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Source parameters of the Bay of Bengal earthquake of 21 May 2014 and related seismotectonics of 85°E and 90°E ridges

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ABSTRACT

Source parameters of the Bay of Bengal earthquake of 21 May 2014 have been studied using full waveform inversion. Its source mechanism thus determined the orientation of the strike slip faulting as NW-SE/NE-SW. The occurrence of past earthquakes along the NE-SW nodal plane suggested its preference as the main fault which could result from the transmission of stresses from the Indian plate boundary. High stress drop of this earthquake (216 bar) is attributed to its location in the intraplate region, strike slip faulting and focus in the colder upper mantle. Comparison of the stress drop of deeper focus Hindukush earthquakes with that of the Bay of Bengal earthquake showed a smaller felt radius due to fractured lithosphere in the Himalayas vis-a-vis more efficient propagation of seismic waves in the peninsular region from the source region of this recent earthquake. The seismological evidence presented for the 85°E and 90°E ridges shows the predominance of strike slip faulting with thrusting on both the ridges. Integrating their source mechanism with that of the May 2014 earthquake, it could be inferred that the Bay of Bengal region (excluding Andaman Sumatra subduction zone) is characterised predominantly by strike slip faulting in the region north of latitude 20°N and strike slip with thrusting in the remaining portion.

1. Introduction

The Bay of Bengal is situated on the northeast of Indian Ocean and is surrounded by Sri Lanka, India, Bangladesh, Myanmar, Andaman, Sumatra and Java islands. It plunges to a depth of about 200 km under the Andaman Nicobar island arc (Srivastava and Chaudhury, 1979) and sinks along the deep oceanic Java trench. This trench is filled by sediments flowing through rivers in the Indian subcontinent. The recent earthquake of 21 May 2014 in the Bay of Bengal with its epicentre midway between the 85°E and 90°E ridges occurred on hitherto unknown tectonic features. Since most of the earthquakes within the Bay of Bengal have been reported as shallow focus, its focal depth of about 50 km in the upper mantle appeared unusual; being about 300 km away from the Andaman-Sumatra subduction zone. This earthquake was widely felt in the coastal regions of India in the states of Tamilnadu, Andhra Pradesh, Orissa and West Bengal with seismic intensity III on the MSK scale. However, higher intensity of IV was reported in Bhubaneshwar (Orissa state) causing minor damage to some houses and injuries to a few people largely due to panic. Isolated felt cases were also reported from far off places in northeast India, and multi-storey buildings in Delhi and Jaipur up to distance of about 1600 km (Martin and Hough, 2015). The source mechanism of this earthquake reported by Singh et al. (2015), Rao et al. (2015) and Mallick and Rajendran (2016) was based on P-wave modelling using data of Indian and teleseismic stations in the epicentral distance of 30–60°. It would however, be of interest to evaluate the source parameters of this earthquake using full waveform inversion. Other limitations of earlier studies pertain to the stress drop of this earthquake, which was either reported unusually high (Rao et al., 2015) or indirectly inferred (Martin and Hough, 2015; Singh et al., 2015).

The objective of this paper is therefore to refine the hypocentral parameters and fault plane solution of the 21 May 2014 Bay of Bengal earthquake using Full Waveform Inversion (FWI). The stress drop due to this earthquake is also determined from S-wave spectra of Indian stations. Two different opinions (Martin and Hough, 2015; Singh et al., 2015) about the causes of the large felt area due to this earthquake are re-examined by comparison with the upper mantle Hindukush earthquakes. Seismotectonics of the 85°E and 90°E ridges has also been discussed in relation to the recent Bay of Bengal and other earthquakes since historical times.

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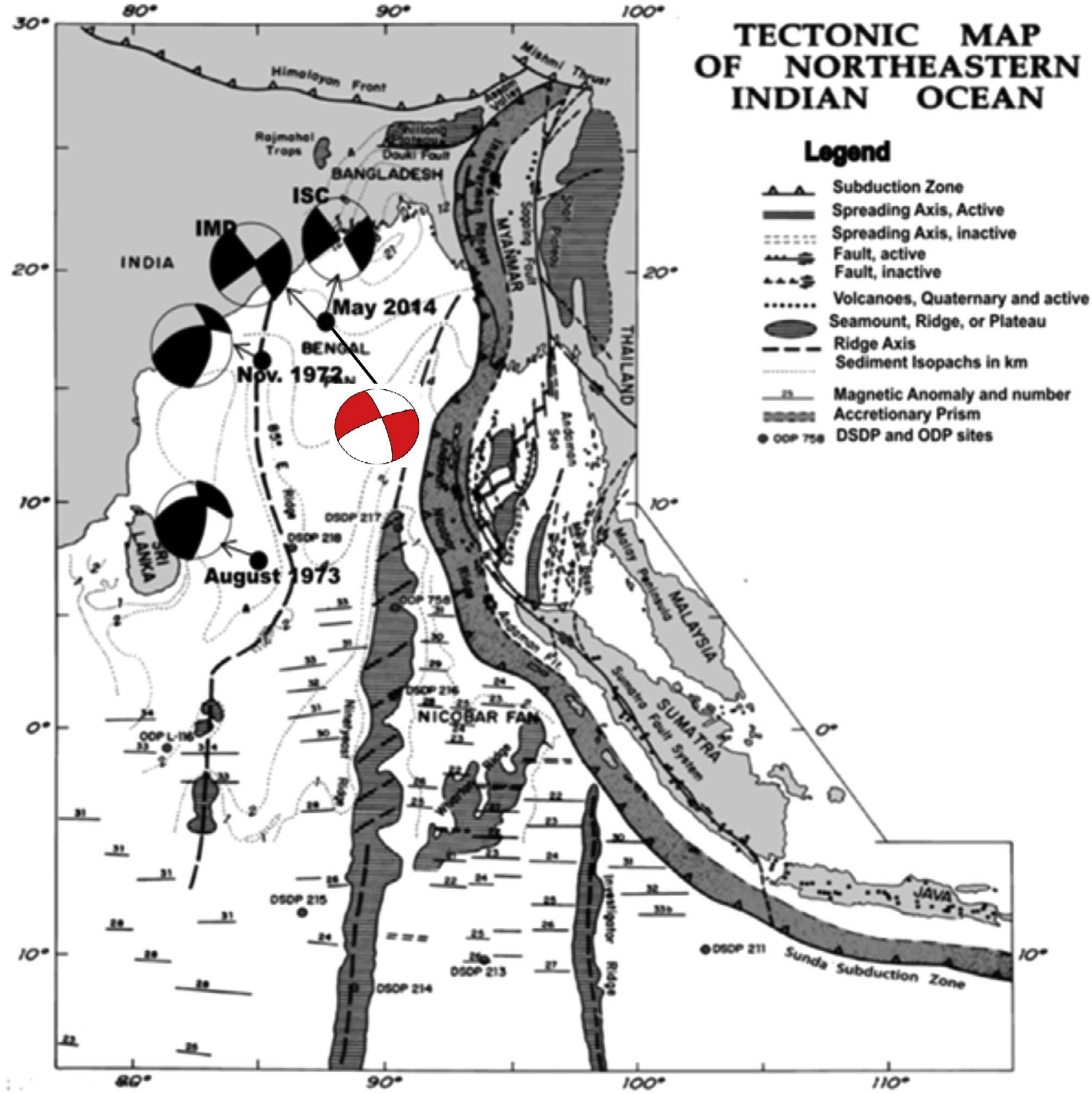


