Electromagnetic Field Monitoring along the San Andreas Fault 1972-2010: What have we learned about Earthquakes, Aseismic Slip, Fault Creep and Distant Volcanic Activity?

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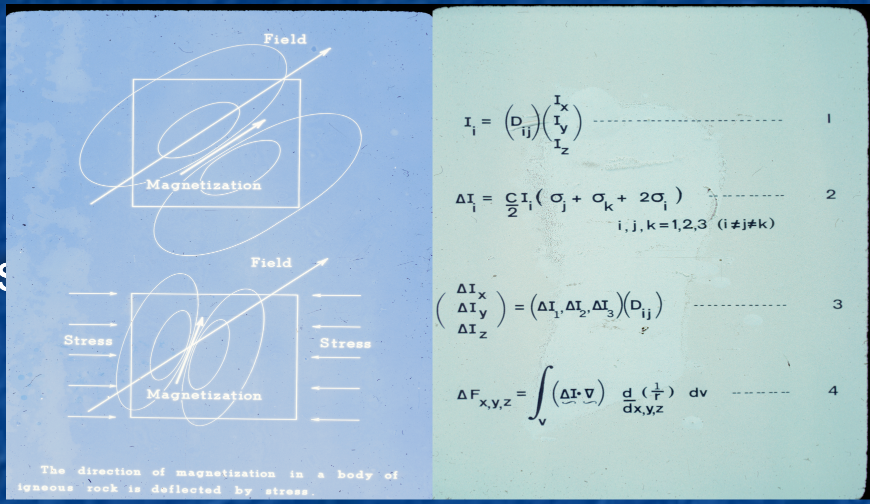
Outline

- Summarize the likely physical processes involved
- Summarize the primary results from this 30+ years of magnetic monitoring within the San Andreas fault system. These include:
  - EM and Aseismic fault slip (Slow Earthquakes)
  - EM and Fault creep events
  - EM Co-seismic signals and Modeling Earthquake Stress Drop
  - EM Signals and Modeling Stress from Radiated Seismic Waves
  - Do Precursory EM Signals Exist?
  - EM and Earthquake Nucleation
  - EM Network signals from Gravity Waves in the Ionosphere resulting from distant Volcanic Eruptions , Teleseismic Eqs. and Tsunamis.
- Conclusions.

Physical Processes I

(See Johnston (1998) review for detailed summary and refs).

- Piezomagnetic Effects (most important)
  - Depends on Change in Stress and Rock Magnetic Properties. Stress sensitivity C ~ 0.1%/MPa
  - Expected signals ~ few nT/MPa for typical fault zone magnetizations and earthquake stress drops of 1-3MPa.
- Electrokinetic Effects (less likely except on volcanoes)
  - Requires large scale continuous or episodic flow for measureable signals
  - Since rock permeability low and variable (~ milliDarcy's), this implies very low flow rates and low fields.



The current density **j** and fluid flow rate **v** in porous media are found from the coupled equations:

$$\mathbf{j} = -s\,\nabla E - \frac{\xi\zeta\nabla P}{\eta}$$

$$\mathbf{v} = \frac{\phi\xi\zeta\nabla E}{\eta} - \frac{\kappa\nabla P}{\eta}$$

where E is streaming potential,
s is the electrical conductivity of the fluid,
ξ is the dielectric constant of water,
η is fluid viscosity,
ζ is the zeta potential,
ϕ is the porosity,
κ is the hydraulic permeability, and
P is pore pressure.

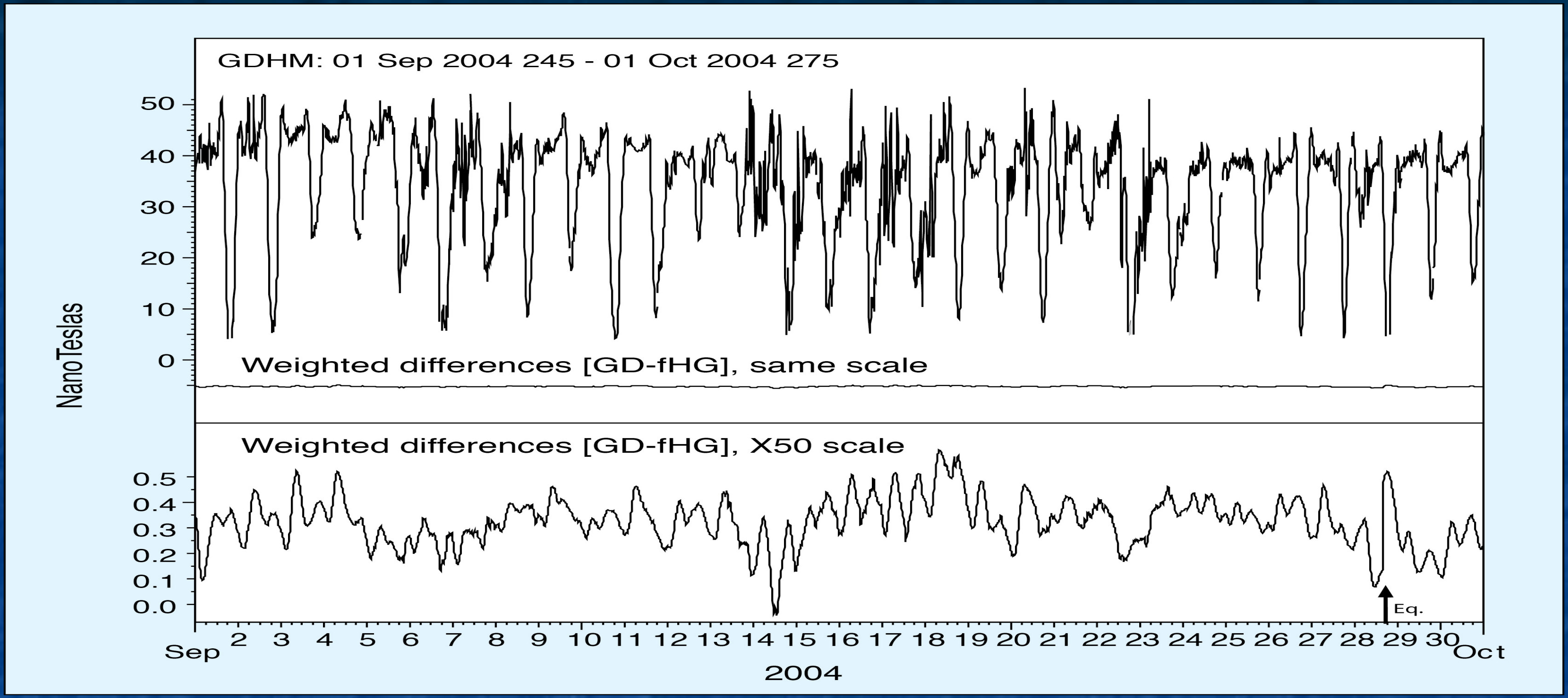
Physical Processes II

- Stress/Resistivity
  - 0.02%/MPa inc. with compression and 0.01%.MPa dec. with shear.
  - Expected signals ~ 0.01% for earthquake stress drops of 1-3MPa.
- Charge generation processes (problematic in conducting crustal materials of 0.01 to 1 S/m – charges short out)
  - Piezoelectric effects (Finkelstein et al. 1973; Baird, 1985)
  - Rock shearing/triboelectricity (Lowell et al., 1980, Gokhberg et al., 1982; Brady, 1992)
  - Solid state mechanisms (Dologlou et al., 1976; Freund, 1992)
- Thermal Demag. and Remag.
  - Slow process (years) because of thermal diffusivity of rock (10^{-6} m^2/sec)
- Magnetohydrodynamic processes
  - $B_i \sim \mu.s.v.d.B_0$
  - Fluid flow in crust too slow because of low rock permeability (milliDarcy's)

