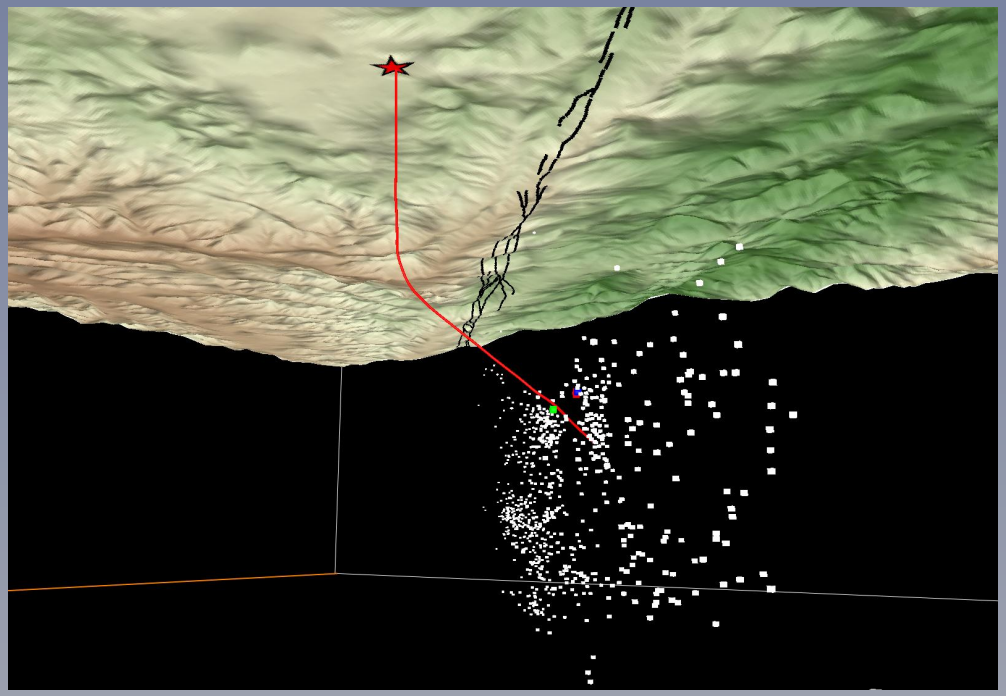
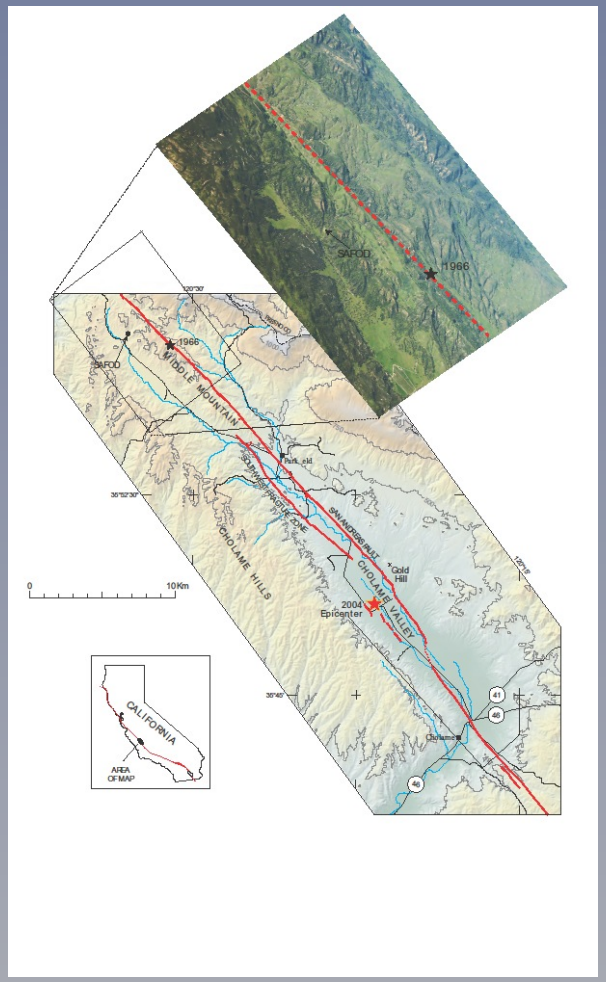
Gutenberg-Richter Breakdown and the Smallest Earthquakes at the San Andreas Fault Observatory at Depth



Bill Ellsworth
U. S. Geological Survey
and
Kaz Imanishi
GSJ/AIST

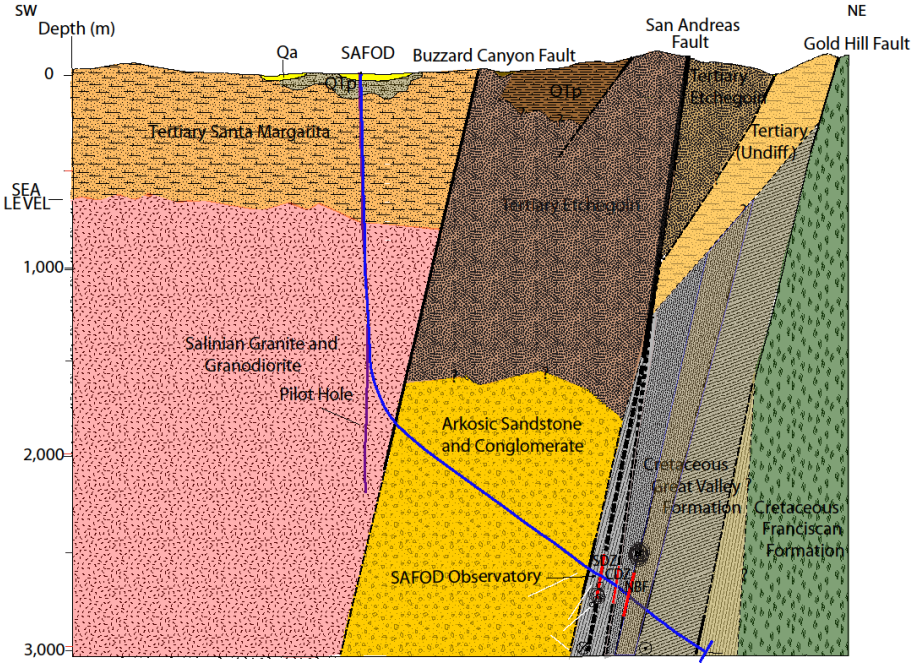
Outline

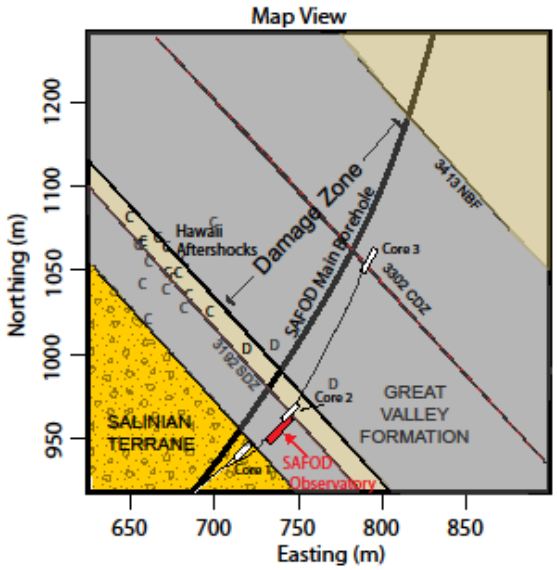


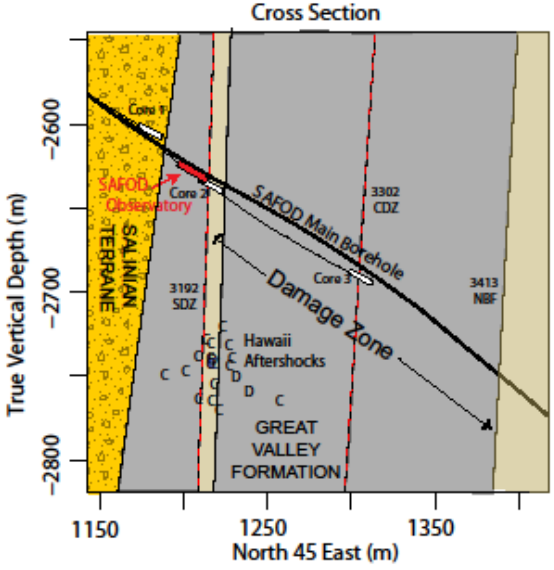
- Overview of the San Andreas Fault at SAFOD
- Nucleation zone size and earthquakes at SAFOD
- Building a Catalog of SAFOD Earthquakes
- Gutenberg – Richter Breakdown
- Summary

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

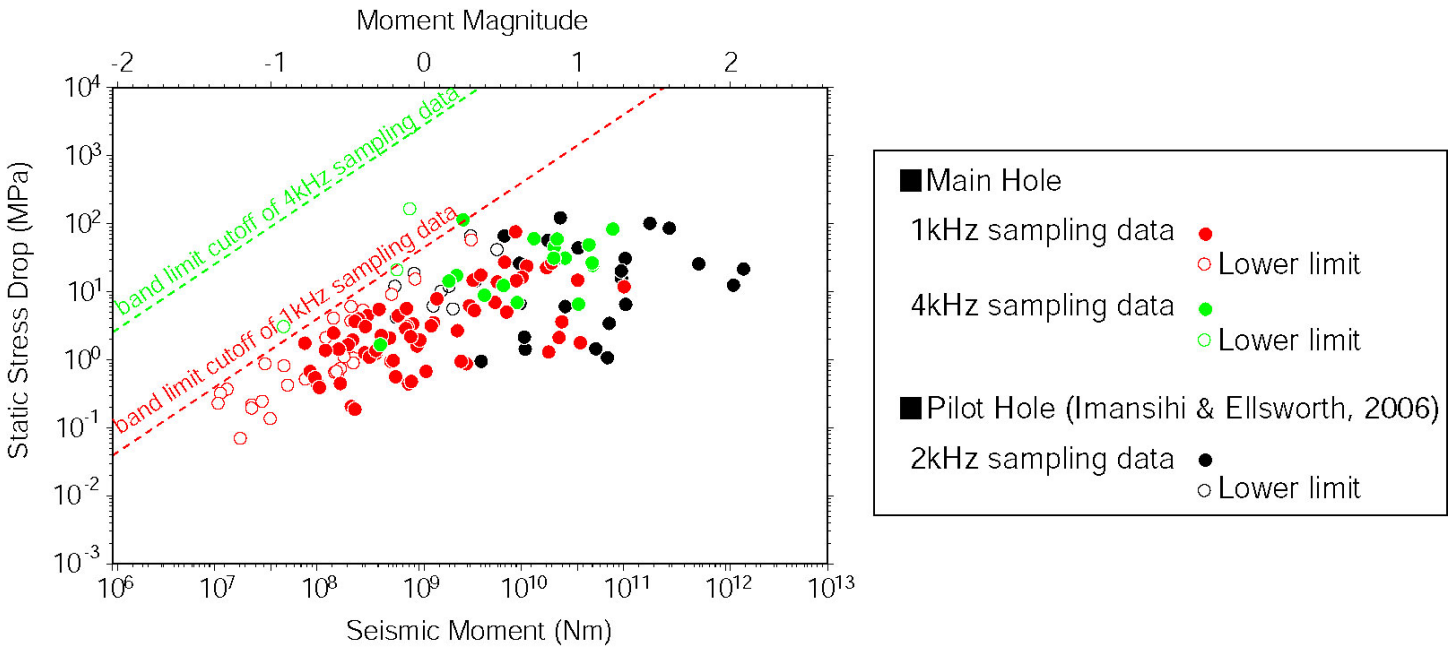
Zoback, Hickman & Ellsworth (*Scientific Drilling*, 2011)



