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Changes in the moment rate and the long term seismic deformation pattern: Before and after 26 Dec 2004 earthquake

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ABSTRACT
A detailed analysis of changes in the long-term seismic deformation before and after the 26 December 2004 mega thrust earthquake shows that there is a drastic increase in the deformation rate and moment release in and around the region where the event have occurred. The partial compression with a component of strike-slip faulting is appeared to be transformed into a completely compressional environment due to the post-2004 earthquake seismic deformation in the Sumatran offshore. The calculated deformation velocities and moment release rate for the region between 1° to 5° N in the offshore Sumatra, is low prior to the mega earthquake, which suggest that strain have been accumulating in the area which has finally ruptured on December 2004. The estimated velocity values along the SFZ seismic belt indicate variation in seismically active deformation with maximum dextral shear motion of 29 mm/yr in the central part to 1 and 8 mm/yr both southward and northward respectively along the SFZ. Except between 0°-2°S, the estimated velocities are significantly less than the geologically estimated slip rates as well as geodetically measured slip rates which suggest that considerable amount of slip along the fault may be taking up aseismically. The Andaman arc also shows a low seismic deformation rate compared to the rates obtained from GPS observations indicating that earthquake data alone cannot be used to calculate short term slip. The vertical component of velocities suggests crustal thinning in the Andaman Sea and crustal thickening all along the fore arc.

INTRODUCTION

The mega earthquake of 26 December 2004 (Mw 9.3) off the coast of Sumatra occurred as a result of the sudden slip of the mega-thrust lock–up zone on the interface between the subducting Indo-Australian plate beneath the Burma plate (Sieh, 2005).The earthquake ruptured more than 1300 km of the boundary (Shearer and Bürgmann, 2010) and the width of the rupture zone is 100-150 km, and maximum slip 20 m (Ishii et al., 2005). But the rupture didn't progress further to the S-SE despite high rapid slip at the initiation of the rupture, which indicates that the rupture front hit a barrier in this direction that broke three months later on 28th March 2005 (Kruger et al., 2005).

Major earthquake events have occurred along this plate boundary in 1797 (~ 8.4), 1833 (~ 9), 1861 (~ 8.5) and1907 (~ 7.8). The 28th march 2005 event ruptured the same region as the 1861 and 1907 events. Nicobar Island in 1881 (~ 7.9) and near Andaman Islands in 1941 (~ 7.9 presumed to involve thrusting motions (Lay et al., 2005). Bilham et al. (2005) observed that large thrust earthquakes in 1847 (~7.5), 1881 and 1941 occurred on intermediate regions of the down-dip boundary areas that have been surrounded and probably incorporated into the 2004 rupture (Figure 1). Cross sections through the Andaman normal to the trend of the trench are consistent with the notion that the 100 km region on the upper surface of the descending Indian plate east of the trench axis was largely aseismic prior to the 2004 earthquake, and that the 1847, 1881, and 1941 earthquakes probably ruptured less than one third of the width of the plate boundary that slipped in December 2004 (Bilham et al., 2005). The GPS observations taken between 1989 and 1994 in west of Sumatra suggest that the entire subduction interface under the islands experienced strain accumulation corresponding to a rate of 30 mm/yr (Catherine et al., 2014). Hence, it is sagacious to consider long term strain accumulation in the eventual rupture zone and stress concentration in the vicinity of the main shock hypocenter.

Here, A detailed analysis of changes in long-term seismic deformation (pre and post-2004 earthquake) has been carried out along the Andaman-Sumatra arc to study the changes that were brought out in the deformation pattern due to intense post-2004 earthquake seismic activity along various segments of the arc, which will be useful to identify areas of increased future seismic hazard along and across the arc.

METHOD AND DATA

The long-term deformation has been calculated using the method of moment tensor summation, which was originally proposed by Papazachos and Kiratzi (1992) based on the formulations of Kostrov (1974) and Jackson and McKenzie (1988). Many workers have subsequently applied this method in seismically active regions (Papazachos et al, 1992; Kiratzi, 1993; Kiratzi and Papazachos, 1995; Papazachos and Kiratzi, 1996; Radhakrishna and Sanu, 2002; Lasitha et al., 2006). So the detailed methodology is not reproduced here due to fear of being cumbersome.

The deformation velocities based on moment tensor summation require knowledge of both the fault plane solutions and the seismic moment for each earthquake complete over a certain magnitude threshold. This actually restricts the method to be applicable for the most recent data; as such information would not be available for older (historic) events. The historic events can also be used, by assuming fault parameters for individual events. Jackson and McKenzie (1988) observed that the historic data being available for large devastating earthquakes only, they influence the calculations. But the method proposed by Papazachos and Kiratzi (1992) allows the use of all available data including historic events though for areas, where the numbers of focal mechanisms are limited, a single large event will influence the calculation of the respresentative focal mechanism tensor because of its large moment. Alternatively, Kiratzi and Papazachos (1995) proposed a simple averaging method, which gives equal importance to all focal mechanisms, which is adopted in the present study. The hypocentral data from NOAA epicentral listing has been used in the study. An earthquake data set of all shallow earthquakes (h≤70 km) during 1900 – 2005 has been considered for the present analysis. Events before 1964 have been compiled from Rothe (1969) and Gutenberg-Richter (1954). For the period of 1953-1965, magnitudes from Rothe listing have been recalculated by Newcomb and McCann (1987). Similarly Engdahl et al. (1998) precisely determined hypo central parameters from ISC listing for the period 1964-1995. We considered these revised magnitudes with events Ms ≥ 4.5 for the present analysis. For events where Ms value is not available, it is obtained from Mb using Mb-Ms relation derived for the region. The magnitudes estimated by Gutenberg and Richter (1954) and Rothe (1969) are equivalent to 20-s Ms (Geller and Kanamori, 1977).

