Seismically active deformation in the Sumatra–Java trench-arc region: geodynamic implications

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Crustal deformation rates (1900–2000) estimated for the Sumatra–Java arc region highlight (i) large variations in dextral shear motion (seismic slip) from 1 mm/yr to 29 mm/yr along the Sumatran Fault Zone (SFZ), (ii) dominantly compression with deformation velocities as high as 19 mm/yr near the equator along offshore Sumatra fore-arc and, (iii) dominance of compression (average 19 mm/yr) in the western part of offshore Java fore-arc that gradually changes to extension (average 3 mm/yr) towards east. While seismic slip rates match well with the geological or GPS derived slip rates between 0° and 2°S along SFZ, the values are much lower for the fault segments north of equator. The deformation pattern in the offshore Sumatra indicates that the Mentawai fault partly accommodates motion due to oblique subduction and suggests local interaction of the Investigator Fracture Zone near the equator. However, north of 2°N, the low deformation velocities in the offshore Sumatra can be attributed to the absence of significant earthquakes during the period of investigation. This long-term seismic quiescence might have caused lock up of stresses that resulted in highly devastating 26 December 2004 earthquake.

Keywords: Deformation, Indian Ocean, Java–Sumatra, moment tensors, seismotectonics.

THE highly devastating and tsunamigenic Sumatran earthquake of 26 December 2004 (~ M_w 9.3) and the large series of aftershock events since then, with another major earthquake of 28 March 2005 (M_w 8.6), have ruptured nearly 1300 km long portion of the plate boundary between the Indo–Australian and the Southeastern Eurasian plates[1–4]. The 26 December 2004 event has given rise to an estimated average slip of more than 5–10 m throughout the rupture length and produced significant static offsets at several far-away permanent GPS sites[5,6]. This abnormally high recent seismic activity has brought to fore, the seismicity of the Indonesian arc system and its extension into the Andaman–Nicobar region. The normal subduction below Java is characterized by the development of typical fore-arc basins. The oblique subduction beneath Sumatra and further north results in partitioning of the convergent motion into thrust and strike-slip faulting. Along the arc, the age and thickness of the lithosphere increase considerably from west to east; from 49–96 Ma below Sumatra to the west to 96–134 Ma below Java[7]. The depth of the Wadati–Benioff Zone (WBZ) also increases in the same manner, from 200 km beneath Sumatra to 670 km beneath Java. This change in the hypocentral depth has been explained as due to the increase in age and subduction zone velocity[8,9].

The 1900 km long trench parallel Sumatran Fault Zone (SFZ) continues northward into the Andaman Sea, where it most likely joins the fracture zones of the back arc-spreading centre near the Andaman Islands[10]. The shape and location of the Sumatran fault, the presence of active volcanic arc and the fore-arc structures are well correlated with the shape and characteristics of the underlying subducting oceanic lithosphere[11].

A 300-km wide strip of the lithosphere exists as a fore-arc sliver plate between the Sumatran fault and the Sumatran deformation front (Figure 1)[13–15]. Seismic reflection data in this region reveal a 600 km long strike-slip fault parallel to the SFZ called the Mentawai Fault Zone (MFZ), just east of Mentawai islands[12]. The MFZ is a zone of weakness that separates the oceanic and continental crust.

In the present study, we have carried out a detailed seismotectonic evaluation of the region by separating the events of the upper plate ($h \leq 70$ km) from that of the WBZ. Nearly 100 years of hypocentral data of such shallow earthquakes within the upper plate and a large number of focal mechanism solutions occurring in the Java–Sumatra subduction zone have been considered in order to study the spatial variation in deformation pattern using the method of summation of the moment tensor.

Data and method of analysis

The method of analysis followed in the present study has been proposed by Papazachos and Kiratzi[16], based on the formulations of Kostrov[17], and Jackson and McKenzie[18]. Many previous workers have subsequently applied this method in seismically active regions[19–23] and therefore details on methodology are not reproduced here.