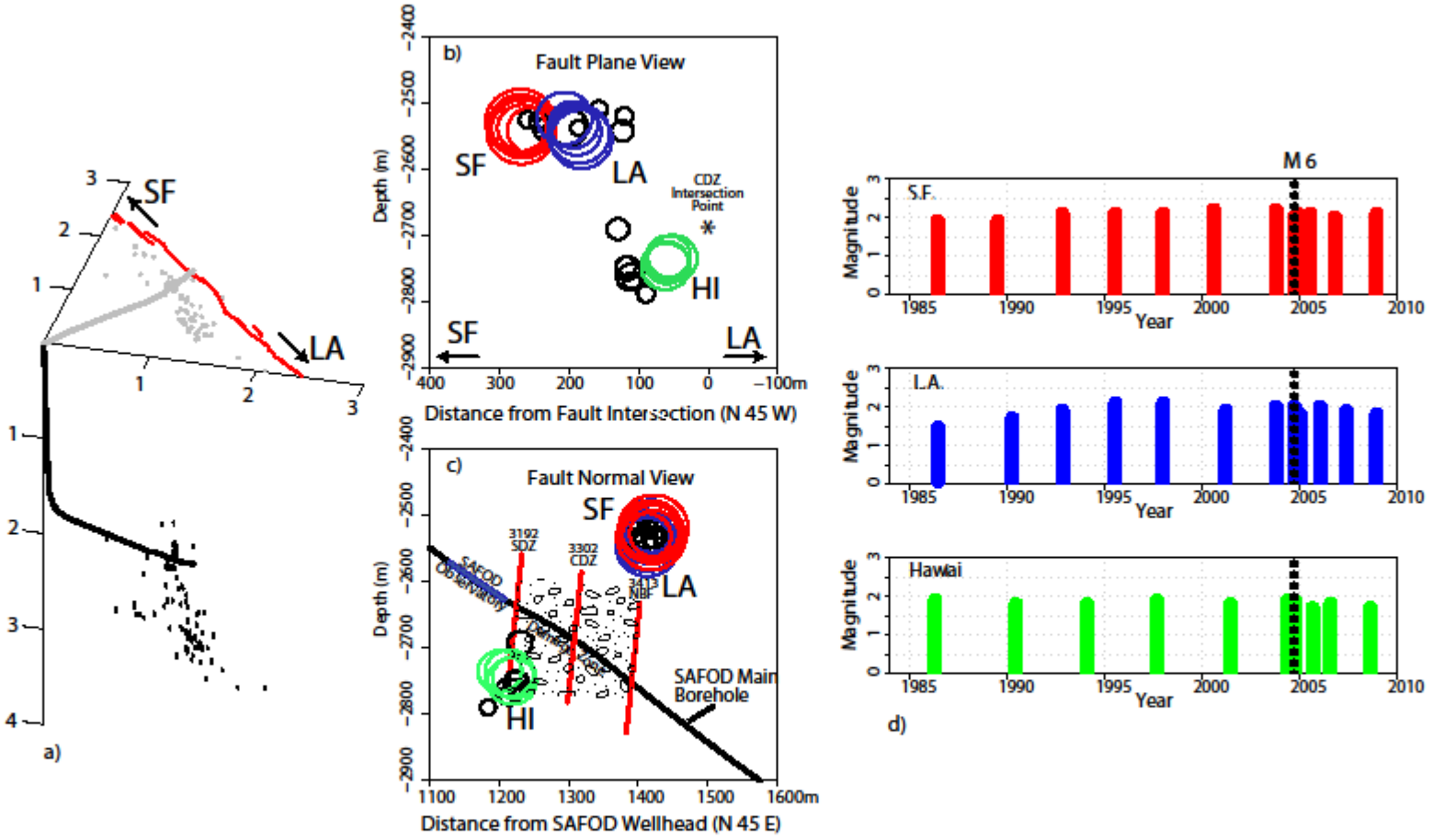




Static Stress Drop vs Seismic Moment

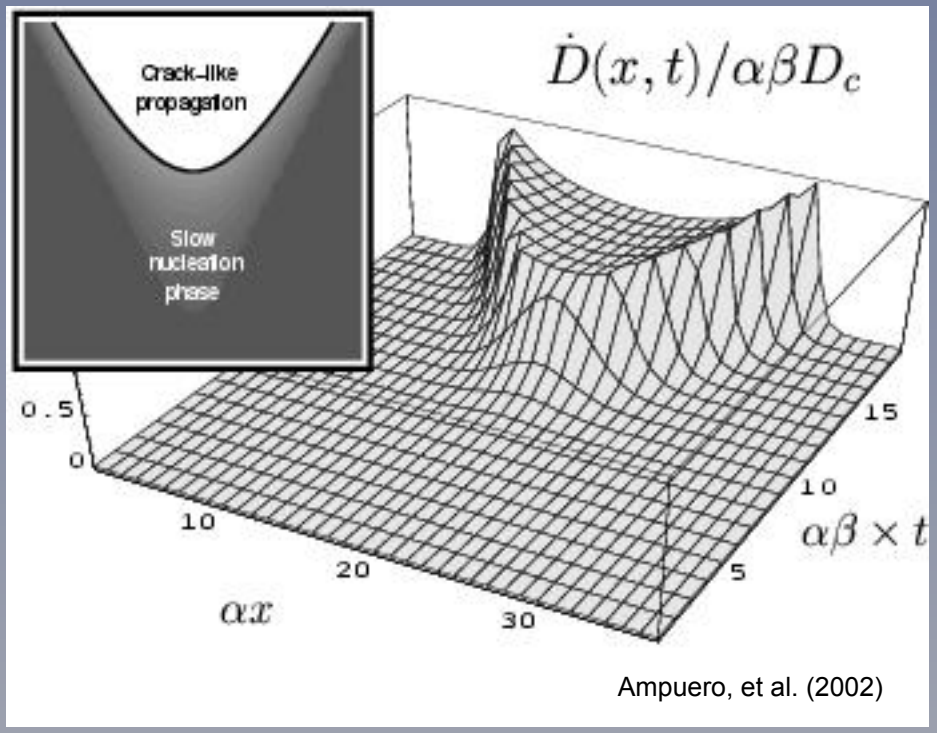


- Individual stress drop estimates span 3 order of magnitude (0.1 to 100 MPa), which do not depend on earthquake size.
- This range is consistent with other microearthquake studies on the basis of a similar approach (e.g., Ide et al., 2001; Abercrombie & Rice, 2005)
- This range is also consistent with moderate and large earthquakes.

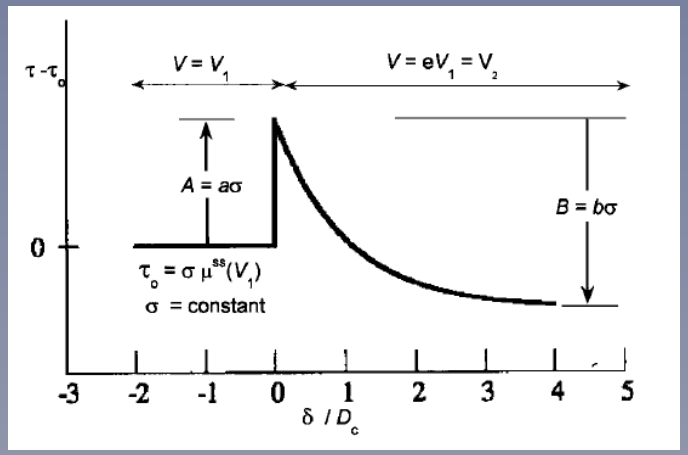

a)
SF
LA
b)
Fault Plane View
SF
LA
CDZ
Intersection
Point
HI
Depth (m)
Distance from Fault Intersection (N 45 W)
c)
Fault Normal View
3192
SDZ
3302
CDZ
SAFOD
Observation
Hole
SAFOD Main
Borehole
Distance from SAFOD Wellhead (N 45 E)
M 6
S.F.
L.A.
Hawai
Magnitude
Year
d)

Slip in a confined region must precede the earthquake instability

Ida (1973), Dieterich (1992)



Ampuero, et al. (2002)



