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Invited Review Article

The global aftershock zone

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ABSTRACT

The aftershock zone of each large ($M \geq 7$) earthquake extends throughout the shallows of planet Earth. Most aftershocks cluster near the mainshock rupture, but earthquakes send out shivers in the form of seismic waves, and these temporary distortions are large enough to trigger other earthquakes at global range. The aftershocks that happen at great distance from their mainshock are often superposed onto already seismically active regions, making them difficult to detect and understand. From a hazard perspective we are concerned that this dynamic process might encourage other high magnitude earthquakes, and wonder if a global alarm state is warranted after every large mainshock. From an earthquake process perspective we are curious about the physics of earthquake triggering across the magnitude spectrum. In this review we build upon past studies that examined the combined global response to mainshocks. Such compilations demonstrate significant rate increases during, and immediately after (~45 min) $M > 7.0$ mainshocks in all tectonic settings and ranges. However, it is difficult to find strong evidence for $M > 5$ rate increases during the passage of surface waves in combined global catalogs. On the other hand, recently published studies of individual large mainshocks associate $M > 5$ triggering at global range that is delayed by hours to days after surface wave arrivals. The longer the delay between mainshock and global aftershock, the more difficult it is to establish causation. To address these questions, we review the response to 260 $M \geq 7.0$ shallow ($Z \leq 50$ km) mainshocks in 21 global regions with local seismograph networks. In this way we can examine the detailed temporal and spatial response, or lack thereof, during passing seismic waves, and over the 24 h period after their passing. We see an array of responses that can involve immediate and widespread seismicity outbreaks, delayed and localized earthquake clusters, to no response at all. About 50% of the catalogs that we studied showed possible (localized delayed) remote triggering, and ~20% showed probable (instantaneous broadly distributed) remote triggering. However, in any given region, at most only about 2–3% of global mainshocks caused significant local earthquake rate increases. These rate increases are mostly composed of small magnitude events, and we do not find significant evidence of dynamically triggered $M > 5$ earthquakes. If we assume that the few observed $M > 5$ events are triggered, we find that they are not directly associated with surface wave passage, with first incidences being 9–10 h later. We note that mainshock magnitude, relative proximity, amplitude spectra, peak ground motion, and mainshock focal mechanisms are not reliable determining factors as to whether a mainshock will cause remote triggering. By elimination, azimuth, and polarization of surface waves with respect to receiver faults may be more important factors.

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1. Introduction

Aftershocks of large ($M \geq 7$) earthquakes can happen nearly anywhere on Earth because their surface waves distort fault zones and volcanic centers as they travel through the crust, triggering seismic failures (Anderson, 1994; Árnadóttir et al., 2004; Beresnev et al., 1995; Brodsky et al., 2000; Cannata et al., 2010; Chelidze et al., 2011; Daniel et al., 2008; Doser et al., 2009; Felzer and Brodsky, 2006; Glowacka et al., 2002; Gomberg, 1996; Gomberg et al., 1997, 2001, 2004; Gomberg and Bodin, 1994; Gomberg and Davis, 1996; Gomberg and Felzer, 2008; Gomberg and Johnson, 2005; Gonzalez-Huizar and Velasco, 2011; Gonzalez-Huizar et al., 2012; Hill, 2008; Hill et al., 1993; Hirosi et al., 2011; Hough, 2001, 2005, 2007; Hough and Kanamori, 2002; Husen et al., 2004; Husker and Brodsky, 2004; Jiang et al., 2010; Johnston et al., 2004; Jousset and Rohmer, 2012; Kilb et al., 2000; Lei et al., 2011; Lin, 2012; Meltzner and Wald, 2003; Miyazawa, 2011; Miyazawa and Mori, 2006; Mohamad et al., 2000; Moran et al., 2004; Pankow et al., 2004; Papadopoulos, 1998; Peng et al., 2011a, 2010, 2012; Pollitz et al., 2012; Prejean et al., 2004; Savage and Marone, 2008; Shanker et al., 2000; Singh et al., 1998; Spudich et al., 1995; Stark and Davis, 1996; Steeples and Sreeples, 1996; Sturtevant et al., 1996; Surve and Mohan, 2012; Taira et al., 2009; Tape et al., 2013; Tibi et al., 2003; Tzanis and Makropoulos, 2002; Ukawa et al., 2002; Van Der Elst and Brodsky, 2010; Velasco et al., 2008; Wen et al., 1996; West et al., 2005; Wu et al., 2011, Yukutake et al., 2011; Zhao et al., 2010). Example results (Velasco et al., 2008) are reprised in Fig. 1; hundreds of Global Seismograph Network (GSN) stations that recorded surface waves from 15 $M \geq 7.1$ mainshocks were filtered and analyzed for local events. A nearly two-fold rate increase is evident when the observations are stacked (Fig. 1A). We plot results from a catalog search for $M > 5$ events on the same time range scales (Fig. 1B), but no $M > 5$ rate increase is associated with 260 $M \geq 7$ mainshocks (e.g., Huc and Main, 2003; Parsons and Velasco, 2011).