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This method requires two sets of data. (i) Seismicity data for estimation of seismic moment rate. (ii) Focal mechanism data for determining the shape of the deformation. We have considered hypocentral data from the NOAA epicentral listing and prepared an earthquake dataset of all shallow earthquakes ($h \le 70$ km) during 1900–2000 for the present analysis. Events before 1964 have been compiled from Rothe[24], and Gutenberg and Richter[25]. For the period between 1953 and 1965, magnitudes from Rothe's listing have been recalculated by Newcomb and McCann[13]. Similarly, Engdahl *et al.*[26] precisely determined hypocentral parameters from the ISC listing for the period 1964–95. We considered these revised magnitudes with events $Ms \ge 4.5$ for the present analysis. For events where *Ms* value is not available, it is obtained from *Mb* using the *Mb*–*Ms* relation derived for the region. The magnitudes estimated by Gutenberg and Richter[25] and Rothe[24] are equivalent to 20-s *Ms*[27]. The seismicity map of the region shown in Figure 2 is for 100 years (1900–2000), which includes all revised estimates of magnitudes and moments by previous workers.

For preparation of the second dataset, about 240 focal mechanism solutions pertaining to the region have been considered from Harvard CMT listings. For clarity, we have shown 86 events of $Ms > 5.5$ as plotted in Figure 3 (ref. 29). It can be seen from the seismicity map that several large earthquakes display distinct correlation with the SFZ as well as the Sumatran Offshore region. While focal mechanisms of earthquakes along the SFZ show mainly right lateral faulting, in the Sumatran fore arc the mechanisms show mostly thrust-faulting.

Identification of seismogenic belts/sources and deformation velocities

Previous studies on seismicity in relation to overall tectonics of the Sumatra–Java arc region gave valuable information on the first-order segmentation of the arc[30], seismic potential and seismicity in different parts of the arc[13] and seismically active domains within the overriding plate[28]. This information along with other geophysical data has been utilized to identify broad and distinct seismogenic belts/sources. These are (i) the SFZ (ii) the Sumatran fore-arc sliver plate consisting of MFZ, (iii) The Sunda Strait region, (iv) Java onshore region termed as Java Fault Zone (JFZ) and (v) the offshore Java fore-arc region. For belts 1 and 4, the