Fig. 1. Tectonic features of the Bay of Bengal showing fault plane solution of May 2014, Sept 1973 and Nov 1972 earthquakes. (Tectonic map after Curray, J. M. (1991)). [Red beach ball: present study]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Tectonics of the Bay of Bengal

The tectonic features of the Bay of Bengal are shown in Fig. 1 (after Curray, 1991). Curray (2014) also presented a synthesis of various scraps of the geological history of this complex region from rift to orogeny. The sedimentary fill in the Bengal fan and the delta exceeding 20 km is mainly derived from erosion of the Himalaya and Tibetan plateau since at least middle Eocene i.e. about 43–50 Ma. The two ridges near the 85°E and 90°E have been considered as aseismic in spite of occurrence of earthquakes up to magnitude 6 over them from time to time. The 85°E ridge extends up to15°N and thereafter it is buried under the uninterrupted Tertiary succession and Quaternary submarine fan deposits from rivers (Ramana et al., 1997). Its detailed analysis showed that the northern most end of the ridge lies at the continental slope/rise area of south of the Chilka lake (Orissa) in the offshore Mahanadi basin (Bastia et al., 2010; Desa et al., 2013). This ridge gradually bends towards the southern part of the peninsular India and takes a southwest turn around Sri Lanka before joining with the Afanasy Nikitin sea mount (Krishna, 2011). The ridge is associated with negative gravity anomaly over the northern part (up to 5°N) and positive anomaly over the southern part. The width of this ridge is variable from 100 to 180 km.

The bathymetric expression of the 90°E ridge is visible up to10°N but seismic reflection data indicated its northward extension up to 17°N (Subrahmanyam et al., 2008). Its width is 300 km or more which is almost twice that of the 85°E ridge. The gravity anomalies are opposite to the 85°E ridge and are strongly positive over the exposed segment but become less marked over the buried portion. The echelon block structure of this ridge in proximity to the convergence zone (90°E ridge – Andaman island arc/ trench) is a consequence of the complex strike slip and subduction related tectonic forces (Moermans and Singh, 2014).

