Crustal earthquake bursts in California and Japan: Their patterns and relation to volcanoes

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Received 29 July 2006; revised 14 September 2006; accepted 19 September 2006; published 26 October 2006.

[1] We analyze 153 bursts of earthquakes in southern California and Japan. The burst patterns are similar in southern California and Japan; they fill a spectrum between "swarm-like" sequences without obvious mainshocks and mainshocks with Omori-law-abiding aftershocks. In agreement with our previous work, the "swarm-like" sequences in Japan have more events, are more voluminous, and tend to expand with time, when compared to "mainshock-aftershock" type sequences. In both regions, we find that the sequences starting with their largest events tend to be much shorter in duration. Bursts within 50 km of volcanoes are similar in character to those elsewhere except they tend to have longer duration. We hypothesize that swarminess is a proxy for fluid pressure redistribution and/or aseismic slip driving the seismicity bursts, and conversely, the mainshock-aftershock-style sequences have end-member behavior that results solely from a cascade of elastic failures. The complexity of the spatial seismicity distribution does not correlate with the style of swarm observed, indicating that fluid conditions and composition are likely more influential than geometry in determining the patterns we observe.
Citation: Vidale, J. E., K. L. Boyle, and P. M. Shearer (2006), Crustal earthquake bursts in California and Japan: Their patterns and relation to volcanoes, *Geophys. Res. Lett.*, *33*, L20313, doi:10.1029/2006GL027723.

1. Introduction

[2] This paper continues our exploration of the spatio-temporal patterns linking bursts of small earthquakes, extending our previous work [*Vidale and Shearer*, 2006] (hereinafter referred to as VS). The large and accurate earthquake catalogs now available for both California and Japan enable us to explore dozens of seismicity bursts in diverse tectonic environments, thus helping to identify characteristic behaviors, which may shed light on the physical processes driving earthquakes.

[3] Our motivation for studying these seismicity bursts is to gain an understanding of the processes by which one earthquake leads to another. As in our previous paper, we see a continuum between two end-member patterns, namely swarms and mainshock-aftershock sequences, and we note features distinct to each classification. We find no clear correlation of the characteristics of the earthquake bursts with proximity to volcanoes in Japan or the diverse tectonic regimes in California, indicating that these patterns are general and wide-spread properties of crustal earthquakes.

2. Seismicity Catalogs and Selection of Seismicity Bursts

[4] We here add 82 seismicity bursts in Japan to the set of 71 bursts in southern California previously described in VS. Our criteria, specified in detail in the first paper, look for isolated, spatially and temporally compact bursts of seismicity, containing enough events for a robust characterization of their properties. We are unavoidably biased toward bursts fitting our selection criteria, but it is likely that other, less well-populated sequences, as well as more spatially extensive sequences, share similar behaviors.

[5] The JMA catalog and its method of construction differ in several ways from the catalog in southern California, so we readjusted the selection parameters. The hypocenters for Japan are not derived from cross-correlated waveforms, so they are not as accurate as those in southern California. This difference led us to relax the compactness required for the bursts – in Japan we required most of the activity to fall within a sphere of 4-km radius, rather than the 2-km radius used in southern California. Also, we had only a 2.5-year catalog for Japan, compared to 19 years for California, but there is a much higher rate of seismicity than in California, so the total number of events is comparable. The depth of the starting point of the swarm is required to be at least 4 km to avoid artifacts in geometry from the upper truncation of seismicity. We set a lower depth limit of 20 km, although a handful of deeper bursts were present, to select only crustal events. Depth limits were not necessary in California. Finally, we chose to apply a 14-day window for Japan (compared to 28 days for California) in order to find a manageable number of bursts, specifically the 82 bursts described below. We retained the same requirement for at least 40 events in a seismicity burst. The window duration affected the swarm duration, but varying the choice of radius and threshold of 40 events did not affect the result.

