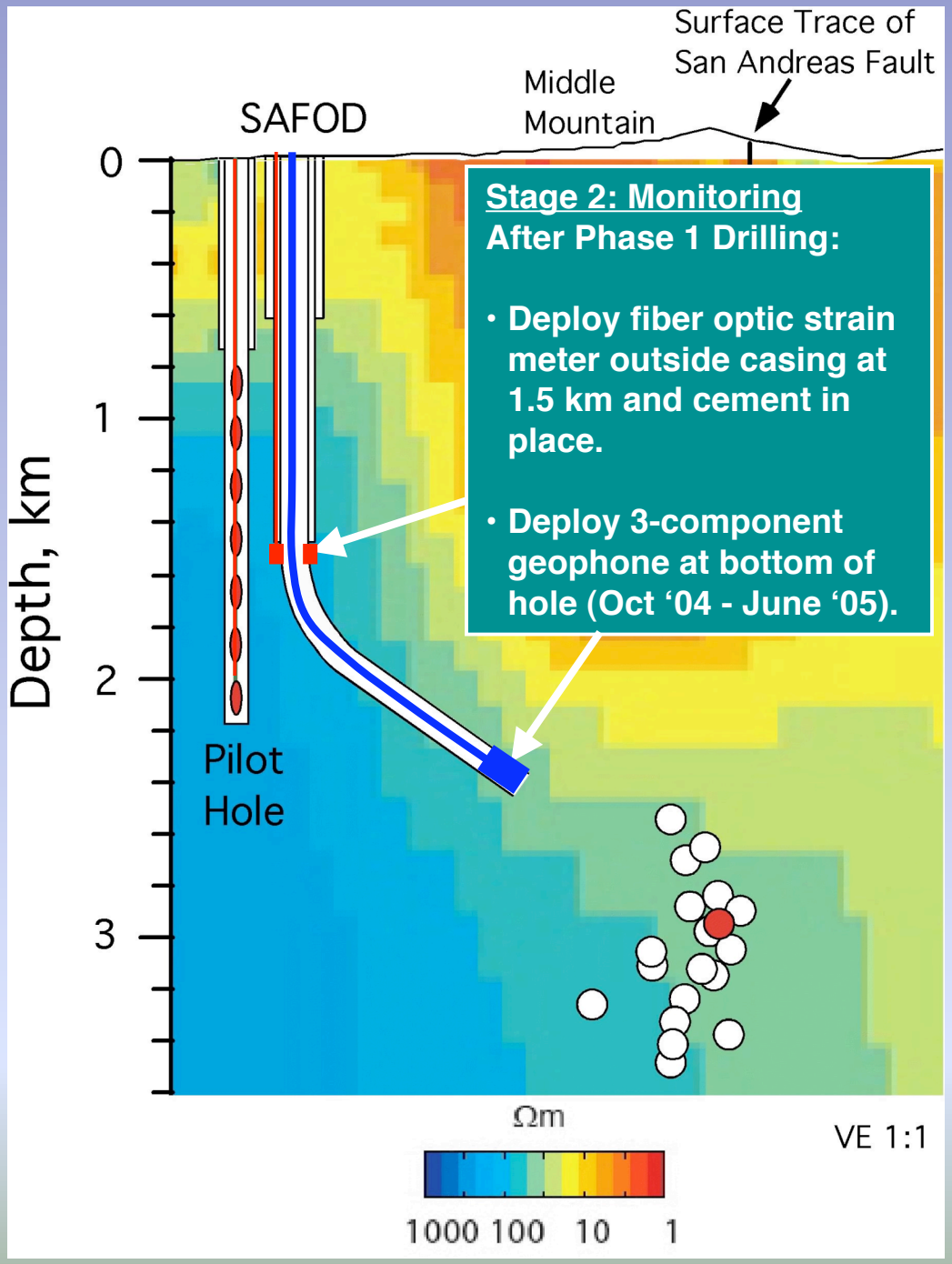




Peter Malin 2004

Monitoring Instrumentation Deployment

Stage 2 - SAFOD Monitoring: 2004 and beyond



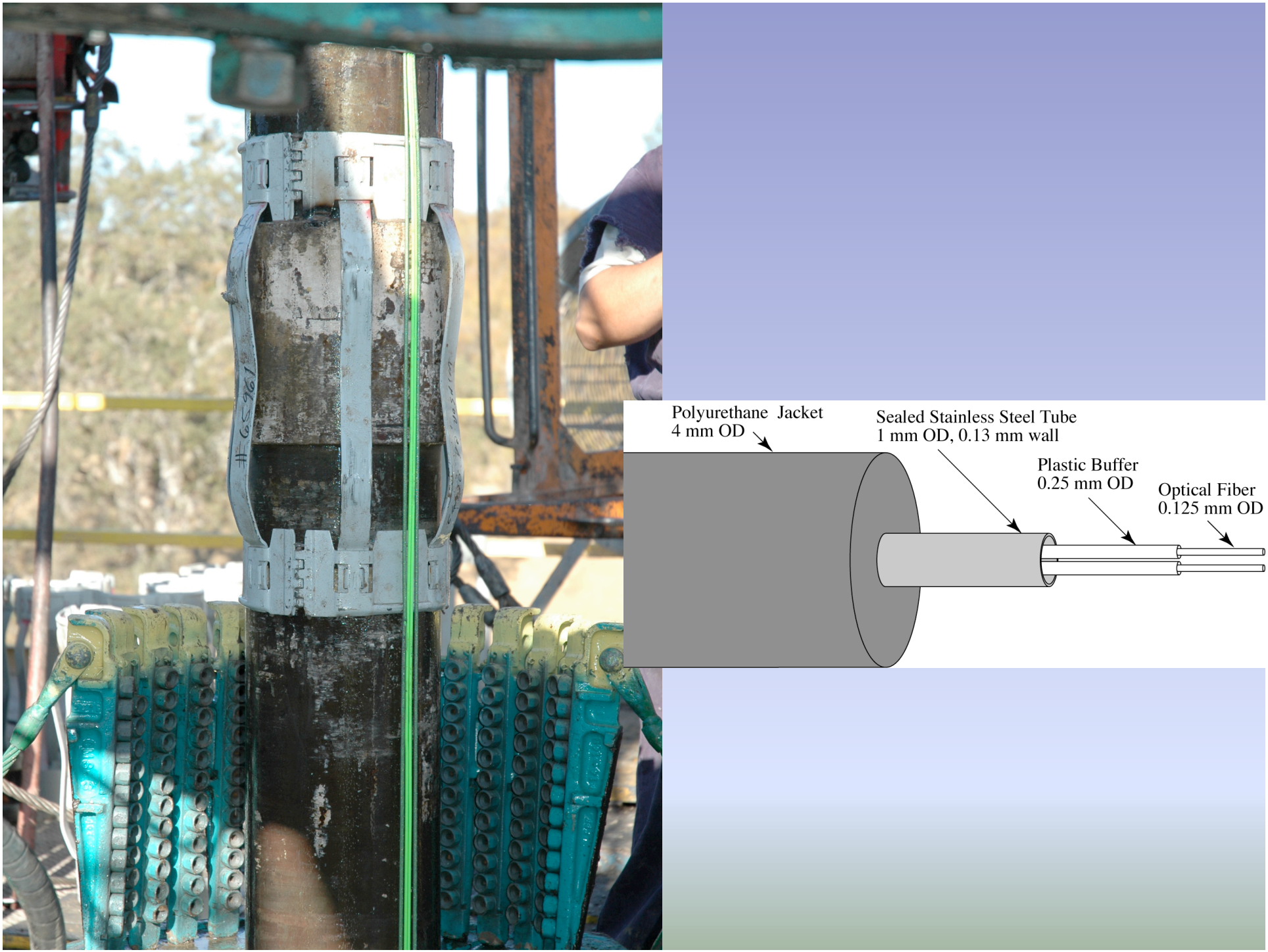
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego