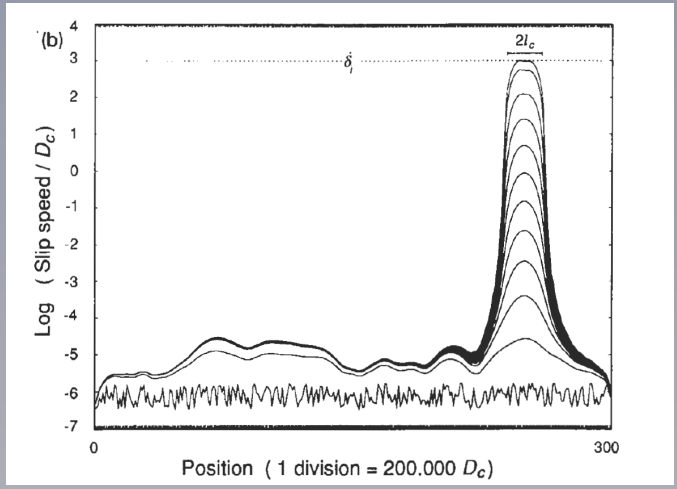
Minimum Rupture Dimension

$$h^* = G\, D_c / ((\sigma_n - P_0)(b - a))$$

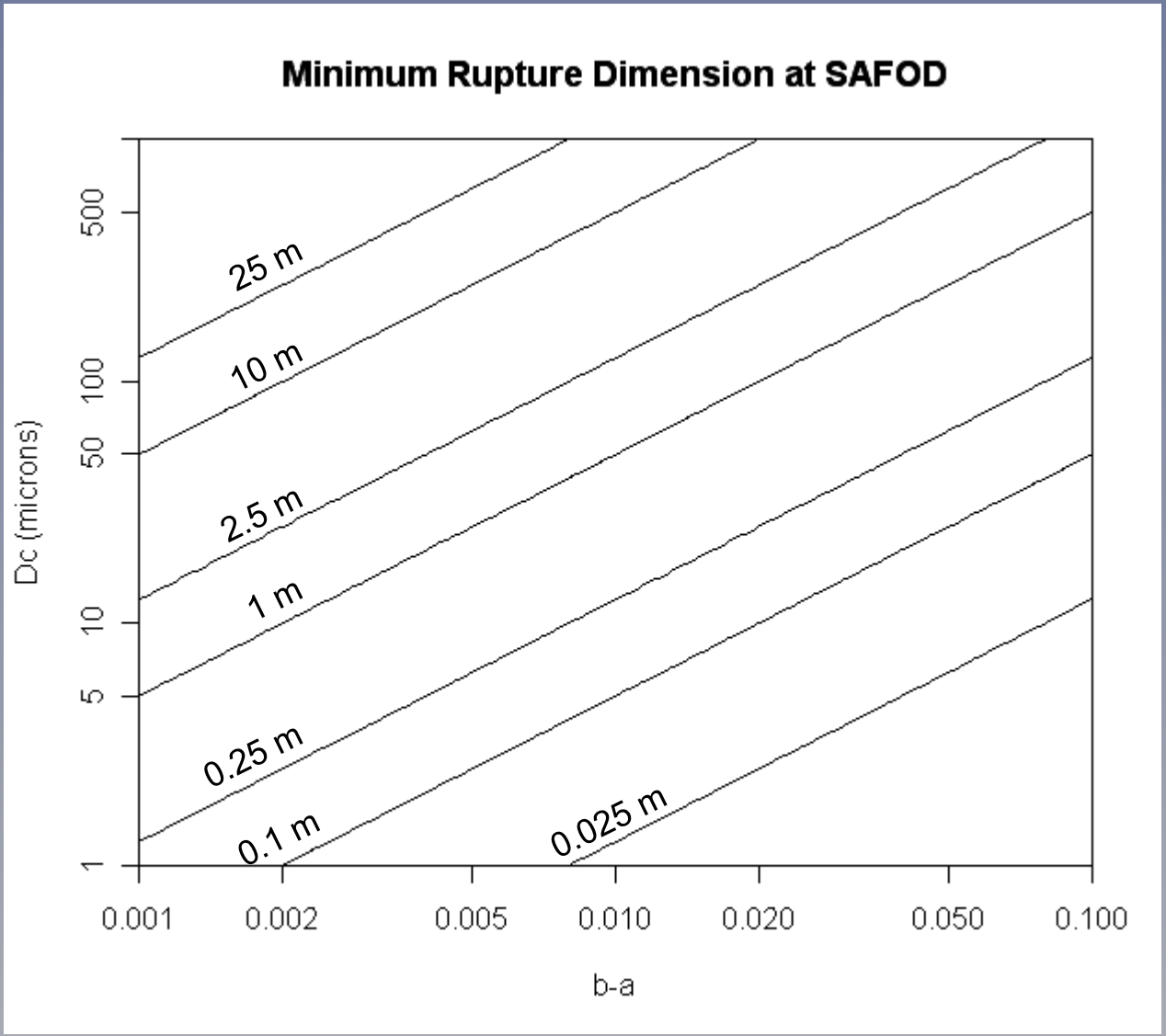
Rice and Ruina (1983)

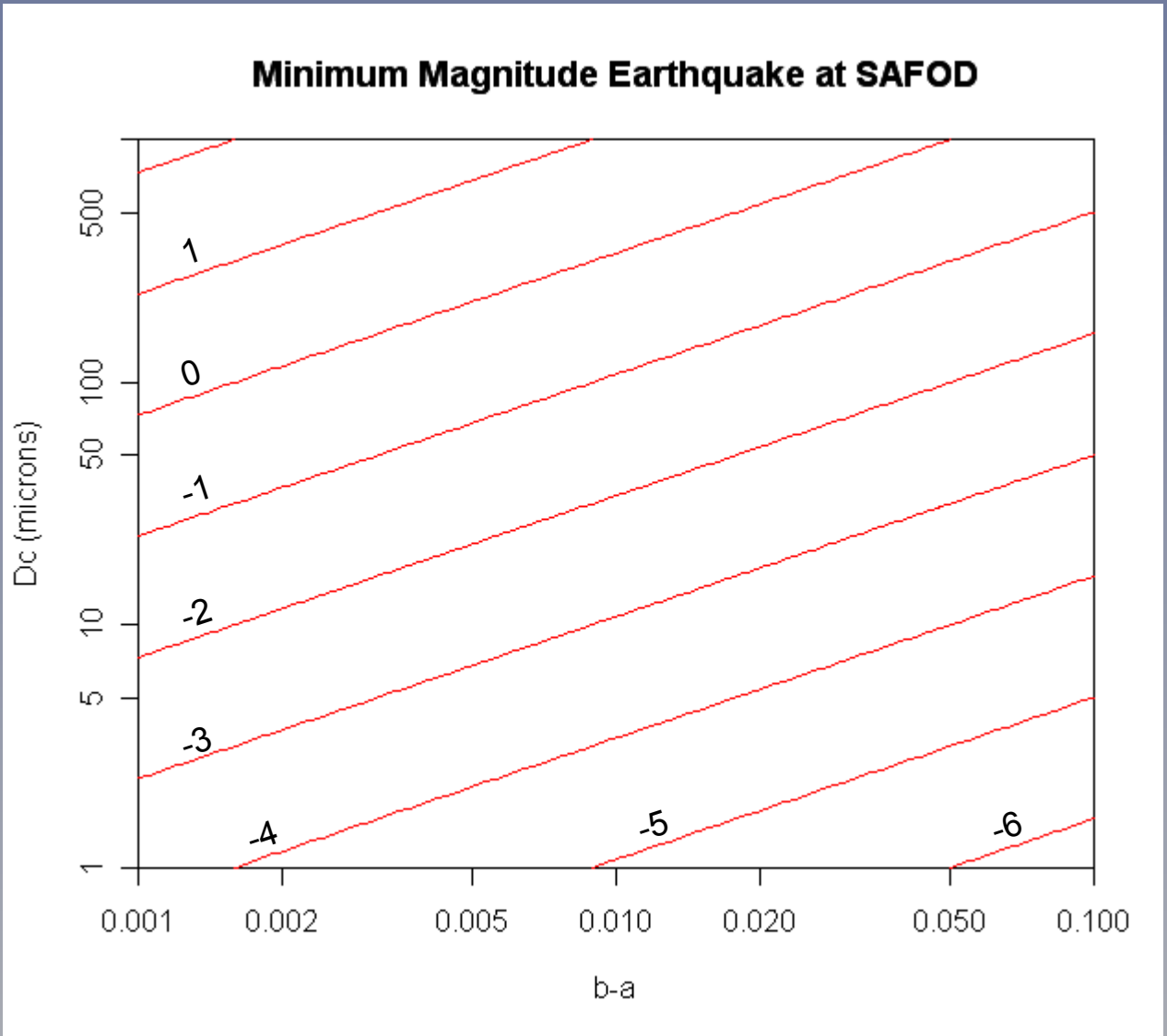
$$h^* = G D_c / ((\sigma_n - P_0)(b - a))$$

G	Shear Modulus = ρV_s^2 = 2 x 10^{10} Nm^{-2}
σ_n	Normal Stress (measured) = 130 MPa @ 3 km
P_0	Pore Pressure = 1 g z = 47 MPa @ 3 km
D_c	Displacement weakening distance
(b – a)	Rate-and-State parameter

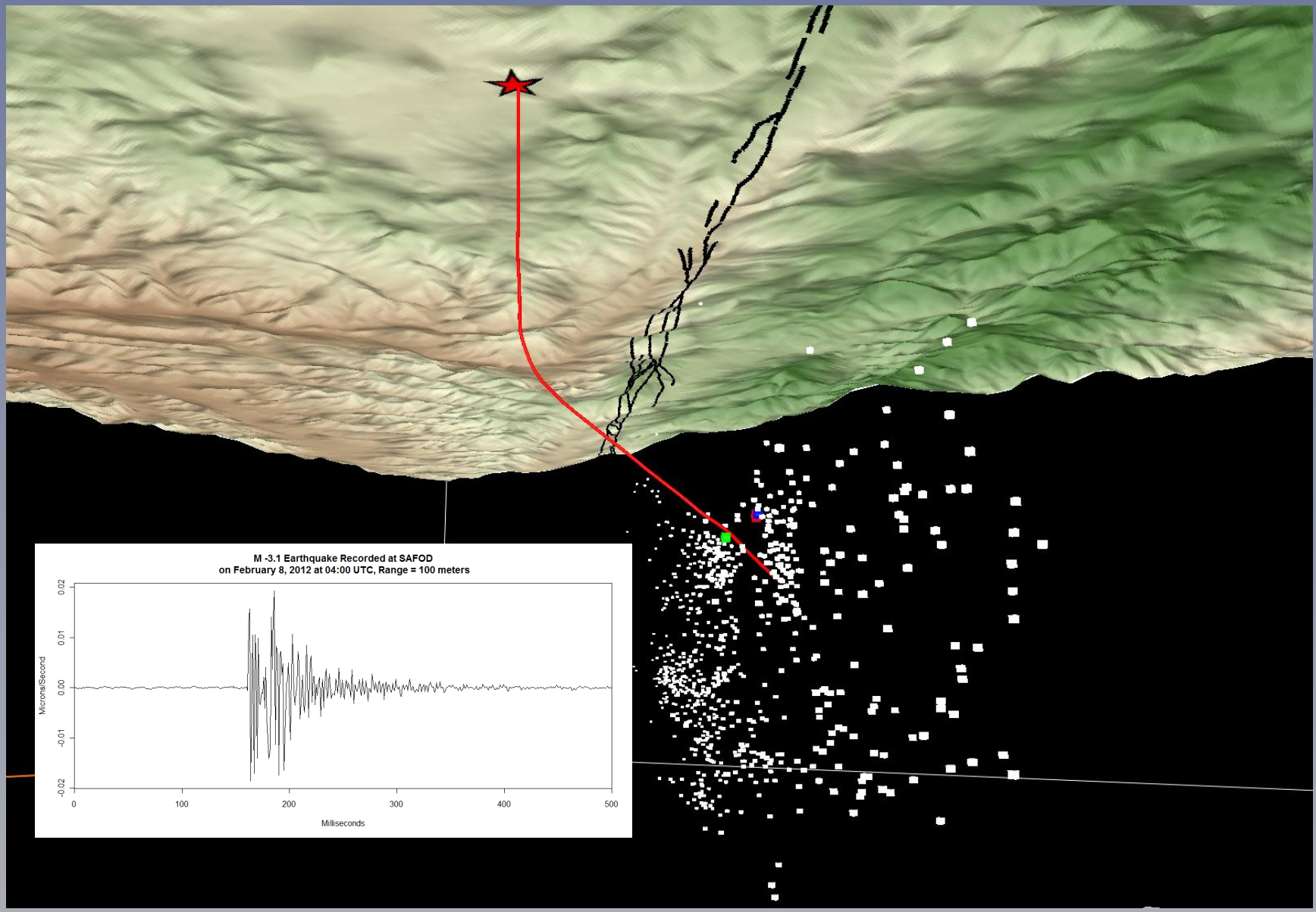


Jim Dieterich (*JGR*, 1992)

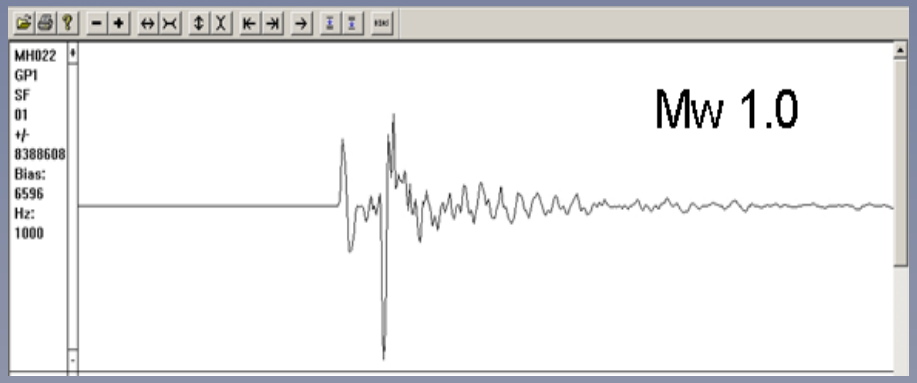

Minimum Rupture Dimension at SAFOD
Dc (microns)
500
100
50
10
5
1
25 m
10 m
2.5 m
1 m
0.25 m
0.1 m
0.025 m
0.001
0.002
0.005
0.010
0.020
0.050
0.100
b-a

