Near-Field Earthquake Source Mechanics at 3.6 km depth, TauTona Mine, South Africa

Malcolm Johnston, USGS

Collaborators: Margaret Boettcher, Art McGarr (USGS) Vincent Heesakkers, Ze'ev Reches (Oklahoma U.), Tom Jordan (USC), Mark Zoback (Stanford), T.C. Onstott (Princeton) and Gerry Van Aswegan (ISSI, ZA)

Outline

- Why did we do this experiment?
- Instrumentation – Design Issues
- Life at 3.6km depth
  - Site plan, Stress State and Installations
- Data and Implications
  - Minimum Magnitude?
  - Nucleation
  - Rupture Propagation
  - Earthquake Energy Budget
  - Strain, Microearthquakes, Eq triggering
  - Strain - Slow Earthquakes
- Conclusions

Why did we do this experiment?

- Current near-surface fault monitoring has reached its limits. Very near-field investigations of eqs. only possible in deep mines or boreholes (SAFOD, KGB, etc). Need knowledge about:
  - Nucleation Processes (scale, growth, cascading events, chemical, pressure and electromagnetic changes)
  - Rupture Processes (velocity, geometry, crack vs pulse modes, sources of heterogeneity, opening modes)
  - Stress/Strain/Strength Relations (load conditions, time variations, seismic vs aseismic)
  - Properties of Active Fault Zones (geometry, friction, composition, rheology and time variations)
  - Microbial activity (effects of earthquakes)

Background: Source Dimensions of Small Earthquakes

(Dieterich, 1992 & Richardson & Jordan, 2002)

Keilis-Borok, 1959:

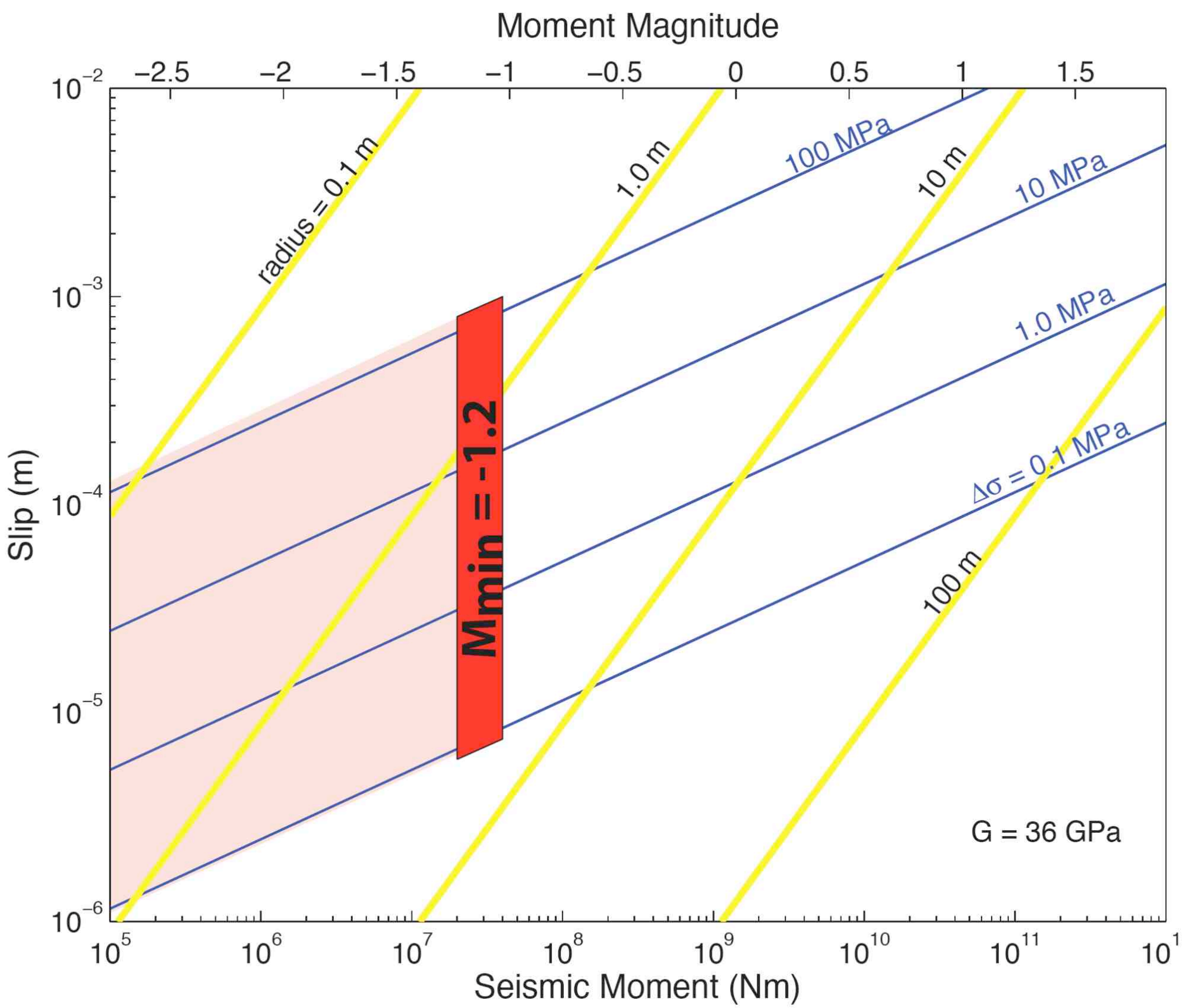
$$radius = \left(\frac{7 M^{\min}}{16 \Delta\sigma} \right)^{1/3}$$

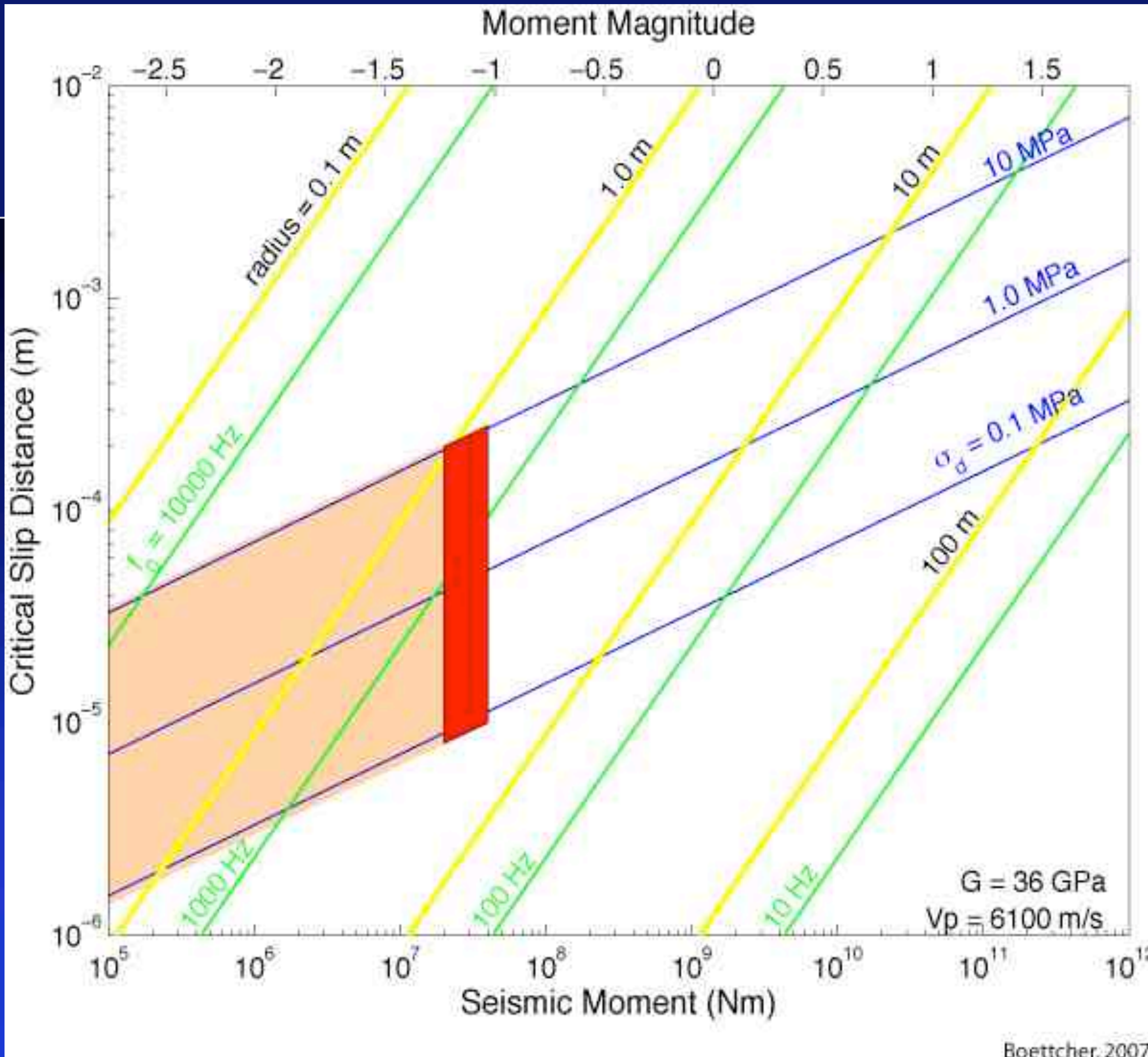
$$slip = \frac{16 \Delta\sigma}{7 \pi G}$$

$M_{min} \leq -1.2$

$r \leq 2\ m$

$D \leq 60$ *microns*





Moment Magnitude
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
radius = 0.1 m
1.0 m
10 m
100 m
10 MPa
1.0 MPa
σ_d = 0.1 MPa
f_0 = 10000 Hz
1000 Hz
100 Hz
10 Hz
G = 36 GPa
Vp = 6100 m/s
Critical Slip Distance (m)
10^-2
10^-3
10^-4
10^-5
10^-6
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
Seismic Moment (Nm)
Boettcher, 2007

Instrumentation Requirements

- Basic Design Criteria, Implications and Questions:
  - Earthquakes M=-4 to M=5, Corner frequencies range from >10KHz to <1 Hz. Implies Very High Frequency Seismology (20KHz sampling, 24-bit recorders, Gbytes/min., Mine-surface telemetry bandwidth, etc)
  - What is Stress/Strain/Strength State? Did not know these when we started.
  - What parameters needed? - acceleration, velocity, displacement, strain, temperature, EM, etc. Need highest resolution & on-scale data thru earthquakes.
  - What dynamic range is needed for each parameter? micro g to 10g, microns/sec to m/sec, angstroms to meters, nanostrain to millistrain, etc.

Instruments Designed, Built and Installed

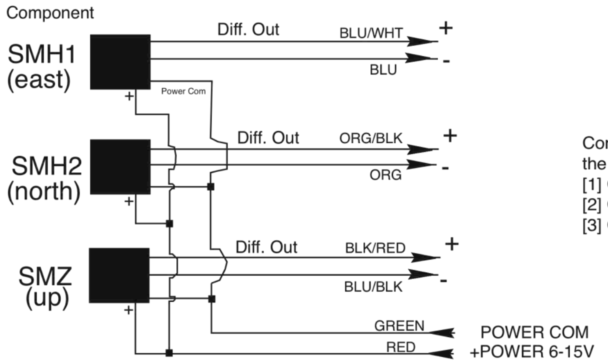
1. Six 6-component weak motion (DC-10KHz, low noise, +-3.5g range) /strong motion (DC-2KHz, +/-10g range) acceleration systems built for installation in 10-30m deep boreholes within the fault zone from 3.4 to 3.6 km depth. Six installed. Two operational. Four inadvertently destroyed by on-site tech.
2. Ten 6-component weak motion acceleration (DC-10KHz, low noise, +/-3.5g range)/seismic velocity (0.01-500Hz) systems built for installation in 10-30m deep boreholes around the fault from 3.4 to 3.6 km depth. Eight 6-component systems installed. Seven operational.
3. Two 110 m cross-fault strainmeters built. Longest/deepest in the world. One installed in 2006 in TauTona across the fault from 3.4 to 3.5 km depth, one planned for Dagbreek fault, Tsepong mine. Six short-base strainmeters awaiting boreholes.
4. Twelve sets of thermistors installed in main traces and through fault segments in 6 locations - 1m to 6m spacing.
5. Six sets of borehole Electric Field monitoring electrodes installed. Not yet recording.
6. Gas and microbiological instruments installed. Recording.

Technical Details:

- Seismic Weak Motion Acceleration (MEMS SF1500S3G, 3-Comp., low-noise, response flat from DC to 10 KHz, +/- 3.5g, 12 KHz sample rate, event mode)
- Seismic Strong Motion Acceleration (Kistler 8305A10M, 3-Comp., response flat from DC to 1KHz, +/- 10g, 12 KHz sample rate, event mode)
- Seismic Velocity Geospace GS-20DM (3Comp., 0.01-500Hz, 12 KHz sampling, event mode)
- Thermisters (0.0001 C resolution)
- Electric field (Pb/PbCL) electrodes (DC to 1KHz)
- Strainmeters (110m cross fault, LVDT transducers, nanostrain resolution), 1m extensometers (differential capacitance transducers, nanostrain resolution)
- Other: Borehole deformation, logging, mapping, etc
- Recorder/telemetry – ISSI 24-bit, 4 channel, 32KHz sampling, differential inputs, 4 asynchronous serial ports

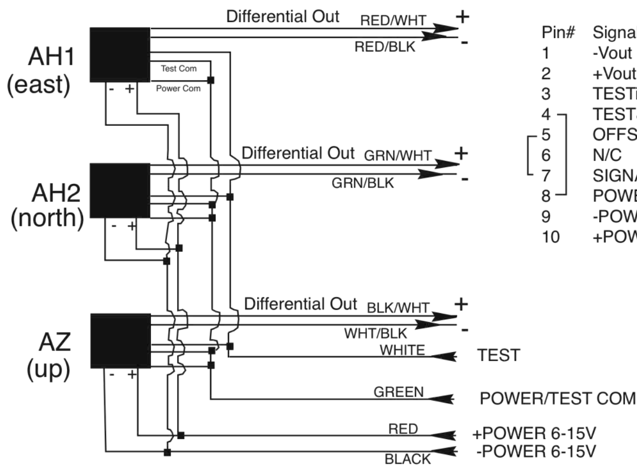
3-Comp 3-G/30G Acceleration Wiring and Color Code (8 UNITS)

Strong Motion Acceleration (10G) [Kisler 8305A10M2]



Connect power in the following manner
[1] Connect Common
[2] Connect -12v power
[3] Connect +12v power

MEMS Acceleration (3G) [Appl. Mems SF1500SF-3g]

