rapidly by biological effects of nutrient enrichment. (iii) Silica-limited steady states have developed in Lake Ontario and Lake Erie and possibly since 1970 in Lake Michigan. (iv) Lake Huron with recent increases in BSI storage may be in a transition between steady states (*3, 10*), whereas silica dynamics have been affected least in Lake Superior where phosphorus enrichment has been least (Table 1).

Initial and subsequent silica steady states differ greatly in relation to associated phytoplankton dynamics. During the early state associated with presettlement phosphorus loadings (Fig. 1), there is surplus silica throughout the year for the predominant oligotrophic diatom assemblages (*3, 21*), whereas during subsequent states diatom growth is limited, at least during part of the year, by supplies of silica and is dependent mainly on recycled silica (*4, 22*).

Noted added in proof: A recent report concluded that the Schelske-Stoermer silica-depletion hypothesis is clearly "undemonstrable in Lake Michigan" (*23*, p. 459) [a similar argument was used in litigation between Milwaukee and Illinois (*23*)]. These results (*23*) were based on data from the Chicago water filtration plant and completely ignored the water-column data from the open lake, which were the main basis for our conclusion that the silica concentrations of Lake Michigan had decreased (*2*). These water-column data indicate that the summer hypolimnetic and winter maximum silica concentrations decreased as much as 3.0 mg $liter^{-1}$ between 1954 and 1969 (*2, 22*). The silica-depletion hypothesis is supported strongly by open lake water-column data (*2*) and by the sedimentary evidence presented here.

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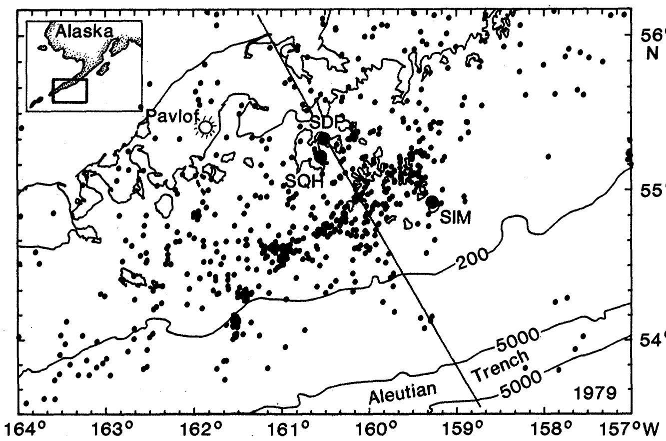
Tilt and Seismicity Changes in the Shumagin Seismic Gap

Abstract. *Changes in the ground surface tilt and in the rate of seismicity indicate that an aseismic deformation event may have occurred between 1978 and 1980 along the plate boundary in the eastern Aleutians, Alaska, within the Shumagin seismic gap. Pavlof Volcano was unusually quiescent during this period. The proposed event would cause an increase of stress on the shallow locked portion of the plate boundary, bringing it closer to rupture in a great earthquake.*

The portion of the Pacific–North American plate boundary in the Shumagin Islands region of the eastern Aleutians has been identified as a seismic gap where a great earthquake (moment magnitude $M_w \approx 8.4$) is expected to occur within the next two decades (*1*). Great earthquakes occurred within the gap in 1788, 1847, and possibly in 1903. The elapsed time (80 to 140 years) since the last great shock is of the same order as estimates of average recurrence times at this plate boundary (60 to 80 years) (*2*). A 10-year record of seismic and geodetic data indicates that an episodic strain release occurred during 1978 and 1979 between the overriding and the subducting plate at depths below 20 km, accompanied by increased regional seismicity and a quiescence of the eruptive activity of Pavlof Volcano.

