What caused the great Sumatran earthquakes of 26 December 2004 and 28 March 2005?

On 26 December 2004, an unusually large and devastating earthquake of magnitude 9.0 occurred off the coast of northern Sumatra (Figure 1). The mega-thrust earthquake that released about 20×10^{17} J of energy triggered a killer tsunami, quite uncommon to the Indian Ocean region, causing massive destruction with a death toll of about 200,000. The hypocentral parameters estimated by the US Geological Survey[1] (lat. 3.298°N, long. 95.779°E, depth 30 km) indicate that the earthquake occurred along the zone of subduction between the India and the Burma plates. The focal mechanism given by the Harvard University[2] has a strike 329°, dip 8° and rake 110°, indicating thrust faulting on a NW–SE trending plane. Based on the shallow aftershock distribution and the known trend of the decollement plane in the subduction zone, it is reasonable to accept the NE-trending shallow dipping fault plane at a focal depth of about 30 km. The earthquake ruptured a large segment[3] (1200 km × 200 km) along the trench from northern Sumatra to northern Andaman Islands, as evidenced by the distribution of a large number of aftershocks of moderate size. However, the unidirectional northward propagation of the rupture and seismicity is quite surprising, and hardly any aftershock activity was observed south of it along the Australia–Sunda plate boundary. Modelling of the fault plane and rupture propagation using teleseismic broadband data[3–7] broadly indicate that the rupture had a total duration of about 500 s and occurred in two major phases, fast at first and slow later, propagating mostly in the NNW direction. The enormous amount of energy released suggests that the 26 December Sumatran earthquake was a mega-thrust event that must have slipped suddenly after a lock-up of several decades, or even a century[8], causing fault movement of about 10–15 m. The last significant event to have occurred on this segment was the 1881 earthquake of *M* 7.9, further north[9].

However, on 28 March 2005, three months later, another great earthquake of magnitude 8.7 occurred just about 250 km southeast of the 26 December event. Interestingly, both the earthquakes have almost identical focal depths as well as focal mechanism solutions. Normally such large earthquakes have return periods of the order of a century or more. Of course, the second earthquake seems to have occurred on a different segment to the south, and was not quite unexpected[3,8,10]. Even then, such close spatial proximity of two great earthquakes occurring within a very short span of three months, raises important questions about the mechanism of stress lock-up over large time periods in convergent plate boundary zones. In the present case, a pertinent question is whether the 28 March event was an aftershock of the 26 December event, and if so, whether a lock-up of the total energy of the two is feasible. Or could the first earthquake have triggered the second one?

It is interesting to note that the epicentral locations of these two great earthquakes are close to the quadruple-junction comprising the India, Burma, Australia and Sunda plates (Figure 1), suggesting the possibility of a multiple-plate interaction model for generation of large earthquakes.