The region encountered a large number of earthquakes

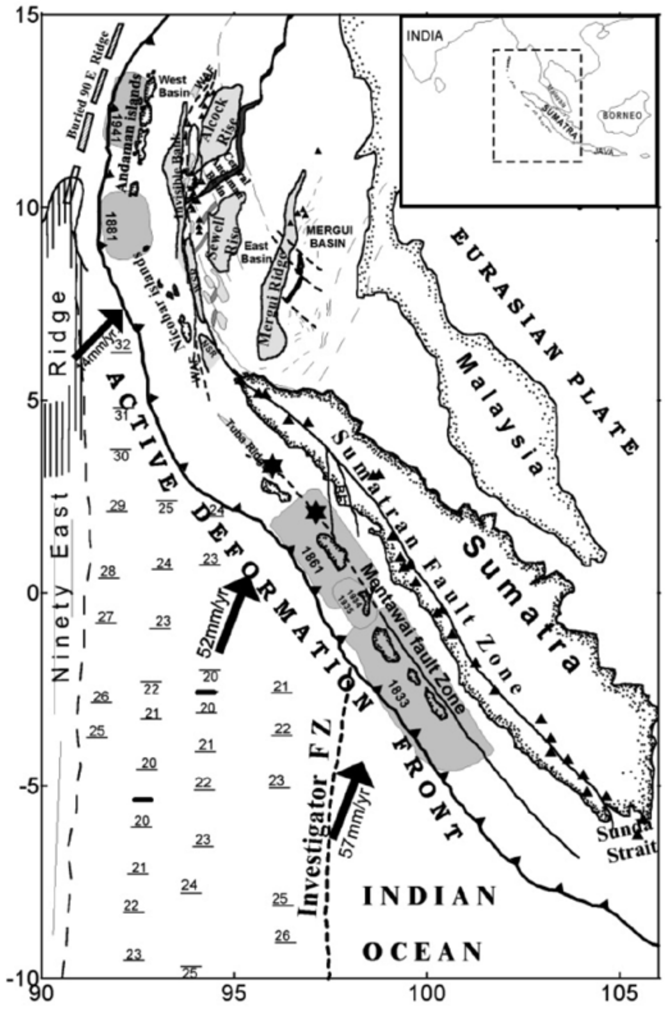

Figure 1. Detailed tectonic map of Andaman-Sumatra arc and adjoining region. The shaded region represent the rupture zones of great earthquakes prior to 2004 Mega earthquake. Stars indicate the locations of Dec 26, 2004 and 28 March, 2005 mega earthquakes.

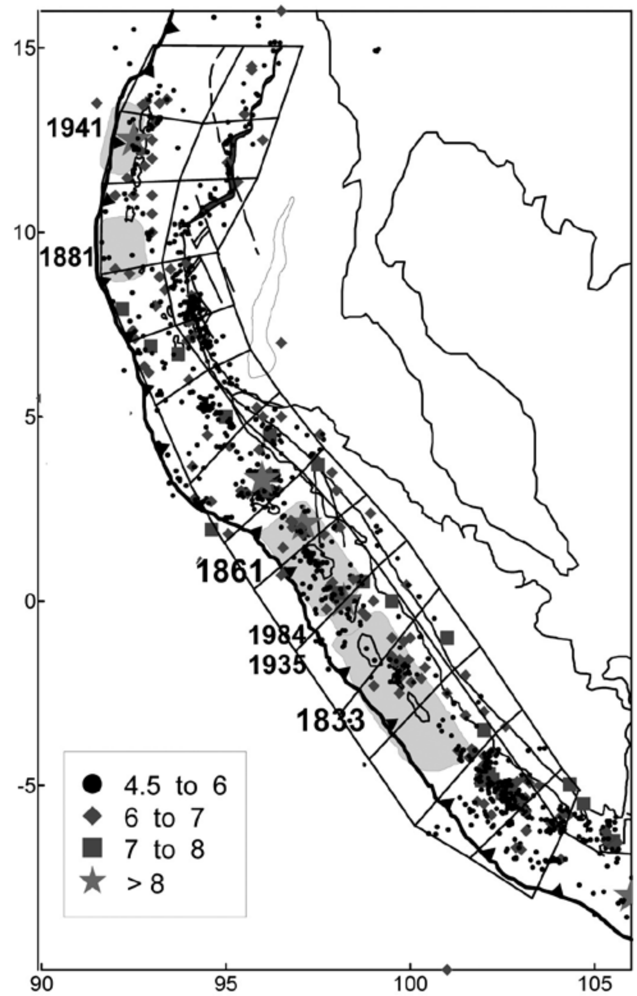

Figure 2. Map showing the Seismicity and moving window configuration of the sources in the Andaman-Sumatra trench-arc region.

along the whole length of rupture zone following the mega thrust earthquake of 26th December 2004. The earthquakes compiled from NOAA epicentral listing for both pre- and post-2004 earthquake periods are shown in Figure 2 and the focal mechanisms of events Ms>5.5 are shown in Figure 3. The velocities are calculated for a period of 1900- 25th Dec 2004 (pre 2004 earthquake data) and for the augmented period (1900-2005), so as to compare the deformation pattern for pre and post mega earthquake. It can be seen from Figure 3 that the post-2004 earthquake events are mostly characterized by dominantly thrust faulting events in offshore Sumatra, between Andaman trench and the fore arc ridge and few normal faulting events in the Andaman back arc spreading region.

