# Reports

## Rupture Zones of Great Earthquakes in the Alaska-Aleutian Arc, 1784 to 1980

Abstract. *Historical documents indicate that great earthquakes ruptured at least a 500-kilometer-long segment of the plate boundary near the Alaska Peninsula in 1788 and 1847. At least half of a major seismic gap in the Shumagin Islands ruptured during those shocks but has not experienced a great earthquake for at least 77 years. Large shocks along this and other plate boundaries occur in bursts followed by several decades during which there is very little energy release.*

The Alaska-Aleutian arc is one of the world's most active earthquake belts (*1*). Even for great earthquakes (magnitude $M > 7.7$), the historic record for the arc was thought to be very short and incomplete and very little information was available on repeat times of large shocks (*1, 2*). A better knowledge of repeat times is needed if one is to estimate seismic hazards more accurately, understand the subduction process, and make progress toward earthquake prediction. We translated a number of documents from Russian that contain material on earthquakes along the arc prior to the advent of an instrumental record in 1897. These descriptions together with more recent instrumental data now make it possible for us to map (Fig. 1) the rupture zones of great earthquakes for nearly the past 200 years in a segment of the arc near the Alaska Peninsula. These and more recent data indicate an average repeat time for great shocks of about 50 to 75 years. Earthquake prediction, seismic hazards, and the historic documents are discussed in more detail in (*3, 4*).

Sykes (*1*) mapped the rupture zones of large earthquakes from 1925 to 1971 along the plate boundary in southern Alaska and the Aleutians by relocating aftershocks (Fig. 1a) of those events. The inferred rupture zones of all known shocks of $M \geq 7.4$ from 1784 to 1980 are indicated in Fig. 1b. Rupture zones of events of $M < 7.4$ do not exceed about 30 km, a dimension small as compared with those of great events. Shocks of $M \geq 7.4$ account for most of the slip that occurs seismically between large lithospheric plates. Since 1938, nine large earthquakes ruptured much of the length of the plate boundary of Fig. 1.

Catalogs in the English language of earthquakes in Alaska and the Aleutians for the period of Russian settlement from 1784 to 1867 contain primarily third- and fourthhand accounts. The important paper by Doroshin (*5*) and other early sources (*6-9*) contain invaluable qualitative descriptions from which we infer approximate rupture dimensions. Reports of the great earthquake of 1788 and its tsunami are available from Unga in the Shumagin Islands, Sanak Island, Kodiak Island, and the Alaska Peninsula. Most of the descriptions of earthquakes during the period of Russian control come from either that 1000-km-long segment of the arc, the westernmost Aleutians, or the region near Sitka in southeastern Alaska. The absence of shocks in other areas is attributed to the lack of a historic record prior to 1897.

We take two or more of the following as indicative of an earthquake that ruptured a considerable (> 100 km) portion of the arc: shaking of intensity IX (*10*) or more at two or more separated localities (*11*), shaking lasting a minute or more, permanent changes in sea level, an associated sea wave (tsunami), ground breakage, landslides, or aftershocks lasting for weeks to months. Localities experiencing such effects are taken to have been near the rupture zone.

Descriptions of these types for 22 July 1788 (*12*) led us to associate them with a great shock that ruptured at least a 600-km segment of the plate boundary. Merkul'ev (*6*) described strong shaking on Kodiak Island, an intense flood (tsunami) consisting of a series of waves, aftershocks every day for a month or longer, and a permanent change in sea level. Davydov (*7*) also mentioned landslides on Kodiak Island and observed that the sea first withdrew from shore and then carried a vessel onto the top of a cabin. Veniaminov (*8*) described strong shaking, landslides, and a "horrible flood" on Unga on the same date. He referred to another flood on Unga 16 days later in which the water rose to 50 sazhens, about 91 m. It is not clear, however, if 91 m is the vertical height of the water or the distance the waves ran up the beach. "The tradition of Aleuts . . . reports that during the flood which took place on Sanak around the year 1790 the water preceded as strong and infrequent large waves" (*8*). Neither the date of the flood on Sanak Island nor the occurrence of an earthquake on 7 August is mentioned in any of the older Russian documents we examined. Dall (*13*), a secondary source, reports tsunami damage to Sanak Island on the date (*12*) of the second flood on Unga. Although the evidence that an earthquake on 22 July ruptured the zone from Kodiak Island to Unga is quite strong, we are forced to rely on Dall's account to infer that a second large shock appears to have ruptured the western half of the Shumagin Gap 16 days later.