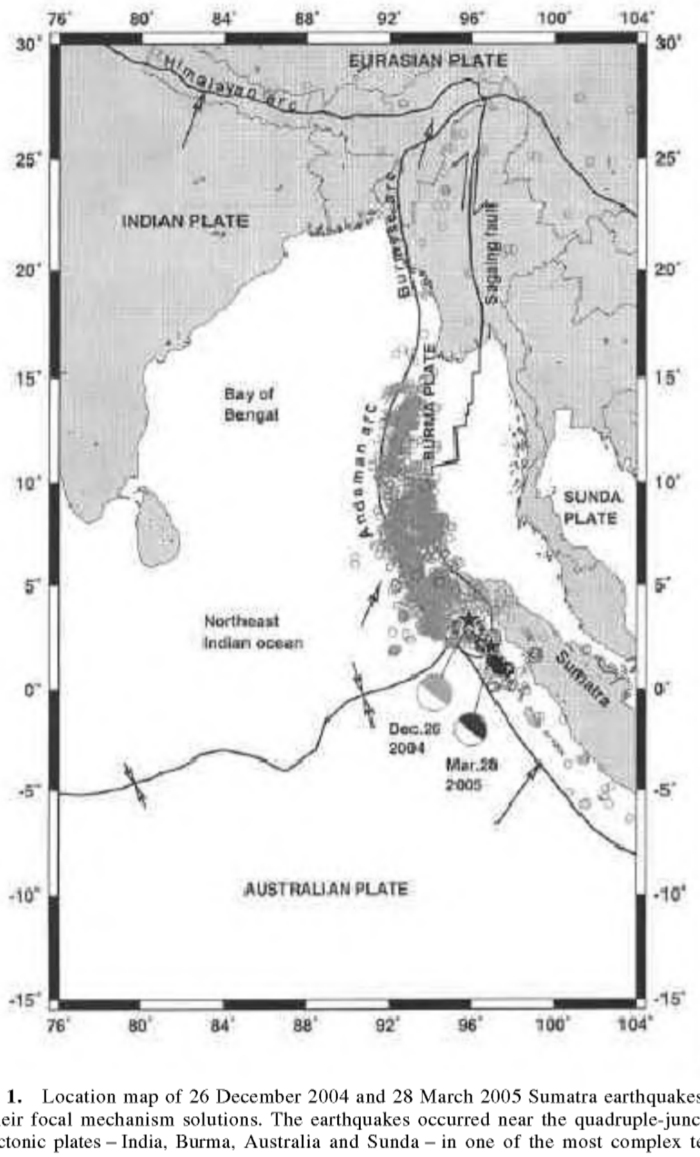

Figure 1. Location map of 26 December 2004 and 28 March 2005 Sumatra earthquakes along with their focal mechanism solutions. The earthquakes occurred near the quadruple-junction of four tectonic plates – India, Burma, Australia and Sunda – in one of the most complex tectonic scenarios.

Table 1. List of the 12 largest earthquakes in the world since 1900, their locations close to plate junctions, and the plates associated with each earthquake. AN, Antarctica; AU, Australia; BU, Burma; CA, Caribbean; CO, Cocas; EU, Eurasia; IN, India; NA, North America; NZ, Nazca; OK: Okhotsk; PA, Pacific; PS, Philippine Sea; SA, South America; SU, Sunda

Location	Date UTC	Magnitude	Latitude	Longitude	Associated plates
Chile	1960 05 22	9.5	38.24 S	73.05 W	NZ, SA, AN
Prince William Sound, Alaska	1964 03 28	9.2	61.02 N	147.65 W	PA, NA
Andreanof Islands, Alaska	1957 03 09	9.1	51.56 N	175.39 W	PA, NA
Kamchatka	1952 11 04	9.0	52.76 N	160.06 E	PA, NA, OK
Off the west coast of northern Sumatra	2004 12 26	9.0	3.30 N	95.78 E	IN, BU, AU, SU
Off the coast of Ecuador	1906 01 31	8.8	1.0 N	81.5 W	NZ, SA, CO, CA
Rat Islands, Alaska	1965 02 04	8.7	51.21 N	178.50 E	PA, NA
Off the west coast of northern Sumatra	2005 03 28	8.7	2.065 N	97.010 E	IN, BU, AU, SU
Assam–Tibet	1950 08 15	8.6	28.5 N	96.5 E	IN, EU, BU, SU
Kamchatka	1923 02 03	8.5	54.0 N	161.0 E	PA, NA, OK
Banda Sea, Indonesia	1938 02 01	8.5	5.05 S	131.62 E	AU, SU, PS, PA
Kuril Islands	1963 10 13	8.5	44.9 N	149.6 E	PA, PS, EU, OK

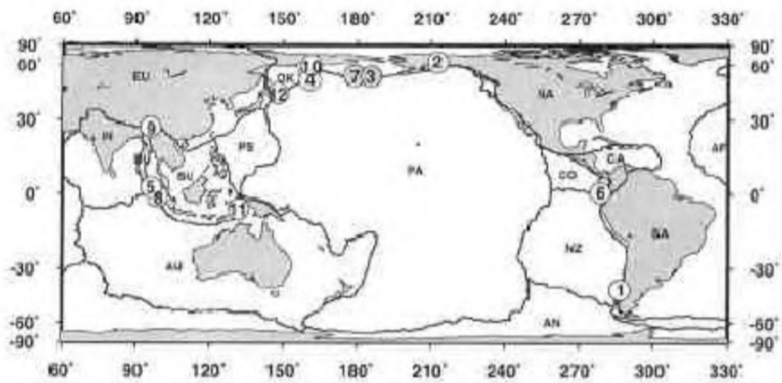

Figure 2. Location map of the 12 largest earthquakes in the world since 1900 (listed in Table 1). Note that most of these locations coincide with multiple-plate junctions except 3 and 7 on the western Aleutian trench (shaded circles).

In fact, this appears to be true on a global scale, as is clearly demonstrated by an examination of epicentral locations of the world's 12 largest earthquakes since 1900 (Figure 2). Details of these great earthquakes and their locations with respect to tectonic plates are listed in Table 1. It can be seen that each of these great earthquakes in the magnitude range of 8.5 to 9.5, falls close to multiple-plate junctions, with the exception of events 3 and 7 on the western Aleutian trench. The 1964 Alaskan earthquake (event 2) appears to be a special case of two-plate interaction, but associated with a junction between a subduction zone in the western Aleutian trench in the north, and a right-lateral strike-slip faulting environment along the San Andreas fault in the east, that seems to act like a triple-junction, aiding stress build-up. On the whole, there appears to be a strong (more than 80%) correlation between epicentral locations of these earthquakes and plate junctions or inflexion points. It would be very interesting to test this model using extensive numerical modelling approaches.

