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# FLUID-PRESSURE INDUCED SEISMICITY AT REGIONAL SCALES

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Abstract. The role of high fluid pressure as a seismogenic agent has been the subject of intense study (Hubert and Rubey, 1959; Hanshaw and Bredehoeft, 1968; Healy and Rubey, 1968; Simpson, 1976; Walder and Nur, 1984; Sibson, 1990). Of particular interest is the so-called fault-valve mechanism (Sibson, 1976; Sibson, 1990) a hypothesis whereby fluid pressure rises (as a result of tectonic compression and pore volume reduction) until crustal failure occurs, triggering seismic activity and upward fluid discharge. Sealing and healing of the rock matrix (Richter and Simmons, 1977; Sprunt and Nur, 1979; Angevine et al, 1982) following coseismic stress drop facilitates reaccumulation of fluid pressure, initiating another loading cycle. The fault-valve mechanism is entertained as a plausible explanation for present-day seismic activity in the western Transverse Ranges of California. We provide a quantitative test of the fault-valve hypothesis that uses geologic data and rates of active tectonics for a cross-section through an active fold-and-thrust belt on the flank of a developing mountain range. Rates of fluid pressure buildup and average recurrence times of large earthquakes in the fold-and-thrust belt are estimated to be on the order of $10^4 Pa/yr$ and hundreds of years, respectively.

## Tectonics of the western Transverse Ranges

The western Transverse Ranges of California (see Figure 1) are part of a tectonic and physiographic province characterized by central highlands dominated by uplift, erosion and strike-slip faulting, and flanked by active fold-and-thrust belts (Keller et al, 1987; Namsom and Davis, 1988; Yeats et al; 1988; see Figures 1 and 2). In the northern fold-and-thrust belt the rate of uplift is about 4 mm/yr (Davis, 1983; Namson and Davis, 1988), and the rate of shortening is approximately 10 mm/yr (Seaver, 1986; Keller et al, 1988; Laduzinsky, 1989). In the southern fold-and-thrust belt, uplift is 4 to 8 mm/yr, and the rate of shortening is approximately 10 to 20 mm/yr (Yeats, 1983; Rockwell, 1983; Rockwell et al, 1988). The rate of shortening across the entire range based on geologic and geomorphological data is possibly as great as 20 to 30 mm/yr and tectonic geomorphic evidence suggests that most active folding is on the edges of the fold-and-thrust belts (Keller et al, 1987; Keller et al, 1988).

The western Transverse Ranges were elevated to their present heights almost entirely during Quaternary time and are still actively being uplifted (Dibblee, 1982). Crustal thickening, associated with folding and thrusting, has played an important role in mountain building processes there. Coseismic uplift of the Ranges occurred as a result of the 1952 Kern County earthquake ($M_s = 7.3$, Figure 1). At the topographic front of the Ranges, near Wheeler Ridge, located at the southern end of the San Joaquin Valley, uplift from that event was 0.6 m. Uplift of approximately 0.1 m was observed near Frazier Mountain, which is approximately 25 km to the south of Wheeler Ridge, in the central highlands of the western Transverse Ranges (Logfren, 1966; see Figure 2).



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## A Hypothesis of Fluid Pressure Buildup

### The Fault-valve Mechanism

Given the tectonic convergence rate of 10 mm/yr in the northern fold-and-thrust belt of the western Transverse Ranges, the following mechanism is proposed as the cause of earthquake activity in that belt (the same processes can also be postulated for the southern belt): (i) fluid pressure rises from hydrostatic to lithostatic levels at seismogenic depths (about 10 km) as a result of pore volume reduction; (ii) rock shear strength drops due to higher pore pressure resulting ultimately in crustal failure and the onset of earthquakes; (iii) there is coseismic stress drop and upward discharge of pore fluid along the rupture zone; and (iv) postseismic self-sealing and healing of the rock matrix takes place (Richter and Simmons, 1977; Sprunt and Nur, 1979; Angevine et al, 1982), that, along with sustained tectonic compression, cause fluid pressure to build back to lithostatic level, completing another loading cycle.