Doroshin (*5*) described ground cracking, landslides, shaking continuing for about 4 hours, and aftershocks lasting about 5 weeks on Ukamok (Chirikof Island, *C* in Fig. 1a) in association with a large earthquake in 1847. He stated that it was impossible to remain standing on Unga during the earthquake and that shocks were felt several times on the Alaska Peninsula. He also described another large shock on Chirikof Island in 1848. We infer that at least a 500-km segment of the plate boundary ruptured in 1847 and 1848. This sequence is particularly significant since that segment broke 60 years earlier. This is probably the best documented repeat time obtained thus far for the arc. Although the effects described by Doroshin are similar to those reported for the 1788 event, he does not mention a tsunami accompanying the event of 1847. From similar reports (*5, 7*) we infer that large earthquakes also occurred somewhere near Kodiak Island in 1792, 1844, and 1854; the dimensions of the rupture zones, however, cannot be ascertained. Other historic shocks are mentioned in (*14*).

A large earthquake occurred off the Alaska Peninsula on 28 September 1880, as indicated by the following effects observed on Chirikof Island (*15*): aftershocks continuing for 19 days, numerous deep fissures, strong shaking lasting about 20 minutes, extensive damage to a log house, several sea waves that traveled about 55 m onshore, and permanent changes in sea level. Moore (*16*) concluded that a vertical displacement of 2 m occurred at that time along a north-

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east-striking fault that crosses the island.

Sykes (*1*) pointed out three segments of the plate boundary in Fig. 1 that had not been the sites of large shocks for many decades and called them seismic gaps. The historical data are particularly relevant in estimating the potential for areas near the Alaska Peninsula to be the sites of future great earthquakes. Recent work (*3*) on the aftershocks, the source region of the tsunami, and the rupture area inferred from the seismic moment indicate that the 1938 event did not rupture into what is called the Shumagin Gap in Fig. 1. Likewise, the generating area of the large sea wave from the 1946 earthquake appears to have been largely confined to its small aftershock area. The rupture zone of the 1948 shock is small and is located farther from the trench than most shallow events of the thrust type. The computed depths (44 and 48 km) of the two largest aftershocks suggest that it may not have ruptured the plate boundary at shallow depths. Hence, a major seismic gap exists between the rupture zones of the shocks of 1946 and 1938.

The record of great ($M > 7.7$) shocks appears to be complete or nearly complete since 1898. The quiescence for great shocks along the entire arc from 1907 to 1938 is remarkable. A sequence of 14 shocks ($M \geq 7.4$) ruptured large parts of the plate boundary from 1898 to 1907. This sequence of large shocks and that from 1938 to 1965 encompassed time intervals that are short as compared to the repeat time of great shocks at a given place. Much of the North Anatolian fault ruptured in a series of large earthquakes from 1939 to 1943 (*10*); the entire plate boundary off northern Japan and the southern Kuril Islands broke between 1952 and 1973 (*17*). Thus, a strong temporal clustering of large events appears to be a common feature of several plate boundaries.

It is difficult to estimate the extent of rupture during the events of 1897 through 1907 in the Aleutians. The apparent absence of large tsunamis (*18, 19*) may be attributed to the distribution of rupture among several large shocks rather than in a few very great events. An event of $M = 8.1$ on 9 October 1900 appears to have been centered near Kodiak Island (*20, 21*). A shock of $M = 8.3$ on 2 June 1903 (*10*) may have ruptured the Shumagin Gap or the 1938 zone or may have been of deeper focus. A shock on 14 July 1899 of $M = 7.7$ was felt on Unalaska and Unga (*21*). Whether the Shumagin Gap or the rupture zones of the 1938 and 1957 earthquakes broke between 1899 and 1903 cannot be resolved at present.

