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Seismicity Trends and Potential for Large Earthquakes in the Alaska-Aleutian Region

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Abstract—The high likelihood of a gap-filling thrust earthquake in the Alaska subduction zone within this decade is indicated by two independent methods: analysis of historic earthquake recurrence data and time-to-failure analysis applied to recent decades of instrumental data. Recent (May 1993) earthquake activity in the Shumagin Islands gap is consistent with previous projections of increases in seismic release, indicating that this segment, along with the Alaska Peninsula segment, is approaching failure. Based on this pattern of accelerating seismic release, we project the occurrence of one or more $M \geq 7.3$ earthquakes in the Shumagin-Alaska Peninsula region during 1994–1996. Different segments of the Alaska-Aleutian seismic zone behave differently in the decade or two preceding great earthquakes, some showing acceleration of seismic release (type "A" zones), while others show deceleration (type "D" zones). The largest Alaska-Aleutian earthquakes—in 1957, 1964, and 1965—originated in zones that exhibit type D behavior. Type A zones currently showing accelerating release are the Shumagin, Alaska Peninsula, Delarof, and Kommandorski segments. Time-to-failure analysis suggests that the large earthquakes could occur in these latter zones within the next few years.

Key words: Alaska-Aleutian seismic zone, Shumagin seismic gap, accelerating moment release, time-to-failure.

Introduction

Interplate thrust earthquake activity in the Shumagin Islands region of the Alaska-Aleutian seismic zone on 13 May 1993 (M_w 7.1) (TANIOKA *et al.*, 1993; BEAVAN *et al.*, 1993) has renewed anticipation for the occurrence of an even larger "gap-filling" earthquake in the near future.

The region known as the Shumagin seismic gap was first identified as a possible site for a future major earthquake by KELLEHER (1970). A pronounced east to west progression of great earthquakes along the Queen Charlotte-Alaska seismic zone (1949 Queen Charlotte Islands, M_w 8.1; 1958 Lituya Bay, M_w 8.2; 1964 Prince William Sound, M_w 9.2) led KELLEHER (1970) to extrapolate that the region at 56 N, 158 W (offshore of the Alaska Peninsula) would be the nucleation point for the next event in this progression of plate boundary earthquakes. At that time, the

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Shumagin Islands region was thought to have ruptured as part of the 1938 M_w 8.2 Alaska Peninsula event (SYKES, 1971). KELLEHER *et al.* (1973) identified the Alaska Peninsula region as fulfilling both initial and supplementary criteria for the likely location of future earthquakes (more than 30 years elapsed since the last major event, and next in line in a progression of earthquake activity, respectively). Subsequent analysis by DAVIES *et al.* (1981) however, indicated that earthquakes in the Shumagin Islands region, previously identified as aftershocks were actually deeper intraplate earthquakes not directly related to the 1938 earthquake. New analysis and relocation of early 20th century seismicity along the Alaska-Aleutian arc by BOYD and LERNER-LAM (1988) and ESTABROOK and BOYD (1989) indicate that the Shumagin gap may have ruptured as three distinct segments (1899 (M_s 7.2), 1917 (M_s 7.4), and 1948 (M_s 7.5)) during this century.

JACOB (1984), and NISHENKO and JACOB (1990) assessed the long-term (i.e., decade scale) seismic potential of the Alaska-Aleutian seismic zone, based on estimates of average recurrence intervals for large and great earthquakes in each individual segment and the amount of time elapsed since the last gap-rupturing earthquake. NISHENKO and JACOB (1990) identified a number of areas with high (i.e., >0.60) conditional probabilities for the recurrence of either large or great earthquakes (depending on the segment) during the interval 1988–2008. These areas include the Yakataga, Shumagin Islands, Fox Islands, Delarof Islands, and Near Islands segments of the Alaska-Aleutian arc.

BUFE *et al.* (1990, 1992) and JAUMÉ and ESTABROOK (1992) have identified the Shumagin Islands/Alaska Peninsula segments as being near the end of a seismic cycle for shallow interplate thrust earthquakes, based on an increase in the regional rate of seismic release since 1985 and the occurrence of a compressional outer-rise earthquake seaward of the Alaska Peninsula in 1990 (M_w 5.3). However, the latter evidence is not definitive, as a more recent (1992) extensional outer rise earthquake was observed nearby. Here we examine the implications of recent seismicity for rupture of the Shumagin Islands/Alaska Peninsula segments and place this recent activity into the context of earlier published forecasts. We also describe the seismic release characteristics of a number of other fault segments along the Alaska-Aleutian seismic zone.

Historical Seismicity

Both the Alaska Peninsula and Shumagin Islands segments have relatively complete histories for large and great earthquakes that span the last 200+ years (see reviews in SYKES *et al.*, 1981 and DAVIES *et al.*, 1981). In addition to establishing recurrence intervals for these segments, the historic record also provides clear evidence for variable modes of earthquake rupture. Both segments ruptured simultaneously, or within a short time of one another during great earthquakes on 22 July and 7 August 1788 and again on 16 April 1847 or 1848. During this century, both segments ruptured independently of one another in a more complex sequence that includes events on 14 July 1899 (M_s 7.2), 31 May 1917 (M_s 7.4), and 14 May 1948 (M_s 7.5) for the Shumagin Islands, and 10 November 1938 (M_w 8.2) for the Alaska Peninsula. Both the 1899 and 1948 events are thought to have only filled in small portions of the Shumagin gap, with the 1948 event being confined to the deeper portions of the plate boundary (SYKES, 1971; DAVIES *et al.*, 1981; BOYD *et al.*, 1988).

The repeat times for those events which are thought to have ruptured the full width of the plate boundary range from 59 to 91 years and provide the primary, empirical constraint for long-term hazards estimates in this region. Based on these data, NISHENKO and JACOB (1990) estimated the probability for the recurrence of a large or great earthquake in the Shumagin and Alaska Peninsula segments to be 0.47–0.57 and 0.13–0.16, respectively, for the interval 1988–1998. Updating these earlier estimates for the interval 1993–2003 has increased the probabilities to 0.49–0.61 and 0.20–0.23, respectively. The joint probability of at least one gap-filling event with $M \geq 7.5$ in either the Shumagin or Alaska Peninsula segments during the 10-year interval 1993–2003 is 0.60–0.70. For comparison, the joint probability of at least one earthquake of $M \geq 7.0$ occurring on one of the four principal fault segments in the San Francisco Bay region during the 10-year interval 1990–2000 is 0.33 (WGCEP, 1990). While the Shumagin-Alaska Peninsula region has a significantly higher hazard during the next decade than the San-Francisco Bay region, the observed historic variability of the mode of rupture for this region does not allow more than a general specification as to the time and size of the next large event. For example, NISHENKO and JACOB (1990) estimate the 90 percent confidence interval for rupture of the Shumagin segment at ±28 years. Both NISHENKO and JACOB (1990) and ESTABROOK and BOYD (1992) recognize that this region may rupture either in a single great earthquake or a series of large events. In the sections to follow we attempt to more precisely define the magnitude and time frame of the next Shumagin Islands earthquake.

