Effects of Seismic Waves on Hydrothermal Systems: Examples from Long Valley, and Implications for Hydrologic Precursors

Evelyn Roeloffs

U.S. Geological Survey

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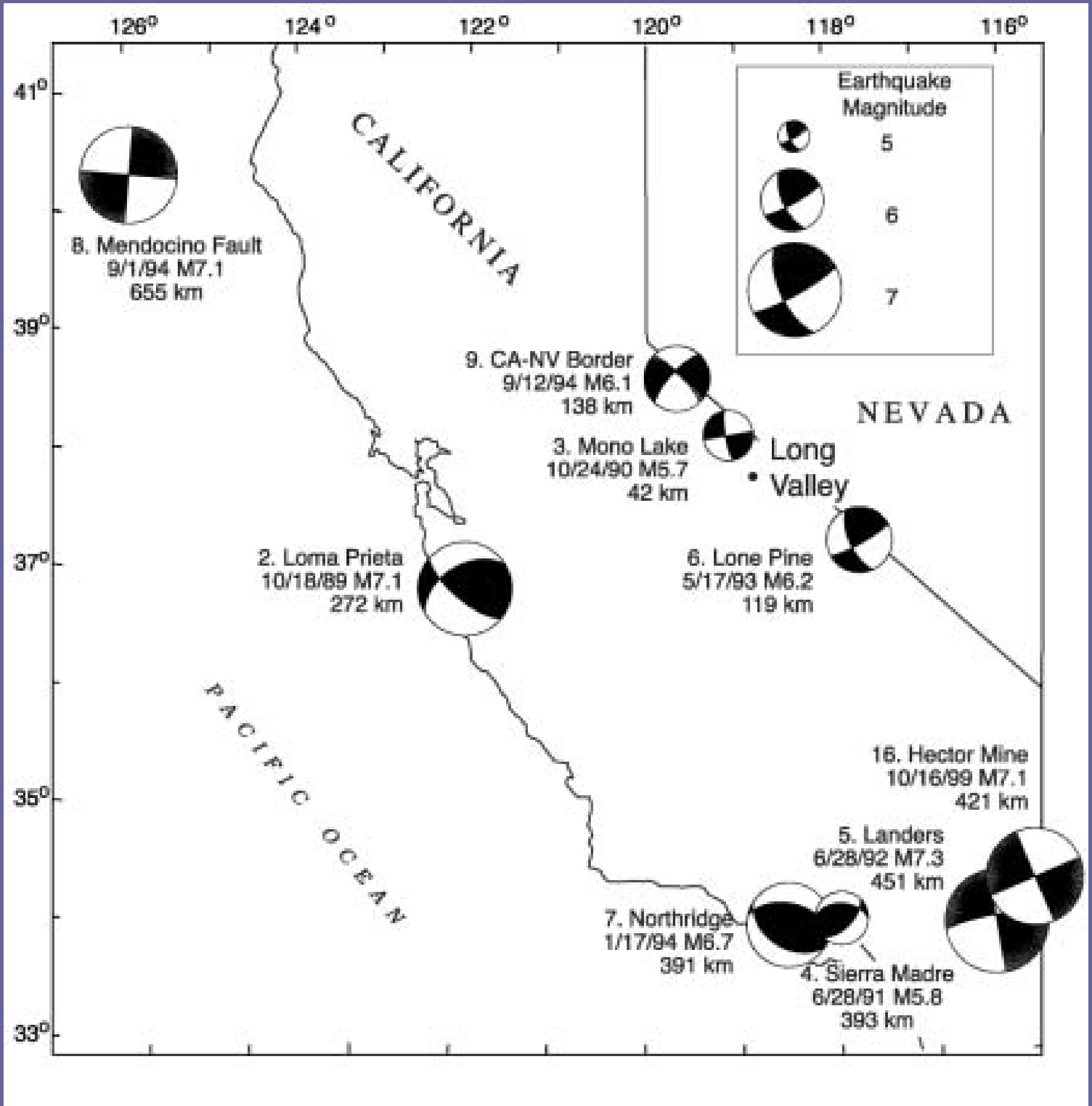
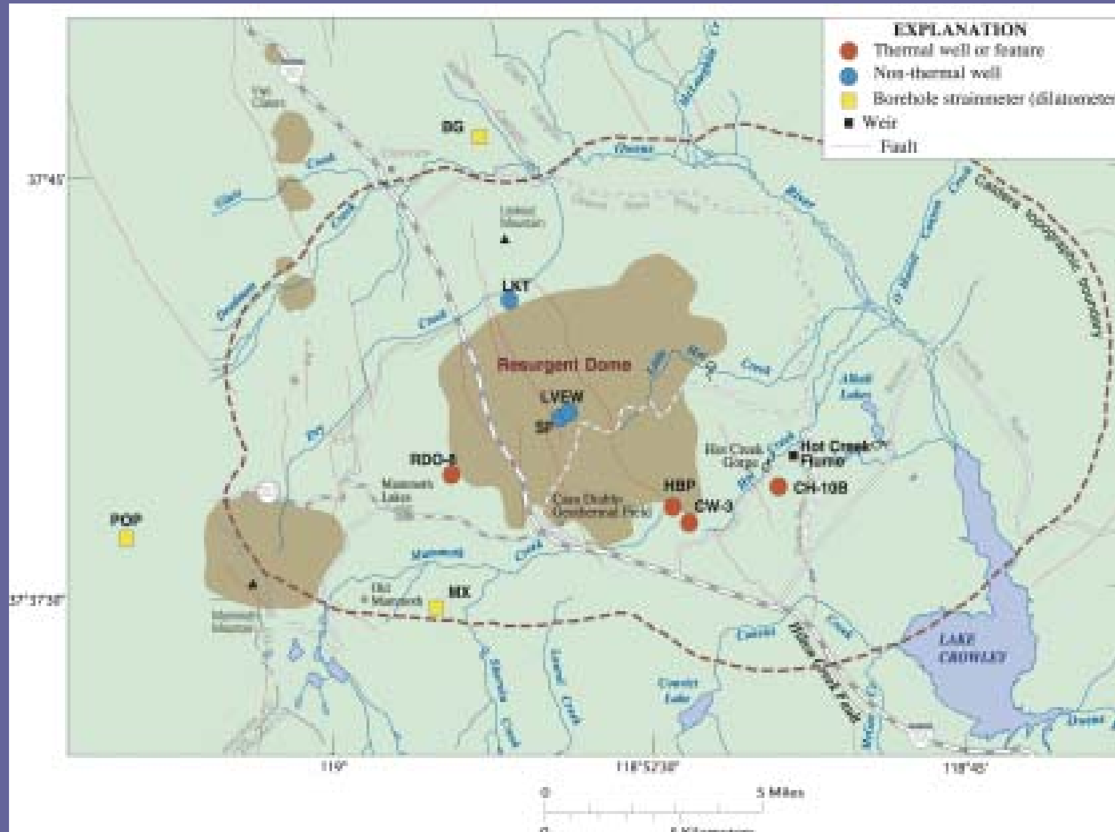
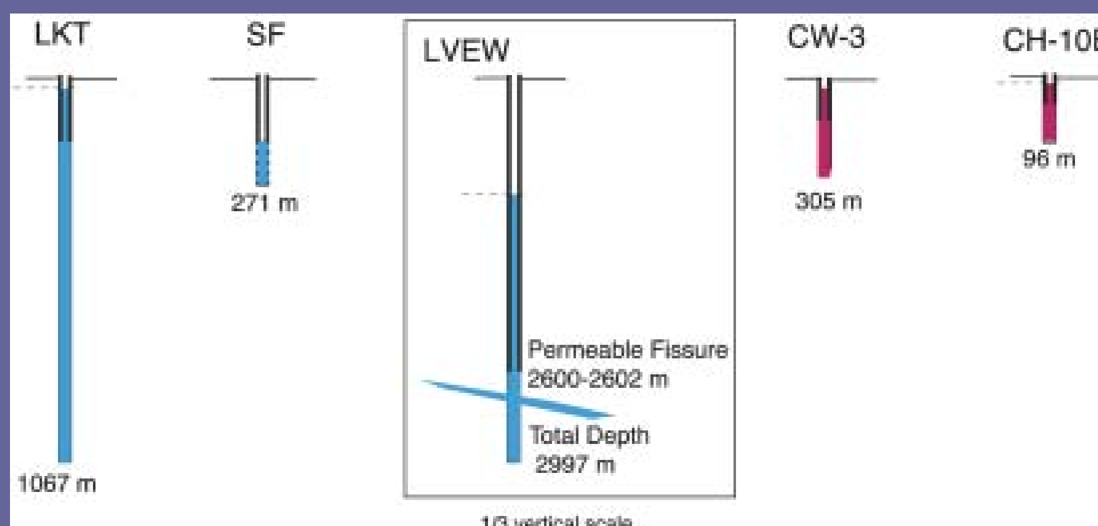
Earthquakes Affecting Water Levels in Long Valley

