Transient Deformation Signals Related to Hydrology: Examples, Mechanisms, and Significance

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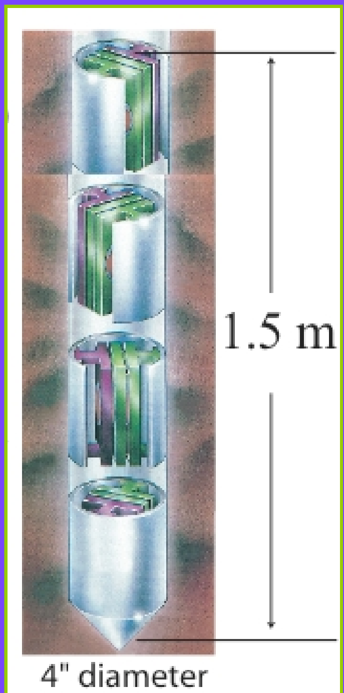
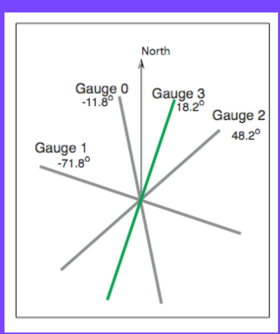
Examples: Based on Borehole Strain, Fault Creep, and Groundwater-Level Data

- **The "Parkfield Transient" - accelerated fault slip, or hydrology?**
  - *Gwyther&Gladwin, Langbein, Nadeau,Gao*
- **Hector Mine earthquake postseismic fluid pressure changes**
  - *Unpublished USGS/USMC study*
- **Strain transients at Long Valley caldera caused by large distant earthquakes**
  - *Many published studies*

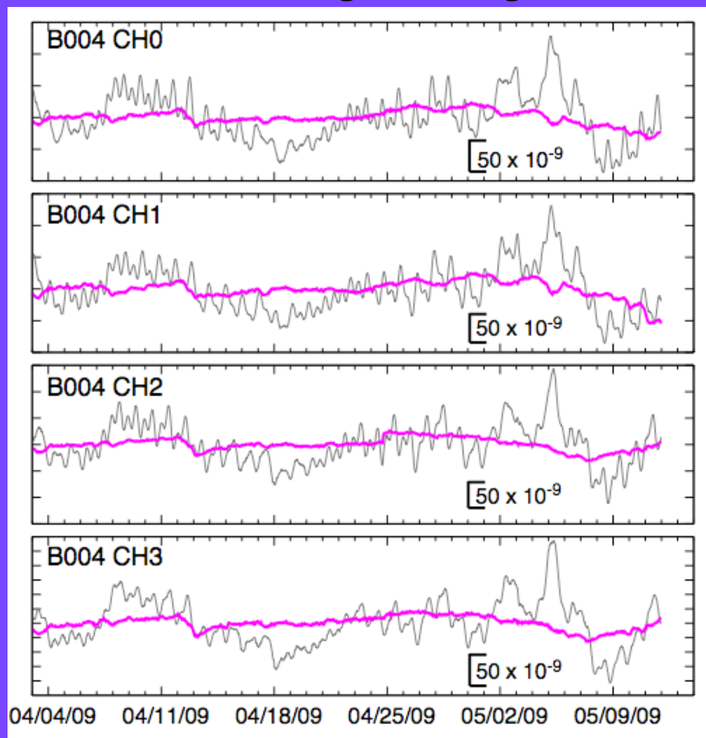
Borehole Strainmeters - PBO example



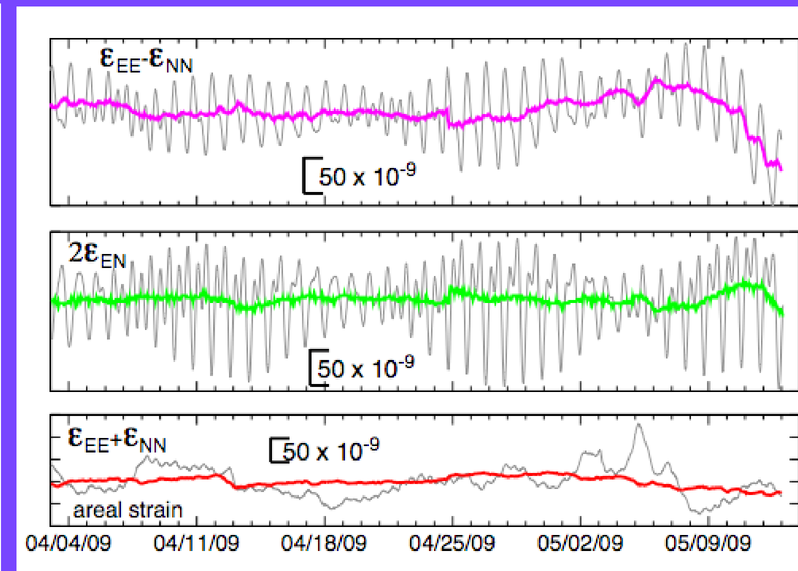


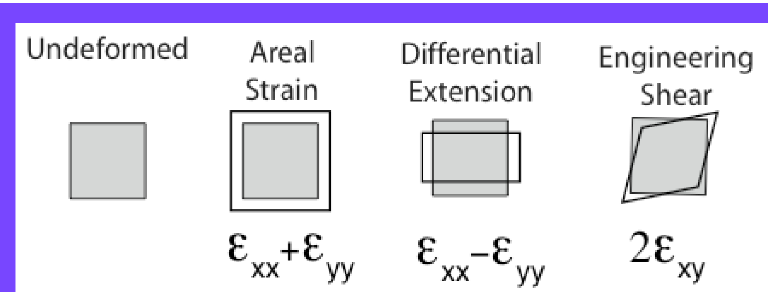
Example: B004, Olympic Peninsula

Individual Gauge Elongations

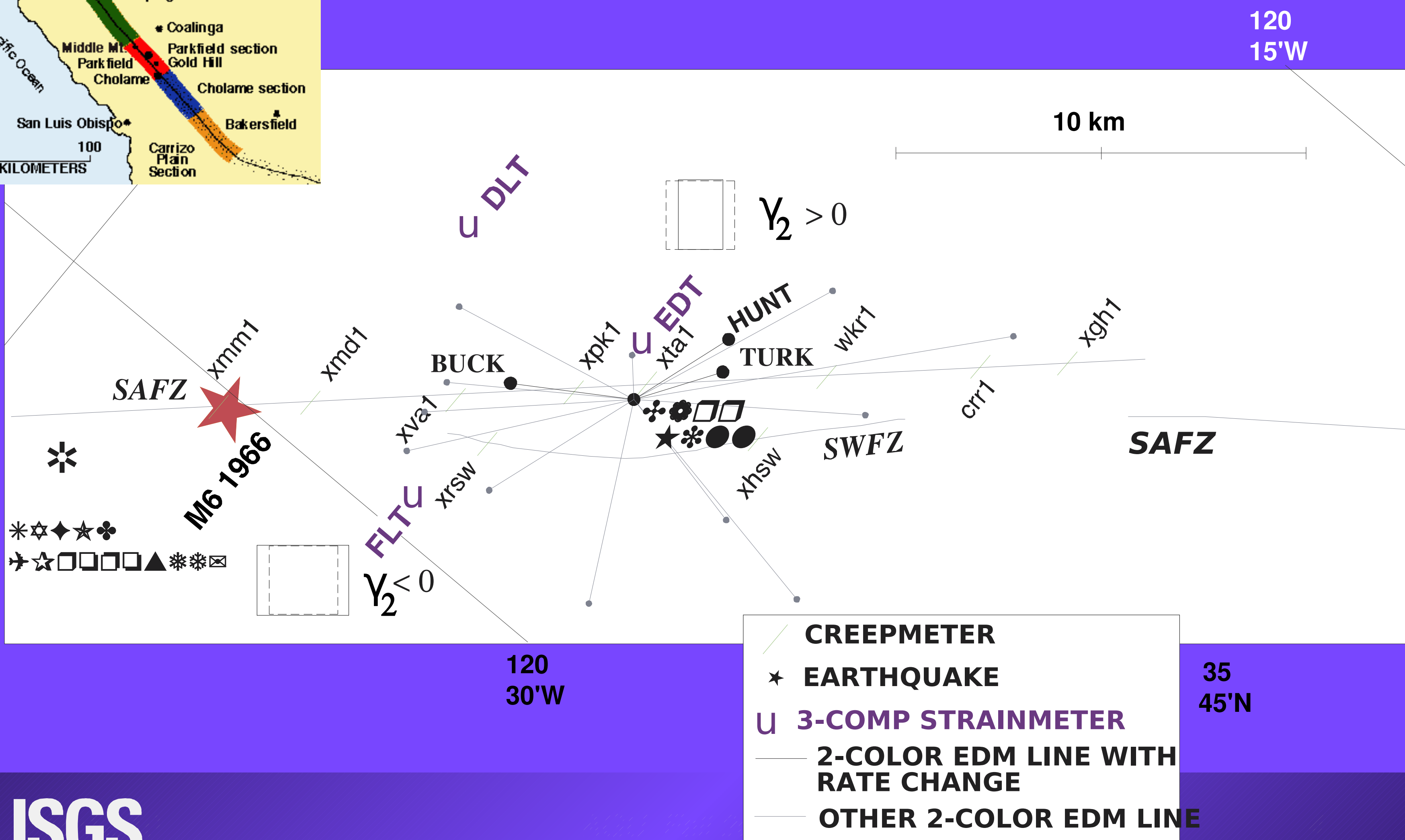


Instrument Strains, E-N coordinates

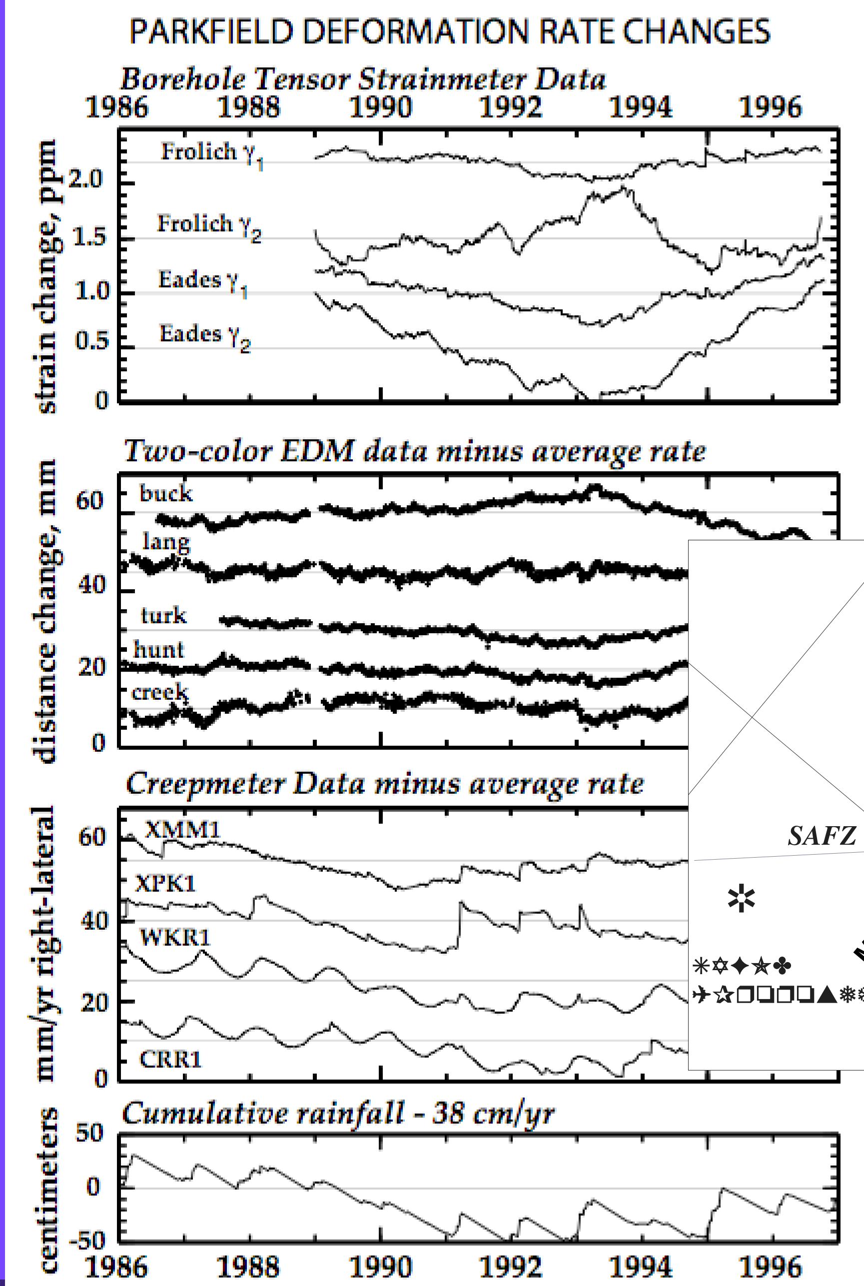


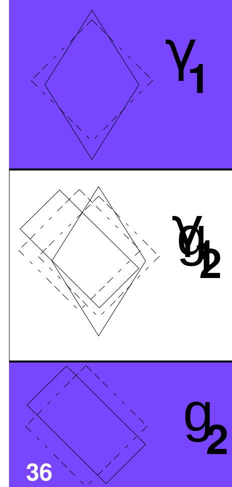


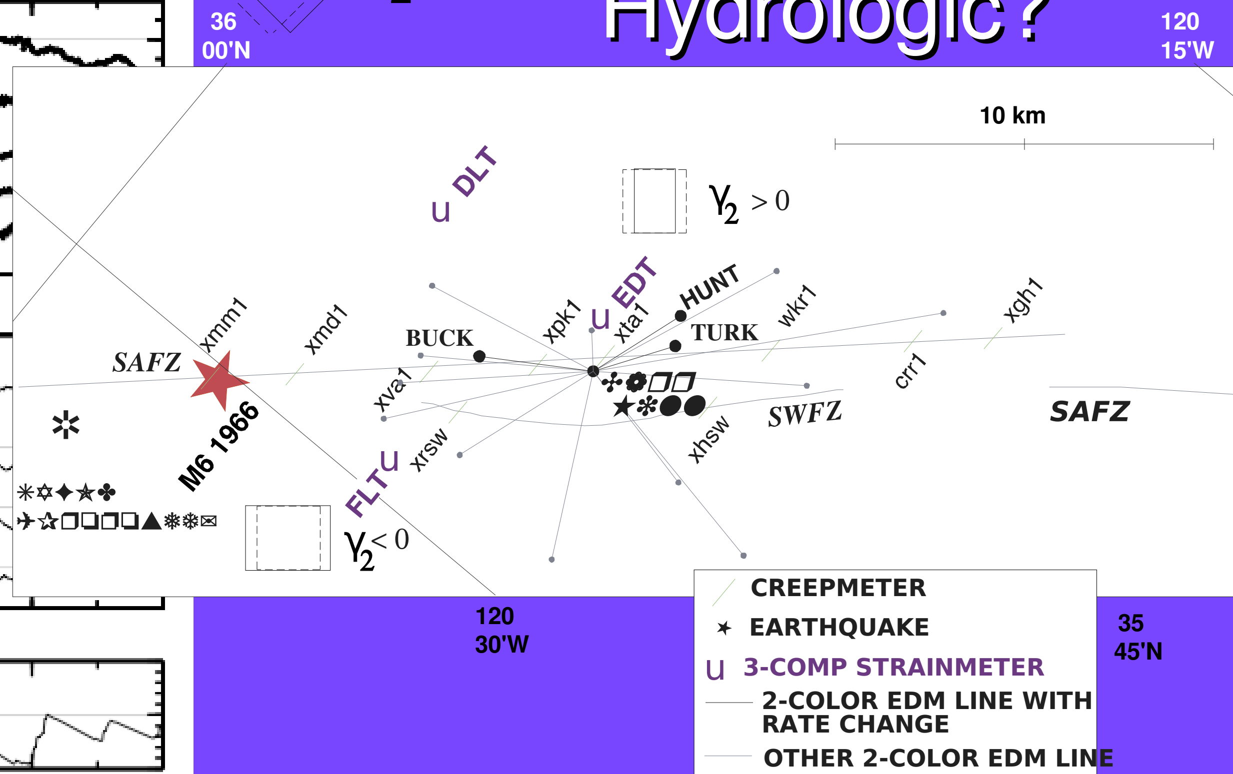
Parkfield: Slip-rate Change or Fluid Pressure Change?