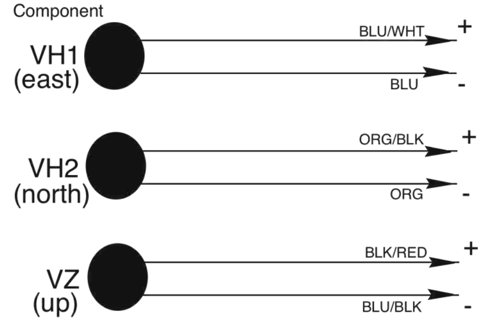


Pin#	Signal Function	
1	-Vout	Signal
2	+Vout	SIgnal
3	TESTin	
4	TEST&OFFSETCom	
5	OFFSETin	
6	N/C	
7	SIGNAL com	
8	POWER com	
9	-POWER 6-15V	
10	+POWER 6-15V	

M. Johnston
Jan 20, 2005

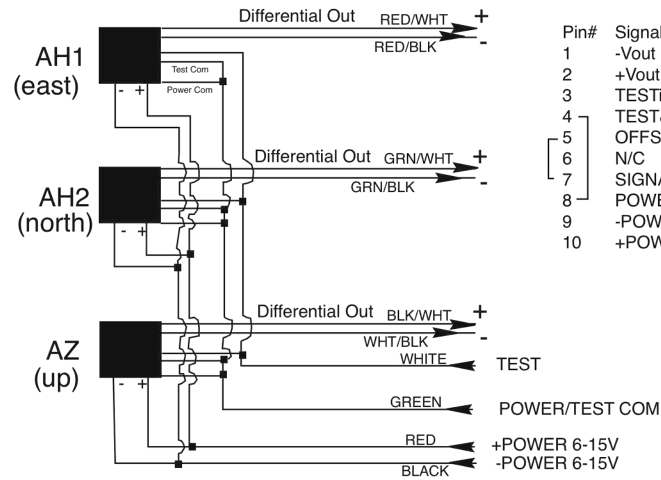
3-Comp Velocity/Acceleration Wiring and Color Code (10 UNITS)

Velocity [Oyo Geospace GS20DM 10Hz, 1000ohm]



Connect power in the following manner
[1] Connect Common
[2] Connect +12v power
[3] Connect -12v power

MEMS Acceleration (3G) [Appl. Mems SF1500SF-3g]



Pin#	Signal Function	
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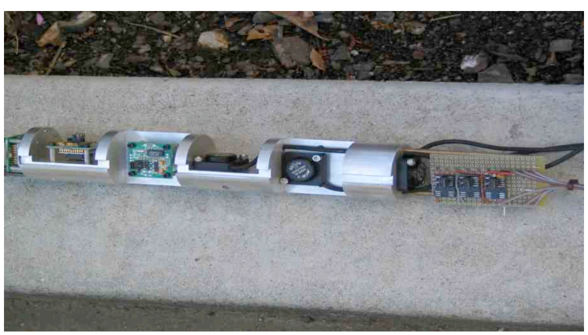
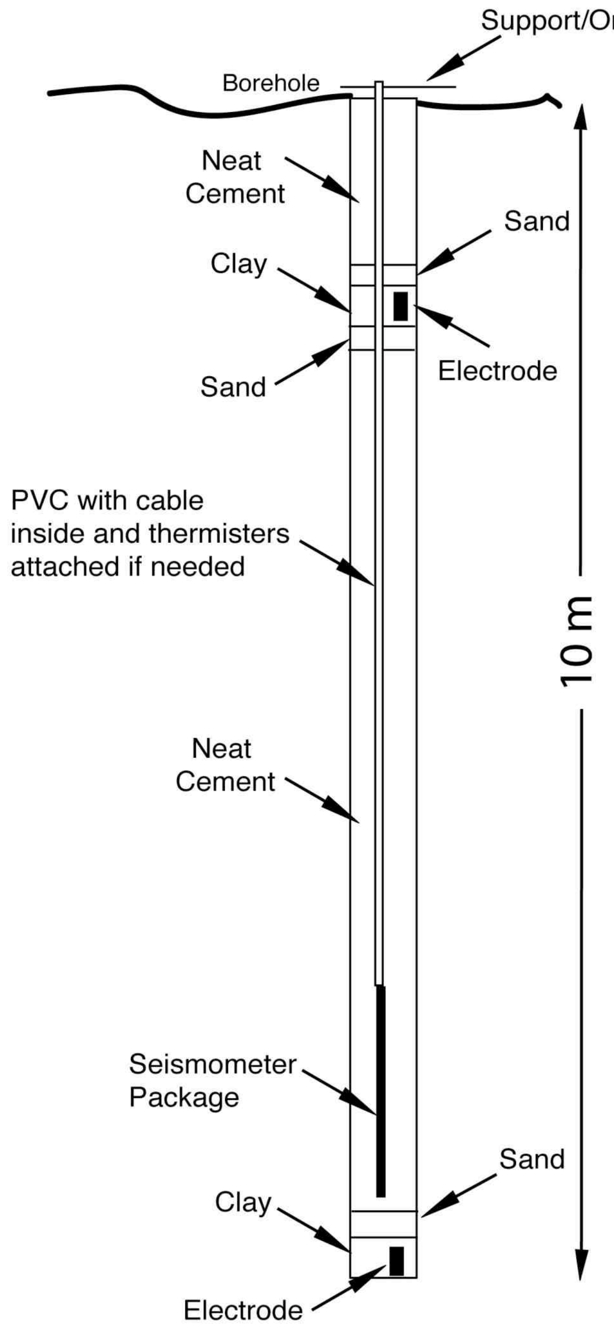
M. Johnston
Jan 20, 2005



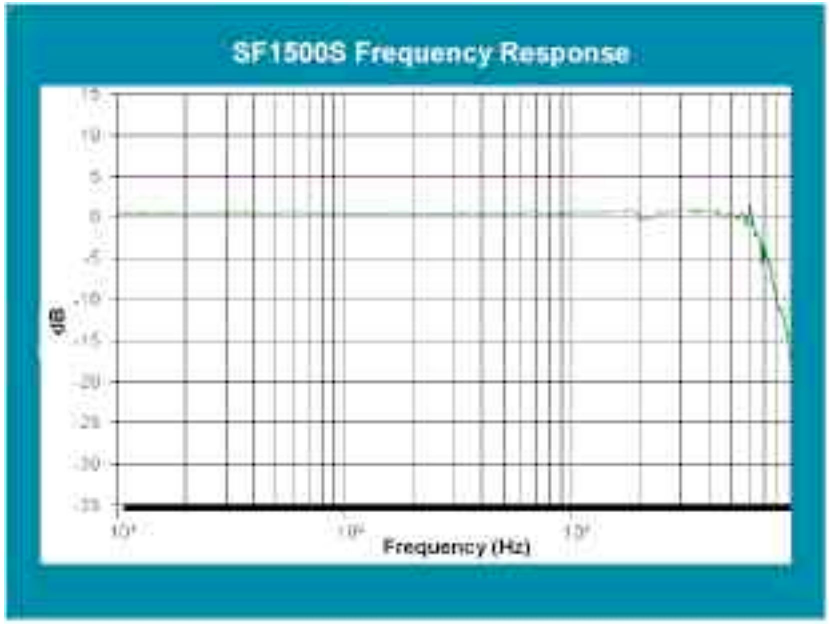
Installation Hole Design#13



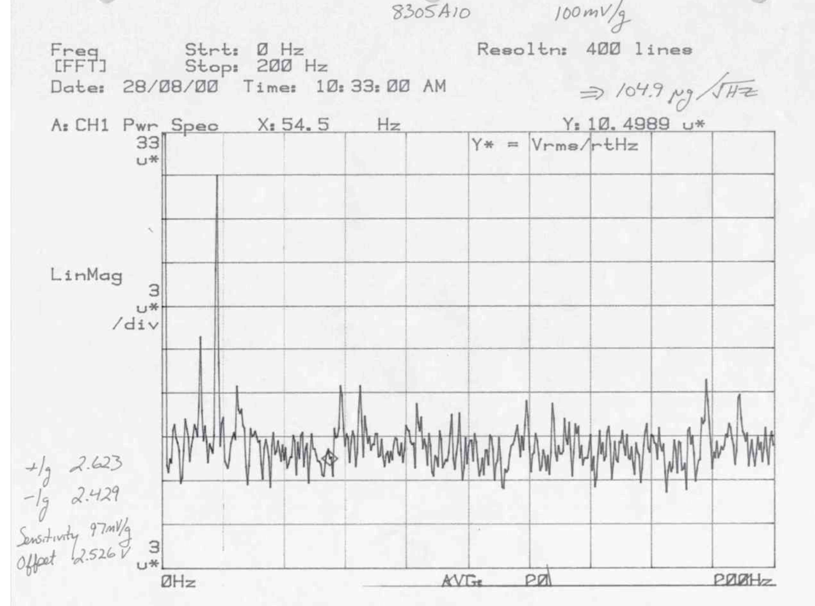
Steps

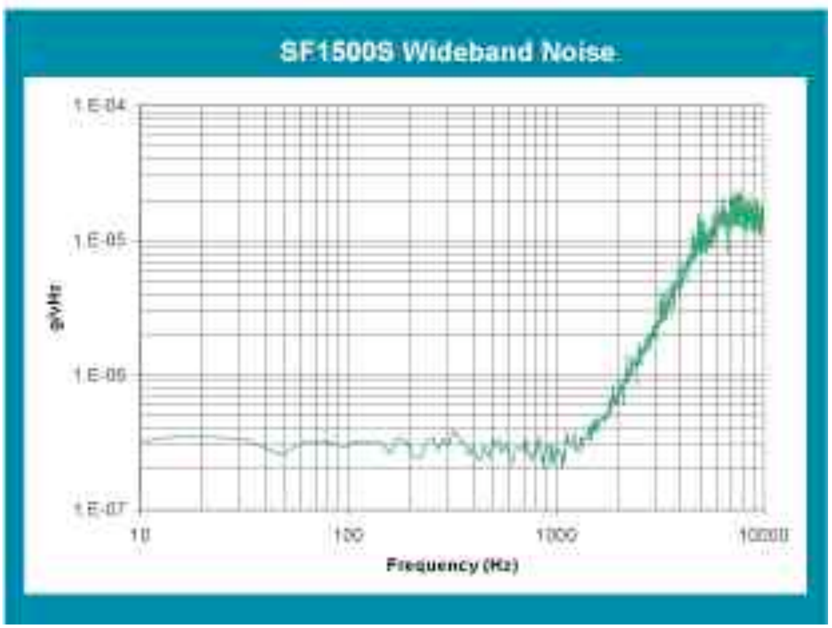
[1] Test Seismometer Attach thermisters if needed to cable.
[2] Measure hole depth
[3] Attach PVC pipe with orientation marks on all sections
[4] Drill cement outlet holes in PVC pipe bottom and support hole orientated NS at surface so instrument will be suspended >25 cm from hole bottom.
[5] Add handful of clay pellets to hole
[6] lower electrode to bottom
[7] Add 5 cm sand
[8] Attach thermisters if needed to PVC pipe. Lower seismometer package to bottom with PVC pipe. Orient NS with support rod.
[9] Mix neat cement and add sufficient to raise bottom to 3 m from surface
[10] Add 5cm of sand
[11] Add handful of pellets
[12] Lower second electrode into pellets
[13] Add 5 cm sand
[14] Cement to surface

Accelerometer Noise Floors

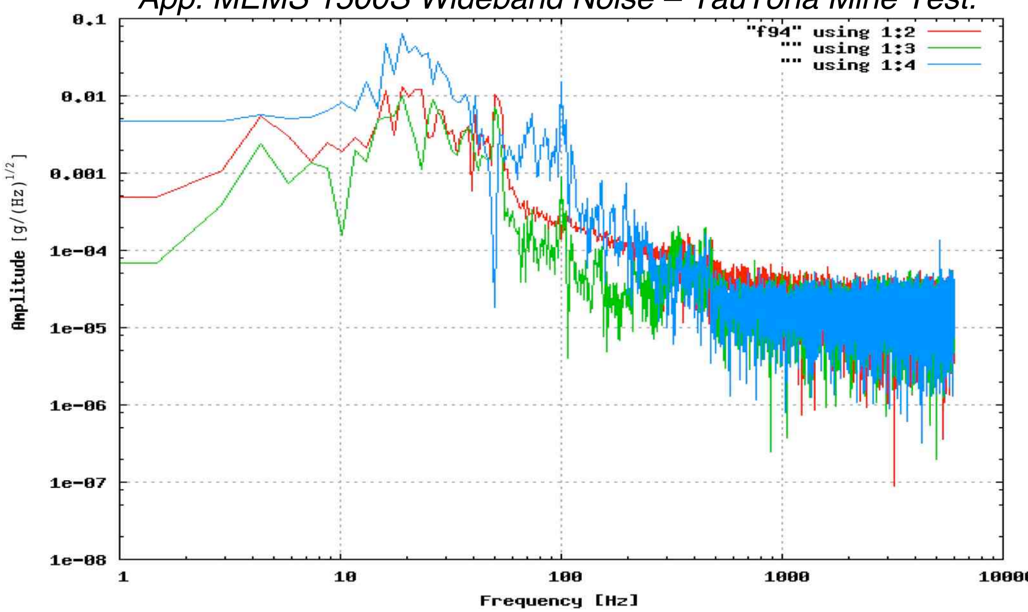


Kistler 8310A10M2 Wideband Noise



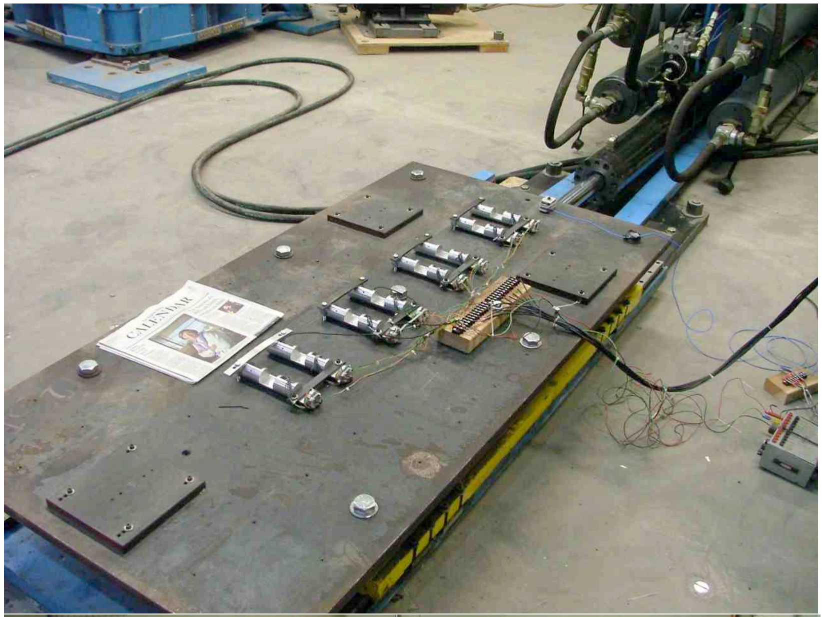


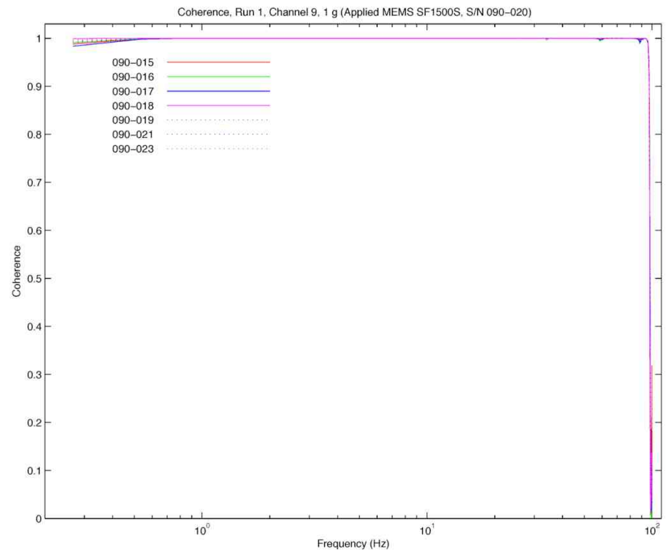
App. MEMS 1500S Wideband Noise – TauTona Mine Test.