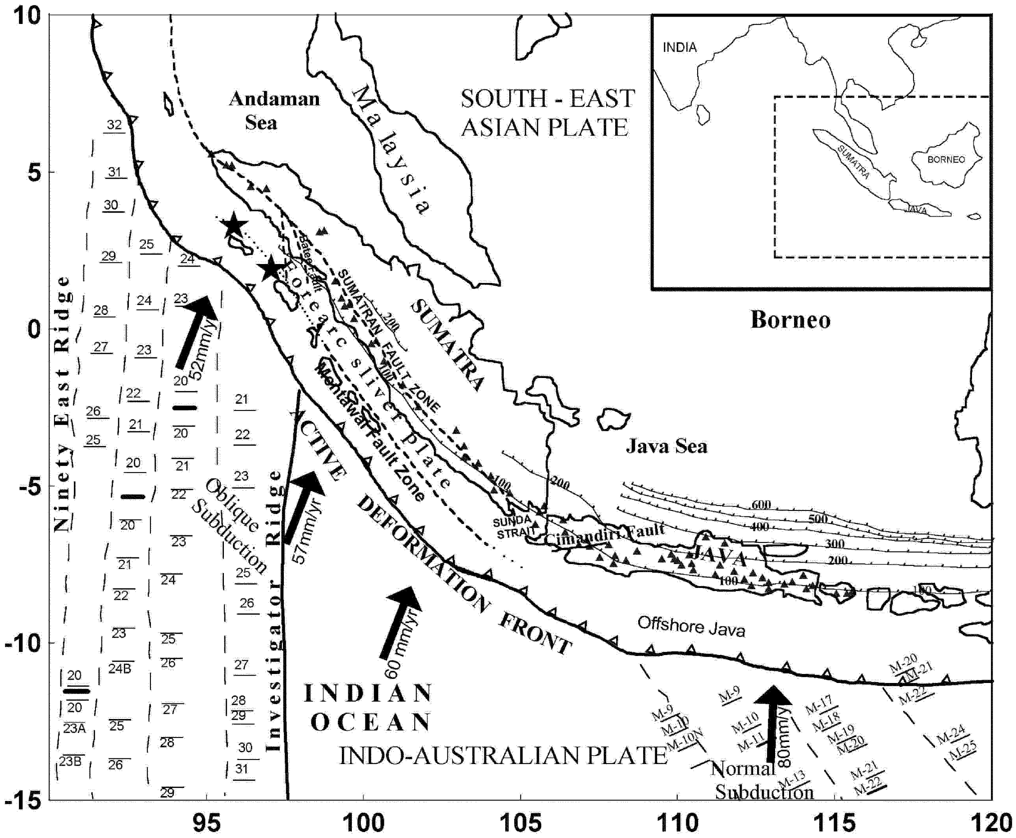

Figure 1. Tectonic sketch map of the Sumatra–Java trench-arc region in eastern Indian Ocean Benioff Zone configuration. Hatched line with numbers indicates depth to the top of the Benioff Zone (after Newcomb and McCann[13]). Magnetic anomaly identifications have been considered from Liu *et al.*[14] and Krishna *et al.*[15]. Magnitude and direction of the plate motion is obtained from Sieh and Natawidjaja[11]. ✯ indicates the location of the recent major earthquakes of 26 December 2004, i.e. the devastating tsunamigenic earthquake ($M_w = 9.3$) and the 28 March 2005 earthquake ($M_w = 8.6$).

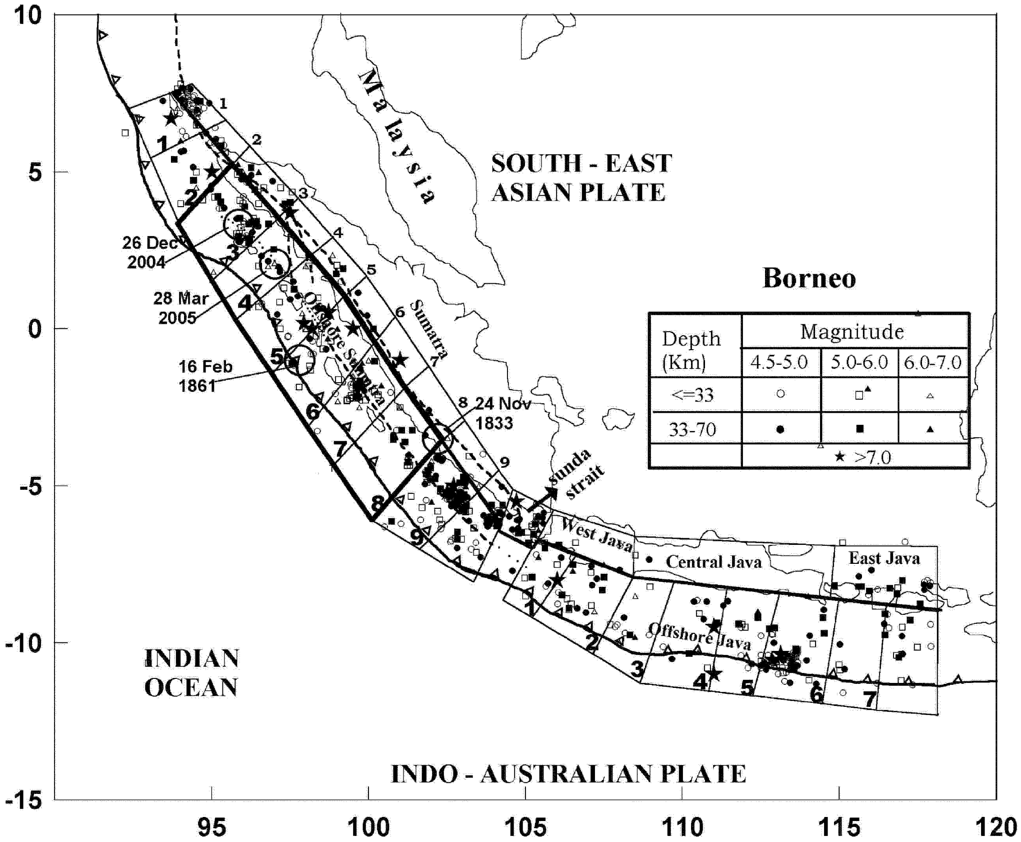

Figure 2. Map showing seismicity and moving window configuration of sources in the Sumatra–Java trench-arc region. The boundary defining the Sumatra and Java Fault zones has been adopted from Slancova *et al.*[28]. The most significant shallow earthquakes in the Sumatran offshore seismic belt are shown as large open circles. The active part of the Sumatran offshore belt is highlighted by a thick line.

