

**Site Velocities Before and After the Loma Prieta
and Gulf of Alaska Earthquakes Estimated From VLBI**

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Abstract

We use VLBI data to determine the preseismic and postseismic velocities of two sites affected by earthquakes. We use the results to limit the degree of variation in strain buildup between great earthquakes. The 1987 and 1988 Gulf of Alaska earthquakes ($M_s=7.6$ each) ruptured the Pacific plate interior. During the earthquakes the Cape Yakataga site, which lies 80 km north of the ruptured lithosphere, moved 78 mm toward the southwest. At the time of the 1989 Loma Prieta earthquake ($M_s=7.1$) the Fort Ord site, which lies 40 km south of the rupture, moved 48 mm toward the north. Components of baselines (1) between Cape Yakataga and Fairbanks and (2) between Fort Ord and Mojave change at the same rate, to within errors, after as before the earthquakes. Postseismic transient effects due to asthenospheric relaxation or deep fault slip (and inferred from differences between the postseismic and preseismic rates) are minor, being 3 ± 7 mm at Cape Yakataga in a 23-month period after the Gulf of Alaska earthquakes and 6 ± 5 mm at Fort Ord in a 21-month interval after the Loma Prieta earthquake. The postseismic transient at Fort Ord corresponds to deep fault slip beneath the Loma Prieta rupture of 0.17 ± 0.15 m. The upper bound (0.46 m) on the postseismic deep slip is one-quarter the observed coseismic slip (2 m). The results suggest that the variation in strain buildup is not great. The characteristic time describing the exponential decay in deep fault slip can be no shorter than 7 years. In sum, the results are consistent with uniform strain buildup in the seismic cycle. They disagree with very fast postseismic strain rates due to an asthenosphere with very low viscosity.

Introduction

The degree of variation in the rate of elastic strain buildup in the time between earthquakes has important implications for the timing of earthquake occurrence and the physical mechanism of strain buildup. The simplest hypothesis [cf. Savage, 1983] is that elastic strain builds up steadily in the time between great earthquakes; during great earthquakes all the strain is released. That the strain rate after an earthquake is faster than the mean interseismic strain rate was postulated by Thatcher [1983]. Fast postseismic strain rates are attributable to either viscous relaxation of the asthenosphere or deep fault slip after the earthquake [Savage, 1990].

Evidence for the existence of postseismic transients in strike-slip regimes comes mainly from triangulation data taken in the two decades after the great 1906 San Franciscan earthquake. This earthquake, with surface wave magnitude of 8, resulted in about 4 meters of right-lateral strike-slip along the San Andreas fault between San Juan Batista and Point Arena. Triangulation data from sites no more than 12 kilometers from the

fault taken in the two decades following the earthquake record shear strain rates ($2.5 \mu\text{strain/yr}$) about three times faster than the mean interseismic rate ($0.8 \mu\text{strain/yr}$) [Thatcher 1975, 1983]. Thatcher's analysis of fits of elastic models to these data suggest that during the two decades after the earthquake the shallow part of the fault was locked but the parts deeper than 10 km slipped about 4 meters, an amount equal to the coseismic slip.

Herein we examine the time evolution of components of two baselines affected by the 1989 Loma Prieta and the 1987 and 1988 Gulf of Alaska earthquakes. The two sites that moved at the time of the earthquakes, Fort Ord and Cape Yakataga, lie about eight times farther from their rupture areas than the triangulation sites analyzed by Thatcher [1975]. But the sites lie near enough to the rupture to be sensitive to deep fault slip. We find that components of baselines change at the same rate, to within errors, after as before the earthquakes. That the rates appear slightly faster after than before the earthquakes suggests that there may be minor postseismic transients due to either asthenospheric relaxation or deep fault slip.

Results

Gulf of Alaska

Earthquakes with surface wave magnitude of 7.6 broke the Pacific plate interior in the Gulf of Alaska in November 1987, and again in March 1988 (Fig. 1). Fault plane solutions and aftershocks [Lahr et al., 1988] record right-lateral strike-slip along a north-striking vertical fault. The Cape Yakataga–Fairbanks baseline (Fig. 2) clearly records abrupt motion during the earthquake [Ma et al., 1990]. Other baselines to Fairbanks exhibit no offsets, so Cape Yakataga is the site that moved.