An Optical Fiber Strain Sensor

M. Zumberge

- Two interferometric cables monitoring a 25 m and a 50 m interval centered at 1300 m

- One surface-to-1300-m loop cable, instrumented with both an EDM and an interferometer


Polyurethane Jacket
4 mm OD
Sealed Stainless Steel Tube
1 mm OD, 0.13 mm wall
Plastic Buffer
0.25 mm OD
Optical Fiber
0.125 mm OD

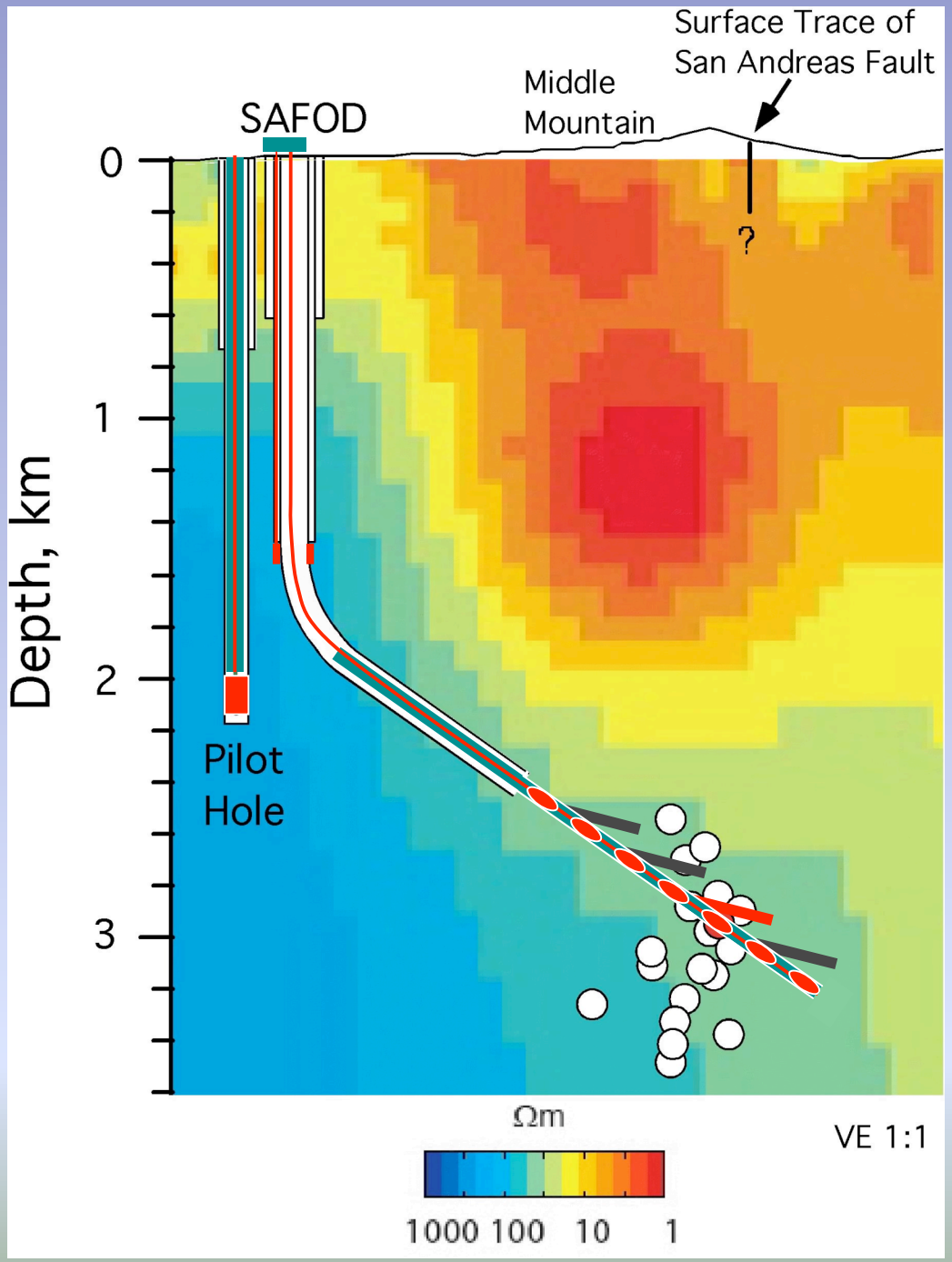
Monitoring Instrumentation Deployment

Stage 3 - Long-Term SAFOD Monitoring:

- Seismometers
- Accelerometers
- Strainmeters
- Tiltmeters
- Pore Pressure
- Temperature

- 2005-2007 prototype

- 2007 long-term deployment



SAFOD Phase 1 Drilling: RealTime Monitoring Downhole Measurements

Real-Time Gas Monitoring

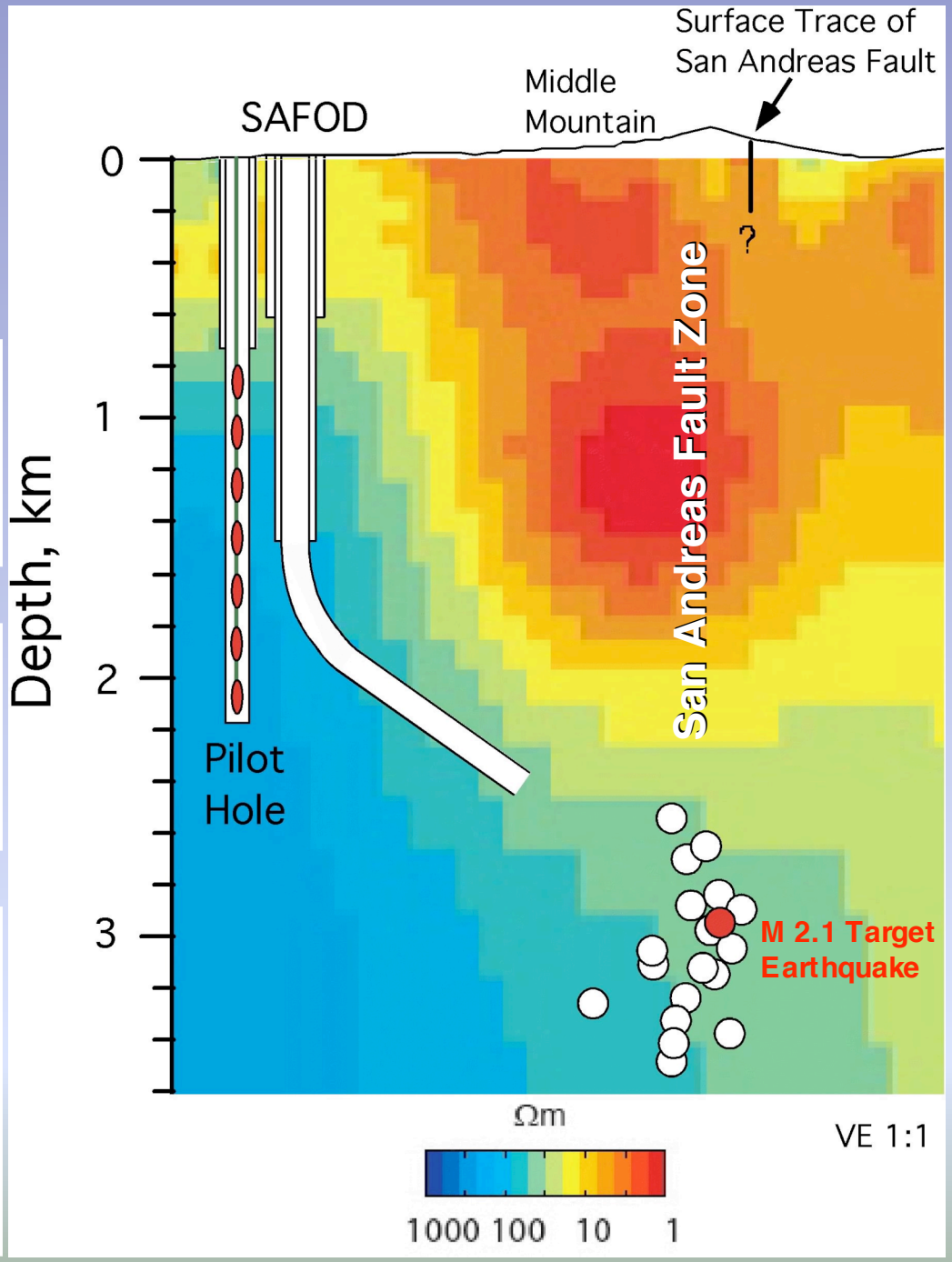
- Used Successfully in Pilot Hole
- Excellent Data from Main Hole