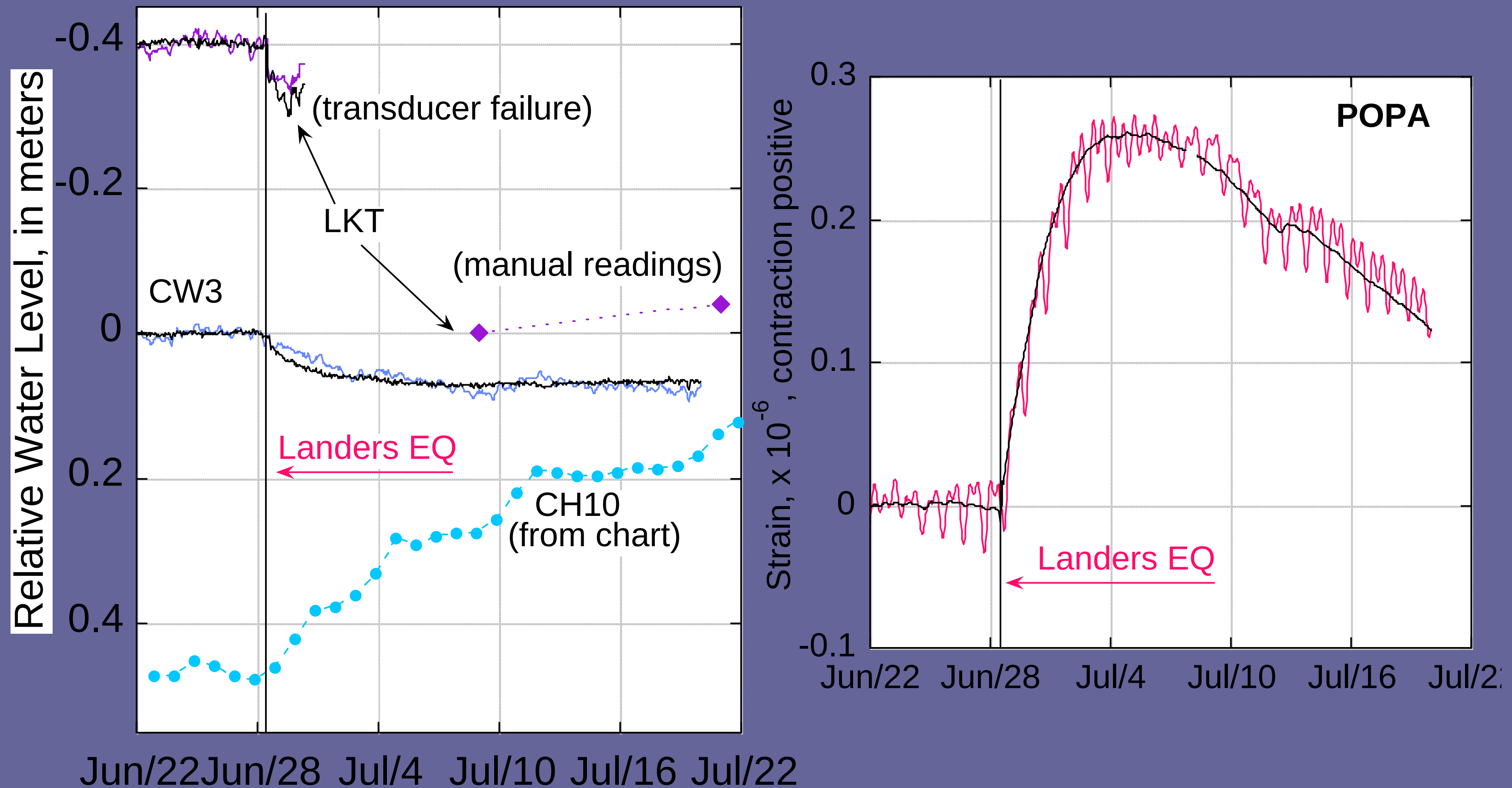


Map of well sites



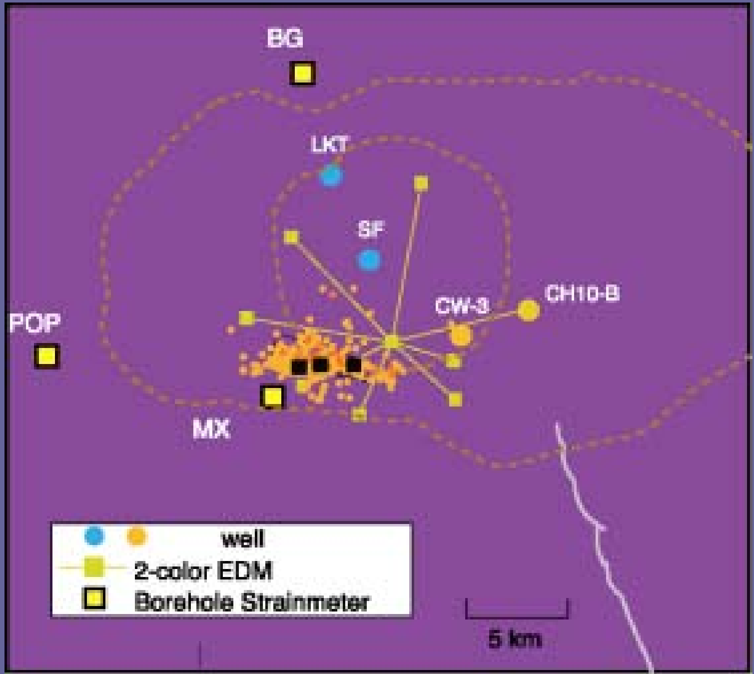


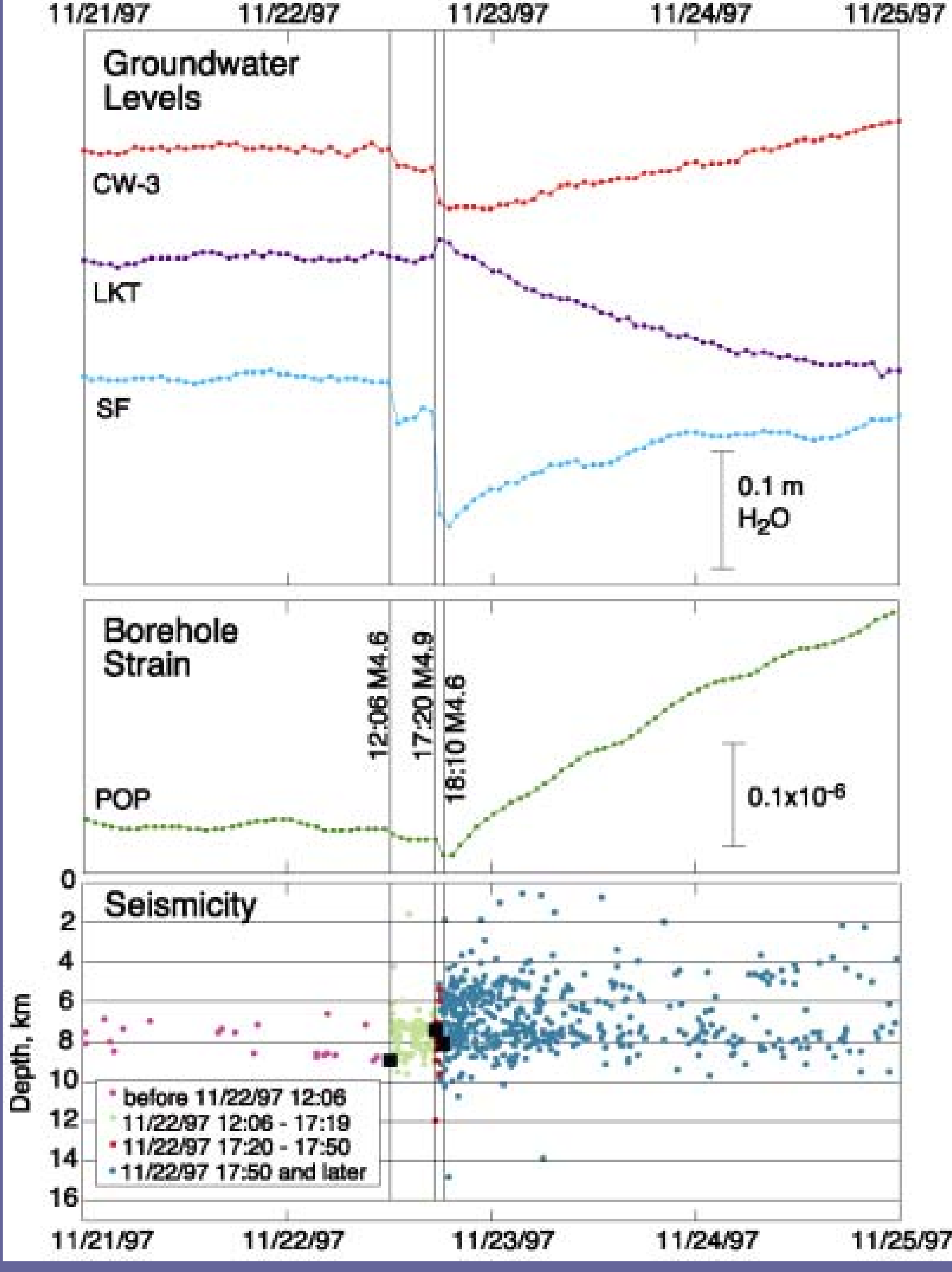
Landers Earthquake M7.3 451 km



Nov. 22, 1997

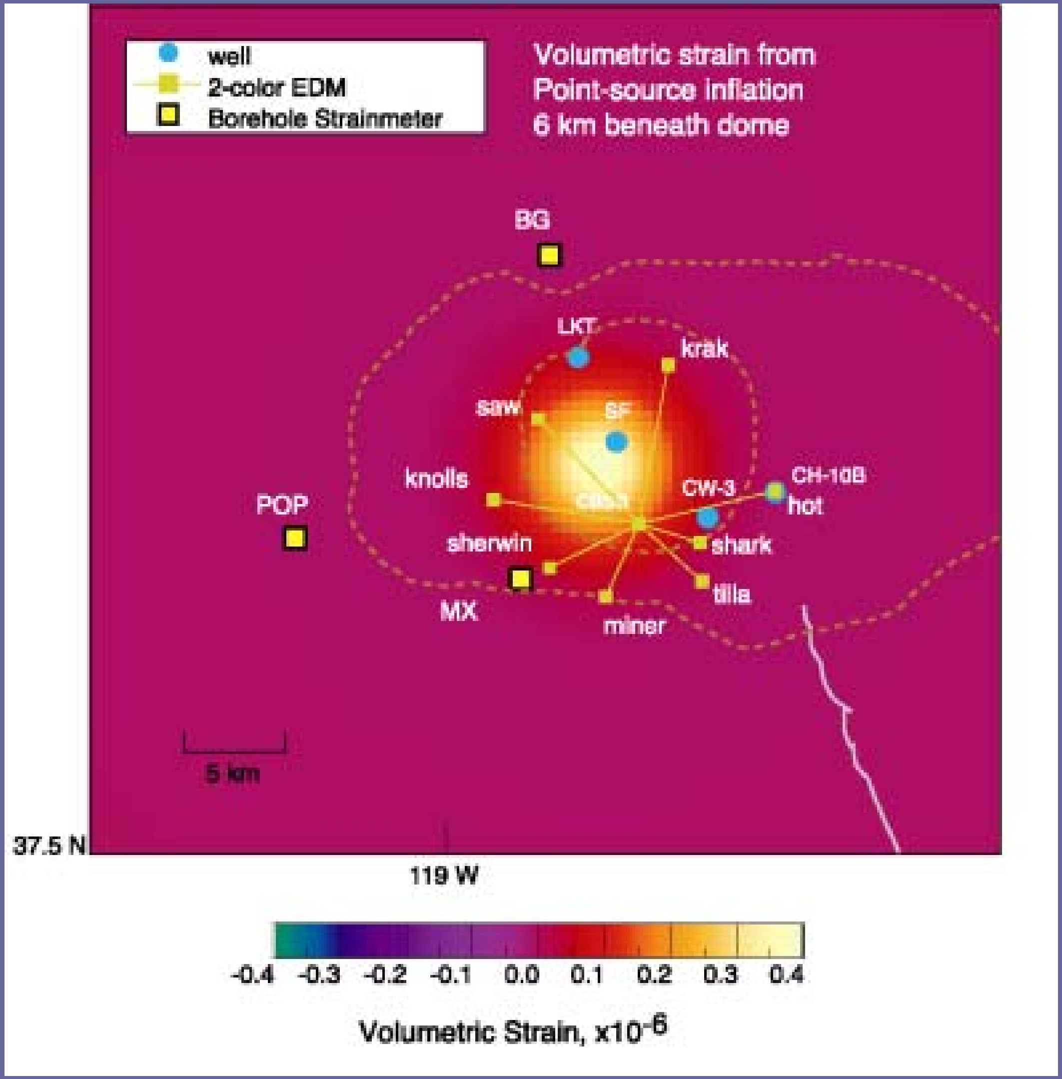
- M4.6-4.9 events with large dilatational components and long duration P-waveforms (*Dreger et al.* [2000])
- Upward-propagating swarm that includes spasmodic bursts (*S. Prejean* [2002])





Hypothesis: Diffusion of pressure drop from dome inflation

- ◆Assume dome extends “intantaneously” by amount below threshold of 2-color EDM network (1 mm)
- ◆Multiply strain from dome inflation by strain sensitivity to get undrained pore pressure change
- ◆Use 2-D finite element model to simulate pressure diffusion as function of time

