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Evolving Towards a Critical Point: A Review of Accelerating Seismic Moment/Energy Release Prior to Large and Great Earthquakes

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Abstract—There is growing evidence that some proportion of large and great earthquakes are preceded by a period of accelerating seismic activity of moderate-sized earthquakes. These moderate earthquakes occur during the years to decades prior to the occurrence of the large or great event and over a region larger than its rupture zone. The size of the region in which these moderate earthquakes occur scales with the size of the ensuing mainshock, at least in continental regions. A number of numerical simulation studies of faults and fault systems also exhibit similar behavior. The combined observational and simulation evidence suggests that the period of increased moment release in moderate earthquakes signals the establishment of long wavelength correlations in the regional stress field. The central hypothesis in the critical point model for regional seismicity is that it is only during these time periods that a region of the earth's crust is truly in or near a "self-organized critical" (SOC) state, such that small earthquakes are capable of cascading into much larger events. The occurrence of a large or great earthquake appears to dissipate a sufficient proportion of the accumulated regional strain to destroy these long wavelength stress correlations and bring the region out of a SOC state. Continued tectonic strain accumulation and stress transfer during smaller earthquakes eventually re-establishes the long wavelength stress correlations that allow for the occurrence of larger events. These increases in activity occur over longer periods and larger regions than quiescence, which is usually observed within the rupture zone of a coming large event. The two phenomena appear to have different physical bases and are not incompatible with one another.

Key words: Accelerating seismic moment/energy, earthquake forecasting, critical point hypothesis, self-organized criticality, stress correlations.

Introduction

Earthquakes do not occur randomly in space and time. Seismology has long recognized this fact and has included this aspect of seismicity directly into its specialized language; we speak of foreshocks and aftershocks, clusters and swarms, precursory activity and quiescence. Some of these patterns, such as the temporal

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decay of the occurrence of aftershocks, follow well-defined empirical laws and a number of plausible physical mechanisms have been proposed to explain their nature. Other patterns, such as the apparent acceleration of seismic moment/energy release prior to large and great earthquakes that we review here, have been proposed more recently and their physical mechanism still remains to be fully explained.

In this paper we review the evidence that at least some $M \geq 6.5-7.0$ earthquakes are preceded by a period of increased occurrence of moderate (generally $M \geq 5.0$) earthquakes in the region surrounding the oncoming large earthquake. In particular, we focus on those cases where the rate of seismic moment or energy release appears to accelerate in the years to decades prior to the large earthquake, and then decrease to a lower level afterwards. We describe what we believe are the major defining features of these accelerating moment release sequences and discuss what implications they hold for the nature of the earthquake process. Finally, we also review models of the earthquake process that we believe shed some light on the physics underlying this seismicity pattern.

Historical Background

The hypothesis that the rate of earthquake activity, particularly of moderate earthquakes, changes in the period between large and great earthquakes has existed for some time. Workers such as WILLIS (1924), IMAMURA (1937), GUTENBERG and RICHTER (1954), and TOCHER (1959) noted changes in the rate of moderate-sized earthquakes before and after great earthquakes in Japan and California. FEDOTOV (1968) was perhaps the first to describe a "seismic cycle" in the occurrence of smaller earthquakes between great plate rupturing events in the Kurile-Kamchatka region. MOGI (1969) further described the evolution of seismicity in the period between great earthquakes. In general, these workers found that, following the aftershock sequence, there is a relative quiescence of earthquake activity (approximately 50% of the interval between great earthquakes) which built up to a higher background level before the next great earthquake.

A number of scientists have also studied the spatial association between earthquakes occurring during the years and decades before great earthquakes. KELLEHER and SAVINO (1975) reviewed seismicity prior to a number of $M \geq 7.8$ earthquakes in the circum-Pacific region. They found that pre-mainshock seismicity clusters around the edges of the oncoming great earthquake rupture zone. MOGI (1969) noted that, in southwest Japan, the earthquakes during the period of increased seismicity concentrate around the periphery of the oncoming rupture zone and that rupture zone itself was relatively quiescent; he referred to such a sequence as a "doughnut pattern." MOGI (1981) also noted that the occurrence of moderate earthquakes in the San Francisco Bay region prior to the great 1906 earthquake appears to fit this pattern.

In general, these early workers suggested that changes in the level of driving stress during the earthquake cycle was the cause of the observed seismicity changes. The great earthquakes that define the cycle release large amounts of accumulated tectonic stress, which is subsequently reacquired through plate motion. The variations in the rate of regional seismicity is seen as a response to this cycle of stress accumulation and release.

Of particular interest to us are the observations of changes in the rate of seismic activity in the San Francisco Bay region between the great 1906 earthquake and the 1989 Loma Prieta earthquake. It was noted by GUTENBERG and RICHTER (1954) that the rate of moderate earthquakes in the several decades following 1906 was considerably less than in the 50 years before the great 1906 earthquake. TOCHER (1959) suggested that a series of $M \geq 5.0$ in the mid-1950s had ended the quiescence following the 1906 earthquake. ELLSWORTH *et al.* (1981) showed that, at an $M \geq 5$ level, the seismicity rate in the San Francisco Bay region at the latitudes of the 1906 surface rupture was significantly higher since 1955 compared with the preceding 50 years. SYKES and NISHENKO (1984) pointed out that the post-1955 $M \geq 5$ earthquakes were concentrated in the southern part of the San Francisco Bay region. They postulated that this may represent a long-term precursor to an $M \sim 7$ earthquake in this region.

An important but sometimes overlooked observation of ELLSWORTH *et al.* (1981) was that, in contrast with the changes in the rate of moderate-sized earthquakes, the rate of smaller earthquakes had remained approximately constant since the 1930s. In a prescient paragraph in their discussion, they suggested that the equilibrium of the San Andreas fault system is controlled by long wavelength forces which are modulated by great earthquakes on the San Andreas fault and tectonic strain accumulation, but that these stress modulations do not disturb the details of the balance between individual parts of the system.

Accelerating Seismic Moment/Energy Release Before Large and Great Earthquakes

Characteristics of Accelerating Seismic Moment/Energy Release Sequences

In the following sections we review cases where there is evidence that accelerating seismic moment/energy release occurred prior to large and great earthquakes, in addition to a small number of cases where this seismicity pattern is known not to have occurred. In this section we first elucidate what we believe are the major characteristics of these sequences, before reviewing specific cases that exemplify these characteristics. The physical interpretation of these features will be covered in a later section.

Based on our review, we find four major characteristics that describe this seismicity pattern:

1. The rate of seismic moment or Benioff strain (the square root of seismic energy) release in moderate earthquakes accelerates prior to the occurrence of the large or great earthquake. In many of these cases this acceleration can be modeled using a power-law time-to-failure relationship to estimate the time and in some cases the magnitude of the oncoming event.
2. The moderate earthquakes involved in the accelerating sequence occur primarily outside the rupture zone of the oncoming large or great earthquake.
3. The change in rate of earthquake occurrence is limited to earthquakes with magnitudes within about 2.0 units of the magnitude of the mainshock.
4. The size of the region in which the moderate earthquakes participating in the accelerating sequence occur scales with the size of the oncoming mainshock.

In our view any physical model vetted to explain this seismicity pattern would have to make predictions consistent with these four observations.

In the sections immediately following we first review cases from the San Francisco Bay region, where accelerating moment/energy release prior to large and great earthquakes was first clearly recognized. We then review other cases in California followed by Alaska, where most of the work on this topic has been conducted. We follow this by reviewing cases outside of California/Alaska. In addition we briefly note other areas were the spatial and temporal patterns of pre-mainshock seismicity appear to match some of the features elucidated above, but which have not been examined for the occurrence of accelerating seismic moment or Benioff strain. At the end we also note two cases where this seismicity pattern clearly did not occur before a large or great earthquake.

Accelerating Moment/Energy Release before Large Earthquakes in the San Francisco Bay Region

On October 18, 1989 an $M = 7.0$ earthquake struck the southern Santa Cruz mountains of California. This was the first $M \geq 7.0$ earthquake to occur in the region of the great 1906 San Francisco earthquake, and its occurrence prompted a number of workers to re-examine the seismic history of the San Francisco Bay region.

