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# The kinematics of crustal deformation in Java from GPS observations: Implications for fault slip partitioning

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ABSTRACT

Our understanding of seismic risk in Java has been focused primarily on the subduction zone, where the seismic records during the last century have shown the occurrence of a number of tsunami earthquakes. However, the potential of the existence of active crustal structures within the island of Java itself is less well known. Historical archives show the occurrence of several devastating earthquake ruptures north of the volcanic arc in west Java during the 18th and the 19th centuries, suggesting the existence of active faults that need to be identified in order to guide seismic hazard assessment. Here we use geodetic constraints from the Global Positioning System (GPS) to quantify the present day crustal deformation in Java. The GPS velocities reveal a homogeneous counterclockwise rotation of the Java Block independent of Sunda Block, consistent with a NE–SW convergence between the Australian Plate and southeast Asia. Continuous GPS observations show a time-dependent change in the linear rate of surface motion in west Java, which we interpret as an ongoing long-term post-seismic deformation following the 2006 $M_w$ 7.7 Java earthquake. We use an elastic block model in combination with a viscoelastic model to correct for this post-seismic transient and derive the long-term inter-seismic velocity, which we interpret as a combination of tectonic block motions and crustal faults strain related deformation. There is a north–south gradient in the resulting velocity field with a decrease in the magnitude towards the North across the Kendeng Thrust in the east and the Baribis Thrust in the west. We suggest that the Baribis Thrust is active and accommodating a slow relative motion between Java and the Sunda Block at about $5 \pm 0.2$ mm/yr. We propose a kinematic model of convergence of the Australian Plate and the Sunda Block, involving a slip partitioning between the Java Trench and a left-lateral structure extending E–W along Java with most of the convergence being accommodated by the Java megathrust, and a much smaller parallel motion accommodated along the Baribis ($\sim 5 \pm 0.2$ mm/yr) and Kendeng ($\sim 2.3 \pm 0.7$ mm/yr) Thrusts. Our study highlights a correlation between the geodetically inferred active faults and historical seismic catalogs, emphasizing the importance of considering crustal fault activity within Java in future seismic assessments.



## 1. Introduction

Most of the great earthquakes in the world have occurred in subduction zone environments, where significant events larger than $M_w$ 8 have ruptured areas extending hundreds of kilometers from the main epicenter (Lay, 2015). An extensive scientific effort has been dedicated to understand the setting of the occurrence of these events in the context of plate tectonics. Geodetic observations have shown, in addition to the long term rotation of tectonic plates, signatures of elastic strain energy accumulation on subduction megathrusts, where areas of high coupling during inter-seismic periods have been used to reveal stress build-up where seismic ruptures are likely to occur (Bürgmann et al., 2005; McCaffrey, 2005; Loveless and Meade, 2010). On the other hand, slip on subduction zones can also be accommodated aseismically on creeping areas within the seismogenic zone and/or the transition zone below the top ~40 km (e.g. Perfettini et al., 2010; Wallace and Beavan, 2010).

The Java subduction zone is one of the most tectonically active plate boundaries in the world, extending ~1700 km from the Sunda Strait to eastern Indonesia. A distinctive feature of this sub-

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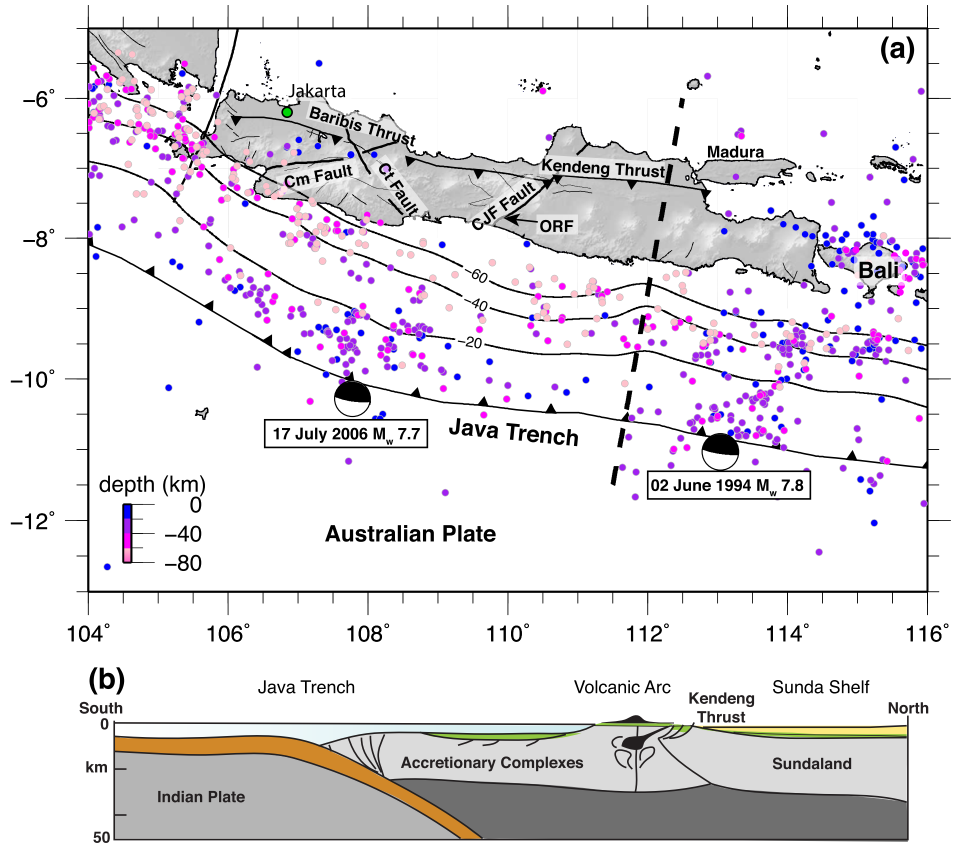


