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Repeating earthquakes in the Yellowstone volcanic field: Implications for rupture dynamics, ground deformation, and migration in earthquake swarms

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ABSTRACT

We evaluated properties of Yellowstone earthquake swarms employing waveform multiplet analysis. Thirty-seven percent of the earthquakes in the Yellowstone caldera occur in multiplets and generally intensify in areas undergoing crustal subsidence. Outside the caldera, in the Hedgen Lake tectonic area, the clustering rate is higher, up to 75%. The Yellowstone seismicity follows a succession of two phases of earthquake sequence. The first phase is defined between swarms. It is characterized by a decay of clustering rate and by foreshock–aftershock sequences. The second phase is confined to swarms and is characterized by an increase in clustering rate, and dominant aftershock sequences. This phase reflects tectonic swarms that occur on short segments of optimally oriented faults. For example, the largest recorded swarm in Yellowstone occurred in autumn 1985 on the northwest side of the Yellowstone Plateau which was initiated as a tectonic source sequence. Fitting experimental dependence of fluid injection with intrusion migration suggests that the 1985 swarm involved, after 10 days, hydrothermal fluids flowing outward from the caldera. The 2008–2009 Yellowstone Lake swarm exhibited a high migration rate of 1 km/day, a decrease in clustering rate without a main-shock, and appears to be associated with magma injection of 1 to 5 m^3/s in a succession of migrating magma fronts that incrementally solidify and fracture at its brittle edges. The 2010 Madison Plateau earthquake swarm on the west side of the caldera initiated as a tectonic sequence but the expansion of the swarm front was associated with hydrothermal fluid migration.

1. Introduction

Earthquake swarms consist of a series of earthquakes closely clustered in space and time without a clear main-shock (Mogi, 1963; Sykes, 1970). Magmatic intrusion can occur coincidently with earthquake swarms in volcanic settings, raising the question of how to distinguish between earthquakes driven by magmatic and tectonic processes and homogeneity of the associated stress field (Bergman and Solomon, 1990; Ruppert et al., 2011). Hill (1977) for example, noted that active volcanic systems commonly experience swarms as a main mode of seismic energy release. However earthquake swarms are not exclusively associated with volcanism (Benoit and McNutt, 1996). Identifying the statistical and quantitative properties of earthquake swarms aid in distinguishing their driving processes. A key characteristic of some Yellowstone earthquake swarms is the migrating front of the hypocenter pattern. Non-migrating swarms are often associated with the release of tectonic stress through an earthquake sequence in which each event participates in the triggering of the next, whereas spatial migration of swarm fronts can best be modeled as fluid related diffusion, i.e., pressurized fluids that triggered incipient fractures and related earthquakes in their migration path.

Tectonic earthquake swarms occur in a variety of fault conditions including regional extensional stress regimes (for example along mid-ocean ridges, Bergman and Solomon, 1990), strike-slip systems (for example on the San Andreas fault, McNally et al., 1978) and subduction zones (swarms associated with the circum-Pacific subduction zone are detailed in Holtkamp and Brudzinski, 2011). While some tectonic swarms progressively end with little consequence (e.g. no large main-shock), others can become foreshock sequences to larger main-shocks and can be interpreted, in retrospect, as precursors (Evison and Rhoades, 1998).

Migrating swarms may result from a temporal stress field perturbation due to a mobile component of crustal fluids (Rubin, 1995) or a mobile and concentrated stress perturbation (Mogi, 1963). Migration of hydrothermal fluid also has been shown to induce migrating earthquake swarms by increasing pore fluid pressure and reduction of the effective normal stress (Fournier, 1999). Magma transport, whether breaching the surface or not, often triggers migrating earthquake swarms by failure at the dike tip or failure of the magma reservoir wall (Hill, 1977; Rubin, 1995; Ukase and Tsukahara, 1996; Roman and Cashman, 2006). The occurrence of earthquake swarms and the variety of triggering processes can complicate both volcano and earthquake hazard assessment. The Yellowstone volcanic field and related areas of strong seismicity offer the opportunity to study both tectonic and magmatic swarms requiring a modern seismic and GPS network such as in Yellowstone.