The "Parkfield Transient": Real Slip-rate Change, or Hydrologic?







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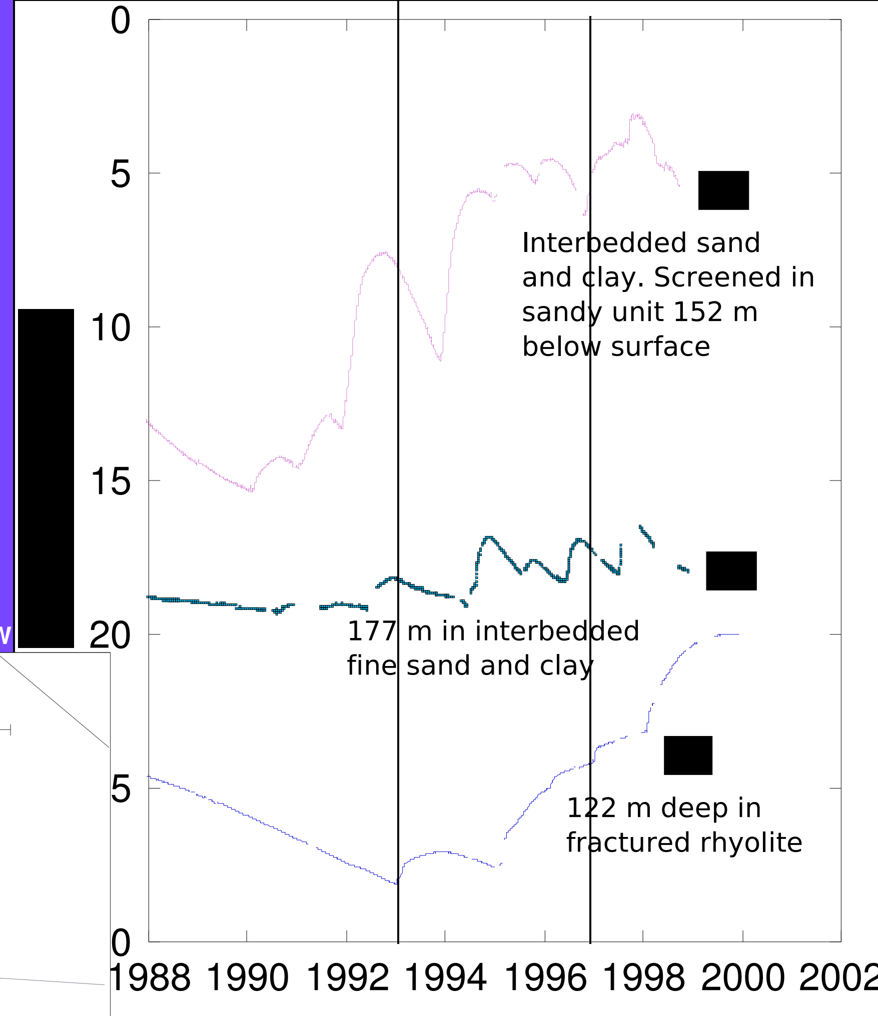
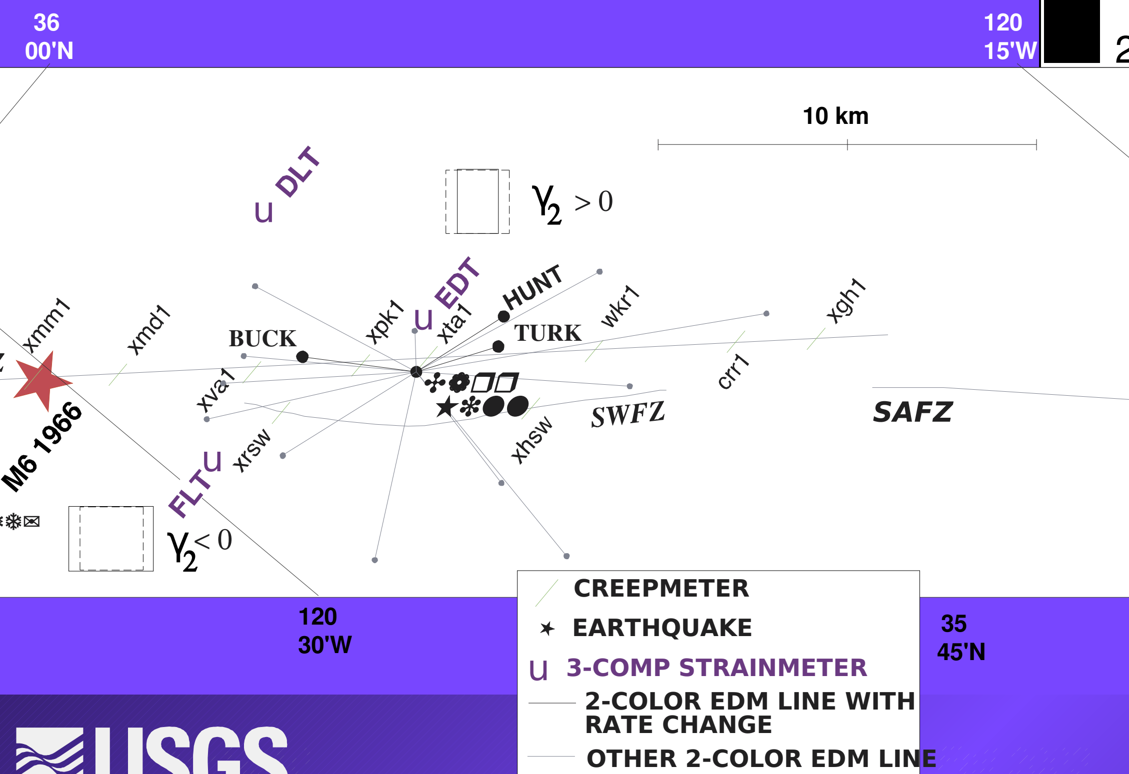
Daily water level records exhibit different time histories in different wells





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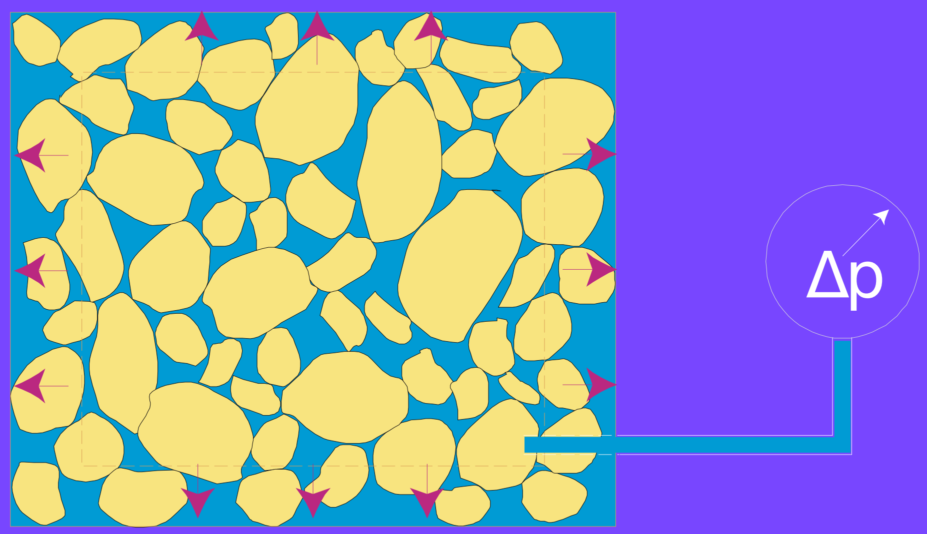
Poroelasticity: Fluid Pressure Changes can Induce Volumetric Strain

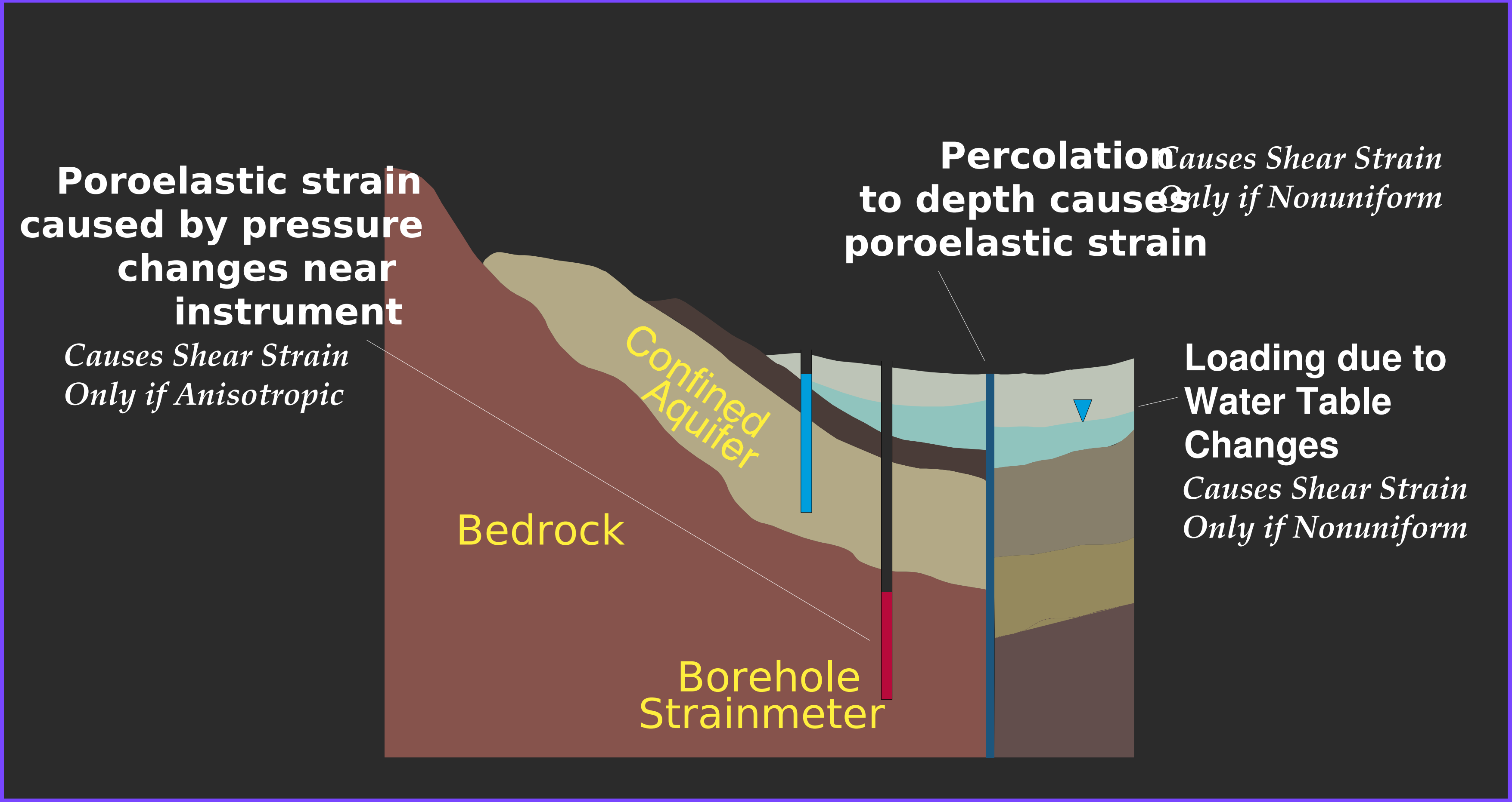
Increasing Fluid Pressure Causes Expansion
Decreasing Fluid Pressure Causes Contraction



$\Delta\pi/\ \Delta\varepsilon_{\kappa\kappa}$ τψπιχαλλ
1–>20 μ/10 $^{-6}$

Constant
Mean Stress

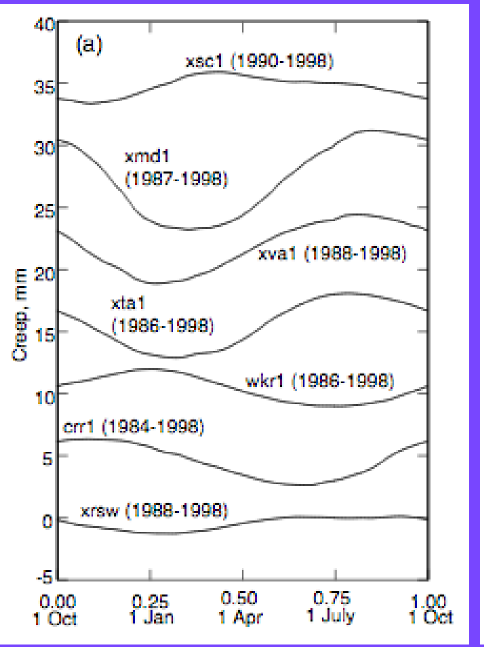
Hydrologic Sources of Strain



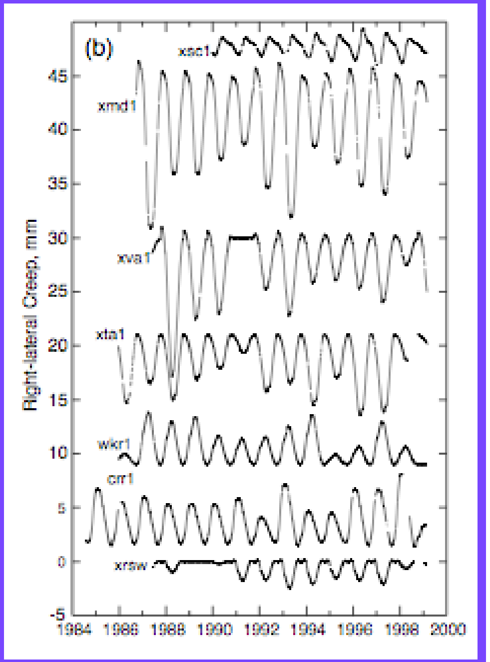
Could Fluid Pressure Cause the Shear Strain-rate Changes?

