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Earthquake swarms in circum-Pacific subduction zones

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ABSTRACT

We systematically and manually search through clusters of earthquakes along circum-Pacific subduction zones to identify potential earthquake swarms. In total, we find 266 potential earthquake swarms: 180 we classify as megathrust and 68 we classify as volcanic due to their proximity to the megathrust or to volcanoes. We focus on the megathrust swarms and demonstrate that: (1) the number of events in a swarm is not a function of the largest earthquake in the swarm, (2) swarms exhibit an approximately constant rate of seismicity that lasts until after the mean timing of events in the swarm, (3) the timing of the largest earthquake in the sequence is no different than the timing of any other earthquake in the sequence, (4) our catalogs of earthquakes comprising swarms (~9000 events) have high b-values (1.5 to 2), and (5) when earthquake swarms are considered as single events using total duration and cumulative moment, they appear to be consistent with the slow earthquake magnitude-duration scaling law presented by Ide et al. (2007). The first three observations, along with the observation that swarms can span very large areas compared to their cumulative seismic moment, argue against static stress triggering as a driving mechanism for earthquake swarms. Along strike propagation velocities are observed for several swarms, showing epicentral propagation of ~10 km/day, similar to other documented slow slip events. Together, this evidence implies that aseismic slip along the megathrust is likely an important mechanism for the generation of megathrust earthquake swarms in circum-Pacific subduction zones. We then conduct a comparison of swarms and large megathrust earthquakes, finding evidence that the two are broadly anti-correlated: megathrust segments with large earthquake swarm gaps are more likely to experience large (Mw>8) megathrust events. We characterize the ubiquity of megathrust swarms at different margins, and suggest that fault properties along Marianas-type margins may allow for earthquake swarms to occur regularly, but other margins may rely on other variables, such as the subduction of a ridge or seamount, to facilitate the generation of megathrust earthquake swarms.

1. Introduction

Relationships between earthquakes are observed by the clustering of earthquakes in space and time. This clustering commonly occurs as mainshock–aftershock (MS–AS) sequences, which are generally interpreted to contain the initial rupture of a fault (the mainshock) and a decaying cascade of smaller ruptures on or very near to the initial rupture plane (aftershocks) (Lay and Wallace, 1995). In fact, aftershock sequences are often used to define the rupture plane of the associated mainshock (e.g., Sykes, 1971; Utsu and Seki, 1954).

Clustering of earthquakes in space and time can also occur as earthquake swarms, which are empirically defined as an increase in seismicity rate above the background rate without a clear triggering mainshock earthquake (Hill, 1977; Mogi, 1963; Sykes, 1970). Earthquake swarms are often associated with volcanic regions and are studied because of their relationship to eruptions or intrusions of magmatic material (Benoit and McNutt, 1996). Earthquake swarms have been documented in areas not associated with active volcanism, such as transform faults (Lohman and McGuire, 2007; Shibutani et al., 2002) and hydrothermal systems (Fischer and Horalek, 2003; Heinike et al., 2009). Triggering mechanisms for these non-volcanic swarms range from associated aseismic slip on associated faults (Lohman and McGuire, 2007) to movement of volatiles in hydrothermal systems (Heinike et al., 2009).

Earthquake swarms at subduction margins not associated with volcanism have been documented in New Zealand (Evison and Rhoades, 1993), Japan (Fujinawa et al., 1983; Matsuzawa et al., 2004), Kamchatka (Slavina et al., 2007; Zobin, 1996), Mexico (Zobin, 1996), and South America (Holtkamp et al., 2011; Lemoine et al., 2001). Studies of earthquake swarms at these convergent margins have been motivated by their potential relation to large megathrust events, although the mechanisms behind swarm nucleation and potential interaction with large megathrust events remains debated (Evison and Rhoades, 1993; Llenos et al., 2009).

Most swarms documented in literature were located with local or regional scale seismic networks, often including offshore networks, and utilize local earthquake catalogs with lower magnitude

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thresholds (e.g., Evison and Rhoades, 1993; Flueh et al., 1998; Vidale and Shearer, 2006). While the heterogeneity of seismic networks prevents a global study of this type, the goal of this paper is to initiate a catalog of earthquake swarms along Circum-Pacific subduction zones using the global scale Preliminary Determination of Epicenters (PDE) data set. The core of this work is an expansion of the manual earthquake swarm search conducted by Holtkamp et al. (2011) over the South American continent.

2. Methods

We download and examine the complete PDE catalog from 1973 to 2010 over the following regions: South America, Mexico/Central America, Alaska, Kurile-Kamchatka, Japan, Taiwan/Manila/Philippines, Sumatra, Vanuatu, and Tonga/New Zealand. Since earthquake swarms have been defined empirically in the past (e.g., Hill, 1977), we begin with our definition of an earthquake swarm that agrees with previously defined swarm properties (detailed below). We define an earthquake swarm to be a noticeable increase in seismicity rate above a visually established background seismicity rate without a clear triggering mainshock. Swarms typically have many earthquakes near the magnitude of the largest earthquake in the cluster so they do not follow Baths Law, which states that the largest aftershock is typically one moment magnitude smaller than the triggering mainshock. We find that many earthquake swarms have abrupt onset and termination of seismicity when compared to background seismicity (e.g., without a decay in seismicity rate as in a decaying aftershock sequence). We use this to help determine if a cluster is a swarm, but it is not a requirement, as it is likely that relatively abrupt termination is a necessary outcome of the visual swarm determination. Fig. 1 outlines these observations with a representative swarm example. In contrast, Fig. 2 shows a typical mainshock–aftershock (MSAS) sequence, in which the mainshock is first in the sequence and is typically one moment magnitude larger than the second largest earthquake (Baths Law), and the sequence typically fades into the background seismicity rate without an abrupt termination.