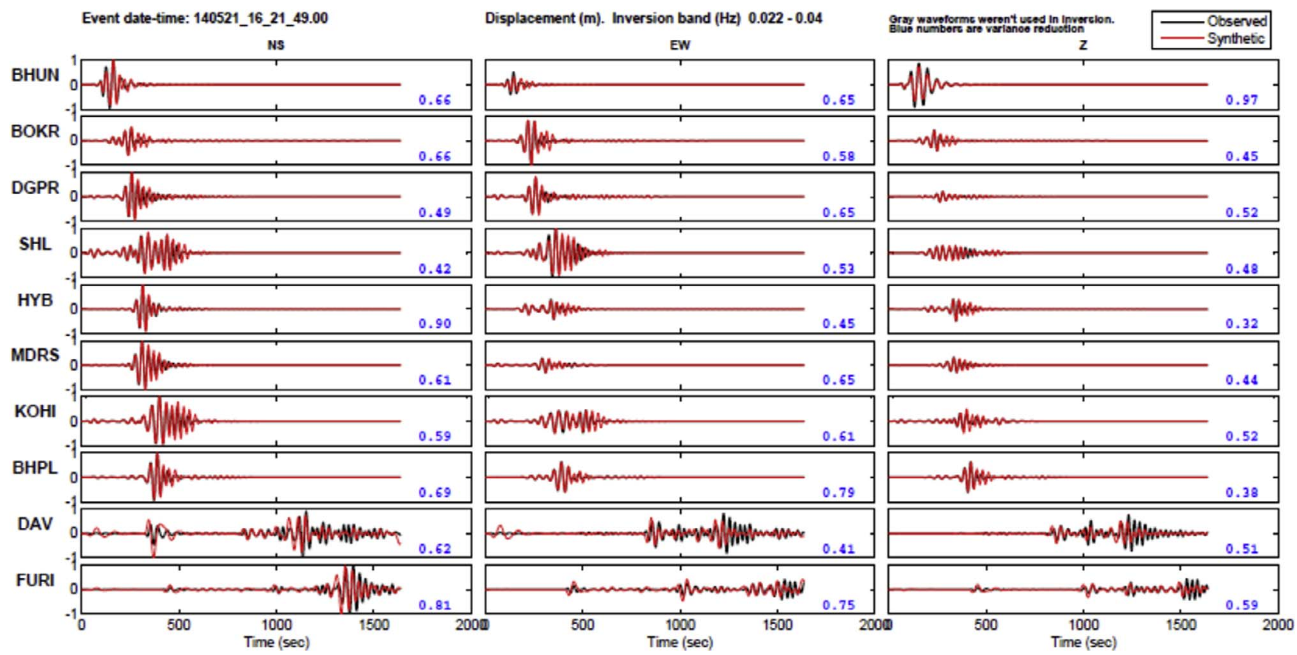


Fig. 2a. Normalized correlation plot between observed (black) and synthetic waveform (red) data. The correlation factor between observed and synthetic data is represented at the right corner of each component inside the box. The waveform was filtered in the frequency band of 0.022–0.040 Hz. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

On the basis of seismic data from near earthquakes recorded at coastal seismological stations around the Bay of Bengal, Verma (1974) found its average crustal structure as 25 km excluding sediments. Brune and Singh (1986) presented the more detailed crustal structure of the Bay of Bengal Fan and found 15 km oceanic crustal thickness increasing to about 25 km near latitude 20°N and over 35 km at its northern part. Later, Brune et al. (1992) proposed a super thick sedimentary basin (about 22 km) under the northern Bay of Bengal using surface wave dispersion, Sn attenuation and geology. The high frequency Sn data indicated a cold upper mantle beneath the Bay of Bengal. Mitra et al. (2008) also found a continent like mantle in the Bay of Bengal with well-marked radial anisotropy.

3. Data and analysis

Seismological data used in this study has been taken from the publications of Pendse (1949), Bulletins of India Meteorological Department (IMD), U.S. Geological Survey (USGS) earthquake catalogue and International Seismological Centre (ISC), U.K.

The fault plane solution was attempted through ISOLA (Sokos and Zahradník, 2008) after constraining the hypocentral location. This code is based on a multiple point source representation and iterative deconvolution method (Kikuchi and Kanamori, 1991; Sokos and Zahradník, 2008). The decomposition in ISOLA for the inversion process namely, volumetric (ISO); compensated linear vector dipole (CLVD) and Double Couple (DC), stipulates that

$$ISO\% + CLVD\% + DC\% = 100\%$$

(Vavrycuk, 2001; Benetatos et al., 2013).

In the present analysis, initially, data from 14 broadband Indian stations (supplementary Fig. S1) including two teleseismic stations (DAV: Philipines and FURI: Ethiopia) was used to model the source parameters of the recent event. The signal to noise ratio was checked initially, to define the proper frequency band for the inversion (Supplementary Fig. S2). To model all the stations in the varying tectonic regions, three different velocity models; Krishna (2004) for the peninsular region, Bhattacharya et al. (2008) for the extra peninsular region and Kennett et al. (1995) for teleseismic stations were used. In order to constrain the depth of the source, the deviatoric point source inversion was carried out for a series of trial source positions lying at various depths below the epicentral location determined by the IMD. A total of 15 trial sources tests with a 5 km vertical separation, spanning from 10 to 80 km depth was undertaken. This type of inversion indicated the preferred centroid depth, which is the first step for moment tensor study. For single source inversion run, frequencies extending from 0.02 to 0.04 Hz with cosine tapering were applied at both the ends. After several iterations, the mismatch was found between observed and synthetic seismograms for Delhi (NDI), Dehradun (DDI), Dharamsala(DHRM) and Gangtok (GTK). Therefore, these stations were excluded from further analysis. A plot of correlation vs DC% is shown in Supplementary Fig. S3. The results were well constrained with 82.1 DC% and maximum correlation of 0.79. The final fault plane solution obtained from inversion of the seismic waveform with their correlation parameter and DC% was plotted and is shown in Fig. 2b. After constraining the depth the multiple source inversion was performed. Usually, this type of inversion is done for large earthquakes using data from teleseismic stations (Sokos and Zahradník, 2008) to reveal more details of the seismic source. In order to run a multiple source inversion, a set of possible source positions need to be defined. In Fig. S4 (Supplementary figure), a map of the trial source positions for the studied event is displayed. In this multiple source inversion run, trial source orientation was taken as strike 226°, dip 81° (Rao et al., 2015) and a reference depth of 60 km (estimated from single source inversion based on the present study). A grid of 90 trial source positions (10 point source along the strike and 9 point source along the dip with a spacing of 0.5 km) was used. Then, using selected frequency band (0.022–0.040 Hz) moment tensor inversion was finally carried out using the data of 10 seismic stations. The correlation between observed and synthetic seismogram was found to be reasonably good as 0.79 (Fig. 2a) with a DC% 82.1 (Fig. 2b). The final focal mechanism showed strike slip movement; one northeast dipping plane with a strike of 341° and 73° dip and the other northwest dipping plane with a strike of 246° and 74° dip. Its details are given in Table 2 along with the focal mechanism estimates by IMD, ISC, Mallick and Rajendran (2016) and Rao et al. (2015) for comparison. The beach balls are also shown in Fig. 1.