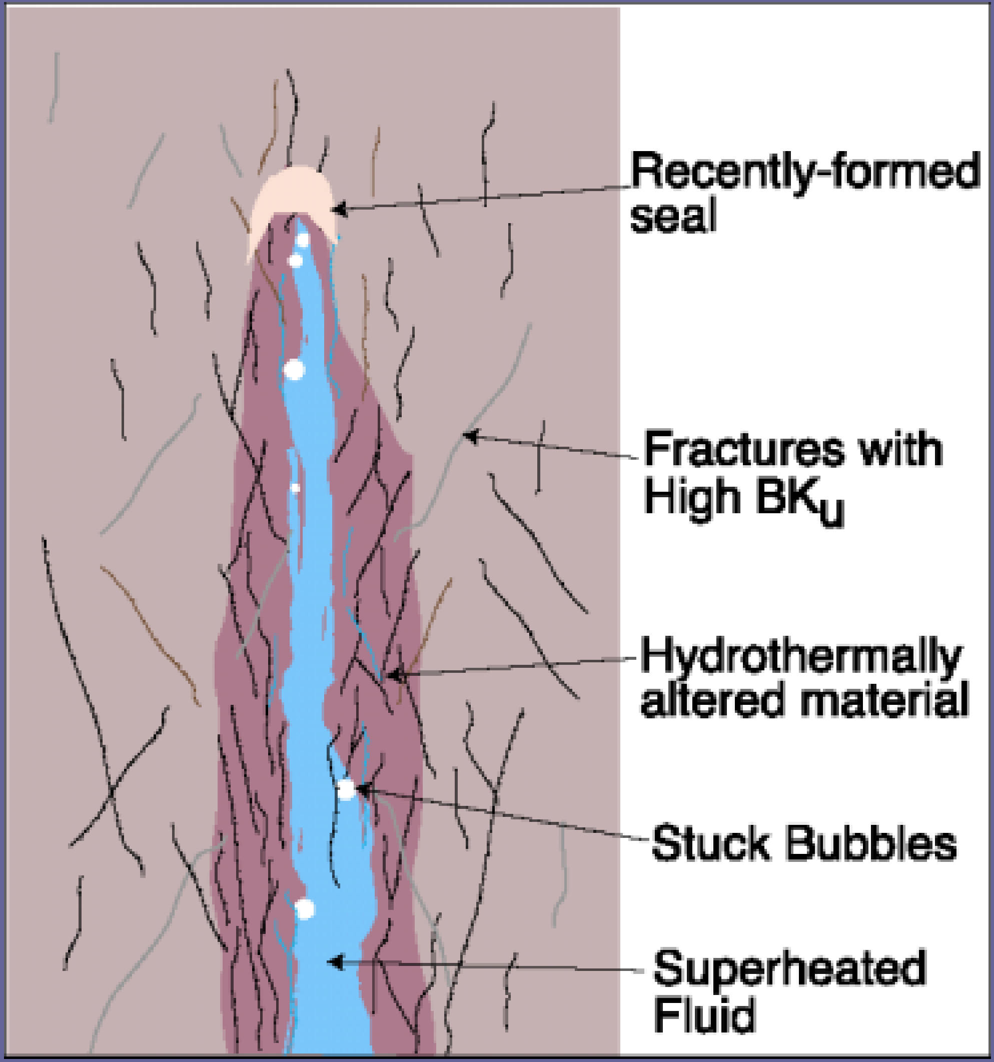


Water-level Rise in thermal well CW-3: Evidence for thermal pressurization

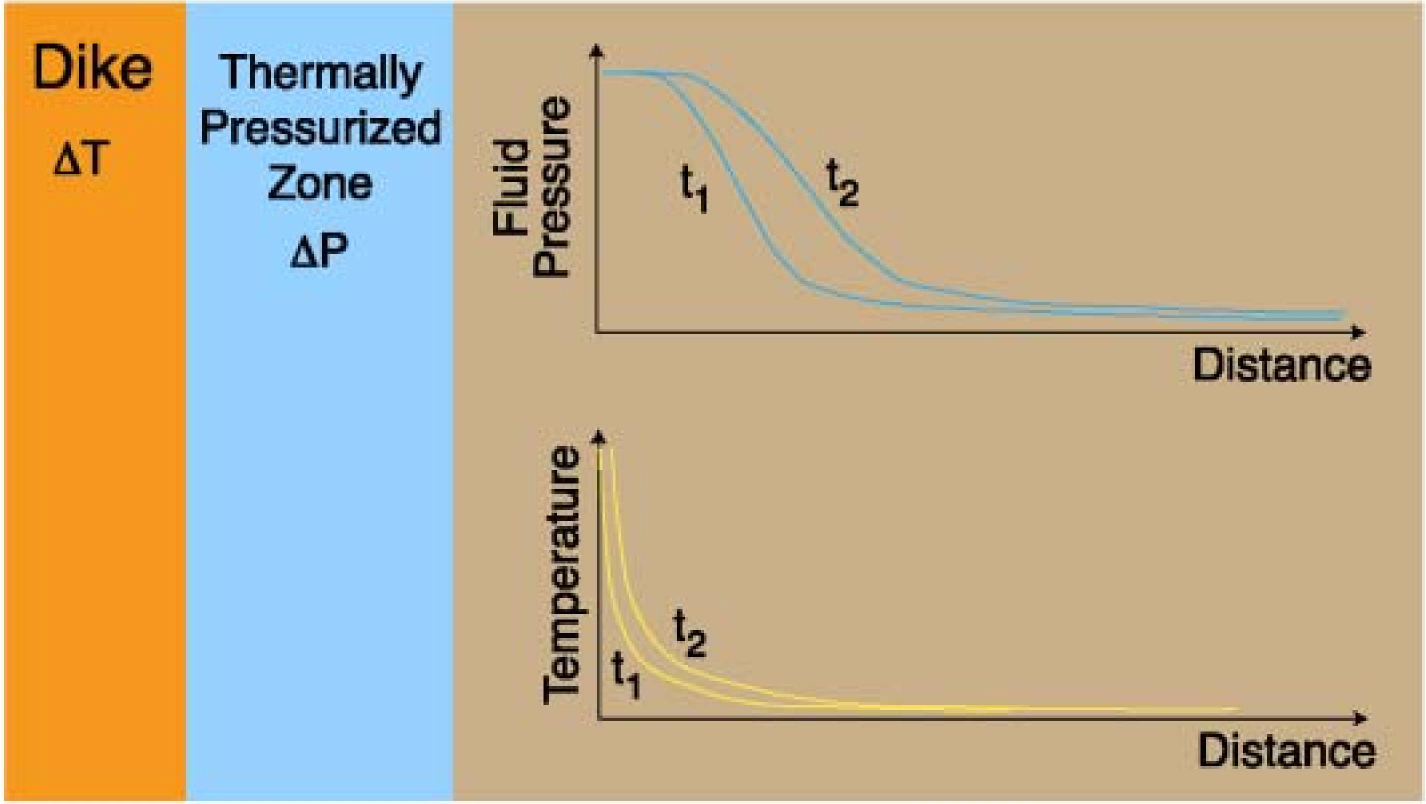
- CW-3 strain sensitivity (25 cm/10^{-6}) -> $2x10^{-6}$ contraction required for 40 cm water-level rise, which is too large
- CW-3 is on a geodetic line that is extending
- No known seismically active structurewould produce contraction at CW-3
- Consider increased pressure in hours after earthquakes somewhere in thermal aquifer
- Increased pressure could be accompanied by up to 5 cm of opening-mode displacement on seismically active planes without violating geodetic data

How seismic waves could affect hot fluids in subsurface fractures

- Relative motion between bubbles and liquids -> bubbles can rise and pressurize
- Local flow between fractures and intact rock could loosen weak material or clear fractures
- Steam flashing during rarefaction does not reverse during compression



Thermal Pressurization



For hydraulic diffusivity 0.01 -> 20 m^2/s:

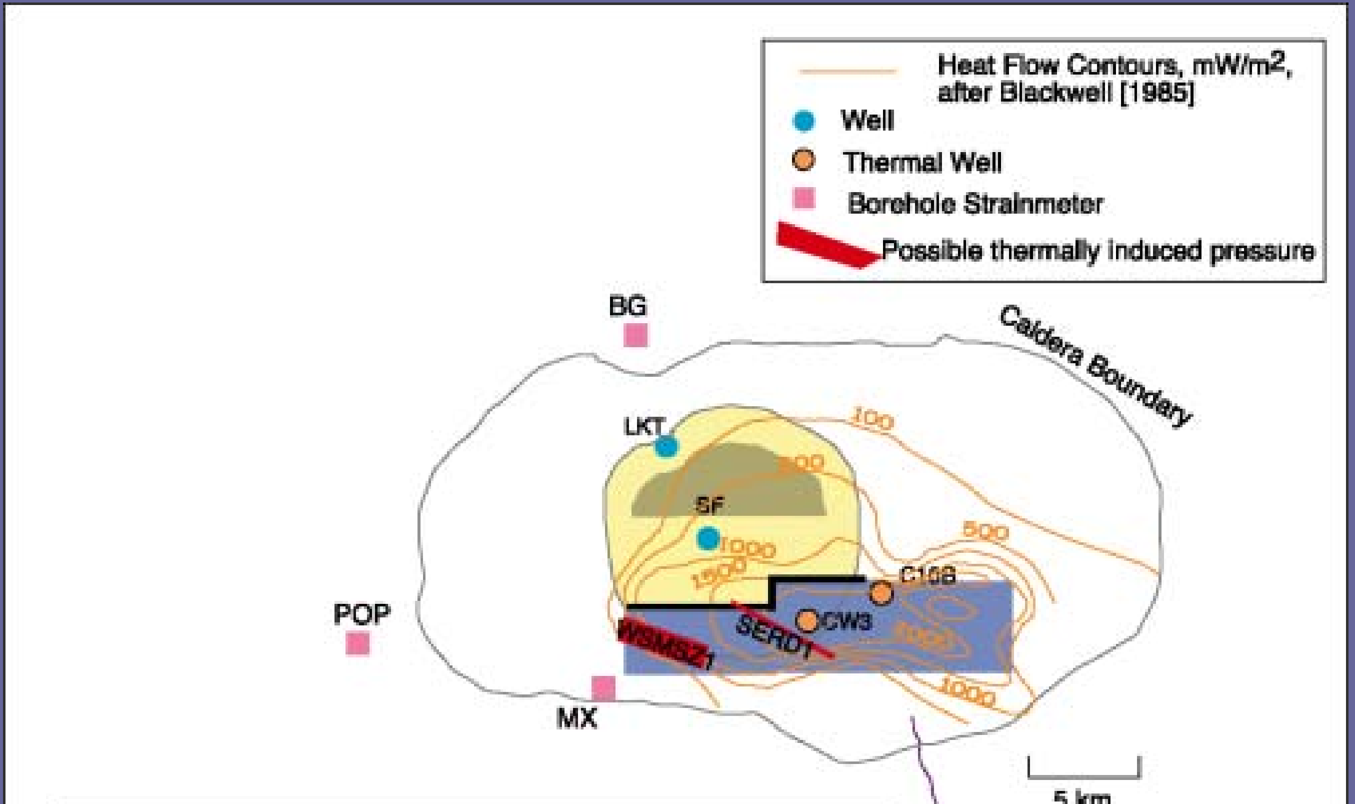
$\Delta p > 9\text{-}11$ m H_2O if $\Delta T > 400^{o}C$