Adjacent to the Shumagin segment to the west, the Unimak Island segment, which last broke in 1946 (M_s 7.4, M_w 8.3), is also thought (NISHENKO and JACOB 1990) to have a high, though not as well constrained, probability of 0.58–0.77 of rupturing within this decade (1993–2003). In contrast to the long historic record of the Shumagin-Alaska Peninsula region, the short sample of 20th century seismic activity available for the region to the west along the Aleutian arc suggests that both the Fox and Delarof segments are characterized by the occurrence of large (M_s 7.0–7.4) earthquakes every 20 to 50 years. Both segments also apparently ruptured in conjunction with the occurrence of the great 1957 Central Aleutian earthquake.

The characteristic mode of failure for the Alaska-Aleutian region has been one of clustering or episodes of activity, where large portions of the Alaska-Aleutian arc

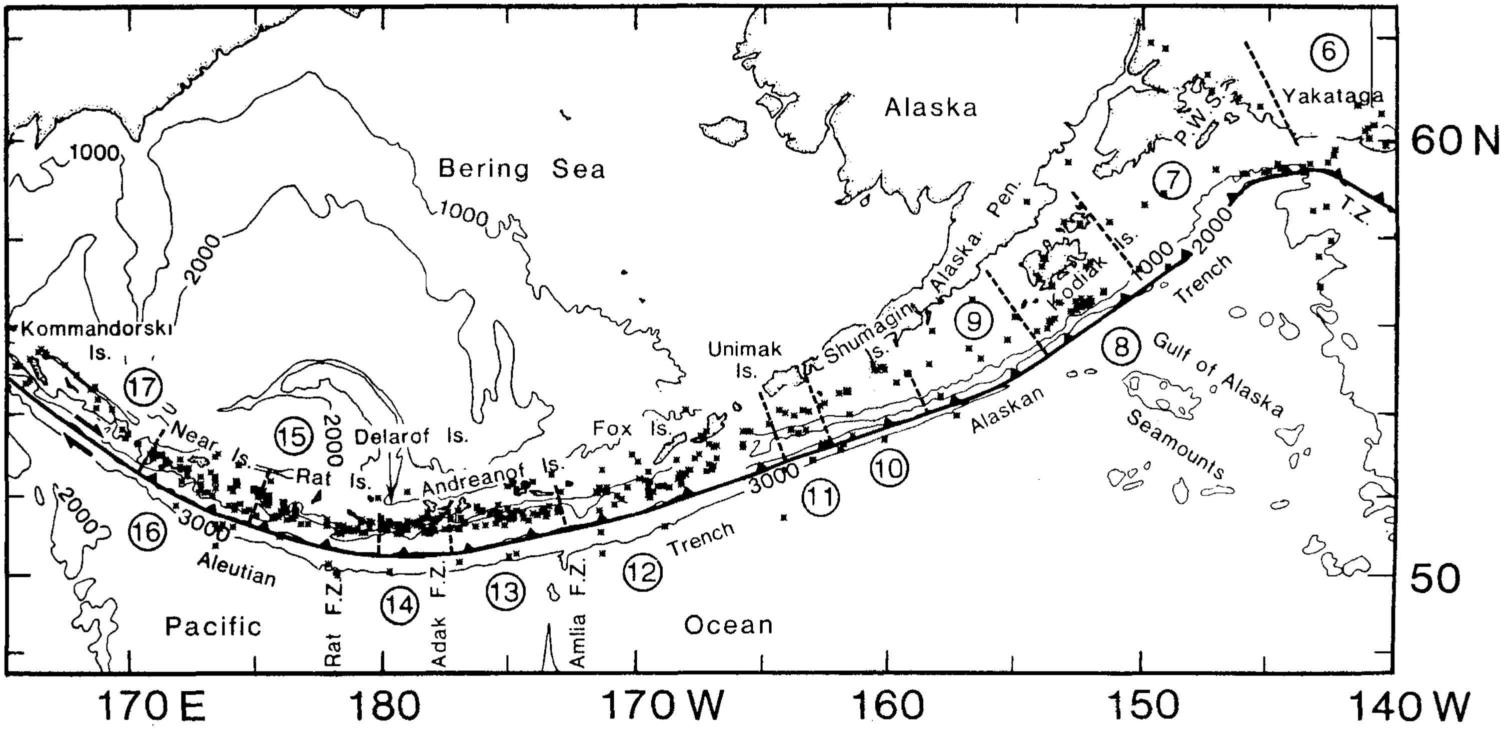

Figure 1
Alaska-Aleutian earthquakes (from JAUMÉ's (1992) catalog, magnitude 5.2 and larger shown) during the period 1965.1 to 1993.5. Map and segmentation after NISHENKO and JACOB (1990).

rupture in a series of events with inter-event times much shorter than the average recurrence interval for individual segments. During major tectonic episodes in the brief periods 1957–1958 and 1964–1965, more than half of the Aleutian-Alaska seismic zone ruptured in great earthquakes. In 1957 a great earthquake (M_w 8.7) originating in the Andreanof segment and its aftershocks ruptured the Andreanof, Delarof, and Fox Islands segments. The 1958 Lituya Bay earthquake (M_w 8.2) broke a large segment of the Fairweather fault. The 1964 Prince William Sound earthquake (M_w 9.2) ruptured the Prince William Sound and Kodiak segments. Finally, the 1965 Rat Islands event (M_w 8.7) and its aftershocks broke both the Rat and Near Island segments. In the nearly 30 years since 1965, the only great earthquake to occur in the region was an M_w 8.0 earthquake in 1986, again rupturing the Andreanof Islands segment.