The Shumagin Islands extend halfway between the volcanic arc and the trench axis (Fig. 1). Hence, leveling lines on the islands are well suited to detect possible tilt changes resulting from deformation along the plate boundary. Data from one line (SQH) releveled nine times since 1972 and another line (SDP) releveled annually since 1977 (*3*) indicate that surface deformation in the Shumagin Islands shows a steady tilt downward toward the trench through 1982, interrupted by a rapid tilt reversal in 1978 to 1980 (Fig. 2a) that is significant at the 99 percent confidence level. Data from a line (SIM) releveled annually since 1978 in the outer Shumagins show a similar reversal, although of smaller magnitude. Even though each data set shows considerable scatter, the fact that all have similar temporal character suggests that the



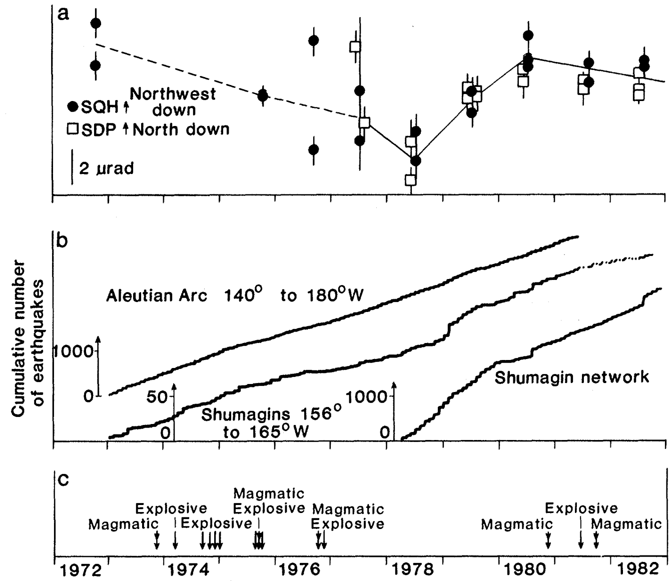


Fig. 1 (left). Earthquakes located by the Lamont-Doherty Geological Observatory Shumagin network in 1979 during the proposed slip event. The diagonal line is explained in Fig. 3. Leveling lines are located at SQH, SIM, and SDP. Fig. 2 (right). Time series of independent data sets that show anomalous changes in 1978 and 1979. (a) Tilt in the Shumagins derived from two short leveling lines SQH and SDP (Figs. 1 and 3). The error bars are $\pm 1\ \sigma$. The tilt rate from 1972 to 1978 at line SQH is 0.9 ± 0.3 μrad $year^{-1}$ down toward the trench. The tilt rate from 1978 to 1980 is 2.2 ± 1.0 μrad $year^{-1}$ in the opposite direction on both lines. The change in tilt rate is > 0 at the 99 percent confidence level. Lines SQH and SDP are separated by 12 km, and the tilt coherence from 1977 to 1982 gives confidence that the signals originate from a source at depth. (b) Seismicity rates for (i) earthquakes (body-wave magnitude $m_b > 4$) recorded in the Aleutian Arc between 140° and 180°W reported by the *Preliminary Determination of Epicenters Bulletin*, excluding the 1979 St. Elias earthquake and its aftershocks; (ii) the Shumagin region between 156° and 165°W and reported in the same source; and (iii) local earthquakes located by the Lamont-Doherty Geological Observatory Shumagin network. The rate change between 1978–1979 and 1980–1982 is significant at the 99 percent confidence level. (c) A plot of significant eruptive activity of Pavlof volcano; "magmatic" indicates that lava fountaining or a lava flow was observed, and "explosive" indicates extensive explosive activity at the summit crater.

signals result from a common source at depth.

The tilt down toward the trench observed between 1972 and 1978, and again between 1980 and the present, is of the correct sense to be interpreted in terms of interseismic loading of the overlying plate when coupled to a converging and descending Pacific plate. The tilt reversal in 1978 to 1980 can be interpreted as the result of a slip event along a shear zone between the descending slab and overlying mantle at depths between 20 and 70 km below the Shumagin Islands (Fig. 3a). To match the observed tilt data, the slip event is modeled as a buried dislocation having a displacement of 0.8 ± 0.4 m at a depth of between 70 ± 10 and ≈ 20 km, which represents the release of about 10 years of accumulated strain at the long-term plate convergence rate of 7.5 cm $year^{-1}$ (*4*). The maximum depth of the slip surface is fairly well constrained by tide gauge data (*5*) that indicate no vertical uplift greater than 0.1 m at line SDP (Fig. 3b). However, the top of the dislocation, near the down-dip end of the main thrust zone, is not well constrained.