- Subsurface pressure variations 3 to 12 m H_2O over period of rate change
- Total shear strain change is about 1×10^{-6} in 4 years
- It's reasonable for 1 m fluid pressure change can produce 10^{-6} volumetric strain
- Significant fluid pressure-shear strain coupling would be needed to explain these strain changes

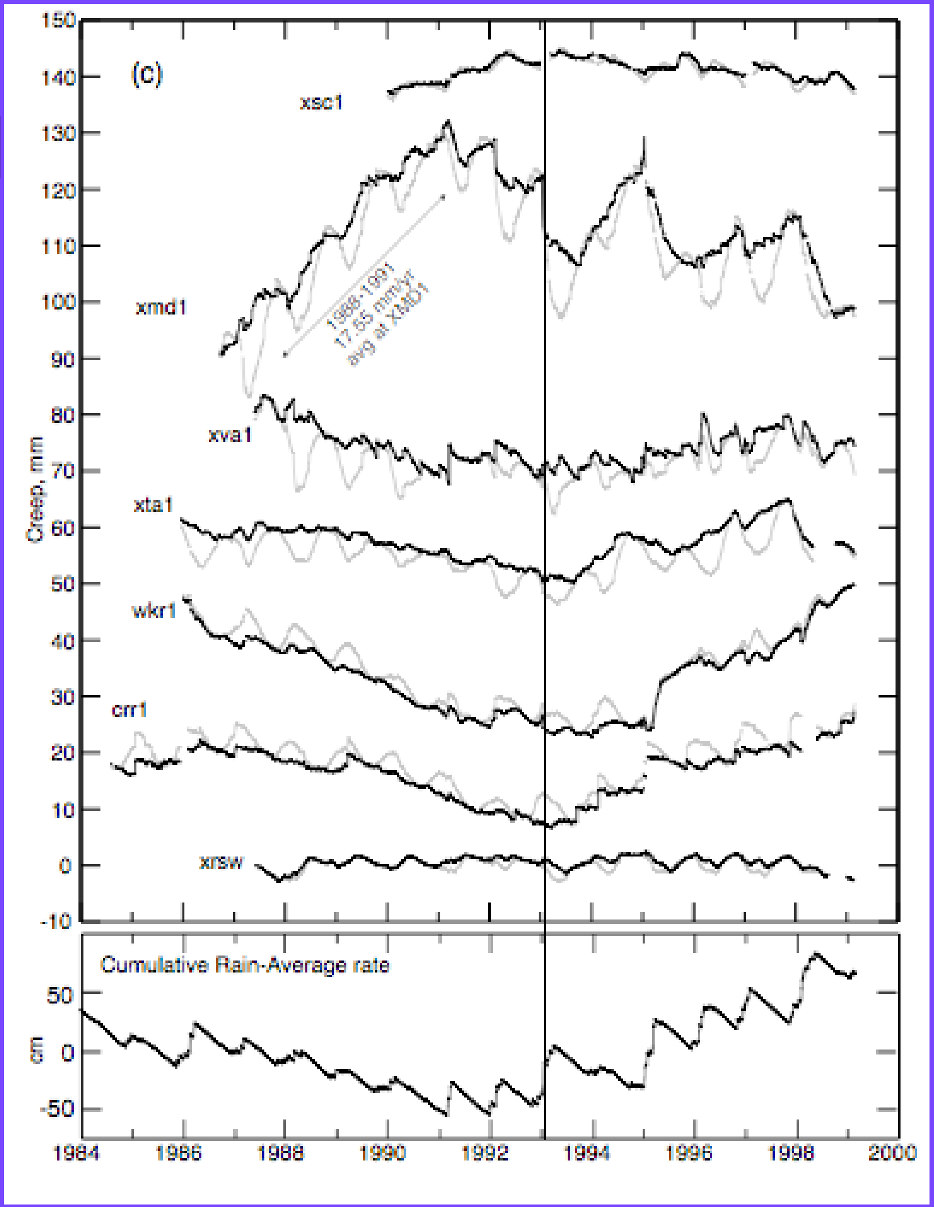
Some creepmeter records can be corrected for seasonal variations

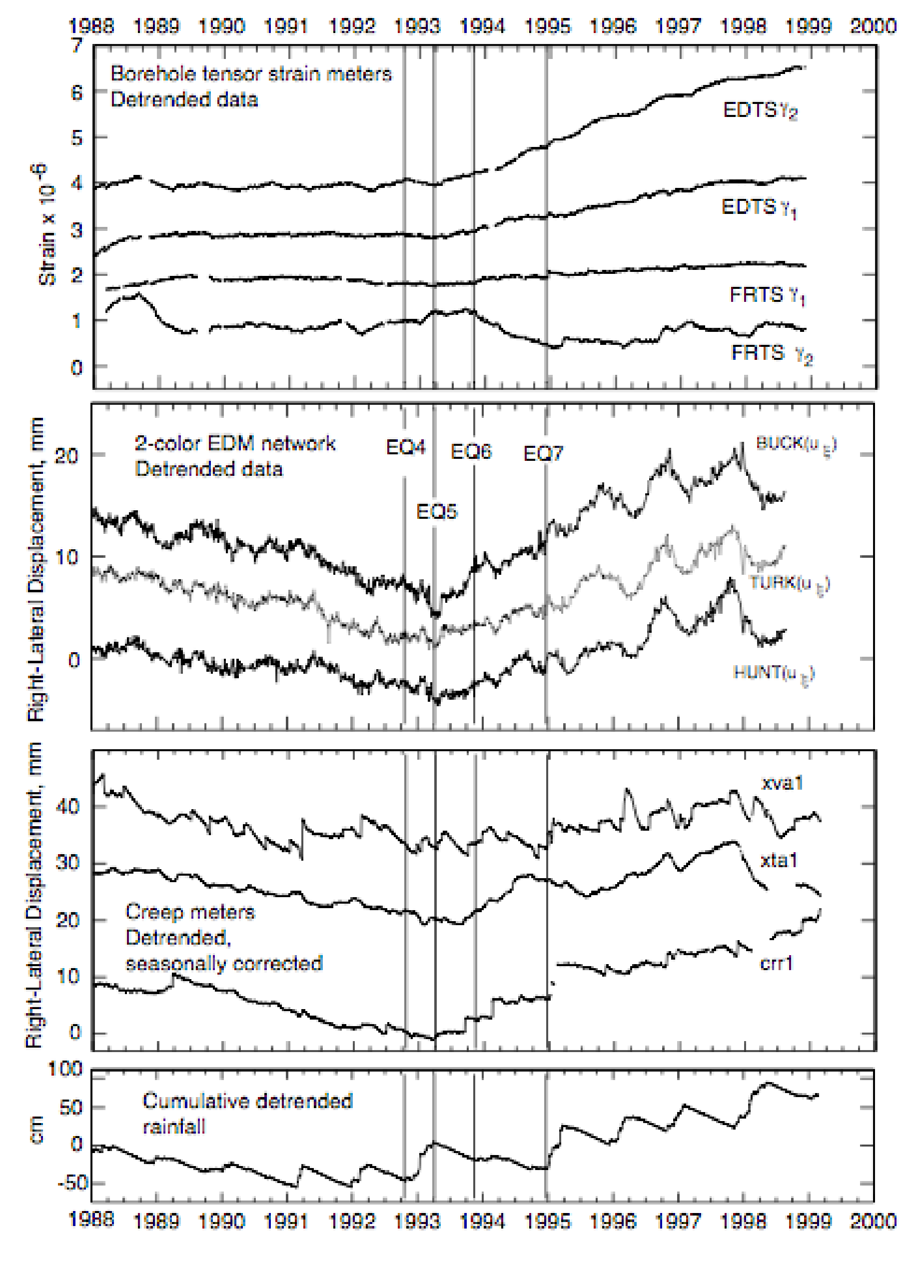


Average annual variation



"Envelope" to adjust for different sizes of annual variations





Corrected data from CRR1 still show slip-rate increase

…but final conclusion that slip-rate really increased was based on shortened time intervals of repeating earthquakes (R. Nadeau and others).

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Creep "surge" criteria are similar to landslide criteria

"Rainfall function" $R(t_k)$

Seasonal approximate ET:

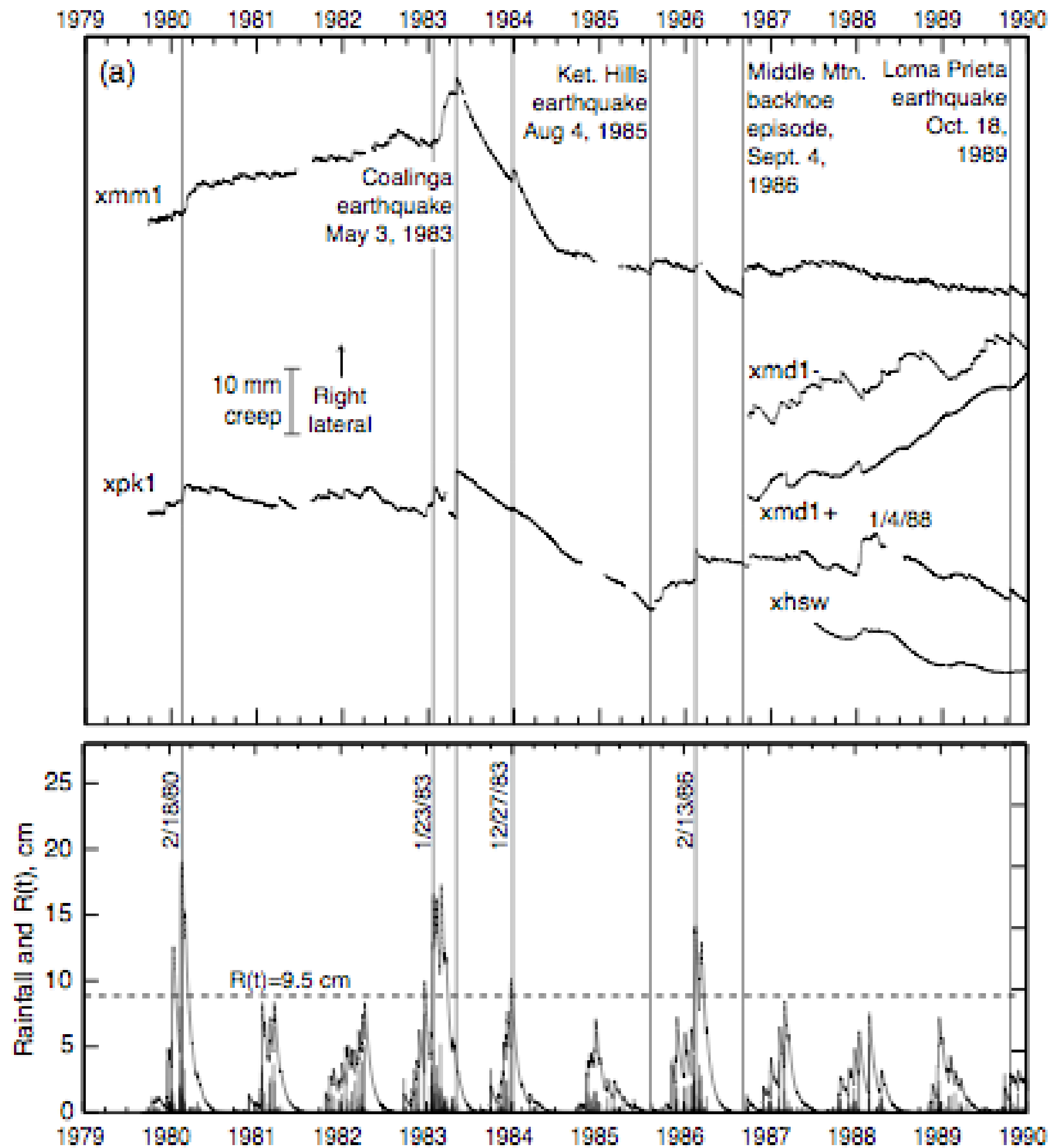
$$e(d_k) = \frac{(1+e_{\min})}{2} + \frac{(1-e_{\min})}{2}\cos\left[\frac{2\pi(d_k - d_{k0})}{366}\right]$$

d_k is the day of the year (1-366)
$e_{\min}$ is the annual minimum ET
d_{k0} is the day with minimum ET

Then account for decay due to subsurface flow:

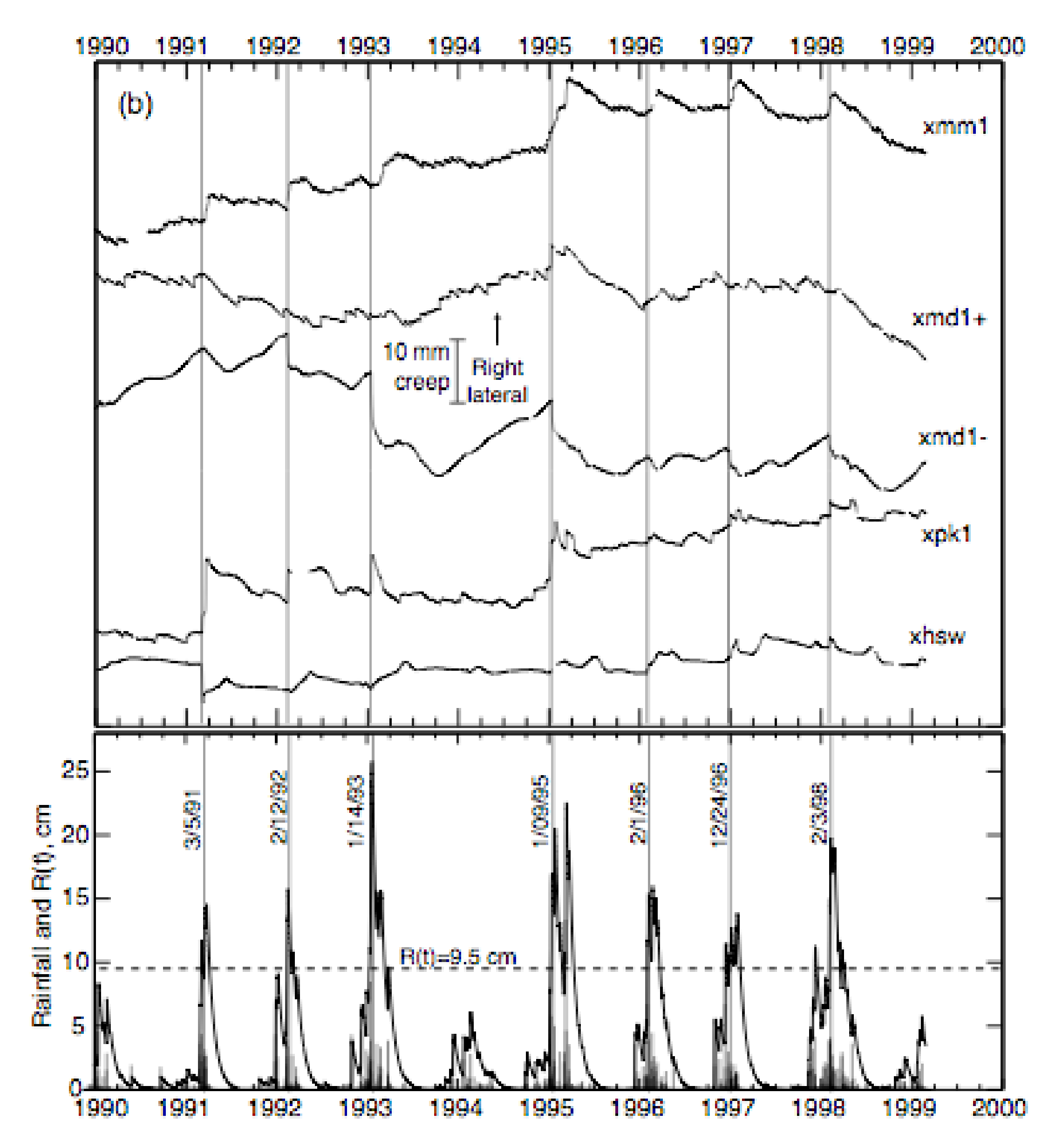
$$R(t_k) = \sum_{m=0}^{m_h} e[d(t_{k-m})]r(t_{k-m})\exp(-2\pi m/\tau_h)$$

$r(t_k)$ is the rainfall on calendar day t_k
τ_h is the time constant of the decay
m_h is number of terms needed for the sum



Same rainfall function predicts creep surges for many years

Similar techniques might be useful in removing hydrologic signals the time series of other sensors with relatively shallow monuments



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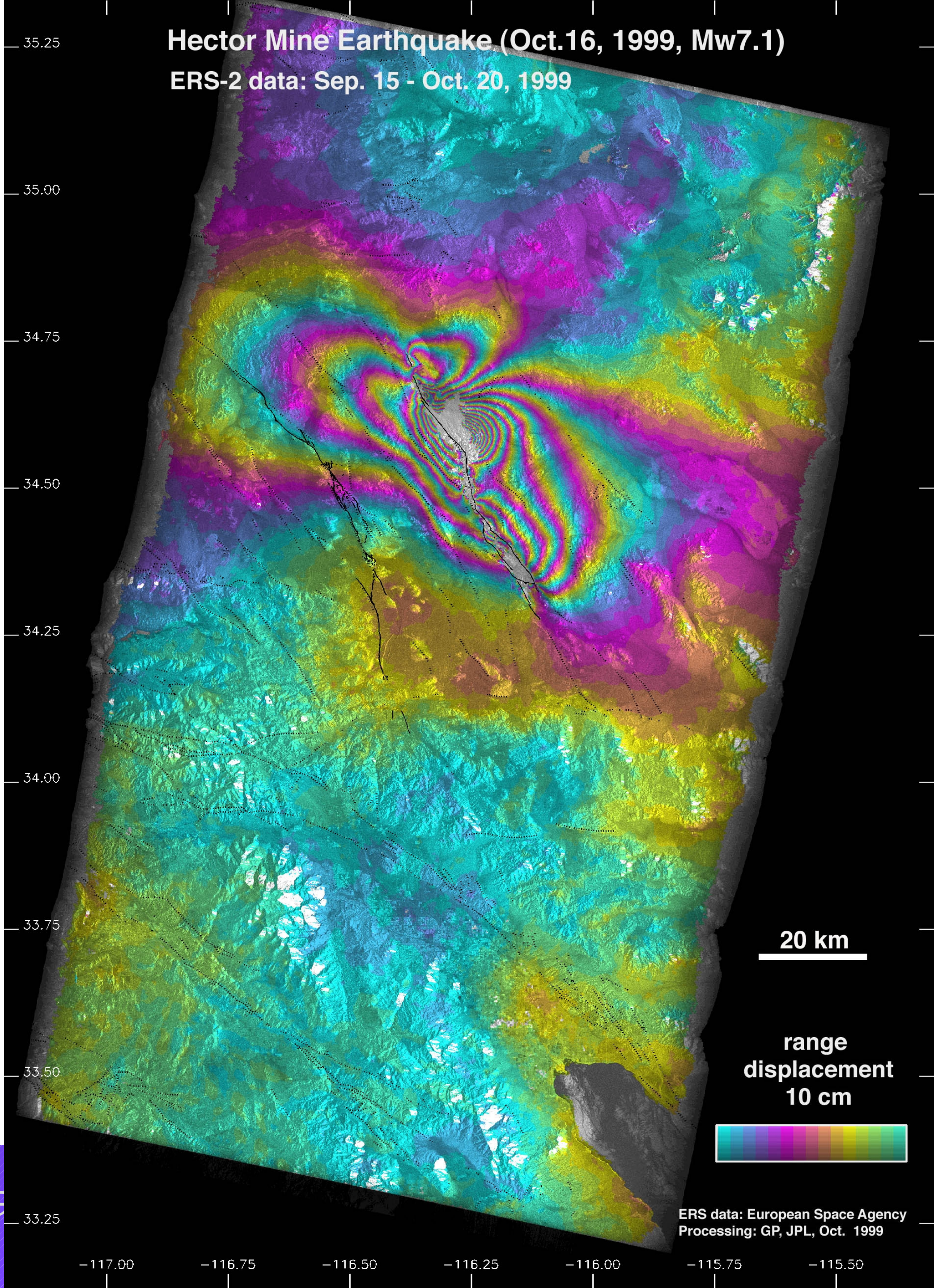
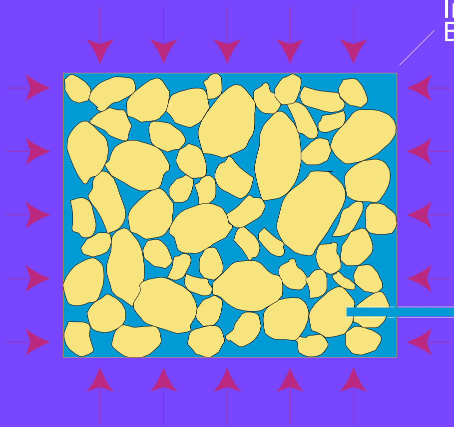
Mw7.1 Hector Mine, California Earthquake: Permanent movement from ERS interferometry

Gilles Peltzer, Frédéric Crampé, and Paul Rosen



1999 Hector Mine, CA Earthquake: Expansion of Surprise Spring Basin



$\Delta\pi / \Delta\varepsilon_{\kappa\kappa}$ = απξ 1 μ/πτμ

$\Delta\pi / \Delta\sigma_{\kappa\kappa}$ = B, 0<B<1

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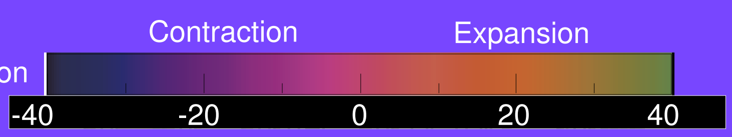
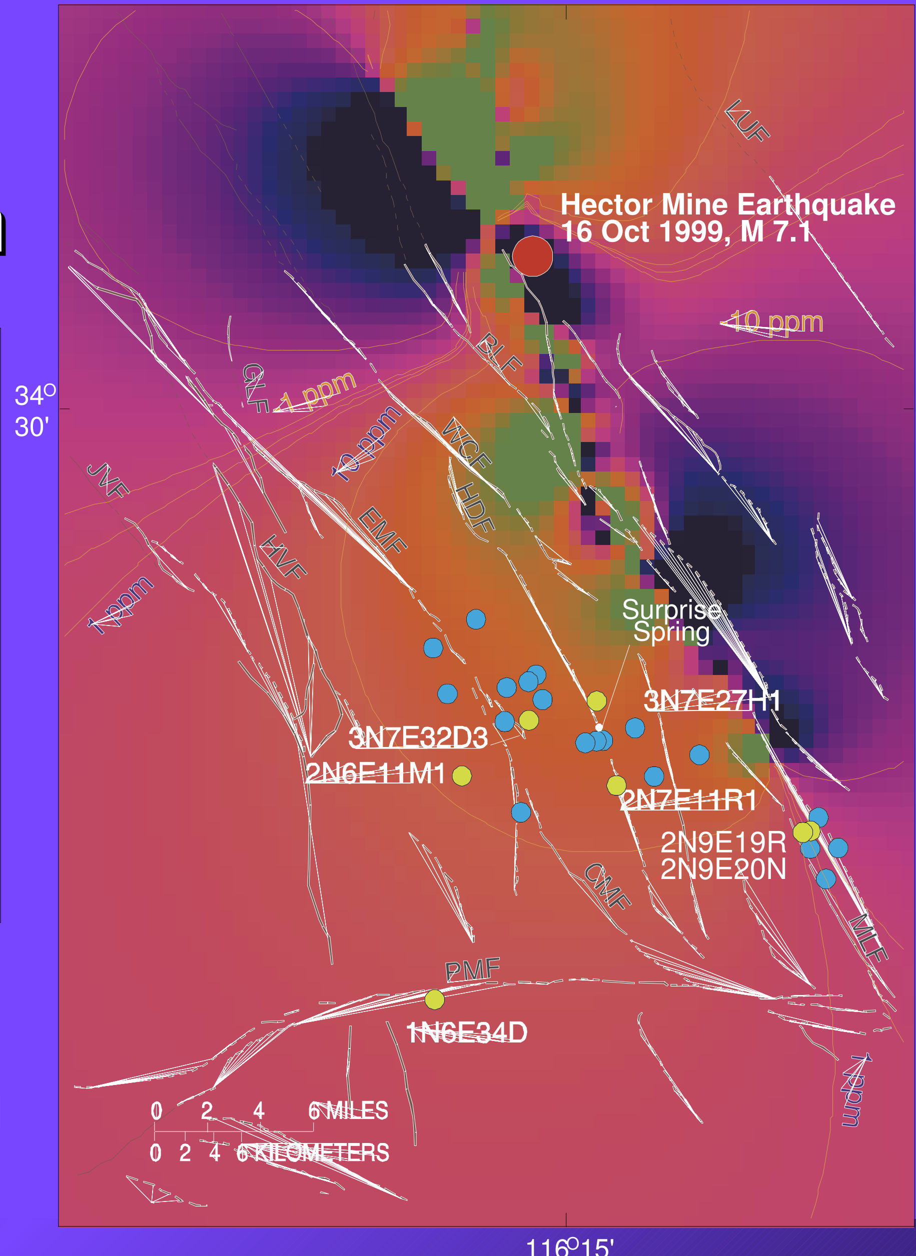
Εξπανσιον Δεχρεασεσ Φλυιδ Πρεσσυρε



● WELL, DISTINCT CHANGE ● WELL, <2 FT CHANGE



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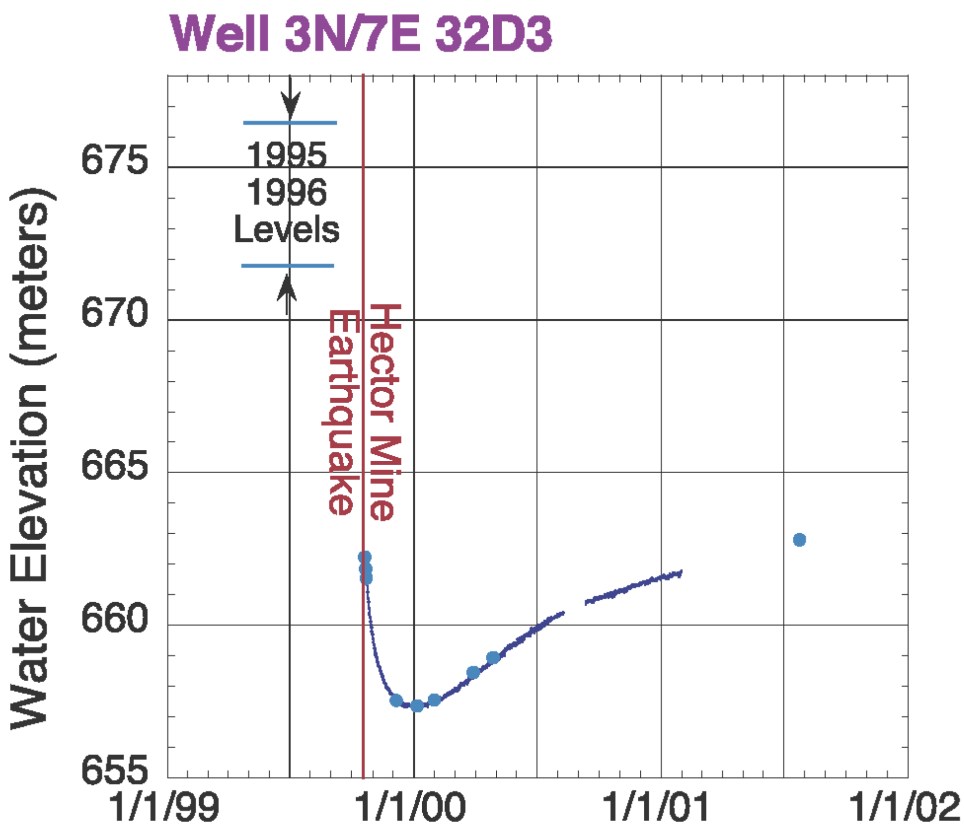
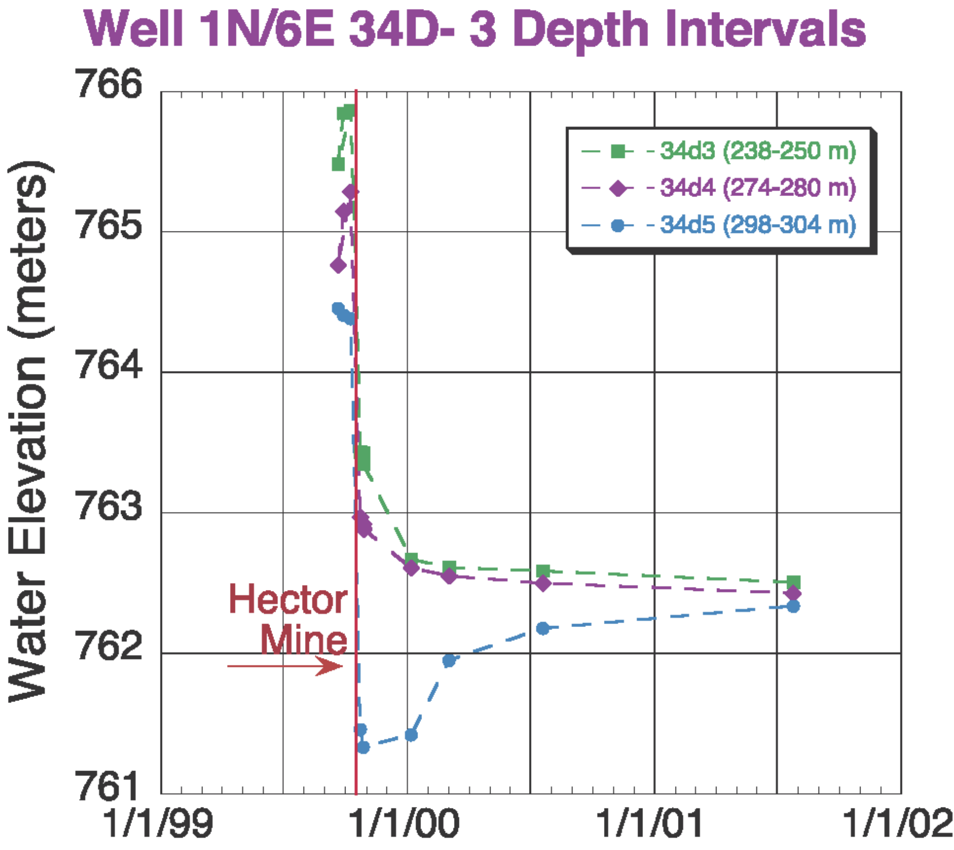
Hector Mine Earthquake Water-Level Drops: Only in the deeper wells





