Physics of the Earth and Planetary Interiors 280 (2018) 1–19

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

More major earthquakes at the Nepal Himalaya? – Study on Coulomb stress perspective

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ABSTRACT

On April 2015 a major earthquake of 7.9 Mw occurred in the Nepal Himalaya, followed by 553 earthquakes of local magnitude greater than 4.0 within the first 43 days including another major event of 7.3 Mw. We resolve the static coulomb failure stress (CFS) change onto the finite fault models of 7.9 Mw after Elliott et al. (2016) and Galezka et al. (2015) and its effect on associated receiver faults. Correlation of aftershocks with the enhanced CFS condition shows that the Elliott et al. (2016) model explains 60.4% and the Galezka et al. (2015) model explains about 47.7% of the aftershocks in high stress regions. Aftershocks were poorly spatially correlated with the enhanced CFS condition after the 7.9 Mw main shock and can be explained by correlation with release of seismic energy from the associated secondarily stressed prominent thrust planes and transverse faults. Stress resolved on the associated receiver faults show increased stress on both transverse and thrust fault systems with the potential of triggering significant aftershocks or subsequent main shocks.

1. Introduction

The major earthquake of 7.9 Mw on 25th April 2015 at the Nepal Himalaya was followed by strong tremors of 6.7 Mw and 6.9 Mw within almost 24 h. After a gap of 17 days, one more major shock of 7.3 Mw rocked the area within distance of about 160 km from the epicenter of the first shock, followed by strong tremor of 6.3 Mw (Fig. 1). These series of earthquakes killed more than 8000 people and created more than 4000 co-seismic and post-seismic landslides (Kargel et al., 2015) with macroseismic intensity reaching up to 8 on the 1998 European Macroseismic Scale (Martin et al., 2015). The main shock was located above the previously well constrained (Ader et al., 2012) locked portion of the Main Himalayan Thrust (MHT), a shallow dipping megathrust accommodating half of the India–Eurasia convergence (Bettinelli et al., 2006). Finite source modeling shows the rupture propagated eastward at a speed of 3.0 ± 0.5 km/s on average releasing a total moment of 7.2×10^{20} N·m (Avouac et al., 2015). The main shock was followed by 553 earthquakes of local magnitude greater than 4.0 within the first 43 days (Adhikari et al., 2015).

Many recent studies (Harris, 1998b; Kilb et al., 2002; Nalbant et al., 2002; Parsons et al., 2006; Som et al., 2013; Stein, 1999; Sumy et al., 2014; Wan and Shen, 2010) have shown that earthquakes produce Coulomb stress perturbations and redistribution in the crust. Although earthquakes serve the overall function of relieving built-up elastic stress in the crust, Coulomb stress in certain regions can actually increase or decrease by the occurrence of coseismic fault slip and can significantly advance or retard events on neighboring faults. Timely studies following large earthquakes illustrate the change of tectonic stresses in the vicinity and on fault, giving rise to the assessment of post-seismic earthquake potential in the region. Coulomb stress changes can influence fault rupture in at least two ways. The first is by raising or lowering the applied accumulating load and secondly by stress changes that might modify properties of the fault and/or its immediate environment (Kilb et al., 2002). Relieved stress during the earthquake moves down the fault and concentrates in nearby sites promoting subsequent tremors (Freed, 2005; Harris, 1998a; Stein, 1999; Toda et al., 2011). It has become clear that the modeling of these co-seismic stress increases, together with the inter-seismic stress loading due to tectonic plate motions, can provide useful information on the state of stress on faults in a given region and can help in the elucidation of temporal variations of seismic hazard (Nalbant et al., 2002).

Several publications on this earthquake have described the rupture process (Avouac et al., 2015; Grandin et al., 2015; Wang and Fialko, 2015), slip pulse (Galetzka et al., 2015), aftershock sequence (Adhikari et al., 2015), ground motion (Martin et al., 2015) and ground displacement (Kargel et al., 2016; Kobayashi et al., 2015) constraining the E-W trending Himalayan thrust systems. This paper focuses on co-seismic stress changes due to the earthquake sequences, their relation

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https://doi.org/10.1016/j.pepi.2018.04.005
Received 29 December 2016; Received in revised form 16 April 2018; Accepted 16 April 2018
Available online 17 April 2018
0031-9201/

with aftershocks, their effect on both the Himalayan thrust and associated transverse receiver fault systems and their significance for future seismic activity in the region.