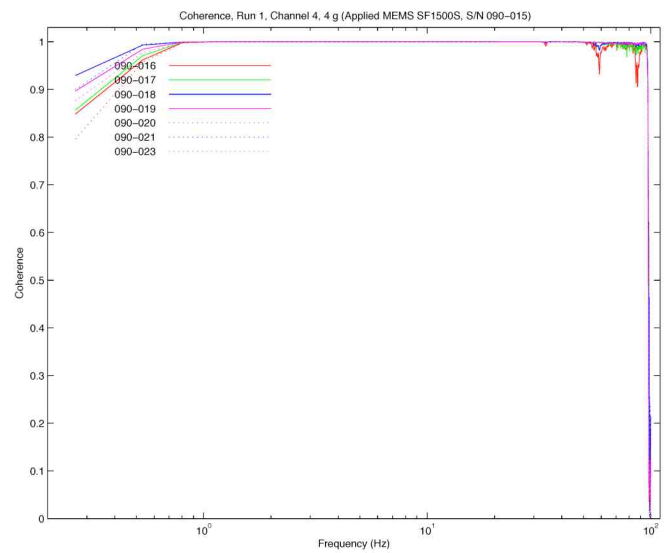


Shake Tests

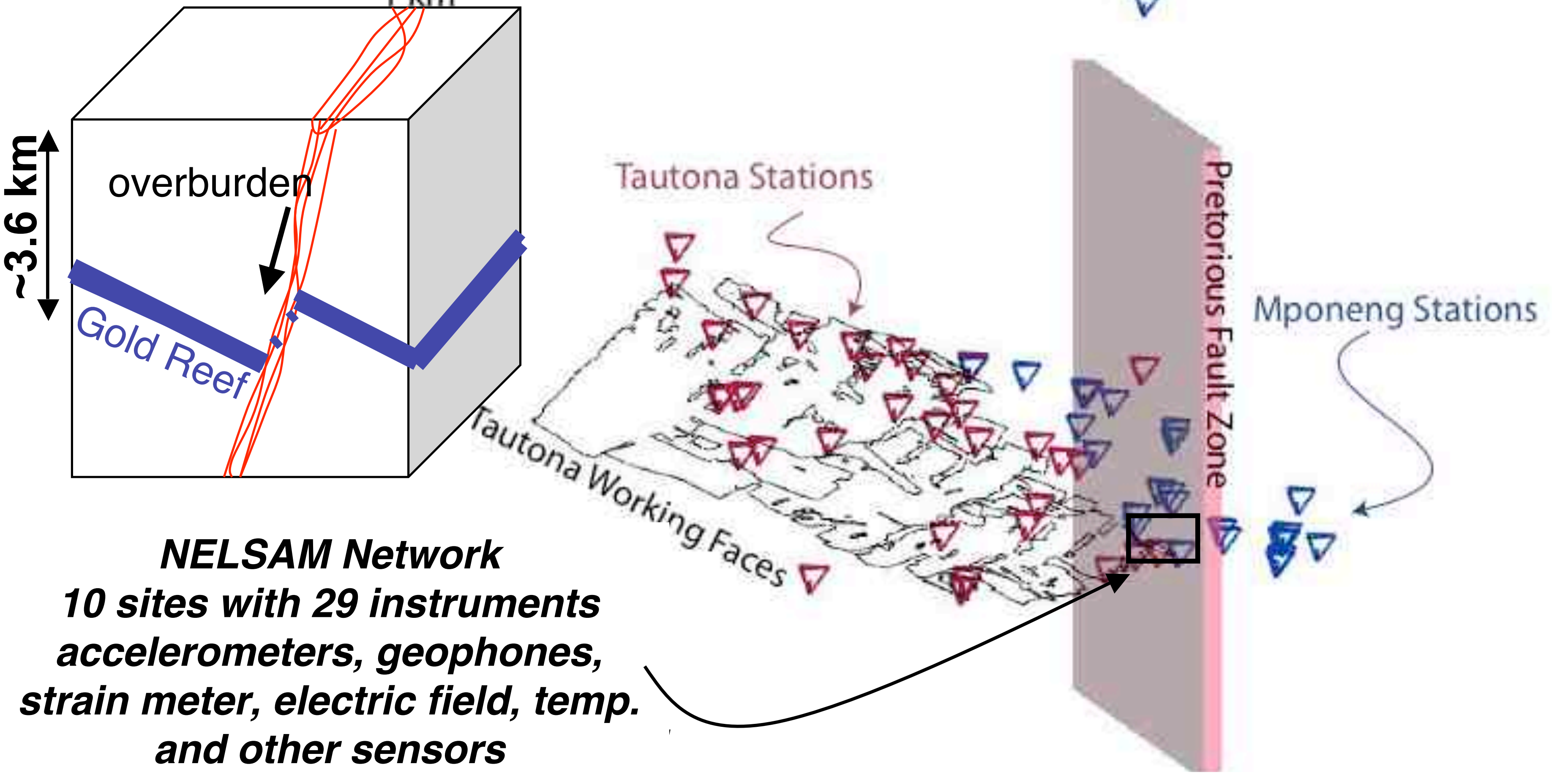
In collaboration with Bob Nigbor, UCLA







Natural Earthquake Laboratory in South African Mines - NELSAM

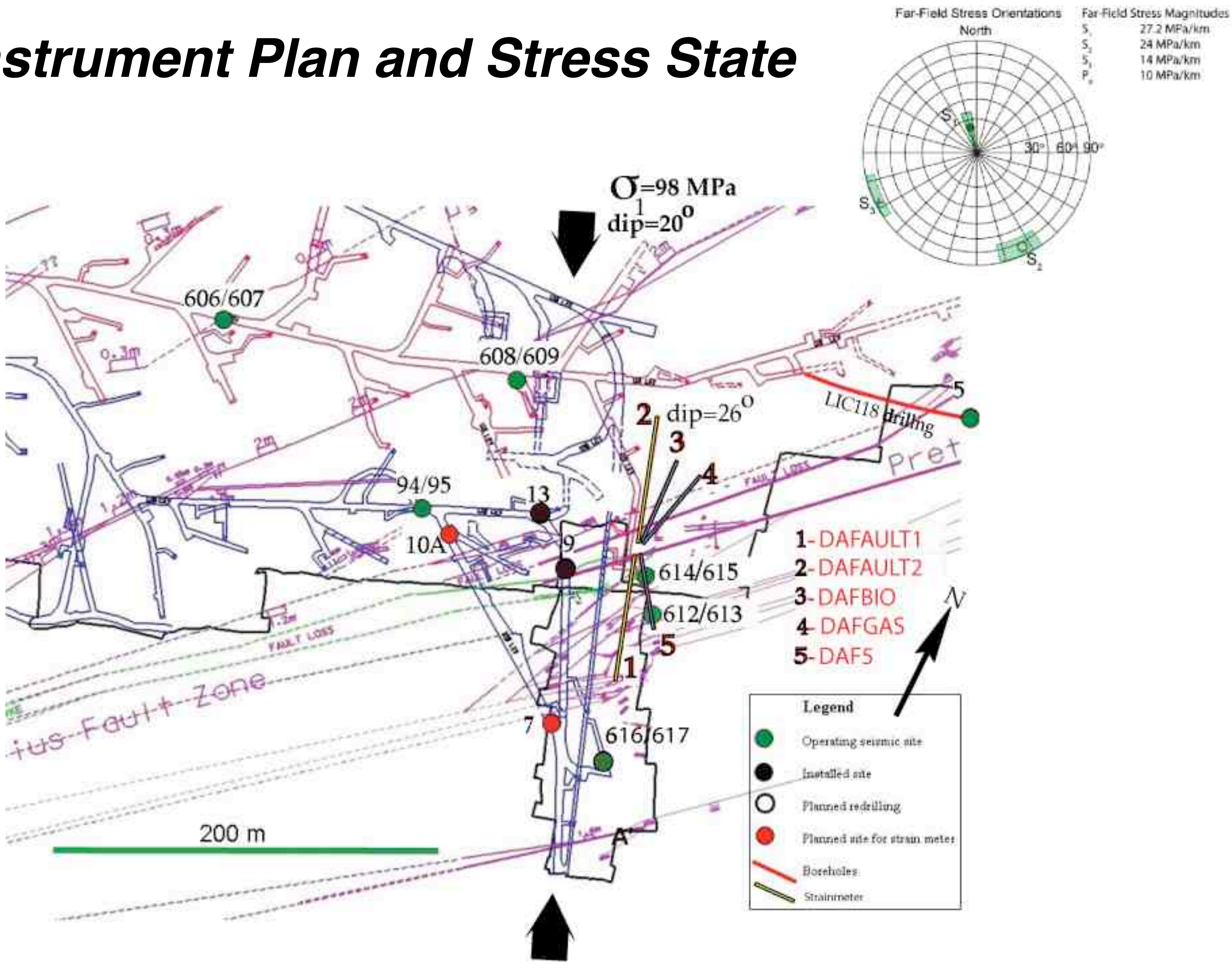


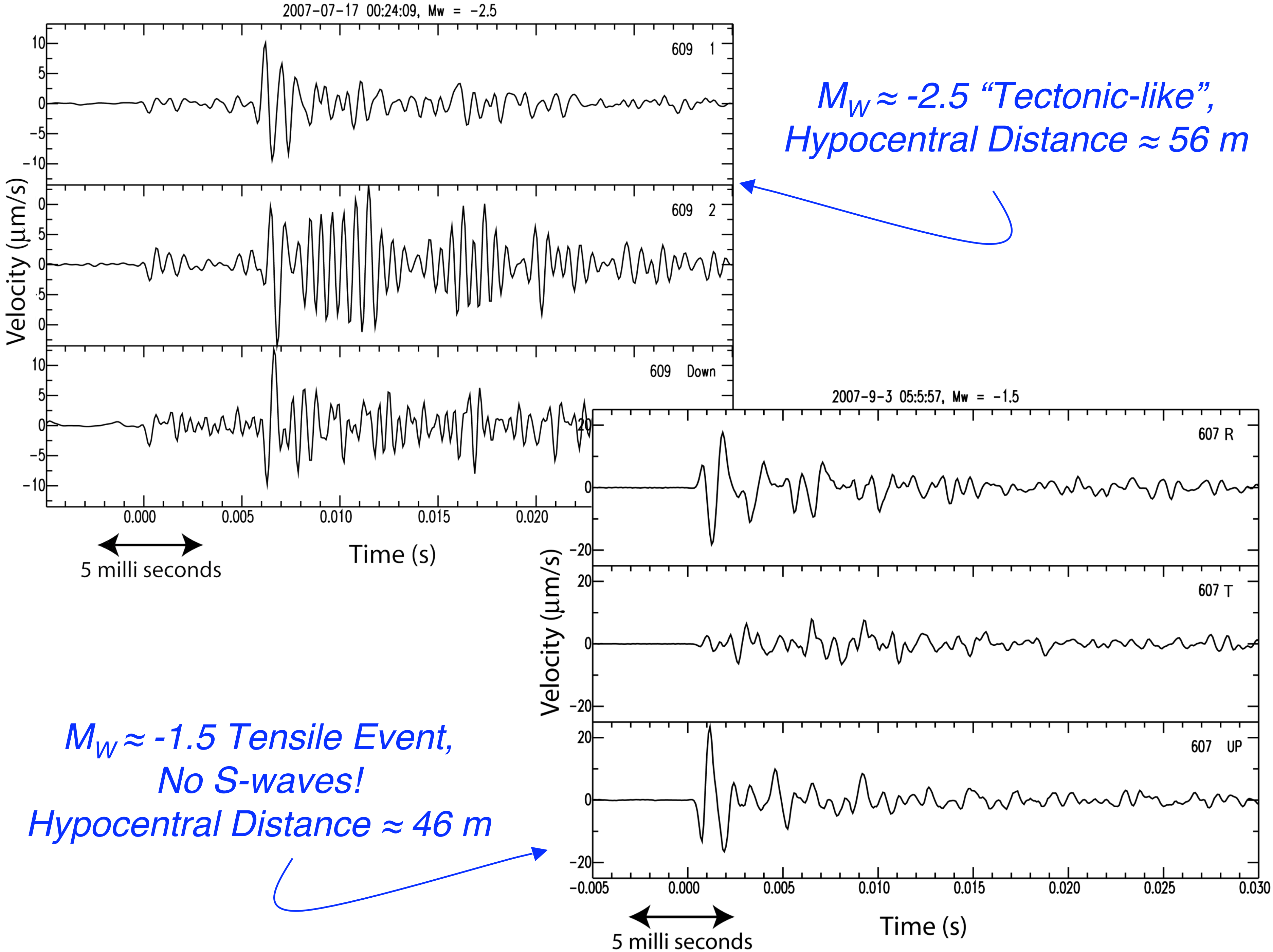
NELSAM Network
10 sites with 29 instruments
accelerometers, geophones,
strain meter, electric field, temp.
and other sensors
100Hz-12 kHz sampling rates

Working Conditions

- Air temperature up to 36-52°C (97-125°F)
- Ambient rock temperature 55 °(131°F)
- Humidity 100%
- Small working space
- Daily working time on-site = max 2 hours
- Earthquakes occur all around (on average one M2/wk)