Source parameters using Brune's model (1970) were also estimated

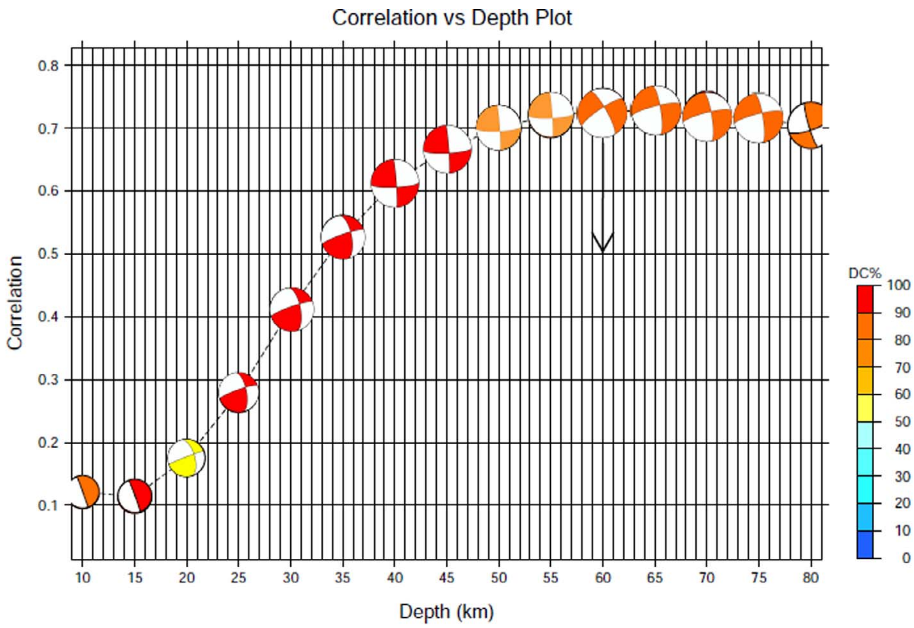


Fig. 2b. Final fault plane solution obtained from inversion of the seismic waveform with their correlation parameters.

from S-wave spectra using data of Indian broadband stations. The S-wave velocity was taken as 4.61 km/s (Bhattacharya et al., 2013) and the density of rocks as 3.1 g/cm^3. The radiation factor and kappa for S-wave were taken as 0.85 and 0.02 respectively. Since the path between the epicentre of the Bay of Bengal earthquake (2014) to the recording stations in India covers mixed oceanic and continental path, Q value needs to be proportionate for the two paths. Singh et al. (2004) suggested a value of 800 for the peninsular India while its value over the oceanic path region in the Bay of Bengal is not known. In view of uncertainty in their values, the commonly global averaged value of 440 for Q was taken. The source parameters estimated for the Bay of Bengal (2014) earthquake are given in Table 3. It may be noted from this table that the average stress drop of the Bay of Bengal earthquake works out as 216 bar. The source spectra of the Bay of Bengal earthquake (2014) from the seismological stations at Bhopal, Bokaro, Chennai, Shillong, and Gangtok are shown in Fig. 3.

4. Seismicity of the Bay of Bengal

The seismicity of the Bay of Bengal (ISC catalogue 1964 to April 2012 updated by USGS data till April 2014) is shown in Fig. 4. It may be noted that the concentration of seismic activity in the Bay of Bengal extends along the eastern boundary of the Indian plate from Andaman and Nicobar islands to Sumatra. The earliest earthquake of very severe intensity in the vicinity of Andaman and Nicobar islands was reported in 1881 (Tandon and Srivastava, 1974). The largest earthquake of magnitude 8.1 in the Andaman region occurred on 26 June 1941 which was followed by many aftershocks. Two large earthquakes occurred in the Nicobar Island and the Andaman Islands on 24 July 2005 (M 7.2) and 10 August 2009 (M 7.5) respectively. Ichikawa et al. (1972) inferred from their focal mechanism solutions that the pressure directions were acting at right angles to the trend of the seismic belt running north to south and tensions intersect obliquely to it. The focal mechanism of these earthquakes suggested thrusting with a small strike slip movement. A well marked deformation of the Indian plate near latitude 7°N, longitude 91°E was shown by normal faulting earthquakes which extended till longitude 94°E before undergoing thrusting. The seismic belt showed two branches north of 10°N (Srivastava and Chaudhury, 1979). One branch extends northwards crossing the India-Myanmar border. The other branch joins the Sagaing fault which is right lateral strike slip type (Ichikawa et al., 1972) and lies between the Indian and Sunda plates. The southern part of this tectonic collision zone extending from Nicobar to Sumatra forms a subduction zone plate boundary which accommodates convergence between the Indo-Australian and Sunda plates giving rise to intense seismicity and mega earthquakes. The largest earthquake in this region occurred on 26 December 2004 (Mw 9.3) which took a toll of about 2,30,000 human lives all-round the Bay of Bengal due to the generation of Tsunami. The Sumatra portion of the Java trench subsided 10–15 m along a 1200 km long rupture plane caused by this mega earthquake. Subsequently, three more great earthquakes occurred on 28 March 2005 (Mw 8.6) and 12 September 2007 (Mw 8.5 and 7.9). The deformed region extended several hundreds of kilometers west of the trench where two large strike slip earthquakes of magnitude 8.6 and 8.2 occurred on 11 April 2012 (Fig. 4). Wei et al. (2013) inferred that these earthquakes apparently reactivated the existing fracture zones and were probably triggered by the unclamping of the great Sumatra earthquake of 2004. It may be noted that some pockets in the continental margin like the Mahanadi and Bengal basins show higher seismicity as compared to the off shore Cauvery and Godavari graben. Within the Bay of Bengal (excluding the Andaman fault zone), seismic activity is widely scattered but shows a relatively larger number of earthquakes along the two ridges near

Table 1
Epicentral parameters of the Bay of Bengal earthquakes near 85°E ridge and neighbourhood.