Several comments are warranted in regard to the hypothetical mechanism just described. First, fluid pressure decreases the effective stress and crustal failure may occur when the fluid pressure is below lithostatic pressure. Therefore, taking lithostatic pressure as the critical stress loading may be conservative, although it is not unreasonable. Several authors (Fyfe et al, 1978; Sibson, 1990) have shown that in thrust stress regimes, which prevail in the study area, fluid pressures can approach and perhaps exceed lithostatic pressure. Second, average permeabilities considered herein are on the order of $10^{-20} m^2$ to $10^{-18} m^2$ (or 10 to 1000 ndarcy), values that have been documented

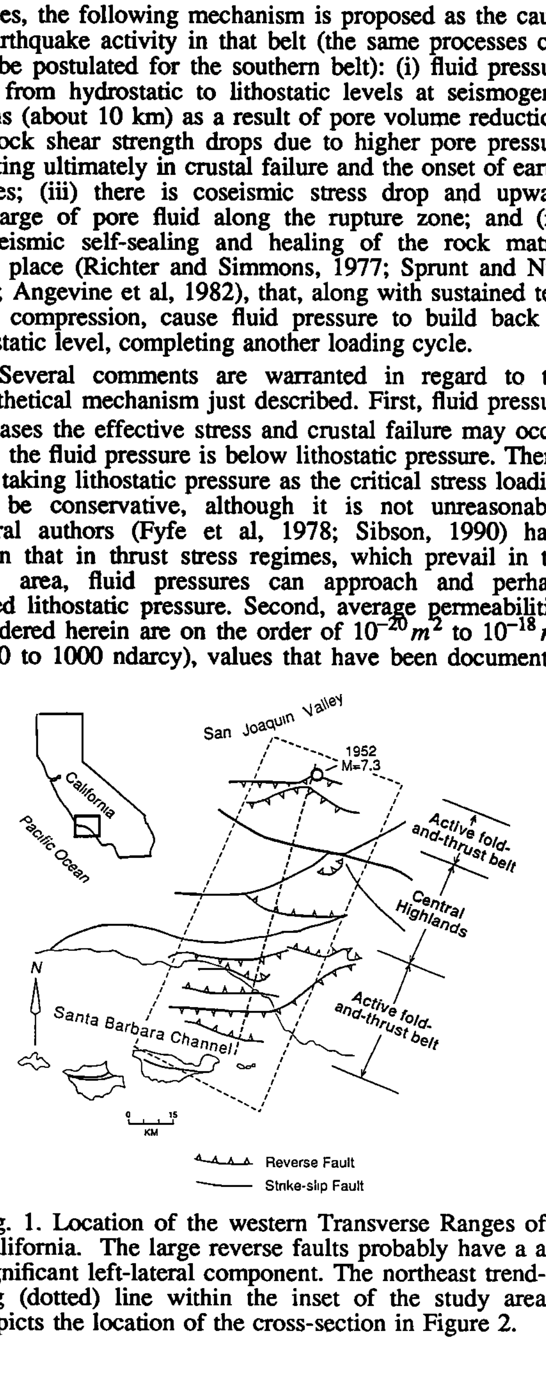


Fig. 1. Location of the western Transverse Ranges of California. The large reverse faults probably have a a significant left-lateral component. The northeast trending (dotted) line within the inset of the study area depicts the location of the cross-section in Figure 2.