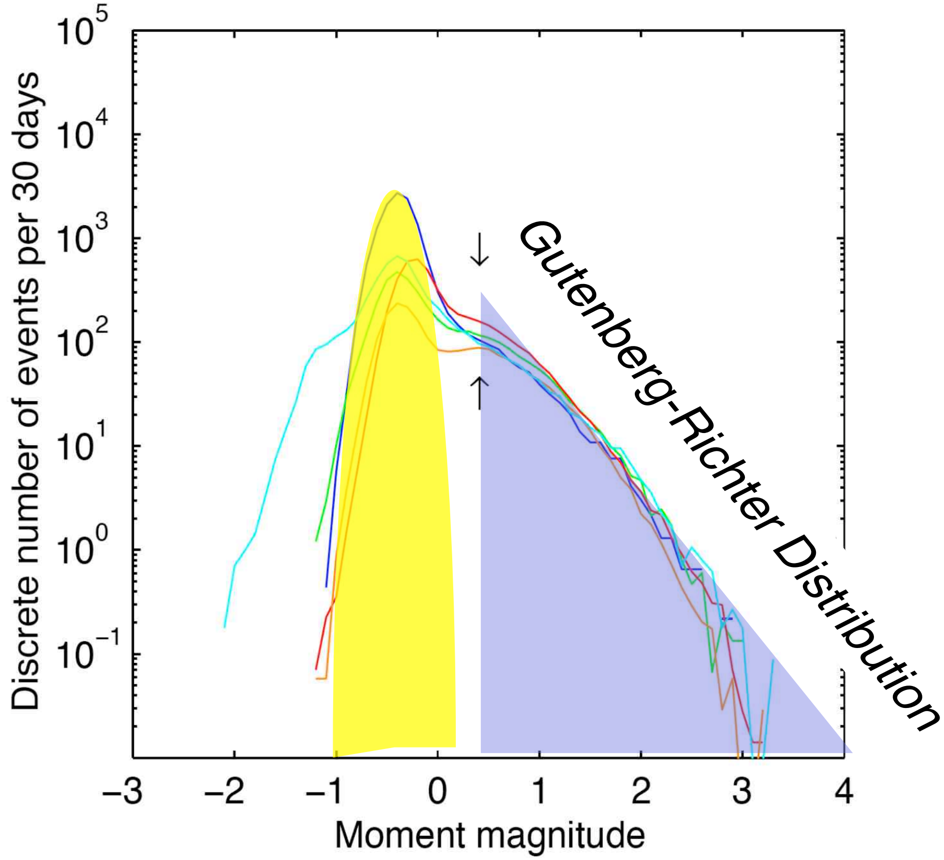
Instrument Plan and Stress State





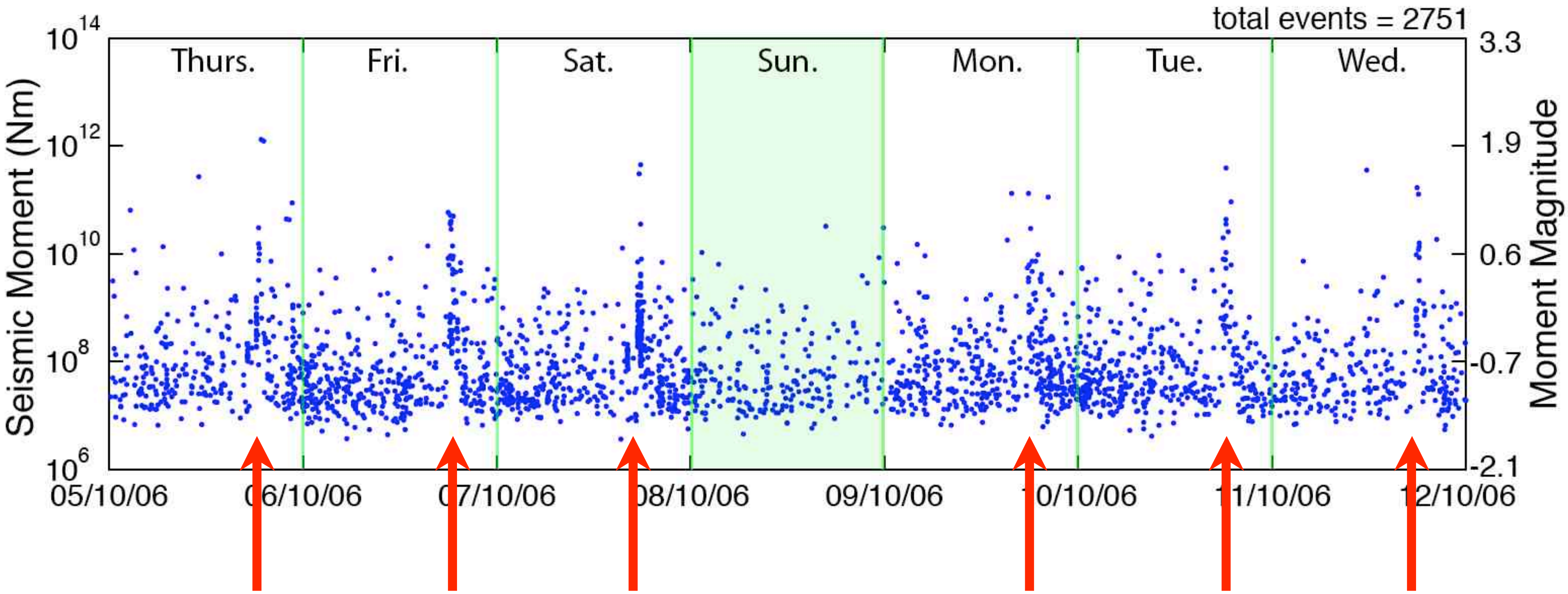
2007-07-17 00:24:09, Mw = -2.5
609 1
609 2
609 Down
Velocity (μm/s)
Time (s)
5 milli seconds
2007-9-3 05:5:57, Mw = -1.5
607 R
607 T
607 UP
Velocity (μm/s)
Time (s)
5 milli seconds
$M_W \approx$ -2.5 "Tectonic-like",
Hypocentral Distance ≈ 56 m
$M_W \approx$ -1.5 Tensile Event,
No S-waves!
Hypocentral Distance ≈ 46 m

Is there a physically-controlled minimum magnitude earthquake?



Richardson & Jordan, BSSA, 2002

Weekly Recorded Seismicity



6-7 pm Ore Production Blasting

Properties of the Magnitude-Frequency Distribution

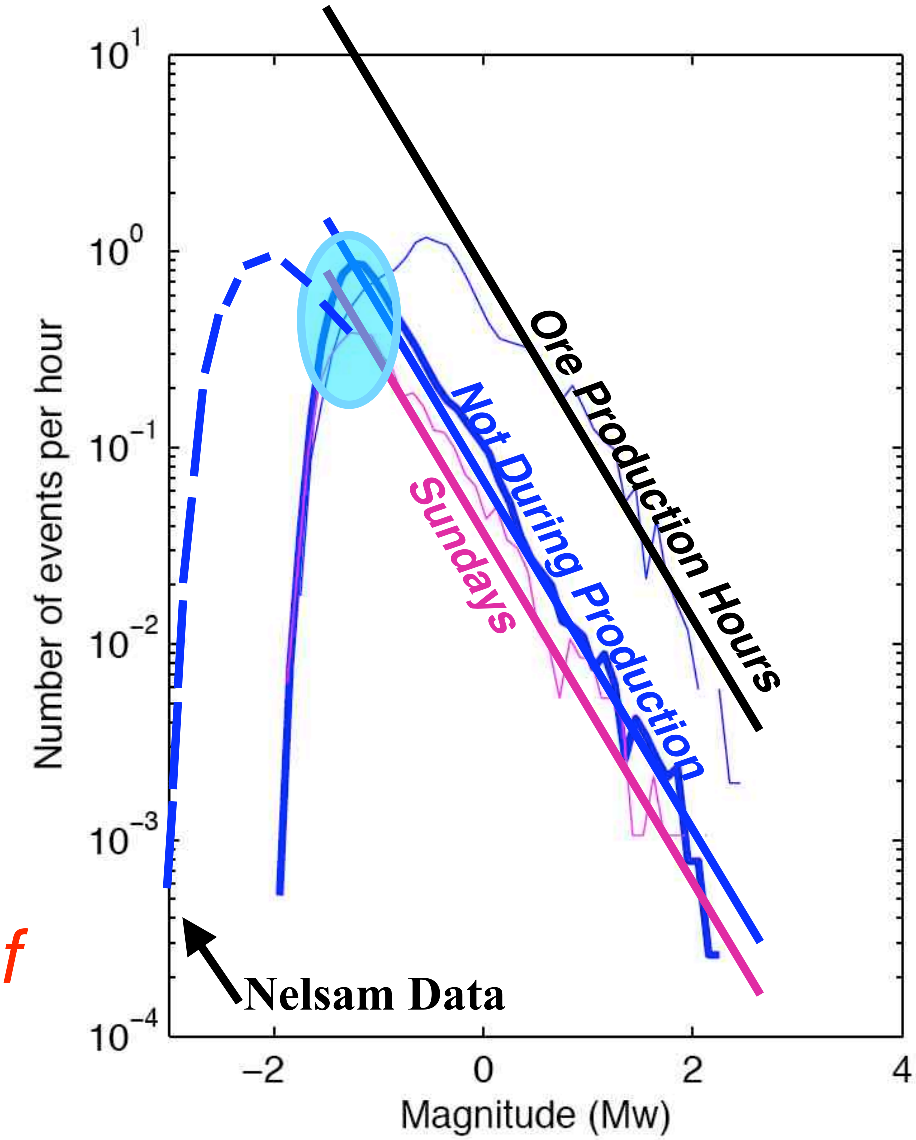
$N = 10^{(a-bM)}$

b-value ≈ 0.85, independent of strain rate

a-value is porportional to strain rate (e.g. McGarr, 1976)

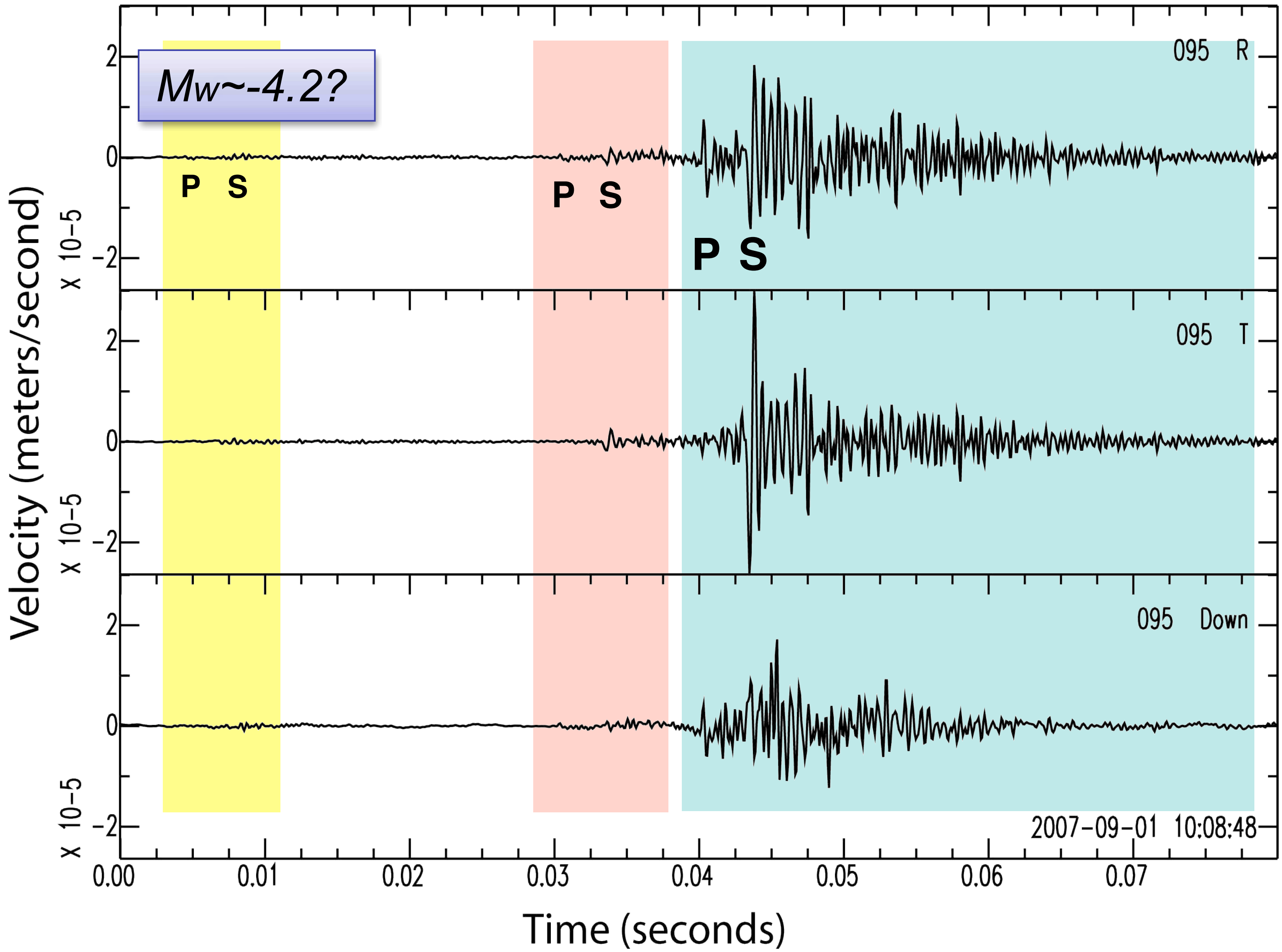
 # events per hour ≥ M_W0.0
0.3 (Sundays)
0.9 (Not During Production)
5.0 (Ore Production)

*Thus, **Detection limit,** not physics, controls the size of the minimum observed earthquakes*

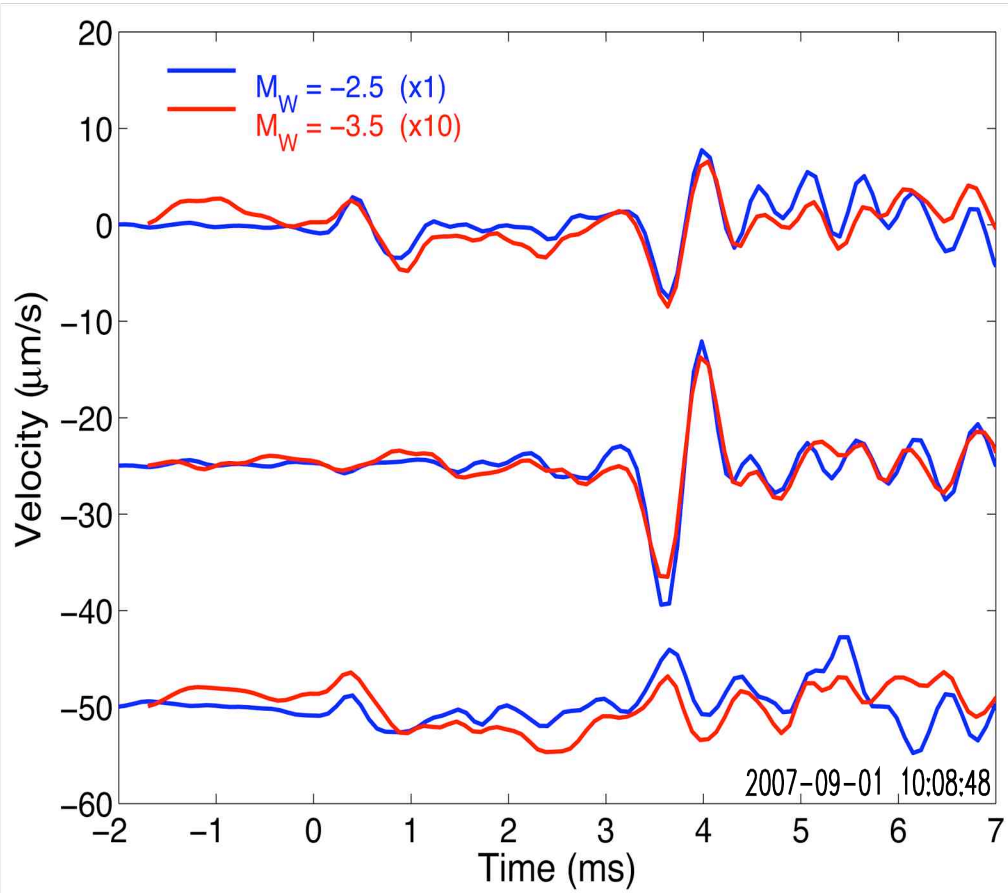


Do foreshocks precede main shocks?