The quadruple-plate junction comprising the India, Burma, Australia and Sunda plates, is indeed one of the most complex tectonic regions in the world (Figure 1). The Indian plate subduction beneath the Burmese plate is highly oblique, varying from an almost NS shear at the Burmese arc in the North[11] to a northeastward continental subduction in the southern Andaman arc[12]. Further south, the Australian plate has a much smoother and faster oceanic northerly subduction beneath the Sunda plate. The scenario is further complicated by the development of a diffuse convergent deformation zone in the northeastern Indian Ocean, between the India and Australia plates in the last few million years[13,14], owing to a greater resistance of the Indian plate against the Himalayan collision zone in the north, compared to the smoother subduction of the Australian plate beneath the Sunda arc in the southeast[15]. Also, the styles of subduction in the India–Burma and Australia–Sunda plate boundary zones are quite dissimilar. While the former has a lower plate velocity (~5 cm/yr) with greater lithospheric coupling, the latter is governed by a higher plate velocity (~6.5 cm/yr)[14] with a smoother oceanic subduction. Further, the depths of penetration of the subducting slabs in these two regions are distinct, as indicated by the shallower focal depths (~230 km) in the Burma–Andaman arc as compared to the much deeper seismicity (~700 km) in the Australia–Sunda plate boundary zone (Figure 3). It appears that the difference in styles of India–Burma and Australia–Sunda plate subductions aided by the nascent development of the diffuse deformation boundary between the India and Australia plates has resulted in splitting of the Indo-Australian lithospheric slab near the junction. This would give rise to distinct India–Burma and Australia–Sunda subduction zones, with a barrier in between that prevents lateral transfer of stress across the two zones (Figure 4). The main evidence for this proposition is as follows:

(i) The Australian plate overrides the Indian plate with an anticlockwise rotation that produces the highest velocity of about 1.2 cm/yr near the junction of the India–Burma and the Australia–Sunda subduction zones (Figure 4). This is likely to generate a NS compression leading to folding or splitting of the formerly continuous Indo-Australian lithospheric slab.

(ii) The great mega-thrust earthquake of 26 December 2004 of magnitude 9.0 was generated at this junction, apparently due to the India–Burma plate subduction.