From VLBI solution GLB868 [Ryan et al., 1993], we estimated the coseismic offsets, preseismic rates, and postseismic rates of the length and transverse components of the Cape Yakataga–Fairbanks baseline (Table 1). During the earthquakes the Cape Yakataga radio telescope site, located 80 km north of the northern end of the rupture, moved 78.0 ± 3.5 mm toward $S47^\circ W$. (Uncertainties quoted after the “ \pm ” are standard errors ($\pm 1\sigma$)). An elastic model predicts, assuming right-lateral strike-slip along a north-striking vertical fault, that the site moves due west, in a direction more westerly than the observed coseismic motion. The coseismic motion of Sourdough is of marginal significance. Its estimated coseismic motion (17.7 ± 7.4 mm toward $N41^\circ E$) is in the opposite direction of Cape Yakataga's motion.

We determined the postseismic rates of the two components of the Cape Yakataga–Fairbanks baseline from 3 measurements taken 4 months after the second earthquake, 3 observations taken 16 months after that earthquake, and 2 data taken 27 months after it. The postseismic rates equal, to within errors, the preseismic rates. The results do not disagree with uniform strain buildup throughout the interseismic period. We estimated the total postseismic transient for each component from the difference between the postseismic and preseismic rates multiplied by the length of the postseismic interval. The postseismic transient recorded in the 23 month period after the earthquake is 2.9 ± 6.9 mm (in the transverse component). This value differs insignificantly from zero and its upper bound (16.4 mm) is one-fifth of the observed offset. (Bounds quoted correspond to two-sided 95% confidence limits ($\pm 1.96\sigma$)).

Loma Prieta Earthquake

The Loma Prieta earthquake of 17 October 1989, with surface wave magnitude 7.1, generated right-lateral reverse slip of 2 meters [Lisowski et al., 1990] along a 37-km-long segment of a steeply dipping fault adjacent to the San Andreas fault (Fig. 3). At the time of the earthquake the Fort Ord radio telescope site, located 41 km south of the southeastern end of the rupture, abruptly moved 47.5 ± 3.8 mm toward $N11^\circ E$. The offsets we estimate nearly equal those previously estimated by Clark et al. [1990]. The coseismic motion of the Presidio site during the Loma Prieta earthquake (10.7 ± 7.8 mm toward $S25^\circ E$) is statistically insignificant, although its best estimate parallels that predicted from the elastic model of coseismic motions. The elastic model predicts, assuming the geodetically-determined parameters of Lisowski et al. [1990], that Fort Ord moved 56.4 mm toward $N01^\circ E$, slightly more than observed, and that Presidio moved 9.6 mm toward $S03^\circ W$, a motion roughly equal to that observed.

We estimated the postseismic rates of the two components of the Fort Ord–Mojave baseline from 9 measurements taken 1 to 4 weeks after the earthquake, 2 observations taken 3 months after the earthquake, and 2 data taken 21 months after it. The earthquake offset is recorded mainly by the transverse component (Fig. 4), which has an azimuth of $N17^\circ E$ at Fort Ord. The rate of change of this component after the earthquakes equals to within errors the rate before the earthquake, though the component appears to change at a slightly faster rate (by 3.6 ± 3.1 mm/yr) after than before the earthquake. The total amount of change of the component in the 20 month postseismic period exceeds the amount predicted from the preseismic rate by 6.0 ± 5.2 mm, one-eighth of the coseismic offset of this component. The upper bound on the total component change is 16.2 mm, one-third of the coseismic offset. Thus, we cannot dismiss the hypothesis that deformation rates are uniform throughout the seismic cycle, but the

best estimate favors the existence of a minor postseismic transient.

Interpretation

Limits on Postseismic Deformation

Variation in strain buildup at the surface of an elastic plate overlying a viscoelastic asthenosphere can be duplicated (Fig. 5) by an equivalent elastic dislocation model [Savage, 1990]. In the equivalent model the postseismic transient is due mainly to slip immediately beneath the segment of the fault ruptured by the earthquake. The shallow fault in the elastic plate slips only at the time of the earthquake, slip is steady on the very deep fault, and the fault at intermediate depths accommodates differences between the shallow and very deep slip.

Herein we loosely adopt Savage's equivalent elastic model. The situation at Loma Prieta differs from the model in Fig. 5 in that (1) the fault dips steeply to the southwest and (2) the real rupture zone is not infinitely long. The Fort Ord site lies far south of the rupture zone, making it necessary to use three-dimensional elastic models [Mansinha and Smylie, 1971] to relate the postseismic transient at Fort Ord to deep slip beneath the fault segment broken by the earthquake. In contrast, that Thatcher's [1975] triangulation sites are no more than 12 km from the fault rupture allowed his use of 2-D elastic models. That the physical mechanism in Savage's and our cases are the same make this extension plausible.