$M_W \approx -3.5$ foreshock(s) prior to a $M_W = -2.5$
hypocentral distance of 28 m

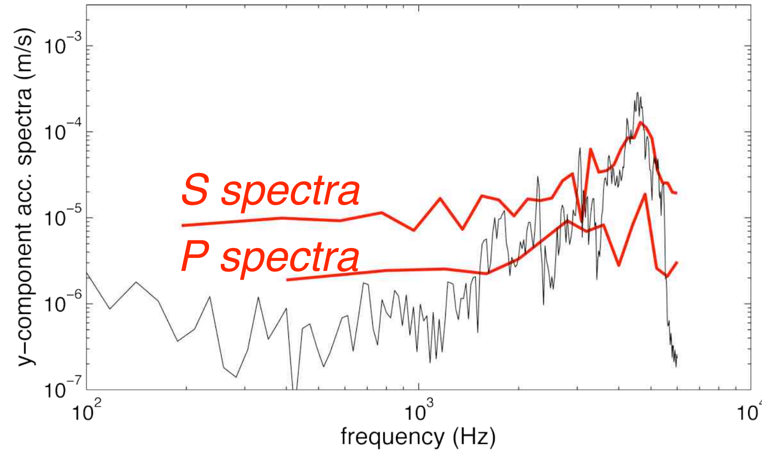


$M_W \approx$ -3.5 foreshock(s) prior to a M_W = -2.5 hypocentral distance of 28 m

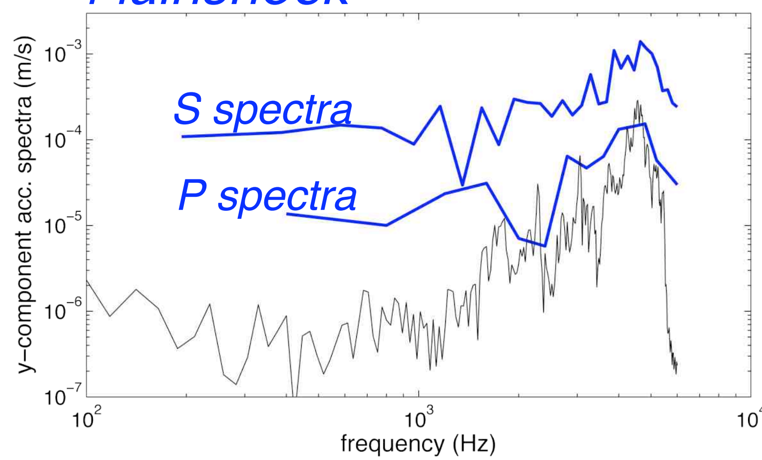


100-1000 Hz

Foreshock



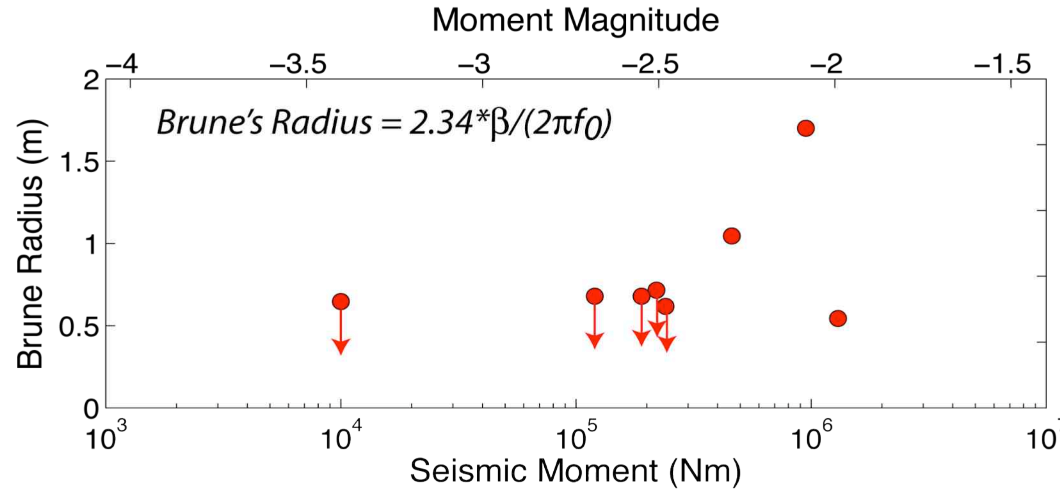
Mainshock



Small Earthquake Source Parameters:

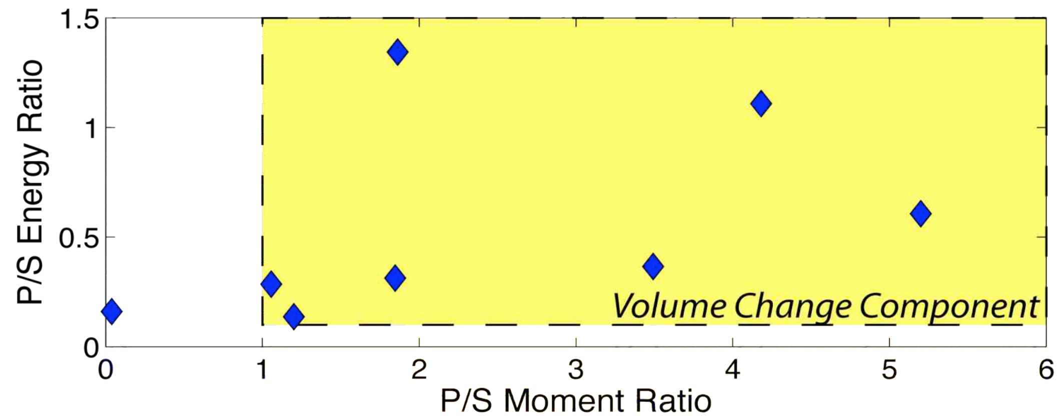
Radius scales with moment

Consistent with both lab and field studies.



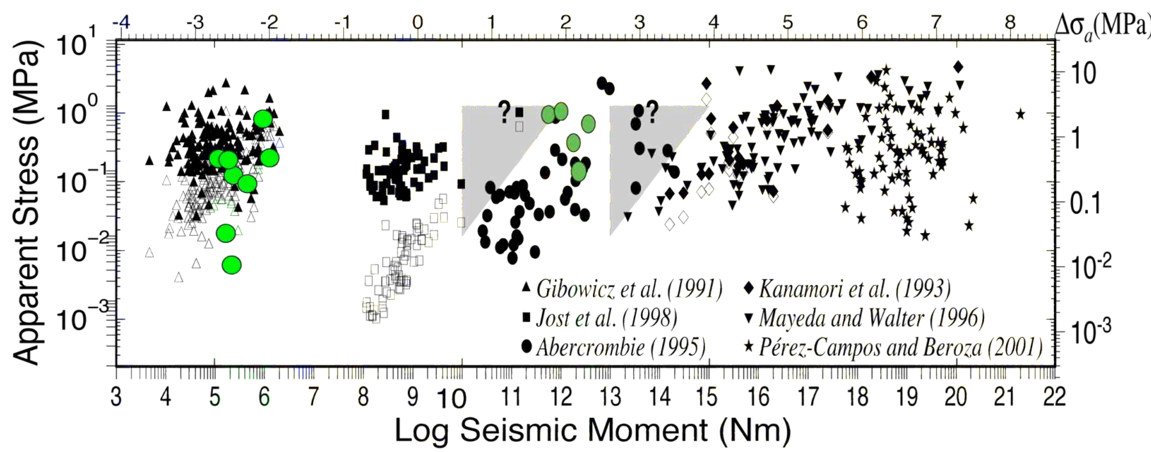
Moment tensors show shear + volumetric components

Possible way to discriminate between mine and tectonic events.



Apparent stress is in the range of previous observations

Shows that the rupture process is the same for small and large earthquakes.

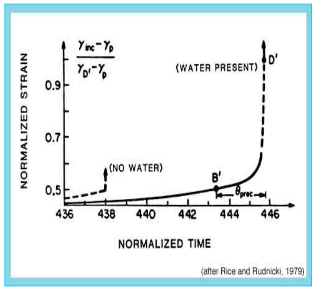


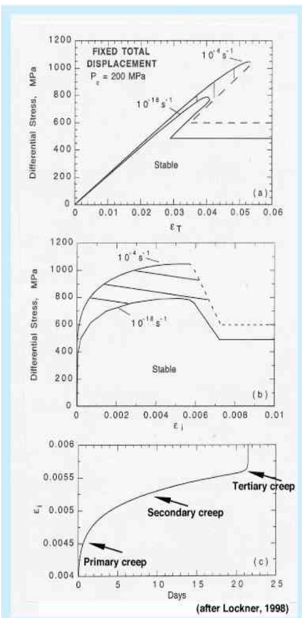
IDE AND BEROZA: DOES APPARENT STRESS VARY WITH EARTHQUAKE SIZE? GRL, V. 28, P. 3349-3352, 2001

Earthquake Nucleation- Motivating Question:

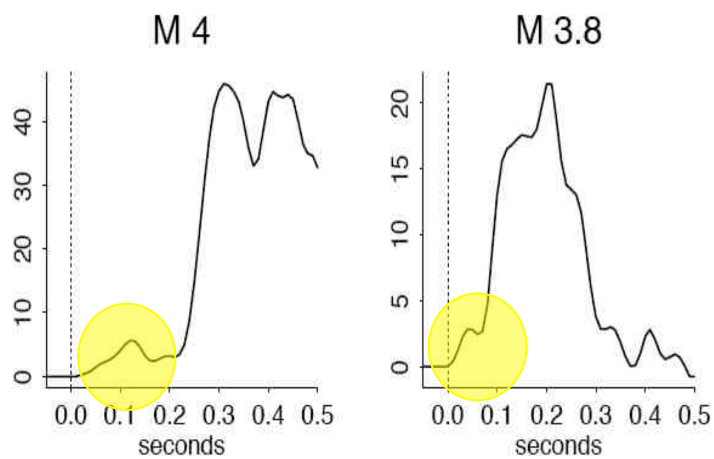
1. *Can we detect an earthquake nucleation process and if so can we determine its scale (temporal and spatial)?*