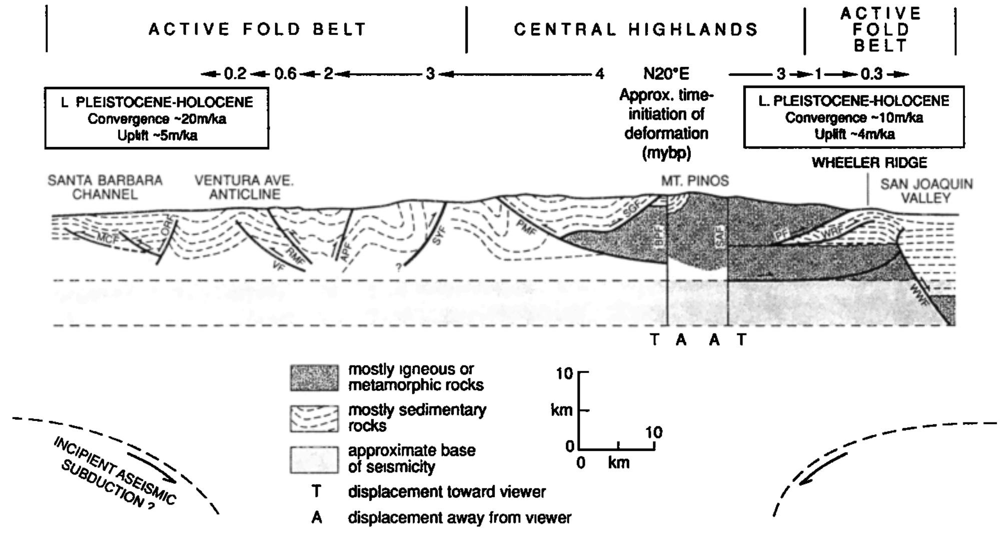


Fig. 2. Generalized geologic section for discussion purposes across the western Transverse Ranges from the Santa Barbara Channel near Ventura N 20 E to Wheeler Ridge near Bakersfield, California. From the San Joaquin Valley to the Santa Barbara Channel, the faults shown are: White Wolf (WWF); Wheeler Ridge (WRF); Pleito (PF); San Andreas (SAF); Big Pine (BPF); San Guillermo (SGF); Pine Mountain (PMF); Santa Ynez (SYF); Arroyo Parida (APF); Red Mountain (RMF); Ventura (VF); Oak Ridge (ORF); and Mid Channel (MCF). Location of the section is shown in Figure 1. Geology is modified from several studies (Yeats, 1981; Dibblee, 1982; Davis, 1983; Keller, 1984; Namson, 1986.)

in the literature (Brace, 1982; Clauser, 1992). In addition, cyclic pressure loading is not a temporally regular process (such as Reid's perfectly periodic model; Shimazake and Nakata, 1980) as might be suggested by the proposed mechanism. In actuality, time-dependent evolution of the stress field and competence of crustal rocks lead to an irregular temporal incidence of earthquakes. Therefore, our model results for average earthquake recurrence must be seen as an approximation to a complex and dynamic phenomena.

## Related Geomorpho-tectonic Evidence in California

The plausability of the fault-valve mechanism in complex oblique reverse strike-slip earthquakes seems to be supported by coseismic and postseismic hydrologic signatures recorded for the $M_s$=7.3 1952 Kern County (Briggs and Troxell, 1955; Rantz, 1962), the $M_s$ = 6.1 1971 San Fernando (Waanamen and Moyle, 1971) and the $M_s$=6.2 1992 Honeydew (R. C. McPherson and L. A. Dengler, personal communication, 1992) earthquakes in California. Interseismic deep ground water release has also been recently documented in similar thrust systems in western California (Unruh et al, 1992). The July 20, 1952, Kern County event was associated with significant stream and spring flow at a variety of locations. For example, in the 658 $km^2$ drainage basin of Sespe Creek near Fillmore, California, some 50 km from the epicenter, discharge increased from 0.48 $m^3/s$ on July 20 to 1.05 $m^3/s$ on July 31. The increase in Sespe Creek discharge is attributed to the July 20 earthquake, and, by September 20, runoff amounted to $2.7x\,10^{-3} km^3$, which was equivalent to 61% of the runoff for the entire previous water year in the Sespe (Briggs and Troxell, 1955). The pattern and volume of water released along and around the faults in the cited California earthquakes are better explained with the fault-valve mechanism than with either the dilatancy (Brace et al, 1966) or coseismic strain (Parry and Bruhn, 1990) models for pore pressure changes during and after earthquakes. In particular, the latter model proposes interseismic crack opening and effective porosity increase, followed by coseismic crack closure and water expulsion in extensional (normal) faulting. The opposite mechanism is believed to occur in compressional (reverse) faulting, and, in consequence, the coseismic strain model predicts a decrease in surficial water levels (e.g., water levels in well, river runoff and spring flow) during reverse faulting earthquakes. The opposite effect has been observed in the cited Kern County, San Fernando and Honeydew earthquakes of California, contradicting the notion that compressional stress regimes characteristically lead to a drop of surficial water levels.