Geophysical Logging

- Successful Logs at 4800'
- Second Suite of Logs at 10,000'

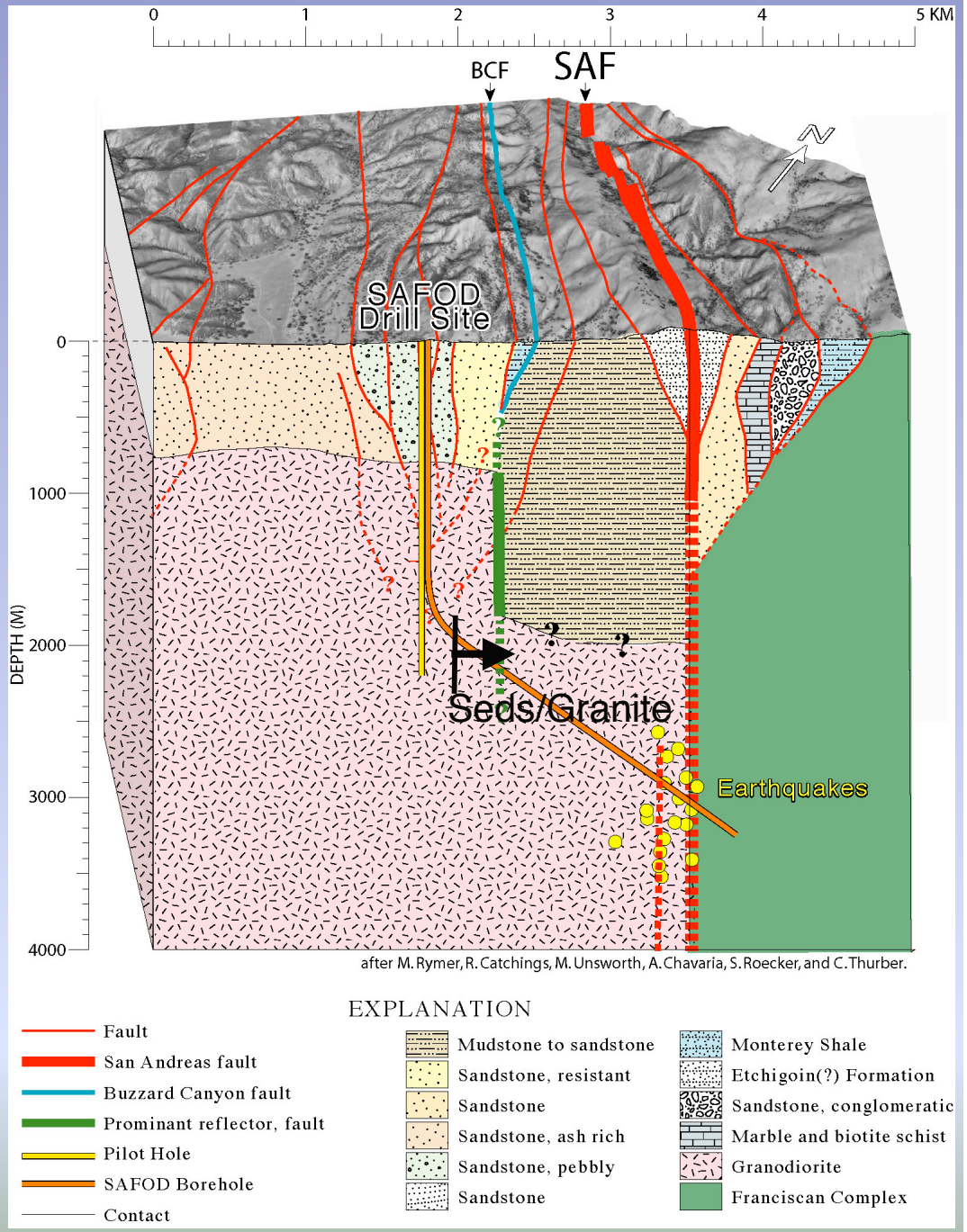
Downhole Measurements

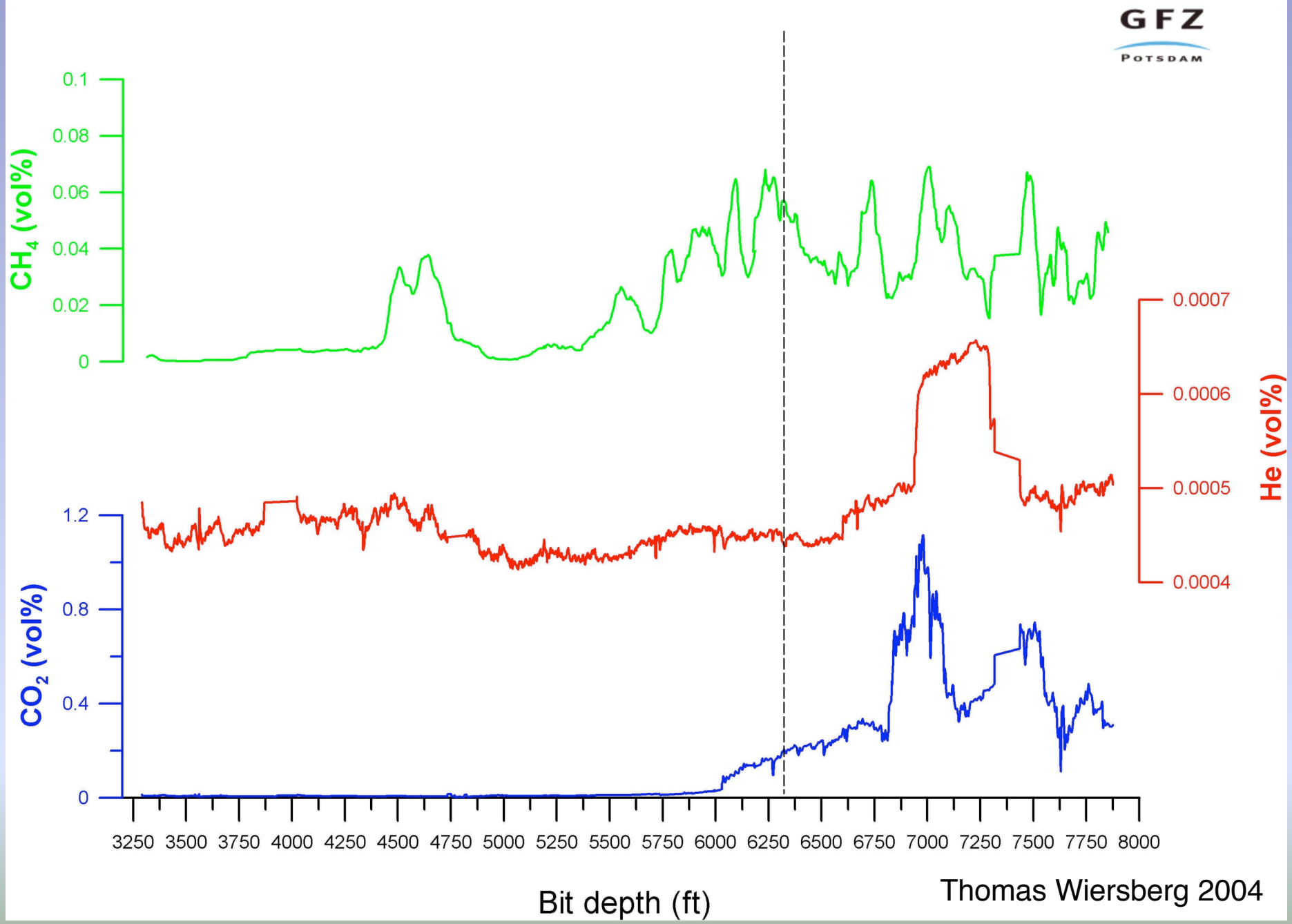
- Successful Hydrofrac
- Unsuccessful Fluid Sampling (perm too low)
- Revised Fluid Sampling Plan