$\Delta p > 6$ m H_2O if $\Delta T = 300^{o}C$

Δp apx 3 m H_2O if $\Delta T = 150^{o}C$

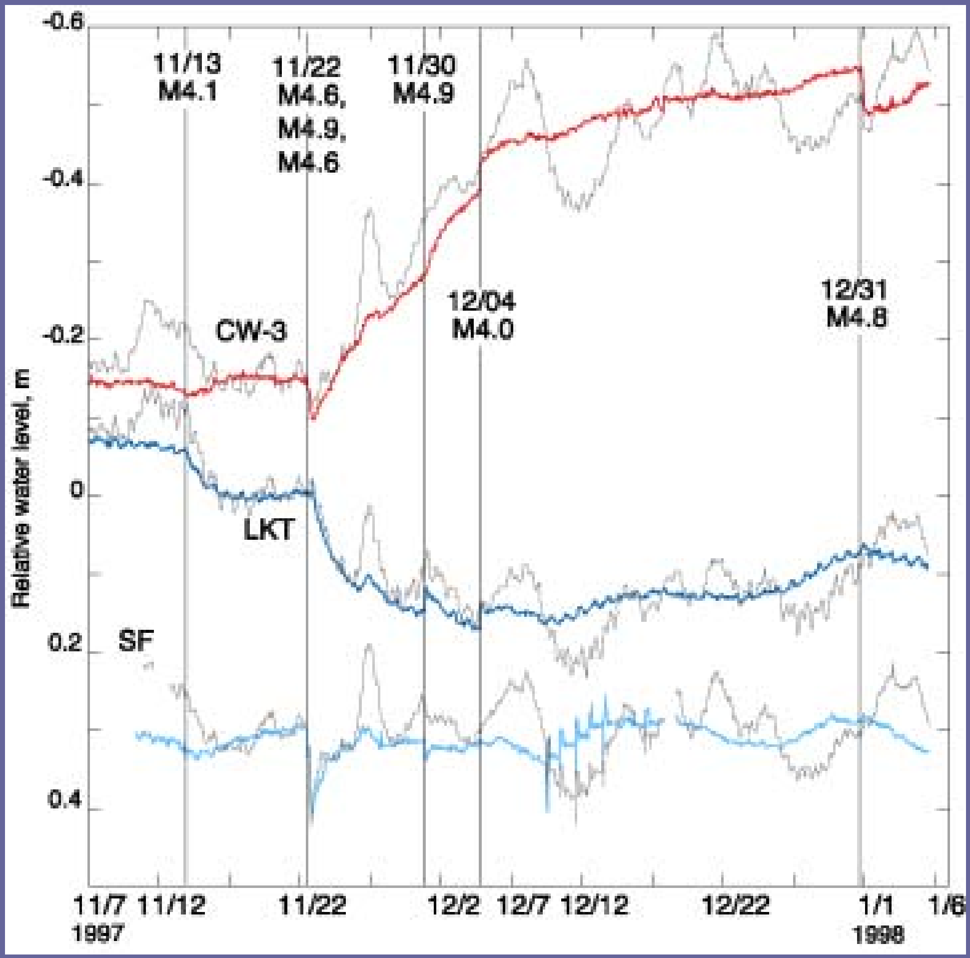
based on analysis by Delaney[1982]

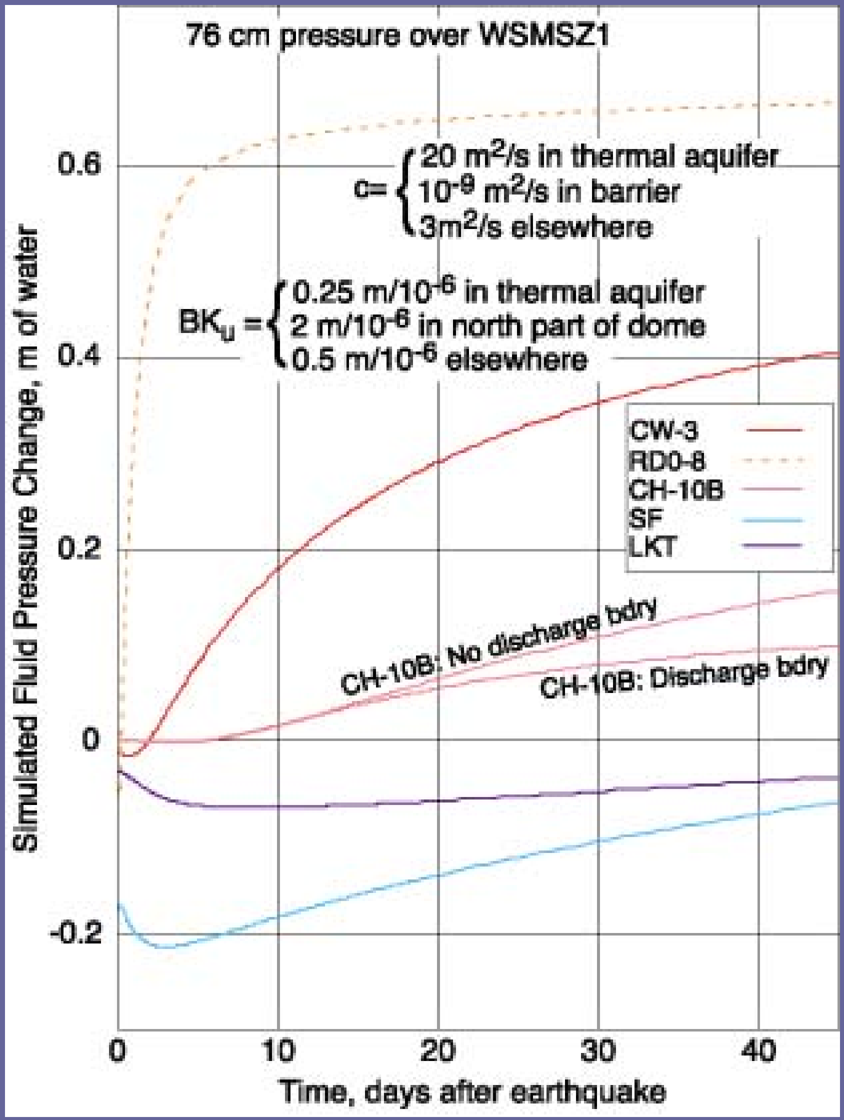
Possible locations of thermally induced pressure



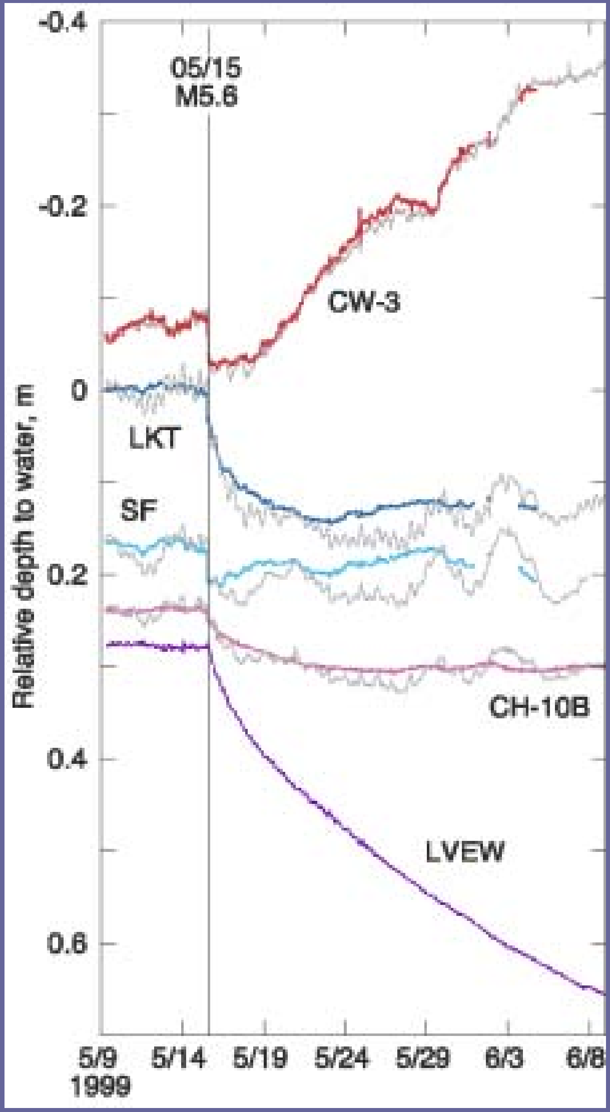
	Hydraulic Diffusivity m^2/s	B K_u m $H_2O/10^{-6}$
Impermeable Boundary	10^{-9}	0.5
Thermal Aquifer	0.1 - 20	0.25
Resurgent Dome	3	0.5
North Part Resurgent Dome	3	0.5-2.0
Elsewhere	3	0.5

