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Testing for the 'predictability' of dynamically triggered earthquakes in The Geysers geothermal field

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A B S T R A C T

The Geysers geothermal field is well known for being susceptible to dynamic triggering of earthquakes by large distant earthquakes, owing to the introduction of fluids for energy production. Yet, it is unknown if dynamic triggering of earthquakes is 'predictable' or whether dynamic triggering could lead to a potential hazard for energy production. In this paper, our goal is to investigate the characteristics of triggering and the physical conditions that promote triggering to determine whether or not triggering is in anyway foreseeable. We find that, at present, triggering in The Geysers is not easily 'predictable' in terms of when and where based on observable physical conditions. However, triggered earthquake magnitude positively correlates with peak imparted dynamic stress, and larger dynamic stresses tend to trigger sequences similar to mainshock–aftershock sequences. Thus, we may be able to 'predict' what size earthquakes to expect at The Geysers following a large distant earthquake.

1. Introduction

Passing seismic waves of large earthquakes can initiate seismic activity at remote distances either directly or indirectly, a phenomenon commonly known as dynamic triggering (Hill and Prejean, 2015). Transient stresses on the order of a few kilopascals generated by large, distant earthquakes are known to dynamically trigger icequakes (Peng et al., 2014), deep tectonic tremor (e.g., Aiken et al., 2013), and shallow microearthquakes (e.g. Hill et al., 1993). The general understanding is that triggered seismicity is "clock-advanced", in that it occurs as a result of these small transient stresses loading an active fault and pushing it toward failure (e.g., Dietrich, 1994; Gomberg, 2010). Recent models of transient stress loading on active faults have indicated that triggering can be somewhat predictable, given certain information about the source of the stresses and information about the receiving fault (Hill, 2012; Gonzalez-Huizar and Velasco, 2011). Thus, future earthquake rate increases due to transient stressing could possibly be predicted, if the conditions under which failure occurs are better understood (Brodsky and van der Elst, 2014).

Regions with high background activity are known to be most susceptible to dynamic triggering (Hill and Prejean, 2015; Aiken and Peng, 2014). The Geysers geothermal field, located in northern California, is an extremely active fault system compared to other geothermal areas in California. Even when considering only events with magnitude (M) ≥ 2, The Geysers produced more earthquakes than other active geothermal fields in California combined over the last 15 yrs (Fig. S1). In addition, large distant earthquakes have repeatedly triggered The Geysers (Prejean et al., 2004; Brodsky, 2006; Aiken and Peng, 2014), making it a favorable region for exploring the characteristics of triggering and the conditions under which dynamic triggering of microearthquakes occurs.

In this study, we expand upon the systematic triggering analysis conducted by Aiken and Peng (2014). In that work, small magnitude earthquakes ($M < 4$) triggered in The Geysers were identified by visual inspection and compared to network-detected catalogs. Here, we apply the matched filter technique (Section 2) with the intention to further improve the catalog completeness for statistical tests. We search for key characteristics that could possibly explain the conditions that promote dynamic triggering of earthquakes, which include seismicity rates (Section 3), spatial extent

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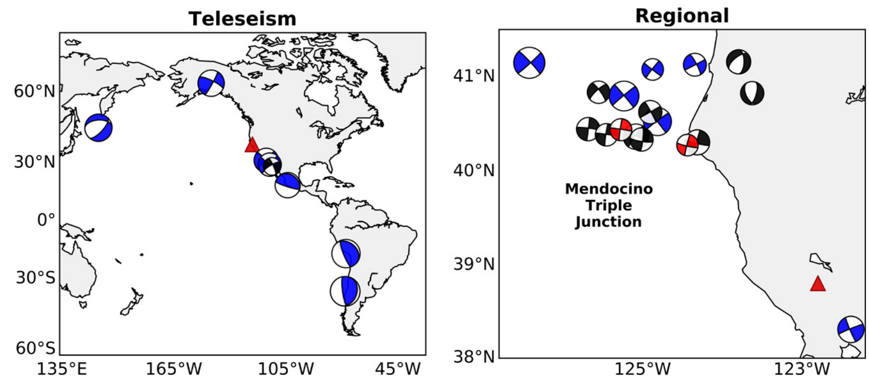

Fig. 1. Map illustrating focal mechanisms of triggering (blue) and non-triggering (black) mainshocks (see Section 2) at teleseismic distances (left) and regional distances (right). Two other non-triggering mainshocks in this study did not have reported focal mechanisms (red). We assigned these two events mechanisms similar to their nearest neighbors. Size of the focal mechanisms corresponds to magnitude (Table 1). The center of The Geysers seismicity is marked by a red triangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Potentially triggering mainshocks investigated in this study.

