Earth and Planetary Science Letters 371–372 (2013) 59–66

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Implications of recent asperity failures and aseismic creep for time-dependent earthquake hazard on the Hayward fault

Manoochehr Shirzaei [a,b,*], Roland Bürgmann [b], Taka'aki Taira [c]

[a] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-6004, USA
[b] Department of Earth and Planetary Science, University of California, Berkeley, CA, USA
[c] Berkeley Seismological Laboratory, University of California, Berkeley, CA, USA

ARTICLE INFO

Article history:
Received 8 November 2012
Received in revised form
14 April 2013
Accepted 17 April 2013
Editor: P. Shearer
Available online 17 May 2013

Keywords:
operational earthquake forecasting
repeating earthquakes
creep on Hayward fault
inverse modeling

ABSTRACT

The probability of large seismic events on a particular fault segment may vary due to external stress changes imparted by nearby deformation events, including other earthquakes and aseismic processes, such as fault creep and postseismic relaxation. The Hayward fault (HF), undergoing both seismic and aseismic fault slip, provides a unique opportunity to study the mutual relation of seismic and aseismic processes on a fault system. We use surface deformation data obtained from InSAR (interferometric synthetic aperture radar), creepmeters and alinement arrays, together with constraints provided by repeating earthquakes to investigate the kinematics of fault creep on the northern HF and its relation to two seismic clusters ($M_w \leq 4.1$) in October 2011 and March 2012, and an M_w 4.2 event in July 2007. Recurrences of nearby repeating earthquakes show that these episodes involved both seismic and aseismic slip. We model the stress changes due to fault creep and the recent seismic activity on the locked central asperity of the HF, which is believed to be the rupture zone of past and future $M\sim7$ earthquakes. The results show that the shallow fault creep stresses the major locked central patch at an average rate of 0.001–0.003 MPa/yr, in addition to background stressing at 0.01–0.015 MPa/yr. Given the time-dependent nature of the creep, occasional deviations from this stressing rate occur. We find that the 2011 seismic cluster occurred in areas on the fault that are stressed up to 0.01 MPa/yr due to aseismic slip on the surrounding segments, suggesting that the occurrence of these events was encouraged by the fault creep. Changes in the probability of major earthquakes can be estimated from the imparted stress from the recent earthquakes and associated fault creep transients. We estimate that the 1-day probability of a large event on the HF only increased by up to 0.18% and 0.05% due to the static stress increase and stressing rate change by the 2011 and 2012 clusters. For the July 2007 south Oakland event (M_w 4.2) the estimated increase of short-term probabilities is 50%, highlighting the importance of short-term probability changes due to transient stress changes.

1. Introduction

Areas of high slip deficit on partially locked faults are likely initiation points of subsequent large earthquake ruptures (e.g. Konca et al., 2008; Moreno et al., 2001; Uchida and Matsuzawa, 2011). Identifying such strongly coupled areas helps to constrain the timing, extent and magnitudes of a future event (e.g. Chlieh et al., 2008; Fialko, 2006; Manaker et al., 2003; Schmidt et al., 2005). Smaller locked asperities may break more frequently during lower-magnitude events (e.g. Nadeau and McEvilly, 1999, 2004; Vidale et al., 1994). While these smaller earthquakes do not generate significant ground shaking, they, together with associated slow-slip transients, may modify the short-term probability of rupture of larger nearby sections of the fault exposed to transient stress increases (e.g. Mazzotti and Adams, 2004). For instance, the large Tohoku 2011 event (M_w 9) was preceded by 51 h by a smaller foreshock and associated slow slip, which suggests a triggering relationship (Kato et al., 2012; Ohta et al., 2012). Therefore, characterizing the relation of seismic and aseismic slip episodes to major locked zones is of great importance for time-dependent operational earthquake forecasting (Jordan and Jones, 2010).

The HF has distinct types of activity, including coseismic ruptures (such as a M_w 6.8 earthquake in 1868), aseismic creep and abundant microseismicity (e.g. Lienkaemper et al., 1991; Schmidt et al., 2005; Toppozada and Borchardt, 1998; Waldhauser and Ellsworth, 2002). The 1868 earthquake likely involved rupture of a large locked section of the fault extending from Oakland to near

* Corresponding author at: School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-6004, USA. Tel.: +1 480 727 4193; fax: +1 480 965 8102.
E-mail address: shirzaei@asu.edu (M. Shirzaei).

0012-821X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2013.04.024

Fremont below a zone of shallow creep in the upper 3–5 km (e.g. Lienkaemper et al., 2012; Schmidt et al., 2005; Shirzaei and Bürgmann, in press). The mean probability for $M \geq 6.7$ events on the Hayward–Rodgers Creek fault zone in the next 30 yr is 31% (Working Group on California Earthquake Probabilities, 2011). This estimate, however, does not consider the effects of the transient changes of fault creep rates and may be modified temporally due to interaction with neighboring systems (e.g. Parsons, 2002; Pollitz et al., 2004).

