Comparison of earthquake source characteristics in the Kachchh Rift Basin and Saurashtra horst, Deccan Volcanic Province, western India

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MS received 2 March 2017; revised 3 October 2017; accepted 8 October 2017; published online 23 May 2018

Seismic source parameters of small to moderate sized intraplate earthquakes that occurred during 2002–2009 in the tectonic blocks of Kachchh Rift Basin (KRB) and the Saurashtra Horst (SH), in the stable continental region of western peninsular India, are studied through spectral analysis of shear waves. The data of aftershock sequence of the 2001 Bhuj earthquake (M_w 7.7) in the KRB and the 2007 Talala earthquake (M_w 5.0) in the SH are used for this study. In the SH, the seismic moment (M_o), corner frequency (f_c), stress drop ($\Delta\sigma$) and source radius (r) vary from 7.8×10^{11} to 4.0×10^{16} N-m, 1.0–8.9 Hz, 4.8–10.2 MPa and 195–1480 m, respectively. While in the KRB, these parameters vary from $M_o \sim 1.24 \times 10^{11}$ to 4.1×10^{16} N-m, $f_c \sim 1.6$ to 13.1 Hz, $\Delta\sigma \sim 0.06$ to 16.62 MPa and $r \sim 100$ to 840 m. The kappa (K) value in the KRB (0.025–0.03) is slightly larger than that in the SH region (0.02), probably due to thick sedimentary layers. The estimated stress drops of earthquakes in the KRB are relatively higher than those in SH, due to large crustal stress concentration associated with mafic/ultramafic rocks at the hypocentral depths. The results also suggest that the stress drop value of intraplate earthquakes is larger than the interplate earthquakes. In addition, it is observed that the strike-slip events in the SH have lower stress drops, compared to the thrust and strike-slip events.

Keywords. Stress drop; seismic moment; focal mechanisms; seismotectonics.

1. Introduction

The Kachchh Rift Basin (KRB) and Saurashtra Horst (SH) in the northwestern Deccan Volcanic Province (NWDVP) of India, experienced several moderate to major intraplate earthquakes over a period of less than 200 years (Rao and Rao 1984; Rajendran and Rajendran 1999, 2001; Gupta *et al.* 2001; Singh *et al.* 2015; Singh and Mishra 2015). The devastating 2001 Bhuj earthquake (M_w 7.7) in the KRB and the earthquakes of M_w 5.0 and 5.1 in the SH that occurred during the years 2007

and 2011 (Yadav *et al.* 2011; Singh *et al.* 2013; Singh and Mishra 2015) renewed the interest of researchers in understanding the seismotectonic settings of these two seismically active regions. In fact, the KRB has been recognized as one of the most active intraplate seismic regions of the world (Talwani and Gangopadhyay 2001; Kayal *et al.* 2002; Rastogi *et al.* 2014; Singh *et al.* 2015). The region has been classified as the highly vulnerable seismic zone V, on the seismic zoning map of India (BIS 2002). On the other hand, the Saurashtra region is classified as a seismically active zone III.

The 2001 Bhuj earthquake has been considered as the largest intraplate earthquake that occurred in the era of modern seismology. Several researchers suggested that the Bhuj earthquake was generated due to fluid filled fractures rock matrices at the depth of 20–25 km (e.g., Kayal *et al.* 2002; Negishi *et al.* 2002; Mishra and Zhao 2003; Mandal *et al.* 2004b; Mandal and Pujol 2006; Sastry *et al.* 2008; Naganjaneyulu *et al.* 2010; Singh *et al.* 2012, 2017). Aftershocks of this earthquake having magnitudes up to M_w 5 have continued for over a decade. Also, several triggered earthquakes of $M_w \geq 5.6$ occurred along different faults in Kachchh, the distant one being about 75 km from the mainshock epicenter (Mandal *et al.* 2007). On the other hand, the SH, which is a different tectonic province, has also been experiencing intermittent tremor activity at some places, during the last two centuries (Srivastava and Rao 1997; Singh *et al.* 2017).