2. Seismotectonics of Nepal Himalaya

Two main exposed structural discontinuities in the Nepal Himalaya are the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT). The MCT separates a high grade central crystalline lithology towards the north from lesser Himalayan sequence of meta-sedimentary lithology towards south. The MCT in Nepal exhibits flat-ramp geometry (DeCelles et al., 2001; Schelling and Arita, 1991), in which the ramp is associated with intense micro-seismicity and low electrical conductivity suggesting possible stress concentration and presence of fluids along the ramp (Avouac, 2003; Lemmonier et al., 1999; Pandey et al., 1999). Folding of MCT has produced several prominent half windows and klippen in Nepal (Schelling and Arita, 1991). One such half window present in eastern part of the study area cut across Gourishakar and Everest lineaments (Fig. 1). Towards the south, the lesser Himalayan sequence glides over the sub-Himalayan sequence (Siwalik) through the interface of the MBT. Most of the shallow focus earthquakes are found to be concentrated between the MBT and the MCT (Dasgupta et al., 2000). The Main Frontal Thrust (MFT) is the southern most major tectonic unit which does not show clear surface expression at the Nepal Himalaya (Valdiya, 2003). Several transverse faults at the higher elevation (Gaurishankar Lineament (GL), Everest Lineament (EL), Arun Lineament (AL), Kanchenjunga Lineament (KL), Teesta Lineament (TL)) and in foot hill regions (West Patna Fault (WPF), East Patna Fault (EPF), Munger Saharsa Ridge Fault (MSRF)) varying in direction between north-west to north-east are tectonically active (Dasgupta et al., 1987; Raiverman, 2000; Valdiya, 1976) influencing fluvial dynamics of the region (Jain and Sinha, 2005).

The oldest recorded major earthquake in the Nepal Himalaya was on 1255, followed by 1408, 1681, 1810, 1833 and 1866 (Jouanne et al., 2004). The 1934, 8.4 Mw Bihar-Nepal earthquake occurred due to reverse left-lateral oblique movement of Himalayan Frontal Fault (Singh and Gupta, 1980), while the 6.8 Mw, 1988 earthquake in the same region was ascribed to strike-slip movement on the EPF (Dasgupta et al., 2000). Intermediate magnitude (5–7) earthquakes of the area occur at shallow depth (10–20 km) and are interpreted due to activation of the thrust planes gently dipping towards north (Ni and Barazangi, 1984). Transverse lineaments of the east Nepal (GL, EL, AL etc.) are reported to be active (Dasgupta et al., 1987) showing strike slip to normal movement patterns (Fig. 1). Intense micro-seismic activities cluster in the Nepal Himalaya between 10 km and 20 km depth. At the Katmandu longitude, the cluster has rounded form and is located in the vicinity of the flat- ramp transition of the Main Himalayan Thrust (MHT) reflecting zone of stress buildup during interseismic period (Jouanne et al., 2004).

3. Coulomb stress modeling

The coulomb failure criterion is one of the most widely accepted condition under which failure occurs in rock. Complete coulomb failure stress due to earthquake is generally divided into static coulomb stress failure and dynamic coulomb stress failure (Kilb et al., 2002). The former focus on the triggering effects of static stress changes due to permanent fault dislocation, while the later focus on the triggering effects due to passing of seismic waves and is transient in nature (Belardinelli et al., 2003). Here, we model static coulomb stress failure criteria which are a combination of normal and shear stress conditions and is defined as;

$$\Delta CFS = \Delta\tau_s + \mu(\Delta\sigma_n + \Delta p) \quad \text{(i)}$$

where $\Delta\tau_s$ is the change of shear stress, $\Delta\sigma_n$ the change of normal stress, μ the friction coefficient, and Δp the change of pore pressure. As per Eq. (i), pore fluid pressure modifies the normal stress as well as friction coefficient, in which the latter can be related to confining stress in the rock by Skemptons coefficient *B* (Rice, 1992) and the Eq. (i) can be written as:

$$\Delta CFS = \Delta\tau_s + \mu'\Delta\sigma_n \quad \text{(ii)}$$

where, $\mu' = \mu\,(1 - B)$ represents the effective coefficient of friction.