On October 2011 (O11) and March 2012 (M12), two seismic clusters struck the northern part of the HF 5–20 km SE of Pt. Pinole (Fig. 1(a)). Fig. 1(a) shows the location and rupture areas of these seismic clusters and the July 20, 2007 south Oakland M_w 4.2 event, which we discuss later. Fig. 1(b) also presents the spatio-temporal evolution of the O11 swarm showing a northward migration of seismicity along the HF. The O11 swarm includes 18 events $0.7 \leq M_w \leq 4.0$ that occurred over a span of 10 days (http://ddrt.ldeo.columbia.edu/DDRT/specevents/2011_M4.0_Berkeley/). Assuming a 3-MPa stress drop, the associated rupture area of the largest event is 1.1 km^2. In contrast to the O11 swarm, the M12 cluster includes a mainshock, immediately preceded by a M_w 3.5 foreshock and followed by several aftershocks. The mainshock (M_w 4.1) ruptured an area of $\sim$2 km^2. As described below, we find that several aftershocks of the two clusters represent repeats of prior failures of the same slip patches, suggesting rapid nearby fault creep (e.g. Nadeau and McEvilly, 1999).

This section of the HF (0–20 km) experienced only 10 $M > 3.5$ events since 1950, according to the ANSS catalog (Advanced National Seismic System). Given the empirical probability that earthquakes in California have a $\sim$5% chance to be foreshocks of subsequent larger events within several days (Reasenberg and Jones, 1989), and the location of the events close to the main locked zone of the HF at depth (Schmidt et al., 2005), the multiple felt events caused concern both in the local communities and among researchers.

In this study we investigate the relation between the subsurface kinematics of HF creep rate, the source locations of the recent seismic clusters and their afterslip zones, and we present

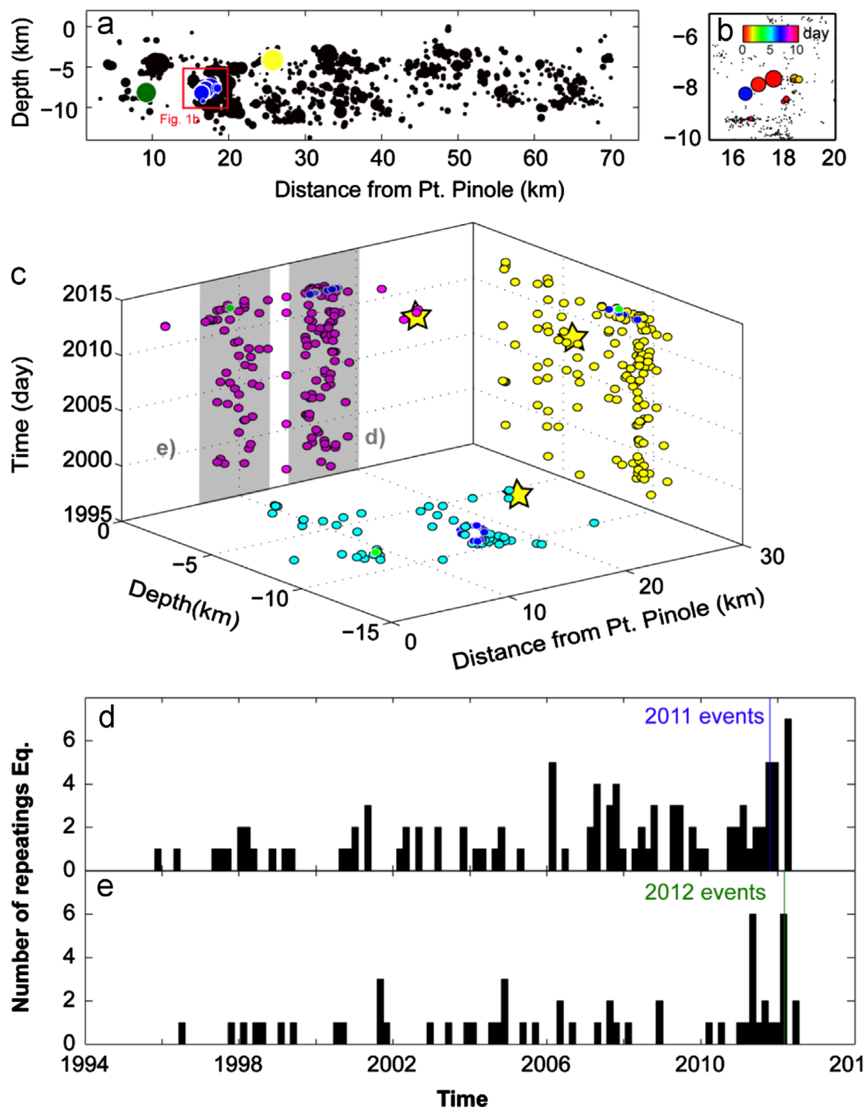

Fig. 1. (a) Relocated microseismicity (black circles, obtained from http://www.ldeo.columbia.edu/~felixw) along the Hayward fault. The October 2011 (O11), March 2012 (M12), and the July 20, 2007 M_w 4.2 south Oakland earthquakes are shown by blue, green and yellow circles, respectively. Note that the M12 events are precisely collocated, therefore, only one event is seen. (b) Spatio-temporal evolution of the October 2011 seismic swarm. The symbol colors reflect the relative timing of events as indicated by the inset color scale (c) The catalog of repeating earthquakes for the past 17 yr at the northern Hayward fault including repeating events participating in the O11 (blue circles) and M12 (green circles) clusters. The yellow star presents the July 20, 2007 M_w 4.2 event. (d, e) 100-day bin histogram of repeating earthquakes for the areas marked in panel (c). Vertical blue and green lines indicate timing of O11 and M12 seismic clusters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)