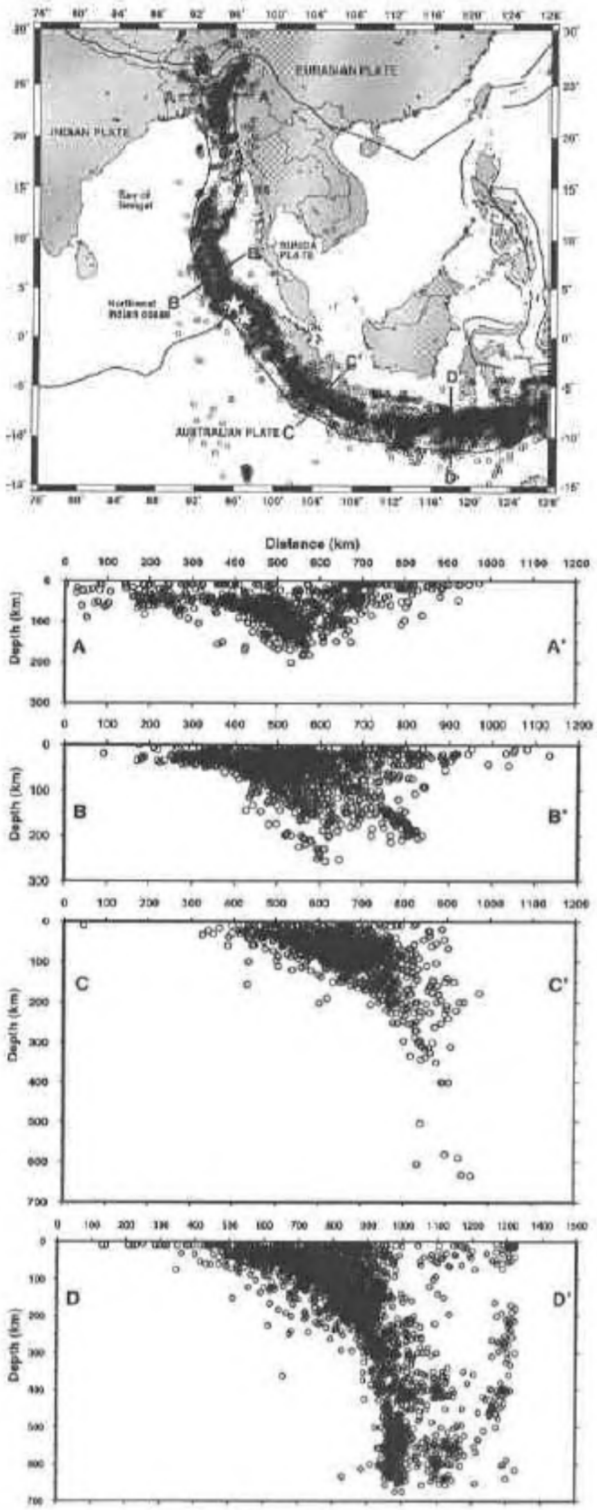

Figure 3. Seismicity trends and depth sections along the India–Burma (AA′ and BB′) and Australia–Sunda (CC′ and DD') subduction boundaries using hypocentral data of earthquakes during 1973 to 2005 with magnitudes greater than 3. Fixed depth solutions have been deleted. Note the variation in the extent of earthquake focal depths, ~230 km in the former and ~700 km in the latter.

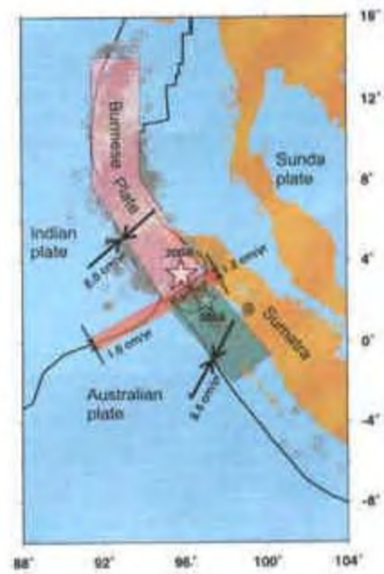

Figure 4. Schematic of the proposed tectonic model to explain the occurrence of two large earthquakes of 26 December 2004 and 28 March 2005 near the quadruple-plate junction of the India, Burma, Australia and Sunda plates. Rupture zones of the two are distinct with a barrier zone in between created by invasion of Australia–India plate boundary. The velocities indicated are computed using the NUVEL1A plate motion model[14].

But, interestingly, both the rupture propagation and aftershock disposition were confined entirely to the north, possibly indicating the presence of a barrier to the south.

(iii) Similarly, the great earthquake of 28 March 2005, due to the Australia–Sunda subduction, was also initiated close to the plate junction, but the rupture extended about 350 km to the south of this barrier.

(iv) The styles of subduction at the India–Burma and Australia–Sunda plate boundaries are quite distinct, with earthquake distribution reaching down to only about 230 km in the former, while it is found up to 700 km in the latter. This also implies distinct dips and depths of slab penetration.

From the above analysis it appears that the India–Burma and Australia–Sunda subduction zones are distinct, with different stress lock-up scenarios separated by a barrier along the Australia–India plate boundary. Details of the nature of this barrier and coupling between the separated slabs at the junction are at present a matter of speculation. In any case, the release of stress along the India–Burma plate resulting in the great earthquake of 26 December 2004, in turn appears to have triggered the release of stress locked up in the Australia–Sunda plate boundary, within a short span of three months, producing the great earthquake of 28 March 2005. Such a triggering mechanism probably explains the frequent occurrence of large earthquakes around this plate junction, as indicated by records of historical earthquakes. Finite element modelling of stress field in three dimensions incorporating the plate geometries, geological ages and hence the mechanical properties of the slabs, their thicknesses, depths of penetration of the subducting slabs along different sections, and the differential velocities of plates involved, is likely to shed further light on the current understanding of the mechanism of multiple plate interactions and the resulting large earthquakes.