Background

- Electromagnetic Field Monitoring Array was initiated along the San Andreas fault in the early 1970's to:
  - Define absolute changes in crustal stress associated with all aspects of earthquake failure, fault slip, crustal deformation and volcanic eruptions.
  - Attempt to predict earthquakes. Stress change was expected with approaching crustal failure (though of unknown scale) and magnetic measurements should independently detect this. New absolute instruments together with new techniques for external noise suppression were available. Earlier attempts in 1850's to the 1930's (and earlier centuries) had failed because 1) Instruments were sensitive to ground shaking, and 2) Spurious EM noise of external ionospheric origin contaminated the data.
  - Attempt to provide remote independent monitoring of the earthquake source process.

Network Design and Noise Reduction

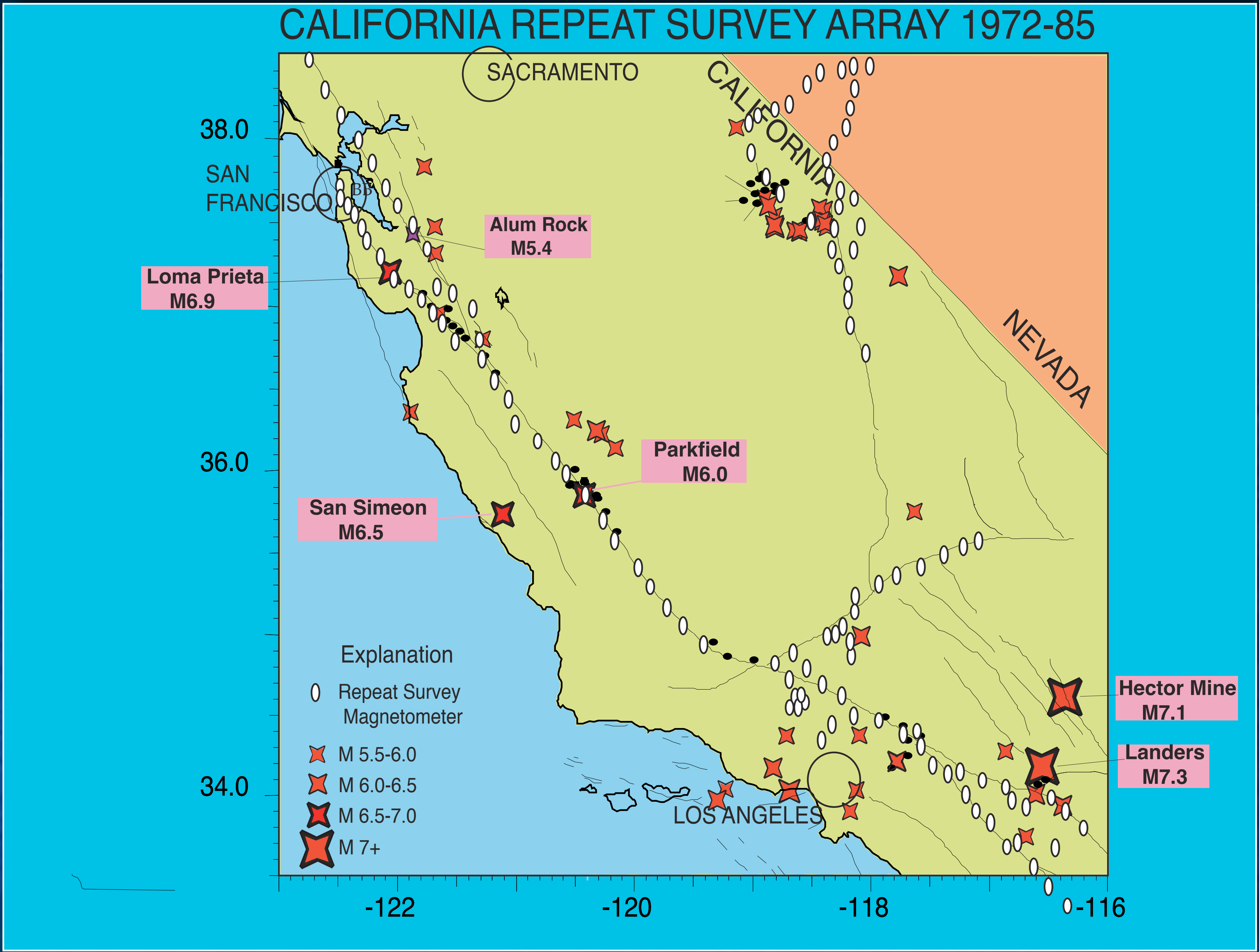
- 

    - For a 10 km instrument spacing, disturbance amplitudes are typically reduced by at least 30 dB or to less than 1 nT. Here the reduction is about a factor of 100.

- Since peak EM signals with eqs. are expected off-fault at ~0.5 fault width, instruments are thus distributed along the fault at about 2-5 km from it.

What EM Signals are expected with Aseismic and Seismic Slip (Earthquakes)?