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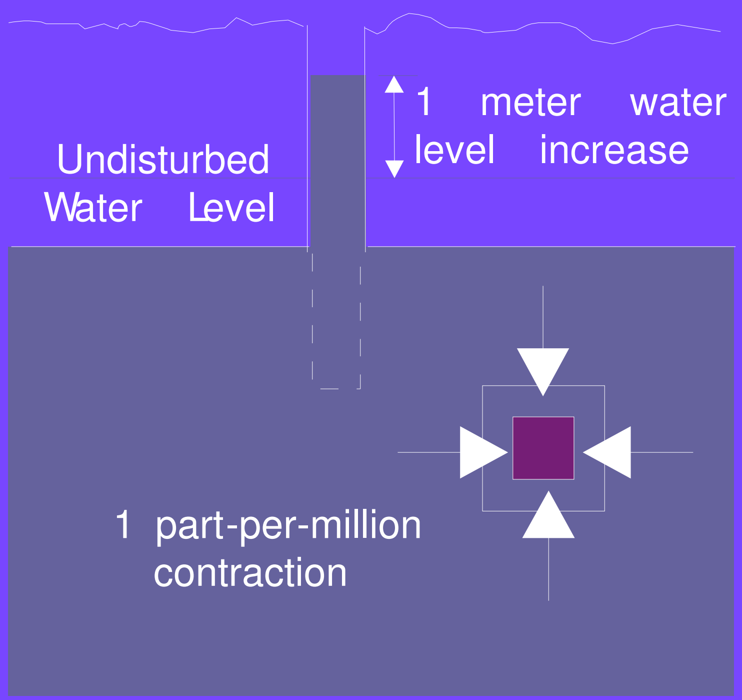
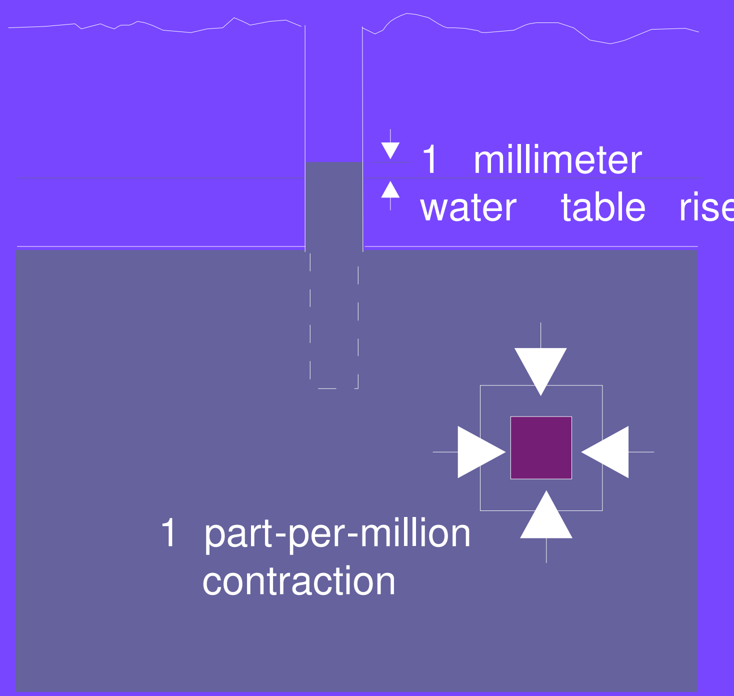
Confined vs. Unconfined Aquifers

"CONFINED" AQUIFER



Contraction of aquifer compresses confined fluid

"WATER-TABLE" AQUIFER



Fluid can move into pore space above water table

Hydraulic Diffusivity Governs Time Scale of Fluid Flow

Hydraulic Diffusivity, c

$$c = k / S_s$$

k = hydraulic conductivity (dimensions L/T)
S_s = specific storage (dimensions 1/L), typically 10^{-7}/m to 10^{-4}/m

(hydraulic conductivity)=
permeability*(fluid density)*g/(fluid viscosity)

Permeability is an intrinsic property of the rock; it has dimensions of L^2, and is usually expressed in darcies, with 1 darcy=10^{-12} m^2. 1 darcy corresponds to a hydraulic conductivity of approximately=10^{-5} m/s for water.

1-D Diffusion equation governs time scale of flow to water table, ie., "degree of confinement"

$p(z,t)$ = time history of pressure change at depth z

$$p(z,t) = -BK_u \varepsilon_0 erf\{[(z - z_w)^2 / 4ct]^{1/2}\}$$

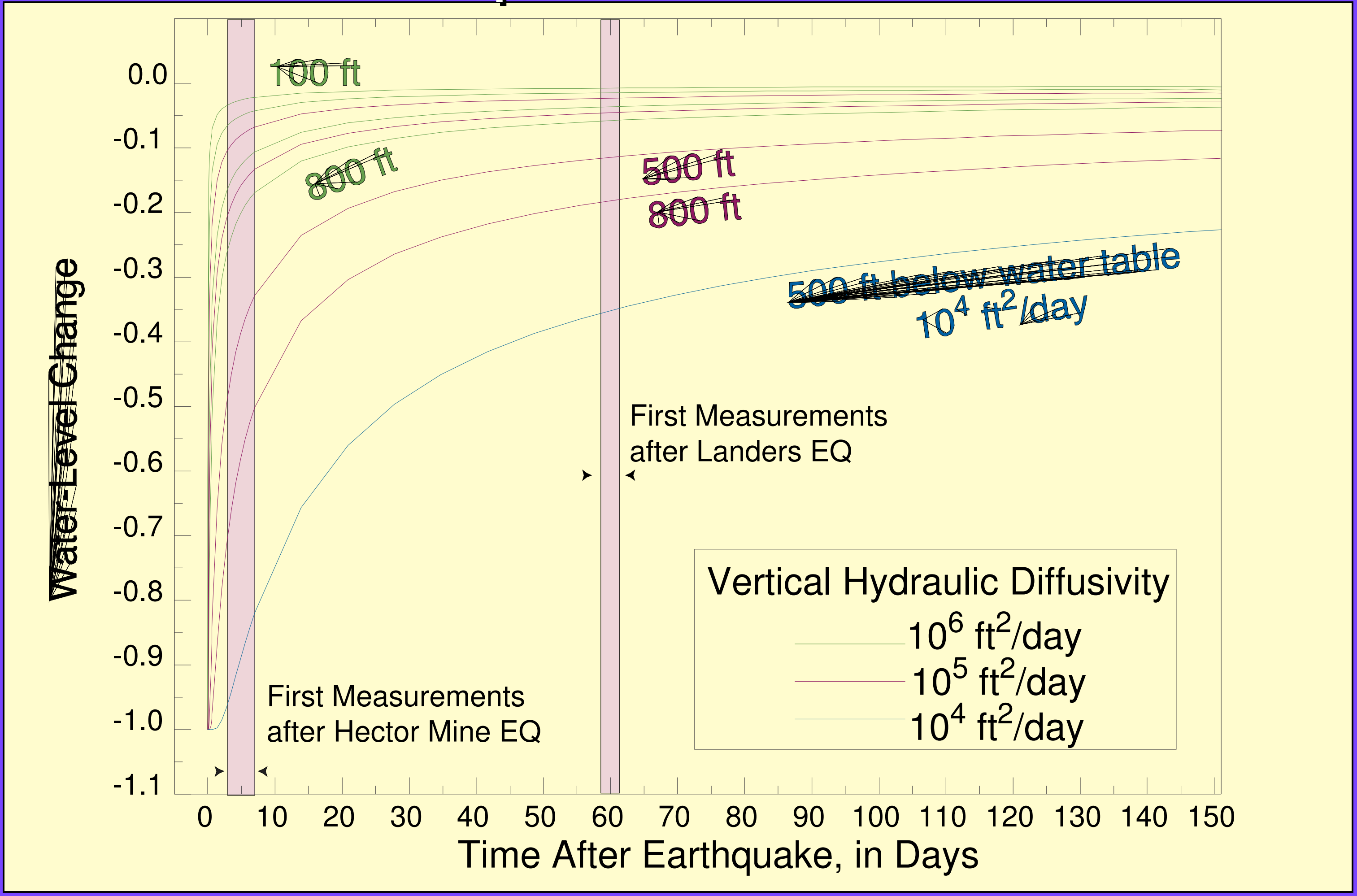
z = depth of the observation

z_w = depth of the water table

$erf\{\ldots\}$ denotes the error function

ε_0 = amplitude of instantaneously applied strain

Water-level changes due to aquifer expansion or contraction re-equilibrate with the water table



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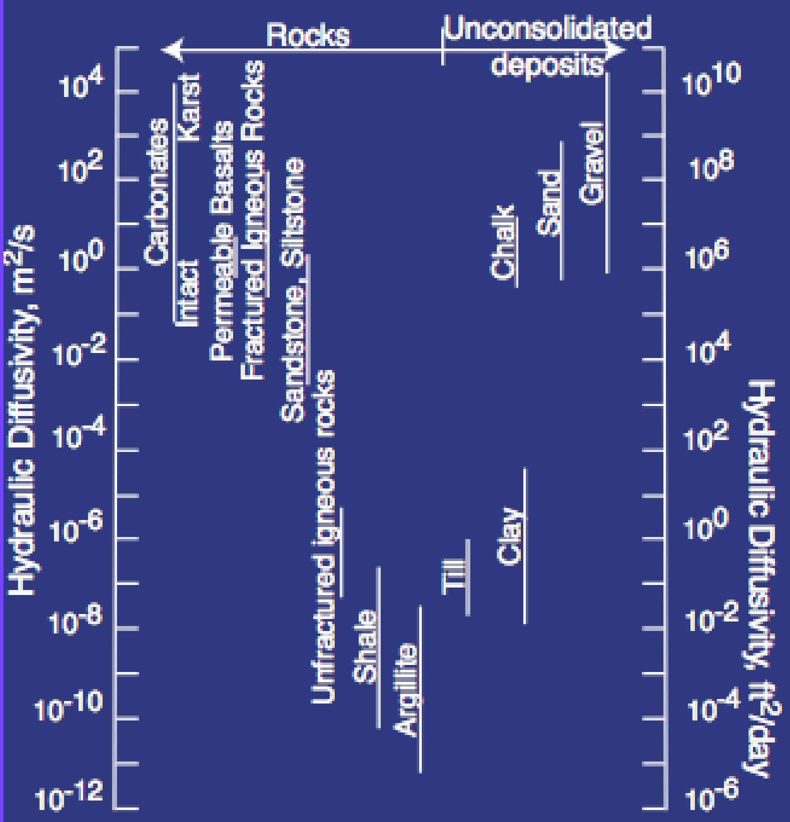
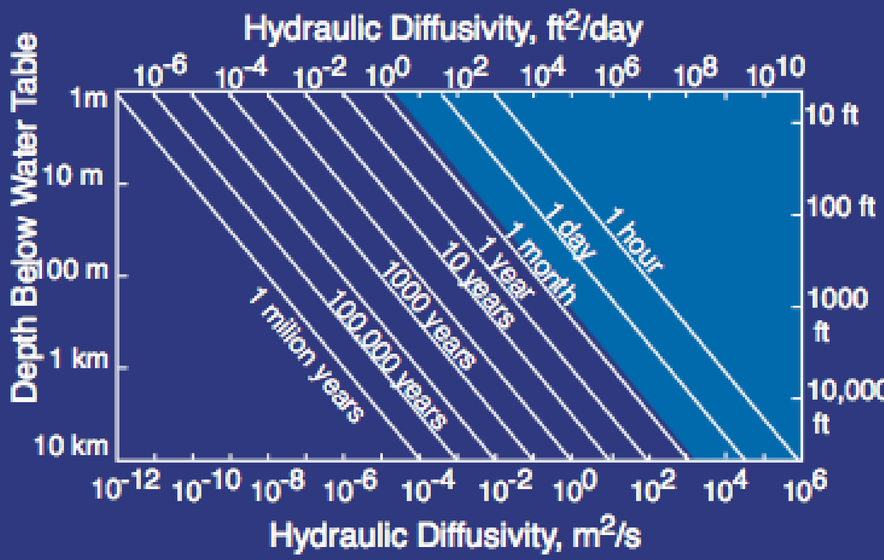
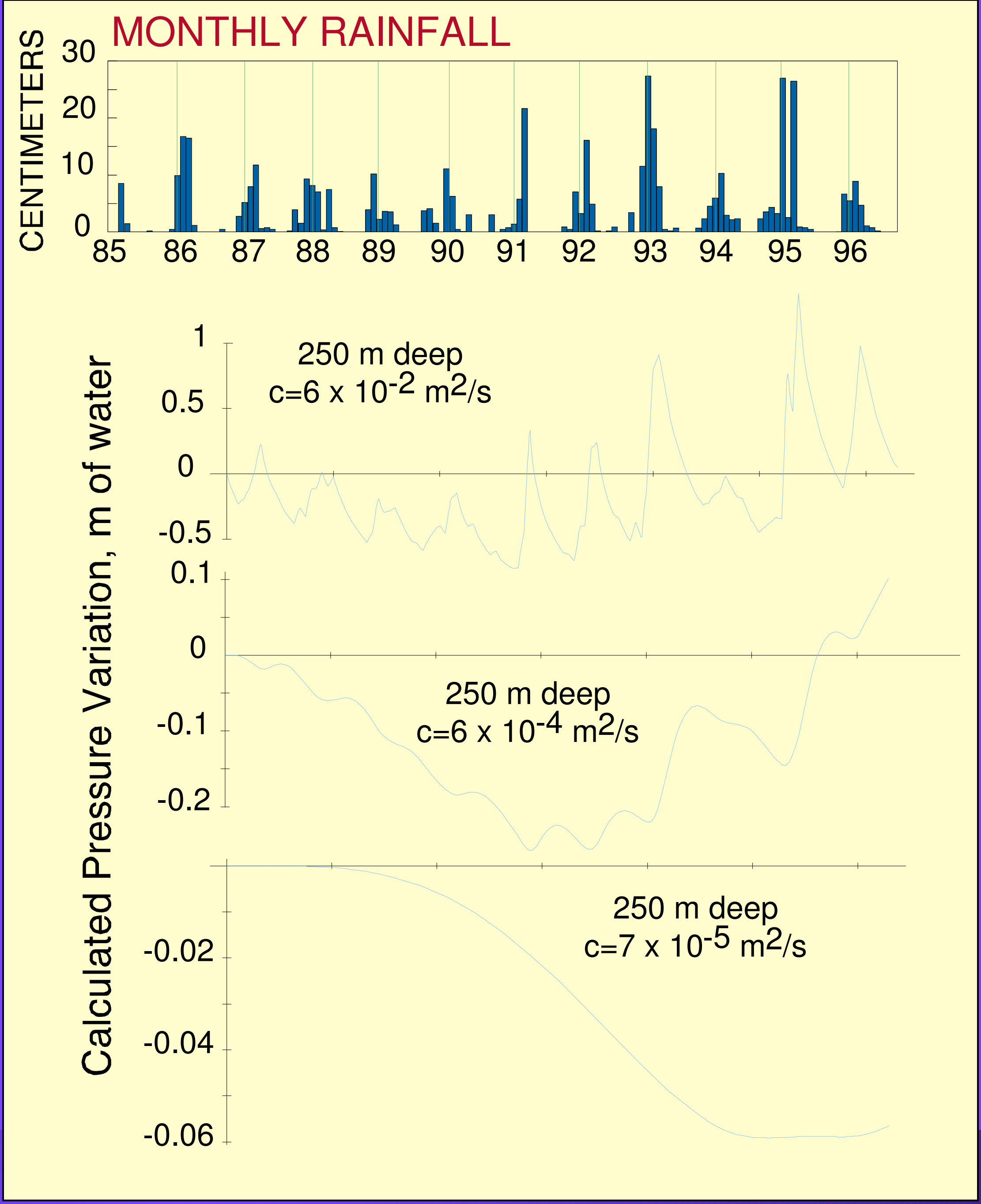
Diffusivities for Various Rock Types