**Fig. 1.** Regional tectonic map of the study area, showing major faults in Java. The colored circles represent the seismicity from the ISC catalog for events of $M_w > 5.5$ and depth <80 km. Focal mechanisms for the 1994 and 2006 earthquakes are from the GCMT catalog (Ekström et al., 2012). (b) is a N–S schematic cross-section (the black dashed line in (a)) modified from Simandjuntak and Barber (1996). Abbreviations are Citandui Fault (Ct), Cimandiri Fault (Cm), Central Java Fault (CJF), Opak river fault (ORF). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

duction is the absence of great megathrust earthquakes ($M_w >$ 7.8). Historical records indicate that few if any large earthquakes have occurred on the Java megathrust (Newcomb and McCann, 1987). The largest earthquakes recorded offshore Java island, during the entire instrumental seismological period, were the 1994 $M_w$ 7.8 and 2006 $M_w$ 7.7 events, which were classified by different studies as classical tsunami earthquakes (Abercrombie et al., 2001; Bilek and Engdahl, 2007). This suggests that either the slip on the Java megathrust is dominantly aseismic and there is insufficient elastic strain accumulation to generate significant megathrust earthquakes, or that the earthquakes in this boundary have recurrence times beyond the span of the observational period. The lessons learned from the Sumatra 2004 and Tohoku 2011 earthquakes show that the lack of recognized large earthquakes in a subduction zone does not preclude the possibility of future large earthquakes.

On the other hand, historical records of earthquakes on Java Island show the occurrence of a series of earthquakes onshore, not related to the megathrust. Harris and Major (2016) reported at least 8 major earthquakes in northwest and central Java. Geomorphological and tectonic studies also support the existence of active faults in the island of Java (Simandjuntak and Barber, 1996; Dardji et al., 1994; Malod et al., 1995). However, the rarity of significant earthquakes in the last century has limited the precise identification of these active structures. Recently, Nguyen et al. (2015) attempted to develop a database of earthquake scenarios based on historical events in Jakarta and showed that the region has experienced devastating earthquakes in the past.

The convergence direction across the Java subduction zone is almost orthogonal to the plate boundary, unlike in Sumatra where the oblique plate convergence has been successfully used to explain the slip partitioning between a trench-normal component and an arc-parallel shear into the Great Sumatran Fault (Fitch, 1972; McCaffrey, 1992). For slip partitioning across the Java Trench, it remains unclear as to whether the parallel component of displacement is taken up by the trench or is absorbed by the overriding plate. McCaffrey (1991) showed that a pole of rotation that fits earthquake slip vectors south of Java predicts higher slip rates in Sumatra than those observed and he provided three hypotheses to explain this discrepancy including (i) the inadequacy of earthquake slip vectors to represent the upper plate deformation; (ii) the existence of faults other than the Sumatra Fault that accommodate forearc deformation off Sumatra or (iii) the presence of a left-lateral shear zone through Java.

To date, very little is known about the tectonics of Java. Recent studies were focused on imaging the structures offshore Java using seismic reflection data and understanding the dynamics of the frontal accretion along the western Java margin (Kopp et al., 2006, 2009; Schlüter et al., 2002). However, details of crustal structures onshore of Java are not known. Simandjuntak and Barber (1996) mapped a major thrust system including the Baribis and Kendeng thrusts that runs East–West through Java and suggested that some segments are still active. At a high angle to this structure, two strike-slip faults (Cimandiri and Citandui faults) cutting across the volcanic arc were identified in West Java forming a v-shaped geometry bounding the Southern Mountains (Fig. 1). While very little is known about the Citandui Fault, the NE–SW trending Cimandiri Fault was proposed as an active sinistral strike-slip fault forming the conjugate of the NW–SE prolongation of the Great Sumatran Fault in the forearc domain (Malod et al., 1995;