Regional Seismic Release

Following BUFE and VARNES (1993), we use the term seismic release to denote measures of seismicity that can be derived or estimated from earthquake catalogs, specifically earthquake parameters (Ω's), such as seismic moment, event count, and square root of energy (or of moment). The Ω is usually estimated from earthquake magnitude (M) by an equation of the form:

$$\log \Omega = cM + d. \tag{1}$$

The coefficient c is 1.5 when Ω is moment or energy (KANAMORI, 1977; HANKS and KANAMORI, 1979), 0.75 for Benioff strain release (square root of energy) or square root of moment, and zero for the event count. Although seismic moment is the preferred parameter for most purposes, including application of the time-predictable model (BUFE *et al.*, 1977; SHIMAZAKI and NAKATA, 1980), we have found Benioff strain release to be especially useful in time-to-failure analyses (VARNES, 1989, and BUFE and VARNES, 1993). Cumulative Benioff strain release is also useful in evaluating background seismic release rates where smaller events are of interest, but where some magnitude scaling is desirable. In contrast, cumulative moment release is typically dominated by the largest earthquake, and cumulative event count allows no magnitude scaling.

Cumulative Benioff strain release curves are shown in Figure 2 for individual segments of the Alaska-Aleutian seismic zone. The segmentation is after NISHENKO and JACOB (1990). We have placed the 1987–88 earthquakes (LAHR *et al.*, 1988), which occurred in the Gulf of Alaska near the boundary between the Prince William Sound segment and the Cape Yakataga segment, into the Yakataga segment. The relation of these strike-slip events to the seismic cycles of either the Yakataga or Prince William Sound segments is not clear. For analysis we have extended the Yakataga segment eastward to 140 W.

Recent Seismicity Trends

Epicenters of earthquakes of M_s 5.2 and larger in the Alaska-Aleutian seismic zone are shown in Figure 1a for the period February 5, 1965 (following the occurrence of the M_w 8.7 Rat Islands earthquake on February 4) through May 25, 1993. Data shown are extracted from JAUMÉ's (1992) catalog of shallow (depth of

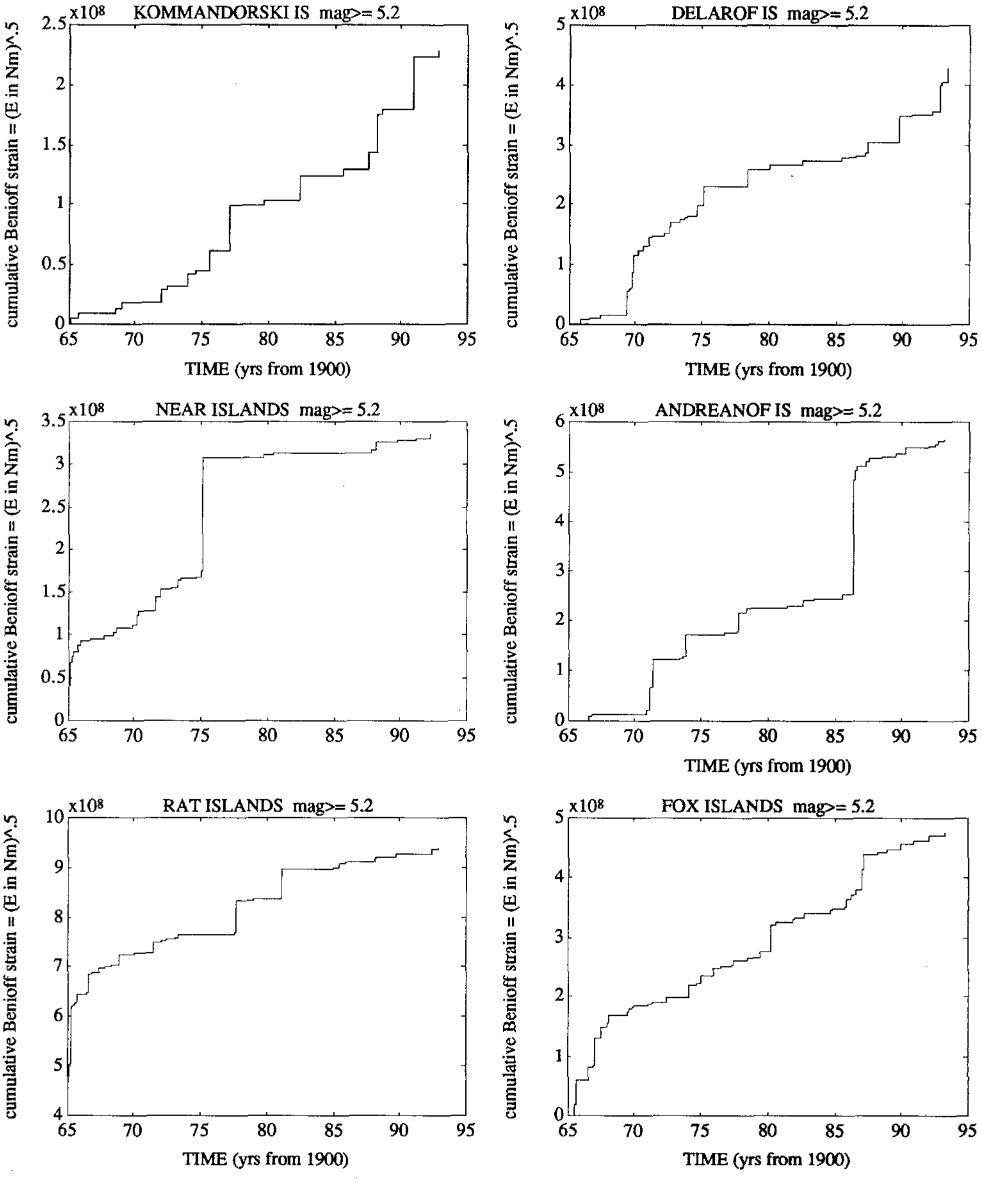

Figure 2(a)