boundaries have been defined by Slancova *et al.*[28]. The offshore belts 2 and 5 have been extended up to the deformation front below the Sumatra–Java trench. As seismicity is variable and no segmentation is possible in the case of belts 1, 2 and 5, it is difficult to demarcate individual seismogenic sources. Hence, we employed a moving-window method having a window length of 3–4° and with 50% overlapping, starting from one end to the other. The advantage of this method is that we obtain a continuous variation in deformation pattern along the length of the active seismic belts and also selecting a different window length does not alter the deformation pattern significantly. We succeeded in defining such sources (moving windows); nine sources each along the SFZ and Sumatran fore arc region, and seven sources in the offshore Java region. Due to low seismicity along the JFZ, it is separated into three seismogenic sources, namely West Java, Central Java and East Java. The Sunda strait is considered as a single seismogenic source. Each window representing the seismogenic source along the arc has been numbered as shown in the Figure 2. The deformation velocities (velocity tensor) have been estimated for each of these seismogenic sources. The eigen values and the corresponding eigen vectors represent the magnitude and direction of the principal components of deformation. For a better understanding of the horizontal plate velocities, only those eigen vectors with a plunge less than 25° have been presented in Figure 4.

Results and discussion

Estimation of the moment release pattern and crustal deformation rates based on 100 years of shallow seismicity in comparison with previous studies, brings out significant information about the Sumatra–Java arc region. Some salient results on the deformation pattern are discussed with a view to understanding the geodynamics of the region.

Sumatran Fault Zone

Most of the focal mechanism solutions along the SFZ show pure right lateral strike-slip faulting, which agrees well with the geological observations. All along its length, the deformation velocities suggest nearly N–S compression and E–W extension.