How much deep slip is needed to generate the observed postseismic transient? Surface motions after the earthquake are dominated by slip between H (17.5 km) and $3H$. Slip in this depth interval of 0.17 ± 0.15 m, in the same ratio of thrust to right-slip observed in the earthquake, results in Fort Ord motion at 6.0 ± 5.2 mm toward $N03^\circ W$, nearly equal to the inferred postseismic transient (6.0 mm toward $N12^\circ E$). The best estimate of the deep slip is one-twelfth the observed coseismic slip. The upper bound (0.46 m) on the postseismic deep slip is one-quarter the earthquake slip.

Slip in the interval from H to $3H$ evolves as an exponential function [Equations 2 and 3 of Savage, 1990]. For times immediately after the earthquake the deep slip evolves nearly linearly with time, and the following equation can be derived:

$$\frac{u_{post}}{u_{co}} = \frac{t_1}{\tau} \quad (1)$$

where u_{co} is the coseismic slip, u_{post} is the postseismic deep slip in the time t_1 immediately following the earthquake, and τ is the characteristic time describing the

exponential decay in deep fault slip. To establish the minimum characteristic time, we substitute the ratio between the upper bound on postseismic deep slip and the coseismic slip:

$$\tau = \frac{2 \text{ m}}{0.46 \text{ m}} \times 1.67 \text{ years} = 7.3 \text{ years} \quad (2)$$

To find the best estimate of the characteristic time, we input the best estimate of the deep slip:

$$\tau = \frac{2 \text{ m}}{0.17 \text{ m}} \times 1.67 \text{ years} = 19.6 \text{ years} \quad (3)$$

The characteristic time of the postseismic transient is no less than 7 years. The best estimate of its value is 20 years.

How does the amount of the postseismic transient observed after the Loma Prieta event compare to that observed after the 1906 San Franciscan earthquake? Triangulation measurements were taken in 1906 immediately after the earthquake but not again until 1925 or 1930, so Thatcher [1975] could not distinguish whether the postseismic transient occurred in the first five years after the earthquake or throughout the 20 year interval. If all 4 meters of slip inferred along the deep part of the fault [Thatcher, 1975] occurred in the first 5 years after the 1906 earthquake, and if the San Franciscan and Loma Prieta earthquakes generated postseismic transients proportional to their coseismic motions, then we would expect to see faster postseismic rates in the transverse component of the Fort Ord–Mojave baseline. On the other hand, if the San Franciscan postseismic transient had a characteristic time of more than about 5 years, then the limits in the postseismic transient derived from the Fort Ord data would be consistent with those of Thatcher.

Conclusions

Components of baselines (1) between Cape Yakataga and Fairbanks and (2) between Fort Ord and Mojave change at the same rate, to within errors, after as before the earthquakes. Any postseismic transient effects due to asthenospheric relaxation or deep fault slip (and inferred from differences between the postseismic and preseismic rates) are minor. The results suggest that the variation in strain buildup is not great. They disagree with very fast postseismic strain rates due to an asthenosphere with very low viscosity. We look forward to future constraints on the size of the postseismic transient from GPS results from data taken in the years immediately following the Loma Prieta earthquake.

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Figure Captions

Fig. 1. Radio telescope sites (open triangles), rupture zones broken by the great Gulf of Alaska earthquakes (oblongs), and faults taking up plate boundary zone deformation. The velocity of the Pacific plate relative to the North American plate is illustrated with open arrows, with adjacent numbers giving speeds in mm/yr. At Cape Yakataga, Pacific-North American plate motion is taken up mainly at the shelf edge structure and along the Fairweather and Chugach Saint Elias faults [Perez and Jacob, 1975].

Fig. 2. Evolution in time of the length and transverse components of the Cape Yakataga–Fairbanks baseline. Lines fit to data either before or after the Gulf of Alaskan earthquakes are dashed.

Fig. 3. Radio telescope sites (open triangles), the surface projection of the rupture zone broken by the Loma Prieta earthquake, and major faults. Contours show the horizontal surface motion generated by 2 meters of slip along the deep fault immediately beneath the Loma Prieta earthquake; motions are in mm. The velocity of the Pacific plate relative to the Sierra Nevada–Great Valley microplate [Argus and Gordon, manuscript in preparation] is illustrated with open arrows; speeds are in mm/yr.