[6] The 82 bursts in Japan consist of 9486 earthquakes out of a total catalog of 467,154 events and the 71 bursts in southern California contain 6920 earthquakes out of 340,291 events, so each is about 2% of the regional seismicity detected. As the largest events in each collection

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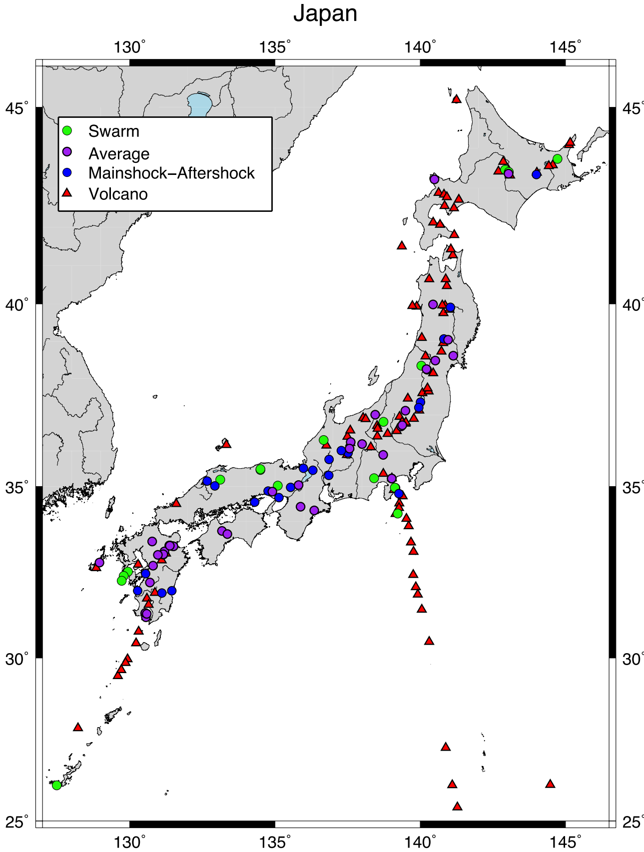

Figure 1. Map of 82 seismicity bursts and regional volcanoes. Mainshock-aftershock style bursts, average bursts, and swarm-like bursts are marked as described in the legend, and red triangles mark volcanoes. Volcanoes are from the list at http://www.volcano.si.edu/world/.

are M4.9, only a tiny fraction of the seismic moment in each catalog is released in these bursts.

3. Differences Between Swarms and Aftershock Sequences

[7] Our previous paper VS noted a set of seismicity-burst parameters that tend to vary together, namely: (1) a large volume of activity compared to the sequence moment release, (2) a lack of correlation between the number of earthquakes and the magnitude of the largest one, (3) the occurrence of the largest event well after the beginning of the sequence, (4) a steady rate of seismicity after an initial burst, and (5) a temporal expansion of the aftershock zone. Those sequences best obeying these properties tend to be most swarm-like; those that least follow these properties tend to resemble traditional models of a single mainshock with aftershocks obeying the Omori law (i.e., mainshock-aftershock type sequences).

[8] The characterization of a sequence as "swarmy" or mainshock-aftershock-like requires caution. While the elastic cascade of mainshock-aftershock sequences begins with the largest event, we expect the frequent presence of foreshocks. How do we distinguish between a large collection of foreshocks and the gradual initiating phase of a swarm? When we consider the time evolution of a sequence, we are able to make a qualitative estimate of which events "belong" to the sequence, and which are isolated temporally. Foreshocks are those events that show temporal isolation from the brunt of seismic activity. By discarding any sequence containing more than 3 foreshocks, we reject sequences for which the onset is not clear, which often has the advantage of eliminating lingering later stages of aftershock sequences.

[9] We classify the sequences as follows. We label events that start with their largest events "mainshock-aftershock-style." Next, among the remaining bursts, we label as "swarm-like" the sequences that are anomalous for more than one factor among (1) large volume compared to cumulative moment, (2) number of aftershocks, (3) late occurrence of the largest event, and (4) expansion of aftershock zone, otherwise we label each burst "average." This results in 23 mainshock-aftershock-like (MS-AS), 40 average, and 19 swarm-like sequences, which are mapped in Figure 1.