The apparent acceleration in the rate of seismic moment release in the San Francisco Bay region prior to the 1989 earthquake was recognized by two groups. As reported by BUFE and VARNES (1993), D. Varnes conducted a time-to-failure analysis of seismic moment in the San Francisco Bay region 1 year prior to the event. Independently, SYKES and JAUMÉ (1990) recognized accelerating moment release prior to both the 1989 Loma Prieta earthquake and the $M \geq 6.8$ San Francisco Bay region earthquakes of 1868 and 1906, plus a 1948 $M = 6.0$ earthquake in southern California.

SYKES and JAUMÉ (1990) found that the rate of seismic moment release in $M \geq 5.0$ earthquakes accelerated prior to the San Francisco Bay region earthquakes of 1868 ($M \sim 7$), 1906 ($M = 7.9$), and 1989 ($M = 7.0$). Like ELLSWORTH *et al.* (1981), they found that there were no significant changes in the rate of occurrence of smaller earthquakes. They found that an exponential increase in the rate of seismic moment release (expressed as cumulative seismic moment) better fit the data in the San Francisco Bay area than a simple linear increase. They attempted to fit the rate-dependent failure equation of VOIGHT (1989) to the cumulative seismic moment data, but were unable to make accurate estimates of the failure time. They also note that the moderate earthquakes participating in the acceleration of moment release appear to occur mostly or totally outside the rupture zone of the oncoming mainshock, even in the case where some of these events occurred very close to the mainshock hypocenter (i.e., the 1988 and 1989 Lake Elsman earthquakes prior to the 1989 Loma Prieta earthquake). Finally, they noted that the seismicity preceding the great 1906 earthquake covered a wider region than that before the events of 1868 and 1989, suggesting that the region of accelerating moment release scales with the magnitude of the oncoming mainshock (Fig. 1).

BUFE and VARNES (1993) focused their work on modeling the accelerating seismicity sequences in the San Francisco Bay area. They applied a power-law time-to-failure relationship to the changes in the rate of seismicity preceding the large and great earthquakes of 1868, 1906, and 1989. They quantified seismicity as cumulative event count, cumulative Benioff strain, and cumulative seismic moment. They used a time-to-failure function of the form:

$$d\Omega/dt = k/(t_f - t)^n \tag{1}$$

where Ω is some measurable quantity describing the rate of seismicity (event count, seismic moment, or Benioff strain), t_f is the time of a large earthquake, t is the time of the last measurement of Ω, and k and n are constants. This formulation was first used by VARNES (1989) to model accelerating seismic moment/energy during 11 foreshock sequences to estimate the time (and in some cases the magnitude) of the mainshock. BUFE and VARNES (1993) show that equation (1) is equivalent to equation (20) of VOIGHT (1989).

BUFE and VARNES (1993) found that, in general, using cumulative Benioff strain release for Ω in equation (1) leads to more accurate predictions of the time of the oncoming mainshock (Fig. 2) than using cumulative seismic moment release. It also allows the magnitude of the mainshock to be estimated. They note that seismic moment is preferable on theoretical grounds (i.e., cumulative Benioff strain becomes unbounded as one goes to smaller and smaller magnitudes), but using cumulative moment as Ω in equation (1) leads to predictions of t_f that are consistently late and that the magnitude of the mainshock cannot be estimated because Ω becomes infinite at t_f.

BUFE and VARNES (1993) had the most success in modeling the accelerating sequences prior to the $M \sim 7$ earthquakes in 1868 and 1989. They found that they could retrospectively predict the time and magnitude of these events to within 2 years and 0.5 magnitude units. They were unable to accurately model the pre-1906 sequence without fixing either t_f or the exponent n. They found that the time of the

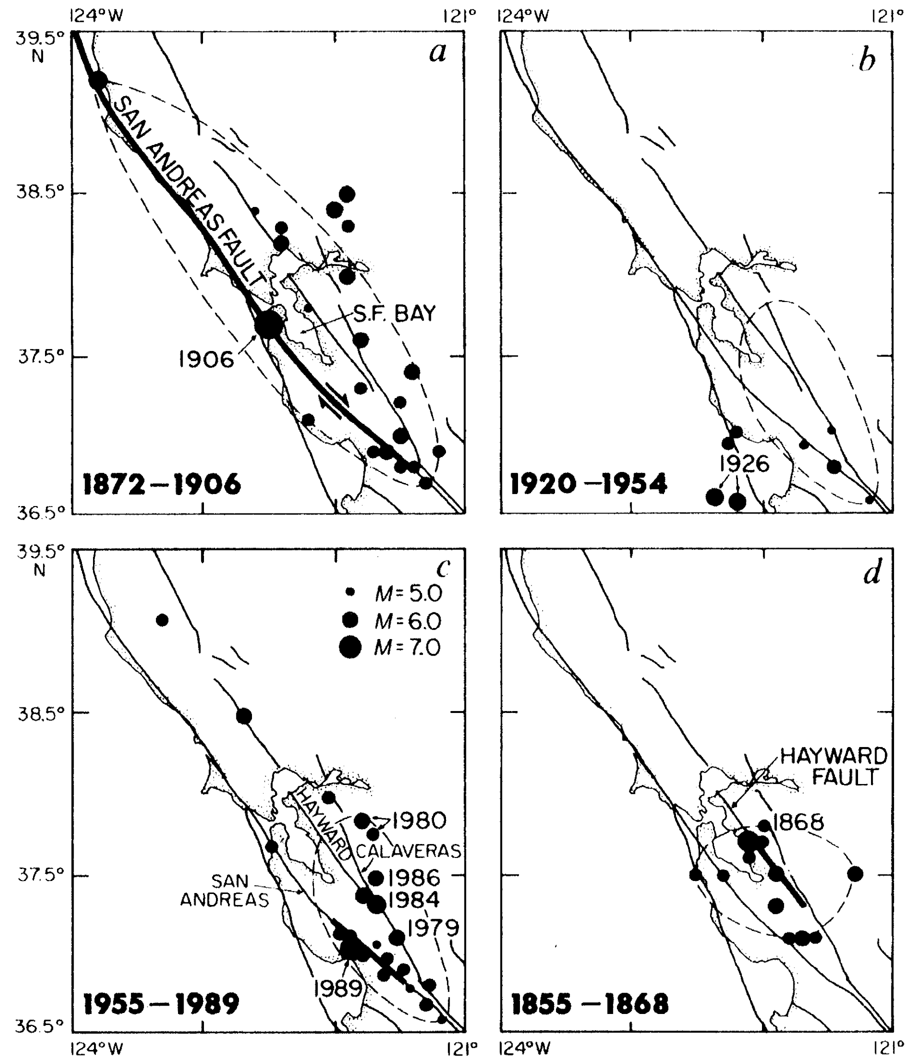

Figure 1
Moderate earthquakes ($M \geq 5.0$) in the San Francisco Bay region during four equal time periods. The area in which earthquakes participating in the accelerating moment release prior to the mainshocks of 1868 ($M \sim 7$), 1906 ($M = 7.8$), and 1989 ($M = 7.0$) are outlined with a dashed line. Note that these areas scale with the magnitude of the oncoming mainshock. Figure 1 from SYKES and JAUMÉ (1990). Reprinted by permission from Nature *348*, 595–599. Copyright (1990) Macmillan Magazines Ltd.