Fig. 4. Evolution in time of the length and transverse components of the Fort Ord–Mojave baseline. Lines fit to data either before or after the Loma Prieta earthquake are dashed. The Fort Ord site marker was moved by man 9 km southward 15 months before the earthquake. We solved for the tie between markers: 4 parameters (slope, intercept, coseismic offset, and marker movement) were fit to the length and transverse data, then observations before the earthquake (triangles) were shifted by the estimated tie to put them in line with observations after the earthquake (circles). The preseismic rates we estimate are from only the first marker.

Fig. 5. The slip distribution in the equivalent elastic model that produces the same surface deformation as the lithosphere–asthenosphere model with characteristic time equal to one-fifth of the recurrence interval. Curves show the slip distribution as a function of time for three depth intervals, $H-3H$, $3H-5H$, and $5H-7H$; straight lines show the slip distribution if strain builds up steadily. “ R ” is the recurrence interval, “ v ” is the mean slip rate, and “ t ” is time since the earthquake. After Savage [1990].

Table 1. Baseline Component Rates and Offsets

	Before mm/yr	After mm/yr	Diff mm/yr	Offset mm	Post mm
<i>Cape Yakataga-Fairbanks</i>					
L	-32.3±2.2	-32.7±4.8	0.4±3.8	26.5±5.6	0.8±7.5
T	3.3±1.3	4.8±1.7	1.5±3.5	73.4±3.2	2.9±6.9
<i>Fort Ord-Mojave</i>					
L	33.6±1.6	33.9±1.6	0.3±2.3	4.2±3.8	0.5±3.8
T	19.4±1.8	23.0±2.5	3.6±3.1	47.3±4.5	6.0±5.2

"L" and "T" are the length and transverse components, respectively. "Before" and "After" are rates of baseline component change in the preseismic and postseismic periods, respectively. "Diff" is the difference between these two rates. "Offset" is the earthquake offset in the baseline component. "Post" is the postseismic transient, calculated by multiplying the difference between preseismic and postseismic rates by the length of the postseismic period. Uncertainties are $\pm 1\sigma$. We computed values of coseismic movements assuming the same rates of baseline component change after as before earthquakes. The Cape Yakataga-Fairbanks baseline is oriented N23°W at Cape Yakataga. The Fort Ord-Mojave baseline is oriented N73°W at Fort Ord.

