LOW VELOCITY ZONES ON THE SAN ANDREAS FAULT: CONTRIBUTION OF PORE PRESSURE, LITHOLOGY, AND STRUCTURE

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III. Understanding Earthquake Processes; and
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Investigations Undertaken

A great deal of evidence has emerged in recent years pointing to the importance of pore fluid pressure in fault zones and fault zone properties (Hickman et al., 1995). The evidence suggests the mechanics of seismogenic faults may be linked to spatial and temporal variations in pore fluid pressure. In the absence of direct measurements of pore pressure obtained through drilling, one of the most promising means of detecting high pore pressure and enhanced fluid content is by seismic measurements calibrated through laboratory data to known fault zone structure. This involves the integration of geophysical data with realistic geologic models of fault zones.

In this project, we have worked on two aspects of research into the effect of elevated pore pressures: one experimental and one theoretical. The experimental part involved measurements of ultrasonic Vp and Vs, while varying confining and pore pressure. The goal of this subtask was to investigate the effect of elevated pore pressure (reaching confining pressure) on velocity in wall rock and on gouge materials. The theoretical studies investigated the effect of pore pressure on post-seismic displacements and the effect of pore pressure diffusion in triggering aftershocks.

Results to date

1. Velocity-Pressure Behavior for Regular Wall-Rock and Fault Gauge

Figure 1 shows the results of acoustic velocity measurement versus confining and pore pressure. On top are data for a regular sandstone sample representative of an intact wall-rock material. On bottom are data for a sample taken from a fault gauge at the Oregon accretionary margin, where the Juan de Fuca plate subducts beneath North America. In both cases, the compressional-wave velocity is plotted versus the differential pressure, defined as the difference between confining and pore pressure.

In the case of wall-rock, the experiments were conducted at different pore pressure levels. Pore pressure level is marked on each plot. The confining pressure was gradually increased to reach zero differential pressure. For the gouge case, first the sample was subjected to the smallest confining pressure (here 3.6 MPa). Then, pore pressure was gradually increased to this confining pressure to achieve zero differential pressure. At this point the next cycle started at which the confining pressure was raised to the next level higher than the previous one (6.78 MPa), and the process was repeated.

In wall-rock sample, velocity is practically a unique function of differential pressure; for all practical purposes, it does not depend on pore (or confining) pressure. This is not true for the gouge sample; the higher the confining pressure the higher the velocity at the same differential pressure. However, in striking exception to this observation, at zero effective pressure (pore pressure = confining pressure), velocity is the same, independent of confining pressure.

We speculate that the increasing confining pressure represents increasing burial depth. Apparently, an increase in burial depth changes the fabric of the gouge material by closing compliant pores and increasing the velocity. This change cannot be reversed by a partial pore pressure increase. Therefore, the impedance contrast between gouge materials and the wall rock decreases with increasing depth. However, as soon as the pore pressure reaches the confining pressure and effective pressure nears zero, impedance in the gouge drops down to the same low level independent of depth, creating a strong contrast with the surrounding rock.

These experiments show that for a given type of gouge material, velocity can be calibrated to the expected differential and confining pressure. Further experiments would establish velocity-porosity changes in gouge materials with pressure (depth). The established velocity-porosity curves, calibrated for each region could serve as quantitative tools for monitoring temporal and spatial pore pressure changes in a fault.

2. <u>The Role of Fluids in Crustal Stress Evolution Following the 1992 Landers Earthquake</u>

Pore pressure is known to significantly affect the mechanical properties of porous materials. In particular, the state of stress and seismic wave velocities cannot be determined in saturated poroelastic materials without knowing the fluid pressure within the material. Furthermore, geochemical processes have been invoked by some as a major element in the earthquake cycle. Pore fluids are the primary transport medium in these processes. It is therefore essential to include fluid effects in theoretical considerations of the physics of crustal processes. There is a growing interest in the seismology community in developing numerical models of crustal stress evolution and fault rupture, analogous to the general atmospheric circulation models used by the meteorology community and general oceanic circulation models used in the oceanography community. Our studies suggest that pore fluid dynamics and coupled poroelasticity must be included in any general model of crustal stress evolution.