S. No	Date	O-time (GMT) (hh:mm:ss.s)	Epicentre (°N/°E)	Focal depth (km)	Magnitude	Source
1	24.11.1972	13:19:12.0	11.6/85.4	Normal	Mb 5.4	Chaudhury and Srivastava (1974)
2	30.08.1973	19:50:03.0	7.1/84.3	Normal	Mb 5.9	Chaudhury and Srivastava (1974)
3	21.05.2014	16:21:48.0	18.3/88.0	51	Mw 6.2[a]	IMD
		16:21:53.0	18.1/88.1	59	Mw6.1	ISC
		16:21:49.0	18.276/88.05	60	Mw 6.0	Present Study

[a] 6.18.

Table 2
Focal mechanism parameters of the 21 May 2014 Bay of Bengal earthquake.

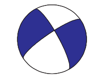
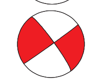
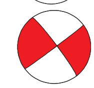
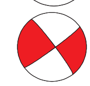
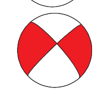
SI No	Date	Str1	Dip1	Rake 1	Str2	Dip2	Rake2	Source	Focal mechanism
1	2014/05/21	341	73	−163	246	74	−18	Present study	
2.		324	81	178	55	88	08	IMD	
3.		323	83	178	53	88	07	ISC	
4.		323	83	174	–	–	–	Mallick and Rajendran (2016)	
5.		226.4	81.9	−14.95	–	–	–	Rao et al., 2015	

Table 3
Source parameters of the 21 May 2014 Bay of Bengal earthquake.

Station component		Mo (dyne cm) 10^{22}	Mw	R(cm) × 10^5	Stress drop (bar)	Corner freq	Ao (cm sec)
Bhopal (BHPL)	Radial	328.34	5.6	1.25E + 03	217.59	0.863	0.0063
	Transverse	1038	6.0	1.25E + 03	542.55	0.825	0.01995
Bokaro (BOK)	Radial	546	5.8	6.56E + 02	285.72	0.825	0.01995
	Transverse	2176	6.20	6.56E + 02	634.15	0.679	0.07943
Madras (MDRS)	Radial	135	5.4	1.03E + 03	32.05	0.633	0.00316
	Transverse	680	5.9	1.03E + 03	98.08	0.537	0.01585
Shillong (SHL)	Radial	187	5.5	8.93E + 02	43.52	0.630	0.0125
	Transverse	469	5.7	8.93E + 02	86.18	0.582	0.0125
Hyderabad (HYD)	Radial	170	5.5	1.02E + 03	117.08	0.904	0.0039
	Transverse	677	5.9	1.02E + 03	335.29	0.810	0.0039
Diglipur (DGPR)	Radial	254	5.6	7.68E + 02	86.64	0.715	0.0079
	Transverse	403	5.7	7.68E + 02	308.06	0.936	0.0126
Gangtok (GTK)	Radial	166	5.4	1.00E + 03	66.41	0.754	0.0039
	Transverse	526	5.8	1.00E + 03	173.87	0.708	0.0126
Average		**553.95**	**5.71**	**9.45E + 02**	**216.22**	**0.742**	**0.015**

Standard deviation Mo – 0.3; stress drop – 0.07; R – 0.0725; f0 – 0.01.

longitudes 85°E and 90°E. The earthquake of magnitude 5.4 in 1972 on the former ridge was widely felt in Tamilnadu (Chaudhury and Srivastava, 1974). Another earthquake of magnitude 5.9 occurred in 1973 almost due south (Table 1). Two more earthquakes on 19 May 1918 (15.9°N, 83.7°E) and 28 August 1964 (12.0°N, 83.4°E) over the 85°E ridge suggest that it is seismically active. The occurrence of another earthquake near 18.0°N, 84.0°E on17 April 1917 further supports the extension of the ridge northwards even though it is buried below the sediments (Ramana et al., 1997). The recent earthquake of 21 May 2014 did not occur over any known tectonic features. But an earthquake of magnitude 6.5 was reported on 21 July 1927 almost south of this earthquake near 15°N latitude (Pendse, 1949). The area south of 10°N is relatively more seismic, possibly due to the readjustment of stresses in the intraplate region caused by the active subduction zone. It may be noted that most of these earthquakes in the Bay of Bengal are shallow focus except near the eastern boundary of the Indian plate extending from the Nicobar to Sumatra island regions.

5. Results and discussion

The focal mechanism solutions of two earthquakes of 1972 and 1973 (Table 1) near the 85°E ridge are shown in Fig. 1 (Chaudhury and Srivastava,1974). The source mechanism solutions of these two earthquakes were also reported subsequently by Bergman and Solomon (1985) and Biswas and Majumdar (1997). It is interesting to bring out the differences in the focal mechanism of these earthquakes with those reported by later workers. Several seismological stations in India are run under river valley and special projects whose data is not reported in ISC/USGS/IMD bulletins. The focal mechanism solutions of these earthquakes therefore made use of larger data of P-wave first motions by Chaudhury and Srivastava (1974), which was not available to later workers. The direction of first motion of P-waves from the original seismograms was also examined by the authors for better control in drawing nodal planes. These well constrained solutions show larger components of strike slip faulting oriented along N/NNE fault instead of thrusting as reported by Bergman and Solomon (1985) and Biswas and Majumdar (1997). However a few focal mechanism solutions by Bergman and Solomon (1985) also show some strike slip movement. As shown in Fig. 1, almost similar focal mechanism solutions for both of these earthquakes suggest a common nodal plane oriented in NNE direction. If this is taken as the fault plane, the solutions indicate strike slip faulting with thrust components dipping at angles ranging from 55° to 70° to the west. Of these two earthquakes, the earthquake of 1972 occurred over the surface manifestation of the 85°E ridge but the earthquake of 1973 was located slightly to its west. However, a closer examination of their epicentres brings out their association with the 85°E ridge and predominantly left lateral strike slip movement. The pressures (compressional) are rather horizontal and directed at an angle