We use these criteria to search through all major circum-Pacific subduction zones for clusters of earthquakes that appear swarm-like. For each region, we systematically examine each apparent cluster of seismicity (apparent as a vertical line of dots in the bottom panel of Figs. 1 and 2). Clusters that appear to have a triggering mainshock or are dominated by a single event are discarded, while the remaining clusters are marked as having swarm-like characteristics. Background seismicity rates in the PDE catalog are highly variable in two ways: (1) reported seismicity rates from 1973 to 2010 vary by about 2 orders of magnitude, likely due to increased instrumentation, and (2) background seismicity varies within each region studies, sometimes drastically (e.g., central Chile, from 30 to 35°S, accounts for half of the seismicity in the South and Central American PDE catalog).

In regions with high background seismicity rate (e.g. Alaska, central Chile), visual characterization of swarms becomes more difficult. In these cases, larger earthquake magnitudes (~1 Mw larger) or larger increases in seismicity rate (e.g., several tens of earthquakes in a period of days to weeks) are necessary to distinguish the cluster, but not both. For example, Holtkamp et al. (2011) find a swarm at the Papudo seamount, South America, without an increase in earthquake magnitudes because there were several tens of earthquakes in a few days. In areas with low background seismicity rate (e.g. southern Chile and Bonin-Marianas Trench) seismicity rate increases can be detected even if only a few earthquakes are large enough to be recorded by regional networks. In Puerto Aysen, southern Chile, for example, we identified two earthquake swarms (1991 and 2007) despite finding less than 15 regionally recorded earthquakes in the PDE catalog. In the case of the 2007 swarm, a local seismic network recorded over 6000 earthquakes without a mainshock (Mora et al., 2008), supporting the use of our approach in cases of limited earthquake numbers in the PDE catalog. For a more detailed examination of the visual detection methodology, see Supplementary Figs. S1 and S2.

In considering ways to pursue an automated swarm detection approach instead, we found that previous studies successfully implementing an automated detection have often relied on a uniform background seismicity level and magnitude threshold, which are conditions that cannot be met in our global study. For example, the method of Vidale and Shearer (2006) constructed an unbiased automated burst detection algorithm that exploited a uniform background seismicity rate, but with limited spatial and temporal scale. Yet even within that dataset, visual classification of swarms was still required. Since we aim to produce a swarm catalog which is not limited in space and time and is produced from a global catalog with widely varying background seismicity rate and magnitude threshold (both vary by several orders of magnitude), it does not allow us to assume a constant background seismicity rate or magnitude threshold. As a result, we rely on a visual swarm detection algorithm. While our visual search is likely incomplete, we are encouraged that the swarm characteristics we present in the next section closely resemble those of Vidale and Shearer (2006).

Since magnitude plays a role in defining earthquake swarms, we seek to establish a consistent magnitude measurement in our catalog search. First, with regards to catalog completeness, we find that in recent years completeness is $\sim Mw = 4$ along major convergent margins. However, in the earlier decades of the catalog, completeness was $\sim Mw = 5$. Secondly, magnitudes given in the PDE catalog are either locally constrained (ML) or regionally/globally constrained (waveform-constrained moment magnitudes for $Mw > \sim 4.5$ in the past 20 yrs and body wave magnitudes for $\sim 4 < Mw < \sim 4.5$). In this analysis, locally constrained magnitudes are ignored as there is no clear conversion to moment magnitudes. When only body wave magnitudes are given, a conversion to moment magnitudes is performed by adding 0.31 to the body wave magnitude (based on an empirical law given by Stein and Wysession, (2003)). Prior to 20 yrs ago, only $Mw > \sim 6$ had waveform-constrained moment magnitudes reported and so earthquakes smaller than this are converted from body wave magnitudes. Considering that magnitude differences in MS–AS sequences are ~1 (Bath's Law), these minor adjustments we make to try to establish a consistent magnitude measurement are not likely to influence swarm detection.

3. Characteristics of earthquake swarms

In total, we find 266 potential earthquake swarms (Fig. 3). We next attempt to classify them according to the tectonic regime where they occurred. There exists a bimodal distribution of swarms in subduction zones: those near the seismogenic megathrust and those near the volcanic arc (perhaps best seen in Supplementary Figs. S3 and S4). 180 swarms lie within the 0 and 50 km depth to slab interface contours, and we classify these as megathrust earthquake swarms. The PDE catalog does not have the epicentral or depth resolution to determine whether these earthquakes represent actual megathrust faulting, but these swarms show thrusting focal mechanisms for every case where magnitudes were large enough to have Centroid Moment Tensor (CMT) solutions (about one quarter of swarms, 47 of the 182). In any case, the proximity of these swarms to the plate interface indicates that the megathrust is playing a prominent role in their formation.

We classify 68 swarms as volcanic, which we define as occurring within ~50 km of an active volcano in the Smithsonians Global Volcanism Program (GVP) database. These swarms are typically shallow (in the crust) and many are associated with volcanic eruptions or documented volcanic activity. We list 18 swarms as other because they don't fit the megathrust or volcanic swarm definitions. These