Expected from Theory and Lab



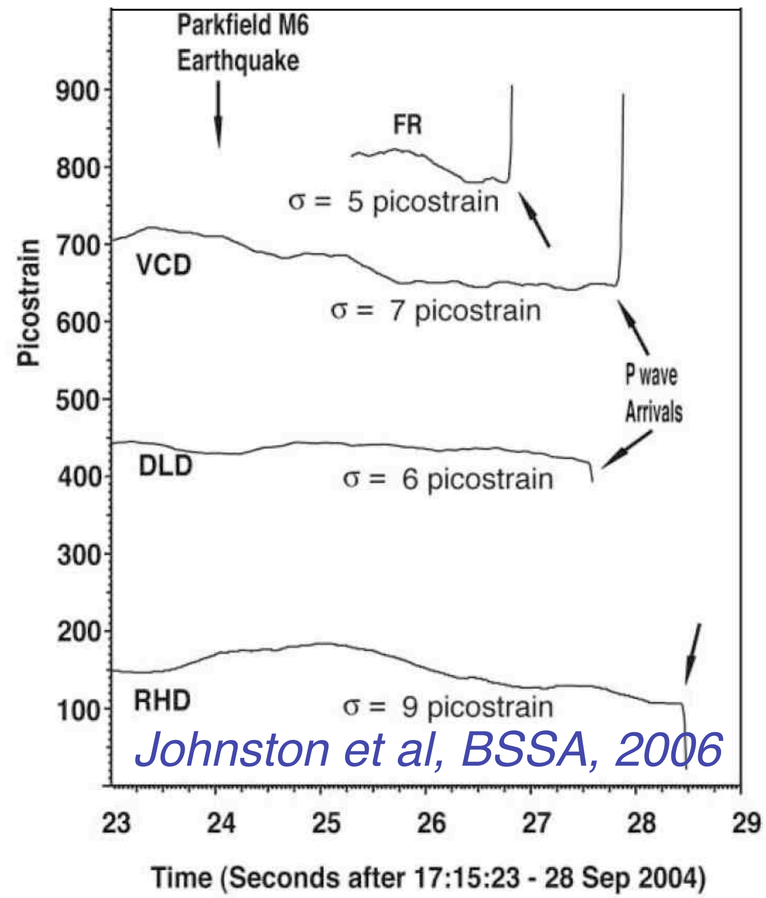


Ridgecrest, California Sequence Seismic Nucleation Phase $M_W \approx$ 2-3



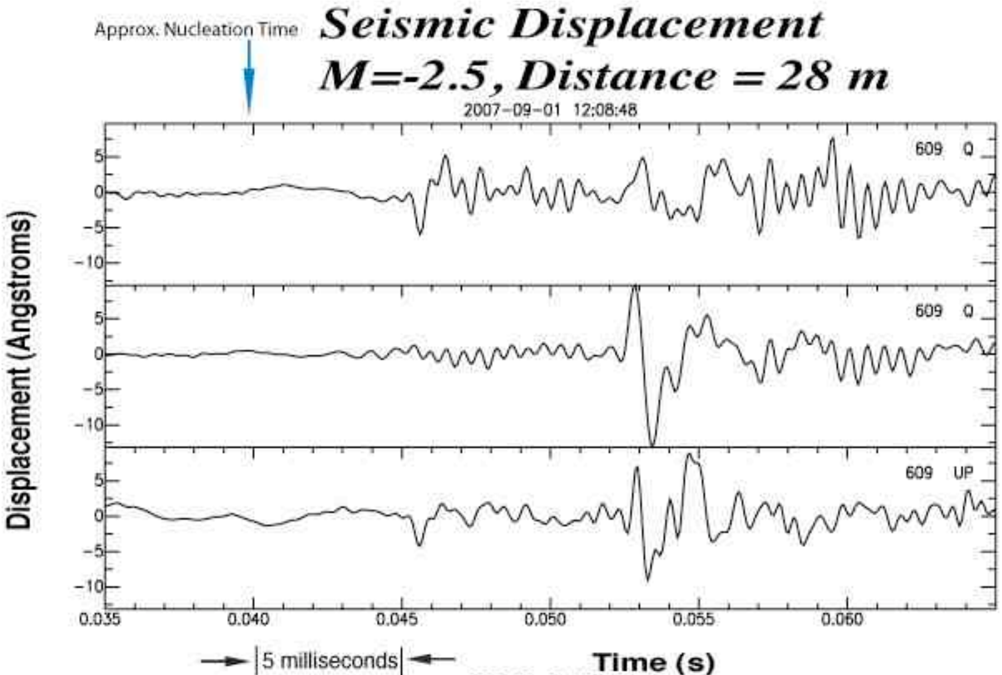
Ellsworth and Beroza, GRL,1998

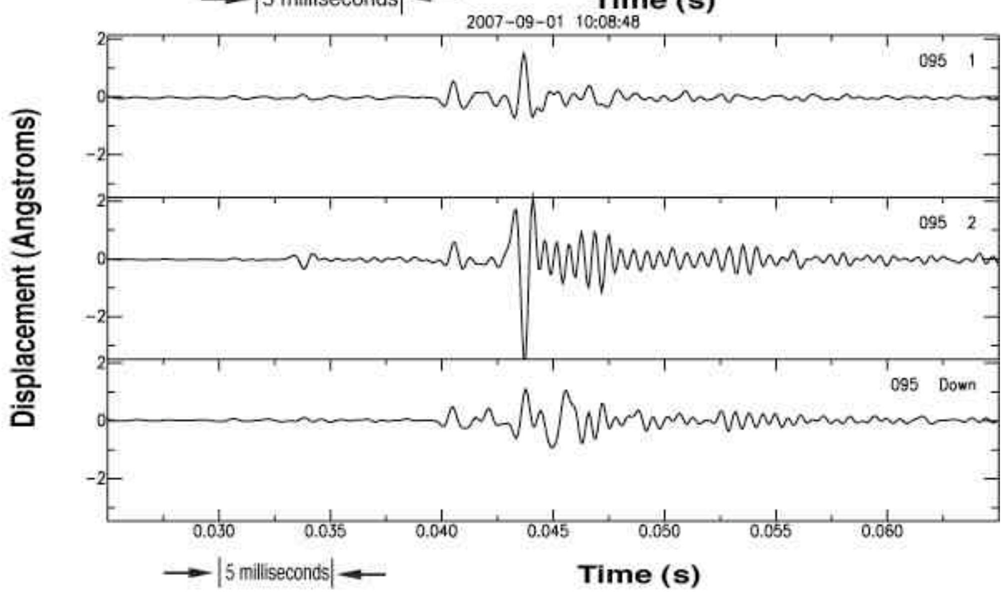
Parkfield Eq. Sept. 28, 2004 M_W = 6.0
No nucleation process $M_W \geq 2$



Johnston et al, BSSA, 2006

What constraints can we place on a nucleation patch size for small earthquakes in the near-field?





Observations

-Search for maximum observable change in strain rate near source nucleation time (if no obvious signal, limit is set by data resolution).

-Calculate moment of source assuming same focal parameters as earthquake that could produce this strain or displacement.

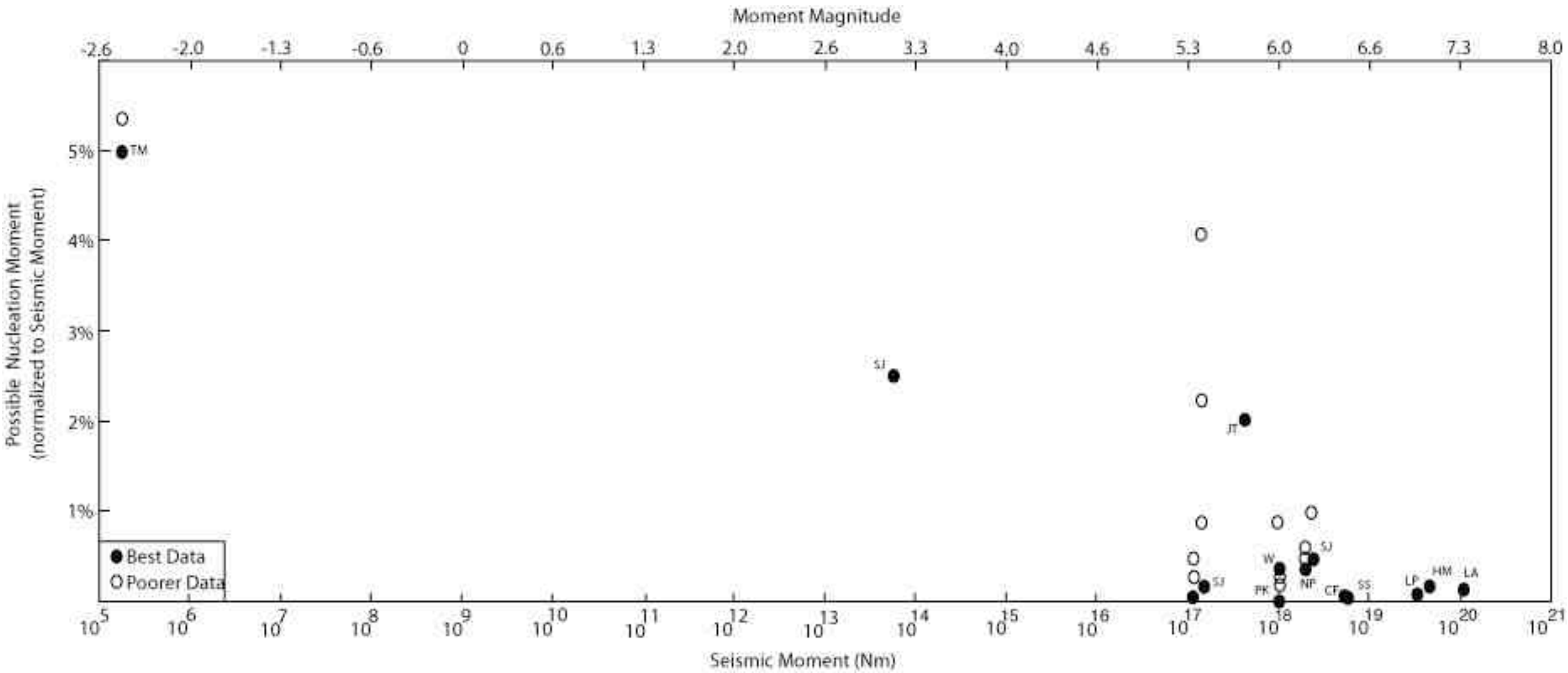
-Determine ratio of nucleation moment to moment to earthquake moment.

-For example:

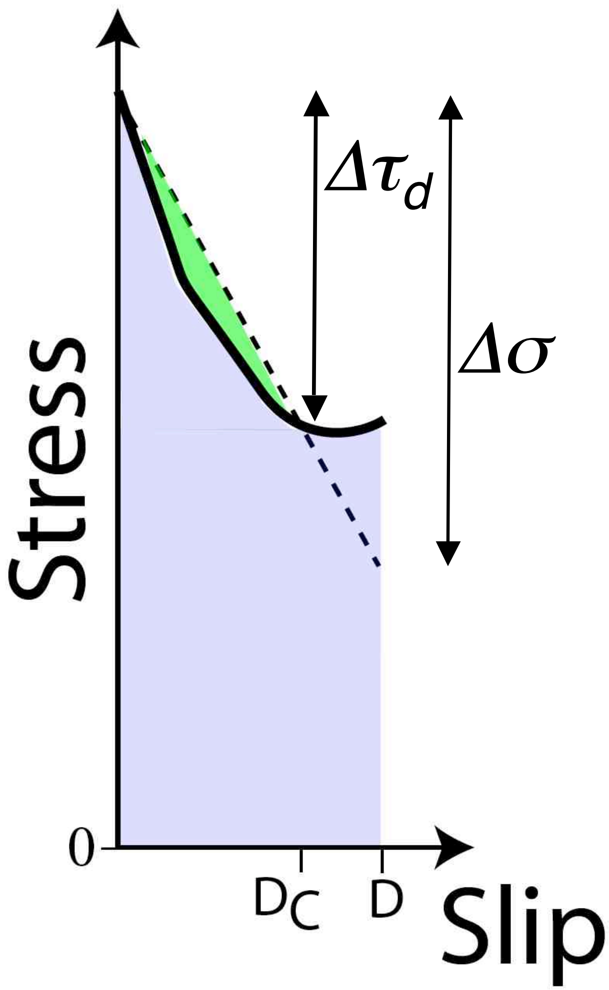
M=-2.5, L=30 cm,
slip =60 microns,
disp. at instrument is <2 A^o,
Distance=28 m.
Mo_e=1.8E5 Nm

Inst. resolution= 0.1 A^o,
Mo_n=<9E3 Nm,
$M_{equivalent}$=<-3.5,
L=<8.5 cm (x_c?)
slip=4 microns (d_c?).
Moment ratio=<5%

Nucleation Size



Estimates of the Nucleation Patch Size
(from laboratory results) (From Boettcher et al., 2009)



slope of the slip weakening curve $\frac{\Delta\tau_d}{D_C} > \frac{7\pi G}{16r}$ *stiffness of the seismic source*

$$radius > \frac{7\pi G D_C}{16\Delta\tau_d}$$

Laboratory Observations:
(Lockner & Okubo, 1983; Okubo & Dieterich, 1984)

(1) $\Delta\tau_d \approx 0.73\Delta\sigma$

(2) $\Delta\sigma \approx 0.1\sigma_n$

(3) $D_C \geq 5\ \mu m$

Mine Parameters: G = 36 GPa; $\sigma_n \approx 80$ *MPa*

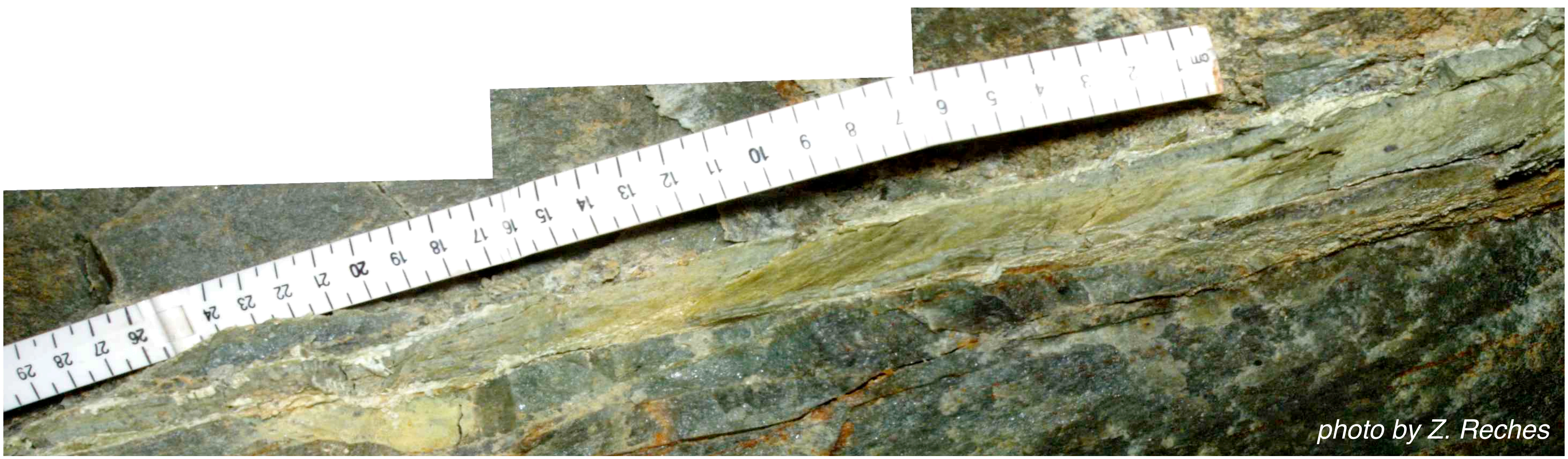
→ $r \approx 5$ *cm,* $M_0 \approx 1e3$ *Nm,* $M_W \approx -4$

→observations of very small mining-induced earthquakes are consistent with laboratory results and surface strainfield observations.

Rupture Propagation- Motivating Questions:

Do large and small earthquakes rupture the same way?