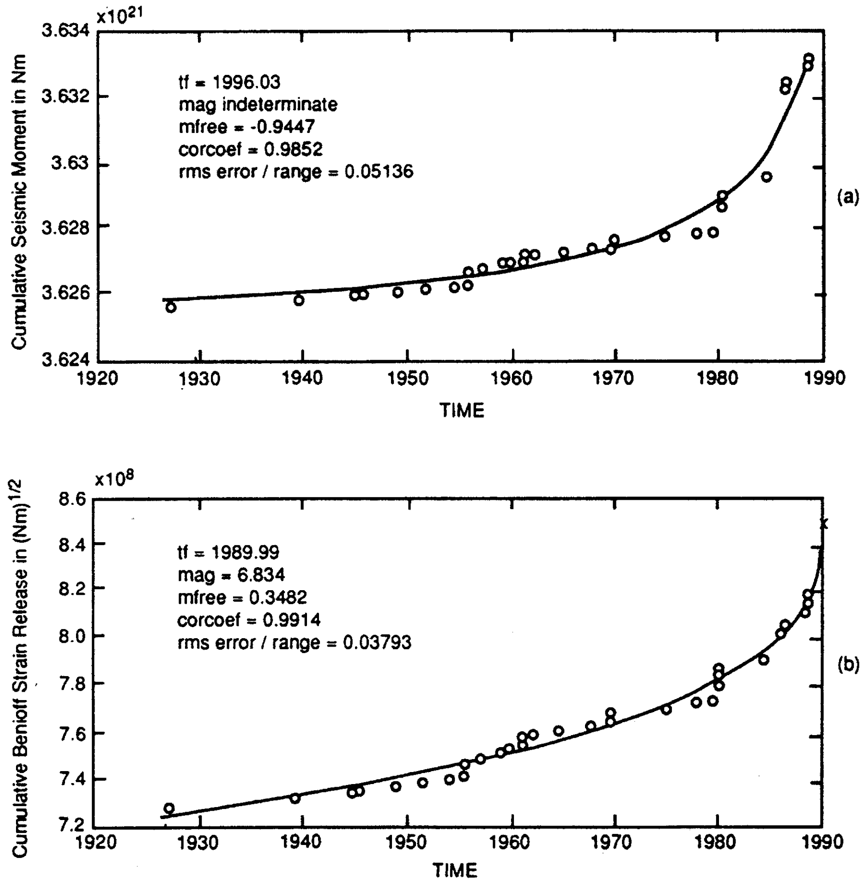

Figure 2

Fits to equation (1) using seismicity in the San Francisco Bay region prior to the 1989 Loma Prieta earthquake. Figure 3 from BUFE and VARNES, J. Geophys Res. *98*, 9871–9883, 1993, published by the American Geophysical Union.

1989 Loma Prieta earthquake could be accurately predicted using moderate earthquakes within 70 km of its epicenter, but that events from a wider region were needed to accurately estimate its magnitude.

BUFE and VARNES (1993) also attempted to model the entire seismic cycle between 1906-type events. They assumed that the pre- and post-1906 seismicity was part of the same sequence, with a period of unknown length missing. Their model, although speculative, predicted a recurrence time of 1906-type events of 230 to 270 years, consistent with paleoseismic results (e.g., HEINGARTNER and SCHWARTZ, 1996). Finally, they suggested that the seismic cycle in the San Francisco Bay region consisted of a long-term acceleration of seismicity leading to the next 1906-type event, punctuated by shorter cycles of acceleration prior to $M \sim 7$ earthquakes. They also suggested that this sequence may be scale-invariant.

Accelerating Moment/Energy Release before Large Earthquakes in California

SYKES and JAUMÉ (1990) pointed out that seismicity prior to the 1948 $M = 6.0$ Desert Hot Springs earthquake appeared to fit the pattern of accelerating moment release, and suggested that this may also be true for the 1952 $M = 7.5$ Kern County earthquake. BUFE *et al.* (1993) report accelerating seismic moment before the $M = 7.3$ 1992 Landers earthquake and BUFE *et al.* (1994a) report the same before the $M = 6.7$ 1994 Northridge earthquake. These results suggested that accelerating seismic moment release before large earthquakes also occurs in California outside the San Francisco Bay region.

A systematic review of changes in seismicity prior to large earthquakes in California and off its Mendocino coast was conducted by KNOPOFF *et al.* (1996). They examined changes in the rate of moderate earthquakes prior to $M \geq 6.8$ earthquakes from 1941 to 1993. They found that all 11 large earthquakes during this period were preceded by increases in the rate of $M \geq 5.1$ earthquakes. Although KNOPOFF *et al.* (1996) examined changes in seismicity rates instead of seismic moment or Benioff strain rates, their findings are consistent with several of the four features elucidated at the beginning of this section. First, they find that the changes in seismicity rates are only well-defined for earthquakes of $M \geq 5.1$ and disappear as one goes to smaller magnitudes. Also, they note that the precursory seismic activity occurs in regions with dimensions up to a few hundred kilometers; i.e., much larger than the rupture dimensions of the $M \geq 6.8$ earthquakes.

More recently, BOWMAN *et al.* (1998) conducted a systematic review of seismicity in California specifically aimed to test for the occurrence of accelerating Benioff strain release before large earthquakes. They examined all $M \geq 6.5$ earthquakes along the San Andreas fault system since 1950 (total of 8). They found that the cumulative Benioff strain prior to all 8 $M \geq 6.5$ earthquakes can be better fit by equation (1) than by a linear increase in Benioff strain. As part of this study they also searched for an optimal "critical region," i.e., a circular region surrounding the epicenter in which the cumulative Benioff strain of the pre-mainshock seismicity best fits equation (1). The results appear to weakly scale with the size of the oncoming mainshock, but the narrow range of mainshock magnitudes considered (6.5 to 7.5) made this observation tenuous. Therefore BOWMAN *et al.* (1998) also analyzed seismicity prior to a few other earthquakes where accelerating moment or Benioff strain is known or suspected to have occurred. These events span a magnitude range from 4.8 to 8.6, and the results appear to support the concept that the region of accelerating seismic release scales with the magnitude of the oncoming mainshock, with $\log R \propto 0.44\,M$, with R being the radius of the critical region.

An important aspect of the work of BOWMAN *et al.* (1998) is that they noted their optimization procedure would also pick out "patterns" given a random set of earthquakes. Therefore, in order to test the significance of their results, they utilized their procedure on a set of 1000 randomly generated synthetic catalogs. They found that an individual random earthquake catalog had close to a 50% chance of generating a spurious acceleration, but that the null hypothesis (i.e., that the Benioff strain accelerations are due to chance) for all eight California cases could be rejected at better than 99% confidence.

Accelerating Moment/Energy Release before Large Earthquakes in the Alaska-Aleutian Subduction Zone

BUFE *et al.* (1990) were the first to point out that accelerating moment release, similar to that seen along the San Andreas fault system, appeared to be occurring since 1975 in the Alaska Peninsula-Shumagin Islands segments of the Alaska-Aleutian subduction zone. JAUMÉ and ESTABROOK (1992) further established the existence of accelerating moment release in this region, plus documented accelerated moment release in the Kodiak Island segment prior to the $M = 9.2$ 1964 Prince William Sound earthquake.

JAUMÉ (1992) examined seismic moment release rates before three $M > 8.5$ earthquakes in the Alaska-Aleutian subduction zone (1957 Central Aleutians, 1964 Prince William Sound, and 1965 Rat Islands earthquakes). HOUSE *et al.* (1981) had pointed out that $6.0 \leq M \leq 7.0$ earthquakes clustered at both ends of the 1957 rupture in the decade before that event. JAUMÉ (1992) found that the rate of moment release appeared to accelerate prior to these events at one or both edges of the oncoming rupture zone. He found, however, that only in the case of the $M = 9.2$ 1964 Prince William Sound earthquake did the regional moment release rate change from a higher rate before the event to a considerably lower rate thereafter.

BUFE *et al.* (1992) showed that the cumulative Benioff strain prior to the 1957 Central Aleutians earthquake could be modeled using equation (1) to estimate the time and magnitude of that earthquake. They also extended the results of BUFE *et al.* (1990) to include the Unimak Island segment to the west of the Shumagin Islands. They noted that the accelerating Benioff strain sequence appeared to be in an early stage, but that their modeling results suggested a failure time for an $M > 7.5$ earthquake around 1997.

BUFE *et al.* (1994b) systematically examined cumulative Benioff strain for $M > 5.2$ earthquakes along the Alaska-Aleutians subduction zone, using the segmentation of NISHENKO and JACOB (1990). They identified three regions of apparent accelerating Benioff strain release: the earlier identified Shumagin Islands-Alaska Peninsula segment, the Delarof Islands segment (Fig. 3) and the Kommandorski Islands segment. They modeled the Benioff strain curves using equation (1) to estimate the time and magnitude of potential oncoming large earthquakes. For the first two segments noted above, they estimated failure times in the interval 1994 through 1996, with magnitudes in the range 7.3 to 8.2. For the Kommandorski Islands segment the expected failure time was relatively poorly constrained, being in the range of 1995 through 2003 with a magnitude range of 7.5 to 8.5.