Four seismogenic zones have been identified in the study region. 1) Andaman forearc (ASF), 2) Andaman Backarc (ASB), 3) Sumatra Fault zone (SFZ), and 4) Offshore Sumatra (OSF). Four sources each along Andaman Fore arc (ASF1- ASF4) and Andaman back arc (ASB1-ASB4) are identified. Nine sources each along SFZ (SFZ1-SFZ9) and offshore Sumatra (OSF1-OSF9) are also identified. A moving window method is employed having a window length of 3–4° and with 50% overlapping, in order to obtain a continuous variation in deformation pattern along the active seismic belts (Lasitha et al., 2006).

Four seismogenic zones have been identified in the study region. 1) Andaman forearc (ASF), 2) Andaman Backarc (ASB), 3) Sumatra Fault zone (SFZ), and 4) Offshore Sumatra (OSF). Four sources each along Andaman Fore arc (ASF1- ASF4) and Andaman back arc (ASB1-ASB4) are identified. Nine sources each along SFZ (SFZ1-SFZ9) and offshore Sumatra (OSF1-OSF9) are also identified. A moving window method is employed having a window length of 3–4° and with 50% overlapping, in order to obtain a continuous variation in deformation pattern along the active seismic belts (Lasitha et al., 2006).

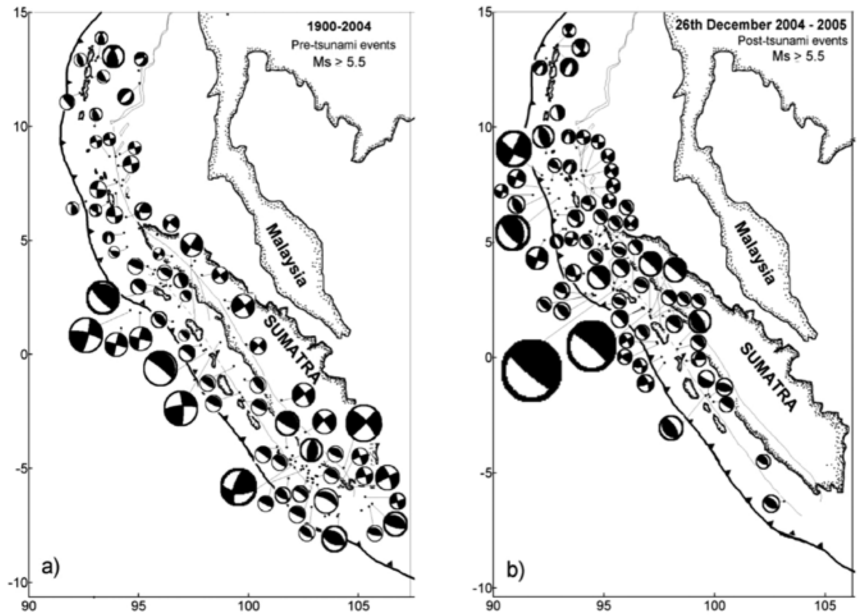

Figure 3. Map showing the events for which focal mechanism solutions are available from the Harvard CMT catalogue. Size of the solutions are based on the magnitude of the earthquake

RESULTS AND DISCUSSION

The results of deformation calculations are shown in Table 1a and Table1b (for Andaman region before and after the mega earthquake) and Table 2a and Table 2b (for Sumatra region before and after the mega earthquake), which show the components of velocity tensor and the eigen system of velocity tensor with errors in eigen values for each of the seismogenic sources (window) in each region. The changes in moment rate after the mega thrust earthquake are shown in Figure 4 and Figure 5 for Andaman and Sumatra arc respectively. Similarly, the deformation pattern obtained for each seismogenic source (window) before and after the mega earthquake is presented diagrammatically in Figure 6 and Figure 7.

A close examination of the moment release rates of both periods gives an idea on level of seismic activity in each of the source regions. Those sources where significantly large earthquakes occurred in the post-2004 earthquake period show large moment rate values, whereas the sources in which post-2004 earthquake activity is negligible, the moment rate is reduced because of averaging over a long period.

In the Andaman region, the fore arc region shows considerable moment release variation, whereas in the back arc region, the moment release rate is not very significant. Though several normal faulting events occurred along the Andaman spreading ridge after the mega thrust earthquake, their moment contribution is low. In the Sumatran region, where both 26th December 2004 and 28th March 2005 events were located, very high moment release rate has been observed in the offshore Sumatra between 2^{o} S–5^{o} N. Along the Sumatran Fault Zone, the moment release rate is significant in the southern part, while southernmost and northern parts of the SFZ remained less affected by large scale deformation in the fore arc region.

The results on crustal deformation rates estimated in the Andaman-Sumatra region before and after the mega thrust earthquake show drastic change in the long-term deformation rate in the northern part of the Sumatra offshore.