- *What are the proportions of radiated seismic energy, frictional energy, and energy of the expanding rupture surface area?*
- *Can we determine the apparent coefficient of friction during sliding from the heat that was released?*
- *Does radiated seismic energy scale with seismic moment*



Constraints on the Energy Budget of the M 2.2 December 12, 2004 Earthquake

$W = M_0 \tau / G$

W = Radiated Energy (E_R) + Frictional Energy (E_F) + Fracture Energy (E_G)

E_F = Heat + Free Surface Energy (E_S)

$M_0 \approx 2.6 \times 10^{12}$ Nm, calculated from long-period amplitude of the displacement seismogram

$\tau \approx$ 11-52 MPa, local measurements & borehole breakouts

$W \approx (2.6\text{x}10^{12}\text{Nm})(11\text{-}52\text{MPa})/(36\text{GPa})$

W = 800 - 3800 MJ

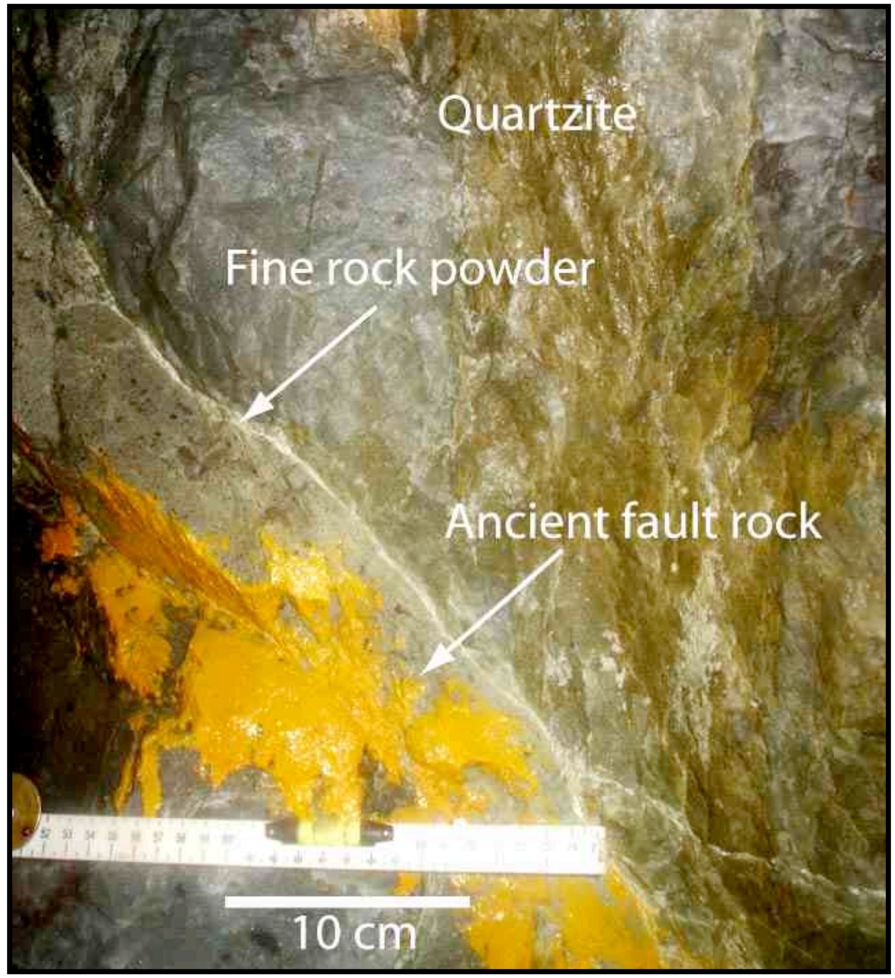
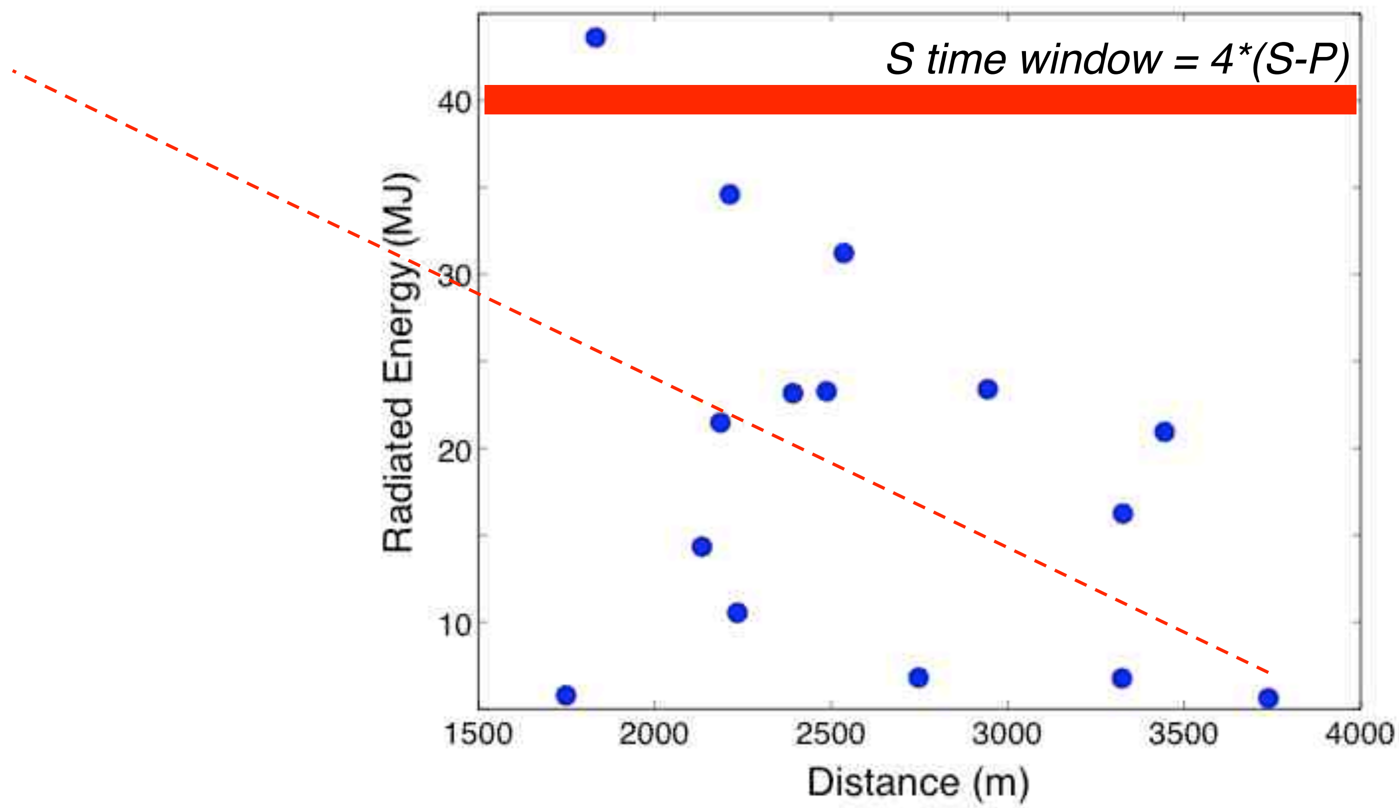


photo by Z. Reches

Earthquake Energy Budget *(From Boettcher et al., 2009)*

*W = **Radiated Energy** + Frictional Energy + Fracture Energy*



Decrease in E_R with distance, due to inelastic attenuation and scattering. We empirically correct for attenuation of the form $e^{-R\gamma}$. And thus obtain an estimate of: ***E_R = 20-40 MJ*** *(depending on chosen S-wave time window)*

Free Surface Energy, E_S

Frictional Energy = Heat + Free Surface Energy

Two 1 mm thick fresh gouge surfaces

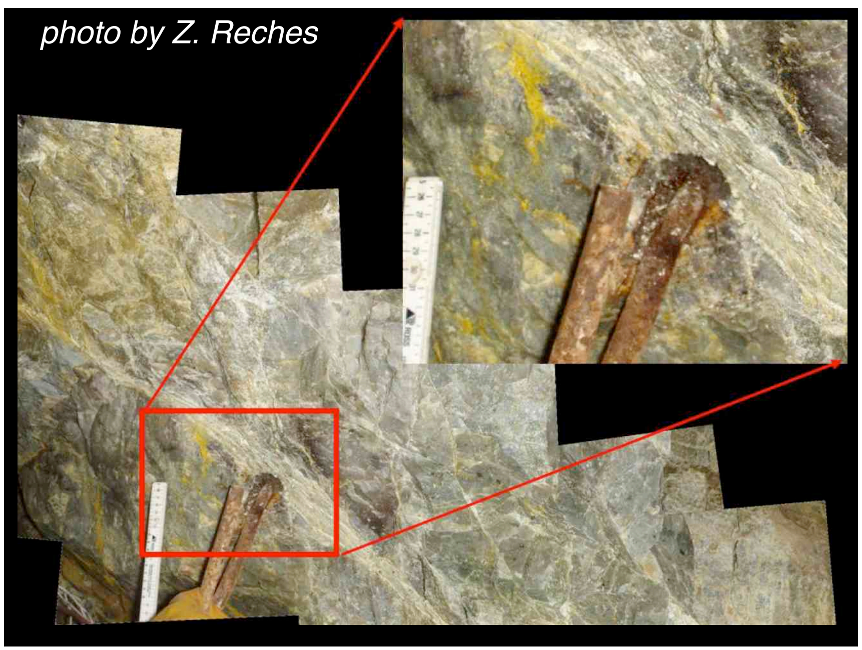
Gouge surface area measurements

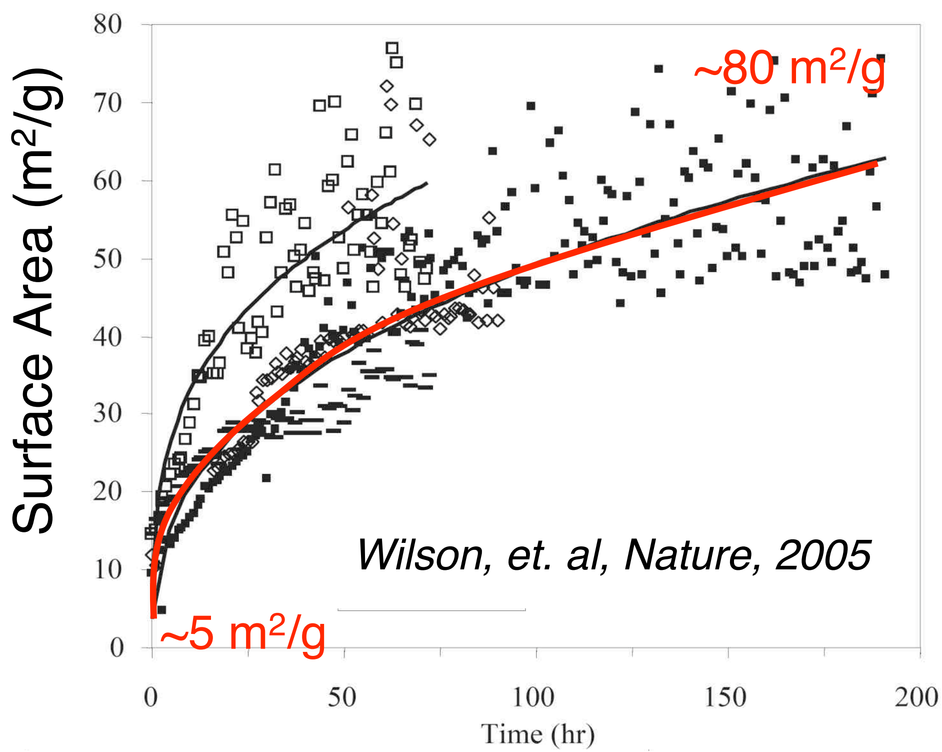
Slip ≈ .025 m

Primary rupture area, $A = M_0/(GD) \approx (2.6e12\ Nm)/(36\ GPa)/(.025\ m) \approx 2900\ m^2$

*E_S= gouge density*gouge surface area (m^2/g)*gouge volume*specific surface area*
$\approx (2\times10^6\ g/m^3)(5\text{-}80\ m^2/g)(.002\ m \times 2900\ m^2)(1\ J/m^2)$

$E_S \approx$ 58 - 930 MJ





Earthquake Energy Partitioning-

Percentage of Seismic Energy (Seismic Efficiency)

$= E_R/W = (20\text{-}40\ \text{MJ})/(800\text{-}3800\ \text{MJ})$

$= <1\%$ to 5%

Percentage of Surface Energy

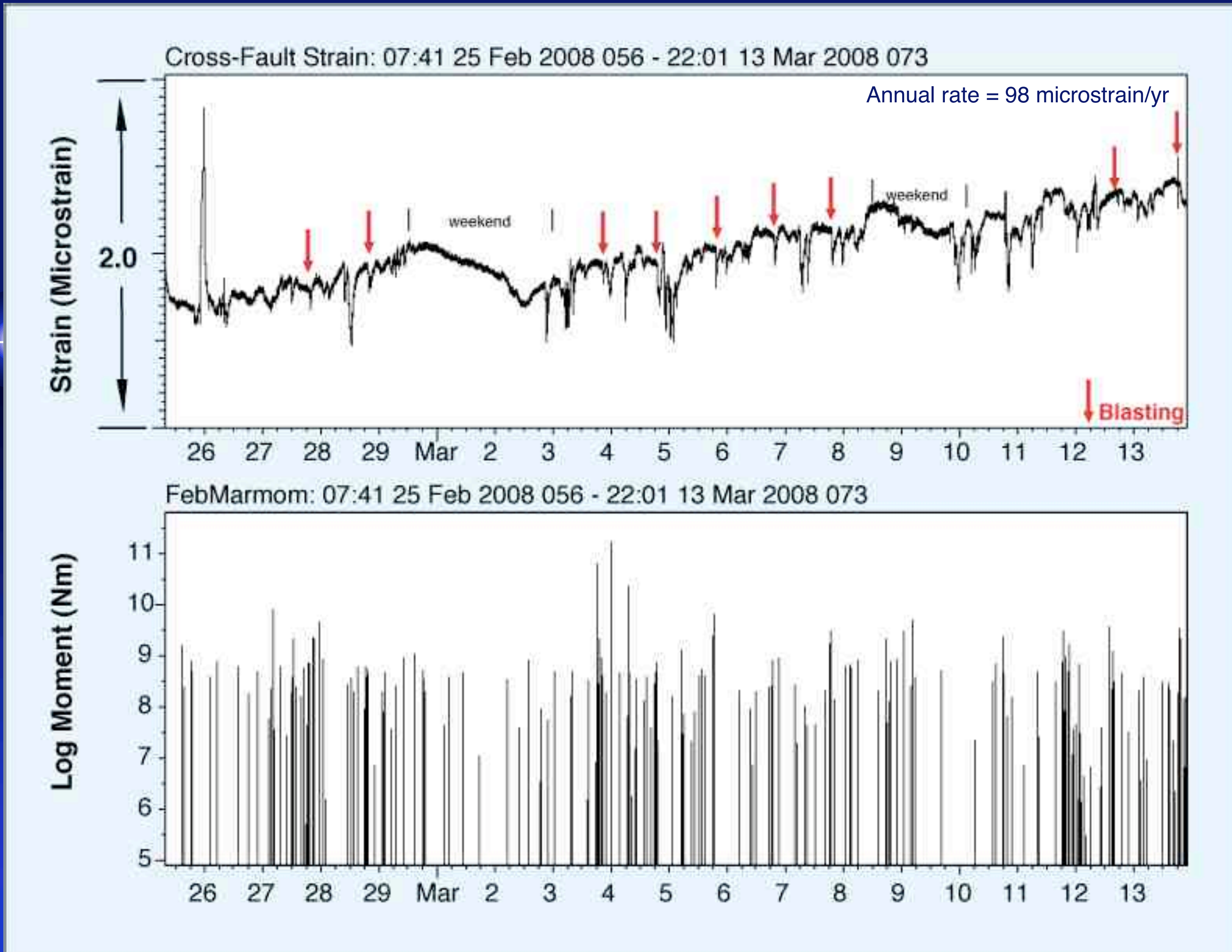
$= E_S/W = (\underline{58} - 930\ \text{MJ})/(800\text{-}3800\ \text{MJ})$

$= 2\% - 100\%$ (likely to be 2%-7%)