[10] We start by verifying that the trends noted by VS in California are general enough to also appear for the Japanese seismicity bursts. Figures 2a and 2b show that MS-AS sequences contain the largest magnitude events and their number of events scales with magnitude, as does the volume of seismicity, despite the lesser precision of the locations in the Japanese catalog. Swarm-like and average sequences behave differently from the MS-AS sequences; the properties of these sequences are relatively independent of the magnitude of the largest event, suggesting the sequences are driven by aseismic slip and/or fluid pressure changes, as we argued in VS, rather than driven by the initial earthquake. The California observation of an initial burst of seismicity, followed by a steady rate of earthquakes through much of the burst for the average and swarm-like sequences, is again observed for the case of Japan, although we do not show a plot here.

[11] Figures 2c and 2d provide further confirmation in Japan of trends first observed in California. The dip of the best-fitting plane to the seismicity is much more often vertical than would occur randomly. In addition, the planes that are very flat, as measured by planarity (defined in VS), tend very strongly to be vertical. Most shallow-dipping planes are MS-AS sequences, even though most MS-ASs have near-vertical planes. The planarities and dip angles did not correlate strongly with tectonic style in California (VS, Figure 14), although we noticed there that the MS-AS sequences have the largest contingent of thrust-faulting mechanisms and shallow dip angles.

[12] We note in Figure 3 an additional trend, not identified in VS, that the MS-AS bursts have at least a factor of three shorter median duration than the average or swarmy sequences in both study regions, and duration does not depend on depth. The durations are shorter in Japan than California, but that appears to arise from the shorter windows used to select the seismicity bursts.

[13] Proximity to volcanoes, as an indicator of higher-than average temperatures and enhanced fluid activity, and depth, may affect the properties of the seismicity bursts in several ways, so we explore these relations in Figure 4. Swarm-like behavior is often noted under volca-

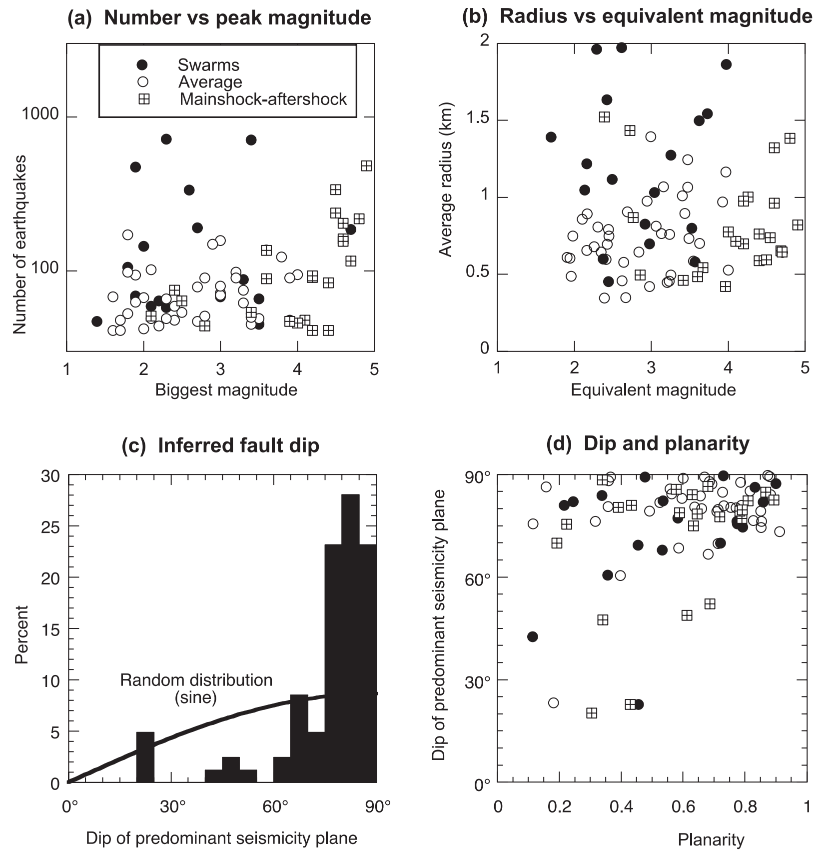

Figure 2. Characteristics of Japanese swarms as measured using parameters previously derived for California. (a) Comparison of the number of events in each sequence as a function of the magnitude of the largest event. (b) Comparison of the swarm radius with the equivalent magnitude of the summed moment in the swarm. (c) Histogram showing that the best-fit planes to seismicity are almost all near vertical. (d) Comparison of the dip of the seismicity planes with planarity.

noes [*Benoit and McNutt*, 1996], and patterns such as hypocentral migration [*Prejean*, 2002] and correlation with geodetic deformation [*Smith et al.*, 2004] have also been noted.