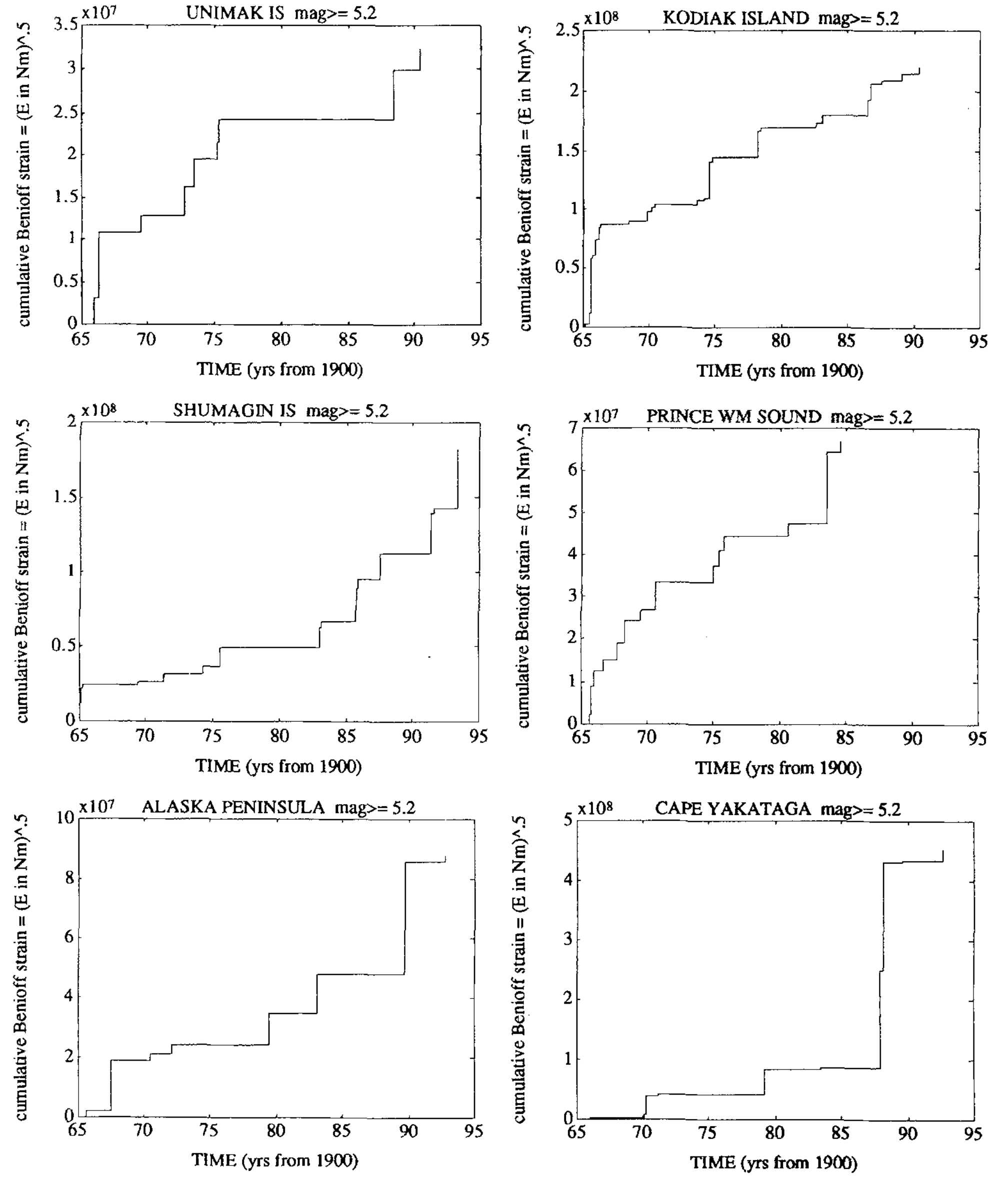

Figure 2(b)

Figure 2

Cumulative plots of Benioff strain release computed from magnitudes for each of the segments shown in Figure 1. Segments are: a) Left column, top to bottom; Kommandorski Islands, Near Islands, Rat Islands. Right column, top to bottom; Delarof Islands, Andreanof Islands, Fox Islands. b) Left column, top to bottom; Unimak Island, Shumagin Islands, Alaska Peninsula. Right column, top to bottom; Kodiak Island, Prince William Sound, Cape Yakataga.

60 km or less) earthquakes, updated using the U.S. Geological Survey National Earthquake Information Service's Preliminary Determination of Epicenters (PDE) data. The Jaumé catalog appears to be complete above about M_s 5.2. We use all earthquakes of M_s 5.2 and larger (see Figure 1), with no requirement that the earthquakes be along the plate interface or be of a particular mechanism. Our model of the earthquake cycle (see BUFE and VARNES, 1993) incorporates regional seismic release within a large volume, here incorporating both the subducting and overriding plates. We previously performed the analyses described below using data for earthquakes at all focal depths from the DNAG (ENGDAHL and RINEHART, 1991) catalog, updated using the PDE, with similar results.

The various segments of the Alaska-Aleutian seismic zone are listed from west to east in Table 1 and identified by name and number in Figure 1, using the segmentation and numbering of NISHENKO and JACOB (1990). We have quantitatively analyzed recent trends of seismic release for these segments along the Alaska-Aleutian seismic zone (including the Shumagin and Alaska Peninsula segments, both individually and jointly) to characterize the mode of strain release. Acceleration or deceleration is determined by analysis of the shape of cumulative Benioff strain release curves to determine whether the rate, or slope of the seismic release curve, is increasing with time (accelerating) or decreasing with time (decelerating). Where persistent acceleration is observed, we have applied time-to-failure analysis to estimate when gap-filling earthquakes may occur. Our analyses indicate that since about 1984 the Shumagin and Alaska Peninsula

Table 1

Seismic release trends ($M \geq 5.2$) in Alaska and the Aleutian Islands

# Segment	Approx. Longitude	1967–1992 25-yr trend	1982–1992 10-yr trend	Segment type	Estimated failure time	Est. M
17 Kommandorski	171–165E	accel	accel	A	1995–2003	7.5–8.5
16 Near Islands	175–171E	decel	—	D		
15 Rat Islands	180–175E	decel	decel	D		
14 Delarof Islands	177–180W	decel	accel	A	1994–1996	7.3–8.2
13 Andreanof Isl.	173–177W	decel*	decel*	D		
12 Fox Islands	164–173W	decel	—	?		
11 Unimak Island	162–164W	decel	—	?		
10 Shumagin Isl.	159–162W	accel	accel	A	1994–1996	7.3–7.7
9 Alaska Pen.	155–159W	accel	accel	A	1994–1996	7.3–7.7
9 & 10 Combined	155–162W	accel	accel	A	1994–1996	7.5–8.2
8 Kodiak Island	150–155W	decel	—	D		
7 Prince Wm. Sd.	145–150W	decel	—	D		
6 Cape Yakataga	140–145W	accel	—	?		

Segment numbers and boundaries are after NISHENKO and JACOB (1990).
— No apparent trend.
* Deceleration observed both before and after the 1986 M 8 earthquake.

segments have both experienced accelerating seismic release (see Figures 3 and 4). Other segments of the Alaska-Aleutian seismic zone showing systematic acceleration are the Kommandorski and Delarof segments.