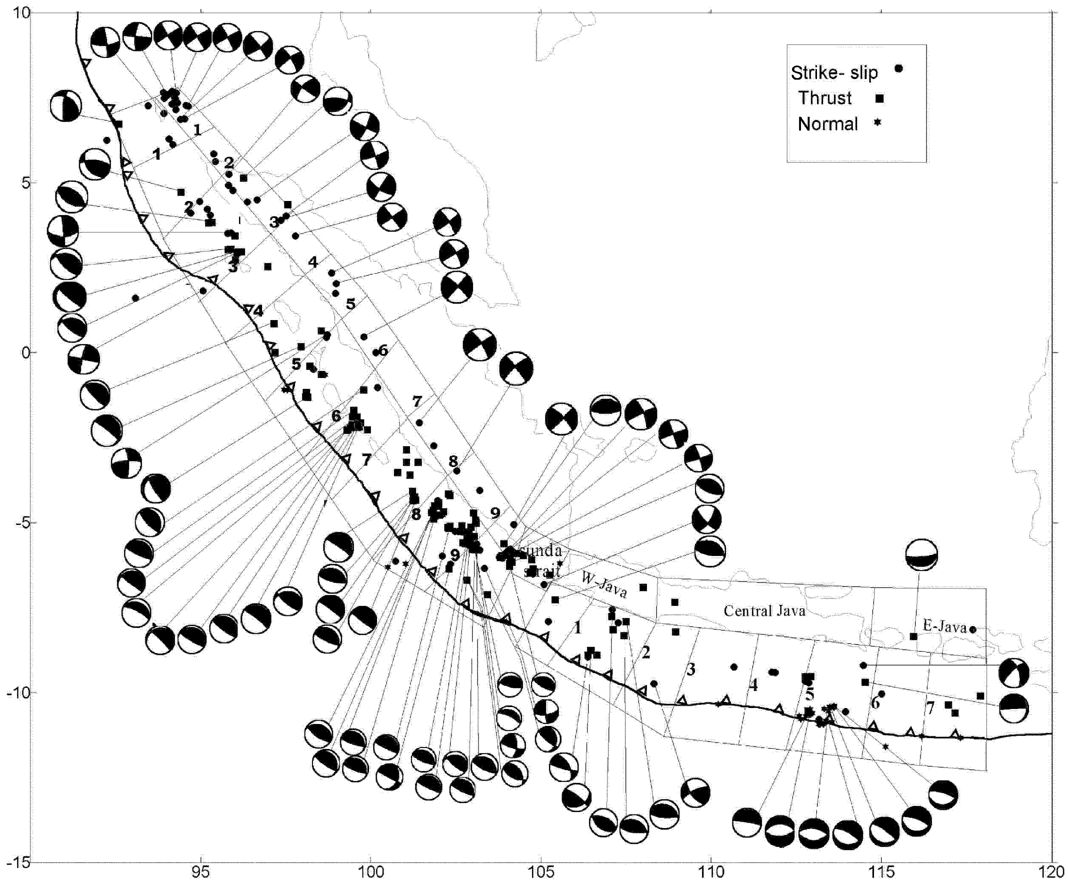

Figure 3. Map showing events for which focal mechanism solutions are available from the Harvard CMT catalogue. For clarity, the mechanisms have been plotted for only those events with $Ms \geq 5.5$. Classification of mechanisms into strike-slip, thrust and normal events is from Kumar *et al.*[29].

The slip rate along the SFZ should range between 30 and 50 mm/yr, assuming that the fault accommodates all the trench-parallel components of convergence between the Indo-Australian and Eurasian plates[31]. Based on SPOT images and topographic maps, Bellier and Sebrier[32] estimated slip rates along SFZ, showing a value of about 23 mm/yr in the north that decreases to 6 mm/yr in the south. Combined analysis of historical triangulation and recent GPS measurements along the SFZ indicate slip rates of 23 to 24 mm/yr[33]. There is a general northward increase in slip rate along the SFZ[34,35]. It is suggested that no significant fore-arc stretching occurs due to slip rate variation along the SFZ and oblique convergence may be accommodated by deformation of 500 km wide zone between the fore-arc to the back-arc domains[35]. The estimated velocity values along the SFZ seismic belt indicate variation in seismically active deformation with maximum dextral shear motion (seismic slip) of 29 mm/yr in the central part to 1 and 8 mm/yr both southward and northward respectively. Except between 0 and 2°S, the estimated velocities are significantly less than the geologically estimated slip rates as well as geodetically measured slip rates, which suggests that considerable amount of slip along the fault may be taken up aseismically.

Sumatran fore-arc region

The Sumatran fore-arc region constitutes the Mentawai islands and the regionally extending MFZ. Majority of strong earthquakes in both the historic and instrumental catalogues of Sunda arc are located in this region. A close examination of the deformation pattern shows that compressive stresses dominate here. The focal mechanism solutions obtained from Harvard CMT catalogue since 1977 in this region and the large 1935 and 1984 events show thrust-faulting mechanisms in the offshore Sumatra[36]. The Sumatran fore-arc perhaps is the most active deformation belt in the region characterized by the occurrence of large historical (1833 and 1861), recent (1935 and 1984) and most recent (2004 and 2005) seismic events. The arc-parallel shear in the Sumatran fore-arc may be taken up on more than one strike-slip fault or shear zone[12]. However, McCaffrey *et al.*[37] observed that this additional strike-slip required might not be accommodated along the MFZ, as the GPS network along the northern part of MFZ does not indicate such large transverse motions. Samuel and Harbury[38] interpreted the trace of the MFZ on the Nias Island to be a reverse fault. Also, there is a significant component of dip-slip in Pliocene along the MFZ[11].