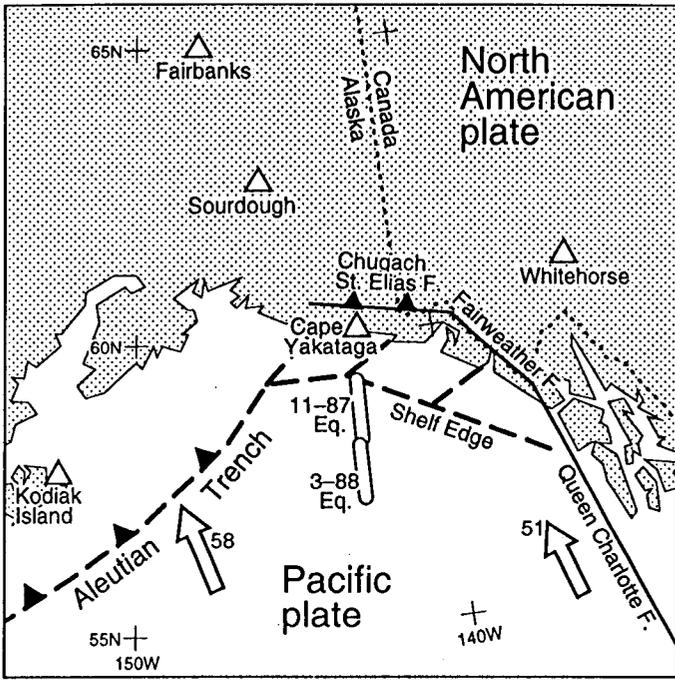


Fig. 1

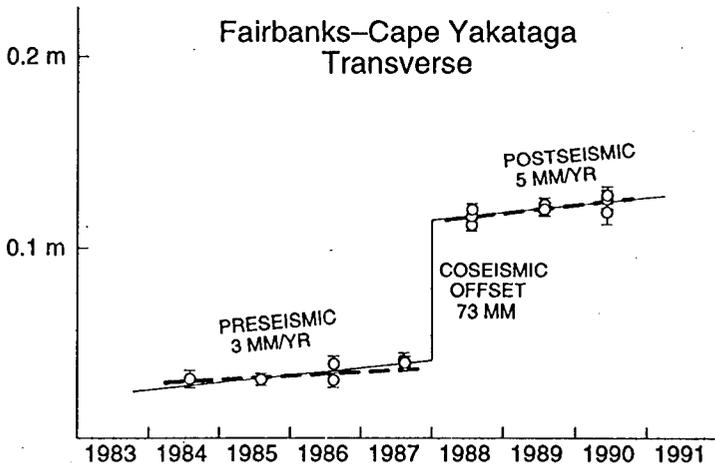
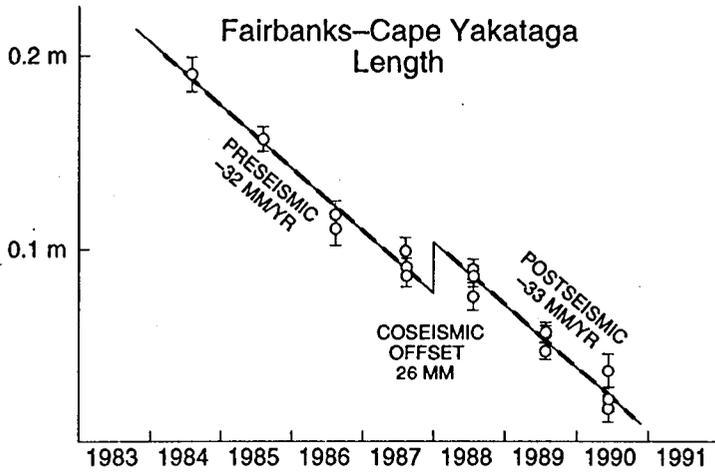