Comparison of long-term deformation pattern before and after the 2004 December mega earthquake suggests that there is a drastic increase in the deformation rate and moment release in and around the region where the event have occurred (Figures 5 and 7). In SFZ and Andaman back arc region, except at few locations, the deformation remains almost constant before and after the events. The deformation pattern indicates the dominance of compressive stresses in the fore arc region with the direction of maximum compression in almost NNE – SSW. While, it is almost normal to the trench in the Sumatran forearc near Nias island region, the compression takes more oblique trend with respect to the trench towards north near Andaman Islands.

The change in deformation before and after the earthquake is very significant in the region between 0^{o} to 4^{o} in the Sumatran offshore. For the sources OSF2 and

Table 1a: Components of velocity tensor and eigen system of velocity tensor for Andaman Fore arc (ASF1-ASF4) and Back arc (ASB1-ASB4) before 2004 mega earthquake.

	Elements of velocity tensorU(mm/yr).						Eigen System of velocity tensor (mm/yr.)								
	U_{11}	U_{12}	U_{13}	U_{22}	U_{23}	U_{33}	λ_1	Az°	Pl°	λ_2	Az°	Pl°	λ_3	Az°	Pl°
ASF1	3.344	-2.288	-0.063	-0.532	-1.164	0.0658	2.035±0.22	337.4	-6.8	-5.966±2.21	69.5	0.8	9.665±0.99	330.9	80.7
ASF2	3.186	0.057	0.018	1.214	-0.044	0.087	1.265±0.13	339.2	-11	-3.145±1.07	69.2	4.2	5.562±0.53	322.9	75.8
ASF3	-0.188	0.139	0.009	-0.142	-0.1	0.036	-0.321±0.0	316.8	-11.8	-0.064±0.007	40	29.7	0.092±0.01	246	57.6
ASF4	-1.881	-0.55	0.416	0.399	0.697	0.156	-2.151±0.2	16.1	-14.4	0.994±0.12	94.4	38.4	-0.169±0.02	302.7	48
ASB1	0.237	-0.582	0.01	-0.091	0.02	-0.035	0.677±0.05	322.9	-0.3	-0.532±0.04	52.9	-2.5	-0.034±0.0	45.9	87.5
ASB2	0.285	-0.262	-0.015	-0.024	0.008	-0.031	0.435±0.04	330.3	-2.1	-0.174±0.01	60.3	0.2	-0.031±0.0	325.5	87.9
ASB3	0.167	-0.512	-0.033	0.075	0.001	-0.036	0.636±0.05	317.6	-2.2	-0.394±0.03	47.5	3.4	-0.035±0.0	259.9	86
ASB4	-0.872	-0.946	0.007	0.95	-0.01	0.004	-1.274±0.11	23	-0.1	1.352±0.12	113	-0.5	0.004±0	100.5	89.5

Table 1b: Components of velocity tensor and eigen system of velocity tensor in the Andaman fore arc back ((ASF1-ASF4) and Back arc (ASB1-ASB4) (calculated including post mega earthquake events upto 2005)

	Elements of velocity tensor U (mm/yr).						Eigen System of Velocity tensor (mm/yr.)								
	U_{11}	U_{12}	U_{13}	U_{22}	U_{23}	U_{33}	λ_1	Az°	Pl°	λ_2	Az°	Pl°	λ_3	Az°	Pl°
ASF1	4.370	-2.544	-0.282	-0.008	0.910	0.956	1.785±0.21	328.3	-1.4	-5.633±0.612	69.8	0.9	7.668±0.86	309.1	87.5
ASF2	2.558	-2.332	-0.015	2.444	0.546	-0.208	2.265±0.17	335.6	-4.9	-3.36±0.33	65.7	3.8	5.672±0.53	304	82.9
ASF3	-2.927	0.082	0.106	-0.515	-0.182	0.282	-2.934±0.33	357.9	-2	-0.551±0.062	87.5	12	0.324±0.036	277.2	77.8
ASF4	-8.467	-3.046	1.232	0.572	0.966	0.974	-9.599±1.248	17.4	-7.9	1.922±0.25	101.5	36.5	0.757±0.098	297.8	52.4
ASB1	0.176	-0.557	0.003	-0.091	0.017	-0.029	0.616±0.05	321.7	-0.7	-0.531±0.043	51.8	-1.7	-0.03±0.002	28.4	88.2
ASB2	0.265	-0.243	-0.022	-0.023	0.006	-0.029	0.404±0.039	330.3	-2.9	-0.161±0.016	60.2	2.4	-0.03±0.003	290.3	86.2
ASB3	0.066	-0.574	-0.03	0.109	0.004	-0.036	-0.487±0.04	43.9	2.4	0.663±0.054	134	1.9	-0.04±0.003	262.8	86.9
ASB4	-1.116	-1.231	0.009	1.252	-0.007	0	-1.64±0.155	23.1	-0.2	1.776±0.168	113.1	-0.3	0	83.2	89.6