On 10 June 1996, an $M = 7.9$ earthquake occurred in the Delarof Islands segment, fulfilling one of the predictions of BUFE *et al.* (1994b). We have re-examined the seismicity in the Delarof Islands segment prior to this event and find that most of the earthquakes contributing to the acceleration modeled by BUFE *et al.* (1994b) occur outside or on the edge of the western part of the rupture zone (Fig. 4). Following the 1996 Delarof Islands event, BUFE *et al.* (1996) updated the results of BUFE *et al.* (1994b) to include more recent moderate earthquakes. Results for the Kommandorski Islands segment changed little, but they again combine the Unimak Island segment with the Shumagin Islands-Alaska Peninsula (as in BUFE *et al.*, 1992), yielding an expected failure time of 1996 through 1998 and magnitude 7.7–8.7. We note, however, that a large to great earthquake did not occur in that area during the period (1994 through 1996) of the first prediction by BUFE *et al.* (1994b).

Accelerating Moment/Energy Release before Earthquakes Outside California and Alaska

Although most studies of accelerating moment/energy release have been conducted in plate boundary regions, BREHM and BRAILE (1998) have applied the technique of BUFE and VARNES (1993) to earthquakes in the New Madrid Seismic

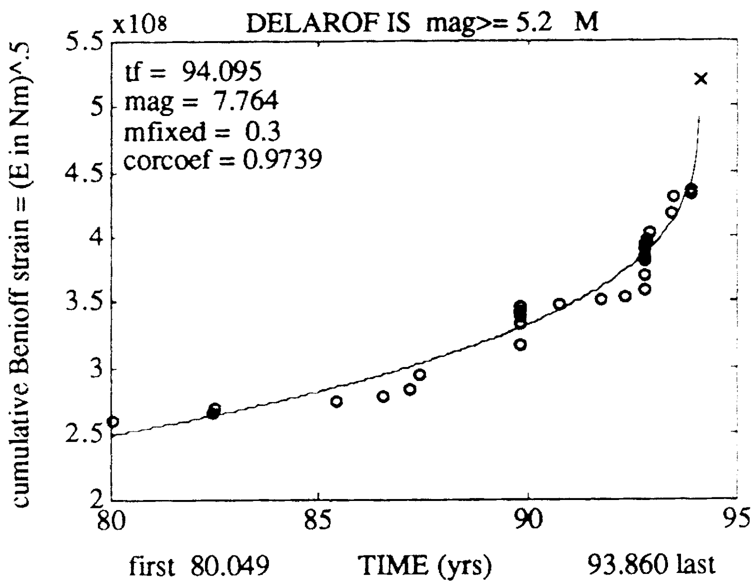

Figure 3
Fit of equation (1) to cumulative Benioff strain release prior to the 1996 Delarof Islands earthquake. Part of Figure 4 from BUFE *et al.*, Pure appl. geophys. *142*, 83–99, 1994, published by Birkhäuser Verlag.

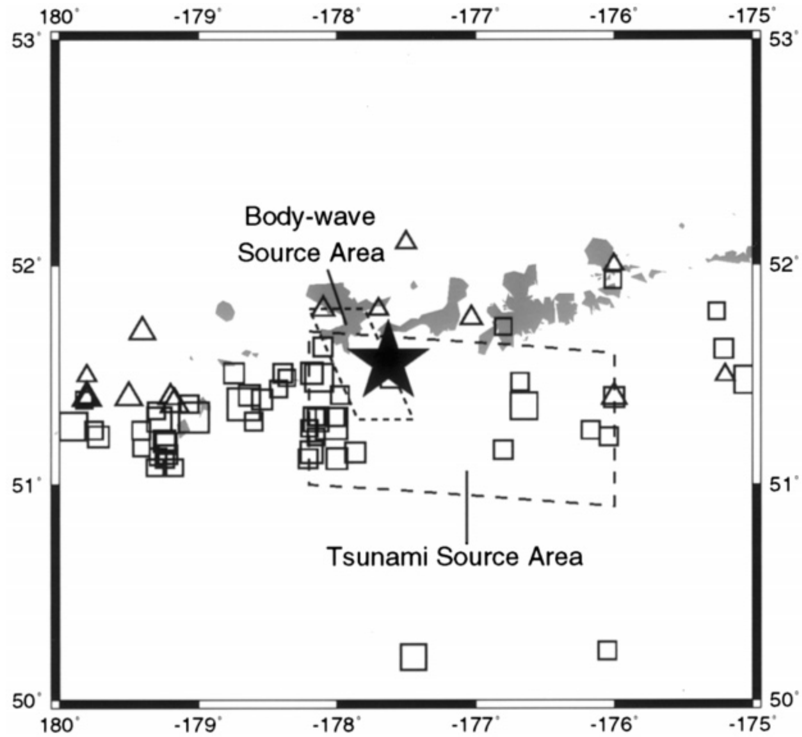

Figure 4
Seismicity ($M \geq 5.5$) in the region of the 10 June 1996 $M = 7.9$ Delarof Islands earthquake. Large star is the epicenter of the 10 June 1996 earthquake. Squares represent seismicity during preceding ten years; triangles represent seismicity during the decade preceding the 9 March 1957 $M = 8.7$ Central Aleutians earthquake. Source areas estimated from tsunami and body-wave analysis are also shown (S. Schwartz, pers. comm.).

zone in the central United States. Surprisingly, they found they can model accelerating Benioff strain sequences before mainshocks as small as $m_b = 3.5$ that yield reasonable predictions of time and magnitude. Of 26 post-1979 mainshocks ranging from $m_b = 3.5$ to 5.2, 16 could be modeled using equation (1). Accelerating Benioff strain sequences were also found before three earlier events, including the 1895 $M = 6.2$ (NUTTLI, 1979) earthquake.

Similar to BOWMAN *et al.* (1998), BREHM and BRAILE (1998) conducted a search for the circular region in which pre-mainshock Benioff strain best fits equation (1). They also found that the size of the region scales with the magnitude of the oncoming event. They suggest that $\log R \propto 0.5 \log M_0$ (seismic moment) provides a reasonable fit to the data, which translates to $\log R \propto 0.75\, M$; i.e., different from the $\log R \propto 0.44\, M$ scaling suggested by BOWMAN *et al.* (1998). We have taken the radius versus magnitude information from Table 1 in BOWMAN *et al.* (1998) and Table 1 in BREHM and BRAILE (1998) and plotted them together in

Figure 5. The best-fitting least-squares line through the combined data set has the relationship $\log R \propto 0.36\,M$, very similar to the value found by BOWMAN *et al.* (1998).

BREHM and BRAILE (1998) show that, at least in some cases, the start of the period of accelerating Benioff strain is marked by a deceleration from a constant background rate. The case they show to illustrate this includes events within a 5-km radius of a magnitude 4.3 earthquake. Given this small radius it is possible all these events are on the same fault; unfortunately BREHM and BRAILE (1998) do not show a map to confirm this. But for many of the accelerating Benioff strain sequences the region involved has dimensions of several tens to greater than 100 km; it is clear in these cases that earthquakes on a number of different faults must be participating.

Like BOWMAN *et al.* (1998), BREHM and BRAILE (1998) tested for the significance of their results, although in a different manner. They randomly selected 20 locations within the New Madrid Seismic zone, and tested for accelerating Benioff strain sequences in regions with radii of 5, 10, 20, 50, and 100 km (total of 100 tests). They report several cases of apparent acceleration without a mainshock, but in most instances these were for mainshocks with $m_b < 3.5$, i.e., smaller than their cutoff. In only two cases were there "false-alarms" (i.e., unfulfilled predictions) for $m_b \geq 3.5$ mainshocks, suggesting a "false-alarm" rate of 2%. They also report preliminary results of another random search method, which suggests a "false-alarm" rate of less than 33%.