The great shocks of 1788 and 1847 appear to have ruptured the entire portion of the arc that broke in 1938. Since it is not clear if that segment also ruptured between 1899 and 1903, an average re-

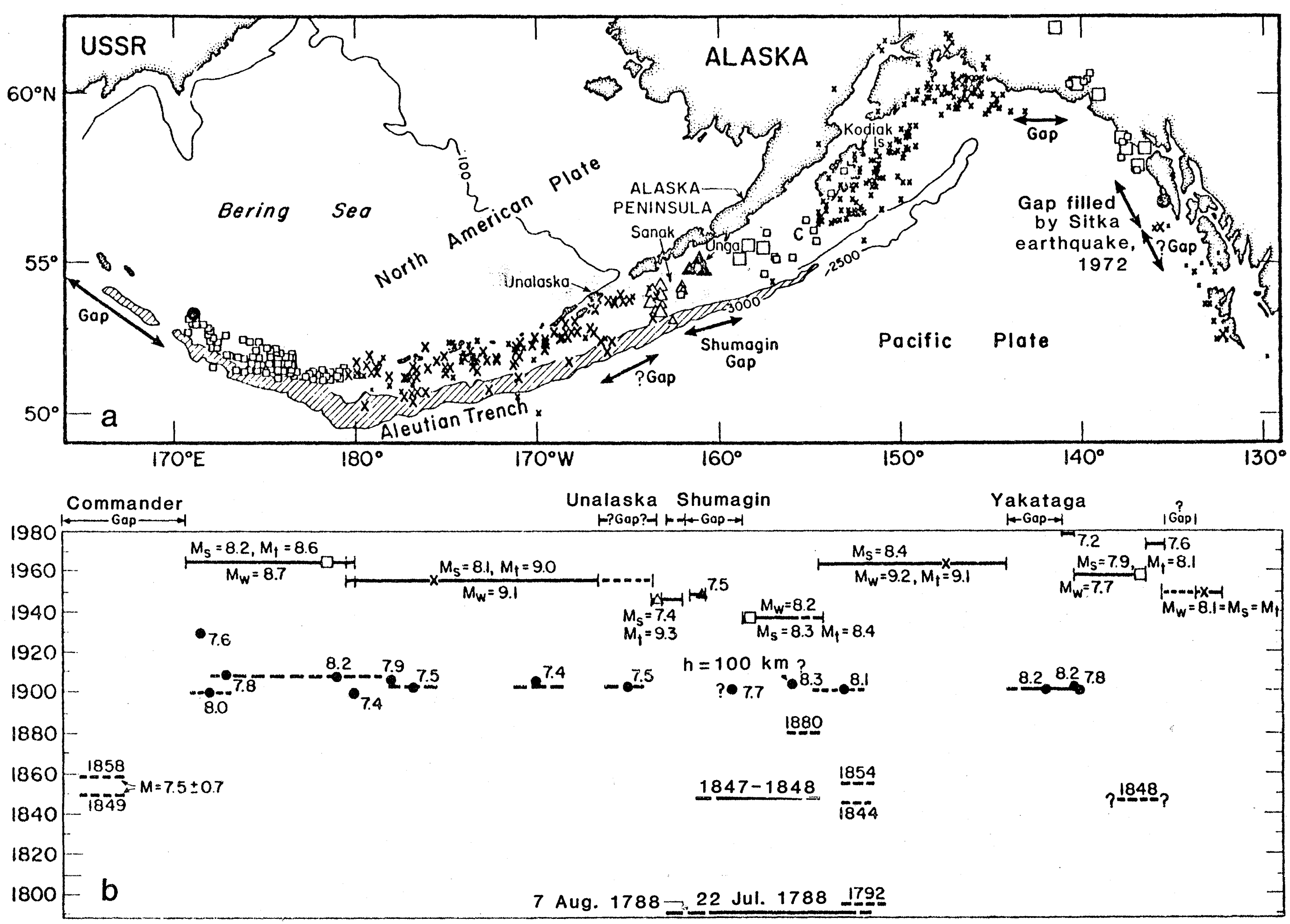


Fig. 1. (a) Rupture zones of earthquakes of magnitude $M \geq 7.4$ from 1925 to 1971 as delineated by their aftershocks along the plate boundary in the Aleutians, southern Alaska, and offshore British Columbia [after (*1*)]. Contours are in fathoms. Various symbols denote individual aftershock sequences; $C$ = Chirikof Island. (b) Space-time diagram showing the lengths of the rupture zones, magnitudes (*10, 24-27*), and locations of main shocks for known events of $M \geq 7.4$ from 1784 to 1980. Dashes denote uncertainties in the size of the rupture zones. Magnitudes pertain to surface wave scale, $M_s$, unless otherwise indicated; $M_w$ is the ultralong-period magnitude (*25*); $M_t$ is the tsunami magnitude (*18*). Large shocks in 1929 and 1965 are omitted that are not on the plate interface and that involve normal faulting in the trench (*28*). The St. Elias shock ($M$ = 7.2) of 1979 filled only part of the gap between rupture zones of the great earthquakes of 1958 and 1964.