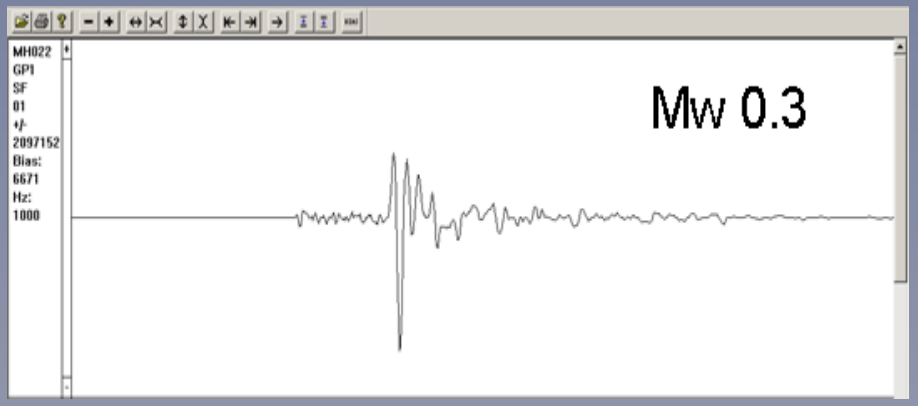

Minimum Magnitude Earthquake at SAFOD
Dc (microns)
500
100
50
10
5
1
1
0
-1
-2
-3
-4
-5
-6
0.001
0.002
0.005
0.010
0.020
0.050
0.100
b-a

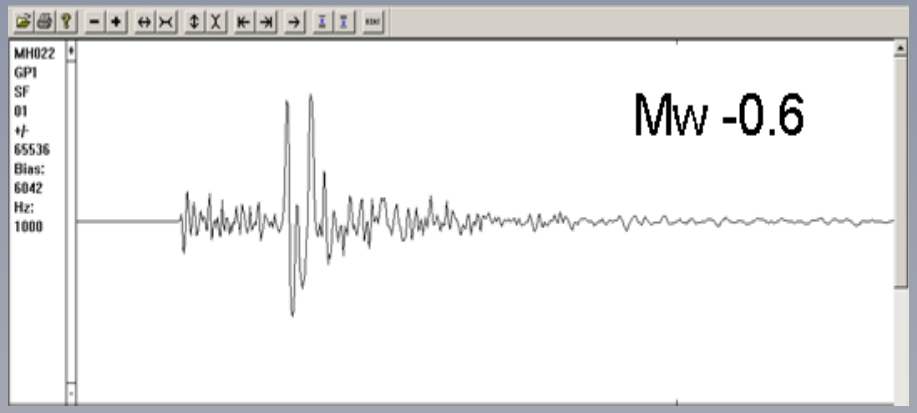
Building a Catalog of SAFOD Earthquakes

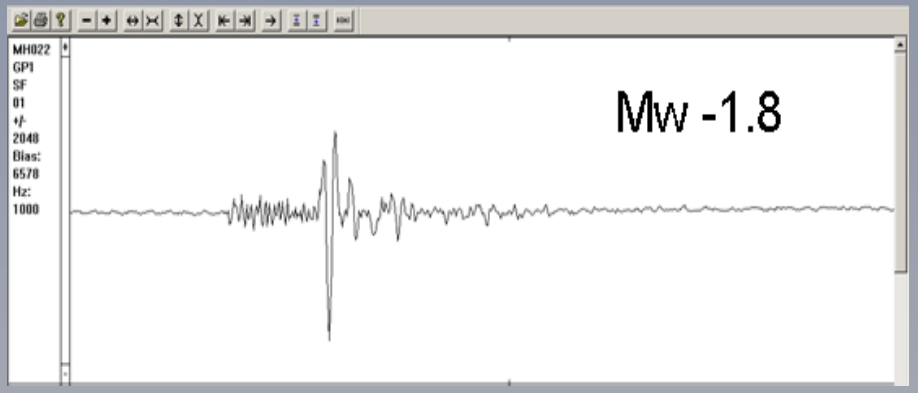


Examples of Earthquakes Recorded in SAFOD at 2.5 km depth





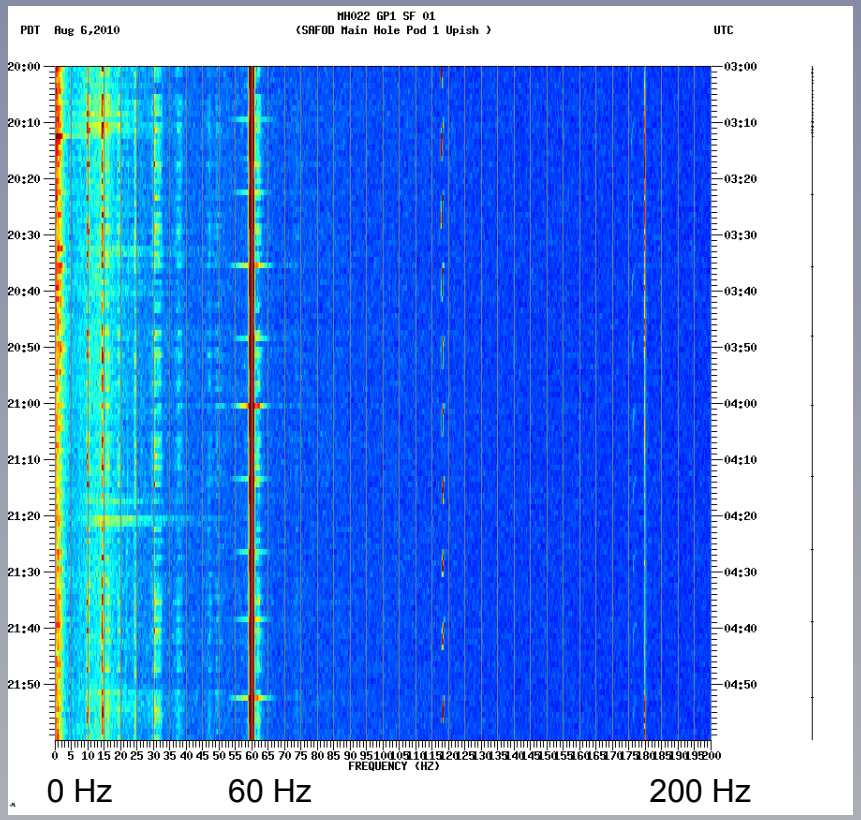


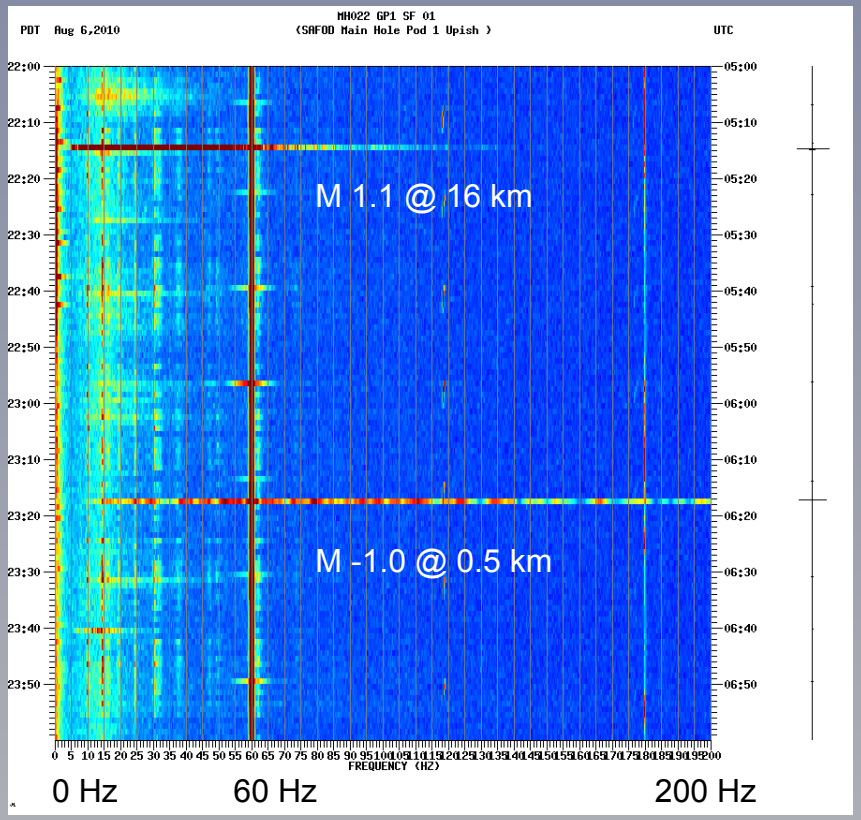


Data Window 0.75 s

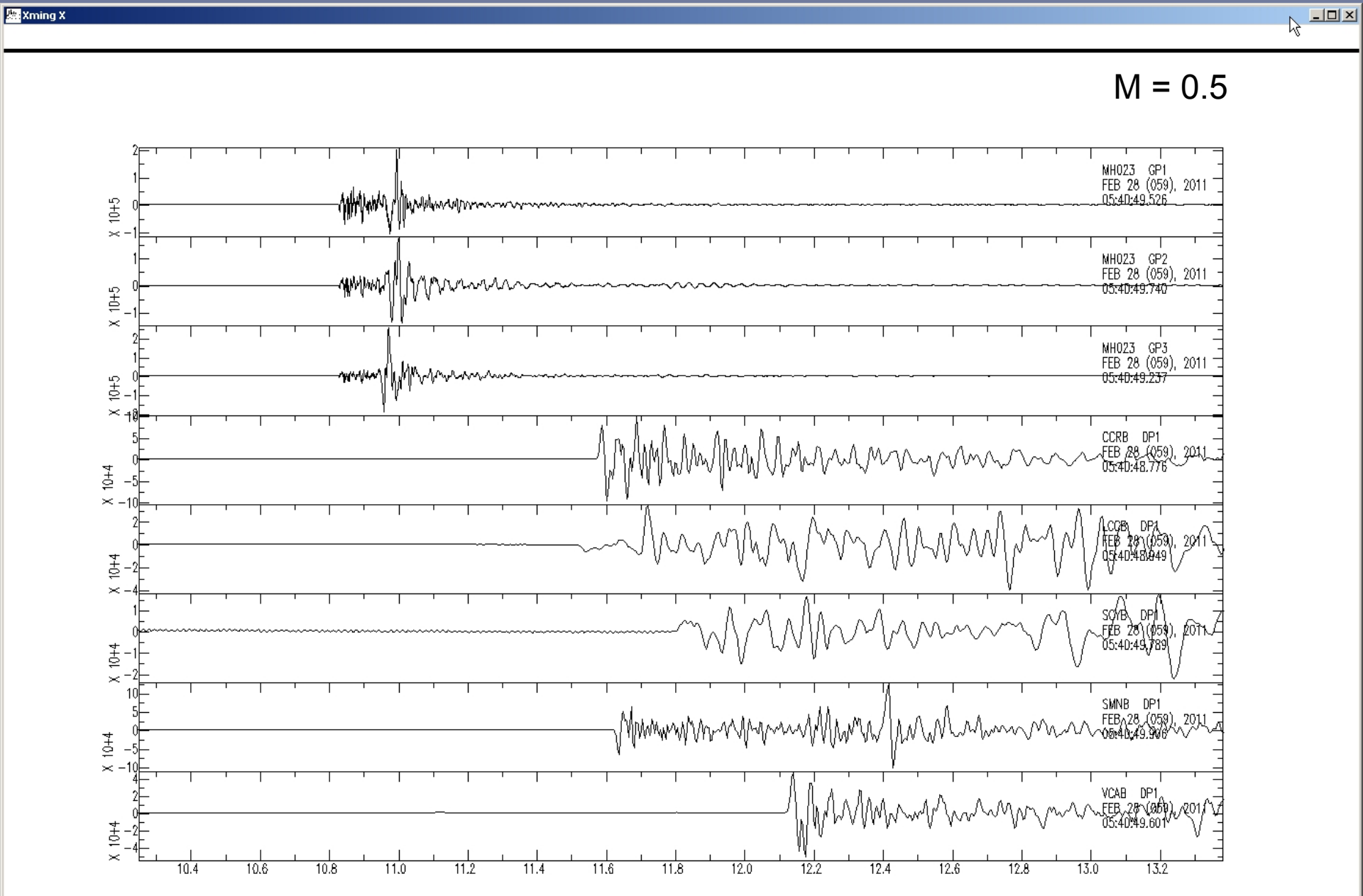
37 months of continuous data acquisition at SAFOD
(MH022: May 2009 – August 2010)
(MH023-025: December 2010 – present)