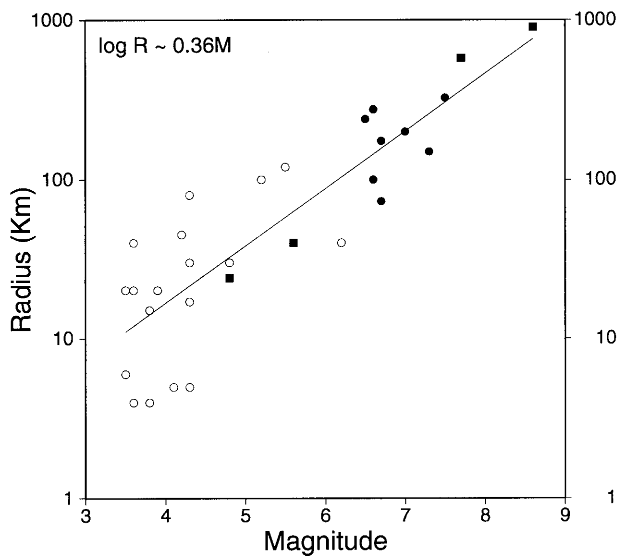

Figure 5
Size of "critical region" relative to magnitude of oncoming mainshock. Filled circles are the eight post-1950 California events and filled squares are the additional four events analyzed by BOWMAN *et al.* (1998). Open circles are the nineteen New Madrid Seismic zone events analyzed by BREHM and BRAILE (1998). The solid line is the best least-squares fit to the combined data set.

Other work outside of California and Alaska includes VARNES and BUFE (1996), who, using data from FRANKEL (1982), found that cumulative square root of moment accelerated before an $m_b = 4.8$ earthquake in the Virgin Islands. Like the cases above, this sequence was modeled using equation (1) to yield an accurate time and magnitude estimate of the mainshock. TRIEP and SYKES (1997) noted that earthquakes of $M > 7.0$ in Asia during the period 1926–1950 cluster near the rupture zone of the 1950 $M = 8.6$ Assam earthquake. They also remark that the rate of $M > 7.0$ earthquakes in Asia was 3.3 times greater during 1900–1957 than during 1958–1994; i.e., that the moment release rate over a large part of Asia decreased following the great 1950 earthquake. BOWMAN *et al.* (1998) used both the Virgin Islands and Assam data sets to extend the magnitude range of their study.

Another region that may potentially exhibit this phenomenon is Japan. The "doughnut pattern" described by MOGI (1969, 1979, 1981) for the seismicity in southwestern Japan before the great Nanki trough earthquakes of 1944 and 1946, is consistent with the spatial and temporal patterns of activity described here. MOGI (1980) also recognized a similar pattern before the great 1923 Kanto earthquake and MOGI (1985) also points out that damaging earthquakes also occurred frequently in Tokyo in the decades leading up to the great earthquake of 1703. To our knowledge these sequences have not yet been assessed with respect to the accelerating moment/energy release model, but we suspect that examining them in this respect will prove a fruitful line of inquiry.

Large Earthquakes without a Preceding Acceleration in Moment/Energy Release

Although the purpose of this study is to review accelerating moment/energy release before large and great earthquakes, any physical explanation of this phenomenon must also explain cases where it does not occur. While attention has not been focused on these cases, two such occurrences are known to us.

First, BUFE *et al.* (1994), in their systematic review of moment release rates in the Alaska-Aleutian subduction zone, found no moment release rate acceleration in the vicinity of the 1986 $M = 8.1$ Andreanof Islands earthquake. This case is of particular interest because the 1986 earthquakes lies within the rupture zone of the 1957 Central Aleutians earthquake, which was preceded by accelerating moment at both ends, and just east of the 1996 Delarof Islands earthquake, which was preceded by accelerating moment at its western end.

Another case is the 1988 Tennant Creek earthquakes in the Northern Territory of Australia. Three $M > 6.0$ earthquakes ($M = 6.2$, 6.4, and 6.7; equivalent to a single $M = 7.0$ earthquake) occurred on adjacent fault segments within 12 hours of each other. What is interesting to us is that this region of central Australia had no record of $M \geq 5.0$ earthquakes within 500 km from Tennant Creek before 1987 (BOWMAN, 1992). This area has been well monitored since 1965 when the Warramunga seismic array was installed 30 km east of the surface ruptures. There was an extended (~ 1 year) foreshock sequence to the 1988 earthquakes, but these events were clustered in what was the nucleation zone of the mainshocks, and not distributed across the surrounding region.

Statistical Tests of Accelerating Moment/Energy Release before Large and Great Earthquakes

There have been three attempts to statistically test the significance of the accelerating moment/energy release patterns we describe in this paper. One test was made by BOWMAN *et al*. (1998) and another by BREHM and BRAILE (1998), which we reviewed in the section above. The other test was executed by GROSS and RUNDLE (1998). They used the DNAG catalog (ENGDAHL and RINEHART, 1991) from 1960 through 1985 and earthquakes with $m_b \geq 5.0$. They fit the cumulative Benioff strain data up to 1985 using either equation (1) or the log-periodic version of SORNETTE and SAMMIS (1995), and tested for "predictions" of $m_b \geq 6.5$ earthquakes up to 1995 in arbitrary zones of the northern Western Hemisphere. They find that a Poisson model better explains the observed seismicity than either of the power-law time-to-failure models.

One criticism we have of GROSS and RUNDLE (1998) is their use of m_b as a measure of an earthquake's size. m_b is known to saturate at $M \sim 6.0$, underestimating the size of larger earthquakes. This could potentially lead to "false negative" results; i.e., not recognizing an accelerating moment/energy release sequence because the size of the largest events were underestimated. In addition, use of m_b in constructing cumulative Benioff strain curves would be very susceptible to artificial changes in earthquake catalogs (HABERMANN, 1987). In our view, use of longer period measures of magnitude, such as M_s or M_w, are preferred.

Physical Mechanisms of Accelerating Seismic Moment/Energy Release Sequences

Early models of the physical process underlying accelerating seismic energy/moment release generally referred to fault and soil creep or damage mechanics processes (e.g., SYKES and JAUMÉ, 1990; BUFE and VARNES, 1993). These authors noted the similarity between the acceleration in the rate of seismic moment release and acceleration in other measures of material deformation seen before failure in many different types of natural and man-made materials. BUFE and VARNES (1993) specifically referred to nucleation/crack propagation and damage mechanics models when deriving equation (1).

JAUMÉ and SYKES (1996) and DENG and SYKES (1997) have examined the occurrence of moderate-sized earthquakes in California in the context of evolutionary stress models that include the effects of large and great earthquakes ($M \geq 7.0$)

plus strain accumulation on major faults. They find that moderate earthquakes occur preferentially in regions of positive stress (quantified as a Coulomb failure function); i.e., in regions where stress has been increased by prior earthquakes and strain accumulation and/or where they have overriden a decrease in stress produced by a previous earthquake. JAUMÉ and SYKES (1996) found that the timing and location of the moderate earthquakes that contributed to the acceleration in moment release prior to the 1989 Loma Prieta earthquake is consistent with their stress evolution model.

Workers such as HUANG *et al.* (1998), SALEUR *et al.* (1996), SAMMIS *et al.* (1996), and SORNETTE and SAMMIS (1995) have begun developing models of the earthquake process based upon the concept that an earthquake represents a type of critical point. In this hypothesis, a large or great earthquake is a consequence of the progressive ordering of a fault system under the influence of many small-scale changes. At the "critical point" correlations exist at all scales and the system moves globally and abruptly. An important feature of this hypothesis is that the accelerating moment/energy release patterns we review in this paper are an expected consequence of systems that either have embedded discrete scale invariance (e.g., a fractal distribution of fault sizes, HUANG *et al.*, 1998) or where such a hierarchy appears spontaneously from the physics of a heterogeneous non-hierarchical system.

The critical point models have a number of attractive features, particularly when viewed against the four characteristics of accelerating moment/energy release sequences described at the beginning of this paper. These models predict power-law time-to-failure behavior of measures of deformation should occur close to the critical point. In addition, log-periodic corrections to equation (1) are also predicted, leading to an equation of the form (SORNETTE and SAMMIS, 1995):

$$\epsilon(t) = A + B(t_f - t)^m\left[1 + C\cos\left(2\pi\frac{\log(t_f - t)}{\log\lambda} + \Psi\right)\right], \tag{2}$$

where $A + B(t_f - t)^m$ is the integrated form of equation (1). SORNETTE and SAMMIS (1995) show that equation (2) yields a prediction of the time of the Loma Prieta earthquake that is closer to the actual time of occurrence and has a smaller uncertainty than using equation (1). However, a similar fit to the Kommandorski Islands acceleration noted by BUFE *et al.* (1994) yields a predicted time (1996.3 ± 1.1) that has since passed.