We have modeled the coseismic stress changes caused by fault slip during the 1992 Landers earthquake and the consequent pore pressure distribution that would result from the stress changes. Using sophisticated numerical codes, we compute time-dependent post-seismic vertical and horizontal displacements and confining stress that would result from the evolving fluid pressures (Figure 2). These computed quantities appear to match the available SAR, GPS, and geodetic data (Peltzer et al., 1996). Our numerical study shows that pore fluid effects are significant and can explain many of the time-dependent post-seismic effects observed following the Landers earthquake.

3. Aftershocks and Pore Pressure Diffusion

A number of seismic phenomena exhibit time-delayed characteristics. Among these are aftershocks, compound earthquakes, and earthquakes induced by hydrologic forcing due to human activities. Though much work has been done to estimate changes in seismic hazard on faults after a nearby event has occurred, much of this has involved only static elasticity modeling. See, for example, the studies by Stein et al., 1992; 1994; 1997. Since the crust is believed to be saturated with water down to seismogenic depths and since there are many clear examples to demonstrate that the crust behaves as a poroelastic rather than as an elastic medium (e.g., Roeloffs, 1996), pore pressure effects should be considered in order to understand the time-dependent nature of faulting processes.

An example of how pore pressure diffusion might trigger an earthquake is discussed in Scholtz (1990). A compound earthquake consisting of two main shocks 12 hours apart occurred on November 23, 1987 in the Imperial Valley of California. The movement in the first shock would have reduced both the normal stress and the pore pressure on the adjoining perpendicular fault. The pore pressure would immediately begin to increase again due to fluid diffusion from regions where the fluid pressure had increased. Presumably, the normal stress would remain unchanged. Thus, the adjoining fault would become weaker as the pore pressure increased, reaching the failure point 12 hours later.

Pore fluids were first proposed as a mechanism for causing aftershocks by Nur and Booker (1972). The idea is relatively simple: when an earthquake occurs, there is an almost-instantaneous modification to the regional stress field. The change in strength of a fault (or rock) is

$$\Delta S = \mu_f (\bar{\sigma} - p),$$

where μ_f is the coefficient of internal friction or simply the frictional strength, $\bar{\sigma}$ is the mean stress, and p is the pore pressure in the fault. Aftershocks will occur on faults where the shear stress exceeds the strength of the fault. Immediately following an earthquake, the pore pressure is changed by an amount equal to the mean stress induced by the earthquake: $p = \bar{\sigma}$. After the earthquake, pore fluids will flow from regions of high pressure (compressional regions) to regions of low pressure (dilatational regions). The applied mean stress field will remain approximately constant, so the strength of the fault will change over time. The number of aftershocks, according to this theory, is proportional to the time rate of change of pore pressure integrated over a region. Moreover, the theory predicts that aftershocks will occur where the pore pressure is *increasing.*

The Nur and Booker theory has been used together with a computer simulation of pore pressure diffusion following the Landers earthquake to compute theoretical aftershock frequencies in regions near the fault trace. This is compared with measured aftershock frequencies. The computed and measured aftershock frequencies over the entire region around the Landers fault are shown in Figure 3.