Preliminary Geological Model:

- Being modified as result of Phase 1 drilling: Sandstones and granite encountered 210 m to the NE of drillsite

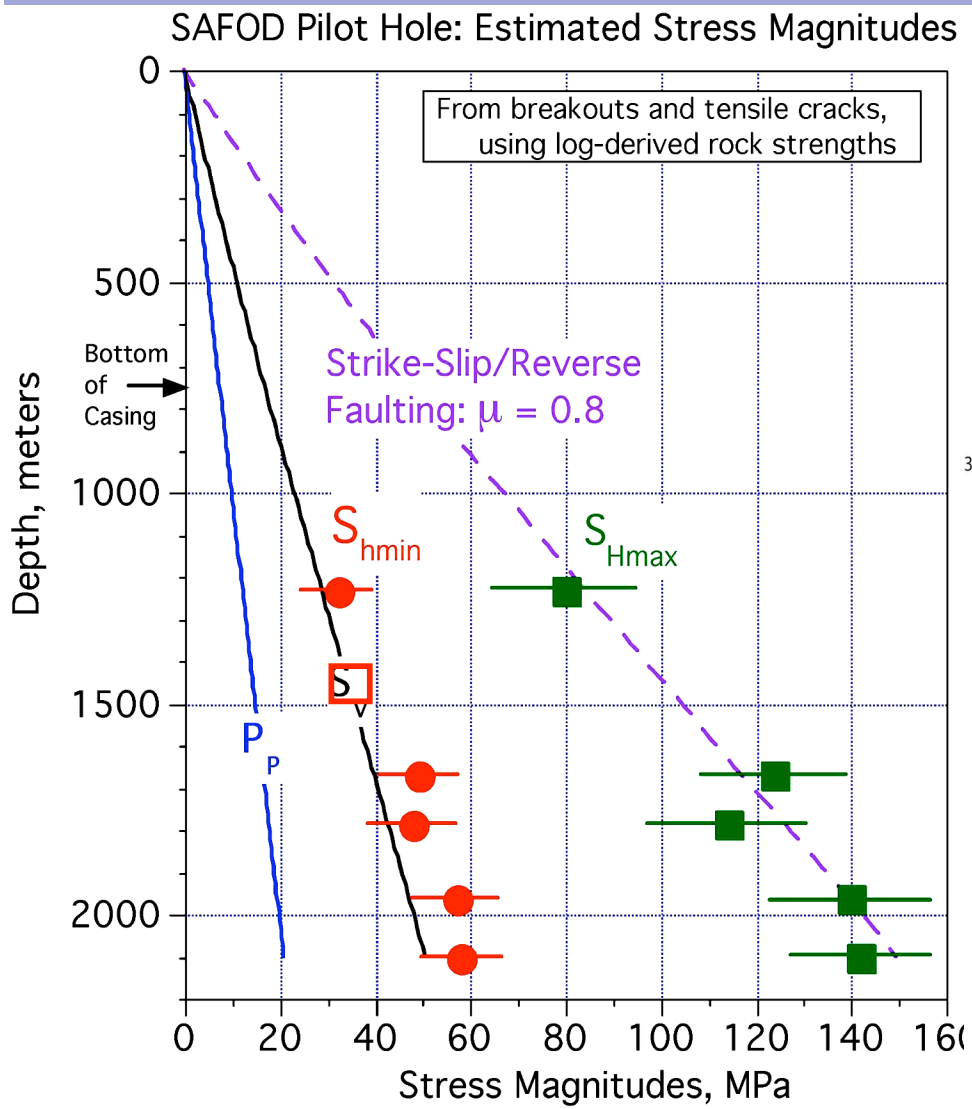


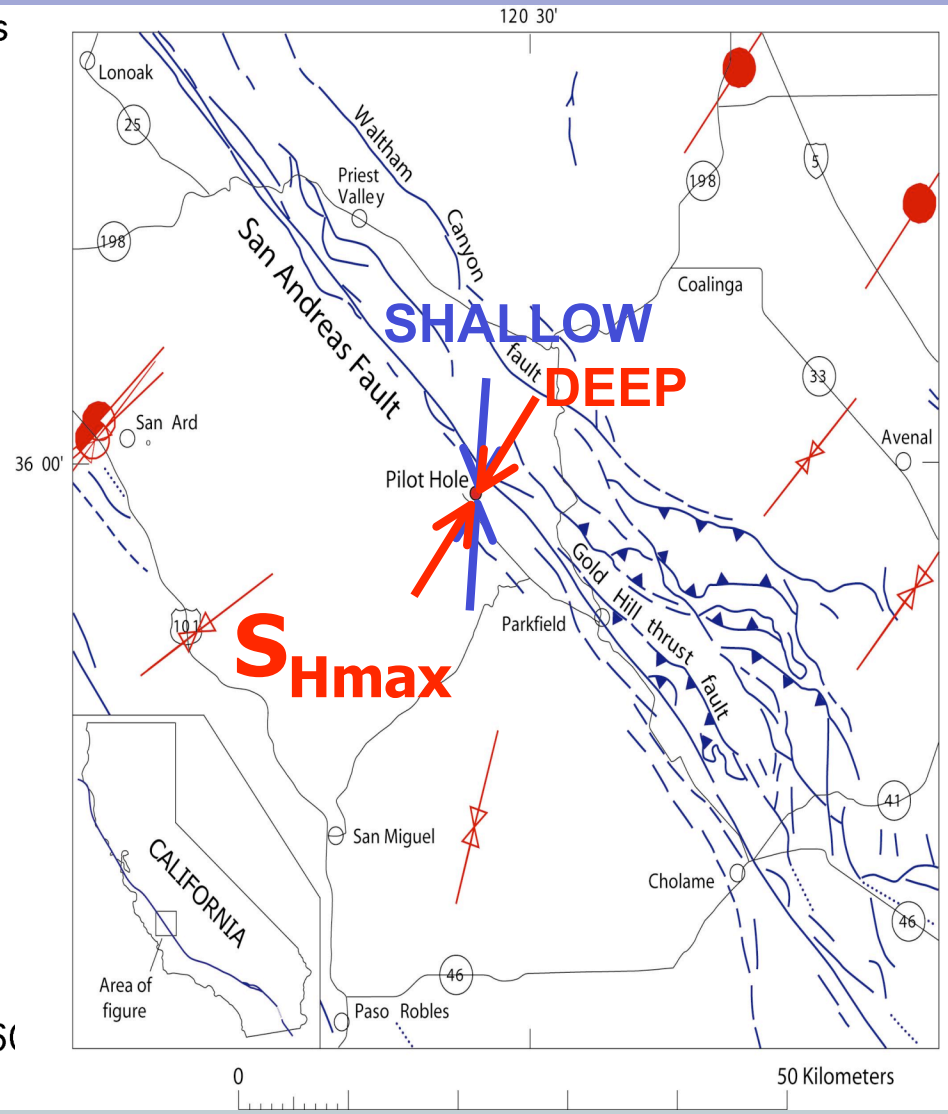


Thomas Wiersberg 2004