- 15 Hz geophone (1000 samples/s)
- Installed at 2.5 km depth
- Earthquakes Identified by Manual Inspection of Bi-Hourly Spectrograms



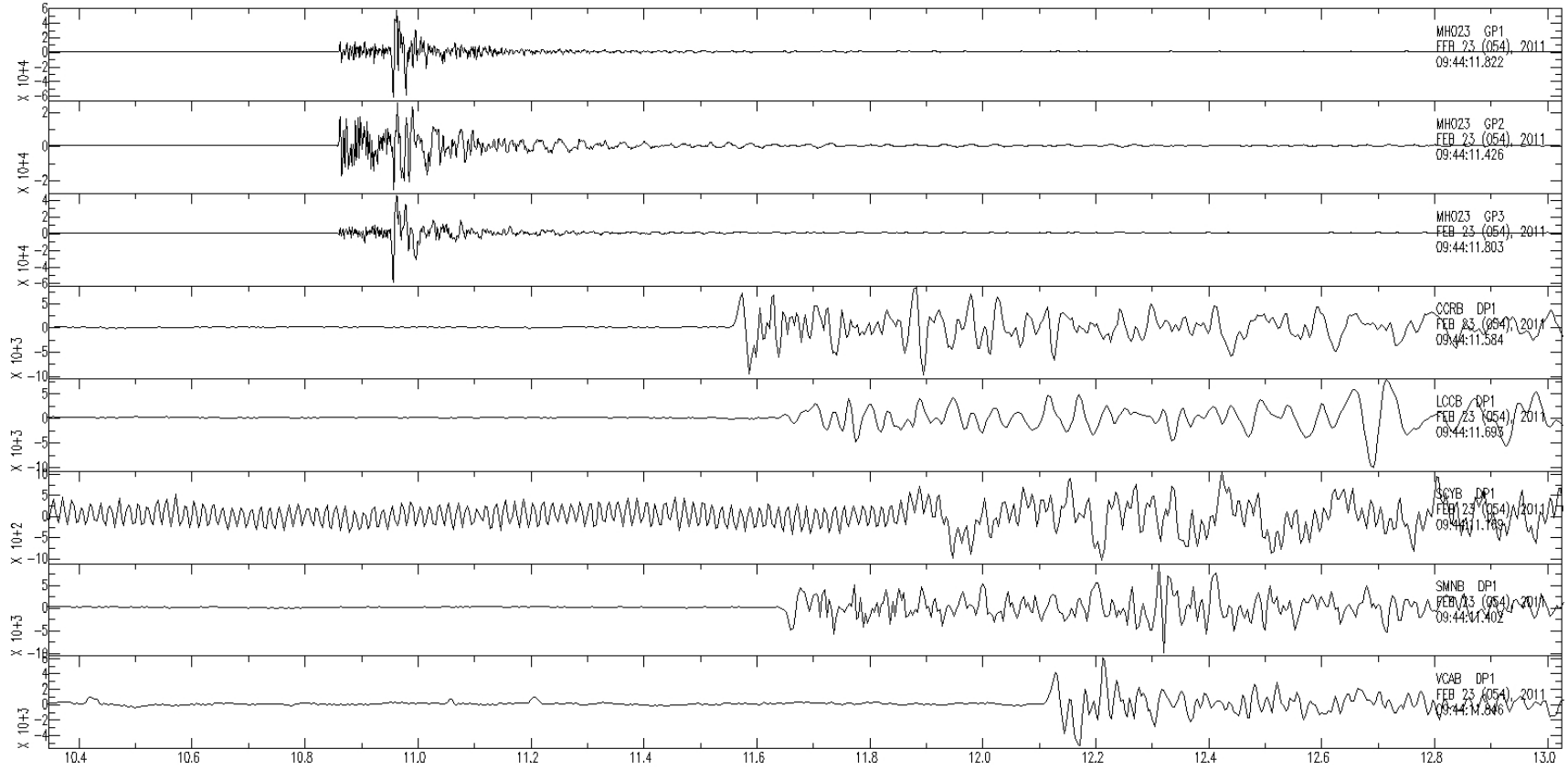


Comparing Seismograms Recorded at -2400 m and -200 m depth

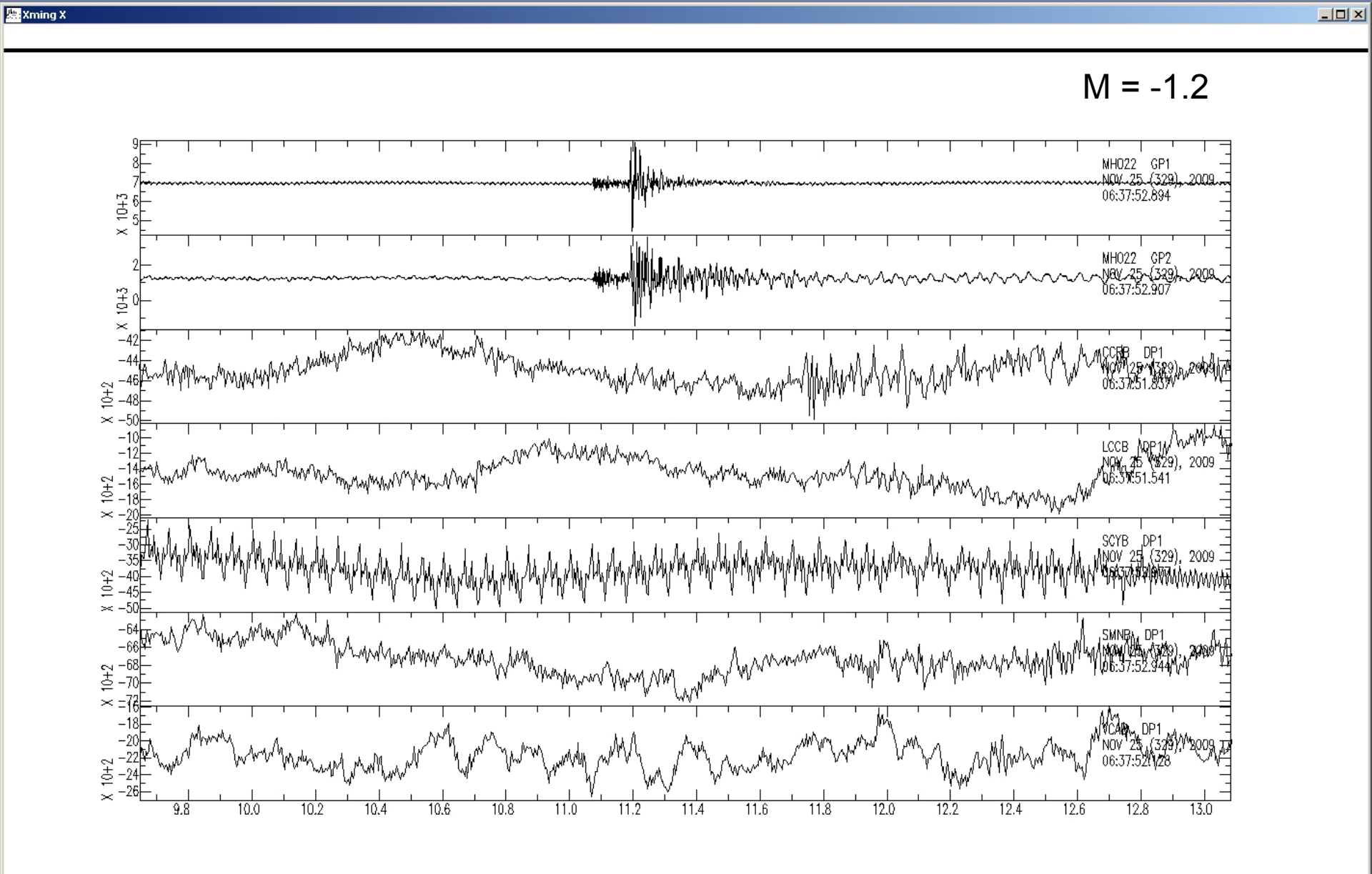


Comparing Seismograms Recorded at -2400 m and -200 m depth

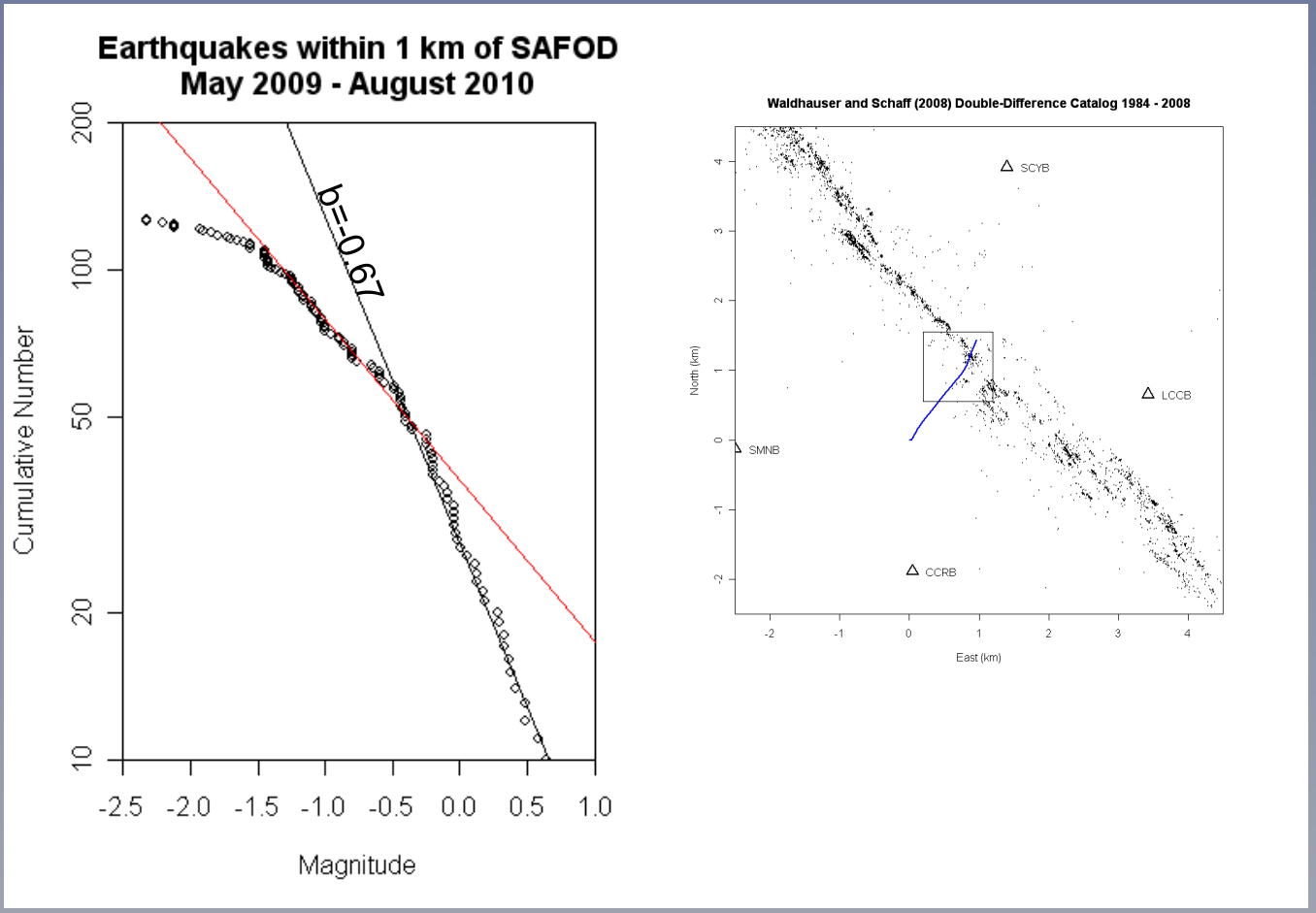