In these critical point models the power-law behavior of seismicity results from the emergence of long-range correlations in the stress field preceding the large or great earthquake. This is consistent with the observation that the earthquakes contributing to the accelerating seismicity occur outside the rupture zone of the oncoming event, and that the area over which they occur scales with the size of oncoming large event. The critical point model is also consistent with the observation that the seismicity rate changes before large and great earthquakes are confined to moderate magnitude events. SALEUR *et al.* (1996) show that even when the system is very close to a critical point in a small local region, it can still be far away from criticality at larger scales. The results of BREHM and BRAILE (1998) suggest that, in some cases, one can observe this approach to criticality even for relatively small earthquakes.

Discussion

Accelerating Moment/Energy Release and the Wavelength of the Stress Field

One aspect that repeatedly arises during our review of accelerating moment/energy release sequence is the notion of *scale*; spatial scales in particular. The region participating in the accelerating seismicity sequences appear to scale with the size of the mainshock; existing data support a relationship of $\log R \propto 0.5\,M$. Changes in seismicity rates appear to only occur for earthquakes above a certain magnitude; i.e., only for earthquake ruptures above a certain length scale. Time scales also appear to be relevant. BREHM and BRAILE (1998) note that the length of the accelerating sequence scales with magnitude in the New Madrid Seismic zone. HUANG *et al.* (1998) find in their model that precursory activity for events smaller than the system size occur on shorter time scales than for system spanning events. When one examines Figures 6 and 8 in BOWMAN *et al.* (1998) one finds that accelerating Benioff strain before the events they examined also appears to scale in time; i.e., over the course of a decade or more before the larger events (e.g., 1906 $M = 7.9$ San Francisco, 1989 $M = 7.0$ Loma Prieta, etc.) but only years to months before the smaller events (e.g., 1968 $M = 6.5$ Borrego Mountain, 1994 $M = 6.7$ Northridge, etc.).

This leads us to the view, consistent with the critical point hypothesis, that the accelerating seismic moment/energy release sequences reviewed here are related to changes in the length scale of the earthquake process with time. That such changes can take place is supported by the work of TRIEP and SYKES (1997), who found that the frequency-magnitude (i.e., b value) statistics of large earthquakes in the broad plate boundary deformation zone of Asia changed dramatically during this century. Earthquakes from 1958 through 1994 have a change in scaling near $M_w = 7.0$, from a b value about 1.0 below to a b value of 2.4 to 3.0 above $M_w = 7.0$, similar to other continental regions. However, during an earlier period (1900–1957) they find that the frequency-magnitude distribution can be described with a b value near 1.0 up to $M_w = 8.2$. TRIEP and SYKES (1997) suggest that, prior to 1957, most of Asia was in a self-organized critical state (SOC). They attribute this to stress changes caused by the great 1950 Assam earthquake, together with slow aseismic slip below the brittle zone.

Building upon this observation, SYKES *et al.* (1997) hypothesized that, although the crust may be in a SOC state over large time and space scales, the occurrence of a great earthquake moves its surrounding region away from a SOC state. Tectonic loading progressively re-establishes a SOC state before the occurrence of the next great earthquake. Observed increases in the rate of moderate-sized earthquakes herald the re-establishment of SOC.

Both the critical point model of HUANG *et al.* (1998), etc. and the model of SYKES *et al.* (1997) imply that a change in the length scale of the underlying stress field drive the observed acceleration in seismic moment/energy release. If so, this should be reflected in the frequency-magnitude scaling of earthquakes in the affected region. To test this hypothesis, we examine the frequency-magnitude distribution of earthquakes during earlier and later periods of several observed accelerating moment/energy release sequences. The cases we examine are three in which accelerating moment/energy release appears to have led to a large or great earthquake (i.e., 1989 $M = 7.0$ Loma Prieta, 1992 $M = 7.3$ Landers, 1996 $M = 7.9$ Delarof Islands) and one where an ongoing accelerating sequence has not yet ended in a large or great event (i.e., the Unimak Island-Shumagin Islands-Alaska Peninsula segments of the Alaska-Aleutian subduction zone). We choose to examine modern examples because earthquake catalogs for these cases are more likely to be complete than for earlier examples. In this initial survey we do not attempt to decluster the earthquake catalogs to remove aftershocks. We note that such declustering preferentially removes smaller events from the catalog (e.g., FROHLICH and DAVIS, 1993); here we are interested in the larger events in the magnitude-frequency distribution and thus would not expect declustering to make a significant difference.

We start with the Loma Prieta case. We use the University of California at Berkeley earthquake catalog because it appears to be complete down to magnitude 3 since 1942 (see JAUMÉ and SYKES, 1996, for a more detailed discussion of this earthquake catalog). Initially we look at earthquakes within 100 km from the 1989 epicenter, and split the catalog into equal earlier (1942–1965) and later (1966–1989) periods (Fig. 6). During the earlier period the b value appears to be linear up to a magnitude (M_L in this case) of 5.2 to 5.3, but thereafter the b value appears to increase and the largest event is 5.6. During the later time period the b value is linear up to a larger magnitude (5.7 to 6.2), and, if the Loma Prieta mainshock is included in the distribution, there is no apparent change in b value. Basically, the largest events in the distribution only occur near in time to the Loma Prieta mainshock. We also examined a larger area (200 km from the Loma Prieta epicenter) as suggested by BOWMAN *et al.* (1998), and get similar results.

In the Landers case, we use the catalog of the Southern California Seismic Network available online from the Southern California Earthquake Center. We examine a region within 150 km from the Landers epicenter and split the catalog into 1972–1982 and 1982–1992 time periods, based upon the results of BOWMAN

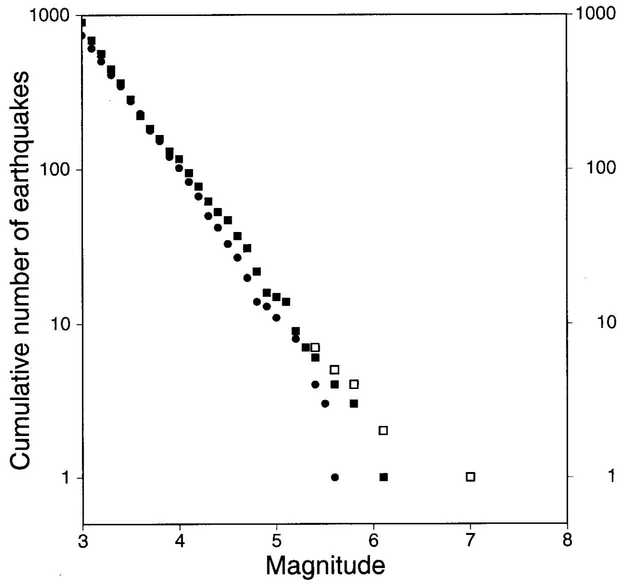

Figure 6
Changes in the frequency-magnitude distribution of earthquakes within 100 km of the Loma Prieta epicenter. Circles—earthquakes during 1942/01/01 through 1965/11/24; closed squares—earthquakes from 1965/11/25 through 1989/10/17. Open squares—same as dark squares but including Loma Prieta mainshock.

et al. (1998). The results are dissimilar to the Loma Prieta case in that the b value appears linear up to the largest magnitude (5.7) during 1972–1982, but similar in that the largest events (up to 6.6) all occur in the latter period (Fig. 7).

A difficulty in examining the Alaska-Aleutian cases is finding a suitable earthquake catalog. Ideally we need a catalog that is both complete to relatively small magnitudes and far enough back in time, plus does not have any saturation problems in magnitude (i.e., like with m_b as discussed above). The Harvard Centroid Moment Tensor catalog does not have saturation problems, but is only complete to $M \sim 5.8$ and only goes back to 1977. The M_s catalog of JAUMÉ (1992) goes back further in time but also is not complete to small magnitudes. The Preliminary Determination of Epicenter (PDE) catalog available online from the U.S. Geological Survey is complete to smaller magnitudes and goes back to 1973. We compared both m_b and M_s in the PDE catalog to M_w in the Harvard catalog, and find that m_b appears to correlate well with M_w at smaller magnitudes and M_s correlates with M_w at larger magnitudes. We find that using the larger of either m_b or M_s is a better representation of M_w than either alone. Therefore, in examining the Delarof Islands and Unimak-Shumagin-Alaska Peninsula cases we use the PDE catalog, looking at earthquakes with depths of 50 km and less and using the largest assigned magnitude.