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1.1. Yellowstone earthquake swarms

The Quaternary rhyolite plateau of Yellowstone National Park (hereafter, "Yellowstone") dominates the geologic setting (Fig. 1). It is the result of bimodal basaltic–rhyolitic volcanism in the lithospheric extensional stress regime of the Basin-Range province (summarized by Smith et al., 2009). It has been shown from seismic tomography that an upper-mantle plume feeds Yellowstone volcanism (Waite et al., 2006; Smith et al., 2009; Obrebski et al., 2010). The plume feeds basaltic fluid into the lower crust and melts the mid and upper crust to form a rhyolitic/basaltic magma reservoir of up to 15% melt (Husen et al., 2004a, 2004b; Smith et al., 2009) underlying the 0.64 Ma Yellowstone caldera (see Fig. 1, and Christiansen, 2001) at depths of 5 to 15 km.

Crustal extension and the crustal magma system in Yellowstone are characterized by the highest conductive heat-flux of the western U.S., ~2 W/m^2 (DeNosaquo et al., 2009; Smith et al., 2009). Also, Yellowstone seismicity is characterized by the highest rate of earthquake activity of the Intermountain Seismic Belt (0.12 eq/km^2/yr) compared to the central Intermountain Seismic Belt (0.03 eq/km^2/yr, Smith et al., 2009). Kinematically, the Yellowtone caldera has undergone multiple cycles of crustal subsidence and uplift at the decade-scale at rates as high as 7 cm/yr (Chang et al., 2007; Puskas et al., 2007; Chang et al., 2010).

Volcano and earthquake hazards (Christiansen et al., 2007), underscored by the deadly Mw7.3, 1959 Hebgen Lake earthquake, on the west side of the Yellowstone Plateau (Chang and Smith, 2002; Pickering-White et al., 2009; Smith et al., 2009) justify the operation of a modern seismic and GPS monitoring network in Yellowstone, operating since 1972, from which we derived the data used in this study. Yellowstone experiences a few hundred to 3000 earthquakes per year, 100 to 150 earthquakes per year being over the maximum magnitude of completeness, estimated to Mc = 1.5 (Farrell et al., 2009). On average, ~44% of Yellowstone earthquakes occur in swarms, releasing ~40% of the total seismic moment (Farrell et al., 2009). Between 1985 and 2011, there has been 90 independent earthquake swarms (Farrell et al., 2009).

For this paper we will examine three of the most important Yellowstone earthquake swarms with well-defined migrating hypocenter fronts. These include (1) the autumn 1985 northwest Yellowstone caldera earthquake swarm (hereafter, AYES, Waite and Smith, 2002), (2) the 2008–2009 Yellowstone Lake earthquake swarm (YLES) documented by Farrell et al. (2010a, 2010b) and (3) the 2010 Madison Plateau earthquake swarm (MPES) documented by Farrell et al. (2010a, 2010b) and Shelly et al. (2012). The relationship between these swarms and the magmatic fluid–rock interactions however is problematic. Moreover better hazard assessment of Yellowstone relies on the ability to discriminate between tectonic, magmatic, and swarms triggered by fluid pressure variations, a key objective of this paper.

