Accelerating Seismic Moment Release and Outer-rise Compression: Possible Precursors to the Next Great Earthquake in the Alaska Peninsula Region

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Abstract. The moment release rate in the Kodiak Island (KI) segment increased prior to the great 1964 Prince William Sound earthquake (M_W = 9.2). Starting in 1983 the moment release rate in the Shumagin Island (SI) segment shows a similar increase. In July 1990, an outer-rise reverse earthquake showed arc-normal compression at a depth of 42 km seaward of the Alaska Peninsula (AP) segment. Because accelerating moment release and arc-normal compression have both been proposed as precursors to large and great earthquakes, we suggest this is evidence that the SI-AP region is nearing the end of the seismic cycle between large thrust earthquakes.

Introduction

The subduction zone south of the Alaska Peninsula (Figure 1) has ruptured this century in three large earthquakes: the 1917 earthquake [M_S = 7.4; M_W = 7.4: *Estabrook and Boyd*, 1992] ruptured the eastern 75 km of the SI segment [*Estabrook and Boyd*, 1992], the great 1938 earthquake [M_W = 8.2; *Brune and Engen*, 1969; *Kanamori*, 1977] ruptured the entire AP segment [*Davies et al.*, 1981], and the 1948 earthquake (M_S = 7.5) ruptured the middle 75 km of the SI segment [*Sykes*, 1971; *Boyd et al.*, 1988]. Historical records suggest both segments ruptured together in great earthquakes in 1788 and 1847 [rupture lengths 600 and 400 km respectively: *Davies et al.*, 1981; *Nishenko and Jacob*, 1990]. Thus, this region shows a variable mode of earthquake recurrence, with repeat times for large and great earthquakes ranging from 59 to 91 years. *Nishenko and Jacob* [1990] calculate conditional probabilities for the occurrence of large earthquakes for the 20 year period 1988-2008 and find that the AP segment has a 37% and the SI segment has a 84% probability of rupture.

There is considerable controversy over whether strain is actively accumulating within the SI segment. Results of geodetic studies are reviewed by *Boyd et al.* [1988] and

Estabrook and Boyd [1992]. *Ma et al.* [1990] present recent results from Very Long Baseline Interferometry.

Accelerating Moment Release

The region chosen for study encompasses a 900 km segment of the Alaska-Aleutian subduction zone (Figure 1). This region is divided into four segments by *Nishenko and Jacob* [1990] based upon its seismic history. In this study we are primarily interested in the central two segments, the AP and SI segments. We also include the adjacent segments to the east (Kodiak Island-KI) and west (Unimak Island-UI) as controls. The calculated 20 year conditional probabilities for rupture of the UI segment are high (94%) and those for the KI segment are low (11%) [*Nishenko and Jacob*, 1990].

Catalog

To determine if the rate of seismic moment release has changed with time, it is necessary to have a catalog of consistent earthquake magnitudes. We have used amplitudes and periods of surface waves recorded at Uppsala, Sweden for earthquakes in the Alaska-Aleutians Islands region in the time period 1930 through April 1989. For 1930 through 1959 and 1961 through March 1980, surface wave magnitudes (M_S) were calculated from the vector sum of horizontal components using the formula of *Van\o(e,ù)k et al.* [1962]. Because Uppsala did not report amplitudes and periods in 1960, we use M_S calculated at M'Bour, Senegal (west Africa) and subtract 0.4 magnitude units, which is the average difference between M_S(Uppsala) and M_S(M'Bour) for Alaska-Aleutian earthquakes in 1959 and 1961. From April 1980 through April 1989 Uppsala reports amplitudes and periods of the vertical component only, and M_S was therefore calculated from it. For May 1989 through July 1991, M_S from the Preliminary Determination of Epicenters (PDE) catalog was used.

For depths and locations of earthquakes, we relied primarily upon the International Seismological Center (ISC) catalog for 1930 through 1987 and the PDE catalog for 1988 through July 1991. In addition, for earthquakes prior to 1962 we used the catalog of *Davis and Echols* [1962] and the Annales de l'Institut de Physique du Globe de Strasbourg (1937-1962) to search for additional locations. Fortunately, Uppsala gives the region of origin of most earthquakes in

their bulletin, so other catalogs can be searched for locations and depths.