peat time of 50 to 75 years is obtained if one divides 150 years (1788 to 1938) by either two or three earthquake cycles. A repeat time of 91 years (1847 to 1938) is obtained if that zone did not rupture in 1880 or between 1897 and 1903. The eastern half of the Shumagin Gap also broke in 1788 and 1847. The gap has not been the site of a great shock since at least 1903. Although the interval that has elapsed since 1903 is somewhat greater than 50 to 75 years, repeat times of historic events along the Nankai trough of southwestern Japan vary by about a factor of 2 (*22*). The repeat time, however, appears to be proportional to the size of the rupture zone and the displacement in the preceding large earthquake (*23*). Since the shocks of 1938 and 1899 to 1903 near the Alaska Peninsula appear to have shorter rupture lengths than those of 1788 and 1847, the experience from Japan suggests that the interval between the last major event and a future large shock will be at the shorter end of the spectrum of repeat times for both the Shumagin Gap and the 1938 zone. Thus, it seems likely that one or more large earthquakes will rupture the Shumagin Gap sometime in the next 10 to 20 years.

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# A Temperature and Precipitation Record of the Past 16,000 Years in Southern Chile

Abstract. *Regression equations relating pollen taxa from surface samples to temperature and precipitation are applied to a radiocarbon-dated pollen sequence in a lake core from Alerce. The resulting curves are a measure of the fluctuations of these climatic variables and show similarities to other late Quaternary records from the Southern Hemisphere.*

The climate of the Southern Hemisphere is primarily controlled by Antarctica and its vast ice sheet (*1, 2*). Nearby continents in the belt of the southern westerlies are cooled by outbreaks of polar air and by the Humboldt and Benguela currents, which transport polar water equatorward along the west coasts of South America and Africa. Our understanding of the timing and nature of climatic changes in the Southern Hemisphere during the Quaternary comes largely from the marine record (*3*) and from glacial (*4-6*) and palynological (*7-9*) studies in the temperate latitudes of Australia, New Zealand, and South America; oxygen isotope measurements in the Byrd Station ice core have provided most of the information on climatic events in Antarctica (*10*). Apparent in these data is the need to quantify in detail the variations in temperature and precipitation. We attempted this by applying multivariate statistics to a 16,000-year pollen sequence in southern Chile.

We first derived a pair of regression equations relating taxa of the modern pollen rain to mean January (summer) temperature and annual precipitation, as estimated from meteorological records at stations distributed over some 14° of latitude (Fig. 1) (*11*). At 26 composite sites 20 taxa were tied to temperature and at 24 sites to precipitation (*12*). The equations were then applied to the fossil pollen in a lake core at Alerce (41°25'S, 72°54'W), just south of the Chilean lake district at the northern extreme of the Valdivian rain forest (*13*). Sediments in the lake were deposited after the wastage of ice of the Llanquihue Glaciation (*9*).

To remove the effect of sample size, pollen data are expressed in terms of the relative frequency of the 20 taxa. Multiple forward stepwise regression shows that 11 taxa explain 91 percent of the variance in the temperature data, with a standard error of estimate of 0.99°C (15 percent of the range of the surface temperatures). Likewise, 11 taxa explain 94 percent of the variance in mean annual precipitation, with a standard error of estimate of 509 mm (14 percent of the range of the surface values).

We further transformed the surface data set before performing the regression in order to give each variable a mean of zero and a standard deviation of unity. The same result can be obtained from analogous equations in which unscaled percentage data are used as the predictor variable; however, when data for lower parts of the core are expressed in terms of deviation from surface means, it is easier to identify significant departures from the surface data set. Although tem-