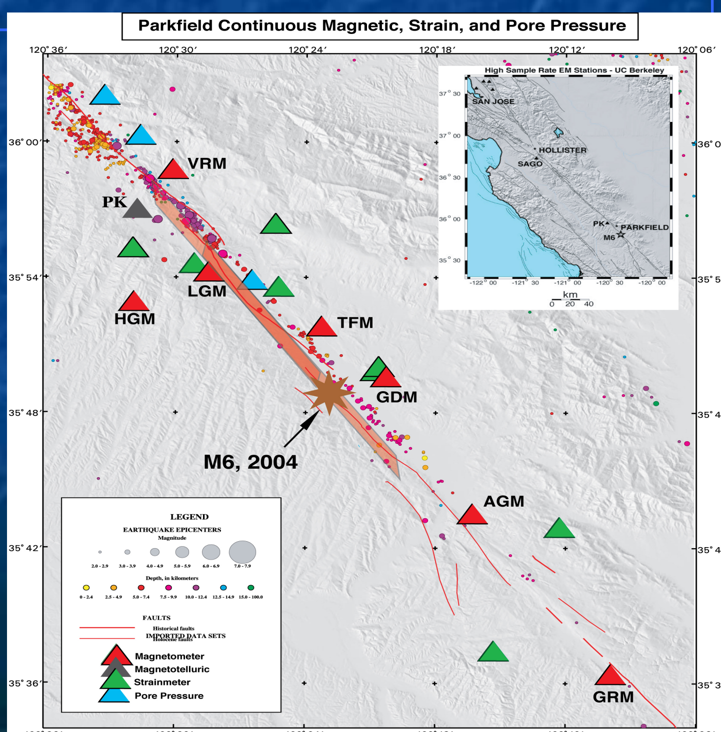
- Aseismic EM signals
  - Fault slip/creep events (Breiner and Kovach, 1967)
  - Aseismic slip events or “slow” earthquakes
- Seismic or Eq. Related EM signals
  - With Co-seismic Static Stress Drop.
  - With radiated Seismic P and S Stress Waves. Care must be taken to avoid spurious second-order effects from ground shaking with rigid installations at sites with low local gradients.
  - During Nucleation and Rupture Propagation. EM radiates at rupture front as bonds broken. Travels speed of light. Attenuates in conductive fault zone regions. Observed in laboratory experiments and with nuclear and conventional explosions. Expected for earthquakes.
  - Preseismically?
  - With Earthq./Volc. Generated Gravity waves.

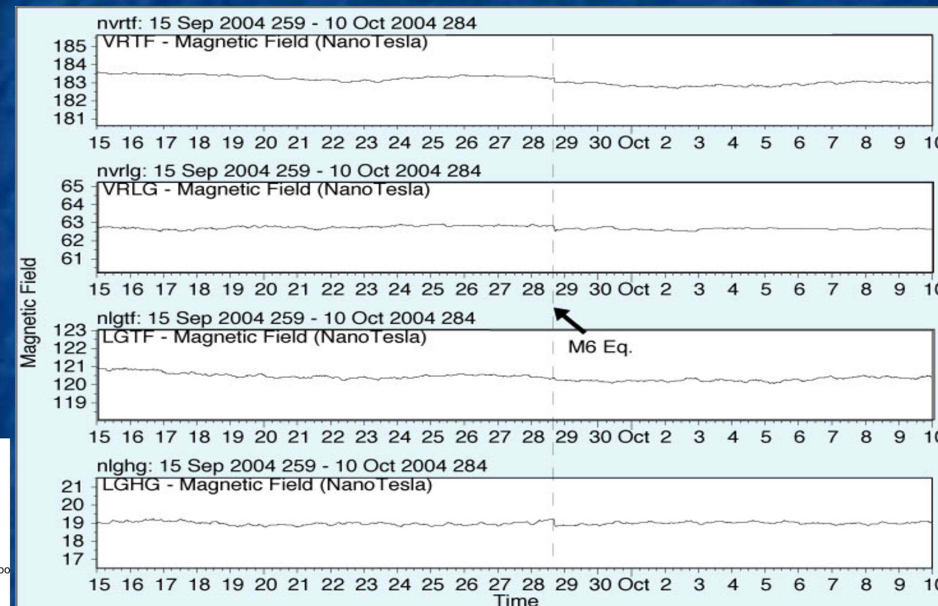


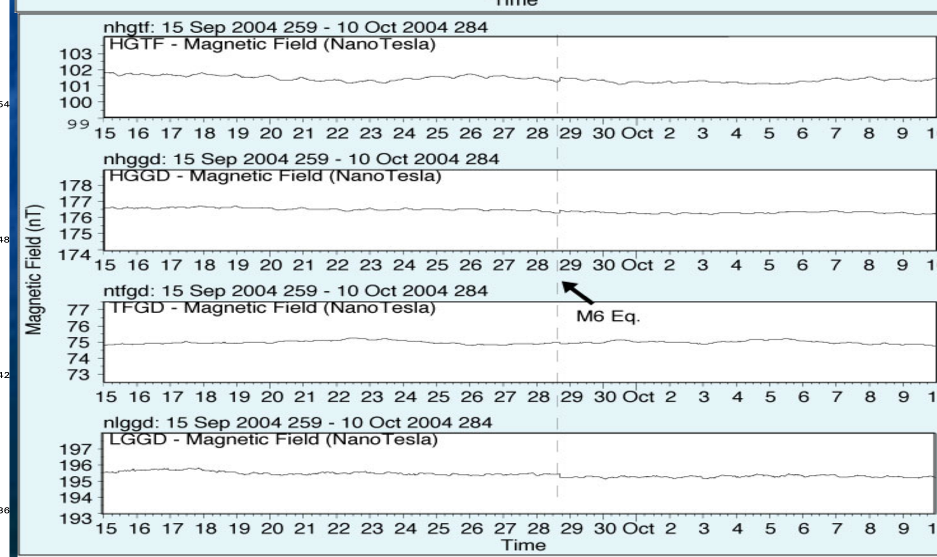
Absolute Total Field Instruments – Permanent Sensor Holders. Also fluxgates and coils
Sampling Synchronized. Data sent by satellite/phone line to Menlo Park
Discriminates Against Ionospheric Disturbances and cultural noise

EM - Co-seismic Regional Static Stress Change

- Many examples. Best are largest/closest events such as
  - M5.9 North Palm Springs, 1986.
  - M7.4 Landers, 1992.
  - M 6.0 Parkfield, 2004.