## Pore Volume Reduction

Based on the regional tectonic setting of the northern fold-and-thrust belt of the western Transverse Ranges, a cross-section parallel to that shown in Figure 2 is isolated for the purpose of analysis. The cross-section of the mountain analyzed here (occupying the area north of the San Andreas fault to the White Wolf fault in the western Transverse Ranges, see Figure 2) has a length of 25 km (based on observed coseismic uplift from the 1952, $M_s$=7.3, Kern County event), a depth of about 10 km (which is compatible with known seismogenic depths in this area), and, without loss of generality, a unit thickness of 0.001 km (1 m). Tectonic convergence occurs along the longitudinal axis of the (unit) mountain section at an average rate of 10 mm/yr, with a strain rate of approximately $10^{-14}\ s^{-1}$ (Keller et al, 1988). The volumetric compression, $\Delta V$, in the (unit) mountain section is then calculated and rounded within our order-of-magnitude treatment to be $50\ m^3/yr$. The bulk matrix is composed of water and mineral grains, with compressibilities of $\alpha_w = 5x\,10^{-10} Pa^{-1}$ and $\alpha_q = 2x\,10^{-11} Pa^{-1}$, respectively (Marsily, 1986). Because the compressibility of water is more than an order of magnitude larger than that of the mineral matrix the volumetric decrease is accommodated at the microscopic level mainly by reduction of pore volume, $\Delta V_w$, i.e., $\Delta V_w \approx \Delta V$.

Tectonic reduction of pore volume and low permeability permit the accumulation of fluid pressure. Mineral deposition in extensional cracks is assumed to prevent fluid drainage as the fluid pressure, $P_w$, rises (see, e.g., numerical calculations in Walder and Nur, 1984, and Bruhn et al, 1990). Based on Darcy's law the (annual) volume of fluid expelled upward in the unit mountain section, $\Delta V_d$, is given by:

$$\Delta V_d = L\ (k \rho_o\, g/\mu) \frac{\partial}{\partial z}\left[\frac{P_w}{\gamma} - z\right] \qquad (1)$$

where $L$ is the length of the unit section (25 km); $k$ is the average permeability (varied from $10^{-20}$ to $10^{-18}$ $m^2$ in our calculations to explore the role of permeability variations at seismogenic depths according to range of permeability values documented in the literature, Brace, 1980; Clauser, 1992); $\rho_o$ is the water density under hydrostatic conditions ($10^3\,kg/m^3$); $g$ is the acceleration of gravity ($9.8\,m/s^2$); $\mu$ is the viscosity of water ($10^{-3}\,kg/m\,s$); $P_w$ is the pore pressure in Newtons per squared meter; $z$ represents the vertical coordinate (varying from 0 to 10 km); and $\gamma\,(=\rho_o\,g)$ denotes the unit weight of water ($10^4\,kg/m^2s^2$). Given all the parameters in equation 1, it follows that the volume of fluid drained vertically as a result of the hydraulic gradient, $\Delta V_d$, is negligible relative to the volumetric compression of water, $\Delta V_w$, for all values of the variable z and attainable fluid pressures. The low water drainage is a direct consequence of the low permeabilities presumed to prevail at seismogenic depths in the study area.

## Energy Balance Considerations

In addition to coseismic water discharge (on the order of $10^2\,m^3$ in the unit mountain section for the 1952 earthquake (Briggs and Troxell, 1955; Rantz, 1962), measurement of high fluid pressure in the southern San Joaquin Valley (Berry, 1973; Sibson, 1990), and coseismic water table rise (Bruhn, 1990), energy-balance estimates suggest the likely seismogenic role of fluid pressure. For instance, considering earthquakes of magnitude similar to the 7.3 event of 1952, the Gutenberg-Richter relationship between seismic energy and surface-wave magnitude (Scholz, 1990) yields an approximate radiated energy on the order of $10^{12}$ Joules over the unit mountain section. Given the dimensions of the unit section and a density of granite of $2.5\,x\,10^3\,kg/m^3$, the work (or mechanical energy) needed to produce an average uplift of 100 mm is also on the order of $10^{12}$ Joules. Given the complex energy partition generated by an earthquake (frictional, kinetic, strain, surface rupture), it is unlikely that the radiated seismic energy will be totally consumed in mountain uplift (i.e., as mechanical energy). This suggests that some mechanism other than those driven by seismic energy, such as the hydraulic role of crustal fluid, must be contributing to coseismic uplift in the western Transverse Ranges.