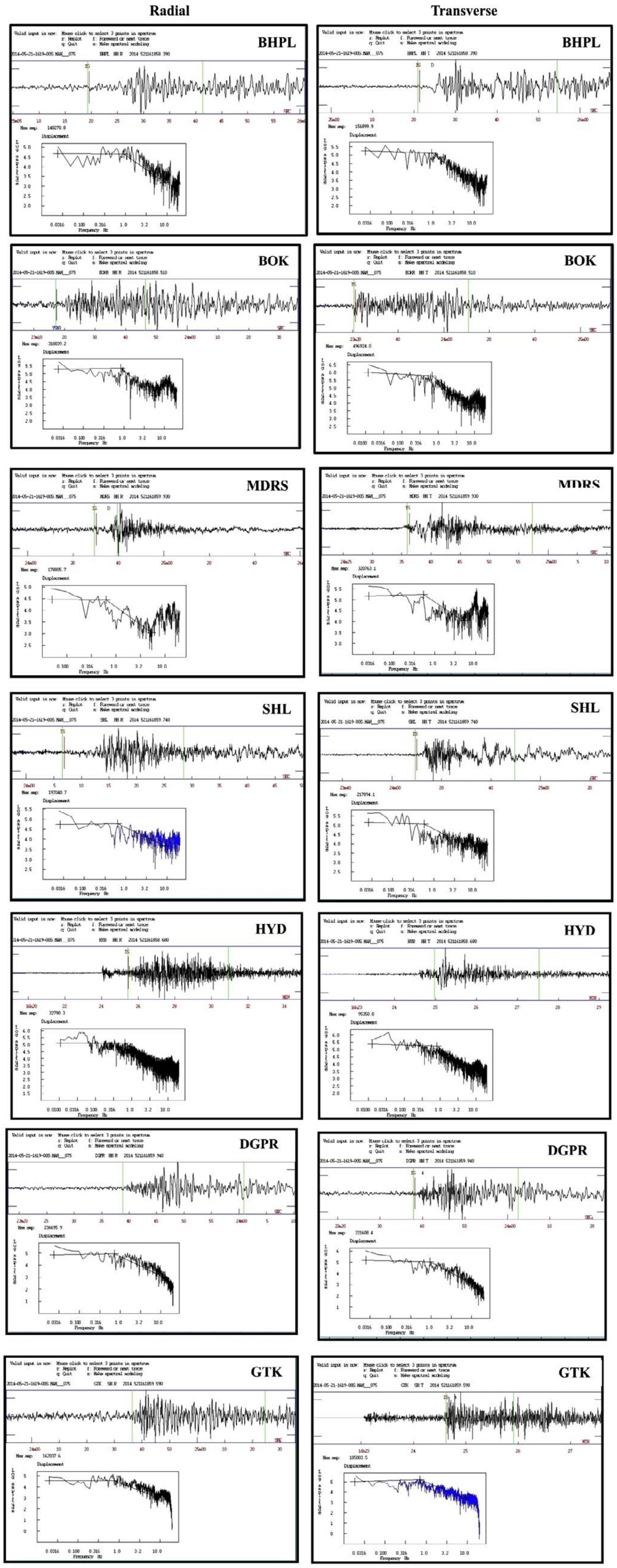


Fig. 3. Spectral analysis of radial and transverse components of Bhopal, Bokaro, Madras, Shillong, Hyderabad, Diglipur and Gangtok seismograms.

of 120° (clockwise) i.e. south-easterly to the strike of the fault/ridge. The focal mechanism of the 25 September 2001 earthquake off the coast of Pondicherry at almost the same latitude as the earthquake of 1972 on the 85°E ridge also showed small strike slip components with left lateral motion along a northeast striking nodal plane although predominant mechanism was thrusting (Murty et al., 2002).

Banghar and Sykes (1969) reported strike slip faulting earthquakes on the 90°E ridge; the slip vector being nearly parallel to the inferred direction of spreading along the southeast branch of the mid- oceanic ridge. Bergman and Solomon (1985) also reported strike slip mechanisms for a few earthquakes with left lateral motion on planes parallel to the ridge. This type of faulting was found from at least 10°S to the northern end of the 90°E, where the ridge meets the Sunda arc. Thus, the earthquakes on the 85°E and 90°E ridges bear marked similarity in the focal mechanism. It may, therefore, be surmised that both the ridges in the Bay of Bengal have strike slip faulting with some thrust components and are moderately seismic.

The centroid CMT solution of the Bay of Bengal earthquake (2014) is shown in Fig. 1. The source parameters of this earthquake as determined by the Harvard, IMD, others and the present study are given in Tables 1 and 2. The results obtained in this study are more refined as compared to Mallick and Rajendran (2016) and Rao et al. (2015) (Table 2). Rao et al. (2015) used 1000 of randomly velocity models to generate the synthetic waveform and obtained a misfit of 41.4% (0.414 normalized errors). They also attempted to refine the location with a finer search of 1 km grid by trial and error method and found its focal depth as 50 km. Mallick and Rajendran (2016) used a similar technique and generated the synthetic waveform of teleseismic stations to estimate the focal depth and fault parameters. However, no discussion was attempted about the variance between DC value and correlation of the modelled waveform. The earlier results could also not well resolve the uncertainties of focal depth so well as compared to the present study. The poor correlation obtained by the earlier authors is attributed to several factors like poor azimuthal coverage and inversion of only P-wave. On the other hand, in the present study, full waveform data with good azimuthal coverage from local and teleseismic stations was used and based on spatial and point source methods, the best seismic source was estimated. The fit between observed and synthetic waveform obtained (Fig. 2b) shows 82.1% DC with a good correlation (~0.79).

