Tectonophysics 721 (2017) 143–150

Contents lists available at ScienceDirect

Tectonophysics

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

Rupture evolution of the 2006 Java tsunami earthquake and the possible role of splay faults

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ARTICLE INFO

Keywords:
Earthquake
Tsunami
Back-projection
Splay faults
Java
Seismology

ABSTRACT

The 2006 Mw 7.8 Java earthquake was a tsunami earthquake, exhibiting frequency-dependent seismic radiation along strike. High-frequency global back-projection results suggest two distinct rupture stages. The first stage lasted ~65 s with a rupture speed of ~1.2 km/s, while the second stage lasted from ~65 to 150 s with a rupture speed of ~2.7 km/s. High-frequency radiators resolved with back-projection during the second stage spatially correlate with splay fault traces mapped from residual free-air gravity anomalies. These splay faults also colocate with a major tsunami source associated with the earthquake inferred from tsunami first-crest back-propagation simulation. These correlations suggest that the splay faults may have been reactivated during the Java earthquake, as has been proposed for other tsunamigenic earthquakes, such as the 1944 Mw 8.1 Tonankai earthquake in the Nankai Trough.

1. Introduction

Tsunami earthquakes are characterized by a disproportionately large tsunami for their size, and often exhibit a disparity between estimates of moment magnitude derived from long and short period seismic radiation (Kanamori, 1972; Kanamori and Kikuchi, 1993). The July 17, 2006 Java earthquake was a classic tsunami earthquake with body-wave magnitude mb = 6.1, surface-wave magnitude Ms = 7.1, and moment magnitude Mw = 7.7 (Ekström et al., 2012; International Seismological Centre, 2013). Such a large variation in magnitude estimates is atypical and may indicate a deficiency in high-frequency radiation compared to low-frequency radiation (Ammon et al., 2006; Newman and Okal, 1998). The 2006 Java earthquake initiated at shallow depth (20 km, (International Seismological Centre, 2013); Fig. 1) and ruptured eastward along the trench axis for ~200 km (Ammon et al., 2006; Bilek and Engdahl, 2007). Given the source dimension, the unusually long source duration (~185 s) indicates anomalously slow rupture propagation for the event (Ammon et al., 2006; Bilek and Engdahl, 2007). The earthquake generated a large tsunami (~8 m) resulting in over 800 fatalities (Fritz et al., 2007; Fujii and Satake, 2006; Mori et al., 2007). This was the second tsunami earthquake that struck the Java region since instrumental records began, and a Mw 7.8 earthquake in June 1994 produced an even larger tsunami (~13 m), resulting in 250 fatalities (Abercrombie et al., 2001; Mori et al., 2007). These two earthquakes are only 600 km apart, highlighting the major tsunami hazard along the south coast of Indonesia (Mori et al., 2007). Is the Java trench prone to more tsunami earthquakes and if so, what properties of the margin promote this type of rupture?

Finite-fault slip models of the 2006 Java earthquake suggest a smooth slip distribution with an unusually slow (~1 km/s) rupture propagation (Fig. 2b). Finite-fault slip models obtained from body waves (P and SH waves, ~0.001–0.2 Hz) have similar slip distributions, with the largest slip concentrated near the hypocenter (Fig. 2b) (Ammon et al., 2006; Bilek and Engdahl, 2007; Yagi and Fukahata, 2011; Ye et al., 2016a,b). In contrast, finite-fault slip models obtained from both body and surface waves (both Rayleigh and Love waves) suggest that the largest slip is close to the trench and is up-dip and ~50 km east of the hypocenter (Fig. 2) (Hayes, 2011; Shao et al., 2011). Surface waves have been shown to be effective at resolving near-trench slip distributions, which are difficult to resolve just with body waves (Shao et al., 2011).

The 2006 Java earthquake was one of the best-recorded tsunami earthquakes with modern instruments. Combining the wealth of data with new observational approaches enables us to investigate the earthquake in great detail. We first analyze bathymetry and gravity

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http://dx.doi.org/10.1016/j.tecto.2017.10.003
Received 10 May 2017; Received in revised form 28 September 2017; Accepted 1 October 2017
Available online 03 October 2017