## The Rate of Fluid Pressure Buildup

The link between pore volume reduction and fluid pressure rise is given by the following constitutive relationship (Marsily, 1986):

$$\rho_w = \rho_o\, e^{\alpha_w (P_w - P_o)} \tag{2}$$

in which $\rho_w$ is the density of water at the fluid pressure $P_w$; $\rho_o$ and $P_o$ denote the hydrostatic water density and pressure, respectively; $\alpha_w$ represents the water compressibility. Water density is related to water mass, $m_w$, and volume, $V_w$, by $\rho_w = m_w / V_w$. (Given the dimensions of the unit mountain section and a bulk porosity of $10^{-2}$, the mass of pore water is on the order of $2.5\,x\,10^9\,kg$).

As the pore volume is reduced by tectonic convergence, the water density and fluid pressure increase. The exact form of the relationship between water compression and fluid pressure rise follows from equation (2) after writing the density of water in terms of the volume and mass of water, and differentiating the resulting expresssion with respect to the fluid pressure $P_w$ to yield the fundamental result (where $\Delta P = P_w - P_o$):

$$\Delta V_w = -(m_w/\rho_o)\,\alpha_w\, e^{-\alpha_w (\Delta P)}(\Delta P) \tag{3}$$

All the parameters and variables in equation (3) have been defined and assigned numerical values previously, except for the unknown $\Delta P$, the average rate of pressure increase. Solution of equation (3) yields the average rate of pressure increase concomitant with tectonic shortening of the unit mountain section. The numerical solution of equation (3) yielded two roots, only one of which is physically meaningful, and is on the order of $10^4\,Pa/yr$. The time to build up pressure from hydrostatic to lithostatic level at seismogenic depth (10 km) given the rate of pressure increase of $10^4\,Pa/yr$ is tens of thousands of years ($10^4$ years). (Simply divide the difference between lithostatic and hydrostatic pressures at seismogenic depths by the average rate of pressure increase). Upon faulting, there is a coseismic shear stress drop of about $10^7\,Pa$, estimated from the 1952 event of magnitude 7.3 (T. K. Rockwell, personal communication, 1991). If it is assumed that crustal stress unloading and postseismic fluid transport equalizes the fluid pressure drop with the stress drop (Rice and Cleary, 1976), the subsequent reaccumulation of fluid pressure (due to sustained crustal compression and self-sealing and healing) to the lithostatic level takes an average time on the order of hundreds of years, completing the loading cycle in the northern flank of the western Transverse Ranges. The average recurrence of the 1952, $M_s$=7.3, Kern County (California) event was estimated from tectonic-geomorphic evaluation of the Pleito fault system (see Figure 2) to be from 300 to 500 years (Keller et al, 1988). For the fault-valve process we have postulated to work the loci of folding must migrate with time incorporating new material to be shortened. In the northern flank of the western Transverse Ranges the topographic expression of the loci of tectonic activity associated with the Pleito fault system (see Figure 2) has apparently migrated northward during late Pleistocene (Keller et al, 1988). If this surficial evidence reflects a similar phenomenom at depth, then, over a time frame of $10^5$ to $10^6$ years, new crustal material is being folded allowing continued accretion of rock, and pore fluid, in the northern edge of the fold-and-thrust belt).

## Conclusions

The above average times are only order of magnitude approximations to processes that have significant temporal variability. Earthquake recurrence is not a perfectly periodic process. Our calculations suggest the possible nature and extent of coupling fluid pressure rise to seismic activity, as well as likely orders of magnitude of time scales over which these phenomena occur. The robustness of the data on rock and water properties and tectonic convergence suggests that the order of magnitude results obtained are also robust (i.e., relatively small changes in any one parameter do not produce a drastic change in the calculated pressure buildup rates and recurrence times). From a geologic standpoint, the calculated fluid pressure buildup and average recurrence times appear to be reasonable. Those calculations are not intended to demonstrate that the mechanism of earthquake onset in the western Transverse Ranges is fully explained by the process of fluid pressure buildup. However, the set of available data, coupled with a simple model based on a seismogenic process that has been verified at smaller tectonic scales (Raleigh et al, 1976), provides reasonable evidence that the fault-valve mechanism is a plausible explanation for significant seismic activity at regional tectonic scales.

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