[14] Seismicity is several kilometers shallower within 50 km of volcanoes, and seismicity bursts have a greater duration. All three classifications of bursts show this pattern. As depth is not observed to correlate with duration

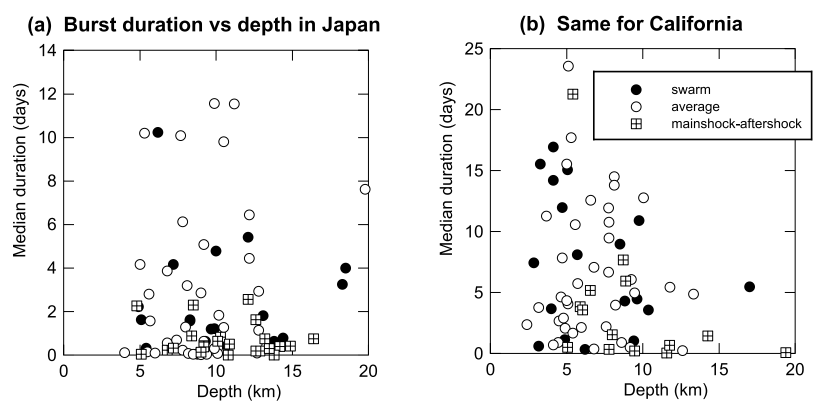

Figure 3. Depth dependence of burst durations. Swarms and average sequences are longer in duration, and tend to be shallow in California. Median durations in Japan are 0.42, 1.2, and 1.6 days for MS-AS, average, and swarm-like sequences. For California, the median durations are 1.5, 4.8, and 6.4 days, respectively. Duration is measured as the median time of events after burst initiation. The differences between durations in California and Japan may be due to the differing length of the time window in the selection criteria.

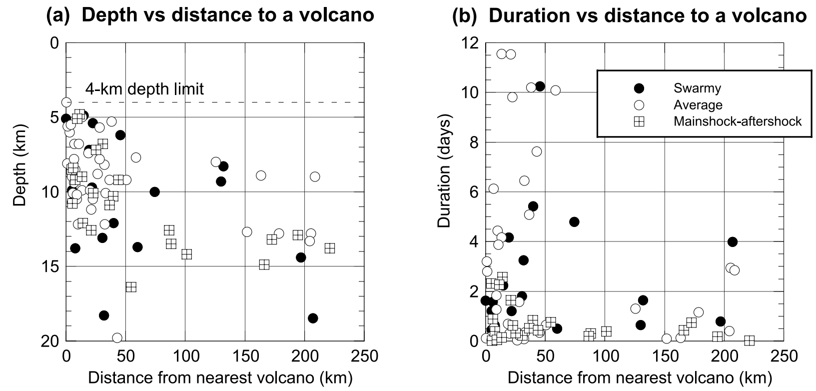

Figure 4. Sequence properties as a function of distance to the nearest volcano. Close to volcanoes, the seismicity is noticeably shallower and longer in duration, as measured by the median time of events within 14 days after burst initiation. However, the mix of swarmy and mainshock-aftershock seismicity bursts does not depend on proximity. As the total window is only 14 days, median durations around 7 days imply that the sequence may still be continuing unabated beyond the end of the window.

(Figure 3a), proximity to volcanoes is most directly related to the duration pattern.

4. Aseismic Slip and Fluids Driving Swarm-Like Behavior

[15] The trends identified here are: (1) shorter durations for MS-AS sequences, (2) the near-verticality of seismicity planes, (3) the extreme flatness of the vertical planes, and (4) the influence of volcanic regions on only the seismicity-burst characteristics of duration and depth. In VS, we showed that the most swarm-like seismicity bursts tend to have radii that expand over time, have more total events, have larger radii for a given cumulative moment, and exhibit a fairly steady rather than decaying rate of seismicity in their early stages. We show here that these patterns also are visible for the Japanese catalog.