Although accelerating moment release has been observed preceding several large earthquakes in California (SYKES and JAUMÉ, 1990), and before two great earthquakes in the Aleutians (JAUMÉ, 1992), not all of the segments along the Alaska-Aleutian seismic zone are characterized by accelerating seismic release preceding large or great earthquakes. The Andreanof segment, which most recently ruptured in great earthquakes in 1957 and 1986, has been characterized by decelerating seismicity (relative quiescence) prior to major failure (KANAMORI, 1981; JAUMÉ, 1992; and this paper, Figure 2). Although the 1957 earthquake originated in the Andreanof segment, its aftershocks extended into the adjacent Fox and Delarof segments. These segments experienced accelerating seismic release in the decade

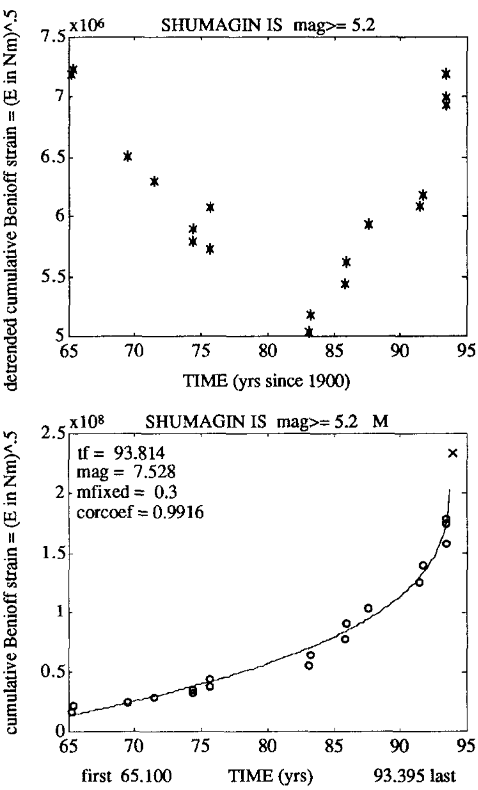

Figure 3

Detrended cumulative Benioff strain for Shumagin segment (approx. 159–162 W longitude) using data for $M_s \geq 5.2$ from JAUMÉ's (1992) catalog. Note change beginning in 1984. (bottom): Time-to-failure analysis for Shumagin segment; t_f is projected time of failure, mag is projected moment magnitude, m_{fixed} is exponent of time to failure in equation (3), and cor_{coef} is correlation coefficient for data fit.

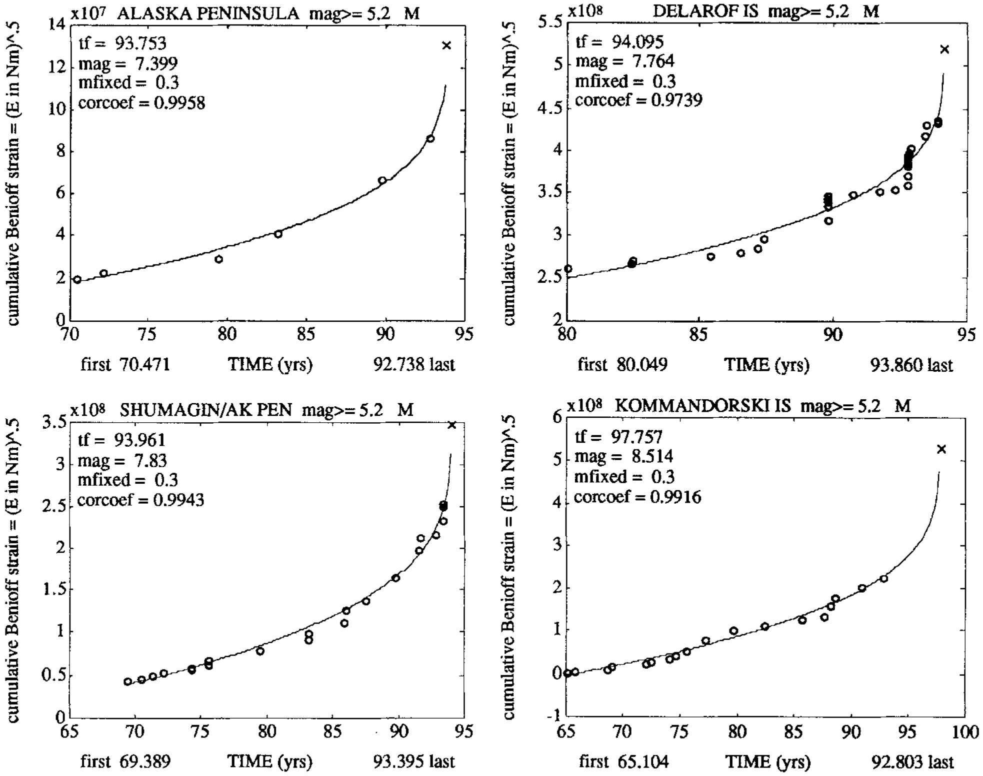

Figure 4

Time-to-failure analyses of cumulative Benioff strain for selected segments of the Alaska-Aleutian seismic zone, using data for $M_s \geq 5.2$ from JAUMÉ's (1992) catalog. t_f is projected time of failure, mag is projected moment magnitude, m_{fixed} is exponent of time to failure in equation (3), and cor_{coef} is correlation coefficient for data fit. Left column, top to bottom: 1) Time-to-failure analysis of the Alaska peninsula segment (155–159 W longitude); 2) time to failure for combined Shumagin Islands and Alaska Peninsula segments (155–162 W longitude). Right column, top to bottom: 1) Time-to-failure analysis of the Delarof Islands segment (177–180 W longitude); 2) time-to-failure analysis of the Kommandorski segment (165–171 E longitude).

before that event. Following the occurrence of the 1986 Andreanof Islands earthquake, the Delarof segment has shown acceleration of cumulative seismic release, continuing to the present. This pattern may result from transfer of stress and is interpreted as an indication of impending rupture of the Delarof zone itself. Immediately to the west, the Rat and Near Islands segments, which were quiescent (KANAMORI, 1981) prior to the great Rat Islands earthquake of 1965, show continuing deceleration from 1965 to the present.

Although the 1965–1993 data do not provide a sufficiently long baseline to firmly establish behavior of individual segments, these data, taken in combination with observations from earlier periods, suggest that some segments, such as the

Delarof Islands segment, are prone to exhibit acceleration of Benioff strain release, while others, such as the Rat Islands and Andreanof Islands segments, tend to show deceleration. The deceleration may indicate progressive locking of a strongly coupled zone or may simply be the result of decay of aftershock activity following a previous large earthquake. Acceleration may be the result of stress redistribution due to aseismic slip, possibly associated with progressive unlocking of a more weakly coupled fault segment. This behavior provides a means of classifying gaps as type A (accelerating or unlocking), as type D (decelerating or locking), or as neither. Some segments, such as the Delarof Islands, may show both A and D types of behavior at different times (see Figure 2). We have classified the Delarofs as predominantly A on the basis of acceleration observed before the 1957 event and acceleration occurring presently. The Kodiak Island segment is classified as D, based on recent seismicity, although JAUMÉ (1992) noted some acceleration in moment release there preceding the great 1964 Prince William Sound earthquake.