Mini-Frac Confirms SS/RF Stress Magnitudes

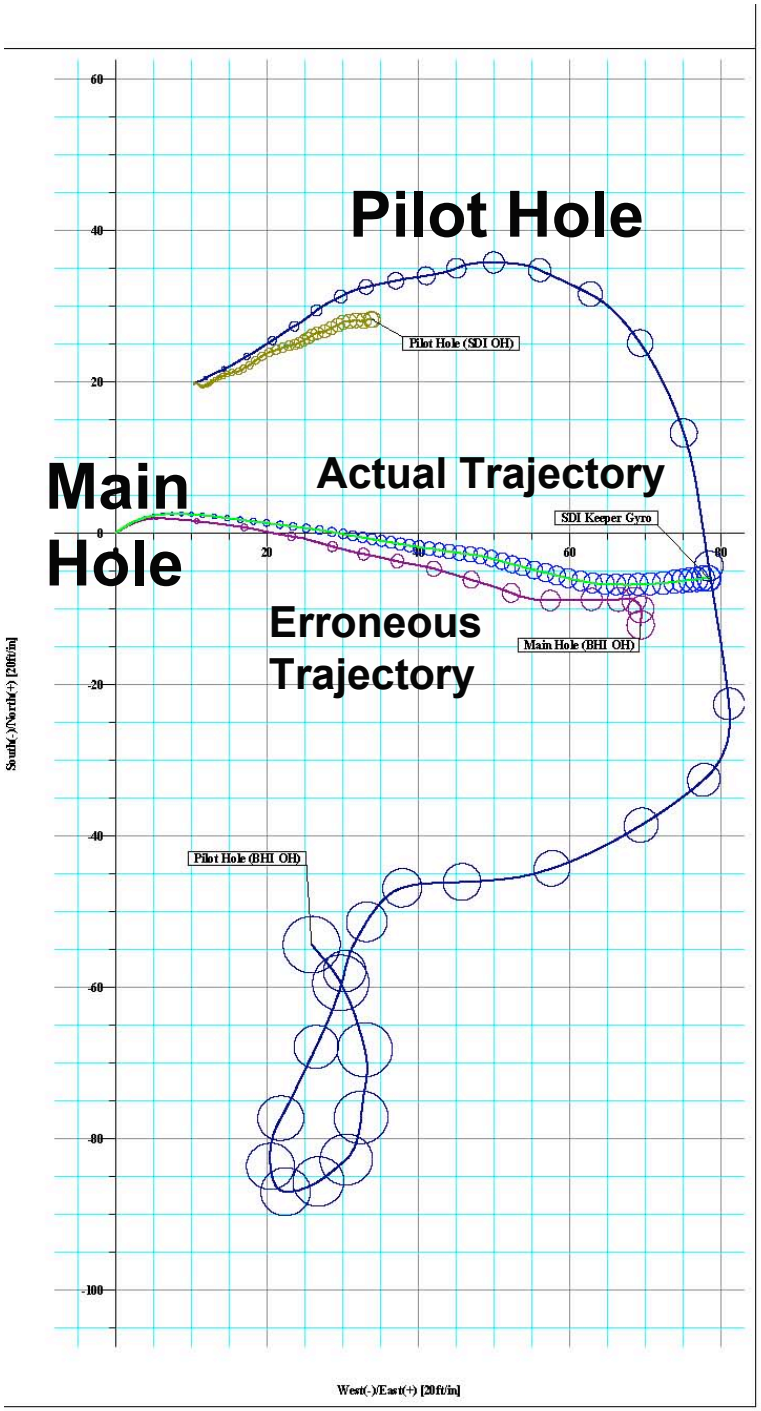
Stress Orientation Consistent With Strong Crust/Weak Fault

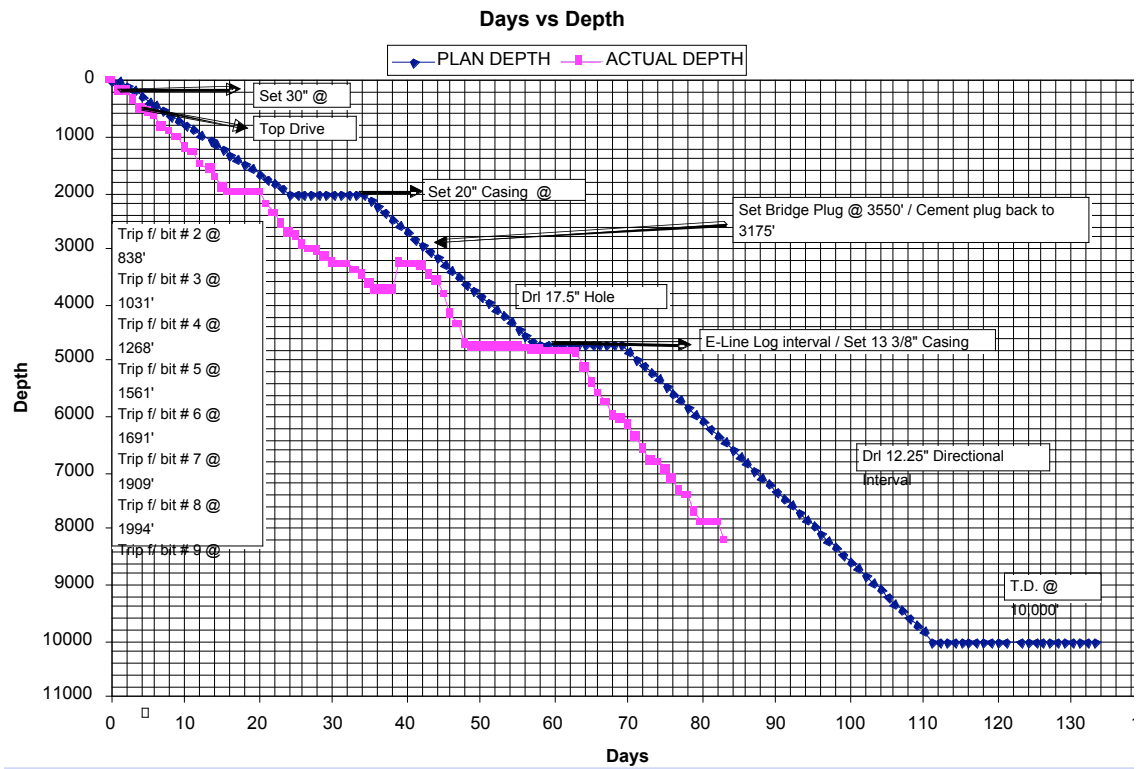




Hickman and Zoback (2004)

Boness and Zoback (2004)