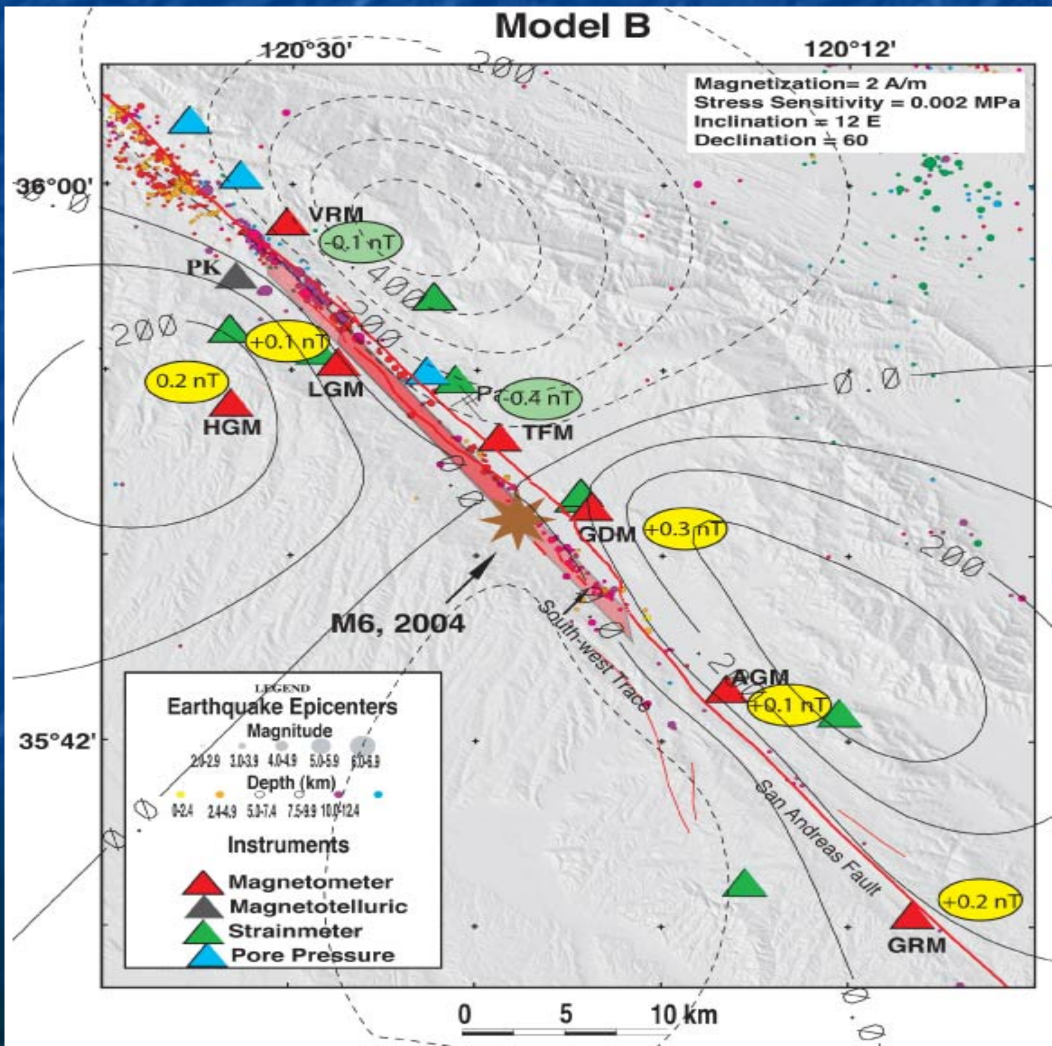






Magnetic/Geodetic Models from Earthquake Stress Drop

Observed and calculated magnetic field from magnetic/geodetic model



-General Agreement between magnetic, geodetic and seismic models.

-Overall, models quite tightly constrained

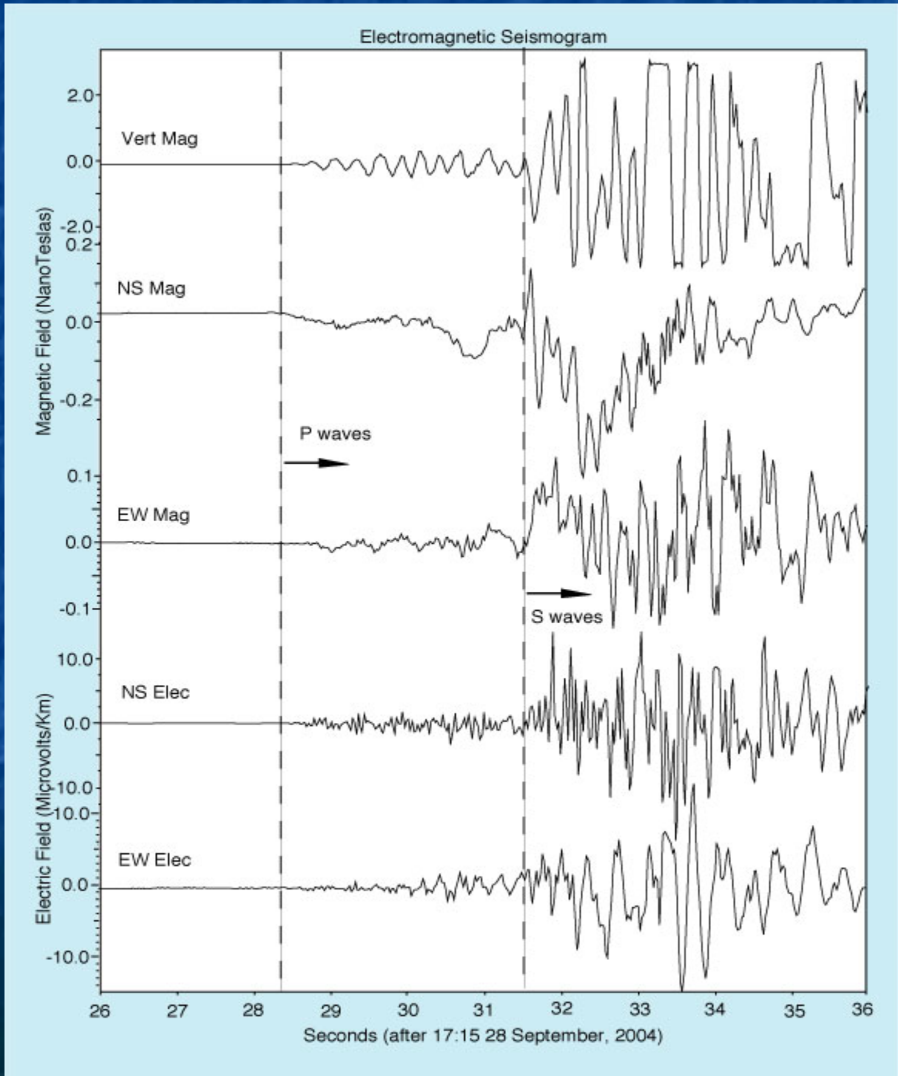
-Stress change from fault slip process is thus generally well understood.