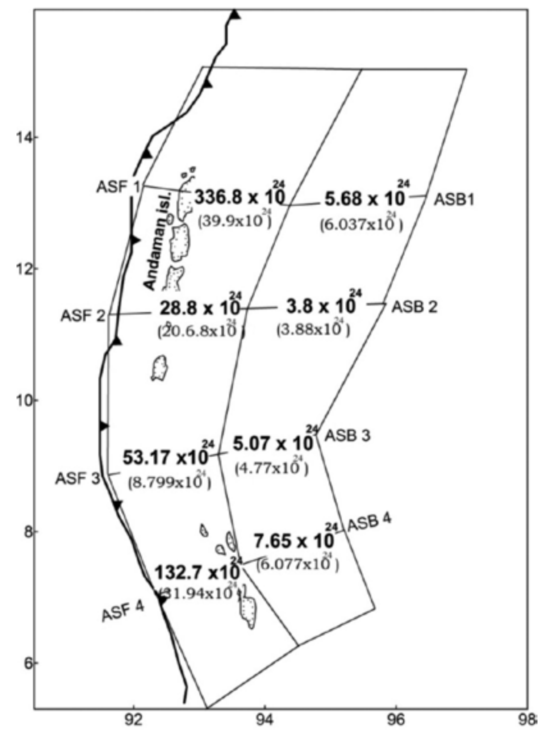

Figure 4. Map showing the difference in moment rate in Andaman region before and after the mega thrust earthquake. The values given in brackets are moment rate calculated before the mega earthquake.

Table 2a: Components of velocity tensor and eigen system of velocity tensor along Sumatra fault zone (SFZ1-SFZ9) and Off shore Sumatra arc region(OSF1-OSF9) (Before 2004 mega earthquake).

Elements of velocity tensor U (mm/yr).							Eigen System of Velocity tensor (mm/yr.)								
	U_{11}	U_{12}	U_{13}	U_{22}	U_{23}	U_{33}	λ_1	Az°	Pl°	λ_2	Az°	Pl°	λ_3	Az°	Pl°
SFZ1	-0.856	-0.576	-0.005	0.865	-0.016	0.01	-1.031±0.09	16.9	0.5	1.04±0.09	106.9	-0.7	0.01±0.00	141.1	89.1
SFZ2	-3.864	1.176	-0.222	1.658	-0.052	0.1	-4.114±0.45	348.5	2.8	1.903±0.20	78.4	-3	0.105±0.01	121.2	85.9
SFZ3	-7.447	1.643	-0.169	3.02	-0.166	0.24	-7.701±0.87	351.3	1	3.284±0.37	81.2	-3.6	0.231±0.02	97.3	86.3
SFZ4	-3.64	-2.275	0.303	4.898	-0.089	0.074	-4.225±0.49	14	-3.6	5.471±0.63	104.1	-1.7	0.087±0.01	39.1	86
SFZ5	-1.29	-0.4	0.054	1.171	-0.037	0.004	-1.355±0.16	9	-2	1.236±0.15	99	-2.1	0.004±0	55.5	87.1
SFZ6	-23.87	-6.896	-0.505	15.963	-0.671	1.091	-25.049±3.58	9.6	1.3	17.144±2.45	99.5	-2.1	1.084±0.15	132.4	87.5
SFZ7	-16.91	-1.846	0.078	8.269	-0.849	0.921	-28.844±4.06	4.2	-0.1	14.384±2.02	94.2	-6.4	1.396±0.19	93.7	83.6
SFZ8	-1.244	-0.131	0.117	0.532	0.043	0.08	-14.052±1.85	4.3	-5.1	6.047±0.8	93.9	4.3	0.981±0.13	324.2	83.4
SFZ9	-2.486	-1.497	0.493	1.927	0.191	0.192	-9.746±1.05	17	-9.3	7.668±0.82	106.9	1	0.887±0.09	10.9	80.7
OSF1	-2.553	-1.116	0.281	1.531	0.241	0.113	-2.875±0.33	14.6	-6.3	1.832±0.21	103.9	5.5	0.134±0.01	333.2	81.6
OSF2	-5.206	-0.115	0.39	1.861	0.414	0.239	-5.237±0.53	1.2	-4.2	1.96±0.19	90.2	13.5	0.17±0.01	287.9	75.9
OSF3	-6.94	-1.422	0.686	1.889	0.784	0.413	-7.247±0.75	9.4	-6	2.351±0.24	97.2	19.6	0.258±0.02	295.6	69.4
OSF4	-11.89	-11.52	3.799	-6.788	3.794	1.644	-22.323±2.55	39.1	-12.6	2.048±0.23	138	-34.8	3.242±0.37	112.3	52.4
OSF5	-8.361	-8.603	3.492	-8.136	3.926	1.404	-18.251±2.08	44.9	-14.9	0.312±0.03	136.8	-7.2	2.846±0.32	71.8	73.3
OSF6	-12.49	-8.397	4.34	-0.89	3.704	1.125	-18.484±2.01	28.6	-15.9	4.395±0.47	107.4	34.4	1.829±0.19	319.3	51.1
OSF7	-1.992	-1.165	0.392	0.413	0.255	0.132	-2.542±0.24	22.3	-9.7	0.896±0.08	111	7.3	0.199±0.01	344.9	77.8
OSF8	-22.55	-6.819	3.79	4.03	2.561	1.517	-24.897±2.48	14.1	-9.2	6.291±0.63	100.5	21	1.601±0.16	306.5	66.9
OSF9	-20.05	-6.409	4.601	2.432	2.887	1.876	-22.845±2.22	15.6	-11.9	5.232±0.51	97.4	34.1	1.867±0.18	302	53.3

Table 2b: Components of velocity tensor and eigen system of velocity tensor along Sumatra fault zone (SFZ1-SFZ9) and Off shore Sumatra arc region(OSF1-OSF9) (calculated including post mega earthquake events upto 2005)