It is important to note that seismicity in type A gaps may be used to forecast large earthquakes using the time-to-failure analysis techniques discussed below. In some instances these large earthquakes may not originate within the type A segment showing the acceleration, but within an adjacent segment. Type D segments, on the other hand, will not show acceleration, but may be quiescent before large or great earthquakes. Epicenters of great earthquakes, such as the 1957 Andreanof Islands ($M_w = 8.7$), the 1964 Prince William Sound ($M_w = 9.2$), and the 1965 Rat Islands ($M_w = 8.7$) earthquakes appear to lie within type D segments. Although the absence of accelerating moment release within these segments is not indicative of low stresses, long-term forecasts (NISHENKO and JACOB, 1990) suggest that these great earthquakes are not due to repeat anytime soon.

Multi-segment ruptures which encompass both type A and D segments, such as the 1957 earthquake and its aftershocks, may be preceded by accelerating moment release within the type A segments. In the case of the 1957 earthquake, the premonitory acceleration of seismic release in the Delarof and Fox Islands segments and quiescence in the Andreanof segment were well developed. As noted by JAUMÉ (1992), the acceleration lies entirely within the Delarof and Fox Islands segments, with deceleration occurring in the Andreanof segment. It is also possible that type A segments may show acceleration preceding large earthquakes in type D segments that do not rupture the type A segment.

Time-to-failure Analysis

VARNES (1983) has shown that creep curves for various materials show decelerating (primary) and accelerating (tertiary) creep and that the most common form of accelerating creep is characterized by the INPORT relation, i.e., the *rate* is proportional to the *IN*verse *P*ower *O*f *R*emaining *T*ime to failure. After VARNES (1989) and BUFE and VARNES (1993):

$$d\sum\Omega/dt = k/(t_f - t)^n. \tag{2}$$

Integrated, this becomes

$$\sum\Omega = A + [k/(n-1)](t_f - t)^m, \tag{3}$$

where Ω is seismic release calculated from magnitude, A, k, and n are constants, $m = 1 - n$, $n \neq 1$, and t_f is time of failure (main shock). VARNES (1989) has shown that Benioff strain release in precursory sequences often follows this relation, and when it does, the time of the main shock may be predicted from the pattern of accelerating release. SYKES and JAUMÉ (1990) investigated the distribution of accelerating moment release on faults in the San Francisco Bay region preceding the Loma Prieta earthquake. BUFE and VARNES (1993) have extended the concept of accelerating seismic release in foreshocks to model the behavior of a type A segment (the northern San Andreas fault) through a complete seismic cycle.

The progressive acceleration of seismic release in the Shumagin Islands segment has been well established (BUFE *et al.*, 1990; DMOWSKA and LOVISON-GOLOB, 1991; JAUMÉ and ESTABROOK, 1992). BUFE *et al.* (1992) applied time-to-failure techniques to analyze the accelerating seismic release which preceded the 1957 earthquake in the central Aleutians (their Figure 1) and to the current accelerating release occurring in the combined Unimak, Shumagin, and Alaska Peninsula gaps (their Figure 2). In this paper we provide time-to-failure analyses for the Shumagin segment, the Alaska Peninsula segment, and the combined regions as well as for the accelerating Delarof and Kommandorski Islands segments. The results of these analyses are summarized in Table 1. Time-to-failure curves for the Delarof, Kommandorski, Shumagin Islands, Alaska Peninsula, and combined Shumagin Islands and Alaska Peninsula segments are shown in Figures 3 and 4.

Results and Discussion

Based on time-to-failure analysis of accelerating seismic release using magnitude ≥ 6 (maximum of M_s or m_b) from the extended DNAG catalog, BUFE *et al.* (1992) predicted the occurrence of one or more large (M 7.4–8.3) earthquakes by 1997 (1992.5–1997.8) somewhere within the combined western Alaska Peninsula-Shumagin-Unimak segments of the Alaska-Aleutian subduction zone. (50–60 N, 156–164 W), "assuming continued acceleration." The recent earthquakes in the Shumagin gap (May 13, 1993, M_s 6.9; May 25, 1993, m_b 6.2) continue the acceleration and are consistent with the projection (BUFE *et al.*, 1992, Figure 2) of increasing cumulative seismic release approaching time of failure. However, the Unimak segment does not show clear acceleration of seismic release (see Table 1) and should probably not be included in the analysis. We have reanalyzed seismic release in the Shumagin and Alaska Peninsula segments, both individually and jointly, using time-to-failure analyses to estimate when gap-filling earthquakes may occur. Our analyses for these segments (Table 1) indicate that the Shumagin and Alaska Peninsula zones each show accelerating seismic release commensurate with the imminent occurrence of magnitude 7.3–7.7 main shocks. Another scenario is that these zones could rupture together in a single, larger event. The occurrence of the 1993 events continues the pattern of accelerating seismic release for the Shumagin Islands segment and for the Shumagin-Alaska Peninsula combined zone. Because the late-stage accelerating cumulative seismic release curve is steep, the estimate of time of failure is not very sensitive to the choice of the exponent of time to failure (see Figure 5). The magnitude estimate of 7.5 ± 0.2 for the Shumagin Islands segment is reasonably consistent with the moment estimate of ESTABROOK and BOYD (1992) for the 1917 Shumagin earthquake.

These results are also generally consistent with other evidence that conditions may be right for rupture of the Shumagin gap (BUFE *et al.*, 1990; JAUMÉ and ESTABROOK, 1992; DMOWSKA *et al.*, 1992). However, LISOWSKI *et al.* (1988) noted the absence of geodetic strain accumulation in the Shumagin gap during 1980–1987, suggesting weak coupling. DMOWSKA *et al.* (1992), estimate that while only 15 percent of the plate convergence takes place seismically, coupling at depths between 20 and 50 km is sufficient to permit the generation of large or great earthquakes.