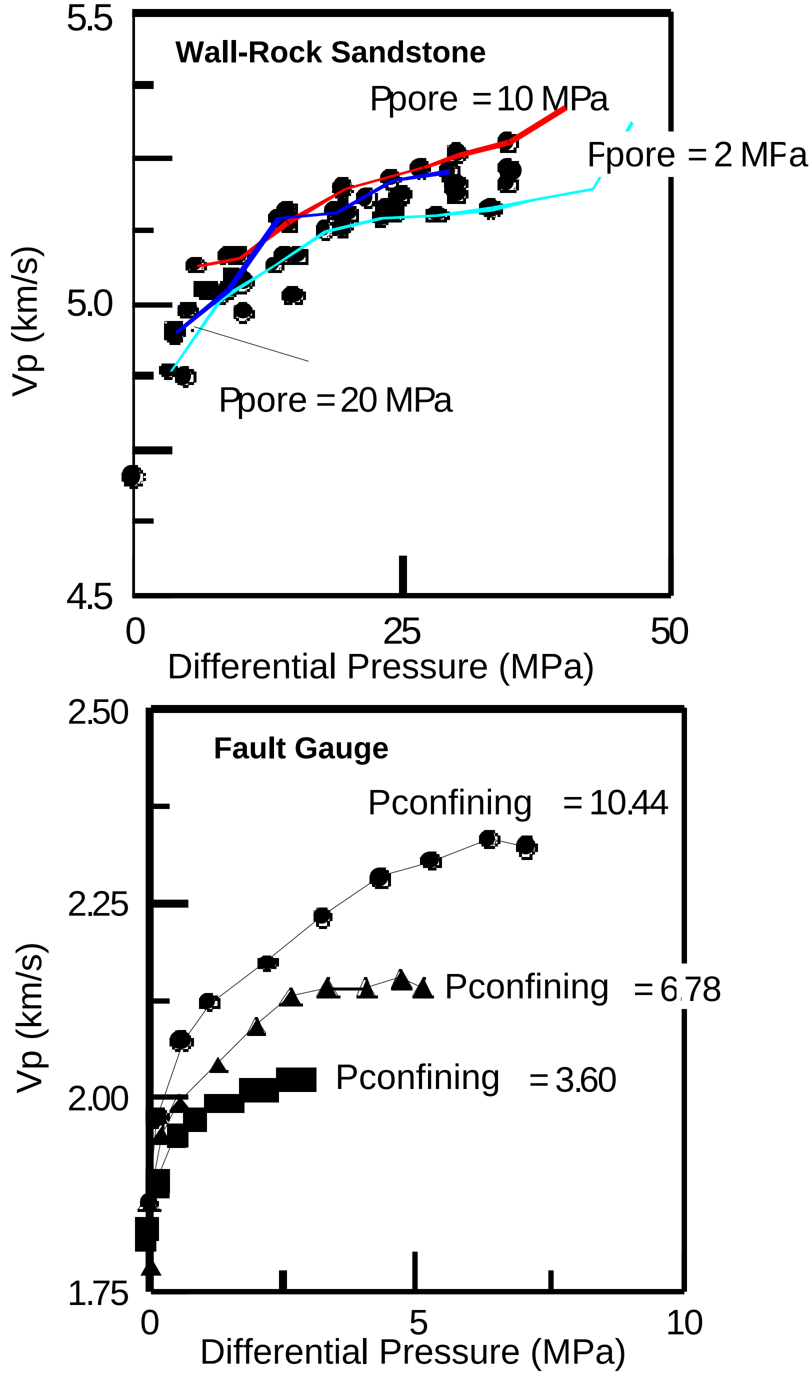

Figure 1. Velocity-Pressure Behavior for Regular Wall-Rock and Fault Gauge. Top: wall-rock sample; bottom: fault gauge sample.

