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Letter

Splay-fault rupture during the 2014 Mw7.1 Molucca Sea, Indonesia, earthquake determined from GPS measurements

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ABSTRACT

The coseismic slip of the 2014 Molucca Sea, Indonesia, earthquake (MOSEQ) is investigated using GPS data from continuously monitoring stations. Coseismic fault models are compared between the main fault, with a 25° west-dipping plane, and the 65° west-dipping splay-fault plane. In analyzing this earthquake with fine faults sized resolution and homogenous fault models, we find that a splay fault ruptured during the mainshock. Our finding suggests that the 2014 MOSEQ occurred on an unmapped fault. Although we have limited GPS data available in the region, our results for coseismic slip are sufficient to explain the available GPS data. Our estimation suggesting that a maximum coseismic slip of around 36 cm occurred near the hypocenter, with cumulative seismic moment of 4.70×10^{19} N·m (M_w 7.1).

1. Introduction

The 2014 Molucca Sea, Indonesia, earthquake, hereinafter termed MOSEQ, occurred at 02:31 UTC, 15 November 2014 at a complex plate boundary in eastern Indonesia between North Maluku Province in the west and North Sulawesi Province in the east. The Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) reported that tsunami waves of three and nine centimeters hit Manado and Jailolo Island, respectively, at a distance of about 150 km in the SW and SE directions, respectively, from the epicenter. Although no casualties were reported due to this earthquake, infrastructure and buildings had reported damage in Gorontalo, Minahasa, and West Halmahera.

The 2014 MOSEQ took place in a region with active arc-arc collision and a subducted plate with an inverted U-shape, having slab-dipping to the west under the active volcanic arcs of Saginhe and to the east under the active volcanic arcs of Halmahera (Hall and Spakman, 2015). The swarm of earthquake activity along the Halmahera arcs in November 2015 suggested that this region is active. Fig. 1 shows the tectonic background of this study, following Hall (2002).

Global Positioning System (GPS) data have been widely implemented in the study of Earth science. GPS has shown the capability to capture tectonic processes during an earthquake cycle associated with the interseismic (Ito et al., 2012; Hanifa et al., 2014; Ohkura et al., 2015), coseismic (Banerjee et al., 2007; Ding et al., 2015; Ito et al., 2016), and postseismic (Ardika et al., 2015; Anugrah et al., 2015; Alif et al., 2016) phases. Clear signals from the GPS data of these three deformation phases have also been reported in NE Japan (Heki et al., 1997).

One of the underlying motivations of this study is to understand crustal deformations related to the 2014 MOSEQ. Here, we present an implementation using GPS data to estimate the coseismic slip distribution of the 2014 MOSEQ. The particular GPS data used for this estimate are static measurements from stations that are part of a nationwide GPS network named the Indonesian Continuously Operating Reference Stations (Ina-CORS).

2. GPS observations and data processing

In this study, we use GPS data obtained from Ina-CORS stations located in the region of the 2014 MOSEQ, which are installed and maintained by the Geospatial Information Agency of Indonesia (BIG). These GPS stations are CTER, CBIT, and CTOL. CTER is located in Ternate city, North Maluku province, while CBIT is located in Bitung city, North Sulawesi province, and CTOL is in Toli-toli city, Central Sulawesi province. Fig. 1 shows location of these GPS stations. The CTER station was constructed on concrete benchmark on top of a roof, while CBIT and CTOL stations were constructed on steel and concrete pillars.