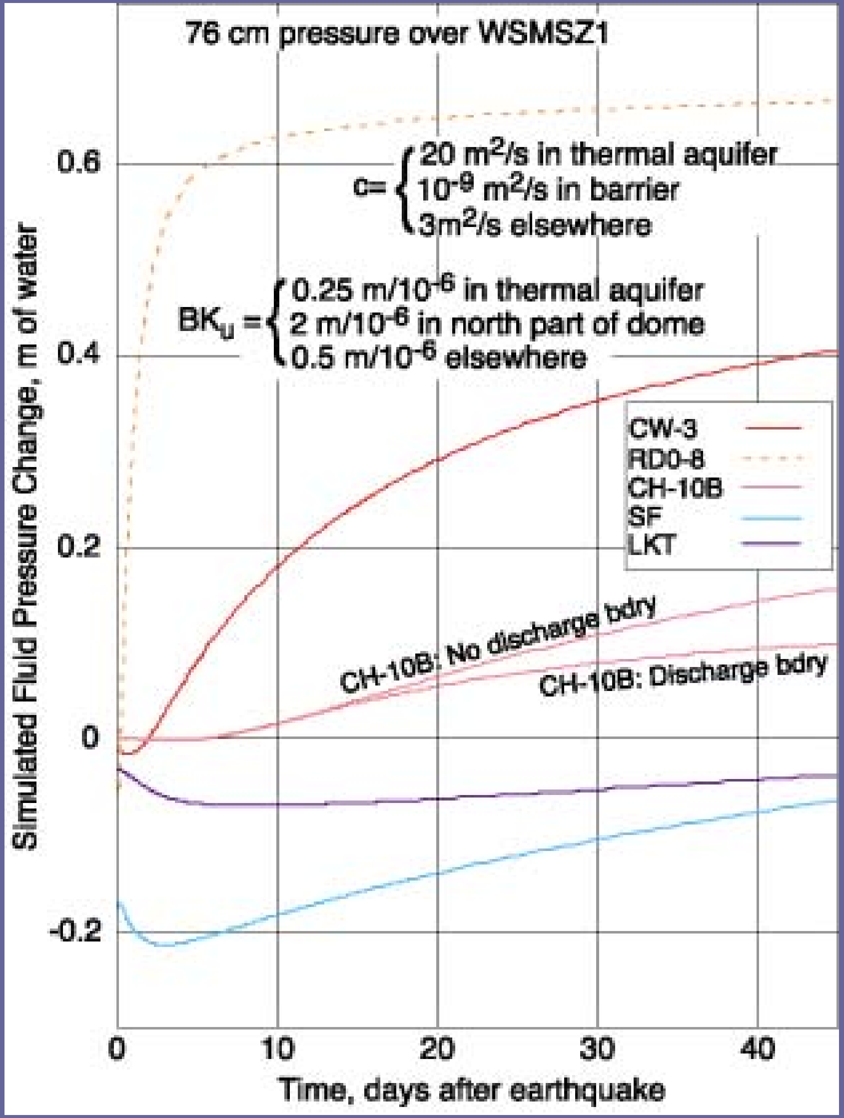
Thermal pressure in West South Moat





May 1999: Diffusive Delay Observed?





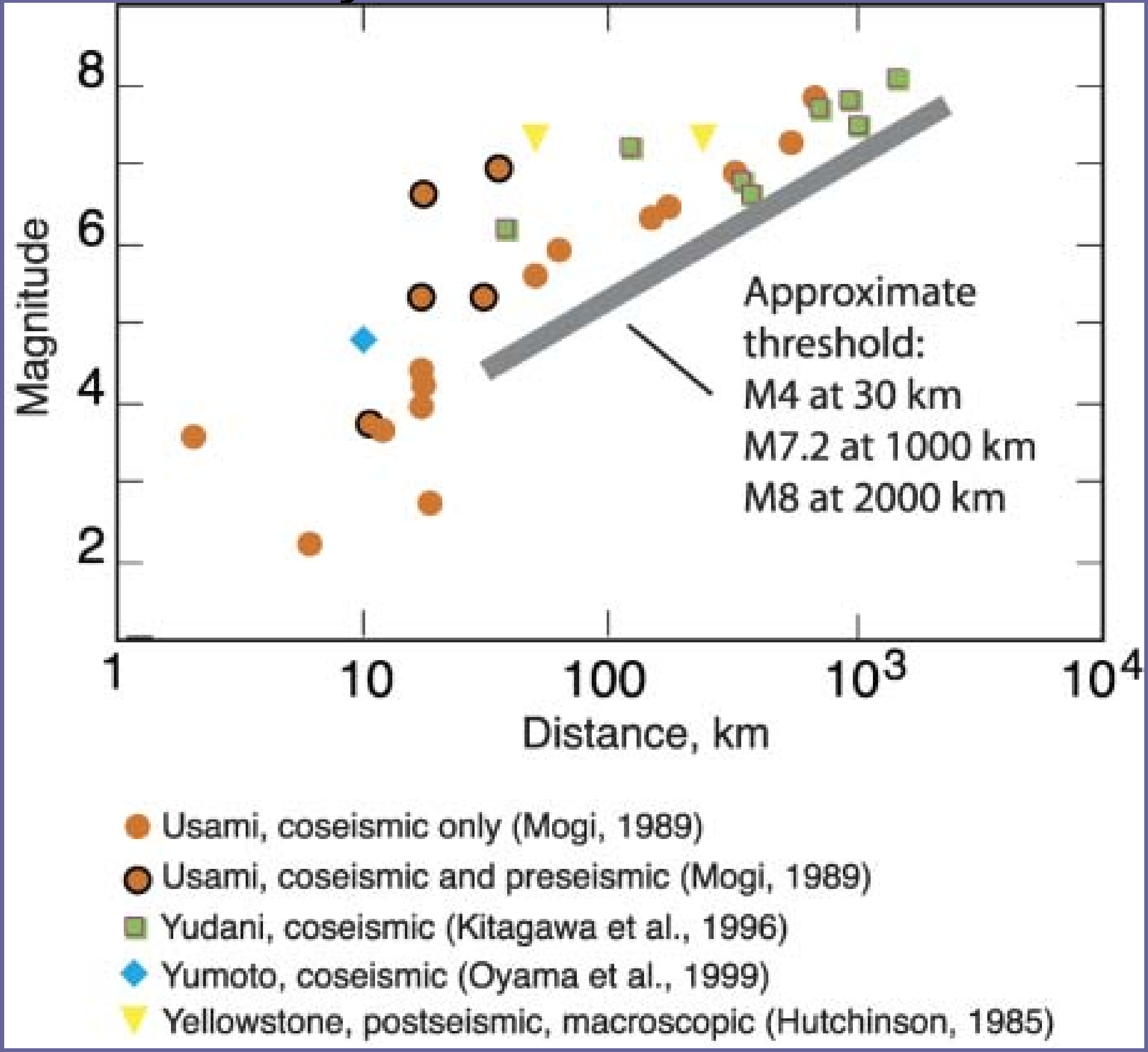
Seismic waves increase pressure/discharge or temperature at many hydrothermal locations, as far as 100’s of km from the epicenter

- Increased pressure or discharge could arise from thermal pressurization
- Changes in temperature may indicate increased vertical permeability, especially when accompanied by chemical or isotopic changes
- Seismic-wave induced temperature changes at seafloor hydrothermal vents imply upward flow over distances of several km in just a few days