See BSSA, V96, S206-220, 2006

EM - Dynamic Stress Waves and Rupture Propagation

EM Seismogram for M6 2004 Parkfield earthquake

- Expect EM effects from
  - Stress waves from seismic P and S waves
  - Rupture Propagation?
- Signals observed starting with first P arrival with larger signals during S wave arrivals



EM - Quasi-static Piezomagnetic Dynamic Stress Model I

Fractional change in magnetization per unit volume, $\Delta \mathbf{I}$, as a function of deviatoric stress, σ is;

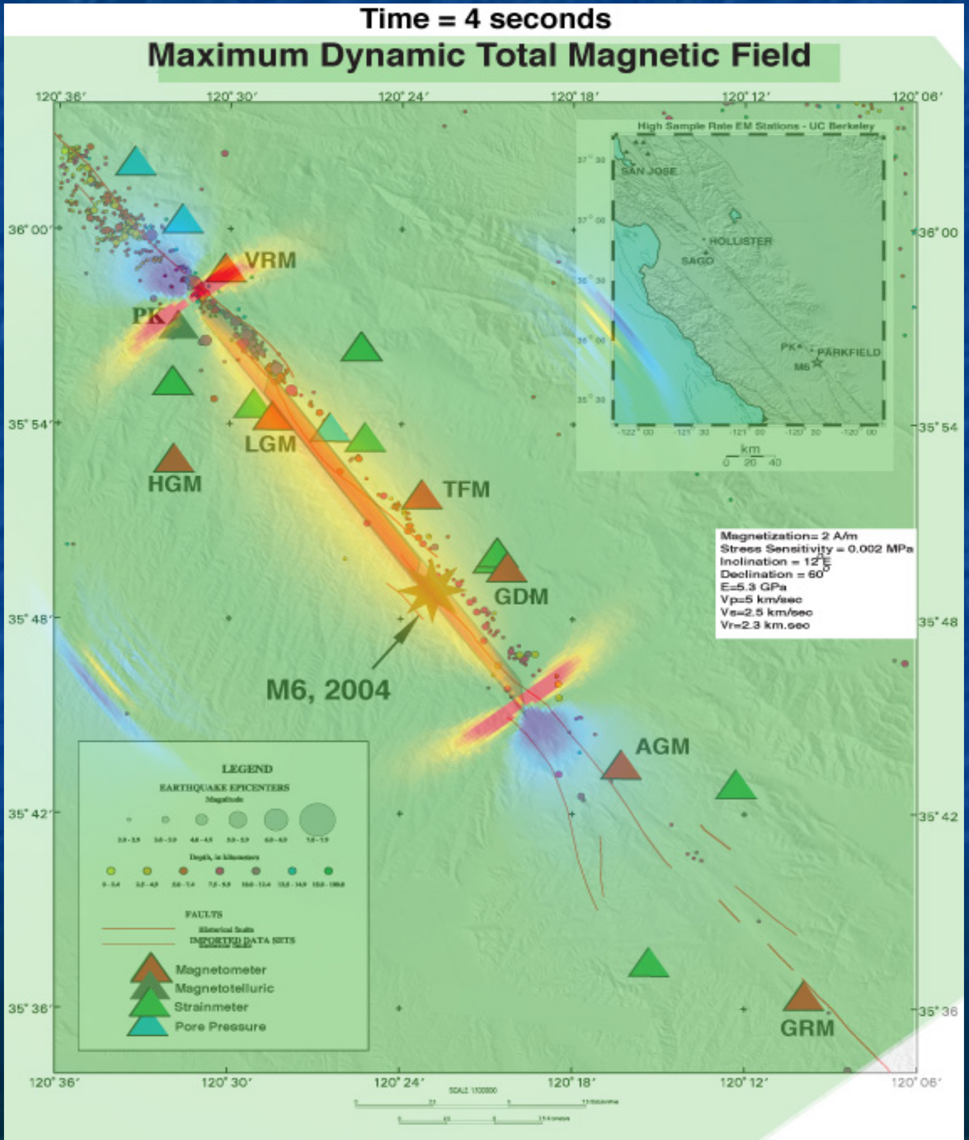
$$\Delta \mathbf{I} \approx K\sigma \cdot \mathbf{I} \qquad (1)$$

where net magnetization is $\mathbf{I}$, K is the stress sensitivity which typically has values of about $3*10^{-3}$ MPa^{-1}. Thus, magnetic field changes expected to accompany earthquakes and volcanoes can be calculated from models of fault rupture and pressure loading in active volcanoes The surface fields ($\Delta \mathbf{B}_P$) at a point, P, can be calculated (e.g. Stacey, 1964) either from,

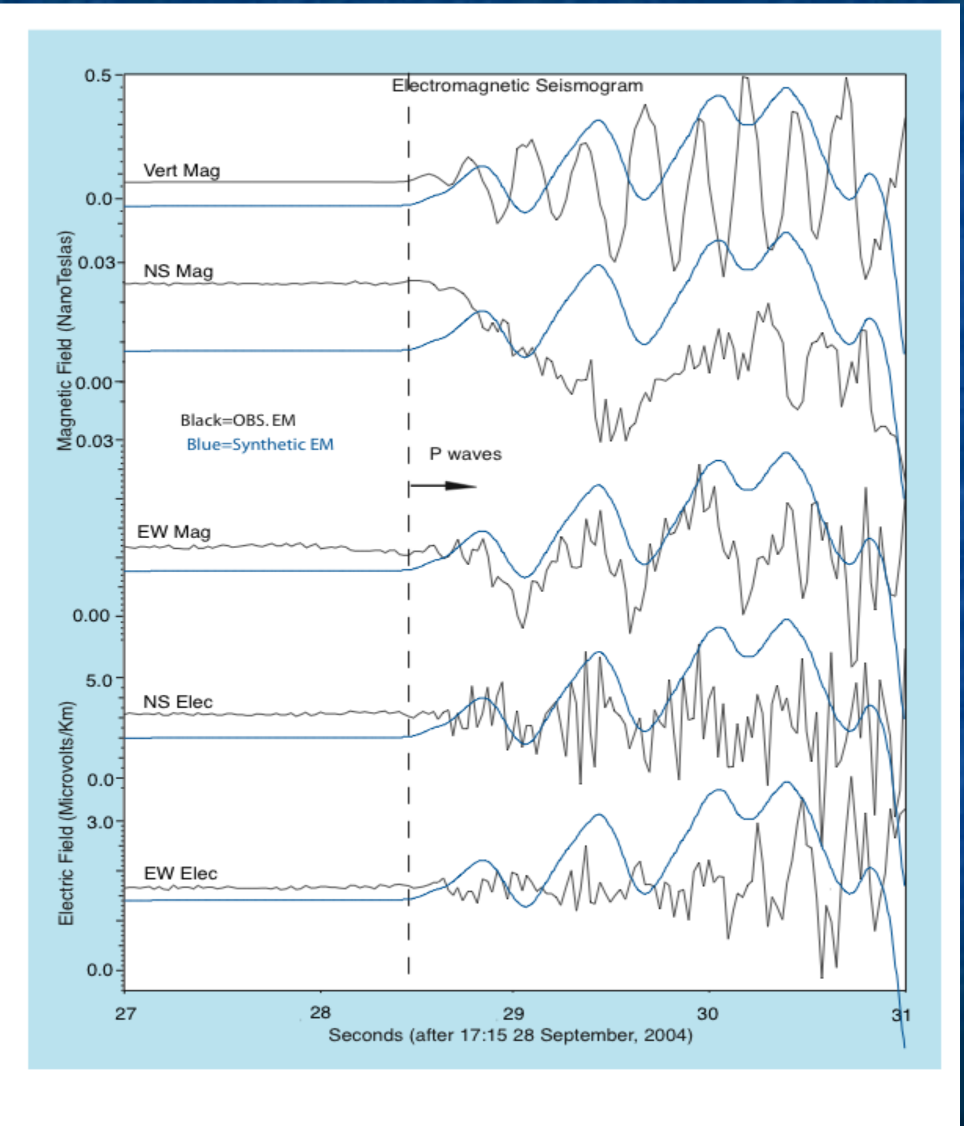
$$\Delta \mathbf{B}_P = -\frac{\mu}{4\pi} \int_V \Delta \mathbf{I}_Q \cdot \frac{\mathbf{r}}{r^3} dv \qquad (2)$$