Failure is promoted if coulomb stress is positive and inhibited, if it is negative. Static coulomb stress changes of less than 1–3 bar can trigger seismicity within 1–2 fault length (Freed, 2005). In this study, we interpret positive ΔCFS as a lower threshold necessary for advancing the time to failure and triggering slip along preexisting faults. To calculate stresses, we simulate faults as dislocation surfaces in an elastic half space (Okada, 1992) using Coulomb 3.3 software (Toda et al., 2011). The Main Himalayan Thrust (MHT) of the Nepal Himalaya shows low friction, ranging between < 0.1 and 0.3 (Bollinger et al., 2004). We use 0.3 as effective coefficient of friction and assumed to be constant for all faults with media property of 3×10^{10} Pa for shear modulus and 0.25 for passion ratio.

4. Earthquake mechanism and source model

Several source models were suggested for the main shock (Avouac et al., 2015; Fan and Shearer, 2015; Galetzka et al., 2015; Grandin et al., 2015; Kobayashi et al., 2015; Lindsey et al., 2015; Wang and Fialko, 2015; Yagi and Okuwaki, 2015; Zhang et al., 2016) with variable rupture length and other inside information variable rupture length and other details. All mechanisms suggest reverse faulting on the MHT and a common feature was that the rupture propagated from the hypocenter toward east to southeast and did not cause surface rupture. Source model for 7.3 Mw aftershock were only available from the USGS and Elliot et al. (2016).

In this study, we used finite fault models of USGS, Galetzka et al. (2015) and Elliott et al. (2016) for the 7.9 Mw mainshock and finite fault models of USGS and Elliott et al. (2016) for the 7.3 Mw aftershock. The USGS models were determined from inversion of teleseismic body waveforms and long period surface waves. The 7.9 Mw model shows rupture surface is approximately 100 km along strike and 80 km along downdip having strike of 295°, dipping 10° towards NNE with released seismic moment of 8.1e + 27 dyne/cm. The rupture surface has been sub-split into 121 sub-faults having dimension of 20 along strike and 15 along dip directions showing maximum slip of 3.1 m. The 7.3 Mw aftershock ruptured along a surface having strike of 305° and dip of 9° with dimensions of approximately 30 km along strike and 20 km along dip and has been subdivided into 441 sub-faults having dimension of 5 along strike and 5 along dip. This after shock released seismic moment of 1.0e + 27 dyne/cm with maximum slip of 3.0 m.

The model of Galetzka et al. (2015) for the 7.9 Mw mainshock was derived from joint inversion of 5 Hz GPS derived velocity waveforms, the GPS static offsets and the INSAR line of sight static displacements measured between February, 22 and May, 3, 2015. The rupture surface is 120 km along strike and 50 km along downdip. The rupture surface was discretized to 300 numbers of 10 × 10 sub-fault segments with a strike of 295° and a dip of 11° showing maximum slip ∼6.5 m to the north of Kathmandu.

Elliott et al. (2016) model for the 7.9 Mw mainshock was derived by combining radar and optical satellite images. This model describes the MHT in a more realistic ramp-flat-ramp geometry. From south-to-north under the Kathmandu area, the MHT comprises of a 30° north dipping ramp from the surface (outcropping as the MFT) to 5 km depth followed by a 75-km-wide, 7° north dipping flat section that ends on a 20° north dipping, 30 km wide, mid-crustal ramp that intersects a shallow (6°) north dipping shear zone of seismic deformation, which coincides well with the deeper portion of the MHT imaged seismically. The rupture surface was discretized to 308 numbers having a strike of 288° with maximum slip of about 6 m. The rupture surface of 7.3 Mw aftershock was modelled in the same geometry of the mainshock with maximum