1.2. Earthquake swarm characterization approach

We employed multiplet analysis to infer time–spatial properties of Yellowstone seismicity that contributes to the understanding of source characterization and process of swarm generation. In this study, we use the term "multiplet" to define a group of earthquakes produced by the re-activation of a self-similar seismic source sharing a common hypocenter location, and characterized by similar body-wave waveforms (Geller and Mueller, 1980; Poupinet et al., 1984; Fremont and Malone,

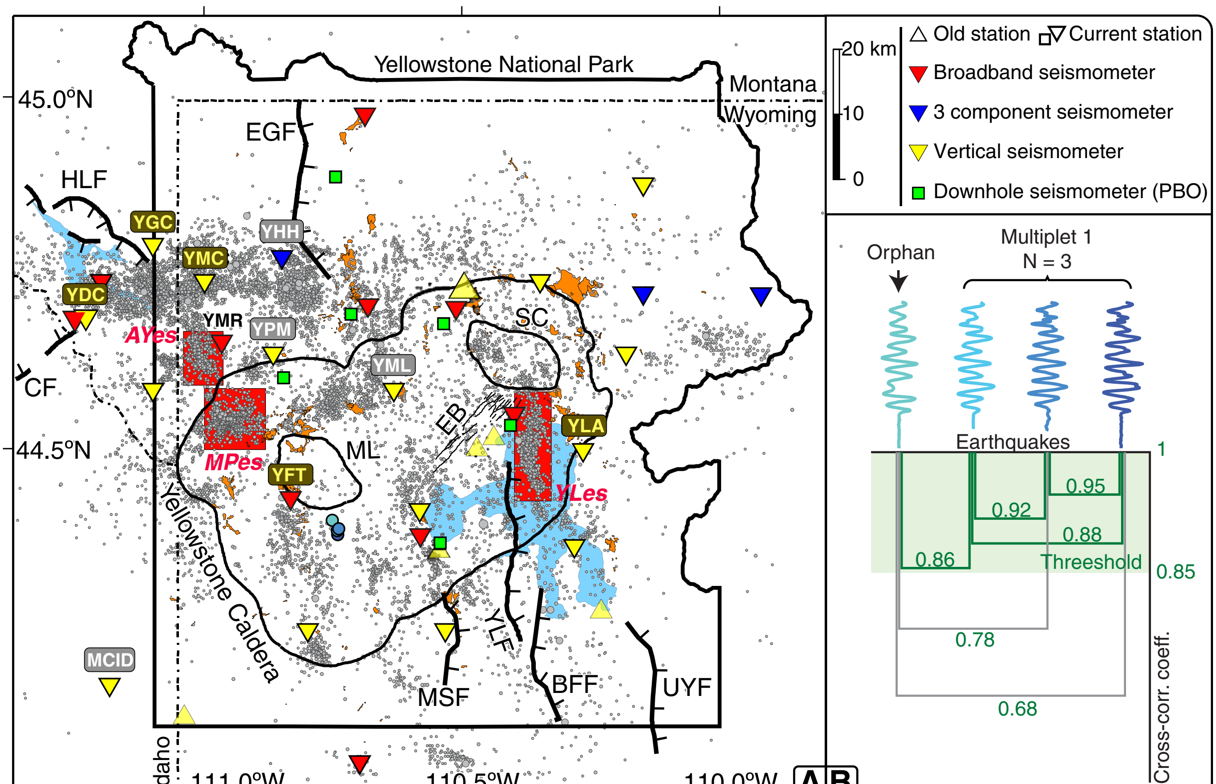

Fig. 1. Map of Yellowstone showing the seismic network stations and earthquakes. Faults are abbreviated as HLF: Hebgen Lake fault; CF: Centennial fault; EGF: East Gallatin fault; MSF: Mt. Sheridan fault; YLF: Yellowstone Lake fault; BFF: Buffalo Fork fault; UYF: Upper Yellowstone Valley fault; ML: Mallard Lake resurgent dome; SC: Sour Creek resurgent dome; EB: Elephant Back fault system). A, gray dots: 33054 earthquake epicenters from 1981 to 2010. A, triangles and squares: seismic stations (see legend). Gray labels: seismic stations used for waveform clustering from 1992 to 2010. Brown labels: seismic stations used for waveform clustering from 1984 to 2010. The chosen set of seismometers provided at least two P-wave picks for every earthquake. B: clustering scheme. Multiplets are made of doublets, which are pairs of earthquakes with a waveform cross correlation coefficients over 0.85 on two stations.