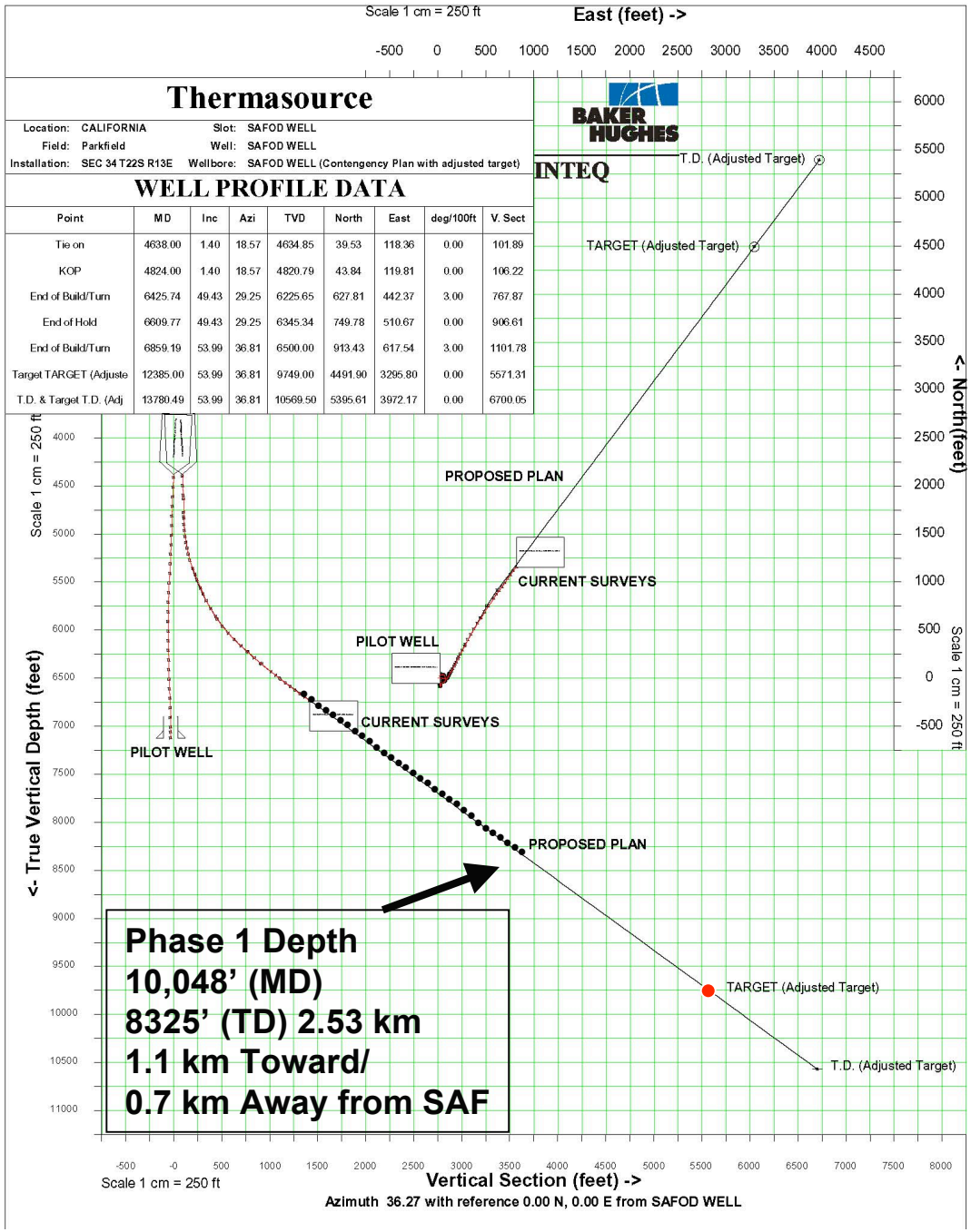
All Costs Associated with Hole Intersection Borne by Directional Drilling Sub-contractor

Thermasource

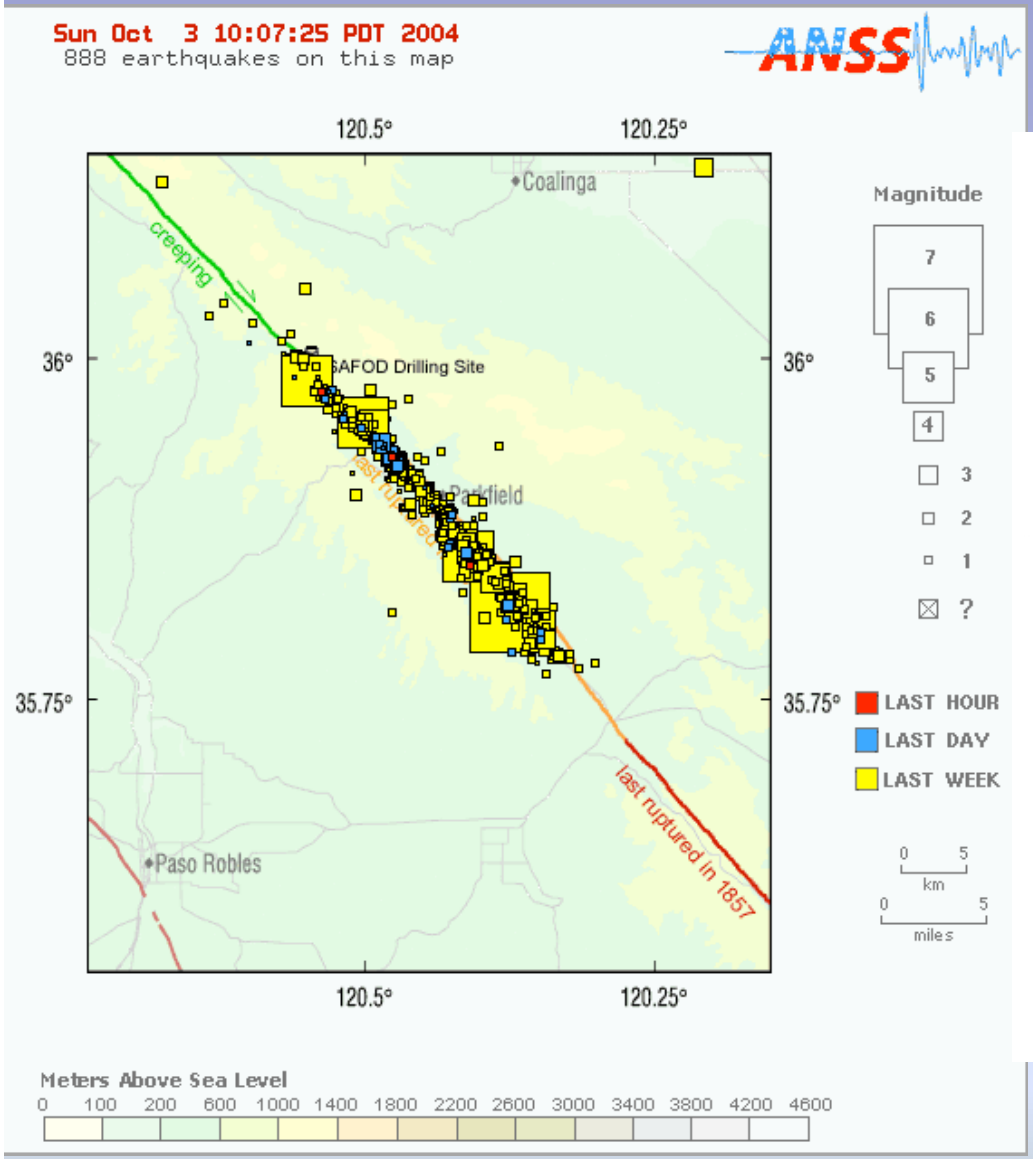
Location: CALIFORNIA Slot: SAFOD WELL
Field: Parkfield Well: SAFOD WELL
Installation: SEC 34 T22S R13E Wellbore: SAFOD WELL (Contengency Plan with adjusted target)