1. http://earthquake.usgs.gov/eqinthenews/2004/usslav/
2. http://www.seismology.harvard.edu/projects/CMT/
3. Stein, S. and Okal, E., *Nature*, 2005, **434**, 581–582.
4. Yagi, Y., 2004, http://iisee.kenken.go.jp/staff/yagi/eq/ Sumatra2004/ Sumatra2004.html.
5. Yamanaka, Y., 2004, http://www.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/2004/EIC161e.html.
6. Ji, C., 2004, http://www.gps.caltech.edu/~jichen/Earthquake/2004/aceh/ aceh.html.
7. Borges, J. F. *et al*., 2005, http: //www.emsc-csem.org/Doc/Sumatra-rupture-process-2004.pdf
8. Sieh, K., *Nature*, 2005, **434**, 573–574.
9. Ortiz, M. and Bilham, R., *J. Geophys. Res. B*, 2003, **108**, 2215.
10. McCloskey, J. *et al*., *Nature*, 2005, **434**, 291.
11. Rao, N. P. and Kumar, M. R., *Geophys. Res. Lett*., 1999, **26**, 3149–3152.
12. Kumar, M. R. *et al*., *Tectonophysics*, 1996, **253**, 155–165.
13. Gordon, R. G. *et al*., *Tectonics*, 1990, **9**, 409–422.
14. DeMets, C. *et al*., *Geophys. J. Int*., 1994, **119**, 893–930.
15. Stein, S. and Okal, J., *J. Geophys. Res*., 1978, **83**, 2233–2245.

ACKNOWLEDGEMENTS. We thank M. Ravi Kumar and D. S. Ramesh for useful suggestions and comments. We are grateful to Director, NGRI for permission to publish this work.

Received 6 April 2005; revised accepted 9 June 2005

N. PURNACHANDRA RAO*
A. HANMANTHA CHARY

National Geophysical Research Institute,
Uppal Road,
Hyderabad 500 007, India
**For correspondence.*
e-mail: raonpc@rediffmail.com

28 March 2005 Sumatra earthquake: expected, triggered or aftershock?

The recent great earthquake of 28 March 2005 (M_w 8.7) occurred about 150 km SE of the earlier giant earthquake (M_w 9.3)[1] of 26 December 2004. Here we attempt to answer (i) whether the recent great earthquake was an expected event whose possibility of occurrence was mooted by McCloskey *et al*.[2]; (ii) whether it was triggered by the giant earthquake of 26 December 2004; or (iii) whether it is an aftershock of the giant earthquake of 26 December 2004.

Before we discuss the first and second issues, which are in a way coupled, we provide a brief description of tectonics of the region. In this region of the two earthquakes, the Indian–Australian plate moves towards NNE at a rate of about 6 cm/year. This results in an oblique convergence at the Sunda and Andaman trench. The oblique motion is partitioned into thrust-faulting and strike-slip faulting[3]. The former occurs in the subduction zone, while the latter occurs on the Sumatra Fault System (SFS), which is located a few hundred kilometres to the east of the trench in the back-arc region. There are also evidences of spreading in the back-arc region, which is consistent with the normal focal mechanisms of the earthquakes. Further southeast, the subduction zone swings towards east and becomes perpendicular to the Indian–Australian plate motion and the entire deformation is accommodated through thrust motion in the subduction zone. Following the 26 December 2004 Sumatra earthquake, aftershocks occurred along the two belts (Figure 1). Thrust-type aftershocks occurred in the subduction zone, while strike-slip and normal-type aftershocks in the region of SFS. McCloskey *et al.*[2] calculated the change in stresses, referred as Coulomb stresses, due to the coseismic reverse slip on the rupture of 26 December 2004 earthquake in the subduction zone and resolved these stresses on the right lateral strike-slip planes corresponding to faults in the SFS, as well as on thrust planes in the subduction zone. They found increase in stress on strike-slip faults in the SFS, and also on the thrust planes in the subduction zone further southeast of the 26 December 2004 giant earthquake rupture. Increase in Coulomb stress in the back-arc region is consistent with the results of Taylor *et al.*[4], who studied the cycle-related stress changes induced by the main event which promotes or decreases the likelihood of strike-slip and/or normal events in the back-arc regions of Aleutians and Indonesia. Incidentally, we also performed such computations independently and arrived at similar conclusions (Figure 1). During February 2005, we circulated our results among many of our colleagues and presented them in some meetings and seminars. In addition, we explored the possibility of triggering of a strong earthquake in NE India and Myanmar and also investigated the swarm of aftershocks immediately east of the Nancowry group of islands, which started on 24 January 2005 and continued for about ten days. Focal mechanisms of these aftershocks indicated strike slip and normal slip motion, with their epicentres on SFS.

The above analyses suggested that the 26 December 2004 earthquake increased Coulomb stresses in three regions, namely near the northern and southern edges of the earthquake rupture, and on the SFS to the east of the rupture in the back-arc region. Increase on the northern edge of the rupture may not be significant as low slip on rupture is reported in this region. Thus the above two regions could be the locale of future earthquakes, as also indicated by McCloskey *et al.*[2]. The recent earthquake actually occurred in the increased stress zone that lies to the southeast of the rupture of 26 December 2004 earthquake.