Fluid-Pressure Data: A Complement to Borehole Strain

Evelyn Roeloffs,
U.S. Geological Survey, Vancouver, WA

Introduction

Water-level monitoring for crustal deformation studies was initially viewed as a low-cost substitute for strainmeters: poroelastic theory implies that fluid pressure in an isotropic porous rock varies in proportion to volumetric strain, with a coefficient in the range of 30-100 cm of water/ppm. Observations of water-level variations induced by earth tides and coseismic static strain support the idea that fluid pressure tracks crustal strain, and can be monitored via water-level measurements in wells. (Unless otherwise stated, fluid-pressure and water-level will refer here to the same physical variable.)

Nevertheless, as water-level and strain data have accumulated, primarily in California and Japan, a new view of fluid pressure has evolved. Water-wells, as strain sensors, have limitations, and acquiring reliable water-level data is not as cheap as initially hoped. On the other hand, it is also now clear that subsurface fluid-pressure changes induce strain changes that are recorded by borehole strainmeters, complicating strain data interpretation. Observations of either borehole strain or water-level changes, especially for pre-earthquake signals, are more readily accepted by the scientific community when both types of data are available. There is increasing evidence that fluid-pressure changes of tectonic origin are not necessarily proportional to volumetric strain of the solid rock, implying that fluid-pressure is an independent physical variable that cannot be inferred from, or substituted for, strain. The concept of the water-well as a strainmeter has thus evolved into a view of fluid pressure and strain as two separate and essential components of a complete crustal deformation measurement.

This mini-proposal outlines scientific objectives for monitoring fluid pressure in the same boreholes as strainmeters. The two main objectives are

1. To measure the fluid pressure changes that accompany crustal deformation.

2. To provide the fluid pressure data required to discriminate between strain induced by hydrologic effects and strain of tectonic origin.

Scientific Objectives for Fluid Pressure Monitoring: Examples

Redundancy in crustal strain measurement: A possible precursor to the 1985 Kettleman Hills earthquake: Recording crustal deformation with more than one type of instrument enhances credibility and helps constrain the physical basis for anomalies. As an example, on August 4, 1985, a M_W 6.1 earthquake occurred near Kettleman Hills, California , 35 km NW of Parkfield, where intensive crustal deformation measurements had begun (Figure 1). *Roeloffs and Quilty [PAGEOPH, 1997]* later noted small water-level rises in two of four instrumented wells, beginning three days prior to the earthquake (Figure 2). A similar change was recorded on one of two borehole volumetric strainmeters. The water-level change was unique in years of data from one of the two wells, but other fluctuations of similar size occur frequently in the other well and in the data from the strainmeter. The IASPEI Subcommission on evaluation of proposed earthquake precursors added this observation as Case 5 to the list of Preliminary Significant Precursors. The simultaneous signals on a borehole strainmeter and in water-level records increased the credibility of the observation, and also suggest that the anomaly involved a crustal strain change.

Hydrology and/or tectonics: Parkfield shear-strain rate change: In late 1992, increased seismicity and shortened recurrence intervals of repeating microearthquake clusters were interpreted to indicate faster aseismic slip over part of the Parkfield segment of the San Andreas fault. With two years of additional data, the slip-rate change became apparent on crustal deformation sensors. *Gwyther et al. [GRL, 1996]* first called attention to increased fault-parallel shear-strain rates measured by two 3-component borehole strainmeters (BTSM's). Since 1993, the NE-striking gages of the EDT and FLT BTSM's, on opposite sides of the San Andreas fault, began recording slower extension and slower contraction, respectively, with relative rate changes of 0.1 to 0.5 x 10^{-6}/yr (Figure 3).

Because the strain-rate change coincided with increased annual rainfall between 1993 and 1995 (Figure 3), concerns arose that groundwater pressure could be a significant signal in the BTSM data. Monument instability is not a problem for the BTSM's, which are 100 m deep in competent rock. But near-surface loading by an elevated water table or poroelastic deformation due to rising groundwater levels would be expected to induce areal strain, with the possibility of shear strain if the fluid distribution is nonuniform. Localized deep infiltration of recharge could also induce shear strain. Fluid pressure measurements from the formations containing the BTSM's would make it much easier to rule out a hydrologic origin for these signals.

Fluid pressure and strain changes triggered by earthquakes: Examples from Long Valley Caldera: Studies of earthquake triggering by static or dynamic stress changes need to assume a value for the fluid-pressure change to obtain the net Coulomb effective stress change. At Long Valley Caldera, numerous examples have been recorded of transient borehole strain and water-level changes accompanying both distant and local earthquakes, which are in general too large to be responses to coseismic static deformation. Many earthquakes have induced transient contractional strain with a time constant of several days at the POPA strainmeter just outside the caldera, as well as increases or decreases of water level in several wells inside the caldera (Figure 4). The strain and water-level changes likely reflect a common process, which may in turn play a role in the caldera's susceptibility to seismicity triggered by distant earthquakes. Mutually co-located strain and water-level instruments would facilitate interpretation of the different directions and time constants of the earthquake-induced deformation.