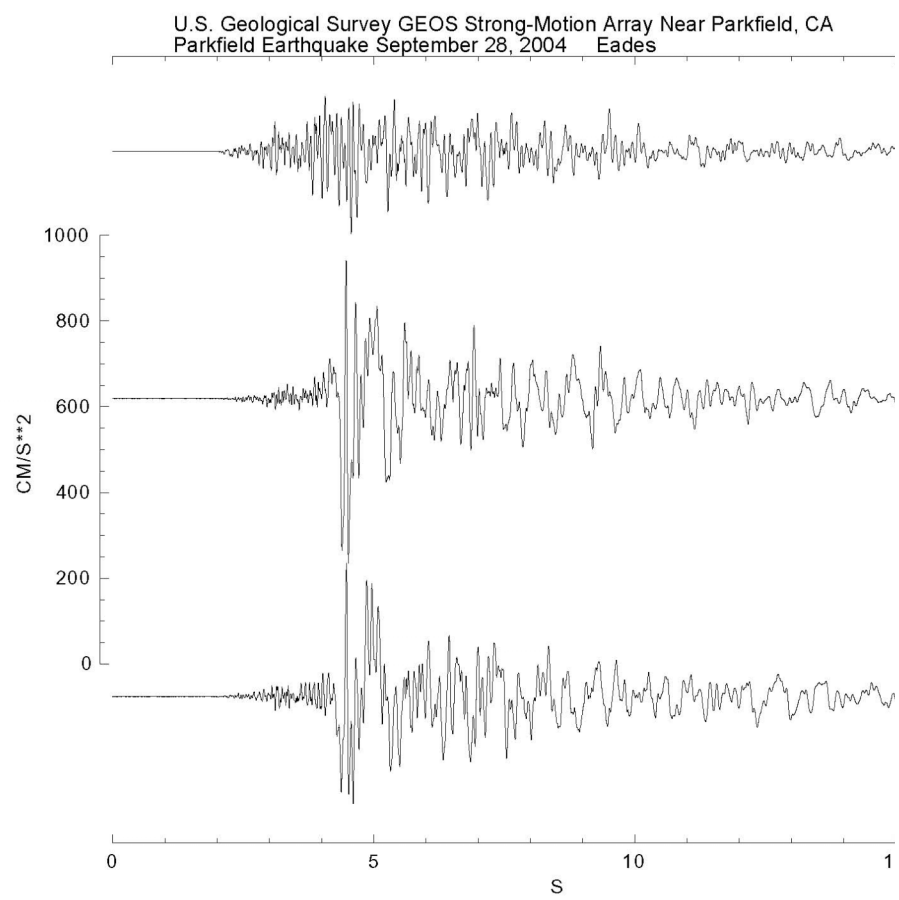
WELL PROFILE DATA

Point	MD	Inc	Azi	TVD	North	East	deg/100ft	V. Sect
Tie on	4638.00	1.40	18.57	4634.85	39.53	118.36	0.00	101.89
KOP	4824.00	1.40	18.57	4820.79	43.84	119.81	0.00	106.22
End of Build/Turn	6425.74	49.43	29.25	6225.65	627.81	442.37	3.00	767.87
End of Hold	6609.77	49.43	29.25	6345.34	749.78	510.67	0.00	906.61
End of Build/Turn	6859.19	53.99	36.81	6500.00	913.43	617.54	3.00	1101.78
Target TARGET (Adjuste	12385.00	53.99	36.81	9749.00	4491.90	3295.80	0.00	5571.31
T.D. & Target T.D. (Adj	13780.49	53.99	36.81	10569.50	5395.61	3972.17	0.00	6700.05



Phase 1 Depth
10,048' (MD)
8325' (TD) 2.53 km
1.1 km Toward/
0.7 km Away from SAF


Sun Oct 3 10:07:25 PDT 2004
888 earthquakes on this map
ANSS
120.5°
120.25°
36°
35.75°
Coalinga
creeping
SAFOD Drilling Site
Parkfield
last ruptured in 1857
Paso Robles
Magnitude
7
6
5
4
3
2
1
?
LAST HOUR
LAST DAY
LAST WEEK
0 5
km
0 5
miles
Meters Above Sea Level
0 100 200 600 1000 1400 1800 2200 2600 3000 3400 3800 4200 4600


U.S. Geological Survey GEOS Strong-Motion Array Near Parkfield, CA
Parkfield Earthquake September 28, 2004 Eades
CM/S**2
1000
800
600
400
200
0
0
5
10
1
S

Sept. 28, 2005

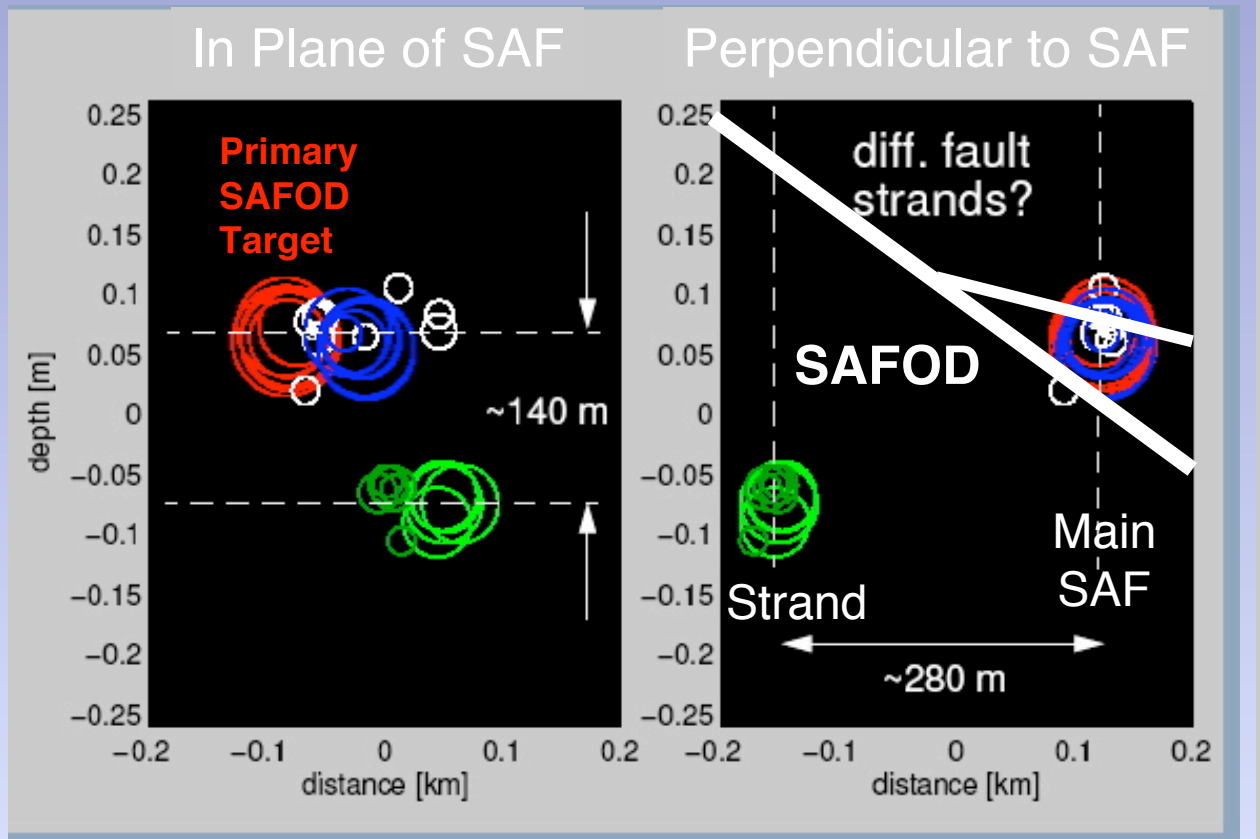
SAFOD and the Sept. 28, 2004 M 6 Earthquake