M = -0.1



Comparing Seismograms Recorded at -2400 m and -200 m depth

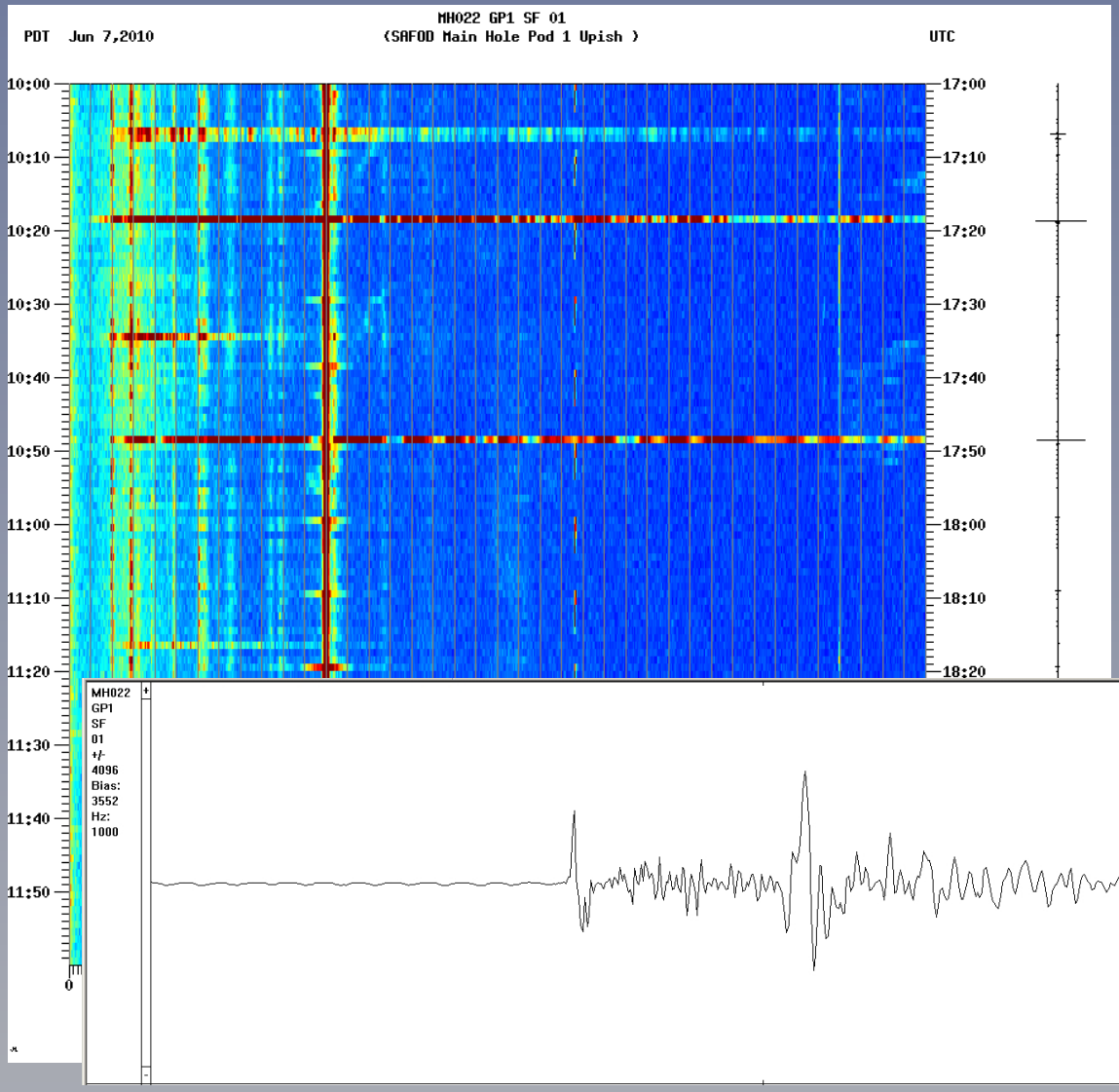


Gutenberg – Richter Magnitude-Frequency Distribution



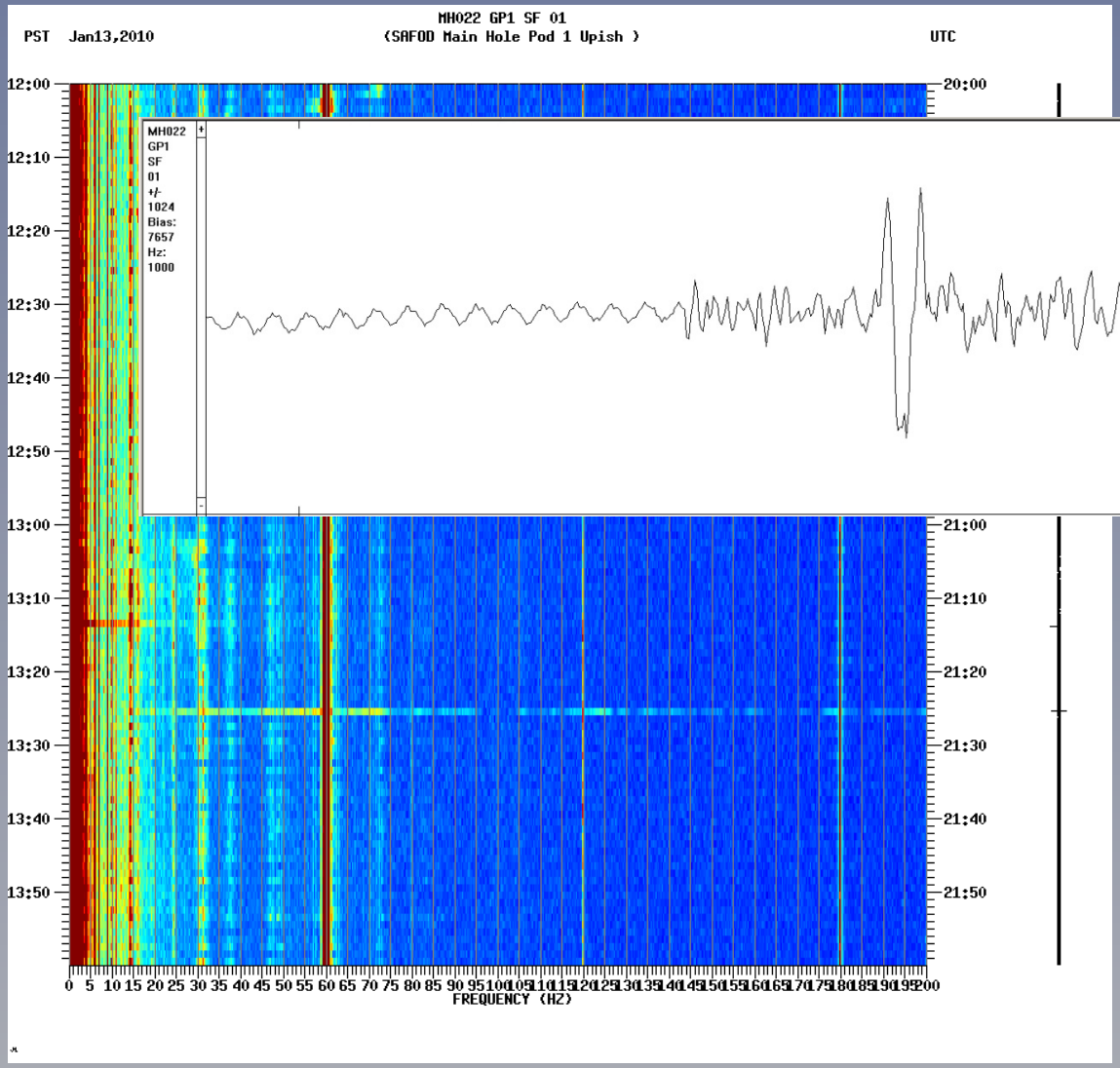
"Missing Earthquakes" Problem

The result could be an artifact, but I think this unlikely as every candidate event is visually examined.