Effect of Diffusivity and Depth on Water-Table Leakage



Subsurface Fluid Pressure Changes Depend on Depth, Hydraulic Diffusivity



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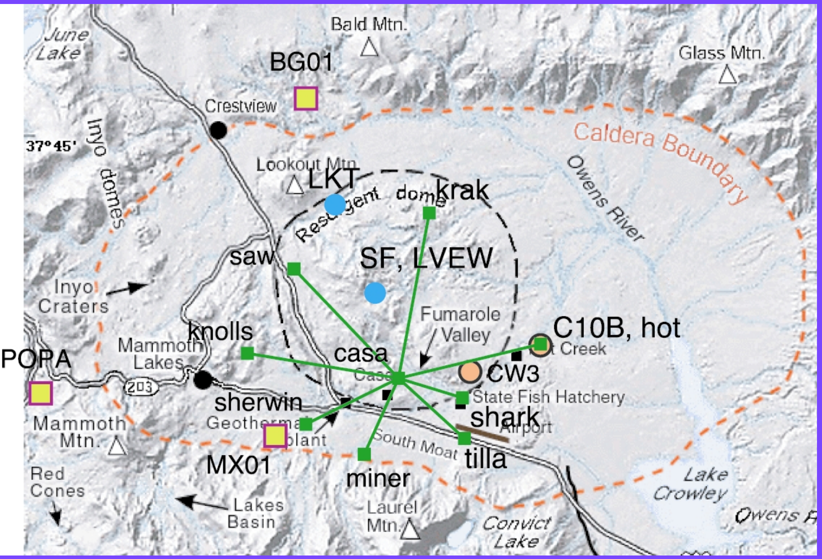
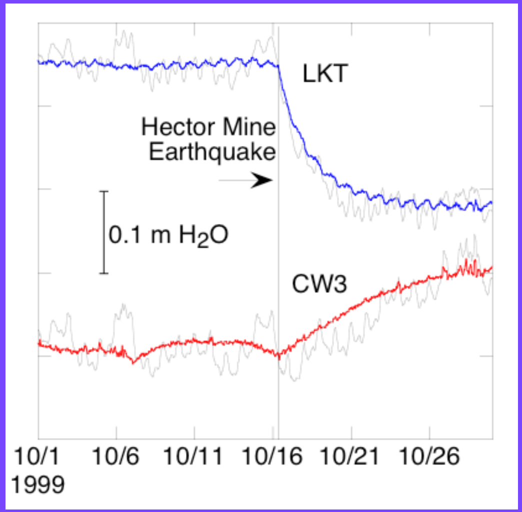
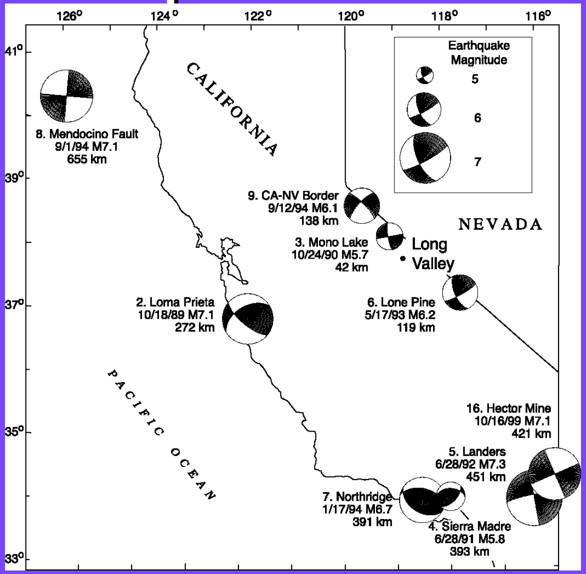
Fluid Pressure Changes at Long Valley Caldera from Distant Earthquakes



All earthquakes on map have produced similar fluid pressure changes

Fluid pressure increases in south moat thermal wells and decreases in non-thermal wells on and around the resurgent dome



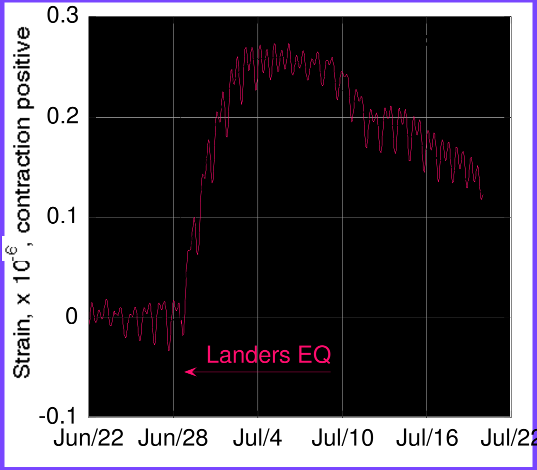


- Hypothesis: fluid-pressure decreases represent increments of dome inflation; increases represent triggered upflow of hot material beneath south moat (Roeloffs et al., JVGR 2003)
- But strain transients are not accounted for by these hypotheses…

Strain Changes Associated with Earthquakes

1992 Landers M7.3 450 km

Remotely triggered seismicity



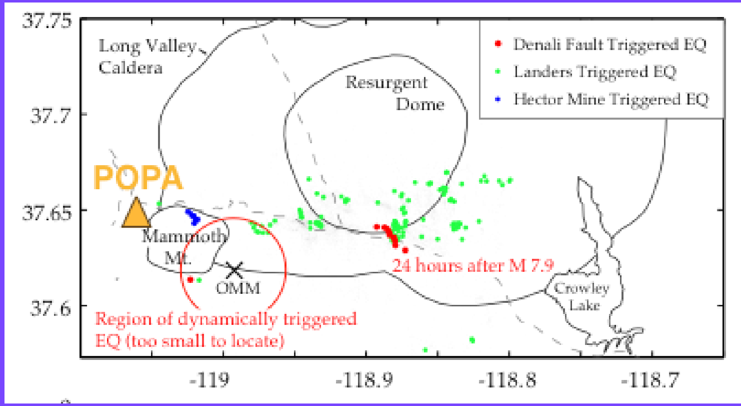
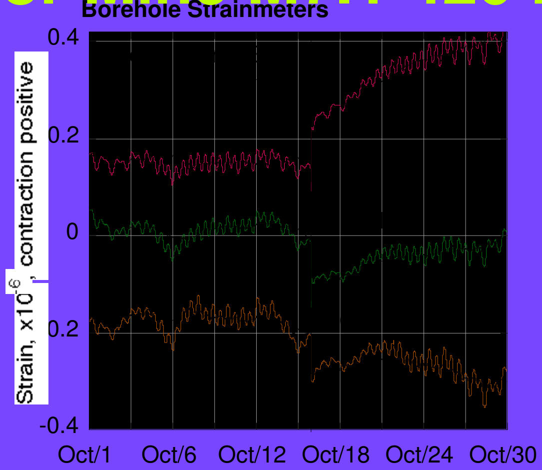


Figure by S. Prejean, USGS

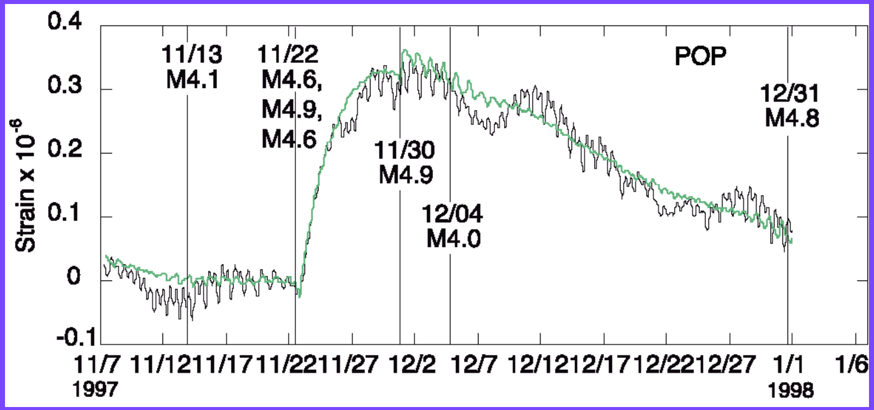
1999 Hector Mine M7.1 420 km

Remotely triggered seismicity



1997 South Moat Swarm

Possible intrusion beneath south moat



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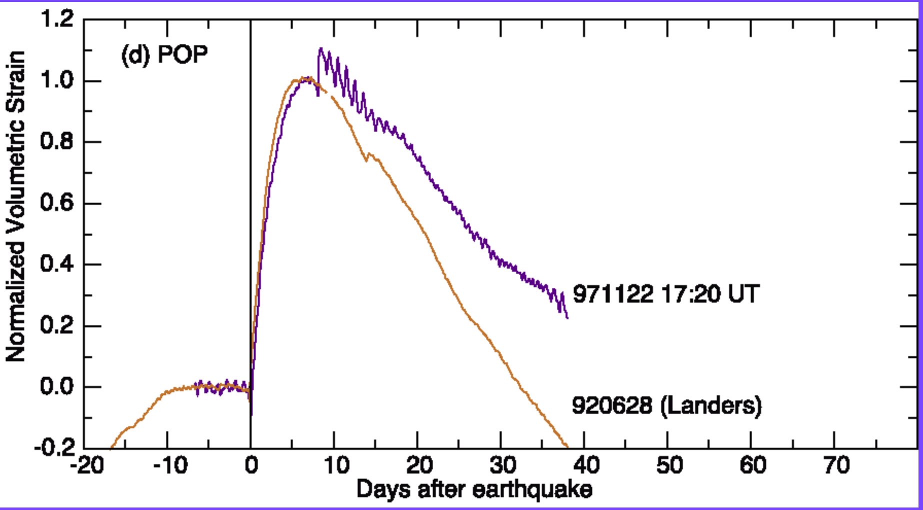
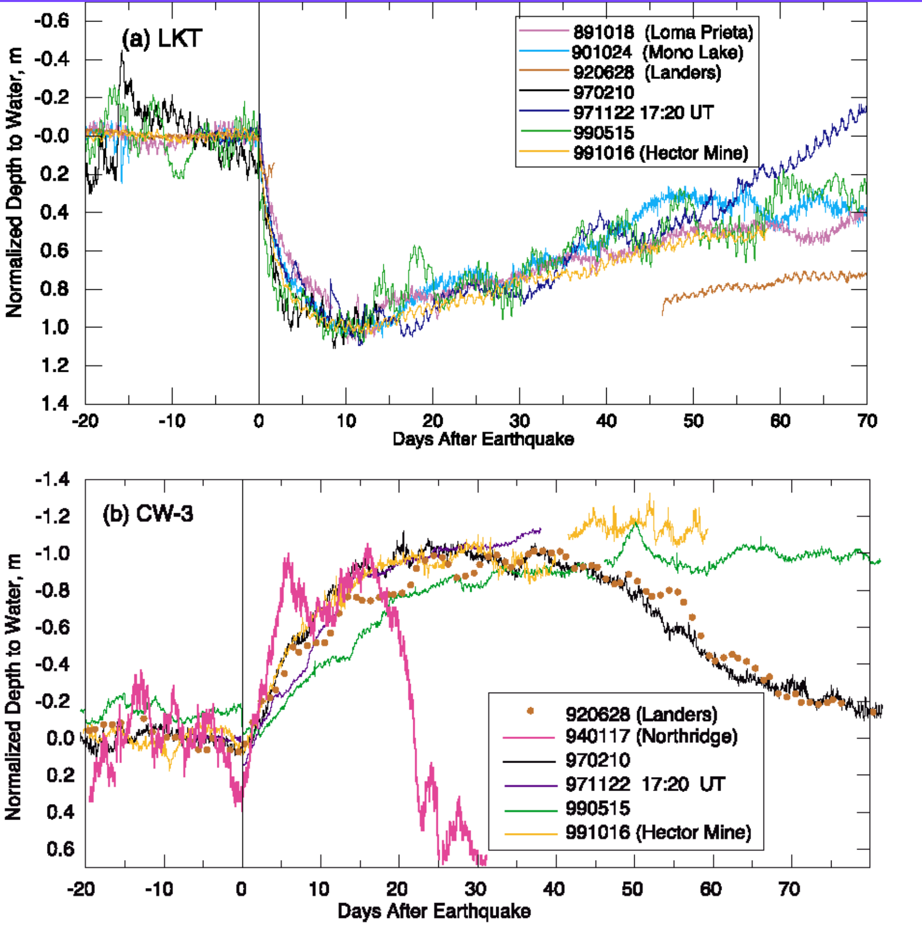
Earthquake-Induced Transients