Elements of velocity tensor U (mm/yr).							Eigen System of Velocity tensor (mm/yr.)								
	U_{11}	U_{12}	U_{13}	U_{22}	U_{23}	U_{33}	λ_1	Az°	Pl°	λ_2	Az°	Pl°	λ_3	Az°	Pl°
SFZ1	-1.038	-0.667	-0.011	1.042	-0.014	0.01	-1.233±0.121	16.3	0.7	1.238±0.122	106.3	-0.5	0.01±0.00	158.7	89.2
SFZ2	-3.817	1.048	-0.219	1.797	-0.035	0.088	-4.017±0.439	349.8	2.9	1.989±0.217	79.7	-2.2	0.096±0.01	132.7	86.3
SFZ3	-6.988	1.437	-0.187	3.058	-0.119	0.204	-7.193±0.818	352	1.3	3.266±0.371	82	-2.7	0.201±0.02`	107.9	87
SFZ4	-3.476	-2.172	0.29	4.677	-0.085	0.071	-4.035±0.471	14	-3.6	5.224±0.61	104.1	-1.7	0.083±0.01	39.1	86
SFZ5	-1.26	-0.391	0.053	1.145	-0.036	0.004	-1.324±0.162	9	-2	1.208±0.148	99	-2.1	0.004±0.00	55.5	87.1
SFZ6	-24.965	-6.692	0.55	21.768	-1.156	0.097	-25.91±3.722	8	-0.8	22.773±3.272	98	-3.1	0.037±0.005	82.6	86.8
SFZ7	-35.044	-1.651	1.818	21.7	-2.565	0.655	-35.177±4.988	1.5	-2.8	22.069±3.13	91.9	-7	0.42±0.059	69.9	82.5
SFZ8	-15.71	-1.792	1.087	8.435	-0.378	0.707	-15.91±2.053	4.2	-3.6	8.594±1.109	94.4	-3.3	0.747±0.096	46.7	85.1
SFZ9	-9.899	-4.598	1.879	6.648	0.608	0.769	-11.41±1.249	14.6	-9.2	7.842±0.858	104.4	1	1.086±0.119	8.4	80.8
OSF1	-5.363	-3.824	1.219	-0.197	0.813	0.823	-7.646±0.859	28.1	-9.8	1.861±0.209	116.4	10.2	1.047±0.118	340.9	75.8
OSF2	-136.22	-44.376	14.985	12.565	13.918	11.212	-150.49±16.83	15.8	-6.4	30.039±3.361	102.2	29	8.011±0.896	297.1	60.1
OSF3	-217.85	-89.621	28.604	20.564	28.465	17.158	-252.64±29.74	18.9	-7.7	59.047±6.951	105.3	25.5	13.469±1.586	304.4	63.3
OSF4	-60.586	-48.867	15.339	-5.5	13.169	5.822	-93.139±11.09	30.7	-11.4	23.953±2.853	117.8	13.9	8.922±1.063	338.6	71.9
OSF5	-14.259	-11.189	3.963	-3.507	3.77	1.51	-22.496±2.539	32.7	-12.6	4.253±0.48	114.2	33.5	1.986±0.224	320.4	53.6
OSF6	-14.095	-8.024	3.777	-1.124	3.076	1.27	-19.034±2.082	26.2	-13.2	3.673±0.402	105.1	39.6	1.412±0.154	311	47.4
OSF7	-2.303	-1.324	0.398	0.416	0.257	0.157	-2.912±0.291	22.3	-8.6	0.964±0.096	111.3	6.7	0.217±0.022	344	79.1
OSF8	-20.799	-6.374	3.467	3.786	2.326	1.395	-22.985±2.304	14.2	-9.2	5.867±0.588	100.8	20.1	1.5±0.15	307.4	67.8
OSF9	-18.435	-6.027	4.16	2.257	2.59	1.726	-21.033±2.057	15.8	-11.7	4.8±0.469	98.2	32.7	1.781±0.174	302.8	54.8

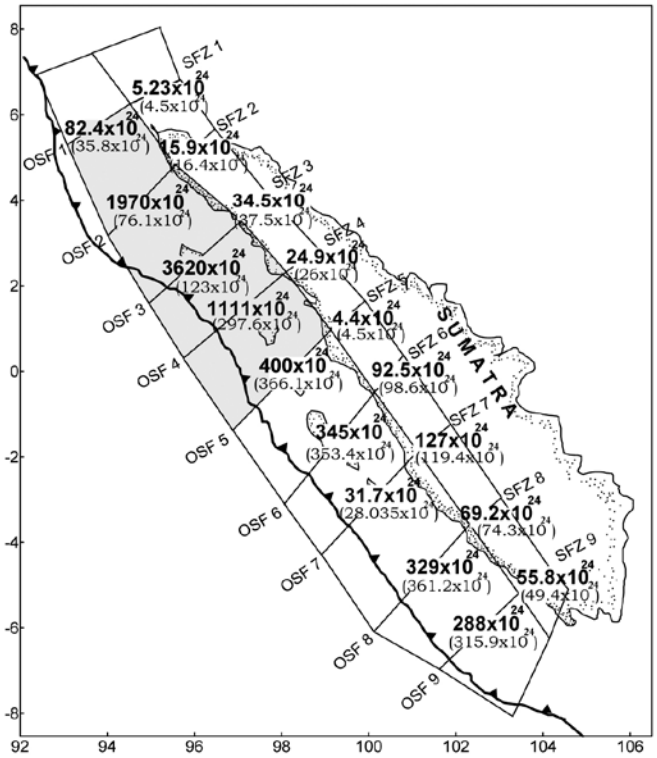

Figure 5. Map showing the difference in moment rate in Sumatra region before and after the megathrust earthquake. Values given in bracket are for pre-mega earthquake event. The light grey shaded region shows significantly large differences in moment rate.