Fluid pressure and earthquake generation: Beyond the well-known principle that increasing fluid pressure promotes frictional or shear failure by counteracting normal stress, fluids are widely suspected to play an intrinsic role in earthquake generation. Although fluid-pressure changes at depths of a few hundred meters may not directly reflect the situation at earthquakes nucleation depths, the few measurements available from deeper boreholes suggest that the fluid-pressure phenomena observed near the surface may also take place at least a few kilometers deep. Technological progress and more examples of tectonic fluid-pressure and strain changes at shallow depths will help justify deeper measurements that may illuminate hypocentral processes.

Technical Aspects of Fluid-Pressure Monitoring

For transient deformation that takes place over about one day, a water-level change of 1 cm is about the smallest that can be resolved unambiguously, and would correspond to about 10-30 ppb volumetric strain. (A borehole strainmeter can resolve a strain change at least one order of magnitude smaller.) In general, water wells are imperfectly sealed from the atmosphere, allowing strain-induced fluid pressure transients to dissipate by equilibration with the water table. For a poorly confined aquifer, this dissipation may take place in several hours, while for a deeper well in a formation with low vertical hydraulic diffusivity, strain-induced water-level changes may persist for weeks. In low-permeability environments, fluid cannot flow into or out of the borehole quickly enough to track formation fluid pressure in response to high-frequency strain variations. The effects of poor confinement or low permeability are most easily detected by looking at phase shifts between water-level tides and strain tides. If a co-located borehole strainmeter provides in situ recordings of strain tides, then the phases of the water-level tides may be used to estimate formation hydraulic properties.

Borehole water level may not track formation pressure perfectly if permeability is low, so high-frequency resolution may be improved by measuring fluid-pressure changes in a packed-off interval. In practice, the improved high-frequency response must be weighed against greater difficulty of sensor replacement and diminished access for manual measurements, cleaning, or sampling. Thus, packing off the borehole is warranted only when high-frequency response is the primary goal, as it is for engineering seismology.

The most useful fluid pressure data would come from the same formation and borehole where a borehole strainmeter is installed. The pressure sensor could be incorporated into the top or bottom of the strainmeter itself. Alternatively, a tube passing through the strainmeter could conduct fluid through the instrument, permitting pressure measurement higher in the borehole. Yet another possibility is to perforate the casing above the strainmeter and measure fluid pressure using a suspended transducer; the changing weight of the water on the strainmeter would induce an easily-correctable strain signal. Modifying strainmeter or borehole construction to permit fluid-pressure measurement might increase the cost per site by $1000-$2000.

In the US, no strainmeter data are available with a pressure-sensing device in the same borehole: most strainmeter boreholes have been backfilled with cement. But if borehole construction avoids connecting previously separated aquifers, then a fluid pressure measurement should be possible without inducing artificial cirulation that might degrade the strain data. Such strainmeter installations exist in Japan and China; access to these data could help identify possible problems with the co-located measurements.

A submersible quartz pressure sensor can be purchased for about $4000, plus cable, and will last at least 10 years. Cheaper transducers using strain-gaged diaphragms

($500-$1000) are less reliable (1 to 5 years lifetimes), but could be used where sensor replacement is easy. Water-levels are generally sampled every several minutes, although in high-permeability formations more rapid sampling (1 Hz) in triggered mode may record seismic-wave-induced water-level oscillations. Typical pressure transducer range is 10 m of water, with resolution of 0.3 mm, allowing recording with 16-bit precision. Thus, water-level data can be recorded as one extra channel on the same equipment used to record strain. Site maintenance requires regular visits to measure the water level as a check against transducer drift or movement, and periodic cleaning of the wellbore.

Water-level data-processing techniques are similar to those for borehole strain data, namely tidal analysis and removal of atmospheric pressure effects. These easily-automated techniques allow water-level and strain data to be processed together.

Summary

Fluid pressure is not simply a crude, redundant proxy for crustal strain. A strong case can be made that borehole strainmeters and fluid-pressure measurements are essential complements to each other. Where both fluid pressure and strain have been measured, the data sets have greatly enhanced each other, but less ambiguous interpretations would be possible if the fluid pressure and strain measurements were co-located. It would be desireable to study existing international data sets to choose the best technique for making co-located fluid pressure and strain measurements. The incremental cost of adding fluid-pressure (water-level) sensing to a strainmeter site is $1500-$5000, depending on the sensor and the way in which the formation fluid pressure is accessed.