- Mainshock and Aftershocks Caused no Operational, Technical or Scientific Problems

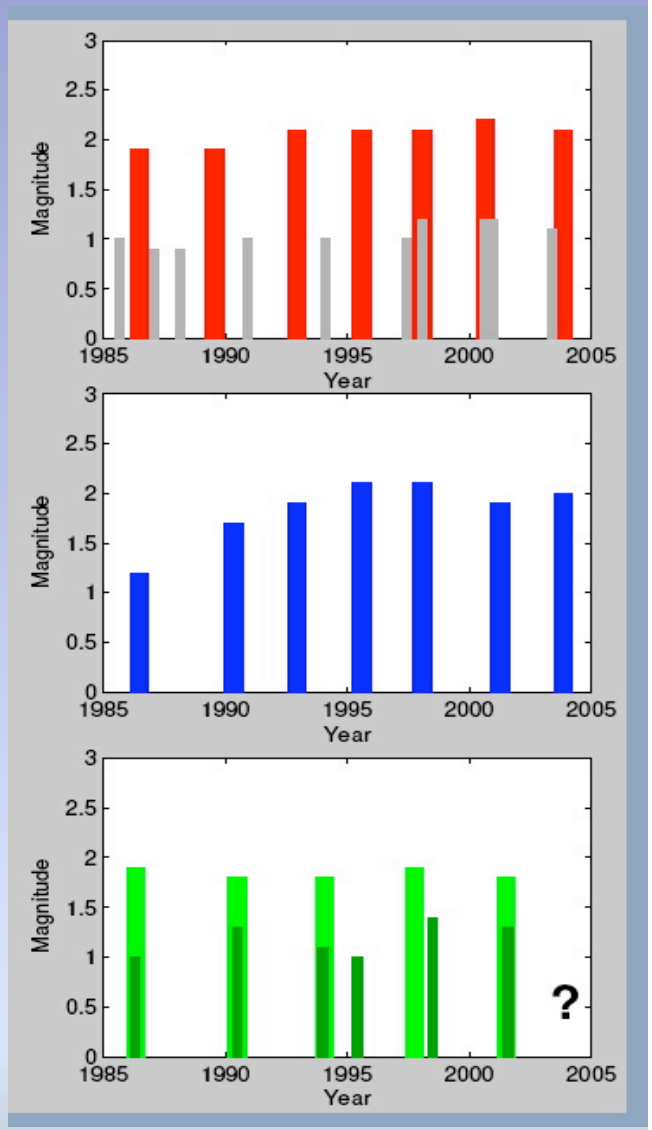
- Mainshock and Aftershocks Recorded on Pilot Hole Array

- Target Earthquakes have Increased in Frequency

Relative Locations of SAFOD Target Earthquakes (Repeaters)

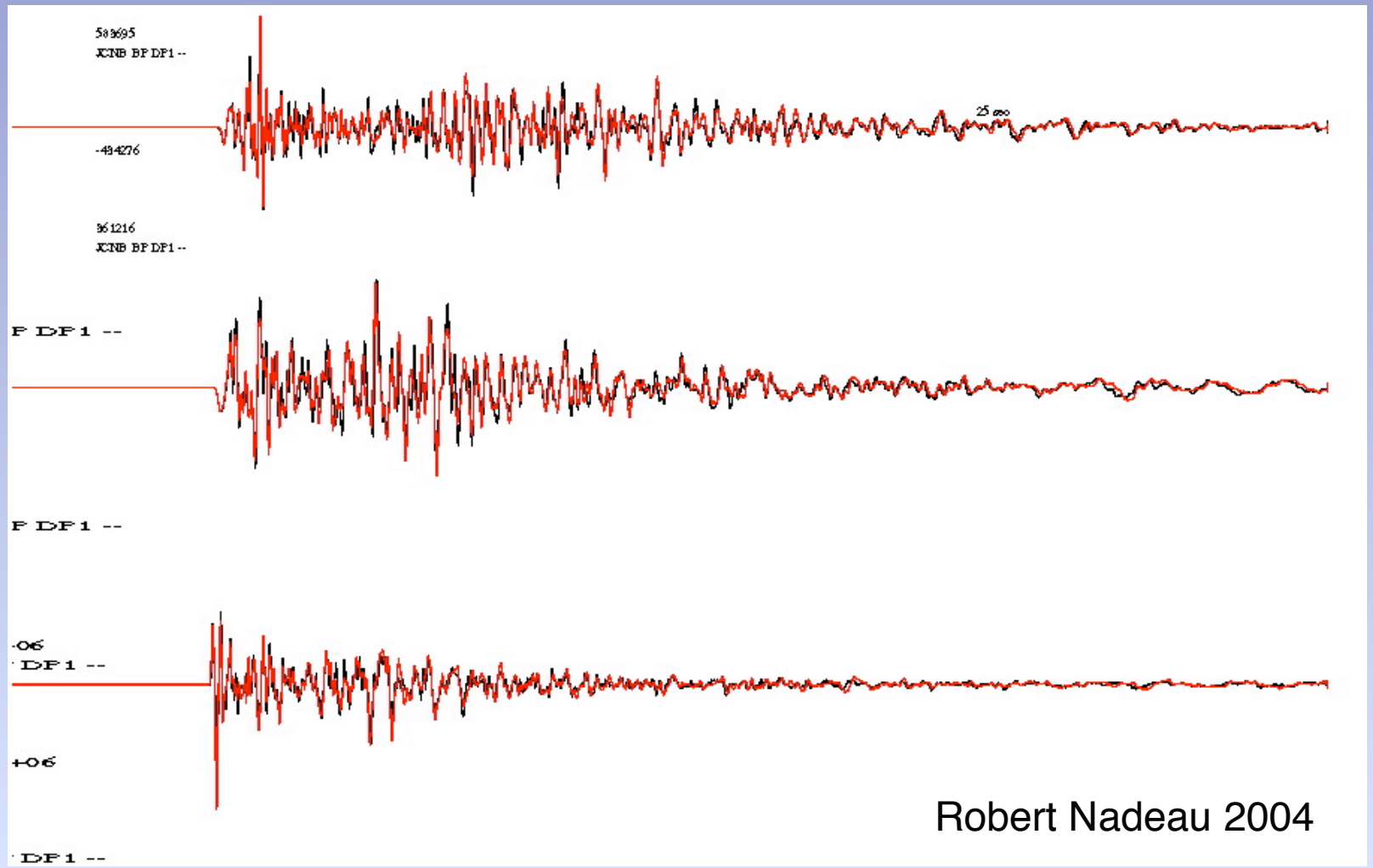


circle size = 9 MPa stress drop model



Felix Waldhauser 2004

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



Robert Nadeau 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 Advisory Structure

SAFOD Advisory Board

Roy Hyndman, Geol. Survey Canada
Jim Rice, Harvard
Don DePaolo, UCBerkeley
Rolf Emmermann, GFZ Potsdam
Teng-Fong Wong, SUNY
Mike Bahorich, Apache Corp
Art McGarr, USGS

SAFOD Technical Panels

Drilling, Coring and Safety

Monitoring Instrumentation

Downhole Measurements

Sampling and Sample Handling