Based upon Figure 4 in BUFE and VARNES (1994), we split the Delarof Islands seismicity in 1980–1988 and 1988–1996 time segments (Fig. 8). As expected, the largest magnitude events ($M > 6.4$) occur in the latter period, but in this case the seismicity rate appears to increase at all magnitudes. This also appears to be the case when the Harvard CMT catalog is used.

In the Unimak-Shumagin-Alaska Peninsula segments, BUFE and VARNES (1994) and BUFE *et al.* (1996) find that the apparent acceleration begins about 1970, thus we are able to use the entire PDE catalog (i.e., from 1973). Initially, we examined each segment separately, but found the Unimak Island and Shumagin Islands segments were similar to one another and dissimilar to the Alaska Peninsula segment. The combined Unimak-Shumagin segment appears similar to the Loma Prieta and Landers examples, except that the deviation in seismicity rate appears to be approximately at magnitude 6.0 instead of 5.0 (Fig. 9). $M > 6.3$ earthquakes all occur during 1985–1996. The Alaska Peninsula case is more complex. The earthquakes in this segment do not appear to form a continuous distribution in magnitude; instead there appears to be a continuous distribution up to near magnitude 6.0 and then a separate distribution for events with $M = 6.7–6.9$. We do note that, as in the other cases explored, the largest event(s) occur in the later time period, whether viewed as one or two magnitude distributions. Nevertheless, only one event of $M > 6$ occurred in each time period.

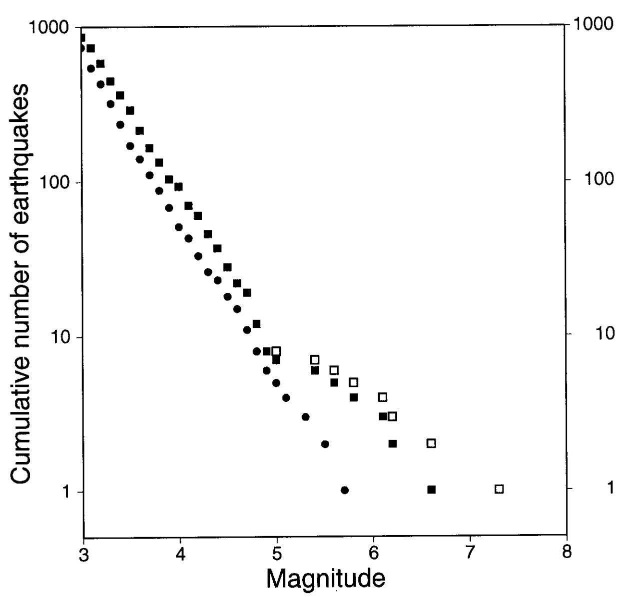

Figure 7

Changes in the frequency-magnitude distribution of earthquakes within 150 km of the Landers epicenter. Circles—earthquakes from 6/28/1972 through 6/27/1982; closed squares—earthquakes from 6/28/1982 through 6/27/1992. Open squares—same as dark squares except including Landers mainshock.

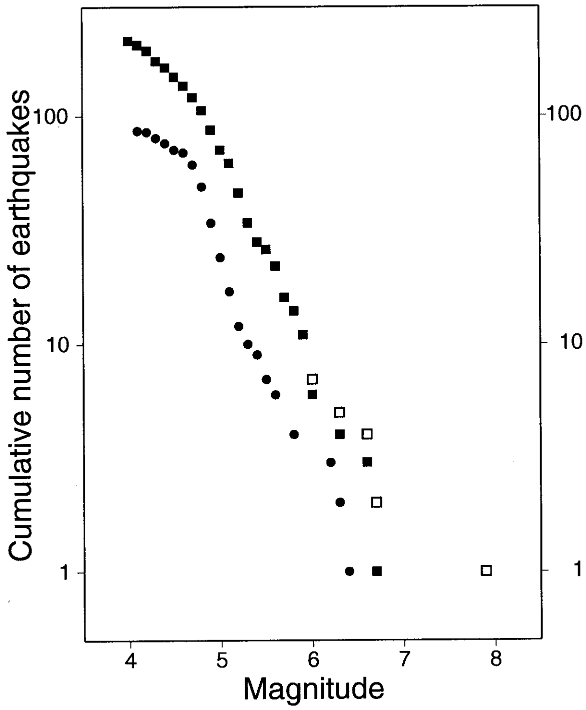

Figure 8
Changes in the frequency-magnitude distribution of earthquakes in the Delarof Islands segment of the Alaska-Aleutian subduction zone. Circles—earthquakes from 6/10/1980 through 6/9/1988; closed squares—earthquakes from 6/10/1988 through 6/9/1996. Open squares—same as dark squares except including Delarof Islands mainshock.

Although the procedure used above can obviously be refined (particularly with respect to potential problems with the earthquake catalog used), at first pass the results appear consistent with the hypothesis that accelerating seismic moment/energy release is the product of increasingly longer correlations in the stress field. The one possible exception to this is the Delarof Islands case, where there appears to be an overall change in seismicity rate; in this sense it is more similar to pre-large event seismicity patterns seen in some block slider models (e.g., SHAW *et al.*, 1992).

Is there any other evidence that long wavelength correlations in the stress field herald a large or great earthquake? The best evidence for this comes from simulation models of the earthquake process. In an early attempt to simulate the fault system in southern California, RUNDLE (1988) speculated that such long wavelength stress correlations would appear to be necessary to drive the large earthquakes in his model, since the model only contained nearest-neighbor stress interactions. Since that time a number of other authors have found that long wavelength correlations in stress appear to be a necessary condition for the occurrence of a large model earthquake, even though the types of simulation models vary greatly; i.e., Burridge-Knopoff block slider models (SCHMITTBUHL *et al.*, 1996), a detailed model of the Parkfield segment (BEN-ZION, 1996), a map-like configuration of southern California faults (WARD, 1996), and a heterogeneous cellular automaton model (STEACY and MCCLOSKEY, 1998). This consistency across a wide range of model types suggests this is a common feature of many-element models with large events.

Other Issues

Several issues with respect to accelerating moment/energy sequences are still unsettled. The first we address is: Why does cumulative Benioff strain appear to produce more accurate predictions than cumulative moment? As noted above, cumulative Benioff strain is an unphysical quantity. Restricting the magnitudes used in the Benioff strain sums to within 2.0 magnitude units of the magnitude of the event one is attempting to predict appears to be a useful practical measure, both because the seismicity changes are confined to moderate magnitudes and it avoids problems with catalog incompleteness. But as far as we know, there is no theoretical justification for using this quantity. A resolution to this problem would be very useful. We note that the number of cases where Benioff strain gives more accurate estimates of time to large events is small.

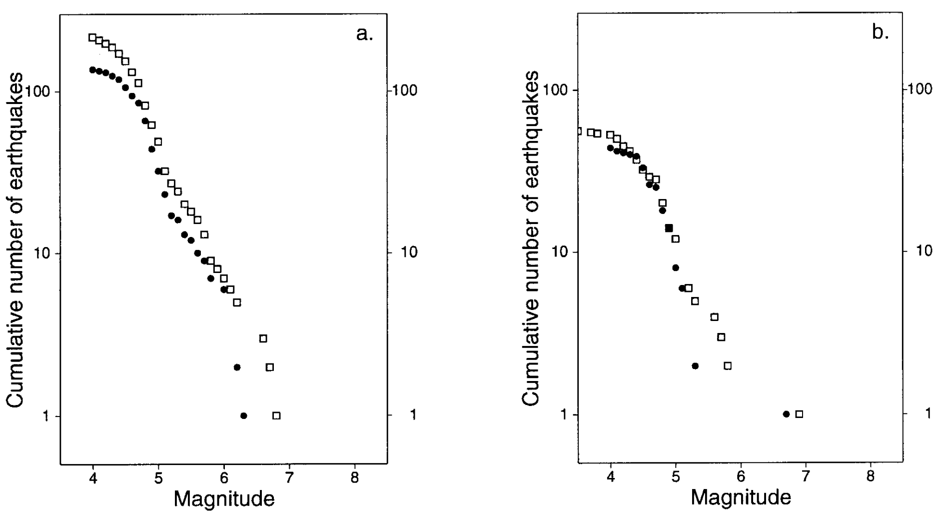

Figure 9
Changes in the frequency-magnitude distribution of earthquakes in the (a) Unimak-Shumagin Islands and (b) Alaska Peninsula segments of the Alaska-Aleutian subduction zone. Circles—earthquakes from 1973 through 1984; squares—earthquakes from 1985 through 1996.