or from the surface piezomagnetic potential, ∇W, (e.g. Sasai, 1994), where

$$\Delta \mathbf{B}_P = -\nabla W \qquad (3)$$



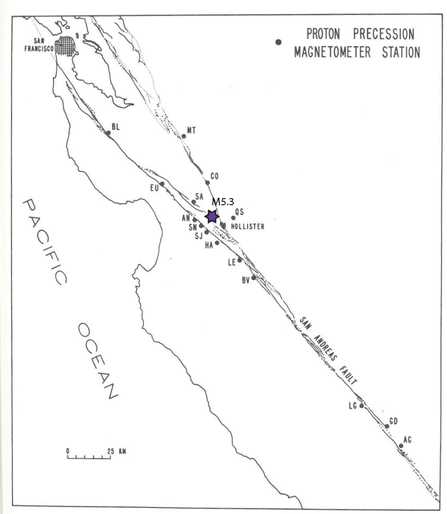
EM - Quasi-static Piezomagnetic Dynamic Stress Model II



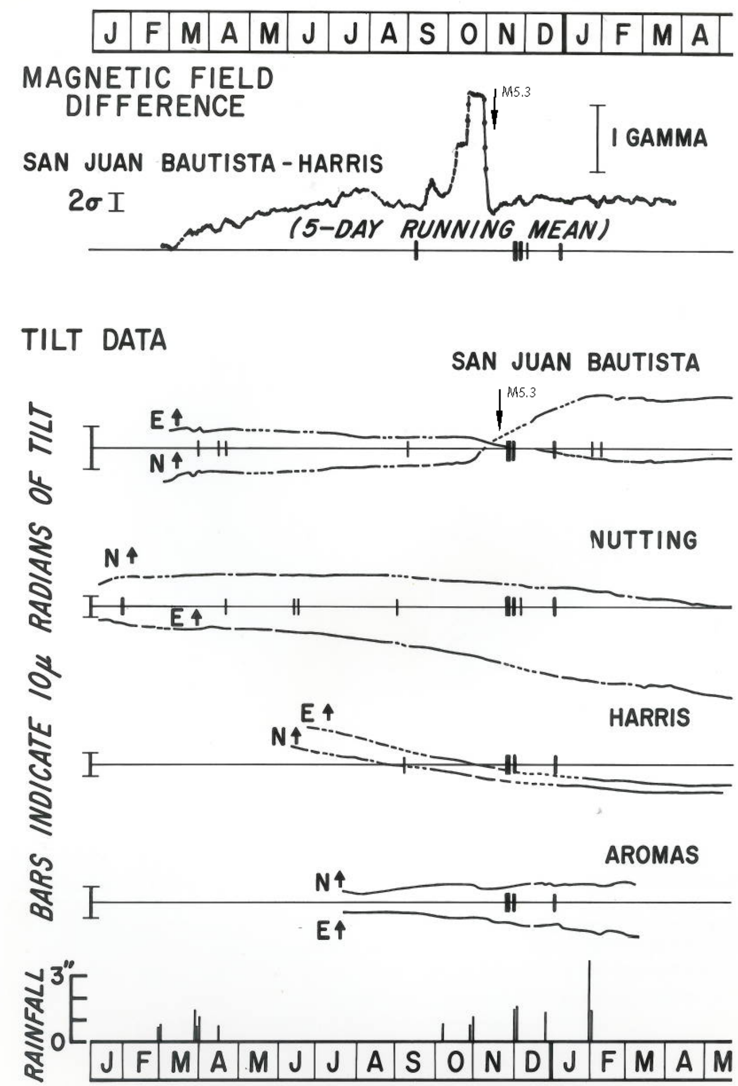
- Finite-element seismic prop. model fits some of the low frequency components in the EM seismogram. Question: Are high-frequency components due to incoherent rupture prop. or ground shaking?
- Comparison with strong motion obs. at site indicates high frequency effects cannot be the result of local ground shaking?

Do Precursory EM Signals Occur?

- Preseismic Events
  - Just one possibility observed in 30+ years of monitoring.
  - Probably resulted from a slow slip earthquake that triggered the M5.3 earthquake near San Juan Bautista, CA in 1974. Subsequent data indicate these slow slip events are common at this location.