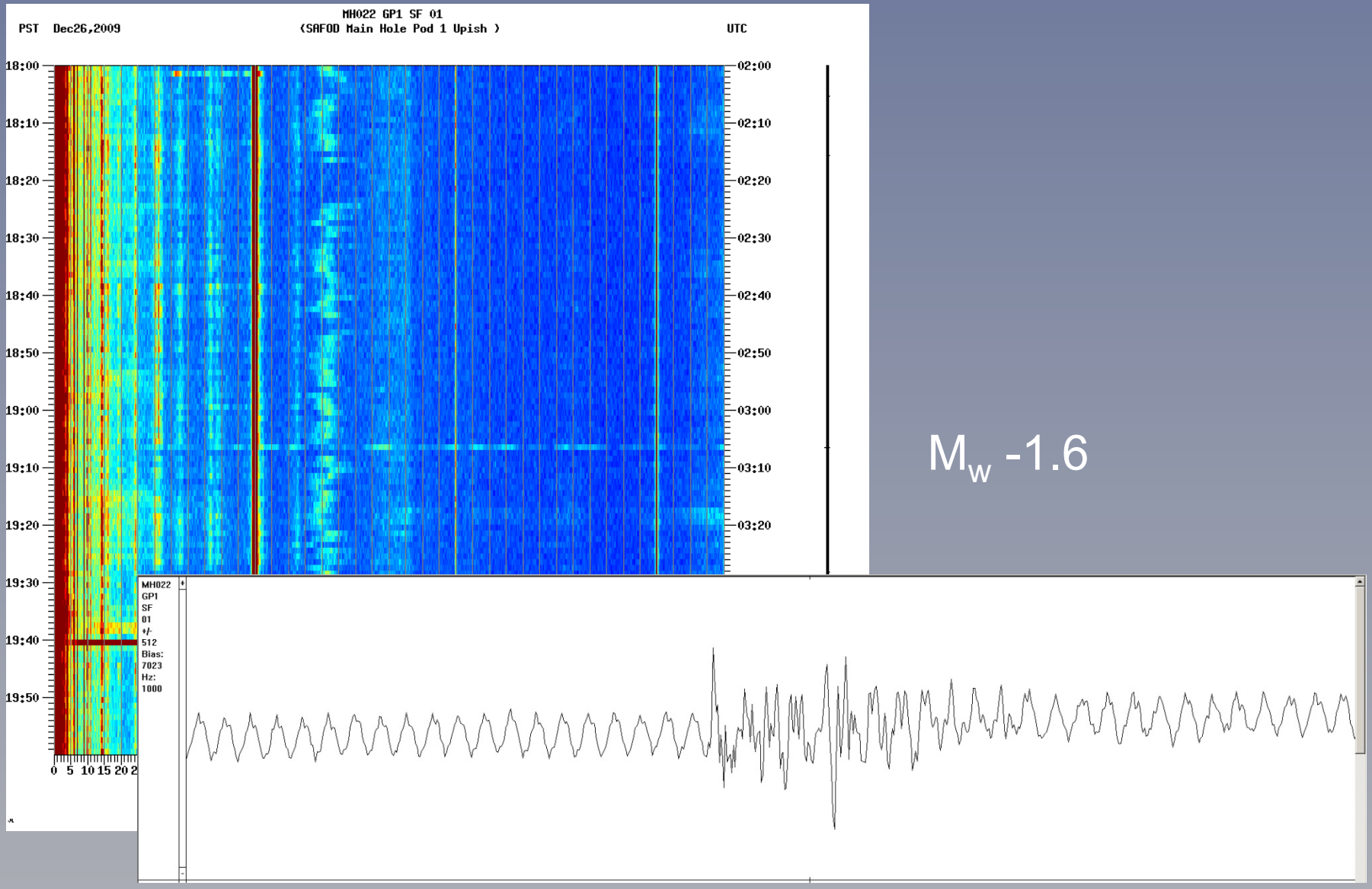
M_w -1.1

Data Window 0.75 s



Data Window 0.75 s

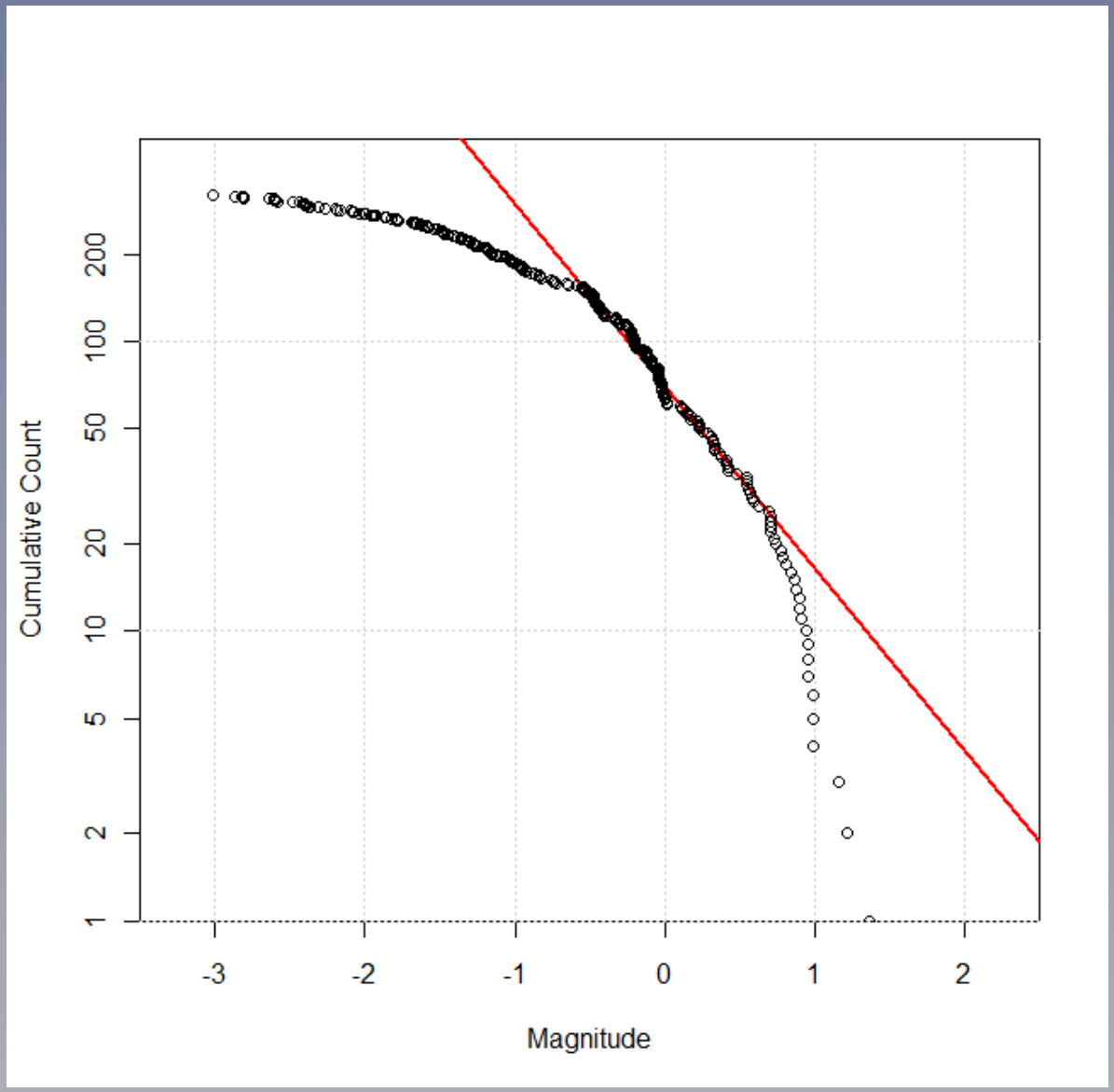
M_w -1.4



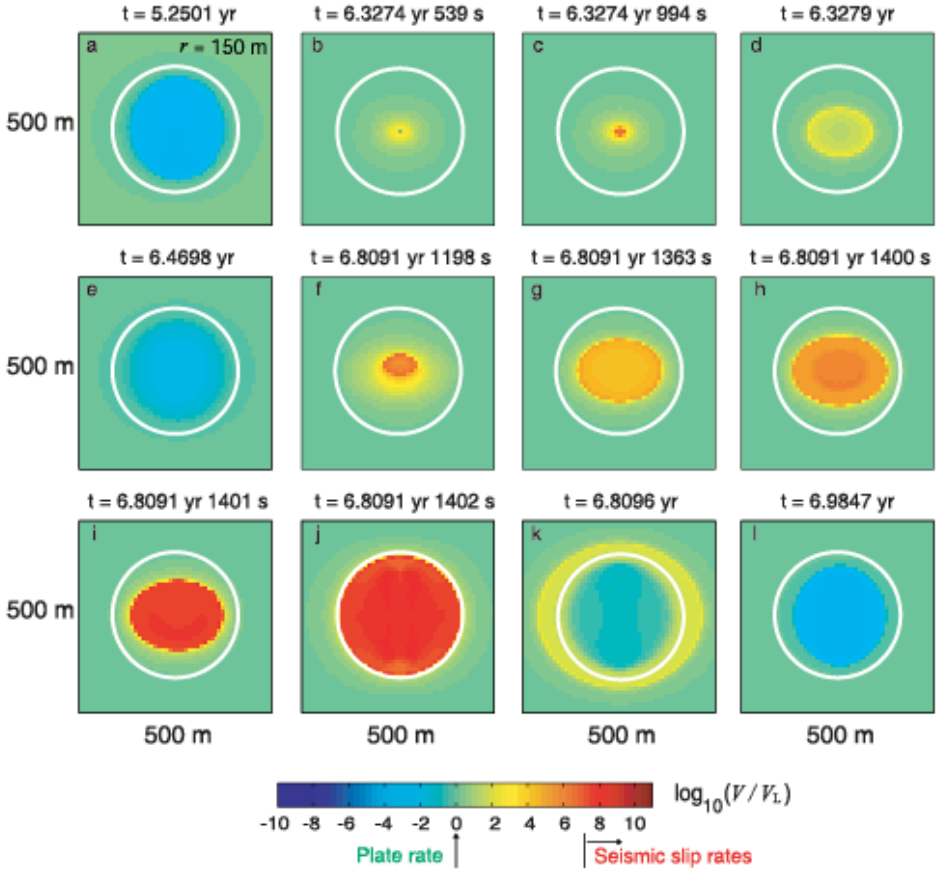
M_w -1.6

Data Window 0.75 s

Earthquakes within 1 kilometers
May 2009 – September 2012

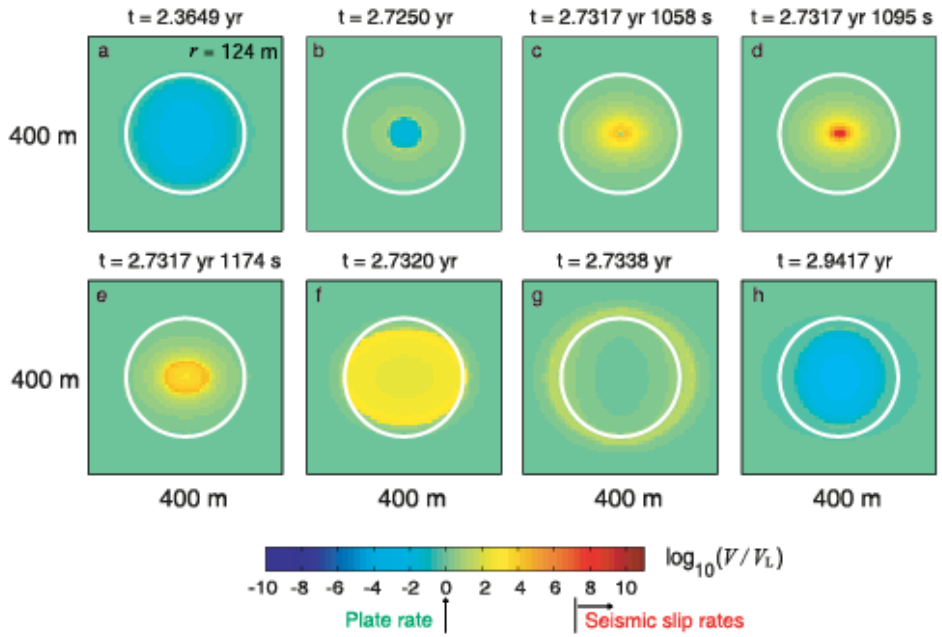


Scaling of small repeating earthquakes explained by interaction of seismic and aseismic slip in a rate and state fault model
T. Chen and N. Lapusta, *JGR*, 2019



