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Coseismic deformation fields and a fault slip model for the Mw7.8 mainshock and Mw7.3 aftershock of the Gorkha-Nepal 2015 earthquake derived from Sentinel-1A SAR interferometry

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ABSTRACT

Coseismic deformation fields caused by the moment magnitude (Mw)7.8 mainshock and Mw7.3 aftershock of the 2015 Gorkha-Nepal earthquake are obtained by analyzing Sentinel-1A/IW ascending and descending interferometry data. Results show that the deformation field associated with the Mw7.8 mainshock roughly resembles a prolate ellipse, extending from the epicenter about 20° east by south. The main region of deformation is about 160 km by 110 km, comprising a large southern area of uplift, and a small northern area of subsidence. Assuming that rupture occurred in a homogeneous elastic half-space, the coseismic fault slip models of the mainshock and aftershock are inverted based on a shallow dip fault constrained by the three data sets, Sentinel-1A/IW descending data, ascending data, and ALOS-2 descending data, separately or in combination. Mainshock slip distributions generated from all three data sets are similar, and inversion constrained by all three in combination reveal a comprehensive fault slip model. Indeed, coseismic slip is mainly distributed within a narrow 40 km zone to the north of the Main Frontal Trust (MFT), and at 6–15 km subsurface depth. In addition, the maximum slip in this event was about 5.1 m, the Mw7.8 mainshock ruptured the deep part of the seismogenic zone, while the region between the southern boundary of the rupture area and the MFT remained locked. Therefore, a considerable earthquake risk remains to the south of Kathmandu. The inverted coseismic slip of the Mw7.3 aftershock was concentrated in a small area, close to, and southeast of the epicenter, with maximum displacement of about 3 m. Finally, because there is no overlap between the two slip areas of the mainshock and aftershock, the gap between them, about 15 km in length, has additional potential to generate future earthquakes.

1. Introduction

The subduction of the Indian Plate beneath the Eurasian Plate causes: uplift, shortening and lateral extrusion of the Tibetan Plateau, strong crustal movement and earthquake activity in the surrounding region (Ader et al., 2012; Zhang et al., 1999, 2003, 2008). On April 25th, 2015, an Mw7.8 Gorkha-Nepal earthquake occurred in central Nepal, causing >8000 fatalities. The epicenter of this earthquake was located at 28.230°N and 84.731°E; this earthquake had a focal depth of approximately 8.2 km (http://earthquake.usgs.gov/earthquakes/eventpage/us20002926#scientific_summary), and was the largest natural disaster to strike Nepal since the 1934 Nepal-Bihar earthquake (Ader et al., 2012). The earthquake triggered avalanches on Mount Everest and in the Langtang valley, and destroyed a number of ancient buildings in the region. The largest aftershock occurred on May 12th, 2015, about 150 km to the east of the mainshock, in the easternmost part of the main fault system.

The 2015 Mw7.8 Gorkha-Nepal earthquake took place in the Himalayan thrust fault system, between the Indian and Eurasian tectonic plates that converge at a rate of ca. 20 mm/yr (Bilham et al., 1997; Ader et al., 2012). Although historical records suggest that large, blind earthquakes do take place along the Main Himalayan Thrust (MHT) fault (Szeliga et al., 2010), surface ruptures from the 1934 Nepal-Bihar earthquake, documented by Sapkota et al. (2013), have been used to imply that a number of large MHT fault earthquakes in the past have caused surface ruptures. Most aftershocks from the 2015 Gorkha-Nepal earthquake were located at least 30 km to the north of the MFT, which suggests that if the earthquake occurred along the MHT fault, it may not have ruptured the shallow part of the fault. Thus, measuring the magnitude and distribution of slip is important for assessing the seismic hazard of the MHT fault.

Interferometric synthetic aperture radar (InSAR) is a key tool for the analysis of the displacements caused by large crustal earthquakes, particularly in remote areas. However, one challenge for traditional InSAR

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has been its limited spatial and temporal coverage, especially in the case of very large events with dimensions in excess of a typical swath width of 70–100 km. That problem can be addressed by employing the Sentinel-1A satellite which has an instrument operating in Terrain Observation with Progressive Scans (TOPS)-SAR IW mode, enabling a repeat time of 12 days and a swath width of 250 km. Although the Sentinel-1A satellite, operated by the European Space Agency (ESA), collects C-band InSAR observations, whose data are prone to be poor coherence. Thus, these satellite observations do not necessarily yield good information on deformation in mountainous areas that have complex topography and dense vegetation coverage, or along a fault with large displacement gradients. A wide-swath mode does allow for global mapping at an increased revisit frequency, while a factor of 3 increase in swath breadth is achieved at the expense of a similar degree of reduced azimuthal resolution. New techniques are required to achieve accuracy down to a very small fraction of a Single Look Complex (SLC) pixel, especially in the azimuth direction. In this paper, we utilize new SAR data to present InSAR line-of-sight (LOS) displacement data from Sentinel-1A ascending and descending observations covering the Mw7.8 Gorkha-Nepal earthquake and its Mw7.3 Kodari aftershock.

Following resolution of the two coseismic earthquake deformation fields, SAR data were further utilized to model and invert fault slip distribution. The centroid moment tensor (CMT) solution and preliminary finite fault inversions of seismic data suggest that earthquake rupture along a NWW trending fault formed primarily in a thrust mechanism. As both the CMT solution and seismically determined finite fault models suggest that the dip angle of the fault is small, InSAR measurement data of coseismic ground offsets from the satellites Sentinel-1A and ALOS-2 were used to determine cumulative fault slip during the Gorkha Mw7.8 earthquake. The robust slip models for the Gorkha-Nepal Mw7.8 and Kodari Mw7.3 earthquakes were then inverted (Fig. 1), and the data and inversion strategy were described, the features of the slip models were obtained. On the basis of these results, seismic hazards along the MHT fault were assessed.