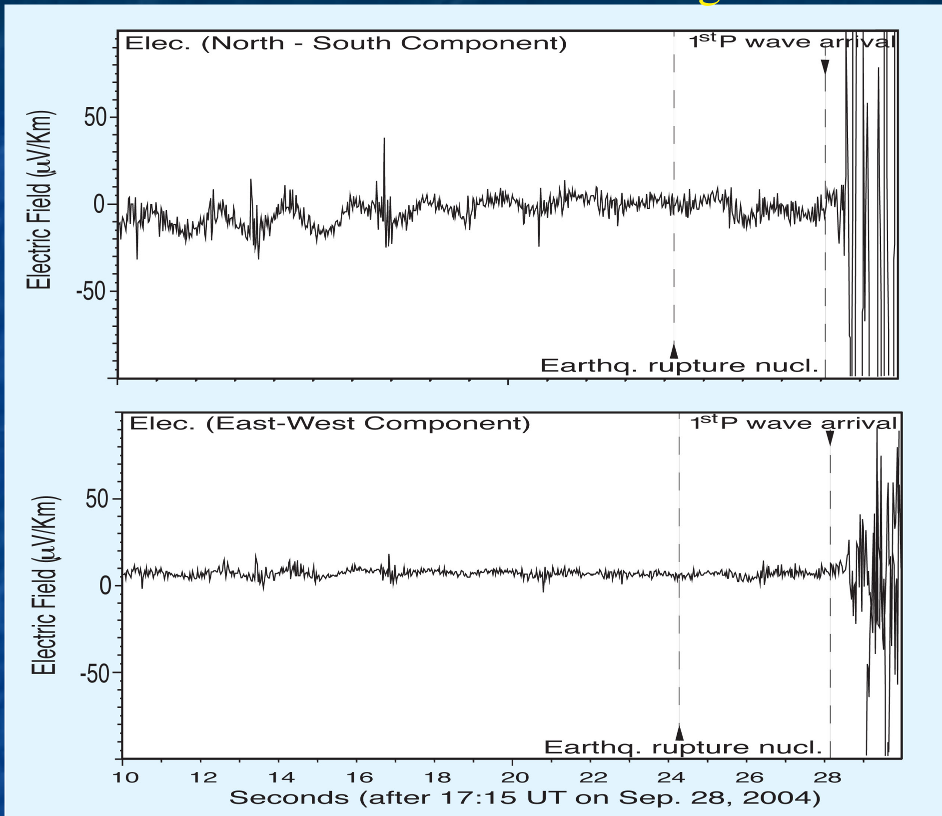
from Johnston et al., 1974

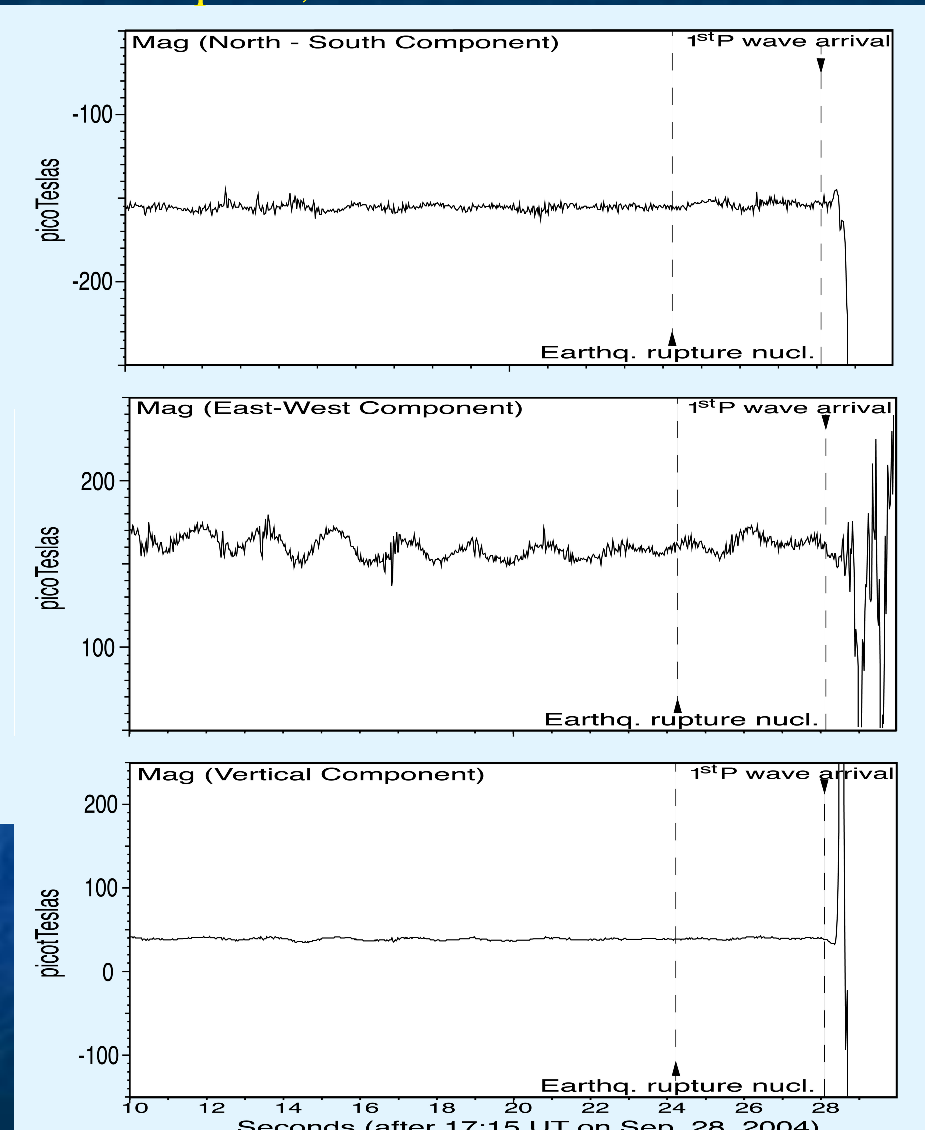


from Johnston et al., 1975

EM – Earthquake Nucleation

e.g. Parkfield M6 Earthquake, 2004





From Johnston, 2006. EM Data from F. Morrison, UCB

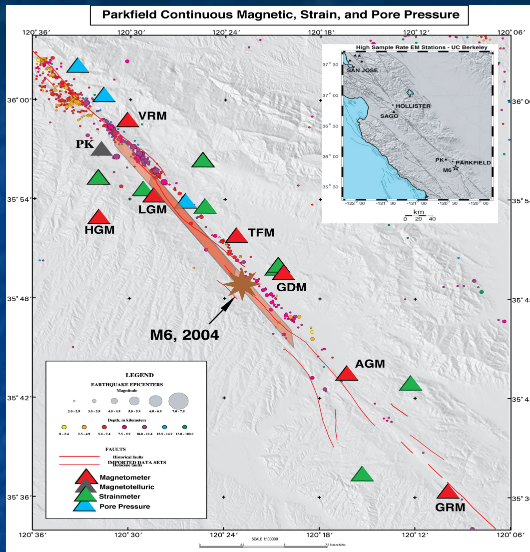
- Comparative Observations
  - During nucleation,
    - Mag. <10 pT, Elec. <20 uV/km
  - With seismic wave radiation,
    - Mag. ~5 nT, Elec. ~10 mV/km (500 times bigger)
  - With static stress change,
    - Mag. ~1nT, Elec. ~2mV/km (100 times bigger)