Earthquake-induced temperature increases at seafloor hydrothermal vents

Location of Seismic Activity	Date of Seismic Activity	Seismic Events	Temperature Sensor location	Distance from seismicity to sensor, km	Time from seismic activity to temperature rise	Average Temperature	Temperature Rise, C	Rise time	Other	Reference
East Pacific Rise	March 22, 1995	Swarm:162 events in 3 hours	Bio9	1	4 days	365°C	+7°C	7 days	Chloride and silica increased	Sohn et al., Nature, 1998
Cobb Offset, Juan de Fuca Ridge	March 1, 1997	Swarm: 75 events; second sequence 70 km north, 5 days later	Easter Island	35-55	3-8 days	5°C	+7°C	>6 months		Johnson et al., EOS, 2001
"	"	"	Smoke and Mirrors	35-55	36 days	2°C	+8 to +13 °C	40 days	Observed at 3 separate sensors	Johnson et al., EOS, 2001
Endeavour segment, Juan de Fuca Ridge	June 8, 1999	M4.5 followed by 2687 more events	Clam Bed	<10	11 days	2°C	+10°C	Apx 30 days	Temperature oscillations in next two months	Johnson et al., Nature, 2000
"	"	"	Easter Island	<10	4 ± 1 days	2°C	+10°C	Apx 30 days	Temperature oscillations in next two months	ohnson et al., Nature, 2000
"	"	"	Axial Seamount	220	8 hours	40°C	+5°C	1 day	Discharge increased 50% at same time	Johnson et al., EOS, 2001

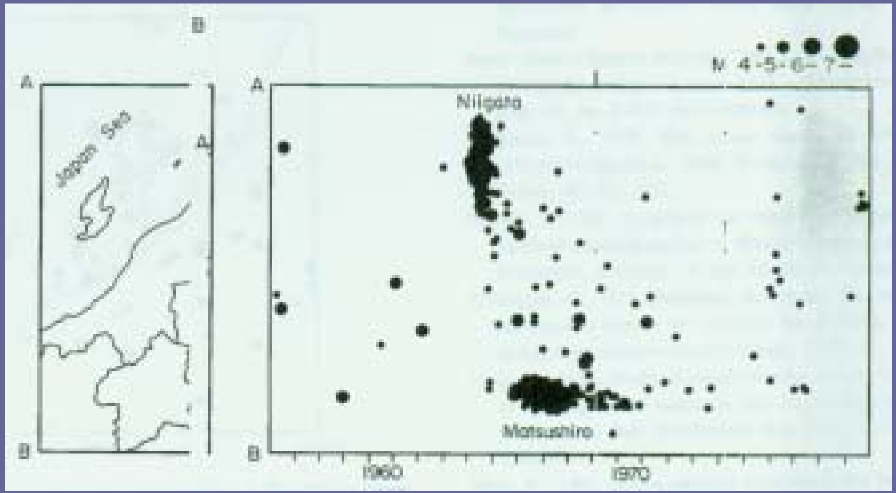
Earthquake-induced temperature changes in hydrothermal areas

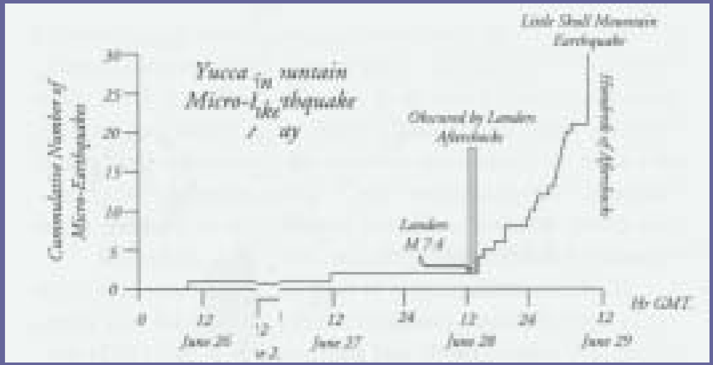


Possible examples: Earthquakes triggered by effect of seismic waves on hydrothermal systems

Seismic Event	Date	Possible Triggered Seismic Activity	Date	Distance, km	Evidence for triggering	Evidence for hydrothermal involvement in triggered activity
Niigata, Japan M7.5	June 16, 1964	Matsushiro Swarm, maximum magnitude 5.4, total energy equivalent M6.3	August 1965-Oct 1967	250	Migration of epicenters from Niigata towards Matsushiro	Swarm Character; Fluid outflow, uplift
Morgan Hill, California M6.2	April 24, 1984	Mount Lewis, California, M5.7	March 31, 1986	18	Microearthquakes near Mt. Lewis epicenter 8 days after Morgan Hill earthquake	Swarm-type foreshocks in September, 1985 and March, 1986
Landers, California M7.3	June 28, 1992	Little Skull Mountain, Nevada M5.6-5.8	June 29, 1992	280	Microearthquakes in Little Skull Mountain source region during coda of Landers seismic waves	