Postpile Strain



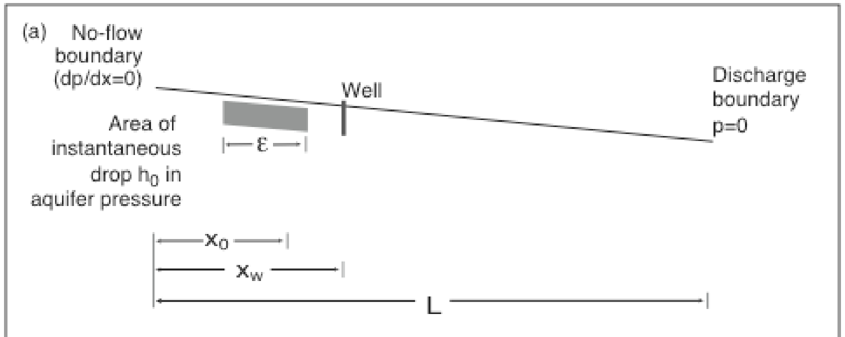
Groundwater Level



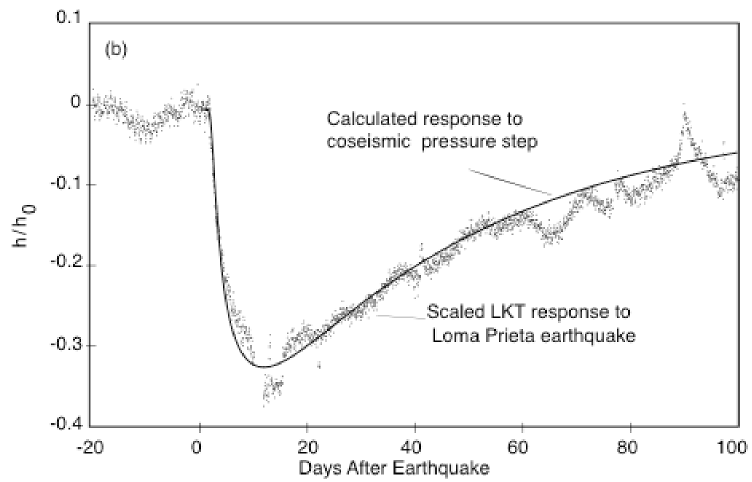
- **Strain as well as fluid pressure transients have repeatable time histories *at each site* when scaled by maximum amplitude**

Strain data: M. Johnston, USGS

Fluid-pressure Transients Match a 1-D Diffusion Model

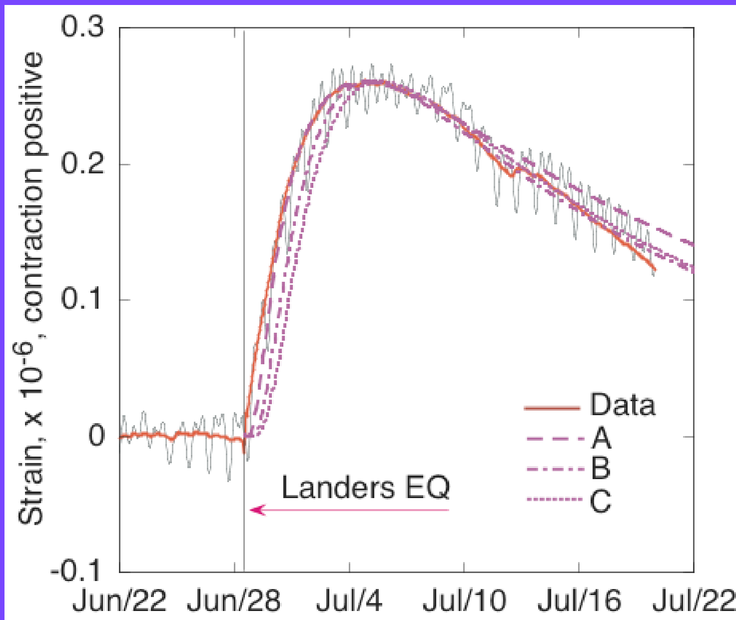


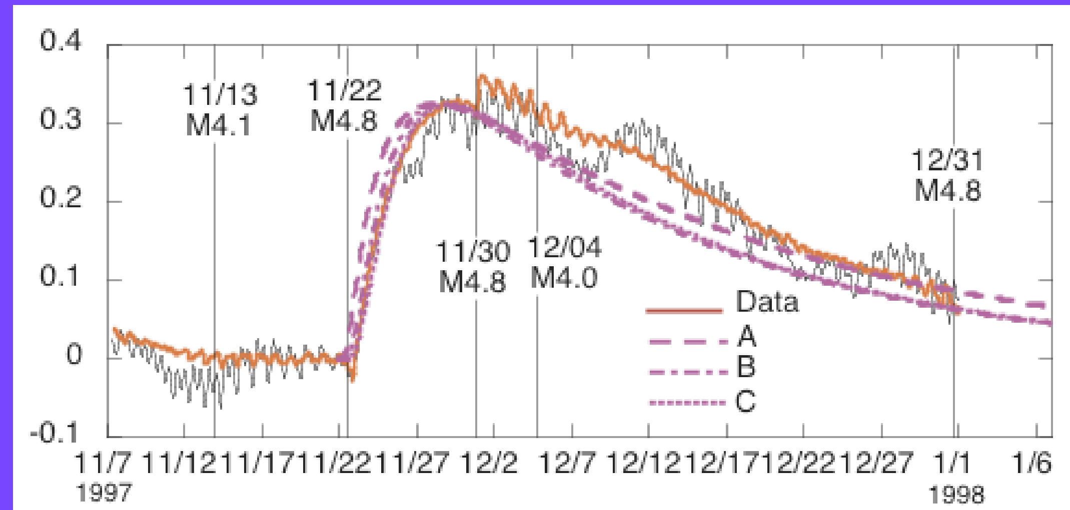
Non-dimensional parameters:	Horizontal Flow Interpretation:	Vertical Flow Interpretation
L^2/c=113 days	L=7000 m	L=2800 m
x_w=0.64 L	x_w=4500 m	x_w=1000 m
x_0=0.5 L	x_0=3500 m	x_0=1400 m
ε=0.5L	ε=3500 m	ε=1400 m
	c=5 m^2/s	c=0.78 m^2/s



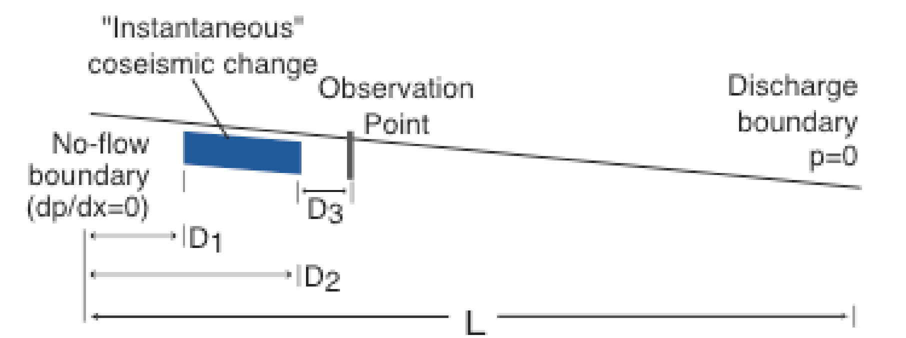
- **Assume a localized pressure change with a step-function time history during the passage of seismic waves**
- **Time history of transient observed in a well is governed by well's distance to abrupt change and to hydrologic boundaries, as well as hydraulic diffusivity**

1-D Diffusion Models for Strain Transients



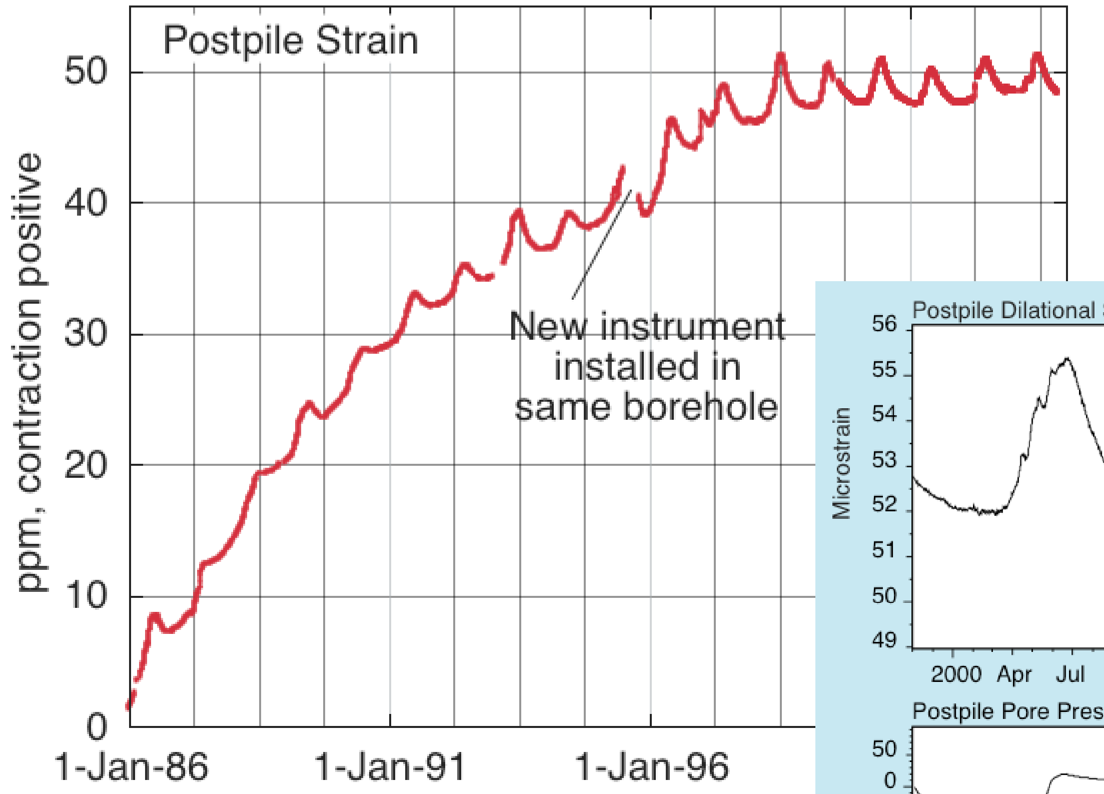


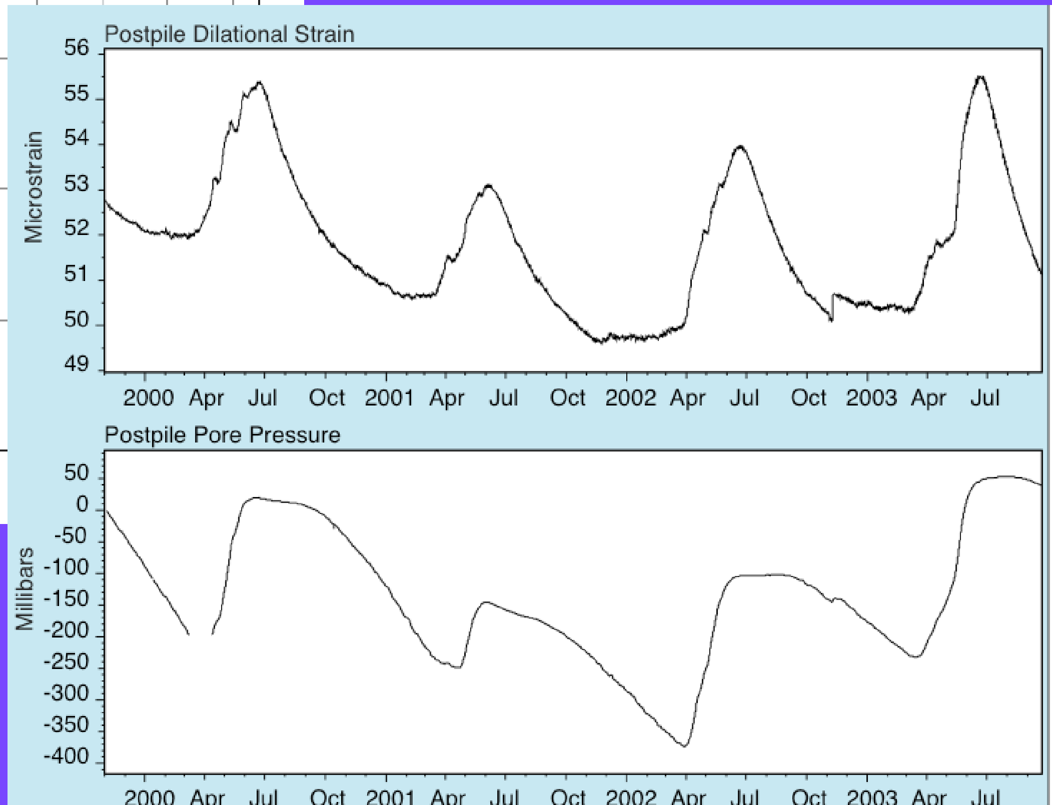
- Time histories of strain transients are also consistent with diffusive decay of a disturbance near, but not at, the strainmeter



	Max Change (Landers)	Max Change (Nov. '97)	L^2/c days	D1	D2	D3
A	0.91	1.14	58	0.1L	0.2L	0.3L
B	1.26	1.58	47	0.11L	0.22L	0.44L
C	1.26	1.57	47	0.1L	0.23L	0.54L