In addition to causing a tilt reversal, the proposed dislocation would perturb the state of stress along the Benioff zone, especially near the ends of the dislocation (*6*). All earthquakes located in 1979 by the Lamont-Doherty Geological Observatory short-period, high-gain Shumagin network are plotted in Fig. 1 and 3c. There is a relatively low level of seismicity along the main thrust zone (the locked portion of the plate boundary) and a high level at its lower edge. There is also a high rate of activity within the upper plate beneath the shelf between the inner wall of the trench and the Alaskan peninsula. This region is characterized by strike-slip mechanisms with near-horizontal *P*-axes that nearly parallel the direction of plate convergence (*7*). The activity tends to form shallow (< 40 km) clusters that trend approximately parallel to the trench. By comparison, the 1981 seismicity, after the slip event, indicates a decrease in the number and a lack of clustering of shallow earthquakes (Fig. 3d).

The temporal distribution of seismicity is illustrated in Fig. 2b as the cumulative number of earthquakes located by the Shumagin network since 1978. The seismicity rate was about twice as great during 1978 and 1979 as since 1980, and statistical tests (*8*) show that the change in rate for earthquakes with local magnitude (M_L) ≥ 2 is significant at the 99 percent confidence level. During both time periods, the *b* value (slope of the earthquake frequency-magnitude relation) was 0.7 ± 0.1 and remained fairly constant. The change in seismicity rate appears to be limited to the Shumagin region since no similar change is seen in the cumulative number of epicenters (*9*) for the whole Aleutian arc (Fig. 2b). Furthermore, no similar bursts in earthquake activity are seen from 1972 to 1978 in the cumulative number of epicenters (*9*) in the Shumagin region. Both the focal mechanisms and the temporal and spatial distribution of the increase in shallow seismicity in 1978 to 1979 are consistent with the static stress field of the proposed dislocation (*6*).

The tilt reversal was mostly aseismic, since the seismic slip resulting from the observed increase in seismicity is too small by an order of magnitude to account for the size of the tilt reversal. Moreover, any vertical slip associated with clusters of shallow seismicity below some of the outer islands would cause tilt signals of opposite sense in the inner and outer islands and would produce larger signals than are observed on the SIM line (Fig. 3a).

From 1977 to 1979 no eruptions of Pavlof Volcano were reported (Fig. 2c), and seismic activity at the volcano was lower than at any other time since 1973 (*10*). Pavlof erupts more frequently than any other volcano in North America and it is possible that the quiescence in eruptive activity and the tilt change may be related, although the quiescence is not by itself statistically significant. Significant spatial and temporal relations be-