	Date	Time	Region[a]	M[b]	Study
Group 1	06/23/2001	20:33:14	Southern Peru	8.1	Aiken and Peng (2014)
	11/03/2002	22:12:42	Denali, AK	7.9	Prejean et al. (2004); Aiken and Peng (2014)
	01/22/2003	02:06:35	Colima, MX	7.6	Aiken and Peng (2014)
	01/04/2006	08:32:32	Gulf of CA	6.6	Aiken and Peng (2014)
	01/13/2007	04:23:21	Kuril Islands	8.1	Aiken and Peng (2014)
	08/03/2009	17:59:56	Baja CA	6.9	Aiken and Peng (2014)
	04/04/2010	22:40:42	Baja CA	7.2	Aiken and Peng (2014)
	02/27/2010	06:34:12	Maule, Chile	8.8	Aiken and Peng (2014)
	08/24/2014	10:20:44	Napa, CA	6.0	This study
Group 2	09/20/2001	08:02:23	MTJ	5.1	This study
	06/17/2002	16:55:08	MTJ	5.2	This study
	08/15/2003	09:22:15	MTJ	5.3	This study
	06/15/2005	02:50:54	MTJ	7.2	Brodsky (2006); Aiken and Peng (2014)
	07/19/2006	11:41:43	MTJ	5.0	This study
	02/26/2007	12:19:54	MTJ	5.4	This study
	05/09/2007	07:50:04	MTJ	5.2	This study
	06/25/2007	02:32:25	MTJ	5.0	This study
	04/30/2008	03:03:07	MTJ	5.4	This study
	01/10/2010	00:27:39	MTJ	6.5	Aiken and Peng (2014)
	02/04/2010	20:20:22	MTJ	5.9	This study
	02/13/2012	21:07:03	MTJ	5.6	Aiken and Peng (2014)
	07/21/2012	01:52:02	MTJ	5.1	This study
	03/10/2014	05:18:13	MTJ	6.8	Aiken and Peng (2014)
	01/01/2015	12:16:15	MTJ	5.3	This study
	01/28/2015	21:08:54	MTJ	5.7	This study

[a] MTJ = Mendocino Triple Junction.
[b] Magnitude as listed in the ANSS/ComCat catalog.

and degree of triggering (Section 4), fault orientation dependence on triggering (Section 5), and The Geysers' stress state prior to mainshocks and during triggering (Section 6).

2. Data and methods

2.1. Mainshock selection

Aiken and Peng (2014) identified 10 large, distant mainshocks that triggered microearthquakes in The Geysers, based on statistically significant increased rate changes after the mainshocks. In each of those cases, microearthquakes ($M < 4$) with S–P time $<$ 10 s were hand-picked using 3-component waveform envelopes from a small number of stations. Here, we re-examine these same triggering mainshocks and also investigate triggering by 15 additional mainshocks. Namely, we select repeating $M \geq 5$ earthquakes from offshore northern California, which Aiken and Peng (2014) suggested to be a possible repeating dynamic triggering source, and the August 24, 2014 M6 South Napa earthquake which occurred ∼80 km southeast of The Geysers (Fig. 1). Our study time period is limited to 2001 to early 2015. A complete list of triggering sources (mainshocks) we investigate in this study can be found in Table 1, each of which is reported in the Advanced National Seismic Systems (ANSS, a.k.a. ComCat) earthquake catalog available from the Northern California Earthquake Data Center (NCEDC). Mainshocks that are possibly repeat triggering sources from the Mendocino Triple Junction (MTJ) are listed in Group 2 of Table 1; all other events are in Group 1.

2.2. Matched filter analysis

We roughly follow the method of Meng et al. (2013) for detecting microearthquakes occurring in The Geysers around the times of each mainshock (Table 1) using the matched filter technique and briefly summarize our approach here. We utilize 17 seismic stations surrounding The Geysers (Table S1). For each station, we retrieve the vertical component continuous seismic waveforms half a day before to 1 day after each triggering mainshock from the NCEDC. This detection time is larger than that of Aiken and Peng (2014), where microearthquakes occurring ±5 h within the main-