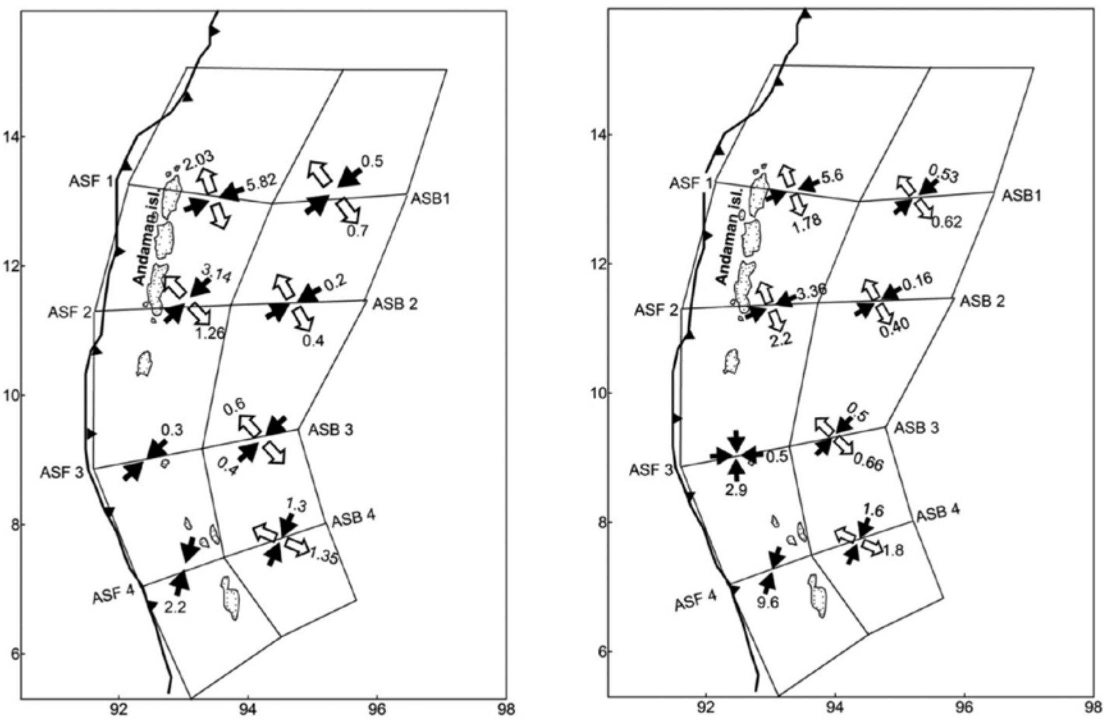

Figure 6. Map showing the differences in deformation velocities in the Andaman region before (left) and after (right) the 26 Dec mega earthquake.

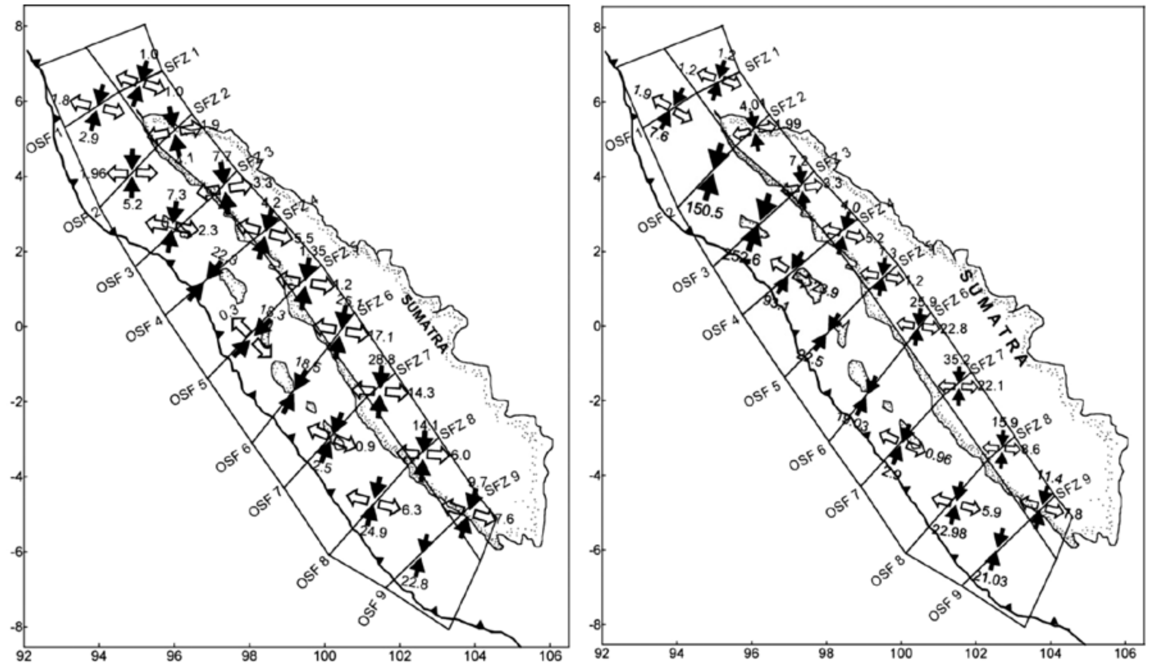

Figure 7. Map showing the differences in deformation velocities in the Sumatra region before (left) and after (right) the 26 Dec mega earthquake.