[16] We do not include focal mechanism information in this study, but noted in VS that in southern California there was some association of swarm-like sequences with normal-faulting mechanisms and MS-AS with thrust mechanisms. Average sequences were intermediate, although closer to the swarm-like than the MS-AS sequences in behavior. However, the majority of bursts of all styles occurred with near-vertical alignment, which was true individually for all focal mechanisms.

[17] There is an emerging model of swarms as a combination of (1) triggering of aftershocks in response to an initial, usually larger event by coseismic stress transfer [*Stein*, 1999] and dynamic shaking [*Brodsky and Prejean*, 2005; *Felzer et al.*, 2004], and (2) a variable component of background seismicity driven by seismically invisible forces such as aseismic slip and fluid pressure variations [*Fischer and Horálek*, 2005; *Hainzl and Ogata*, 2005; *Klein et al.*, 2006; *Lombardi et al.*, 2006; *Vidale and Shearer*, 2006]. Aseismic slip and fluid disturbances may well be coupled. These patterns have been interpreted for several individual well-instrumented swarms [e.g., *Hainzl and Fischer*, 2002; *McGuire et al.*, 2005; *Prejean*, 2002; *Segall et al.*, 2006; R. B. Lohman and J. J. McGuire, Earthquake swarms driven by aseismic creep in the Salton Trough, CA, submitted to *Journal of Geophysical Research*, 2006]. Our contribution in VS and this paper is to survey many such swarms to search for general patterns.

[18] The longer duration of sequences in volcanic regions is not easily explained by higher temperatures, as previous work has demonstrated that hotter crust harbors shorter aftershock sequences [*Kisslinger and Jones*, 1991; *Mogi*, 1962]. Other explanations that have been offered for longer aftershock sequences include greater fault zone heterogeneity [*Mikumo and Miyatake*, 1979], higher fractal dimension of aftershock hypocentral distributions [*Guo and Ogata*, 1997], or lesser fractal dimension of surface fault traces [*Nanjo et al.*, 1998]. As complications in fault zone structure, or, similarly, higher fractal dimension of faults, are likely visible as less planar clouds of seismicity, we can distinguish the bursts occurring on simple versus complicated fracture planes. However, as we noted above, there is little correlation of burst duration with degree of planar or linear seismicity alignment, as some of these models would predict.

[19] The general lack of correlation (not shown here) of seismicity-burst style with planarity, linearity, and the magnitude and direction (vertically, sideways, or outward) of time migration may indicate that the fluid conditions or other compositional drivers are much more influential than the fault geometry in determining the style of the seismicity bursts.

[20] Our observation of larger volumes affected in swarms suggests that the aseismic disturbances can cover larger areas than predicted by stress transfer or shaking alone, and the tendency for swarm-like sequences to expand indicates that the spatial pattern of the aseismic disturbances also expands over time. The dominance of vertical hypocentral alignment suggests a connection by density-driven fluid flow rather than by stress transfer, which instead would be expected to be more isotropic. However, we note that the vertical alignment is of planar seismicity clouds, not generally linear seismicity streaks, as would be the strongest evidence for vertical fluid movement. There are several striking cases of vertical chimneys of seismicity in these bursts, but they are not a common morphology.

[21] Much remains unknown about why seismicity often occurs in bursts, but we are more thoroughly ascertaining the empirical patterns to their occurrence. To recap, we

verified here the trends identified in VS, and added a correlation of protracted duration with swarminess and with proximity to volcanoes, plus some geometrical trends. We are coming closer to uncovering the specific physics governing why earthquakes in some bursts arrive in apparently random sequences while others more closely obey Omori's law for aftershocks.

[22] The variable degree of seismicity "swarminess" in space and time may present difficulty for modeling catalogs with epidemic-style (ETAS) models. The generality of our swarmy, average, and MS-AS classification in two disparate regions suggests the trends are global. We next plan to explore where ETAS models fail as a litmus test of the times and locations of aseismic slip or fluid redistribution.

[23] **Acknowledgments.** This text has benefited from suggestions from Heidi Houston, Emily Brodsky, and Karen Felzer. Zhigang Peng gathered the earthquake catalog from Japan. Rowena Lohman and Jeff McGuire provided insightful reviews.

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