Fig. 2

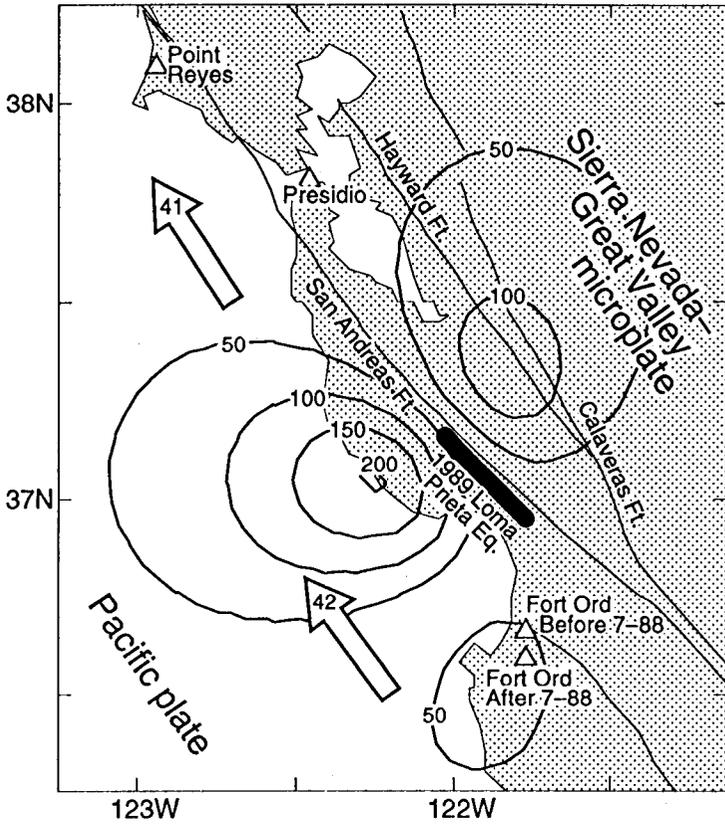


Fig. 3

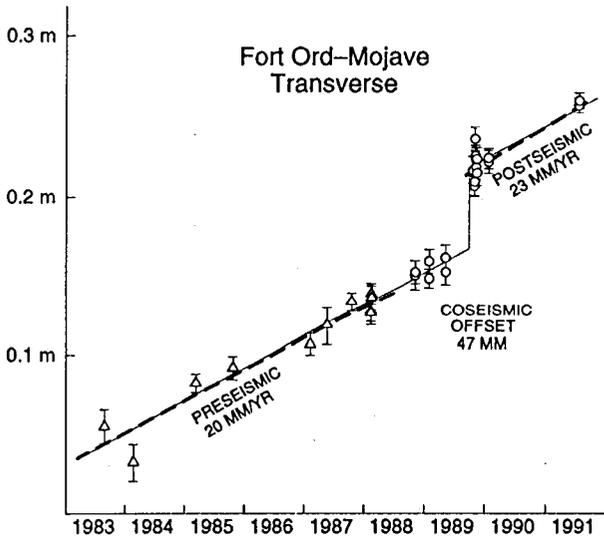
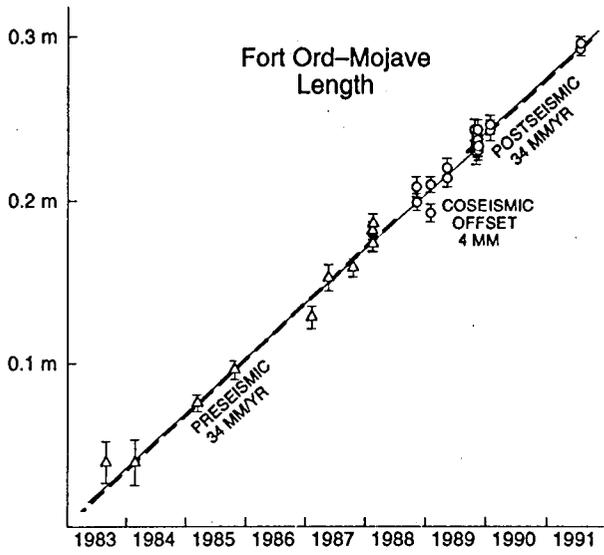


Fig. 4

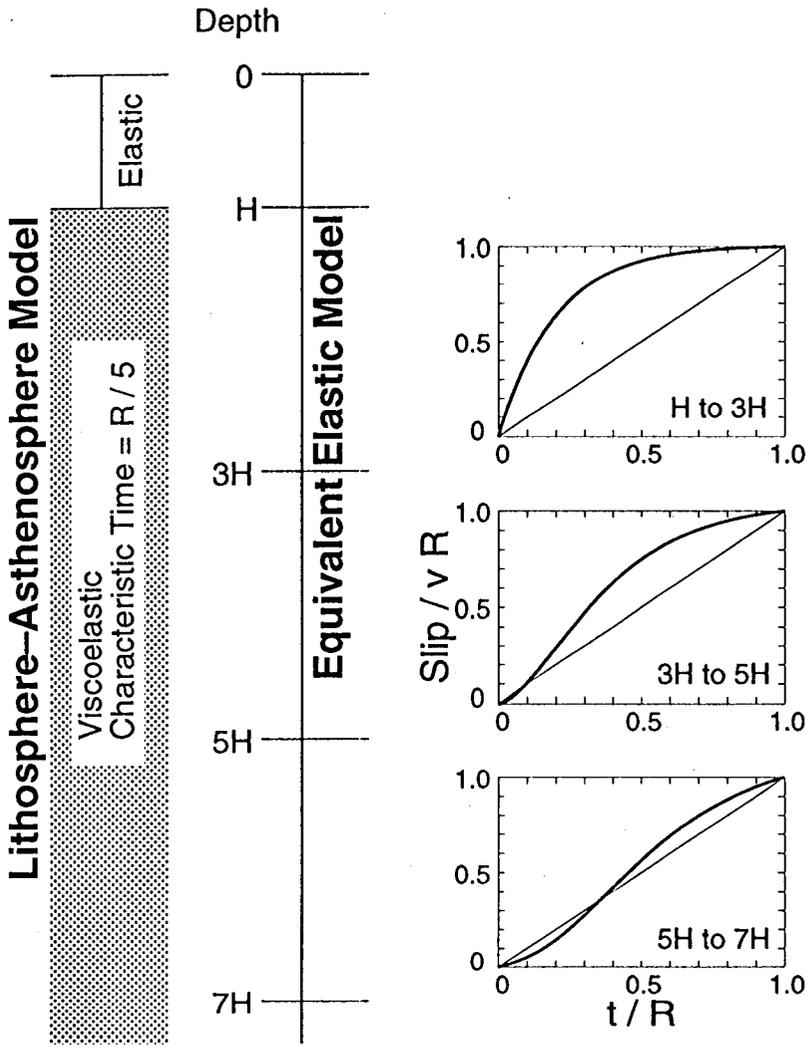


Fig. 5