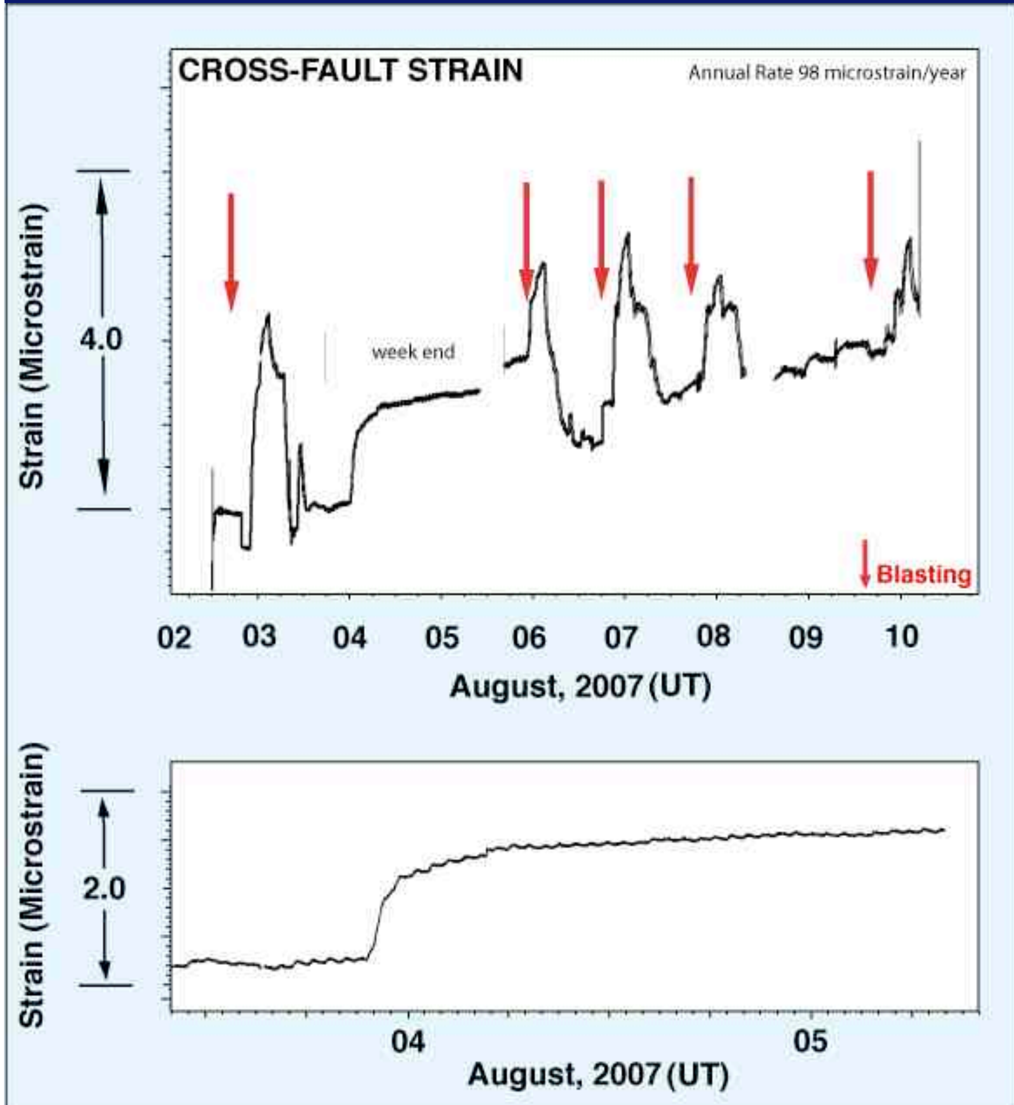
The Dec. 12th, 2004 earthquake fits with previous studies of both mining induced seismicity as well as large tectonic earthquakes. Radiated seismic energy and free surface energy are only small contributors to the total energy budget (e.g. Spottiswoode & McGarr, 1979; Chester et al, 2005; Yamada et al, 2005).

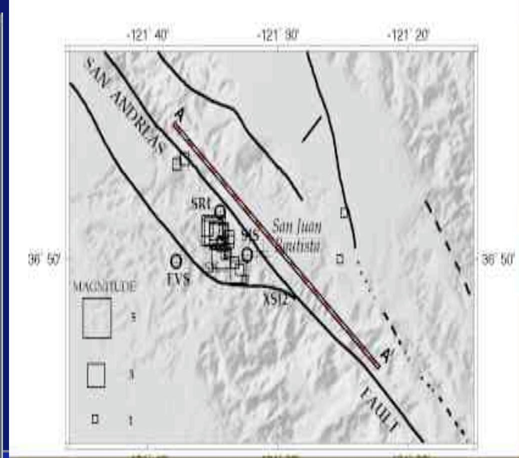
Most of the energy release is likely to be in form of heat.

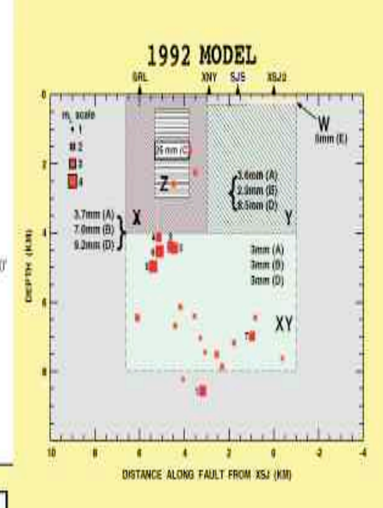
Strain and Microearthquake Moments

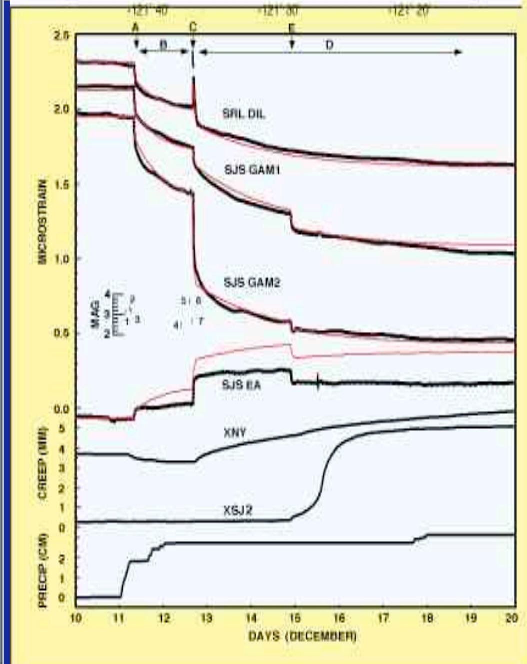


Slow Earthquakes?









Strain event like slow slip events on the San Andreas fault

Conclusions 1

1. A high resolution monitoring network installed at 3.6 depth across and in the Pretorious fault in the Tau Tona Mine in South Africa includes 3_component weak/strong motion seismic acceleration and velocity sensors, thermal sensors, electric field sensors, total fault strainmeter and gas and microbiology. Despite serious logistical difficulties, over 1 million events have been recorded in range $-3.5<M<2.5$.

2. Detection limitations, not earthquake source physics, control the apparent observed minimum magnitude earthquakes in TauTona Mine.

3. The Gutenberg-Richter b-value ≈ 0.85 and is independent of strain rate, while the a-value is directly proportional to strain rate.

4. Source parameters for these smaller magnitude earthquakes are consistent with those obtained from laboratory and field studies. Thus, we are now bridging laboratory observations of “earthquakes” and conventional seismology.

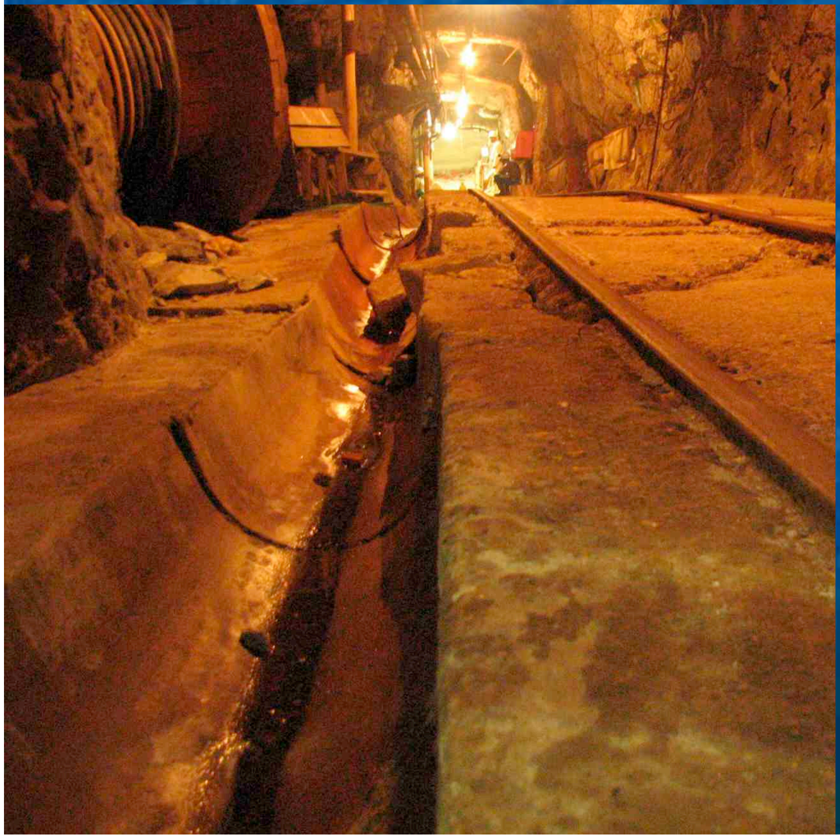
Conclusions 2

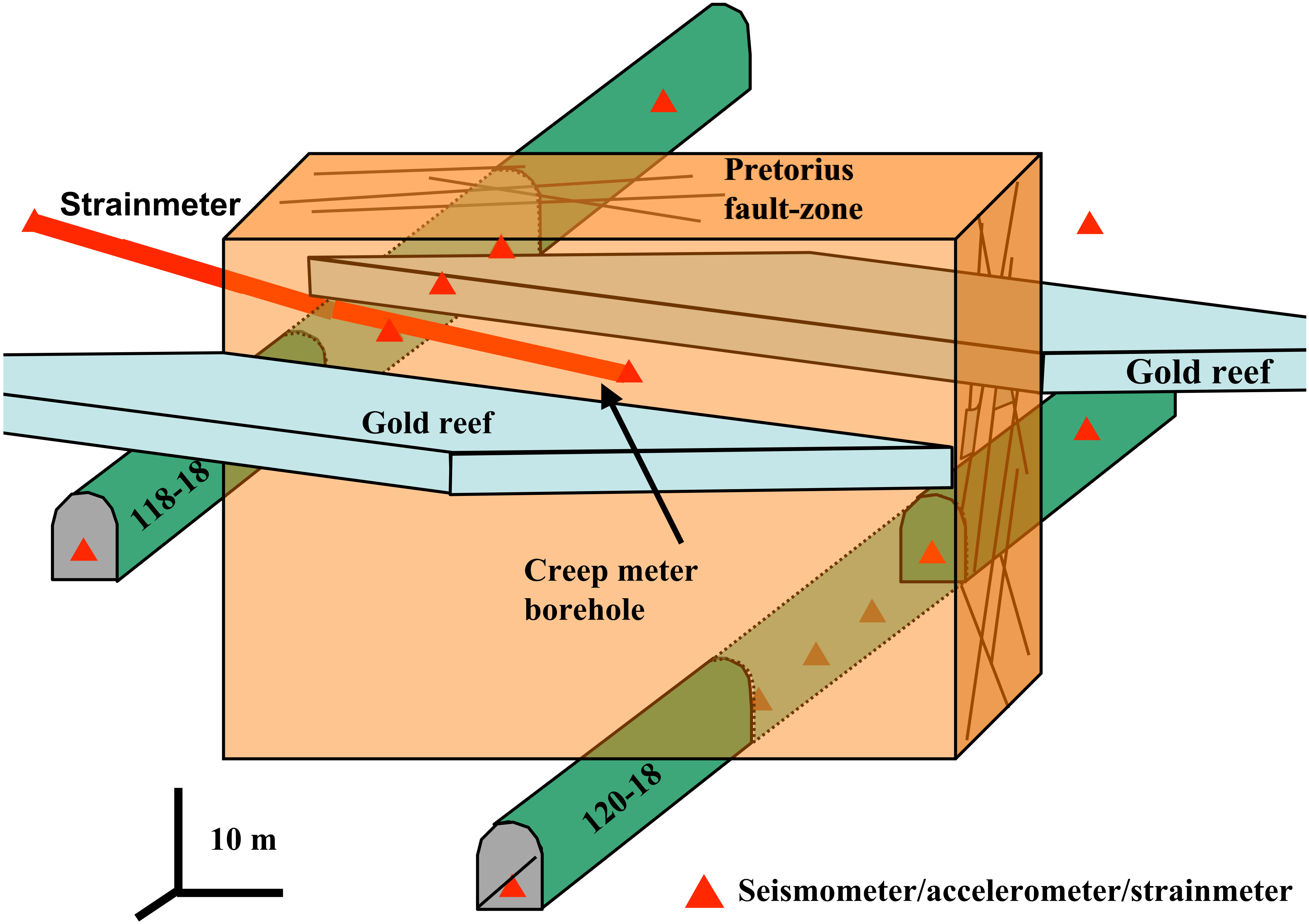
5. Earthquake nucleation moment release, M_n, is a small fraction of M_w and does not scale with earthquake magnitude. Thus, similar behavior is observed over 25 orders of magnitude from M=-3.5 to M=7.5 for major tectonic earthquakes. The size of an eq appear to be determined by what stops the rupture not how it starts. Bad news for earthquake prediction!
6. Preliminary strain data indicate aseismic strain events are common, particularly following blasting with related triggered microseismicity. Aseismic strain events (slow earthquakes?) occur also during non-mining times.
7. Using underground observations, stress measurements, and high-frequency seismic records, we calculate the total energy released during the Mw 2.2 event on Dec. 12th, 2004 to be W ≈ 800-3800 MJ.
8. Radiated Seismic and Free Surface energy account for a small portion of the total energy budget: radiated energy = <1% to 5%; free surface energy is most likely between 2%-7%. Most energy appears go into heat.
9. E_R/M_0 calculated for a number of mining induced earthquakes falls into the range of values seen for similar earthquakes in previous studies.

Second NELSAM site:

The Dagbreek fault *(Tshepong mine, Welkom area)*

- M > 4.0 events along the Dagbreek fault in 1976, 1986 and 1999
- 40-60 km long; throw up to 1 km; significant horizontal slip
- Gently dipping segments with gouge up to 1 meter thick
- Fault is actively creeping in Tshepong




Strainmeter
Pretorius
fault-zone
Gold reef
Gold reef
118-18
Creep meter
borehole
120-18
10 m
Seismometer/accelerometer/strainmeter