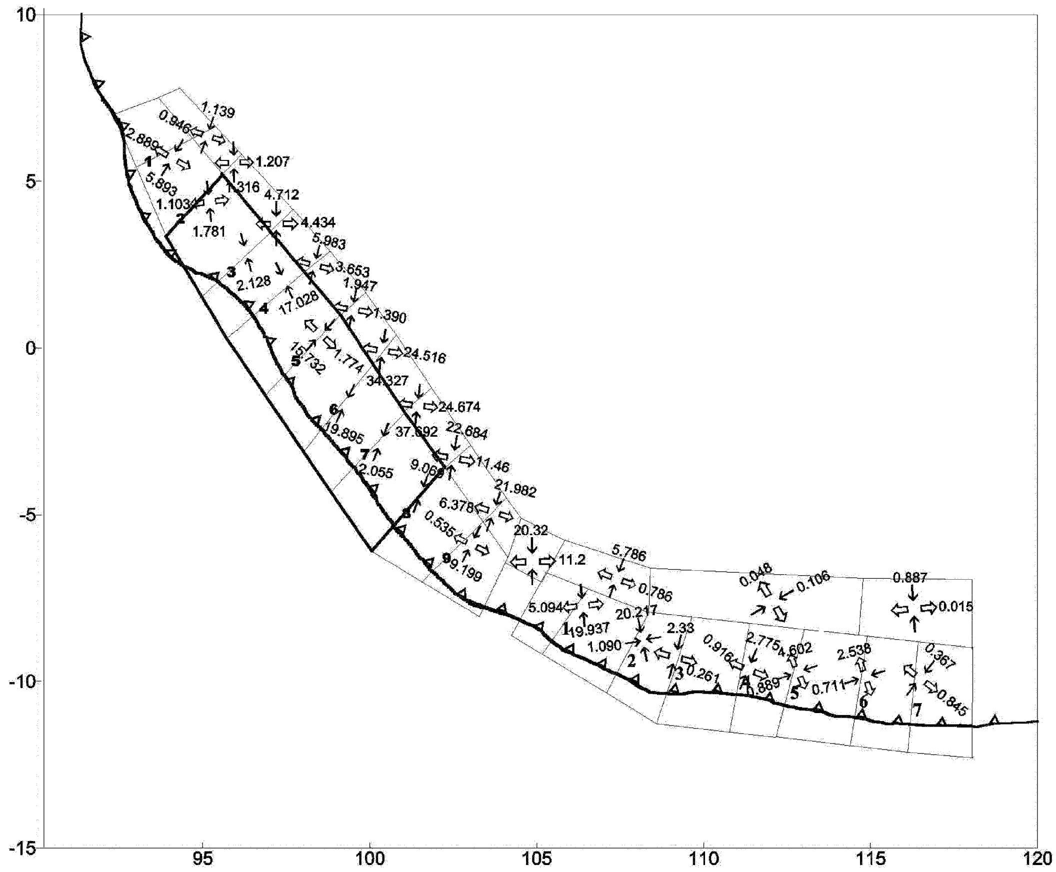

Figure 4. Distribution of deformation velocities calculated for overlapping seismogenic sources in the Sumatra–Java trench-arc region. Values are in mm/yr. Converging arrows indicate compression, while diverging arrows indicate extension.

The deformation velocities estimated for the offshore Sumatra fore-arc region indicate dominantly compression, with higher compressional velocities of 19 mm/yr along N45° near the equator. The deformation pattern further indicates that a portion of the motion is taken up by strike-slip or oblique slip, which means that the MFZ partly accommodates motion due to oblique subduction. Higher deformation velocities (sources 4–6) near the equator may imply the effect of local interaction of the Investigator Fracture Zone, as evidenced by the occurrence of the 1935 and 1984 events[36]. Such subducted ridges or seamounts may act as a mechanical barrier and produce large earthquakes[39]. Newcomb and McCann[13] suggested that the interaction of the Investigator Fracture Zone might have increased interplate coupling in the region. Based on GPS observations, Prawirodirdjo *et al.*[40] observed abrupt change in coupling of the fore-arc to the subducting plate on either side of the equator. This boundary coincides with the rupture zones of the 1833 and 1861 thrust earthquakes. Geodetic data of Bock *et al.*[41], and coral growth around Batu islands region[42] have been used by Simoes *et al.*[43] to identify the locked fault zone down to a depth between 35 and 57 km. However, north of 2°N, the Sumatran fore-arc region (sources 2 and 3) is characterized by the absence of any significant earthquakes in the historical as well as recent earthquake catalogues, which give rise to low deformation values in this region. The long quiescence in this region indicates lock-up stresses over large time intervals, which subsequently resulted in the occurrence of the highly devastating earthquake of 26 December 2004. This mega thrust earthquake caused increase in co-seismic stress on thrust planes in the subduction zone further southeast[44,45] and gave rise to the second major event on 28 March 2005.