Even with recalculation of magnitudes from a single station, the possibility of magnitude bias and detection level changes in this catalog exist. In 1956 Uppsala changed seismometers from which it reported amplitudes (a Wiechert to a Benioff 1-90 seismometer). We also looked at surface wave magnitudes calculated with amplitudes from the Galitzin seismometer at Kiruna, northern Sweden, which operated continuously through the instrumentation change at Uppsala. In comparing Uppsala and Kiruna magnitudes before and after the instrumentation change, we find no systematic change in Uppsala magnitudes. We also directly compared Uppsala and PDE magnitudes before May 1989 found no significant magnitude bias.

The instrumentation change in 1956 lowers the detection level at Uppsala. We attempted to determine the minimum magnitude of homogeneity of our catalog using the magnitude signature technique of *Habermann* [1987], and found that real seismicity increases associated with the aftershock sequences of the great earthquakes in 1957, 1964, and 1965 cloud the interpretation. The best case minimum magnitude is 5.7 and the worst case is 6.5. In the moment release versus time plots that follow, we plot cumulative moment release both for earthquakes with $M_S \geq 6.0$ and $M_S \geq 6.5$.

Moment Release Rates

Direct estimation of seismic moments for worldwide earthquakes have been available on a consistent basis only since 1977 [e.g. *Dziewonski et al.*, 1981]. Determining moment release rates since 1930 requires that we estimate moment from magnitude. *Ekström and Dziewonski* [1988] derive a relationship between M_S as reported by the PDE and scalar seismic moment (M_O) determined using the centroid moment tensor (CMT) technique [*Dziewonski et al.*, 1981]. We assign M_O values to each $M_S \geq 6.0$ earthquake using Ekström and Dziewonski's relationship.

Cumulative seismic moment release for 1930 through July 1991 is shown in Figure 2 for the KI, AP, SI, and UI segments. We include only those earthquakes with epicenters between the trench and the arc; earthquakes with epicenters in the trench seaward of the SI segment are not included. Two great earthquakes occurred within this region during this time period: the 1938 Alaska Peninsula

earthquake, which ruptured the AP segment; and the 1964 Prince William Sound earthquake, which ruptured both the KI and Prince William Sound segments. The main shock moment release in these great earthquakes has been removed from Figure 2, so that changes in the moment release rate of only moderate and large earthquakes (M_S = 6.0 - 7.5) can be examined.

Starting in the east, we find that there is a period of high moment release rate in the KI segment (Figure 2a) twelve years prior to the great 1964 earthquake. Five $M_S \geq 6.0$ earthquakes occur during this time period, as opposed to one in the previous 23 years. All of these earthquakes are located south of KI. Following the 1964 aftershock sequence, the moment release rate appeared to return to its pre-1950's value.

In the AP segment (Figure 2b), the available time prior to the great 1938 earthquake is too short to determine if any change in moment release rate occurred. The moment release rate since 1938 appears constant, with most of the moment release (after the 1938 aftershock sequence) coming in three $M_S \geq 6.9$ earthquakes in 1951, 1964, and 1989. The February 6, 1964 (M_S = 7.0) earthquake is the eastermost of these, about 100 km from the western edge of the KI segment. *Stauder and Bollinger* [1966] refer to this earthquake as a "preshock" of the great 1964 earthquake, but what, if any, mechanical connection they have is not known.

The moment release in the SI segment is dominated by the May 14, 1948 (M_S = 7.5) earthquake, which accounts for over half the moment release. There is no apparent change in moment release rate prior to this earthquake. The moment release rate since 1983 is 4.5 times larger than that from 1948 to 1975. The increase is due to four $M_S \geq 6.0$ earthquakes within the last 9 years, whereas only three occurred in the 20 year period 1956 to 1975.

Like the SI segment, moment release in the UI segment is dominated by one earthquake, the April 1, 1946 (M_S = 7.4) earthquake. There are no $M_S \geq 6.0$ earthquakes prior to this event. Since 1946 the moment release rate in this region appears constant (note that an earthquake in 1987 is included in both the SI and UI segments, since its location falls on the border between the two segments).