Another issue regards the "background" frequency-magnitude distribution of seismicity from which the accelerating sequence departs. SYKES *et al.* (1997) suggested that accelerating moment/energy release represents a return to a SOC state following a great earthquake. The Loma Prieta (Fig. 6) and Unimak-Shumagin (Fig. 9a) cases fit this model very well. But in the Landers case (Fig. 7) the "background" appears to already be in a SOC state, as found by SORNETTE *et al.* (1996) for the entire southern California region; during the moment/energy acceleration the region appears "super-critical." The Delarof Islands case (Fig. 8) appears to be most consistent with a change in seismicity rate at all magnitudes, although the largest events only occur during the later period.

The difference between northern and southern California may be a function of the time since the last great earthquake. In southern California the time since the last great earthquake on the San Andreas ranges from 141 to around 300 years, depending upon location. In northern California the previous great earthquake was 83 years before the 1989 Loma Prieta event. Thus the "background" stress state in southern California may simply be more evolved from the last great earthquake than in northern California. Another difference between northern and southern California is the much greater contribution of thrust/reverse faulting events to the frequency-magnitude statistics in the latter region. Thus one is seeing the state of a coupled strike-slip/compression system in southern California, as opposed to a primarily strike-slip system in northern California.

The Unimak-Shumagin case (Fig. 9a) seems simply to be a "scaled-up" version of those in California. The Alaska Peninsula (Fig. 9b) and Delarof Islands cases (Fig. 8) are more difficult to comprehend. If one considers only the $M < 6.0$ seismicity in the Alaska Peninsula segment it resembles California closely; but where do the $M > 6.5$ earthquakes fit in? For the Delarof Islands case we note that it lies just to the west of the 1986 $M = 8.1$ Andreanof Islands event. Stress transfer along strike after a subduction thrust event would be expected to increase the driving stress on adjacent segments. Thus the frequency-magnitude statistics of the 1988–1996 time period may reflect this stress change, which would both increase the total number of events and also likely help increase the long wavelength component of the stress field.

What are the Necessary Conditions for Accelerating Moment/Energy Release?

As noted in our review of cases, there are examples where accelerating moment/energy release has not occurred before a large or great earthquake. Thus this cannot be a universal condition of the earthquake process. Therefore the question arises: What features of the earthquake process and/or the fault system in which earthquakes occur are necessary to give rise to this phenomenon? Based upon our review, we tentatively put forth some potential answers to this question, in hopes of stimulating further work on this topic.

The first condition, which was remarked upon by SYKES and JAUMÉ (1990), is that a certain degree of heterogeneity in the fault system seems to be required. It is possible that a hierarchical distribution of fault lengths (for continental regions) or asperity sizes (for subduction zones) is necessary, as suggested by HUANG *et al.* (1998). This may explain why there was no acceleration observed before the great 1986 Andreanof Islands earthquake; i.e., the rupture zone contained a number of small (much less than the width of the fault zone) asperities but no large ones, as suggested by moment release distributions derived from body waves (DAS and KOSTROV, 1990). Conversely, moment release in the 1996 Delarof Islands earthquake appears to be concentrated in one large asperity west of the epicenter (KISSLINGER and KIKUCHI, 1997; SCHWARTZ, 1996).

The second condition regards the density of faults and/or asperities. As remarked by SALEUR *et al.* (1996), accelerating moment/energy release appears to be a cooperative phenomenon in a many-body system. If the "cooperation" arises as a result of elastic interactions between the elements of the system, increasing the distance between elements will decrease the interactions and eventually each element would act more or less independently. This may explain the lack of regional seismicity preceding the 1988 Tennant Creek, Australia earthquakes. Early aftershocks are all concentrated in the immediate vicinity of the rupture zones of the large events, although triggered events at greater distances start occurring nearly two years later (BOWMAN, 1992) and continue at least through May 1996 (AGSO, 1996). We speculate that the faults that ruptured in the Tennant Creek earthquakes are a relatively isolated set and not part of a regional system.

A final necessary condition appears to be the presence of an earthquake large enough to influence the stress state of a significant part of the fault system. The minimum size of such an event would likely depend upon the fault system in question. Based upon our review, we expect that the *minimum* size of such an earthquake is one where the rupture length exceeds its downdip width; probably by a factor of two or more. Earthquakes whose rupture length is considerably greater than the width are more efficient in decreasing regional shear stress. This is clearly illustrated in Figure 8 of KING *et al.* (1994). A rupture with a length/width (L/W) ratio of 1 increases and decreases regional stress in nearly the same proportions; for an event with a L/W ratio of 6 shear stress is decreased in a broad region parallel to the fault but only increased near the rupture tips. In effect, the efficiency at which a large earthquake changes the regional stress state is as much a function of its rupture length as its total moment.

If all or some of the points stated above are necessary conditions for the existence of an accelerating moment/energy release seismicity sequence before a large or great earthquake, it is clear that a study such as that conducted by GROSS and RUNDLE (1998) would likely yield inconclusive results, even using a different set of earthquake magnitudes and time windows. A challenge would be to determine which fault systems would be expected to generate such patterns *a priori*; i.e., using information other than the moment/energy release rates. We believe the best course of action may be to first construct numerous simulation models of fault systems, based upon different real world examples. Hopefully this will make clear what the necessary preconditions are for the seismicity pattern we review here, and guide us in making predictions of the future behavior of real fault systems.

Conclusions

There are a growing number of cases reported where the occurrence of a large or great earthquake is preceded by an accelerated rate of moderate-size earthquakes occurring in its surrounding region. The rate of moment and/or energy release in these sequences can be modeled using a power-law time-to-failure relationship; in some cases an accurate prediction of the time and magnitude of the oncoming event can be made. At least one great earthquake (the 10 June 1996 $M = 7.9$ Delarof Islands event) has been predicted before its occurrence using this methodology, and evidence suggests the time and magnitude of several other $M \geq 7.0$ earthquakes could also have been predicted. The locations of these events, however, could only have been specified as within a broad region, significantly greater than the rupture length of the large or great event.

The moderate earthquakes that make up these accelerating sequences generally occur outside the rupture zone of the oncoming event and often on separate faults altogether. These sequences are therefore not part of the rupture nucleation process, but are cooperative phenomena of the elements of the regional fault system. The size of the participating region appears to scale with the magnitude of the oncoming rupture, at least in continental regions. Only earthquakes with magnitudes within ~ 2.0 magnitude units of the mainshock magnitude appear to participate; the rate of occurrence of smaller events does not change. In addition, the larger events during the accelerating sequence occur preferentially during the latter half of the sequence.

The model that is most consistent with these observations is one where a large or great earthquake is considered to be analogous to a critical point. At this critical point correlations exist at all scales within the fault system, and an event spanning a significant part of the system is possible. The accelerating moment/energy release sequence is therefore a consequence of the ordering of the fault system, where the regional seismicity is responding to the establishment of progressively longer wavelengths in the stress field. The occurrence of a large event decorrelates the regional stress field at longer wavelengths, but leaves the stress field rough at short wavelengths.

The existence of such a seismicity pattern appears to require a certain regional fault system structure and density. Simulation models using a hierarchical distribution of fault and/or asperity sizes match this pattern well, but other types of fault distributions may also support this pattern. The prescence of earthquake events spanning a large part of the fault system also appear to be a prerequisite, since only these events are capable of effecting the stress field at long wavelengths.

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