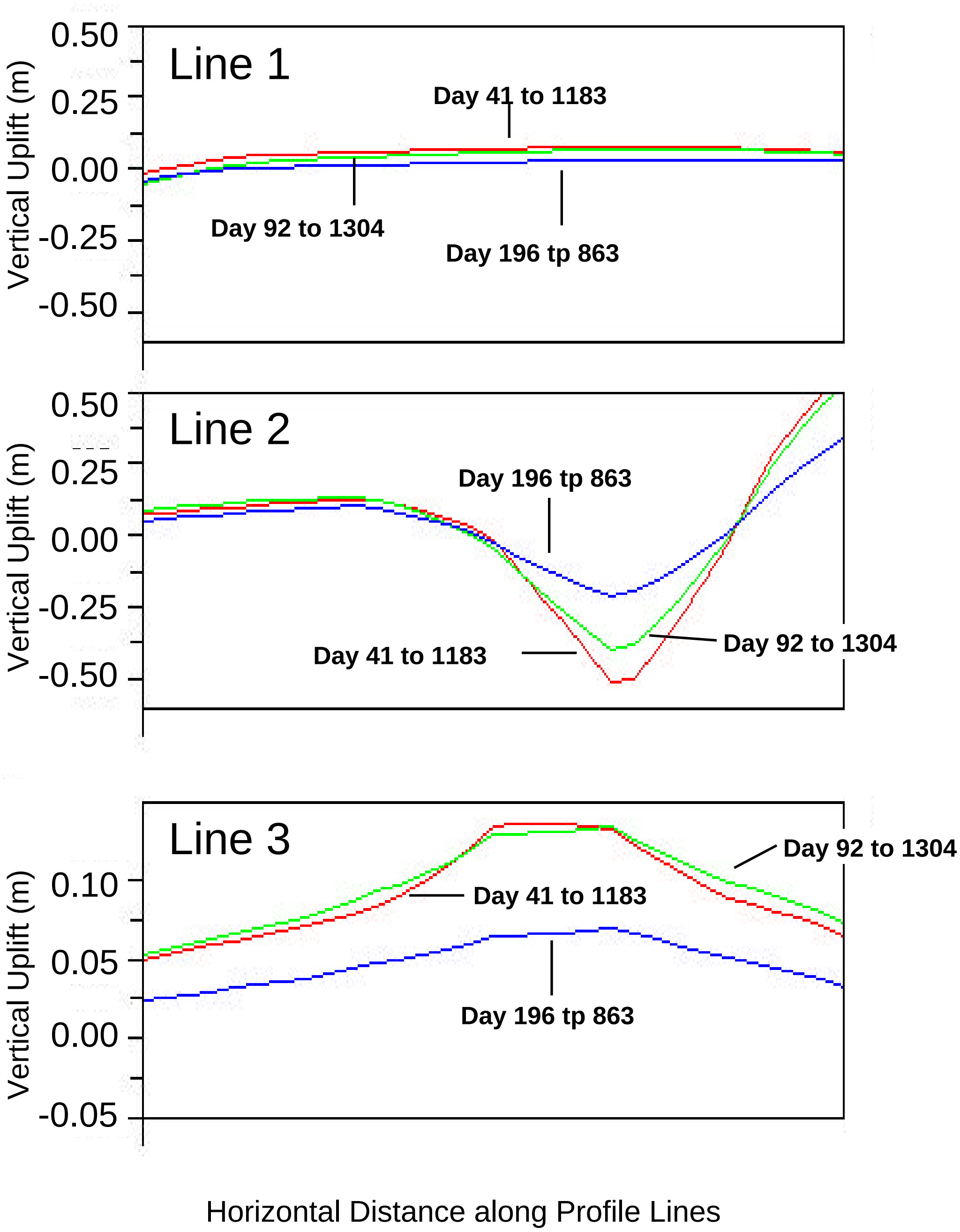

Figure 2. The Role of Fluids in Crustal Stress Evolution Following the 1992 Landers Earthquake. Vertical uplift profiles at three different locations and for different time intervals after the earthquake (as shown in the graphs).

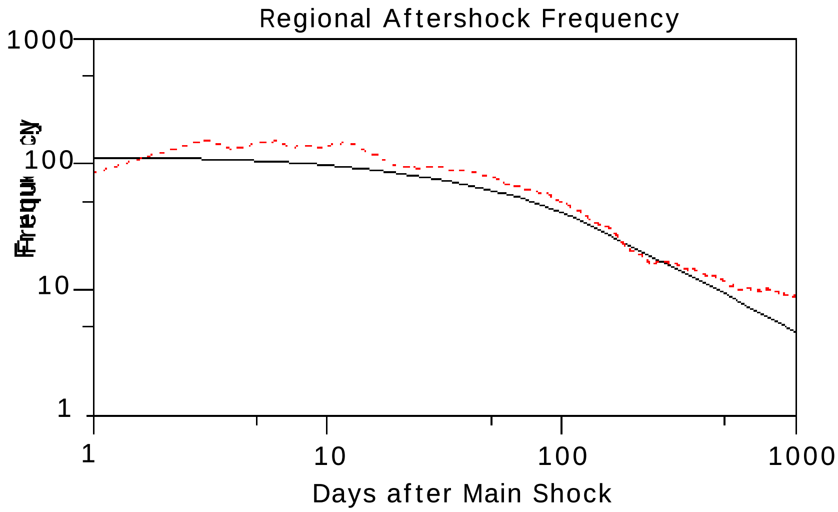

Figure 3. Aftershocks and Pore Pressure. Dotted line: observations; solid line: computer simulation.

Non-Technical Summary

The velocity of seismic waves through the rocks and sediments within seismically-active faults may provide clues to the stresses which govern the occurrence of earthquakes. We are studying how this velocity depends on stress and pore pressure for fault and wall rocks. Laboratory measurements on representative samples indicate that comparing velocities in these rocks may be diagnostic of stress and fluid pressure in the subsurface. We have also modeled the how pore pressure can cause vertical and horizontal movements and cause aftershocks. These results may ultimately lead to improved ability to map out physical conditions inside potentially earthquake-producing fault segments.

Reports published

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