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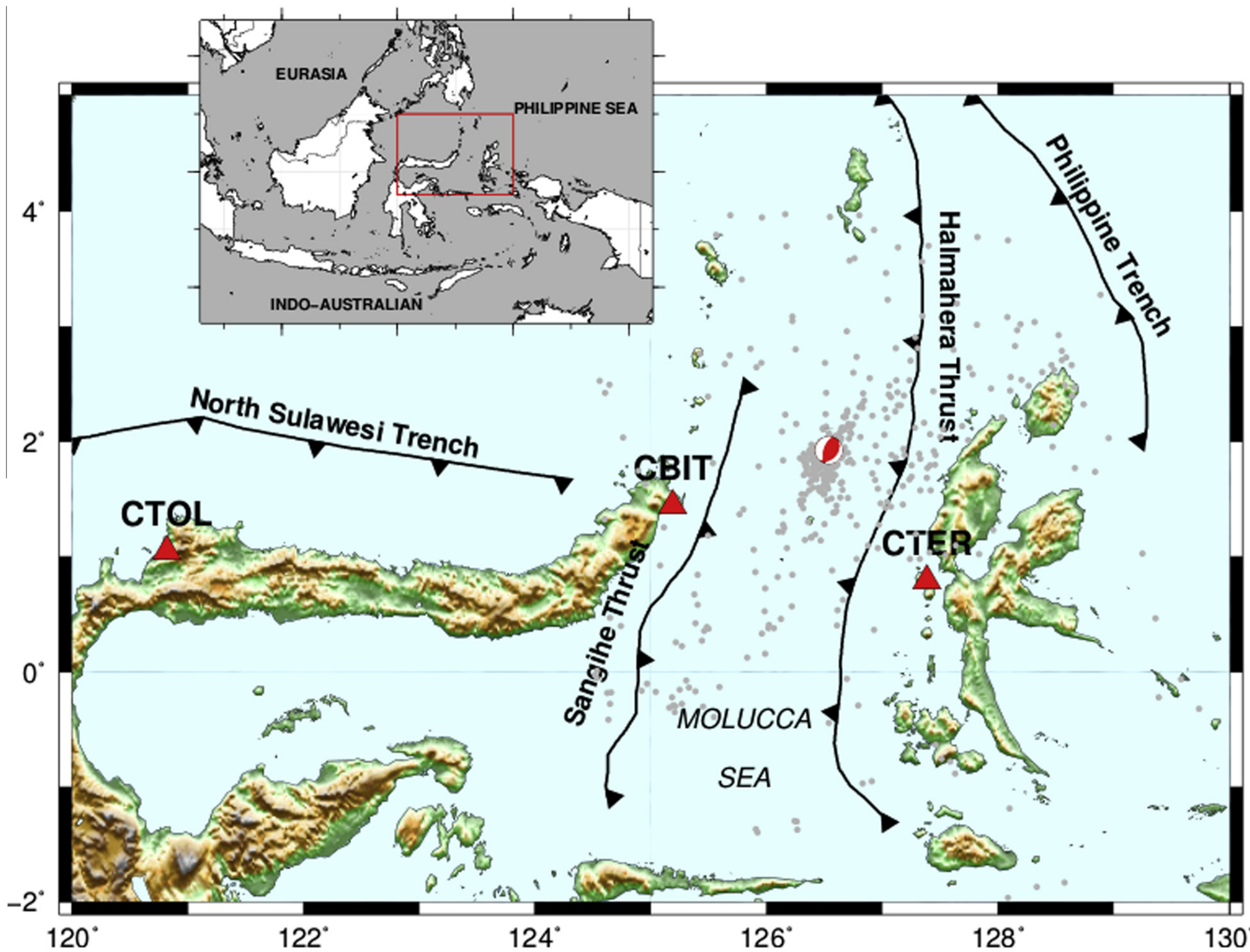

Fig. 1. Tectonic background of this study. The beach ball indicates the location of the 2014 MOSEQ. Gray dots represent the locations of aftershocks. Red triangles denote the location of the GPS stations used in this study. Inset shows the larger regional setting.

We analyzed GPS data from each station using GAMIT/GLOBK software (Herring et al., 2010a,b). During our analysis, we included the International GNSS Service (IGS) stations of BAKO, CNMR, COCO, CUSV, DARW, DGAR, GUAM, HYDE, IISC, KARR, KAT1, KOUC, PIMO, TNML, TOW2, PNGM, XMIS, YARR, PBRI, ALIC, and NTUS, and tie our local network to the ITRF2008 reference frame (Altamimi et al., 2011).

Our analysis steps of these GPS data are as follows (Gunawan et al., 2016). First, daily position with atmospherically used, loose-constraint, prior GPS phase observations; the orbit and earth-orientation parameters were fixed. Second, combination of these positions and the covariance with GPS solutions computed as part of MIT's processing for the IGS. Then, examination on the antenna changes is applied. Third, we analyzed daily solutions from GPS data at each GPS station and subtracted the velocity of three days after the 2014 MOSEQ to three days prior the mainshock, using the result as the coseismic displacements associated with this earthquake at each GPS station. In the second and third steps, we mapped the loosely constrained solution onto a well-constrained reference frame by minimizing the position and velocity differences of selected stations with respect to a priori values defined by the IGb08 realization of the ITRF2008 reference frame. Fig. 2 shows the coseismic displacements at CTER, CBIT, and CTOL.

We found that the coseismic displacements of each GPS station directed towards earthquake rupture, with displacements at CTER towards the NW direction while displacements at CBIT and CTOL directed towards the NE (Fig. 2). Our results show that CTER experienced large coseismic displacements of up to 15 mm, while CBIT and CTOL experienced displacements of 6 mm and 3 mm, respectively.

3. Coseismic fault models

We use observed coseismic displacements from the GPS data to infer the coseismic slip of the 2014 MOSEQ. Our first model (Model 1) is constructed using a strike of 200°. In this model, sub-faults are sized 10 km × 25 km. In addition, the depth on top of the fault plane is shallow, at 5 km with a 25° west-dipping fault plane (Hall, 2002). Fig. 3 shows a schematic cross-sectional view of the fault models used in this study.

We perform the coseismic slip inversion assuming an elastic half-space model (Okada, 1992). In order to reduce the model parameter, we fixed the rake at 75°. During our coseismic slip analysis, we used a priori information regarding spatial variation in fault slip. This information is combined with the observational equation to construct a Bayesian model that includes a hyperparameter (Gunawan et al., 2014). We describe the inversion algorithm to solve the coseismic slip distribution by minimizing the following function

$$s(m) = (d - Gm)^T E^{-1} (d - Gm) + \alpha^2 m^T H m \tag{1}$$

where d is observed coseismic displacements from GPS data, G is Green's function contains synthetic displacement calculated from a priori fault slip information of 1, m is the model parameter, H is