Sunda Strait

The Sunda Strait is a consequence of the northwestward motion of the southwestern part of the Sumatran block along the Central Sumatran Fault. The extension zone widens southwestward and changes into a composite zone of strike-slip as well as normal faulting[46]. It is observed that the area is subjected to NW–SE extension because of the motion along Sumatran Fault and to NE–SW compression because of subduction. The region is a comparatively quiet zone with a cluster of moderate and large earthquakes immediately adjacent to the west coast of Java. Some studies indicate southward extension of the SFZ in the Sunda Strait[11,47].

The region shows a compressional deformation of 20.32 ± 2.73 mm/yr along the north direction and extensional deformation of 11.2 ± 1.5 mm/yr along N 88°, giving rise to a dextral slip of 13 mm/yr in the region.

Java Fault Zone

Seismicity in this region is extremely low compared to that along the SFZ. Lack of major events in the Java region has been ascribed to differential motion at the plate margin, which is principally being taken up either aseismically or by small-magnitude earthquakes[13]. As seismicity is sparse, the JFZ has been divided into three individual segments as mentioned previously. The eigen system of the velocity tensor for the JFZ indicates dominance of compressional deformation. While western Java shows a compression of 5.7 ± 0.8 mm/yr along N20° direction and extension of 0.8 ± 0.1 mm/yr along N110° direction, deformation in central and eastern Java is negligible due to the absence of large earthquakes within the upper plate.

Java fore-arc region

Offshore Java region shows considerable seismicity and earthquake focal mechanisms show thrust and strike-slip events with few normal faulting events. The strike-slip events may account for the presence of the Cimanderi Fault in Western Java (sources 1 and 2). Deformation velocities indicate dominance of compression (average 19 mm/yr) in the western part, which gradually changes to extension (average 3 mm/yr) towards the eastern part. The deformation pattern further indicates that the Java segment of the arc is seismically less active than the Sumatran segment during the period of investigation, as also observed by Newcomb and McCann[13] based on historical earthquake records. They attribute this difference due to variation in interplate coupling related to the age of the subducting lithosphere in these two regions.

Conclusions

Based on 100 years of hypocentral data of shallow earthquakes in the Sumatra–Java trench-arc region, a detailed seismotectonic evaluation in terms of active crustal deformation pertaining to five major seismogenic belts/sources is made using the method of summation of moment tensors. The results indicate large variation in dextral shear motion from 1 to 29 mm/yr along the SFZ. The estimated slip rates are in good agreement with the geological or GPS-derived slip rate estimates along the fault between 0 and 2°S. Very low slip rates in other segments of the fault suggest that considerable amount of slip along the fault may be taken up aseismically. The deformation velocities estimated for the offshore Sumatra fore arc region indicate dominantly compression with higher compressional velocities of 19 mm/yr along N45° near the equator due to the local interaction of the Investigator Fracture Zone. The deformation pattern further indicates that the MFZ partly accommodates motion due to oblique subduction. Deformation velocities for the Sunda Strait show compression of 20 ± 2.7 mm/yr along N–S and extension of 11 ± 1.5 mm/yr along E–W direction and give rise to dextral slip of 13 mm/yr. Western Java shows considerable compressional deformation, whereas deformation in the central and eastern Java is negligible. In the offshore Java fore arc region, deformation velocities indicate dominance of compression (19 mm/yr) in the western part, which gradually changes to extension (3 mm/yr) towards the east. The crustal deformation pattern further indicates that the Java segment of the arc is seismically less active than the Sumatran segment during the period of investigation.

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