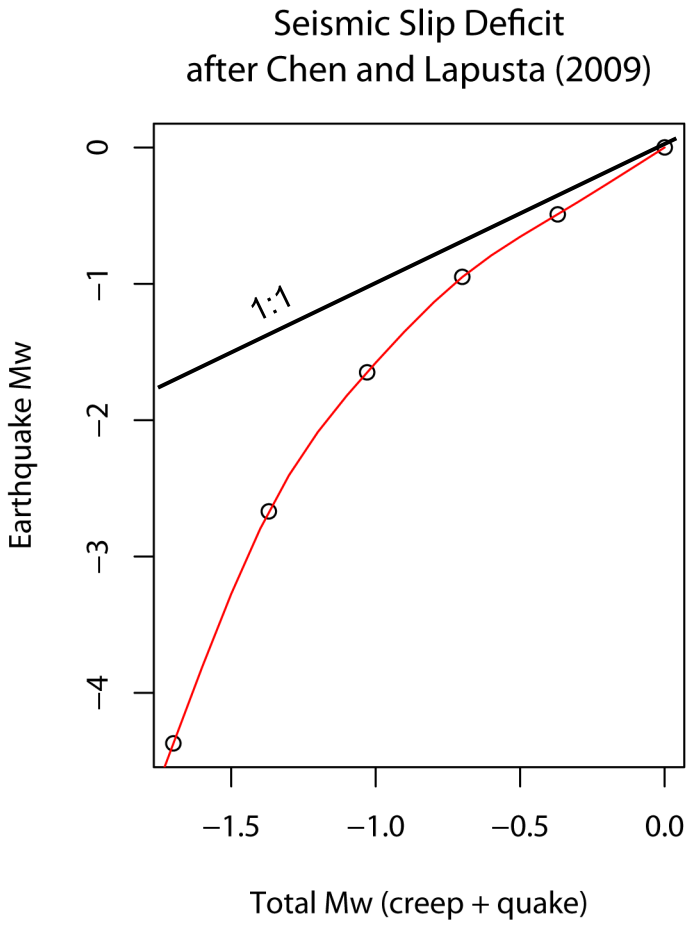
Ratio of Seismic Moment/Total Moment = 0.3
for patch radius of 130 m

Scaling of small repeating earthquakes explained by interaction of seismic and aseismic slip in a rate and state fault model
T. Chen and N. Lapusta, *JGR*, 2019



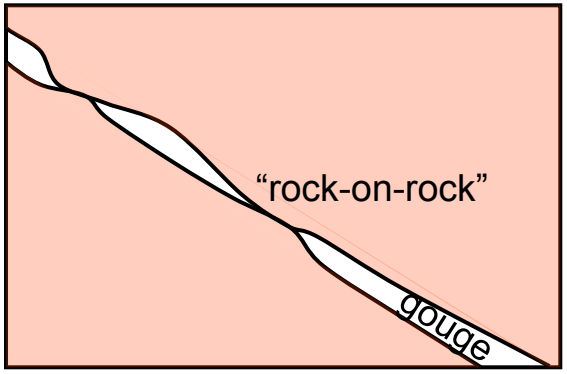
Ratio of Seismic Moment/Total Moment = 0.01
for patch radius of 124 m

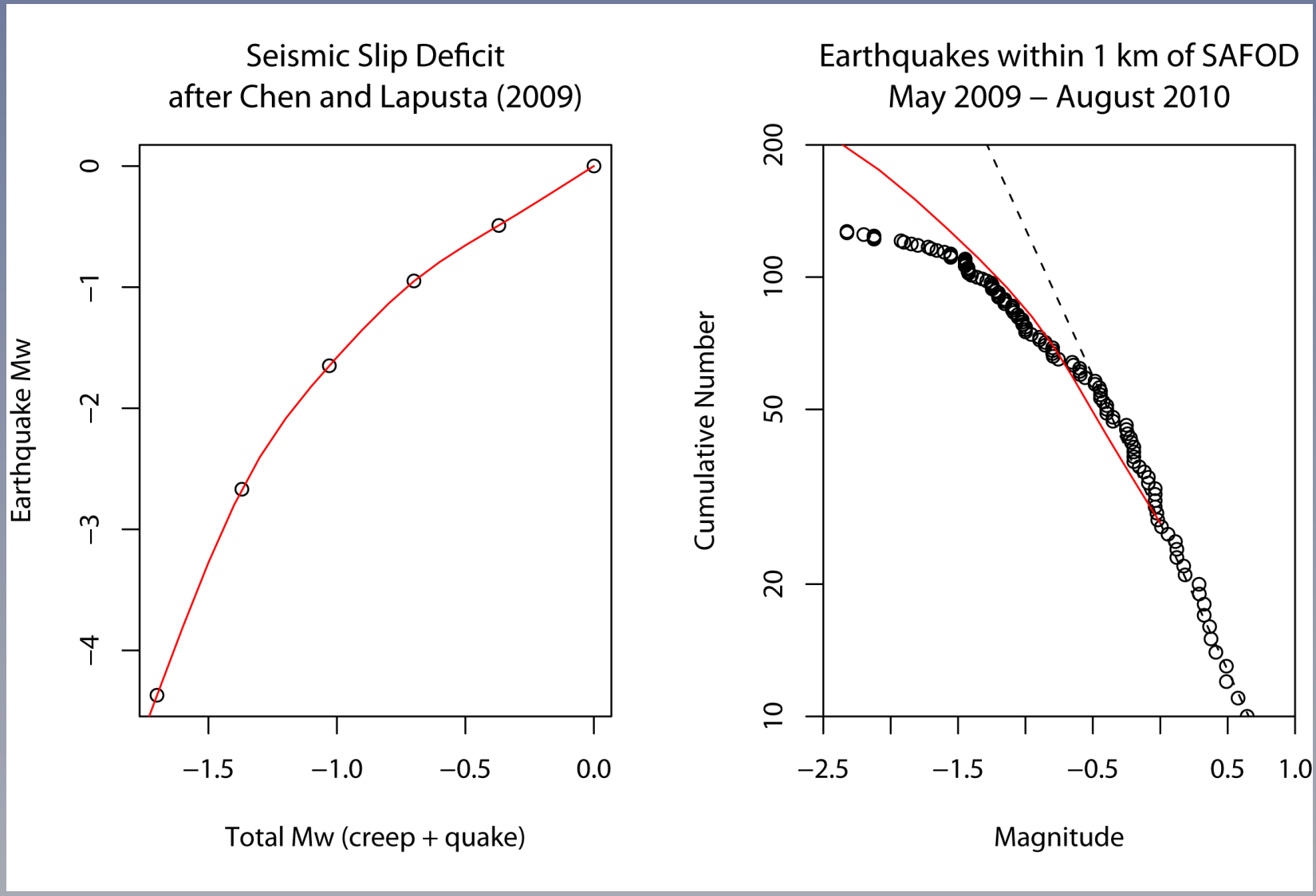
Rate-and-State Model for the Bottom of the Magnitude Scale

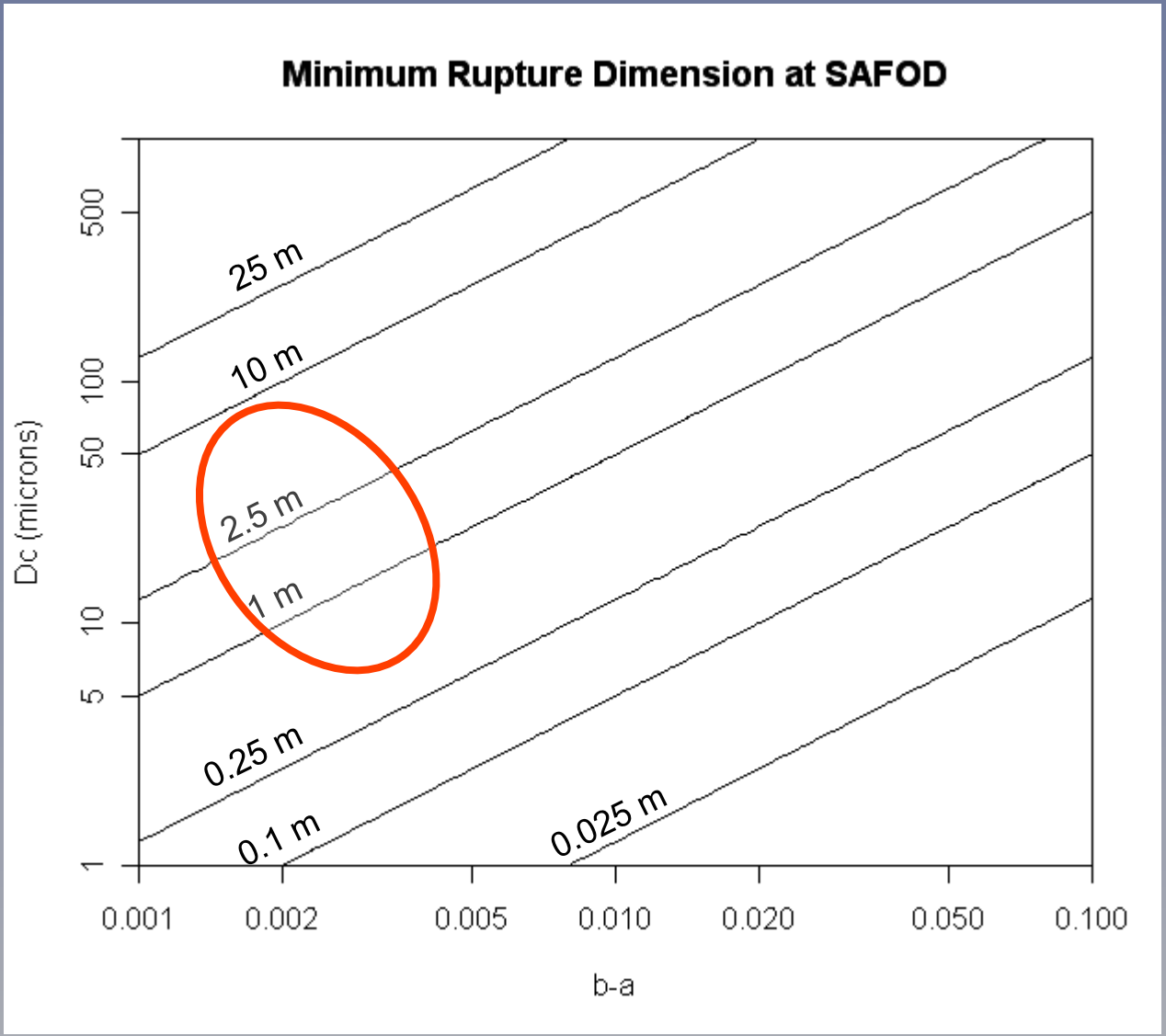


Assumptions

- SAFOD earthquakes caused by small velocity-weakening contact areas on an otherwise creeping fault.
- Population statistics of patches that produces a constant b-value for patch radii >> h* continues in a self-similar manner for radii <= h*.
- The fraction of the total moment released by each patch in seismic waves follows the Chen and Lapusta curve.




Seismic Slip Deficit
after Chen and Lapusta (2009)
Earthquake Mw
0
−1
−2
−3
−4
−1.5
−1.0
−0.5
0.0
Total Mw (creep + quake)
Earthquakes within 1 km of SAFOD
May 2009 – August 2010
Cumulative Number
200
100
50
20
10
−2.5
−1.5
−0.5
0.5
1.0
Magnitude


Minimum Rupture Dimension at SAFOD
Dc (microns)
500
100
50
10
5
1
25 m
10 m
2.5 m
1 m
0.25 m
0.1 m
0.025 m
0.001
0.002
0.005
0.010
0.020
0.050
0.100
b-a

Summary of SAFOD Results

- Earthquakes on the San Andreas Fault near SAFOD follow the universally observed magnitude-invariant stress drop scaling down to at least M = -1. Stress drops generally fall in the range between 1 and 100 MPa. High stress drops suggests these repeating earthquake occur on small patches where high-strength rocks are in contact along the otherwise weak San Andreas Fault.

- The cumulative frequency-magnitude curve for earthquakes within 1 km of the deep SAFOD seismometer deviates from a constant b-value below Mw -0.5. The discrepancy does not appear to be a detection artifact.

- The breakdown in frequency-magnitude statistics below M = -0.5 is consistent with laboratory-derived values for rate-and-state friction. For earthquakes near the stability limit, most of the slip during the seismic cycle occurs aseismically.