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Constraints on 2004 Sumatra–Andaman earthquake rupture from GPS measurements in Andaman–Nicobar Islands

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Abstract

The 26 December 2004 Sumatra–Andaman earthquake (Mw 9.0–9.3) is the greatest earthquake of the modern seismological era. The rupture characteristics of the earthquake, particularly in the Andaman–Nicobar region, are not well resolved from seismological or far-field geodetic data. Here, in this article we present, campaign mode Global Positioning System (GPS) measurements of coseismic displacements at 13 sites in the Andaman–Nicobar Islands before and after the 2004 Sumatra–Andaman earthquake. These measurements provide improved estimates of rupture characteristics in the region. Coseismic horizontal ground displacement of 1.5–6.5 m towards the southwest and coseismic vertical displacement, mostly subsidence, of 0.5–2.8 m occurred along the Andaman–Nicobar Islands with maximum displacements in the Nicobar Islands. We estimate coseismic slip under the Andaman and Nicobar Islands as 3.8–7.9 m and 11–15 m, respectively. The length of the rupture is estimated to be about 1500 km with a width varying from 120 km under Middle Andaman Island to 160 km under Great Nicobar Island. GPS measurements during January 11–22, 2005 from Port Blair suggest rapid afterslip in the postseismic period. Limited GPS data available from 1995 measurements at two sites in Andaman provide evidence of strain accumulation that varied significantly in the 10 yr preceding the earthquake.

Keywords: Sumatra–Andaman earthquake; GPS measurements; coseismic displacements; Andaman–Nicobar Islands; rupture characteristics

1. Introduction

The 26 December 2004 giant Sumatra–Andaman earthquake (Mw 9.0–9.3) occurred in the Sumatra–Andaman subduction zone where the Indo-Australian plate underthrusts the Burmese plate [1,2]. The motion of Indian plate relative to Sunda plate is about 4 cm/yr towards N20°E while that of Australian plate in the northern Sumatra region is about 5 cm/yr towards N8°E [3]. The oblique motion between the Indo-Australia and Burma–Sunda plates is accommodated through predominantly thrust motion in the Sumatra–Andaman trench region, and through predominantly strike-slip motion in the Andaman Sea ridge-transform system in the back arc region and the Sumatra fault system in the south [4,5,6]. The rate of convergence in the Andaman and Sumatra region is not well constrained and the estimate ranges from 14 to 68 mm/yr [6–10]. No great earthquake ($M \geq 8$) has been reported from the Andaman–Nicobar and northern Sumatra region, though major events in 1847 (M 7.5), 1868, 1881 (M 7.9) and 1941 (M 7.7) have occurred in the region. Great earthquakes in 1797,

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1861, 1833 and 2005 have been reported from the subduction zone near and southeast of Sumatra [2,11].

The 2004 Sumatra earthquake nucleated off the western coast of northern Sumatra and propagated north–northwest. Fast slip occurred in the southern part with a magnitude of slip reaching 15 m, which extended to the north–northwest direction at a velocity of 2.5 km/s, rupturing the 1300-km-long plate boundary in about 8–10 min [12]. The seismological data do not constrain slip on the rupture under Andaman–Nicobar islands reasonably well, as most of the slip in this part occurred at a time scale beyond the seismic band [2,12]. In the subsequent 1-h period, additional slow slip occurred in the Andaman–Nicobar region [1,2,13,14]. However, Ishii et al. [15], who used Hi-Net seismic array data from Japan, did not find evidence to support slow slip on the northern part of the rupture. Vigny et al. [3] also argued against slow slip and suggested that the entire displacement at GPS sites in the northern Thailand occurred in less than 10 min after the earthquakes. Using far-field GPS sites about 400–3000 km from the rupture, they derived a slip model for this earthquake. In addition to the far-field GPS data [3,14,16], rupture models have been constrained by data from five near-field sites in Andaman–Nicobar Islands [17]. Here, we improve resolution on slip and rupture characteristics using coseismic displacements derived from GPS data from 13 sites in Andaman–Nicobar islands. We provide evidence of postseismic deformation in the region and evidence of strain accumulation in the preceding 10 yr of the earthquake. Further, we discuss the possibility of earthquake triggering near the northern edge of the rupture.

2. GPS measurements and coseismic displacements

In 1994–95, the Survey of India (SOI) established 30 GPS sites in the Andaman and Nicobar Islands covering virtually every major island. In March 2004, 13 sites were again occupied. After the 26 December 2004 earthquake, 12 sites could be reoccupied as the site at Car-Nicobar was damaged by the earthquake and the tsunami. These sites are on the eastern coast of the islands (Fig. 1). The western coast of Andaman Island is mostly a reserved area for local tribes. The sites consist of either a steel pin cemented into bed rock or a mark on a L-shaped steel angle embedded in a concrete pillar of dimension of about 1 m × 1 m, reaching to bedrock. In the 12-day-long campaign of January 2005, the Port Blair site was continuously occupied throughout the survey. Daily 24-h GPS data files from the 12 sites were processed using GAMIT/GLOBK [18,19]. We also included IGS stations at HYDE, IISC, COCO, BAKO, DGAR, SAMP, NTUS, PIMO, KIT3, POL2 and WETZ in the processing. The last three sites were constrained to their ITRF coordinates. Coordinates of all the sites were estimated in the ITRF2000 reference frame. The coseismic displacements derived at IGS sites are reported in our earlier article [16]. Difference in coordinates of sites in the 2004 and 2005 surveys in Andaman–Nicobar Islands is mainly due to coseismic displacements. Due to the gap of about 10 months in the two measurements, the estimated displacement may contain contribution of secular plate motion of ~5 cm/yr [8–10] with reference to Indo-Australian plate, which is insignificant here. However, there could be some contribution from postseismic deformation as the measurements were carried out after about 2 weeks of the earthquake. Evidence of postseismic deformation can be seen at Port Blair (see Postseismic deformation) and in our subsequent campaign mode measurements in Andaman–Nicobar region. These measurements suggest that even in the postseismic period, the sites continued to move towards WSW, i.e., in the direction of coseismic displacement. Thus, the gap of 2 weeks in the GPS measurements after the earthquake must have led in overestimating the coseismic displacements. At sites in Thailand, Indonesia and Malaysia, the postseismic deformation in first 15 days is estimated to be about 10% of the coseismic displacement [3]. However, in the absence of any such direct measurements in Andaman–Nicobar region, we restrain ourselves to quantify it and assume it to be entirely coseismic. Coseismic displacements at these sites are shown in Fig. 1 and Table 1. For the coseismic displacement at Car-Nicobar, we have adopted the estimate provided by Jade et al. [17] as our site was damaged. Even at this site there may be contribution from postseismic deformation, as the measurements were made 2 months after the earthquake.

Horizontal displacement of about 4–6.5 m and subsidence of 1–2.8 m occurred in the Nicobar Islands. In the Andamans, horizontal displacement of 1.5–5.0 m occurred with an intervening low displacement of 1.5–2 m in Middle Andaman Island. Coseismic subsidence of less than a meter occurred in the Andaman except on North Andaman Island, where uplift of 0.5–1.0 m was estimated. We find that these displacements are consistent with the sparser observations of coseismic displacement from 5 GPS sites [17,20] and with the inferred pattern of subsidence and uplift derived from reports of apparent sea level changes [11,21,22].

Large displacements at all sites attest that the rupture extended up to the North Andaman Island. The direction of horizontal displacement vectors towards SWS (Fig. 1) suggests that the slip on the rupture was predominantly