OSF3, the extensional deformation rate becomes negligible after the major events. In the source OSF2, where the 26^{th} December 2004 event was located, the compressional deformation rate increases from 5.2 mm/yr to 150.5 mm/yr. In the next overlapping window OSF3, where both the 2004 December and 2005 March events occurred, the compressional deformation rate changes from 7.3 mm/yr to 252.6 mm/yr. In the next source OSF4, where the 28^{th} March 2005 was located, the compression rate changes from 22.3 mm/yr to 93.1 mm/yr. The partial compression with a component of strike-slip faulting is appeared to be transformed into a completely compressional environment due to the post-2004 earthquake seismic deformation in the Sumatran offshore. Subduction of topographic features such as ridges and seamounts has been found to cause broadly distributed deformation in the fore arc (Gardner et al, 1992; Chung and Kanamori, 1978) mainly compression in the upper plate (Whittaker et al, 2007) . Geodetic strain and rotation rates show that the northern off shore Sumatran region endures a highly compressive regime (Michel at al., 2001), which can be attributed to the Subduction of Wharton Ridge and Investigator Fracture Zone (IFZ). The present study also suggest a dominantly compressive environment in Sumatra fore arc. The calculated deformation velocities and moment release rate for the region between 1° to 5° N in the offshore Sumatra, is low prior to the mega earthquake, which suggest that strain have been accumulating in the area which has finally ruptured on December 2004. A study made by Lay et al in 2005 suggested that the logical regions for concern about the future large earthquakes are the Sumatran fault zone and southeast of the 2005 rupture, the adjacent region failed in 1833 which likely to have accumulated substantial strain. In the present study, the calculation of deformation velocities which incorporated earthquake information upto 2005 shows that the source OSF7 is showing low moment rate and deformation rate even after the mega thrust earthquake. This potential region later witnessed two major earthquakes in Sept 12, 2007 of magnitudes 8.4 and 7.8; the sources fall in the rupture zone of 1833 event. These independent estimates confirm that the concept of seismic gaps, deformation velocities and moment rate should be applied in the active seismic belts for understanding/assessing the seismic hazard.

Bellier and Sebrier (1994) estimated slip rates along SFZ, which is 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 SFZ also indicate slip rates of 23 to 24 mm/yr (Prawirodirjo et al., 2000). 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 along the SFZ. Except between 0°-2°S, the estimated velocities are significantly less than the geologically estimated slip rates as well as geodetically measured slip rates which suggest that considerable amount of slip along the fault may be taking up aseismically.

Bilham et al. (2005) suggested the reverse slip in the Nicobar islands (7° N) was more than twice as much as the slip in the Andaman islands (12ºN) after the mega thrust earthquake. The unusual compression deformation near the Nicobar Islands region (ASF3) observed in the post-2004 earthquake period in the present study could be an indication of such reverse slip. Geophysical studies indicate the Ninety East Ridge (NER) partially subducts below the Andaman trench (Curray et al., 1982; Mukhopadhayay and Krishna, 1995; Gopala Rao et al., 1997; Subrahmaniam et al., 2008; Gahalaut et al., 2010). Between 5°-10°N, in the Andaman arc, the rate of deformation is very low prior and after the major earthquake. Lack of post seismic after slip even after the major earthquake suggest strong coupling in the region, where NER might have acted as a structural barrier (Gahalaut et al ,2010). Guzman-Speziale and Ni (1996) reported a significant decrease in the number of earthquakes in the frontal arc region at around 8º–10ºN latitude where the NER appears to impinge on the subduction zone, wherein the window ASF3 shows a low deformation rate before mega earthquake and an unusual deformation pattern after the mega earthquake. 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 (Lay et al., 2005; Ammon et al., 2005). Based on GPs observations, Gahalaut et al (2006) observed that maximum slip of 15.1 ± 0.2 m on rupture occurred between 7 and 9^0N latitudes, which seemed to be not accommodated by the seismicity, as there is no major variation in the deformation velocities before and after the mega earthquake. Velocity calculations based on earthquake data alone may not give a true indication of the short term slip, as the after slip was largely seismic and did not contribute to the aftershocks (Gahalaut et al, 2008).

The deformation studies prior to the 2004 earthquake event shows a compression of 0.2-0.5 mm/ yr along a mean direction of N 55º and extension of 0.4-0.7 mm/yr along a mean direction of N 320º along and across the Andaman spreading ridge. The events along the back arc spreading region also include an earthquake swarm of July 8, 1984 with most of the mechanisms reported by Dziewonski et al. (1983) showing dominantly normal faulting. Such a faulting pattern for swarms along the slow-spreading ridges indicates extensional tectonic activity (Bergman and Solomon, 1990; Radha Krishna and Arora, 1998). The vertical component of velocities indicates crustal thinning in the Andaman Sea and crustal thickening all along the fore arc.

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