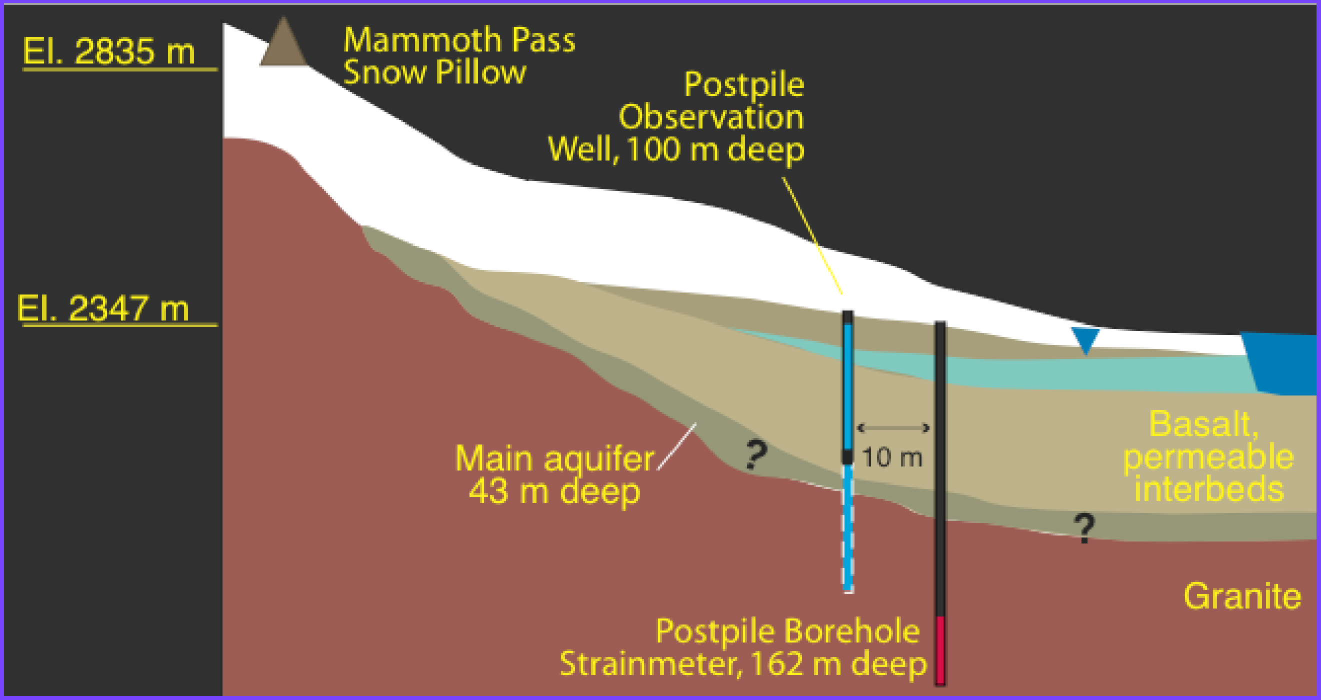
Long-term Strain and Fluid Pressure Data





Strain data and fluid pressure data: M. Johnston, USGS

Possible Sources of Seasonal Strain

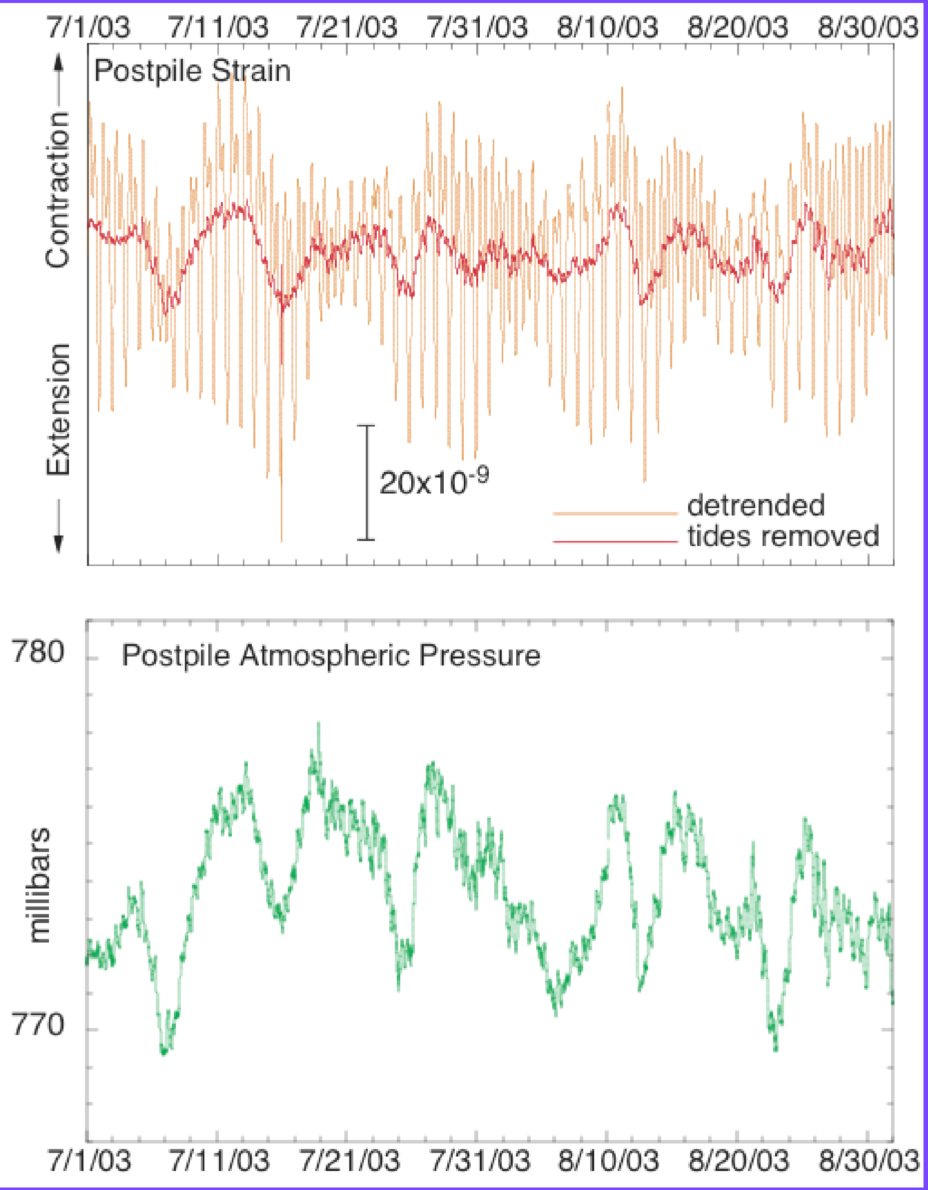


- Loading
  - snow on surface
  - fluid mass added above the strainmeter
- Poroelastic strain induced by increasing fluid pressure
  - in rock immediately adjacent to strainmeter
  - in overlying aquifers where pressures are changing

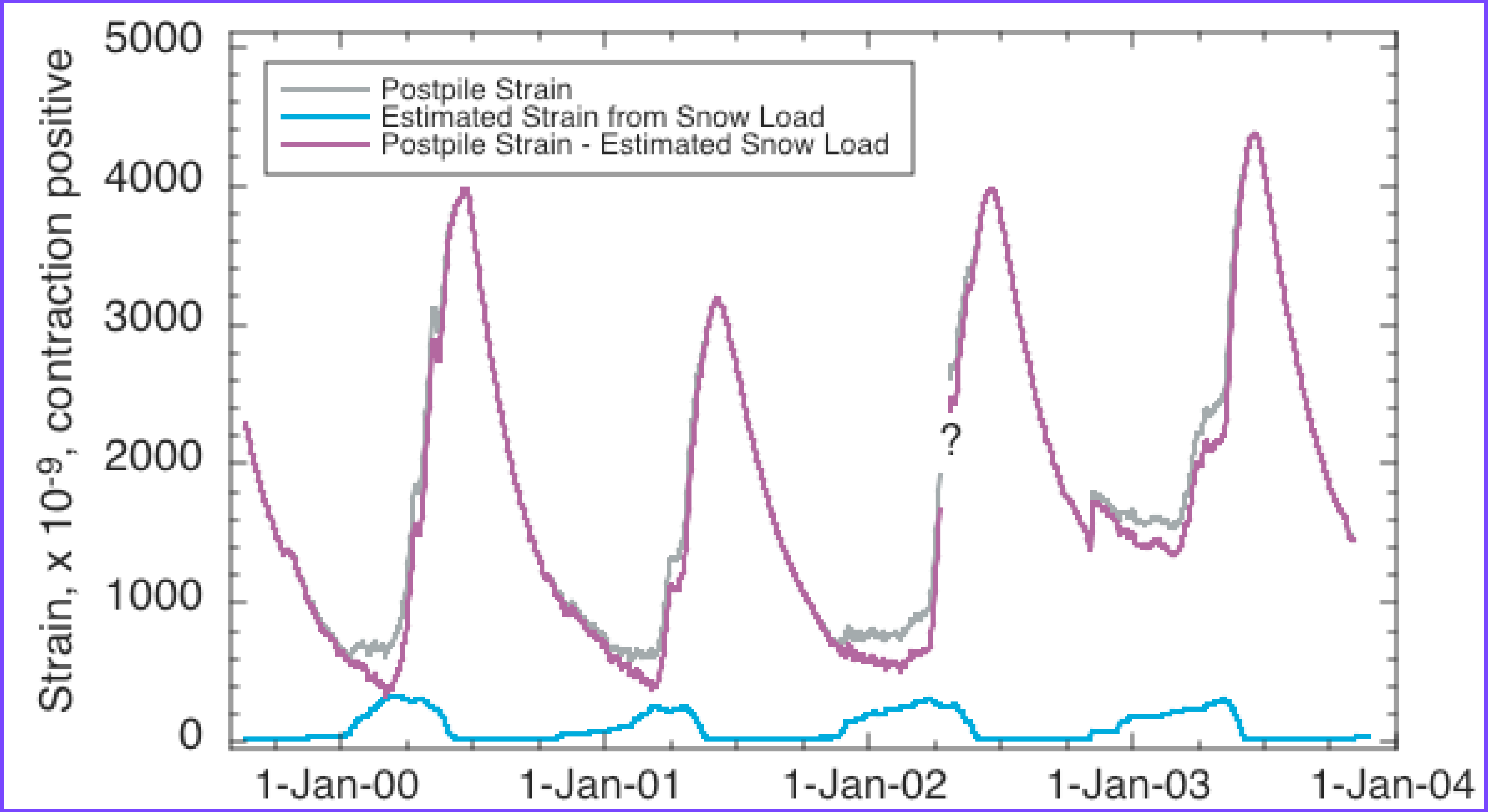
Response to Surface Loading by Atmospheric Pressure

- **Increasing atmospheric pressure produces contractional strain**
- **Surface-loading efficiency:**

  2.9-3.7x10^{-9}/millibar



Strain Induced by Snow Loading



- **Estimated strain from snow load =Weight of Snow water content x Surface loading efficiency**

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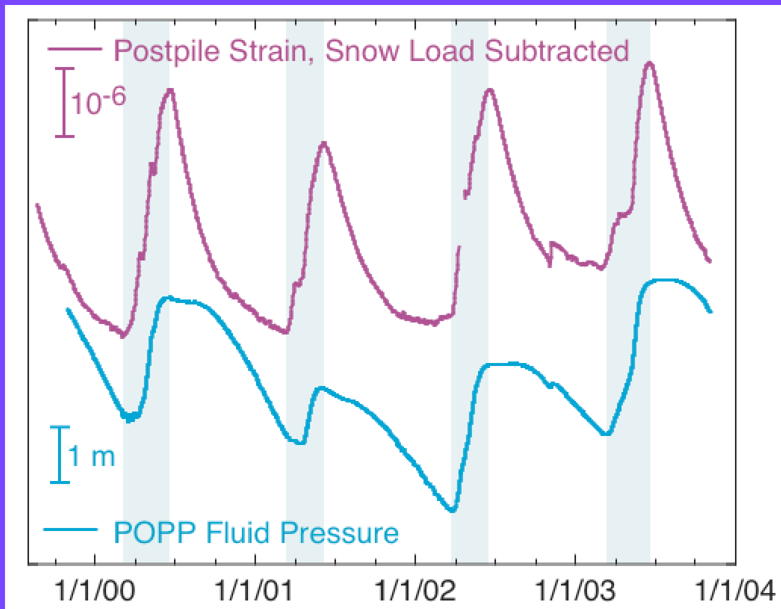
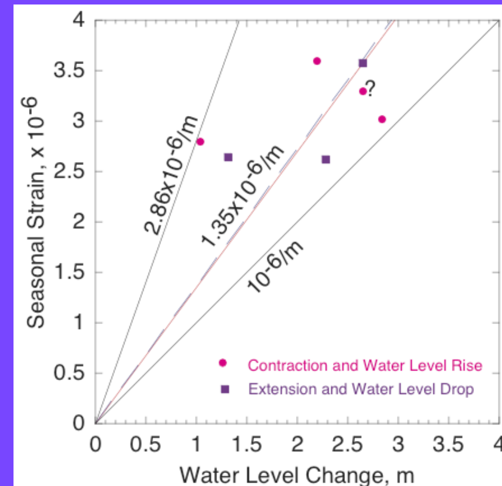
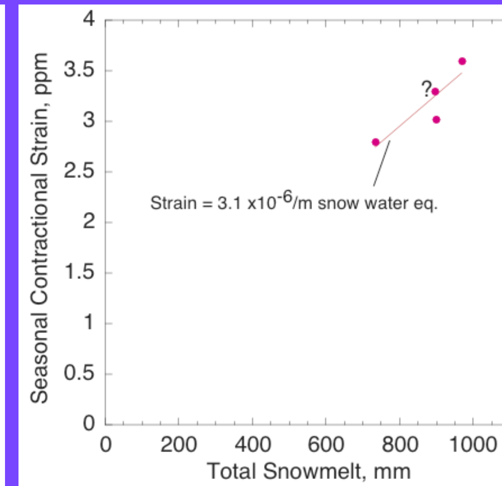
Strain and Fluid Pressure Variations







- **Strain is only roughly proportional to fluid pressure in the monitoring well**

  -monitoring well pressure may not equal pressure near strainmeter

  -deformation of overlying aquifer could play a role
- **Comparing amplitudes of total seasonal strain and fluid pressure changes, peak transient strain of 0.26-0.33 x 10^{-6} could be produced by a fluid pressure change of 0.1 to 0.33 m of water**

Conclusions

- **Strain transients may be responses to fluid-pressure changes:**
  - **1: Virtually identical time histories of two earthquake-induced strain transients match same type of 1-D pressure diffusion model as fluid pressure changes**
  - **2: Large seasonal strains coincide with fluid pressure changes and are roughly proportional to them**
- **Strain transients could be accounted for by fluid pressure increases of 0.1-0.33 m, similar in size to fluid pressure changes at LVC induced by earthquakes**
- ***BUT: the fluid pressure changes could also be caused by deformation*.**