At near radii ($r < 1000$ km) there is a very clear (~50-fold) $M > 5$ earthquake rate increase during the first hour after 260 $M \geq 7$ mainshocks that decays rapidly by Omori's law, and is obvious for at least 10 days (Fig. 2). The same analysis for the rest of the planet outside 1000 km radii from mainshocks shows no detectible rate increase during any period (Fig. 2B). The 1000 km radius was chosen because Parsons and Velasco (2011) found that to be the greatest distance that significant $M > 5$ earthquake rate increases were seen. Elevated rates within a 300 km radius are observed to persist for ~7–10 years (Faenza et al., 2003; Parsons, 2002).

Key questions then are: Why aren't dynamically triggered $M > 5$ earthquakes correlated with passing surface waves across the global aftershock zone the way smaller earthquakes are? Is there no comparable hazard in the global aftershock zone to that in the local zone? Perhaps we haven't yet observed this simply because $M > 5$ earthquakes are orders of magnitude less frequent than smaller shocks by the Gutenberg and Richter law ($\log(N) = a\text{-}b\text{M}$; Ishimoto and Iida, 1939; Gutenberg and Richter, 1954). However, extrapolation of the Velasco et al. (2008)

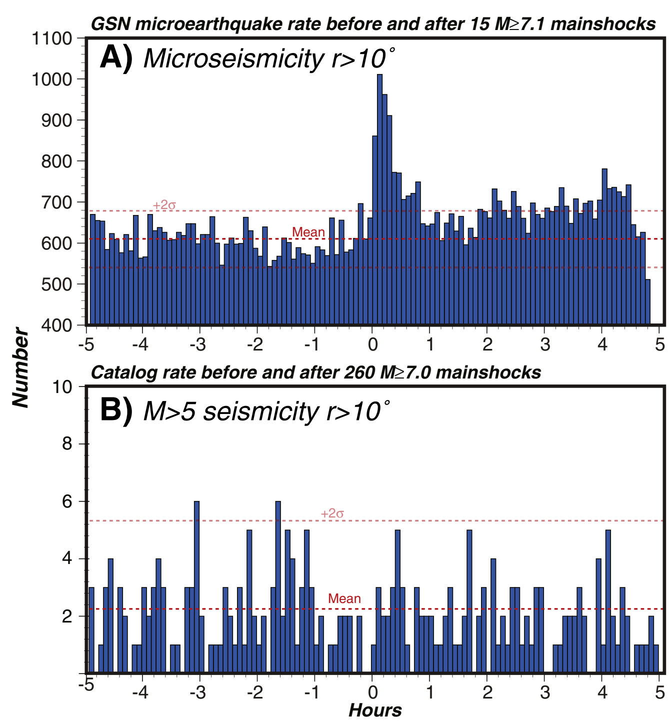

Fig. 1. In (A) remotely triggered earthquakes recorded on GSN stations identified by Velasco et al. (2008) are shown. The significant rate increase persists for slightly less than 1 h. Little is known about these events, which were not located by regional networks. In (B) a search of the 34-year $M > 5$ catalog shows no rate increase associated with 260 $M \geq 7$ mainshocks.