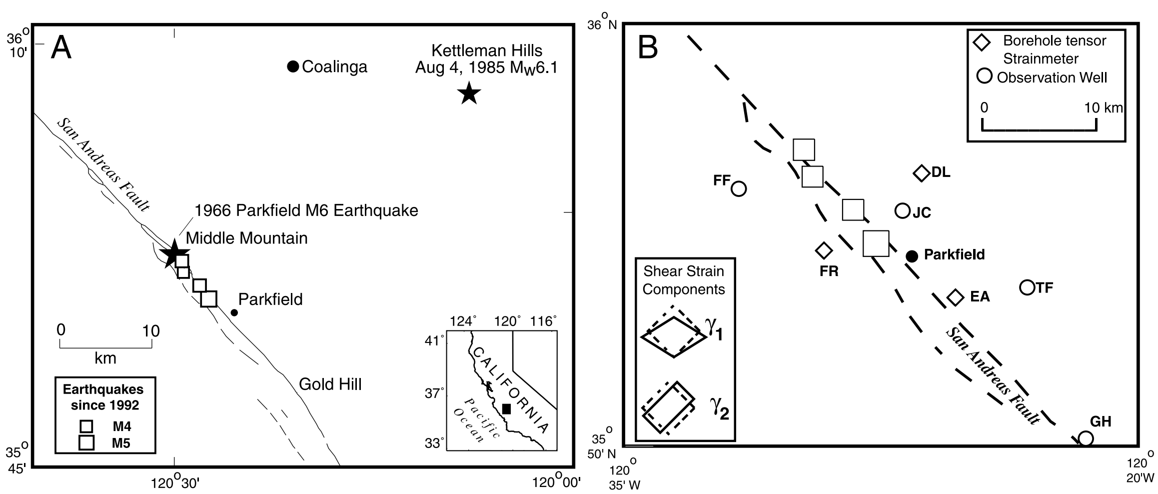

Figure 1. Maps of the Parkfield area, showing locations of water wells and strainmeters.

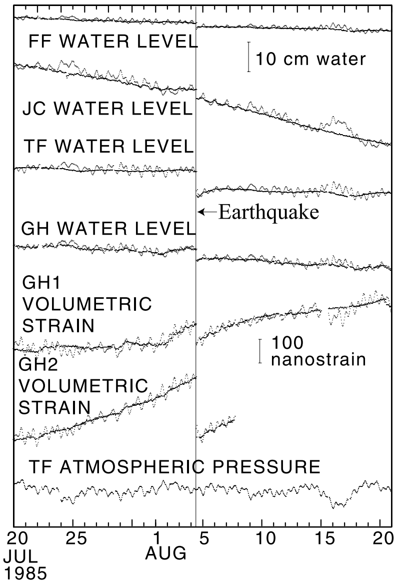

Figure 2. Water-level and strain data from Parkfield, CA, around the time of the August 4, 1985 Kettleman Hills earthquake. Raw water-level and strain data are shown in gray, and data with tidal and atmospheric pressure effects removed are superimposed in black.

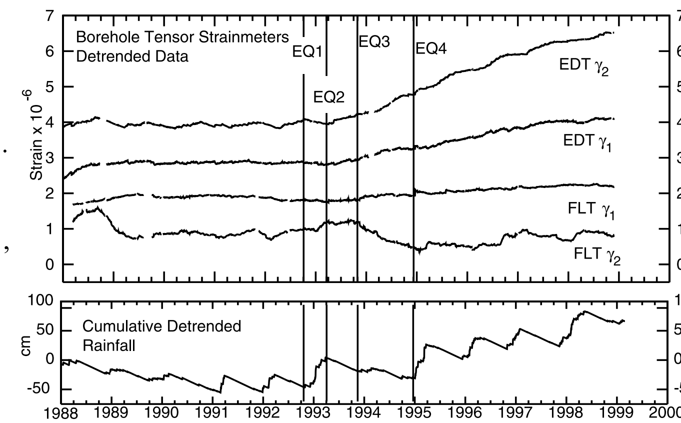

Figure 3. Data from borehole tensor strainmeters at Parkfield, showing shear strain rate change. Sense of strain components is shown in Figure 1b. Strain data are courtesy of R. Gwyther et al., and have been detrended.

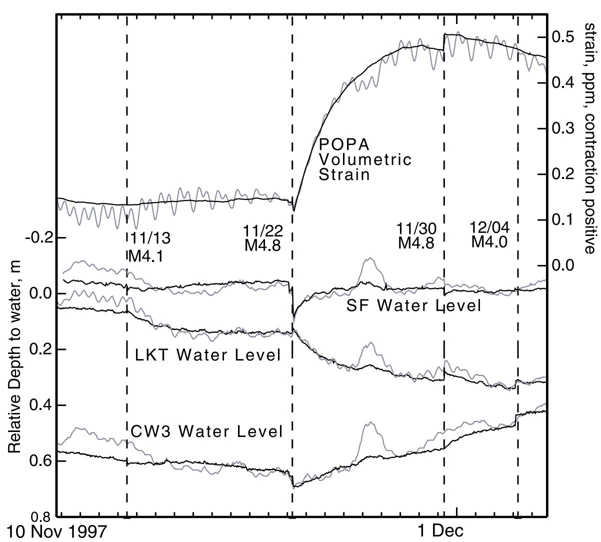

Figure 4. Data from the POPA borehole strainmeter and from several water-level monitoring sites at Long Valley caldera, California, during seismic unrest in November, 1997. Raw water-level and strain data are shown in gray, and data with tidal and atmospheric pressure effects removed are superimposed in black.