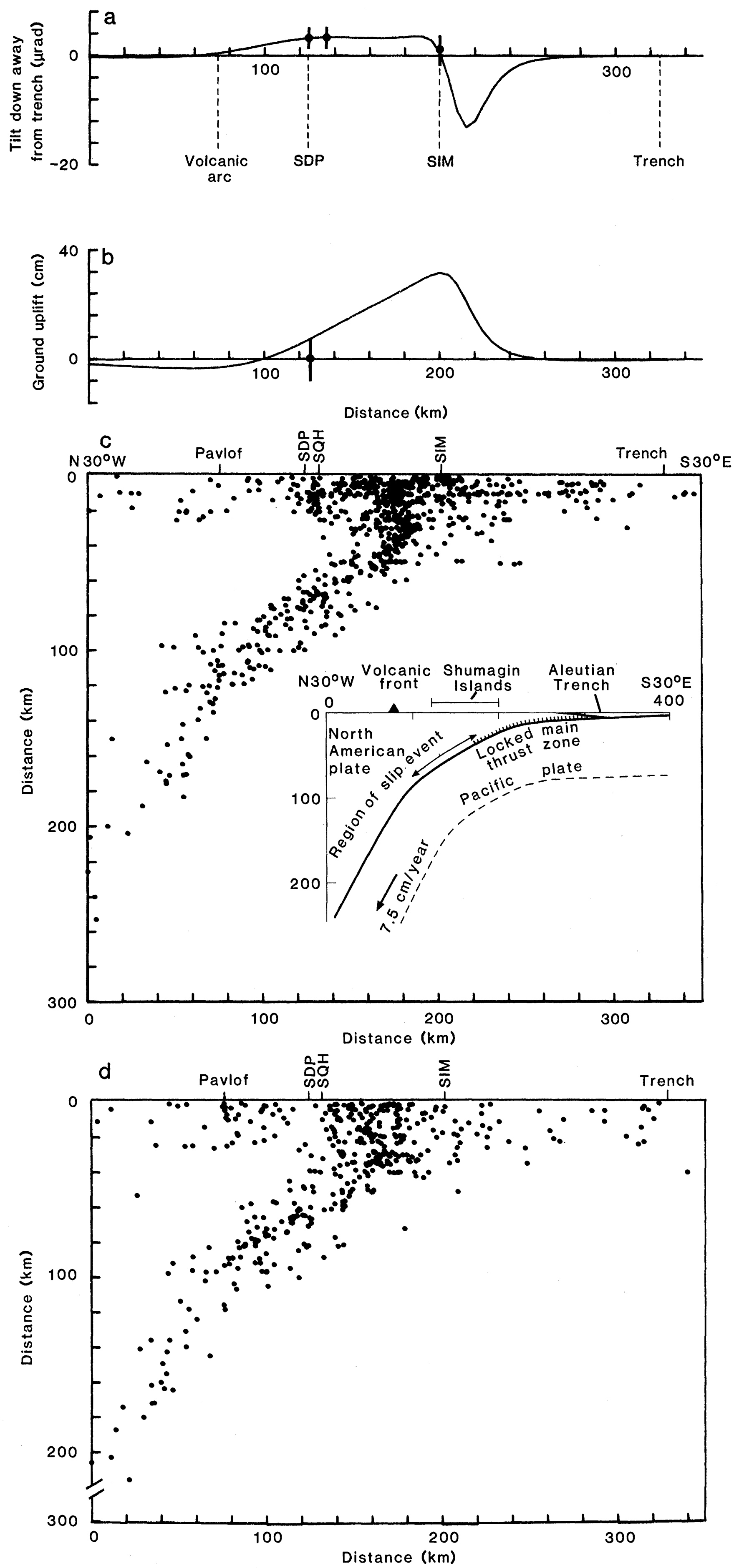


Fig. 3. Theoretical tilt (a) and vertical displacement (b) observed at the surface as the result of a 0.8-m thrust on a plane dipping 32° at a depth between 20 and 80 km. The plotted data points and $\pm 1\text{-}\sigma$ error bars are in (a) the measured tilt changes between 1978 and 1980 on leveling lines at SDP, SQH, and SIM and in (b) the land level change at line SDP deduced from National Oceanographic Survey sea level data. (c) Cross section of seismicity located by the Shumagin network in 1979 during the proposed slip event. The cross section strikes N30°W across the Shumagin Islands as shown in Fig. 1. The inset shows the positions of the locked main thrust zone and the modeled slip event. (d) Cross section of seismicity located by the Shumagin network in 1981, after the slip event.

tween large intraplate earthquakes and eruptive activity of volcanoes along convergent plate margins have been found (*11–13*). A tilt reversal in 1945 to 1948 in the South Kanto district of Japan, observed at two different bench marks 70 and 85 km north of Oshima Island (*14*), coincided with a reduction in volcanic earthquakes (*12*) and a cessation of eruptions at Mihara-yama Volcano on Oshima Island (normally, the volcano erupted nearly every year). The cessation of volcanic activity can be interpreted as a phenomenon secondary to the immediate changes ($\approx$ 400 m) in elevation of the floor of the summit crater that occurred, for instance, just prior to the Great Kanto earthquake of 1923 (surface wave magnitude $M = 7.9$) and the Boso-oki earthquake of 1953 ($M = 7.5$) (*11*, *12*).

The change in strain in the Shumagins could be similar to the one reported near Palmdale, California, which has been interpreted as a slowly migrating slip event on a horizontal detachment surface at a depth of 10 to 30 km (*15*). The large areal extent of the California strain episode suggests that the strain and seismicity are causally related (*16*).