Outer-rise Earthquake

On July 25, 1990 an earthquake occurred seaward of the AP segment. We have inverted digitally recorded broadband

P and long period SH waves from the Global Digital Seismic Network and Incorporated Research Institutions for Seismology network for scalar moment, source-time function, source mechanism, and depth using the method of *Náb\o(e,ù)lek* [1984]. We take the source crustal structure to be 4.6 km of water, 10 km crust with P, SH wave velocity and density of 6.50 km/s, 3.75 km/s, and 2900 kg/m^3, over a halfspace of P, SH wave velocity and density of 8.0 km/s, 4.62 km/s, and 3300 kg/m^3. The receiver structure is a halfspace with P-, SH-wave velocities and density of 6.0 km/s, 3.46 km/s, and 2750 kg/m^3. We assume a t* (travel time / Q average) of 0.7 s for P waves and 4 s for SH waves.

The preferred mechanism (strike 276_±30_, dip 26_±5_ rake 83_±24_) shows reverse faulting with the P-axis nearly horizontal and oriented subnormal to the trench (Figure 3). The moment is 9.7(±2.6)x10^{16} Nm (M_w 5.3) and the depth is 42±1 km. Errors are standard errors scaled by the factors described in *Náb\o(e,ù)lek* [1984]. The teleseismic (PDE) location places this earthquake seaward of the trench. Although the earthquake is 200 km outside the network, arrival times across the SI network rule out a location in the main thrust zone east of the Shumagin Islands. This and the depth of the earthquake constrain it to be in the lower (oceanic) plate, and not at the plate interface. This is the first outer-rise earthquake along the Alaska-Aleutian subduction zone known to have a reverse mechanism [*Lay et al.*, 1989].

Discussion

Accelerated moment release along the Alaska-Aleutian thrust zone is seen in the KI segment prior to the great 1964 Prince William Sound earthquake and since 1983 in the SI segment. *Sykes and Jaumé* [1990] show that accelerated moment release preceded three large earthquakes in the San Francisco Bay region of California. *House et al.* [1981] report the occurrence of two swarms of M ³ 6.0 earthquakes at opposite ends of the aftershock zone of the great 1957 central Aleutians earthquake three years prior to that event. *Imamura* [1937] reports increased numbers of moderate size earthquakes before great earthquakes in the Tokyo region in 1703 and 1923. This type of seismicity increase is similar to that predicted to occur in the later stages of the seismic cycle by *Fedotov* [1968]. *Sykes and Jaumé* [1990] note that the spatial pattern of moderate size earthquakes in the San Francisco Bay region resembled the "donut" pattern described by *Mogi* [1969]. The earthquakes that occur prior

to the great 1964 earthquake resemble this in that they are located either at the edge or just outside its rupture zone.

Presently, the SI segment shows an accelerated moment release rate, relative to the period 1948-1983. In all previous examples we have examined, the earthquakes that comprise the accelerated moment release occur outside the rupture zone of the oncoming large or great earthquake. Accelerated moment release preceded the great 1957 and 1964 earthquakes, but not large (M_s = 7.4-7.5) earthquakes in 1946 and 1948. Although the SI segment can clearly produce large earthquakes, previous workers have suggested that it cannot itself generate a great earthquake [*Boyd et al.*, 1988; *Nishenko and Jacob*, 1990; *Estabrook and Boyd*, 1992]. Historical records suggest that portions of the SI segment have indeed participated in great earthquakes [1788 and 1847; *Davies et al.*, 1981], but only in association with the adjacent AP segment. Thus accelerated moment release in the SI segment may not be precursory to a large earthquake within the SI segment itself, but to a great earthquake that includes all or part of the SI segment plus portions of adjacent segments.

The recent outer-rise earthquake offshore from the AP segment shows compression subnormal to the arc. Previous studies of outer-rise earthquakes [e.g. *Christensen and Ruff*, 1988; *Lay et al.*, 1989] have found only outer-rise tensional earthquakes along the Alaska-Aleutian subduction zone. The clearest temporal relationship between outer-rise earthquakes and large interplate thrust events along the Alaska-Aleutian subduction zone has been the activation of outer-rise tensional events following the great earthquakes of 1957, 1964, and 1965 [*Stauder and Bollinger*, 1966; *Stauder*, 1968; *Christensen and Ruff*, 1988; *Lay et al.*, 1989].