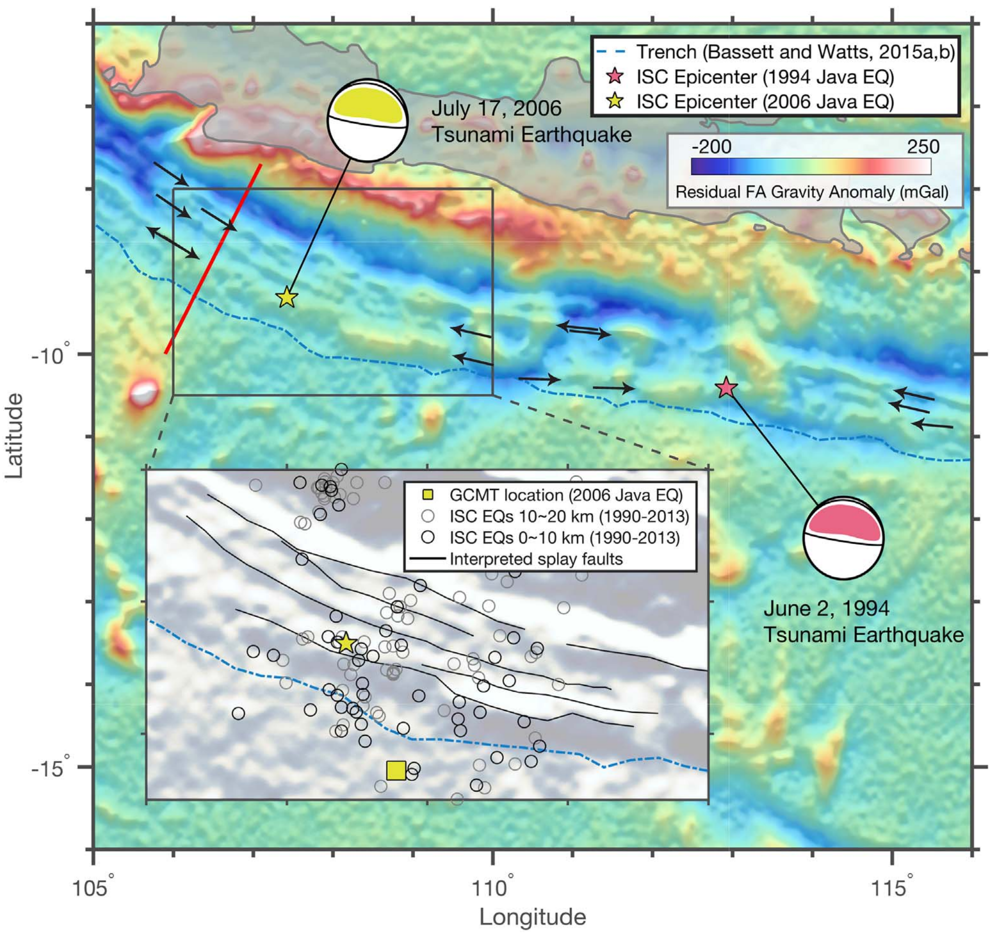

Fig. 1. Residual free-air gravity anomaly, splay faults at Java subduction zone and shallow seismicity near the 2006 Java tsunami earthquake. Black arrows show splay faults revealed by residual gravity. Insert: black circles are earthquakes (EQ) from 1993–2013 ISC catalog with M > 4 and depth shallower than 10 km, gray circles are earthquakes (EQ) from 1993–2013 ISC catalog with M > 4 and depth between 10 and 20 km (International Seismological Centre, 2013). Black lines are the interpreted fault traces from the residual gravity anomaly in this study. Red line is coincident seismic reflection and refraction profile SO137-03/SO138-05, which resolved steep dipping splay faults and correlates with the delineated residual gravity anomaly. Trench-axis is from Bassett and Watts (2015a,b).

anomalies in conjunction with active-source seismic profiles to constrain margin structure and the location of splay faults. We then build on published kinematic slip models of the 2006 Java earthquake source by performing global P-wave back-projection using two different frequency bands to examine the earthquake kinematics. In addition, we back-propagate first-crest arrivals in tsunami waveforms of five nearby tide gauges at various azimuths to locate tsunami sources. Our high-frequency back-projection results suggest a unilateral rupture extending ~200 km with a slow first-stage rupture (~1.2 km/s) from west to east until ~65 s and a fast second-stage rupture (~ 2.7 km/s) from ~65 to 150 s. The second-stage rupture colocates with a major tsunami source located by first-crest tsunami back-propagation. The spatial correlation between the stage-two rupture imaged by back-projection and splay fault traces delineated by gravity data suggests that splay faults may have been reactivated during the 2006 Java earthquake and possibly contributed to tsunamigenesis. This mechanism of enhanced tsunami excitation due to splay faulting has been proposed for the 1944 Mw 8.1 Tonankai earthquake in the Nankai Trough (Moore et al., 2007).

2. Tectonic setting and residual gravity anomaly

The Java subduction zone accommodates underthrusting of the Indo-Australian plate beneath Eurasia at approximately 67 mm/yr (Tregoning et al., 1994). The incoming plate in offshore western Java is structurally complex, hosting a dense population of seamounts and the Roo Rise oceanic plateau (Shulgin et al., 2011). The forearc is characterized by an outer-arc high, which typically extends 100 km from the trench-axis with water-depths of 2–3 km (Kopp et al., 2002; Planert et al., 2010). Landward of the outer-arc high, the Lombok forearc basin extends along the coastline of Java for over 400 km.

Short wavelength topographic and gravimetric anomalies can illuminate detailed structure of the overthrusting and subducting plates. These short wavelength features can be effectively extracted using spectral averaging methods designed specifically to suppress steep topographic and gravimetric gradients across subduction zones (Bassett and Watts, 2015a,b). Application of these methods to the Java subduction zone reveals a long array of lineations in the residual gravity field, encompassing the full ~100 km trench-normal width of the outer-arc high and the full ~ 800 km along-strike extent of the Java margin (Arrows, Fig. 1). Where 2D seismic reflection and refraction profiles traverse the forearc (Red line, Fig. 1), the gravity lineations are consistent with the locations of splay faults imaged in the overthrusting plate (Kopp et al., 2009). The lateral continuity of the residual gravity field allows us to extend this interpretation along strike, which indicates that the outer-arc high is pervasively faulted and that splay faults are almost certainly present within the source region of the 1994 and 2006 tsunami earthquakes (Fig. 1).

3. Seismic P-wave back-projection

We perform P-wave back-projection using the procedure described in Fan and Shearer (2015), using vertical-component velocity records from the International Federation of Digital Seismograph Networks (FDSN) seismic stations that are available and distributed by the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS). Because back-projection techniques do not make assumptions about fault geometry or rupture velocity, they are able to resolve complex earthquake behavior, such as variable rupture velocity, multiple events, and very early aftershocks (Ishii et al., 2005; Kiser and Ishii, 2011; Koper et al., 2011; Meng et al., 2012; Nissen et al., 2016;