The seismic and geodetic evidence we present suggests that shallow crustal seismicity and stress may be influenced by temporal changes in the rate of aseismic slip occurring down-dip from the brittle, shallow region of the main thrust zone. Similar ideas have been investigated theoretically in strike-slip environments (*17*). We speculate that these stress changes may also influence the timing of great earthquakes. The inferred slip event may be one in a series of such events that occur at quasi-regular intervals during the earthquake cycle, and the occurrence of a great shock may be more probable during these events. Alternatively, the slip event may be an indication of increased tectonic activity along the plate boundary that is a forerunner of the future great earthquake in the Shumagin region.

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Sulfuric Acid Droplet Formation and Growth in the Stratosphere After the 1982 Eruption of El Chichón

Abstract. *The eruption of El Chichón Volcano in March and April 1982 resulted in the nucleation of large numbers of new sulfuric acid droplets and an increase by nearly an order of magnitude in the size of the preexisting particles in the stratosphere. Nearly 10^7 metric tons of sulfuric acid remained in the stratosphere by the end of 1982, about 40 times as much as was deposited by Mount St. Helens in 1980.*

Instrumented balloons, capable of altitudes in excess of 30 km, have been used to study the formation and growth of H_2SO_4 droplets from sulfurous gases injected into the stratosphere during the 28 March and 3 and 4 April 1982 eruptions of El Chichón Volcano in southern Mexico. The optical particle counters used in this work cover the size range from 0.01 to 1.8 μm in radius (r) (*1, 2*). Studies of earlier eruptions (*2–4*) have revealed considerable information on the gas-to-particle process that occurs in the stratosphere after major volcanic eruptions. However, none of these eruptions injected nearly as much material to as high an altitude as the 1982 El Chichón eruption. This eruption appears to be a once-in-a-century event that has apparently already produced a 3° to 5°C heating in the equatorial stratosphere (*5*) and will probably cause a measurable climatic perturbation. Thus, measurements made during the formation of the global aerosol layer are of the utmost importance in understanding this phenomenon.

Figure 1 shows the average integral particle concentration versus size as measured by balloon-borne particle counters in the main stratospheric particle layer at an altitude of 25 ± 0.5 km over Laredo, Texas, in May 1982, about 1½ months after the eruption. We observed large excesses of particles in both the small (r = 0.01 μm) and the large (r = 1 μm) size ranges. The concentration at 0.01 μm (~ 200 cm^{-3}) represents an average of data with considerable fluctuation in the 1 km of altitude. Concentrations as high as 750 cm^{-3} were present.

The data in Fig. 1 have been fitted with normal distributions in the logarithm of r. Such distributions are thought to be representative of the physical processes occurring. Such a size distribution, in differential bimodal form, may be expressed as

$$n(r)dr = \sum_{i=0}^{1} \frac{N_i}{(2\pi)^{1/2}} \exp\left(-\frac{\alpha_i^2}{2}\right) d\alpha_i$$

where $n(r)$ is the number concentration of particles per dr at r, N_i is the total concentration of the ith mode, and

$$\alpha_i = \frac{\ln(r/r_i)}{\ln \sigma_i}$$

where r_i is the ith modal radius (the median radius) and σ_i is the ith modal width (dimensionless). The integral of $n(r)dr$ above a radius r gives $N(> r)$, the integral concentration of particles, which is the measured parameter.

Also indicated in Fig. 1 is the preeruption distribution (dotted curve) as measured at Laramie during February to April 1982. Although the aerosol concentrations were slightly disturbed in the 18-km region at this time as a result of a smaller unidentified volcanic eruption in early 1982, the aerosol concentrations at 25 km appeared normal and are considered representative of preeruption data for Texas as the latitudinal particle gradient in the stratosphere is small during undisturbed periods (*6*).

Even though the log-normal fit to the data in Fig. 1 is not unique, the data could not be fitted with a single distribution of this type. The measured size distribution is clearly bimodal with mode radii at about 0.02 and 0.72 μm. These values could be varied slightly; however, a small- and a large-particle mode definitely appear to be present. The large-particle mode has nearly the same concentration as the preeruption mode; this result suggests that it has evolved through growth of the latter. The small-particle mode, which was not present prior to the eruption, is indicative of new