2. Sentinel-1A SAR data and processing

2.1. Sentinel-1A SAR data

On April 3rd, 2014, the Sentinel-1A satellite was launched by ESA. In this study, a dataset that consists of four SAR acquisitions by the C-band S1A sensor of this satellite in TOPS mode, specifically designed for interferometric applications to guarantee a very large spatial coverage, is employed. The TOPS mode is burst-based, electronically steering the beam periodically in elevation to cover several adjacent sub-swaths. During the acquisition period, the antenna beam is also switched cyclically between different sub-swaths. This allows for a significant improvement in range coverage. At the same time, a steady drift of squint angle, backward to forward, is introduced over the course of the burst transmission to broaden the size of the illuminated area in the azimuth direction. The SAR data here, collected in Interferometric Wide Swath (IWS) TOPS mode, is characterized by a swath extension of about 250 km and a coarse spatial resolution of approximately 14 m and 2 m along the azimuth and range, respectively. The use of wide-swath modes allowing for global mapping at an increased revisit frequency and an increase in the swath breadth by a factor of 3 comes at the expense of reduced azimuthal resolution by an equivalent factor.

In the immediate aftermath of the Gorkha-Nepal earthquake, Japanese and Australian scholars published results of coseismic deformation studies online using L-band ALOS-2 data. These preliminary results showed that while interferometric fringes can be clearly distinguished (http://www.abc.net.au/news/2015-05-05/satellites-shows-future-nepal-earthquake-likely/6446618), on the basis of Sentinel-1A data, these fringes remain unclear. To verify these results, we downloaded the relevant Sentinel-1A/IW data and extracted the coseismic ground deformation. After finishing data processing, it was found that some data do allow for the generation of clear, continuous interferometric fringes, while others cannot. Parameters of all processed interferograms are shown in Table 1.

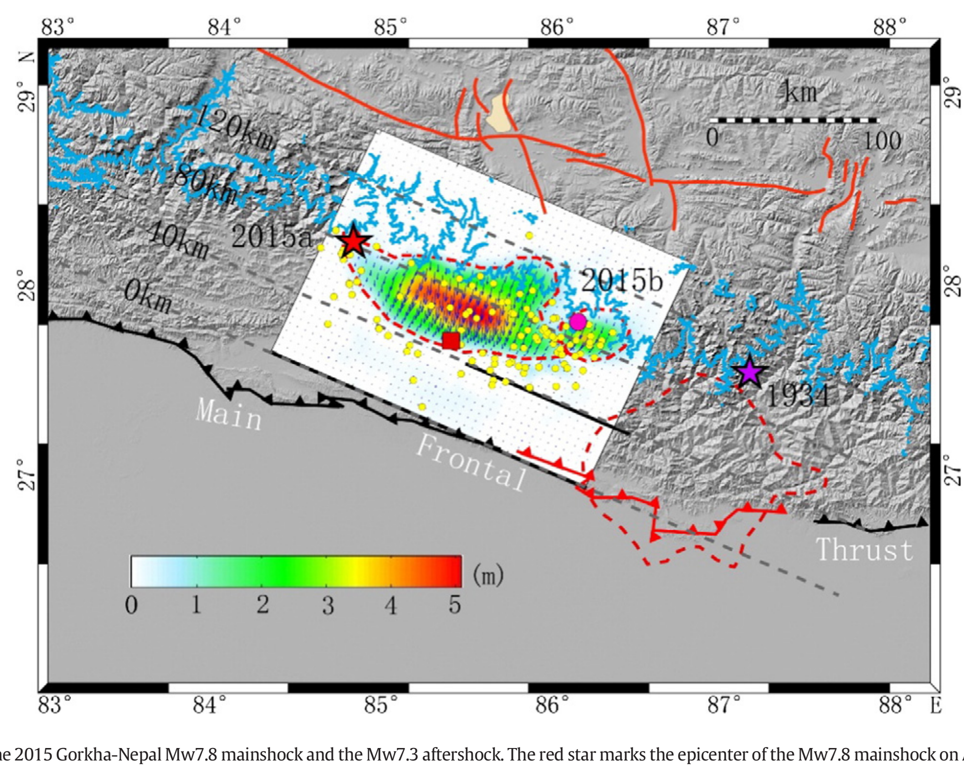

Fig. 1. Slip distribution of the 2015 Gorkha-Nepal Mw7.8 mainshock and the Mw7.3 aftershock. The red star marks the epicenter of the Mw7.8 mainshock on April 25th, 2015, the pink dot marks the epicenter of the Mw7.3 aftershock on May 12th, 2015, and the yellow dots mark additional aftershocks (from http://earthquake.usgs.gov, on July 7th, 2015). The black straight lines are the top traces of fault planes in our inversion model in the Mw7.8 mainshock and the Mw7.3 aftershock, while the gray dashed line is the distance from the MFT at an interval of 40 km. The red dashed lines denote the rupture areas from the 2015 Mw7.8 mainshock, the Mw7.3 aftershock, and the 1934 Mw8.6 Bihar-Nepal earthquake (Chen and Molnar, 1977), while the blue line marks the 3500 m contour line of the digital elevation model (DEM), based on a three arc-second SRTM DEM (from http://www2.jpl.nasa.gov).