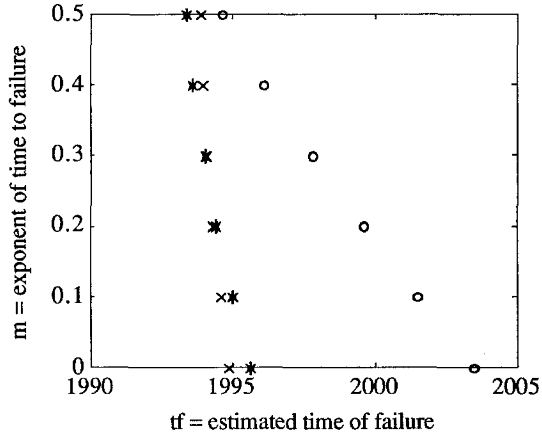

Figure 5

Stages of time to failure for segments of the Alaska-Aleutian seismic zone. Time of failure is shown as a function of exponent (m) of time to failure ($t_f - t$) in equation (3). Preferred value of m is 0.3 (range of 0.1 to 0.4) based on experience in ongoing postdiction studies of other events. Symbols are: * combined Shumagin Islands and Alaska Peninsula segments, × Delarof Islands segment, ○ Kommandorski Islands segment.

Other segments of the Alaska-Aleutian seismic zone showing systematic acceleration (see Figure 4) are the Delarof Islands segment (since 1980) and the Kommandorski Islands segment (since 1965 and possibly earlier). We are projecting the occurrence of a large earthquake ($M \geq 7.4$) in the Delarof segment (177–180 W) of the Aleutian arc by 1996. The recent Delarof Islands earthquake (May 15, 1993, M_s 6.6) occurred only two days following the Shumagin Islands event, and extends the acceleration curve for the Delarof segment, increasing the probability of a subsequently larger event. Interpretation of this acceleration is complicated by the possibility that the acceleration may be sympathetic or triggered, and the culminating earthquake, as in 1957, could originate in the adjacent type D Andreanof (or possibly Rat) Islands gaps and may or may not rupture the Delarof segment. In the Kommandorski segment (165–171 E), plate motion is nearly parallel to the plate boundary and no large earthquakes have recently occurred there. However, large or great tsunamigenic earthquakes may have occurred on this segment in the mid-1800s (SYKES *et al.*, 1981). The Kommandorski segment appears to be in an earlier stage of the failure process, with a larger uncertainty in estimated time of failure. Additional acceleration of seismic release in this segment will be required to narrow the uncertainty.

Time-to-failure analysis curves are shown in Figures 3 and 4 for the four segments (Kommandorski, Delarof, Shumagin, and Alaska Peninsula) showing clear, consistent acceleration of Benioff strain release. The results of time-to-failure analyses of accelerating segments are summarized in Table 1. The forecast time windows are somewhat larger than suggested in Figure 5 to account for the discontinuous nature of the seismicity used to determine time of failure. The computed times of failure cluster around 1994.0 for all but the Kommandorski segment. None of the events has occurred by the end of 1993, hence the expectation for their occurrence is asymmetrical, with the tail extending into the future. As additional smaller earthquakes occur in a given zone, the time-to-failure analysis should be updated. Failure of several of these zones is probable within the next few years.

Multiple large but discontinuous fault segments in the Alaska-Aleutian seismic zone have ruptured within relatively short (2-year) time periods in the past (BUFE *et al.*, 1992). The projected cluster of large earthquakes in the Alaska-Aleutian seismic zone within a period of a year or two is thus not without precedent and appears to be the normal mode of strain release in this region.

Conclusions

We have classified segments of the Alaska-Aleutian seismic zone as type A (accelerating) or type D (decelerating), based on cumulative seismic release histories for the time period 1965.1–1993.4. Data (through 1993.9) from four segments experiencing accelerating seismic release have been analyzed to estimate time of failure. The analyses indicate that the Shumagin segment and the Delarof segment are rapidly approaching failure (i.e., gap-breaking earthquakes of *M* 7.3 or greater are likely within 3 years). Accelerating seismic release has also been analyzed for the Kommandorski Islands segment, where culmination appears to be less imminent and time of failure not so well determined. It appears we are nearing the beginning of an episode of large or great earthquakes in the Alaska-Aleutian seismic zone, similar to the long-distance temporal clustering that has occurred in the past.

Tsunamis are one of the greatest hazards associated with large or great earthquakes along the Alaska-Aleutian seismic zone. These not only affect the epicentral region, but the entire circum-Pacific community. Numerical simulations of tsunamis generated along the Alaska-Aleutian seismic zone indicate that the west coast of Canada and the United States are more vulnerable to sources along the eastern portion of the seismic zone (i.e., the Shumagin Islands) than the central or western portion (i.e., the Delarof Islands) (HOUSTON *et al.*, 1975). Hence, the recurrence of an earthquake the size of the 1788 event along the Alaska Peninsula would have significant economic consequences for the west coast of the United States and Canada. Additionally, models by ZOWALIK and MURTY (1989) indicate that the maximum energy for a Shumagin Islands tsunami would be directed towards the south and southeast (i.e., towards the Hawaiian Islands). Recognition of these facts is important for future hazards mitigation planning in these regions.

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REFERENCES

BEAVAN, J., GILBERT, L., and LARSON, K. (1993), *A GPS Reoccupation of the Shumagin Island, Alaska, EDM Network: Effects of the May 13, 1993* M_w *7.1 Earthquake*, EOS (Transactions, American Geophysical Union), *74*, 92.

BOYD, T. M., and LERNER-LAM, A. L. (1988), *Spatial Distribution of Turn-of-the-century Seismicity along the Alaska-Aleutian Arc*, Bull. Seismol. Soc. Am. *78*, 636–650.

BOYD, T. M., TABER, J. J., LERNER-LAM, A. L., and BEAVAN, J. (1988), *Seismic Rupture and Arc Segmentation within the Shumagin Islands Seismic Gap, Alaska*, Geophys. Res. Lett. *15*, 201–204.

BUFE, C. G., HARSH, P. W., and BURFORD, R. O. (1977), *Steady-state Seismic Slip—A Precise Recurrence Model*, Geophys. Res. Lett. *4*, 91–94.

BUFE, C. G., JAUMÉ, S. C., NISHENKO, S. P., SYKES, L. R., and VARNES, D. J. (1990), *Accelerating Moment Release in the Alaska Subduction Zone: Precursor to a Great Thrust Earthquake?* EOS (Transactions, American Geophysical Union), *71*, 1451–1452.

BUFE, C. G., NISHENKO, S. P., and VARNES, D. J. (1992), *Clustering and Potential for large Earthquakes in the Alaska-Aleutian Region*, Proceedings, Wadati Conference on Great Subduction Earthquakes, University of Alaska, 129–132.

BUFE, C. G., and VARNES, D. J. (1993), *Predictive Modeling of the Seismic Cycle of the Greater San Francisco Bay Region*, J. Geophys. Res. *98*, 9871–9883.