Since the combined thickness of crust consisting of sediments and lower basaltic layer does not exceed 30–40 km in the north Bay of Bengal (Brune et al., 1992), it is obvious that this earthquake occurred in the upper mantle. Towards the south of the epicentre of this recent earthquake in 2014, another earthquake of magnitude 6.5 was reported on 21 July 1927 (Pendse, 1949) suggesting that the region is moderately seismic. Considering the seismic activity along the nodal plane oriented NE-SW (Fig. 4), the left lateral strike slip nodal plane is adopted as the fault plane. It is may be clarified that the NW-SE oriented nodal plane chosen by Mallick and Rajendran (2016) based on the aftershocks cannot be accepted as these shocks were not recorded by the IMD, USGS, and ISC. This observation may also be verified from the seismogram of the Bay of Bengal earthquake (2014) recorded at Bhubaneshwar (Supplementary Fig. S5). Our results agree with those of Rao et al. (2015) who also inferred north easterly nodal plane as the main fault plane. The earthquake of 12 June 1987 near the coast of Bangladesh (21.8°N, 89.7°E) which showed pure strike slip motion on either plane (Biswas and Majumdar, 1997) suggested the possibility of extension of the NE oriented fault up to the head Bay. In view of this, the Bay of Bengal earthquake (2014) cannot be associated with the 85°E ridge as inferred by Mallick and Rajendran (2016).

The deeper focal depth of 60 km of the Bay of Bengal earthquake (2014) shows brittle failure nature of the upper mantle in the region. McKenzie and Priestlay (2005) examined the thermal structure of oceanic and continental lithospheres and suggested their mechanical behaviour to depend upon temperature alone. It is well known that temperature dependence of thermal conductivity lowers the

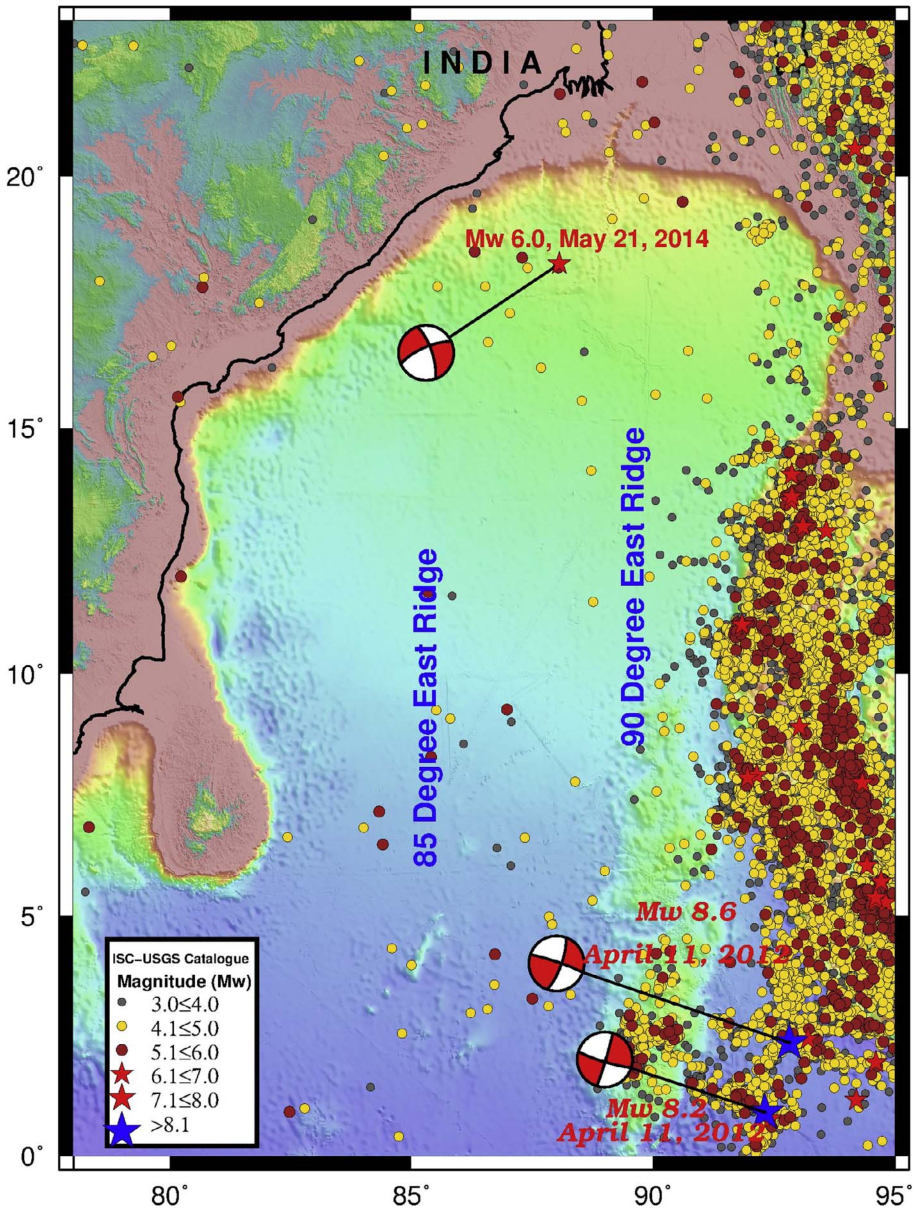


Fig. 4. Seismicity of the Bay of Bengal (ISC catalogue from 1964 to April 2012 and USGS catalogue from 1 May 2012 before 21 May 2014). The Inset shows Indian seismic stations used for waveform inversion. (Green square – stations finally used in analysis; Red square – stations excluded). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature within the oceanic lithosphere. This appears to be supported by the inference of cold lithosphere in the Bay of Bengal (Brune et al., 1992). Thus, the rigidity of rocks increases possibly due to the metamorphic conversion of basalt to eclogite near the source of the recent earthquake.