Dmowska and Lovison [1988] and *Dmowska et al.* [1988] suggest that the locking of a thrust zone would lead to a stress regime in which outer-rise compression earthquakes will preferentially occur. *Ward* [1984] showed that the addition of a horizontal compressional force to an elastically bending plate has the effect of putting more of the plate into compression. Studies of outer-rise earthquakes suggest that compressional outer-rise earthquakes occur preferentially offshore of strongly-coupled subduction zones [*Christensen and Ruff*, 1988] and during the latter stages of the seismic cycle [*Lay et al.*, 1989]. In light of this, the occurrence of an outer-rise compressional earthquake offshore from a segment that has moderate to high conditional probabilities is significant. It may not only suggest that the corresponding

nearby segment of the main thrust zone is locked but is in an advanced state of stress accumulation prior to a major event.

Conclusions

A period of accelerated moment release occurred prior to the great 1964 Prince William Sound earthquake in the vicinity of KI. We find no evidence for accelerated moment release prior to large earthquakes in 1946 and 1948, but our catalog does not allow us to determine if accelerated moment release occurred prior to the great 1938 earthquake. At present, accelerated moment release appears to be occurring within the SI segment. This type of moment release rate increase has been suggested as a precursor to M ³ 7.0 earthquakes in the San Francisco Bay region. On July 25, 1990, an outer-rise earthquake showing compression subnormal to the trench occurred seaward of the rupture zone of the great 1938 Alaska Peninsula earthquake just east of the SI segment: this is the first recorded occurrence of this type of earthquake in the Alaska-Aleutian subduction zone. Outer-rise compressional earthquakes have been proposed by others as intermediate-term precursors to large thrust earthquakes in a subduction zone. Accelerating moment release and outer-rise compression, taken together with conditional probabilities derived from the analysis of repeat times, suggest that the thrust zone in the AP/SI region may be near the end of the seismic cycle leading to the next large or great thrust earthquake.

Acknowledgements. We have benefited from discussions with S. Nishenko, C. Bufe, and L. Sykes. We thank G. Abers, J. Beavan, K. Jacob, and an anonymous reviewer for detailed reviews. We thank Margie Yamasaki for maintaining the station bulletin library and the Albuquerque Seismic Lab for providing the GSN day tape. This work was supported by Department of Energy grant DE-FG02-ER13221D (C.E.), National Science Foundation grant EAR9124194 (S.J.) and U.S. Geological Survey grant USGS-14-08-0001-G-1976 (S.J.). This is Lamont-Doherty contribution 4879.

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(Received November 6, 1991;
accepted January 6, 1992.)

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Paper number 91L7180.

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Fig. 1. Map of southwestern Alaska and eastern Aleutian Islands. Heavy bars delineate four segments discussed in the text. Circles represent epicenters of shallow (depth ² 60 km) earthquakes with M_S ³ 6.0 from 1930 through July 1991. Focal mechanism of the July 25, 1990 outer-rise earthquake is also shown. Stars are epicenters of the 1917 Shumagin Islands, 1938 Alaska Peninsula, 1946 Unimak Island, and 1948 earthquakes. The 4000, 5000, and 6000 meter bathymetry contours are shown and the arrow delineates the NUVEL1 relative plate motion vector [DeMets et al., 1990].

Fig. 2. Cumulative seismic moment release in Nm from 1930 through July 1991 for: a) Kodiak Island (KI), b) Alaska Peninsula (AP) c) Shumagin Islands (SI), and d) Unimak Island (UI) segments. Circles represent moment release in M_S ³ 6.0 earthquakes and triangles represent moment release in M_S ³ 6.5 earthquakes. Note the moments of the 1964 and 1938 mainshocks have been eliminated from 2a and 2b, but the aftershocks remain.

Fig. 3. Inversion results for the July 25, 1990 outer-rise earthquake. Shown are observed (solid) and synthetic (dashed) broadband P- and long period SH-waves. Focal mechanism is a lower hemisphere projection; sourcetime function is in the center and amplitude and time scales are on the lower right.