DAVIES, J., SYKES, L., HOUSE, L., and JACOB, K. (1981), *Shumagin Seismic Gap, Alaska Peninsula: History of Great Earthquakes, Tectonic Setting and Evidence for High Seismic Potential*, J. Geophys. Res. *86*, 3821–3855.

DMOWSKA, R., and LOVISON-GOLOB, L. C. (1991), *Stress Transfer and Seismic Phenomena in the Shumagin Islands, Alaska*, EOS, Transactions American Geophysical Union, *72*, *Supplement*, 322.

DMOWSKA, R., and LOVISON, L. C. (1992), *Influence of Asperities along Subduction Interfaces on the Stressing and Seismicity of Adjacent Areas*, Tectonophysics *211*, 23–43.

DMOWSKA, R., ZHENG, G., RICE, J. R., and LOVISON-GOLOB, L. C. (1992), *Stress Transfer, Seismic Phenomena and Seismic Potential in the Shumagin Gap, Alaska*, Proceedings, Wadati Conference on Great Subduction Earthquakes, University of Alaska, 150–152.

ENGDAHL, E. R., and RINEHART, W. A., *Seismicity map of North America project*. In *Neotectonics of North America* (Slemmons, D. B., Engdahl, E. R., Zoback, M. D., and Blackwell, D. D., eds.) (Boulder, Colorado, Geological Society of America 1991) Decade Map Vol. 1, 21–27.

ESTABROOK, C. H., and BOYD, T. M. (1992), *The Shumagin Islands, Alaska, Earthquake of 31 May 1917*, Bull. Seismol. Soc. Am. *82*, 755–773.

HANKS, T. H., and KANAMORI, H. (1979), *A Moment Magnitude Scale*, J. Geophys. Res. *84*, 2348–2350.

HOUSTON, J. R., WHALIN, R. W., GARCIA, A. W., and BUTLER, H. L. (1975), *Effect of Source Orientation and Location in the Aleutian Trench on Tsunami Amplitude along the Pacific Coast of the Continental United States*, Res. Rep. H-75-4, 48 pp., U.S. Army Waterways Exp. Station Hydraul. Lab.

JACOB, K. (1984), *Estimates of Long-term Probabilities for Future Great Earthquakes in the Aleutians*, Geophys. Res. Lett. *11*, 295–298.

JAUMÉ, S. C. (1992), *Moment Release Rate Variations during the Seismic Cycle in the Alaska-Aleutians Subduction Zone*, extended abstract, Proceedings, Wadati Conference on Great Subduction Earthquakes, University of Alaska, 123–128.

JAUMÉ, S. C., and ESTABROOK, C. H. (1992), *Accelerating Seismic Moment Release and Outer Rise Compression: Possible Precursors to the Next Great Earthquake in the Alaska Peninsula Region*, Geophys. Res. Lett. *19*, 345–348.

JONES, L. M., and MOLNAR, P. (1979), *Some Characteristics of Foreshocks and their Possible Relationship to Earthquake Prediction and Premonitory Slip on Faults*, J. Geophys. Res. *84*, 3596–3608.

KANAMORI, H. (1977), *The Energy Release in Great Earthquakes*, J. Geophys. Res. *82*, 2981–2987.

KANAMORI, H., *The nature of seismicity patterns before large earthquakes*. In *Earthquake Prediction*, an International Review, M. Ewing Ser. 4 (Simpson, D., and Richards, P., eds.) (American Geophysical Union, Washington D.C. 1981) pp. 1–19.

KELLEHER, J. A. (1970), *Space-time Seismicity of the Alaska-Aleutian Seismic Zone*, J. Geophys. Res. *75*, 5745–5756.

KELLEHER, J. A., SYKES, L. R., and OLIVER, J. (1973), *Possible Criteria for Predicting Earthquake Locations and their Applications to Major Plate Boundaries of the Pacific and Caribbean*, J. Geophys. Res. *78*, 2547–2585.

LAHR, J. C., PAGE, R. A., STEPHENS, C. D., and CHRISTENSEN, D. H. (1988), *Unusual Earthquakes in the Gulf of Alaska and Fragmentation of the Pacific Plate*, Geophys. Res. Lett. *15*, 1483–1486.

LISOWSKI, M., SAVAGE, J. C., PRESCOTT, W. H., and GROSS, W. K. (1988), *Absence of Strain Accumulation in the Shumagin Seismic Gap, Alaska, 1980–1987*, J. Geophys. Res. *93*, 7909–7922.

NISHENKO, S. P. (1989), *Circum-Pacific Seismic Potential 1989–1999*, U.S. Geological Survey Open-File Report 89-85, map.

NISHENKO, S. P., and JACOB, K. H. (1990), *Seismic Potential of the Queen Charlotte-Alaska-Aleutian Seismic Zone*, J. Geophys. Res. *95*, 2511–2532.

SHIMAZAKI, K., and NAKATA, T. (1980), *Time-predictable Recurrence Model for Large Earthquakes*, Geophys. Res. Lett. *7*, 279–282.

SYKES, L. R. (1971), *Aftershock Zones of Great Earthquakes, Seismicity Gaps, and Earthquake Prediction for Alaska and the Aleutians*, J. Geophys. Res. *76*, 8021–8041.

SYKES, L. R., KISSLINGER, J. B., HOUSE, L., DAVIES, J. N., and JACOB, K. H. (1981), *Rupture zones and repeat times of great earthquakes along the Alaska-Aleutian arc, 1784–1980.* In *Earthquake Prediction*, an International Review, M. Ewing Ser. 4 (Simpson, D., and Richards, P., eds.) (Washington, D.C., American Geophysical Union 1981) pp. 73–80.

SYKES, L. R., and JAUMÉ, S. C. (1990), *Seismic Activity on Neighboring Faults as a Long-term Precursor to Large Earthquakes in the San Francisco Bay Area*, Nature *348*, 595–599.

TANIOKA, T., SATAKE, K., RUFF, L., and GONZALES, F. (1993), *Fault Parameters and Tsunami Excitation of the May 13, 1993 Shumagin Islands Earthquake*, EOS, Transactions, American Geophysical Union *74*, 92.

VARNES, D. J. (1983), *Time-deformation Relations in Creep to Failure of Earth Materials*, Proc. 7th Southeast Asian Geotechnical Conf. *2*, 107–130.

VARNES, D. J. (1989), *Predicting Earthquakes by Analyzing Accelerating Precursory Seismic Activity*, Pure Appl. Geophys. *4*, 661–686.

ZOWALIK, Z., and MURTY, T. S. (1989), *On Some Future Tsunamis in the Pacific Ocean*, Natural Hazards *1*, 349–369.

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