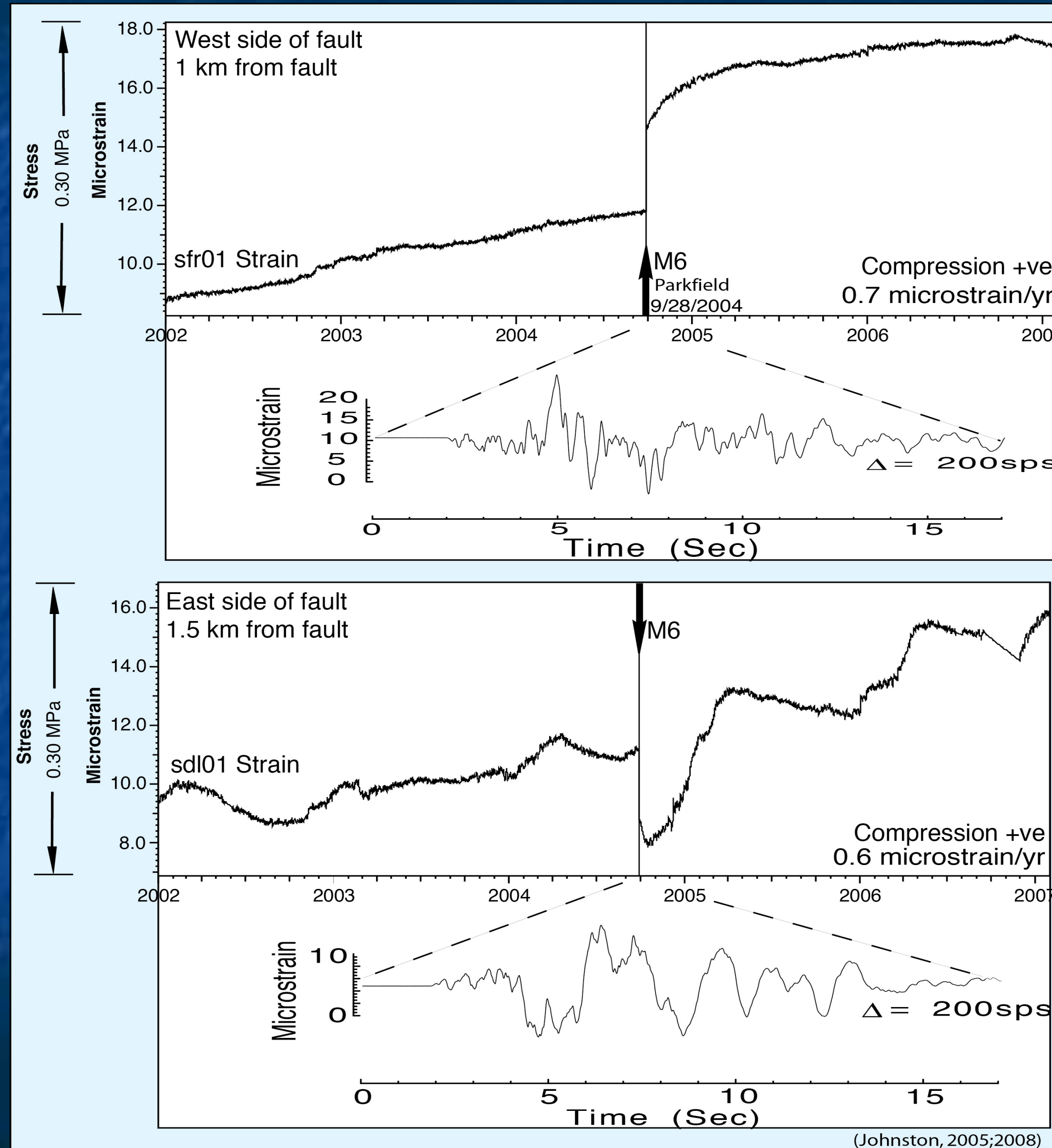
No observable nucleation signals observed in near-field of >30 M5.5+ events

Conclusions

- Earthquakes generate surface magnetic and electric fields of no more than 5 nT and 10 mV/km co-seismically (i.e. during primary energy release).
- Seismomagnetic models from these data are consistent with geodetic and seismic models of these earthquakes provided data are corrected for external ionospheric, magnetospheric and cultural disturbances.
- Pre-earthquake moment release associated with earthquake nucleation in the epicentral region is less the 0.01% of earthquake moment release.
- Crustal stress change from plate loading prior to failure is very smooth with no detectable indications of failure nucleation in magnetic and electric filed data, or crustal stress/strain data.
- In 30+ years of monitoring just one local 1.5 nT magnetic signal was recorded on three independent magnetometers in the week before a M5.4 earthquake but this was likely related to aseismic fault slip (a slow earthquake) that may have subsequently triggered the M5.4 earthquake.
- Synchronized EM networks readily detect propagating electromagnetic disturbances in the ionosphere/magnetosphere resulting from atmospheric gravity waves from co-seismic ground displacement, surface waves, tsunamis and volcanic eruptions such as the 1980 Mount St. Helens volcanic eruption.

Crustal Strain, Prior to, During and After Earthquakes



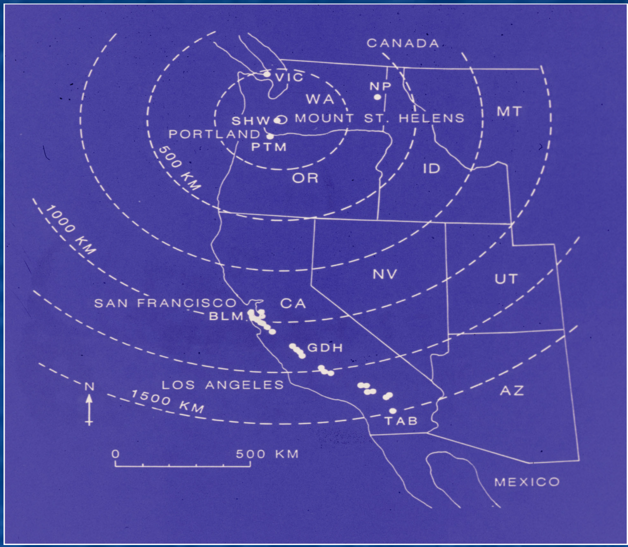


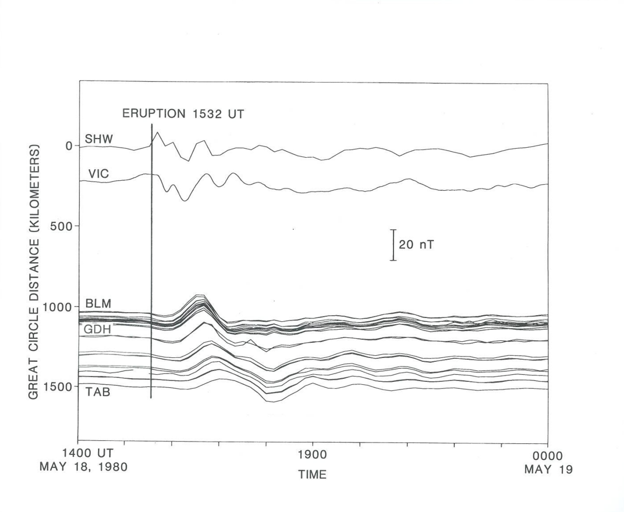
(Johnston, 2005;2008)

- Uniform Stress/Strain Accumulation
- Coseismic signals – Offsets and Dynamic waves (Relate to source)
- Post Seismic response

EM - Traveling Ionospheric Disturbances (TIDS)

- Generated by acoustic (gravity) waves caused by static and dynamic ground displacement with earthquakes, explosive eruptions from volcanoes and tsunamis that are coupled into the atmosphere and trapped in the Ionosphere/Earth wave guide.
- Various dispersive phases propagate at 250-400 m/s at distances beyond 1000 km. This is consistent with GW theory (Francis,1976)
- TIDS are also observed following large earthquakes (e.g. M9 Tohoku earthquake in 2011).





(see Mueller and Johnston, 1987