Allmann and Shearer (2009) reported that the stress drop is 3–5 times higher for strike slip faults as compared to thrust faults. Thus, higher stress drop in the Bay of Bengal earthquake (2014) as compared to similar magnitude thrust type Jabalpur earthquake (1997) in the peninsular India (IMD Report, 1998) is attributed to its strike slip focal mechanism, deeper focal depth and focus in the upper mantle. A question arises, whether the Bay of Bengal earthquake (2014) with focus in the upper mantle could be considered as an intraplate earthquake. Gangopadhyay and Talwani (2003) found that the failed ridge is one of the places where most of the intraplate earthquakes occur. The detailed geophysical investigations have not been carried out in the epicentral region of this earthquake. However, a more quantified approach to distinguish interplate and intraplate earthquakes suggested much larger stress drop for the later (Tandon et al., 2001). Srivastava et al. (2013) also supported this result by comparison of stress drop of Bhuj (2001) and Muzaffarabad (2005) earthquakes, which had same magnitude (Mw 7.6) and thrust type focal mechanism in the intraplate as well as interplate regions of the Indian plate. Keeping this in view, the large stress drop of the Bay of Bengal earthquake (2014) as compared to that of Sikkim earthquake (2011) in the Himalaya region with similar strike slip mechanism and focus in the lower crust/mantle, corroborates it as an intraplate earthquake. However, the stress drop (900 bar) for the Bay of Bengal earthquake (2014) reported by Rao et al. (2015) appears to be overestimated possibly due to the influence of seismic noise at the coastal stations. Such large stress drop for an earthquake has not been reported globally (Mohammadioun and Serva, 2001). The southwest region to the Andaman Sumatra arc also showed several high stress drop intraplate events (Allmann and Shearer, 2009). An apparent variation occurs with lower stress drop near the epicentre of the great Sumatra Andaman earthquake of 2004 and higher stress drops in the north along the Nicobar island chain as well as in the southeast (Allmann and Shearer, 2009). The location of the Bay of Bengal earthquake (2014) about 300 km away from the Andaman-Sumatra subduction zone in the intraplate region with large stress drop is attributed to supercontinents like crust embedded over cold and more rigid upper mantle, strike slip faulting and larger focal depth. The reactivation of this deep seated fault in the northern bay is attributed to the combined influence of stresses transmitted from the collision zone of Indian Eurasian plate boundary in the north as well as in the east. Integrating the source mechanism of the Bay of Bengal earthquakes of 2014 and 1989 (Biswas and Majumdar, 1997) with those of the 85°E and 90°E ridges, it may be inferred that the northern part (above 20°N) of the Bay of Bengal (excluding Andaman Sumatra subduction zone) is characterised by strike slip faulting while the remaining part is characterised by strike slip mechanism with some thrusting particularly over the ridges.

As mentioned earlier, the Bay of Bengal earthquake (2014) was felt over a much larger area as compared to other similar magnitude earthquakes in the peninsular India like Koyna (1965), Killari (1993) and Jabalpur (1997). Martin and Hough (2015) attributed this effect to large stress drop of the Bay of Bengal earthquake. However, Singh et al. (2015) compared strong motion data of the Bay of Bengal earthquake (2014) with that recorded during Jabalpur (1997), Bhuj (2001) and Sikkim (2011) earthquakes and suggested that the influence of the medium through which seismic waves travelled was the predominant cause rather than higher stress drop for such a large felt radius. A comparison of the felt radius of the Bay of Bengal earthquake with the deeper focus Hindukush earthquakes characterised by thrust faulting (Tandon and Srivastava, 1975) brings out that earthquakes of magnitude 5.5 or more in the later region are felt to a lesser distance of about ~1000 km up to Delhi in spite of their high stress drops (Khalturin et al., 1977). It is well known that the transmission efficiency of seismic waves is much less for fractured lithosphere in the Himalayan region due to multiple collisions of the Indian Eurasian plates while even lesser magnitude earthquakes in the peninsular India are felt over a much longer distance (Ramachandran and Srivastava, 1991). Thus, the suggestion of Singh et al. (2015) appears to be more appropriate and may not be attributed to high stress drop as inferred by Martin and Hough (2015). However, detailed geophysical and seismological characteristics of the new fault associated with the 21 May 2014 earthquake needs to be undertaken through various geophysical surveys including the deployment of ocean bottom seismographs.

6. Conclusions

(i) The source mechanism of the 21 May 2014 Bay of Bengal earthquake has shown strike slip faulting with preference for NE oriented nodal plane. The stress drop of this earthquake (216 bar) is much less as compared to that reported by Rao et al. (2015). Relatively large stress drop of this earthquake in the Bay of Bengal is attributed to its occurrence in the intraplate region, strike slip faulting and focus in cold upper mantle. The focal depth of this earthquake source is estimated as 60 km.

(ii) The seismological characteristics of the 85°E and 90°E ridges are broadly similar with predominantly left lateral strike slip motion and smaller thrust components. Also, earthquakes up to magnitude 6 have occurred on both the ridges. In view of this, these two ridges can no longer be described as aseismic.

(iii) Contrary to the earlier results, the northern portion (north of 20°N) of the Bay of Bengal (excluding Andaman-Sumatra subduction zone) is characterised by strike slip faulting and remaining portion as strike slip with thrust components.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2017.10.030.

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