Matsushiro and Little Skull Mtn: Evidence for triggering

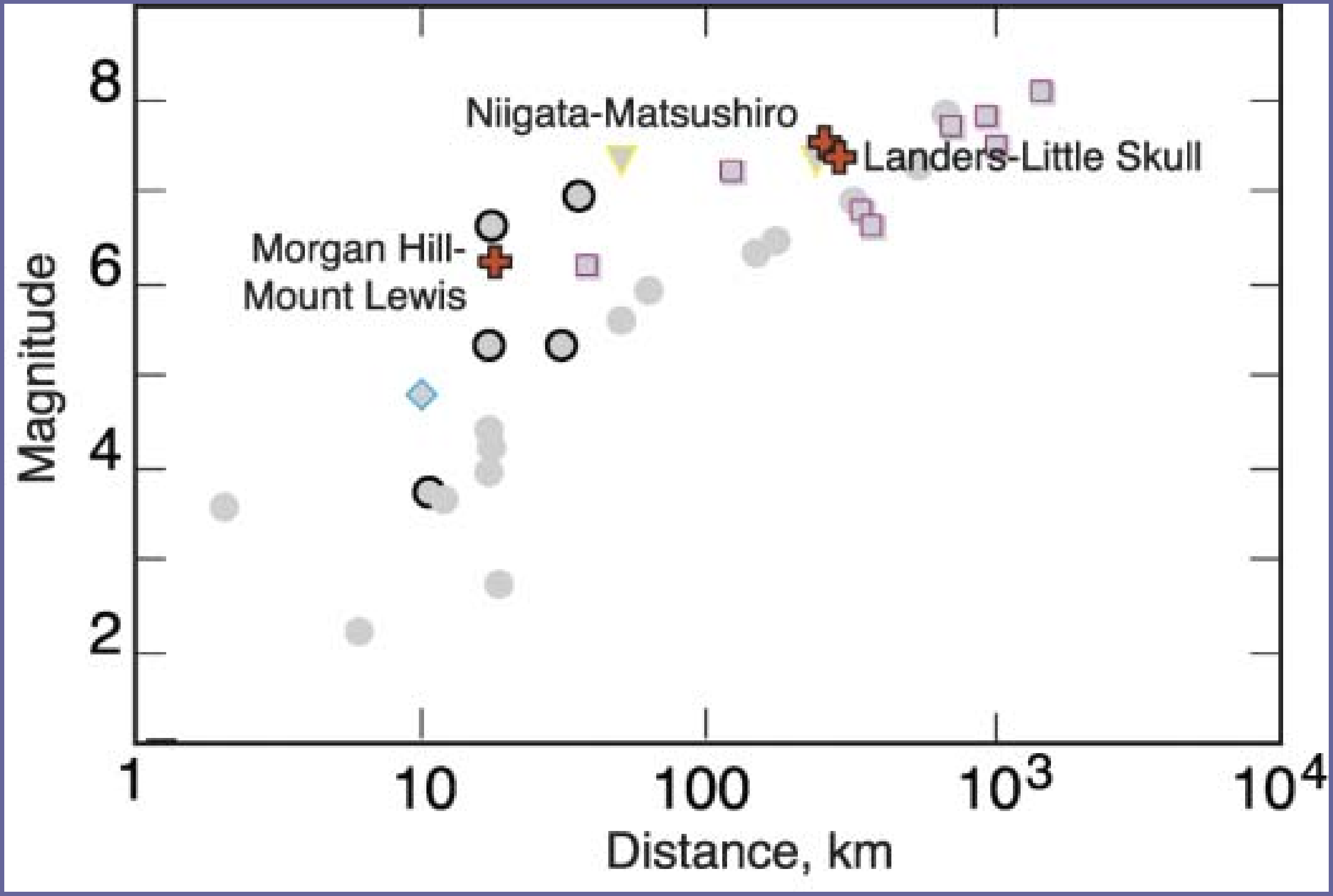




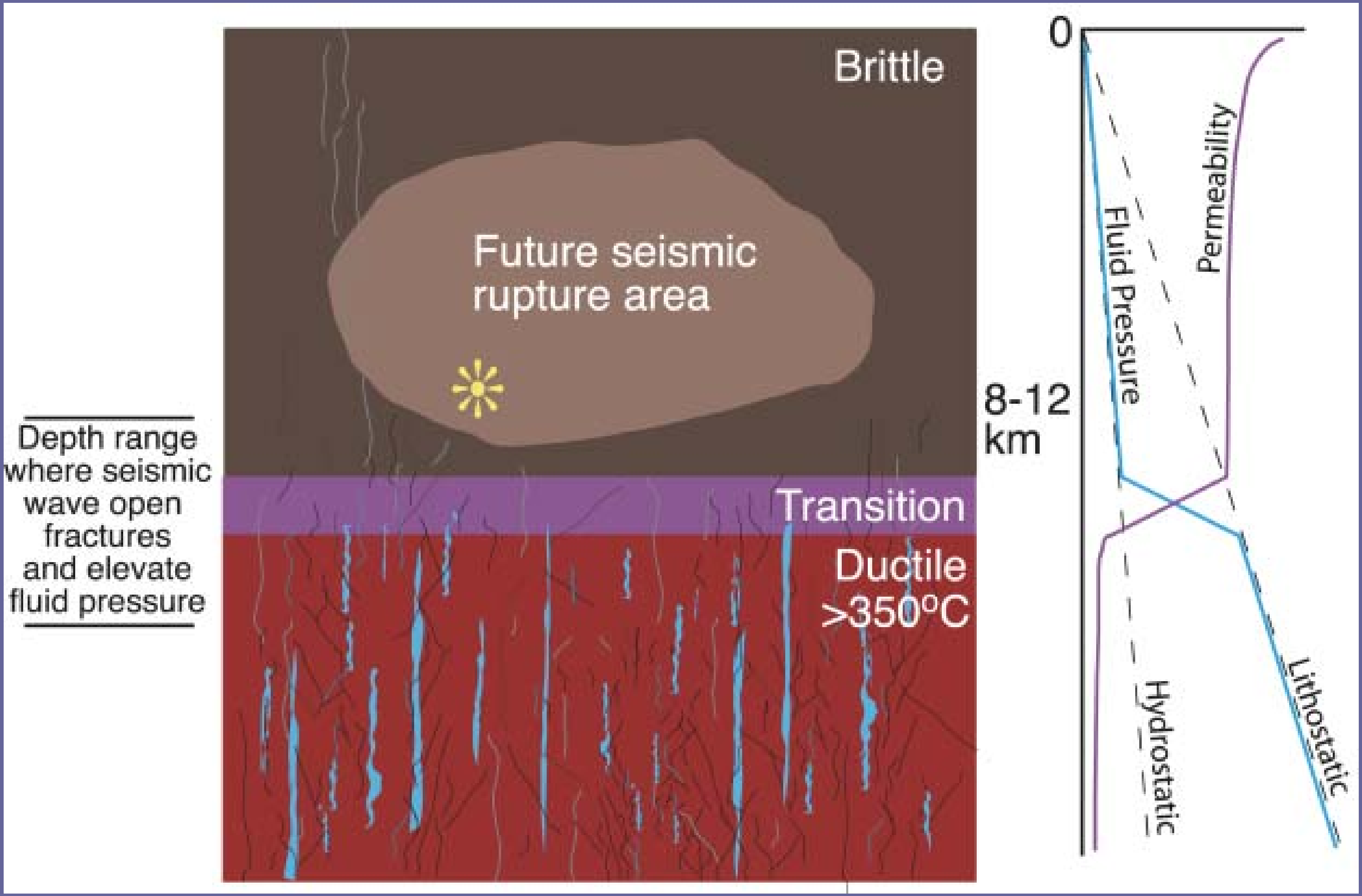
• Seismicity following the Niigata earthquake migrated toward the Matsushiro area during two years (Mogi, 1989)

• Microseismicity near Little Skull Mountain began immediately after the Landers earthquake (Smith et al., 2001)

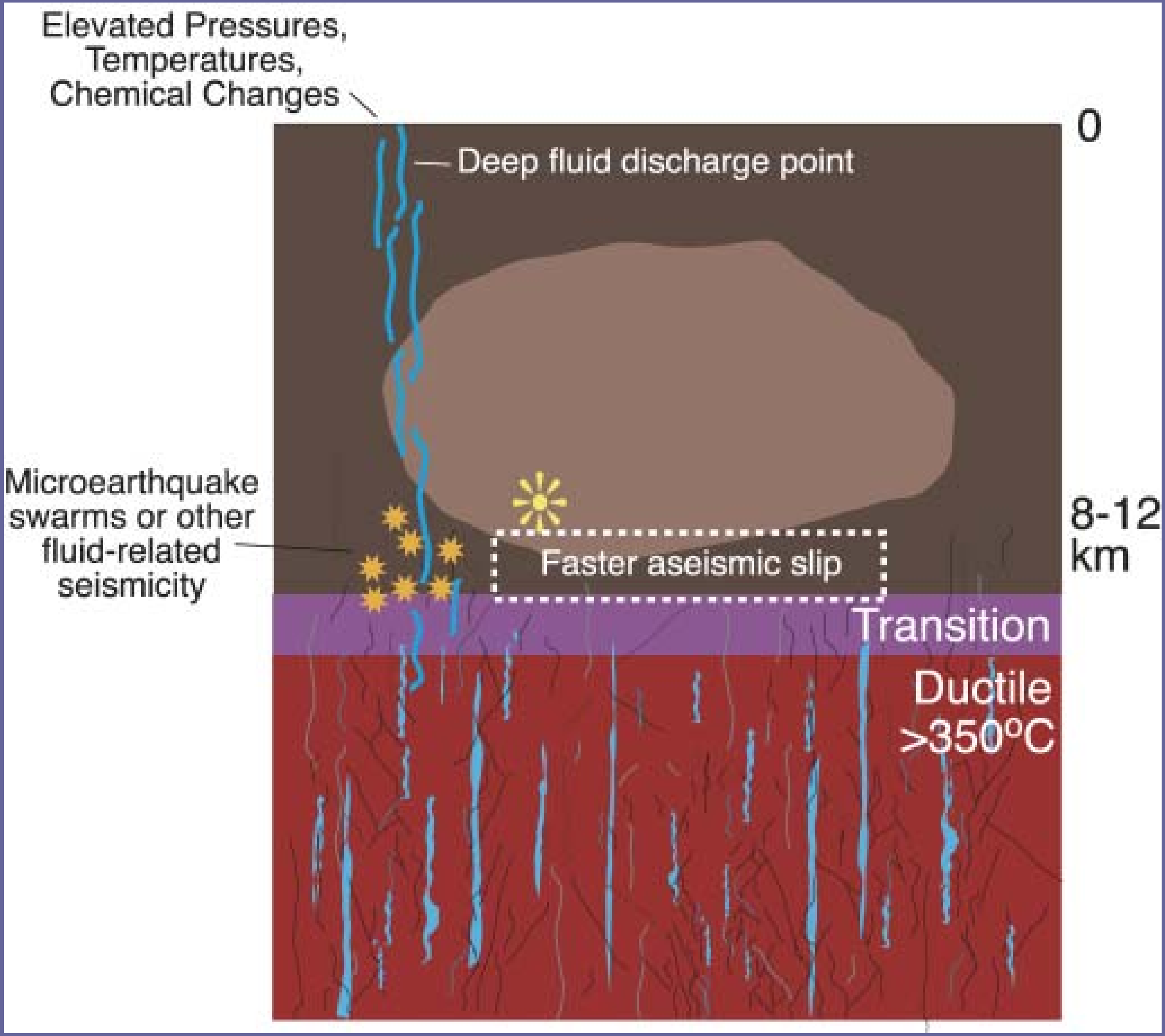
Earthquake triggering distances compared to distances for influence of seismic waves on hydrothermal systems



Seismic waves could affect fluid pressure at base of seismogenic crust



Types of precursors



Conclusions

- Seismic waves tend to increase fluid pressure/discharge or temperature in many hydrothermal settings, 100's of km from the epicenter
- Hydrothermal conditions exist at the base of the seismogenic zone for crustal earthquakes, probably with low effective confining pressure
- Seismic waves can probably affect fluid pressure or permeability at the base of the seismogenic crust, possibly leading to delayed triggering of earthquakes
- These effects on deep, hot, fluids might be detectable as seismic swarms, geodetic rate changes, or changes in fluid pressure, temperature, or chemistry
- Deep, hot boreholes or springs where waters of deep origin discharge would be the best hydrologic observation points