It has now been established that the intracratonic seismicity in the KRB is associated with the E–W trending failed rift basin (Biswas 2005) that is underlain by a Precambrian basement. The rift basin is bounded by two major faults, the E–W trending Nagar Parkar Fault (NPF) in the north and the ENE–WSW trending North Kathiawar Fault (NKF) in the south (Biswas 2005). This basin is experiencing inversion tectonics under a compressional stress regime due to the northward movement of the Indian plate. The seismicity within the rift basin is fault controlled. On the other hand, the seismotectonics of the SH is hitherto less studied. In contrast to Kachchh, the seismicity in Saurashtra is confined within a horst structure, which is bound by faults on all sides. The southern fringe is bound by the extended Narmada–Son Fault (NSF), the northern boundary by the NKF, the western boundary by the WNW–ESE trending West Coast Fault (WCF) and the eastern one by the extension of WCF. The focal depths of the 2007 and 2011 Talala earthquakes are shallower than 20 km (Singh *et al.* 2015). Additionally, the SH is associated with episodic swarm activity with reports of sounds at several places such as Lalpur, Kalawad, Chotila, Botad, Chobari, Surendranagar and Ankolvadi in the NWDVP, Gujarat (Chopra *et al.* 2008a; Singh *et al.* 2017). The KRB and the SH, that are adjacent to each other exhibit remarkably distinct tectonic characteristics. In this context, it is interesting to compare the source parameters (SPs) of small to moderate earthquakes

recorded by a very dense network of broadband seismic stations.

Aki (1967) and Brune (1970) proposed a procedure to quantify the size of an earthquake. They modeled the average displacement spectrum of an earthquake with three independent parameters, the low-frequency spectral flat level (Ω_o), high-frequency spectral decay (typically ω^{-2}) and corner frequency (f_c). Although, several methods are used to study the earthquake source parameters, time-domain modeling of waveform amplitudes and source time functions (Langston and Helmberger 1975; Cohn *et al.* 1982), analysis of the spectra of P, S or surface waves (Aki 1967; Brune 1970; Hanks and Kanamori 1979; Fletcher *et al.* 1984) are commonly employed. The spectral parameters (Ω_o and f_c) may be used to estimate other SPs like seismic moment (M_o), stress drop ($\Delta\sigma$) and source radius (r). Corner frequency (f_c) is related to the dimension of the fault and Ω_o is related to M_o . It is well known that $\Delta\sigma$ represents difference between the initial and final stress present on the surface of a shear dislocation is a significant source parameter associated with M_o (Aki 1967; Brune 1970).

Earthquake SPs are important to understand the seismotectonics of a region (Abercrombie and Leary 1993; Chung 1993; Chung and Gao 1995; Akinci *et al.* 2013), assess the seismic hazard associated with a seismically active region (e.g., Lee *et al.* 2003; Kumar *et al.* 2015) and simulate the ground motion for a given magnitude (Boore 2003), where actual seismograms are not available. Earlier studies based on SPs are mainly restricted to the moderate to large size earthquakes (e.g., Negishi *et al.* 2002; Bodin and Horton 2004; Singh *et al.* 2004) and small earthquakes in the 2001 Bhuj source zones (e.g., Mandal and Johnston 2006; Mandal and Dutta 2011; Saha *et al.* 2012; Rapolu and Mandal 2014; Kumar *et al.* 2014, 2015; Trivedi and Parvez 2015; Nagamani and Mandal 2017). The results revealed that the mainshock is associated with a higher stress drop than those along the plate boundaries. The upper bound value of stress drop of earthquakes in the study regions is roughly equal to the Bhuj mainshock (table 1). However, the SPs of small earthquakes vary significantly, in all the studies (table 2). The variation of parameters could be due to the different size of earthquakes and the limited events recorded during restricted time-periods. Nagamani and Mandal (2017) argued that the static stress drop values are higher than the apparent stress drop values. Based on waveform modeling, Mandal and

Table 1. Earthquake source parameters of the 2001 Bhuj mainshock (M_w 7.7).

Stress drop ($\Delta\sigma$) MPa	Seismic moment (M_o) N-m	Source radius (r)	Rupture area (km^2)	References
20	—	—	—	Antolik and Dreger (2003)
12.6–24.6	4.5×10^{20}	20–25 km	—	Negishi <i>et al.</i> (2002)
16 ± 2	$(2.3\text{--}3.6) \times 10^{20}$	—	1300 km^2	Bodin and Horton (2004)
20	3.4×10^{20}	—	—	Singh <i>et al.</i> (2004)

Table 2. Estimated earthquake source parameters in the Kachchh Rift Basin by earlier studies.

M_w	Stress drop, $\Delta\sigma$ (MPa)	Seismic moment, M_o (N-m)	Source radius, r (m)	Corner frequency (Hz)	References
2.16–5.74	0.63–20.7	1.95×10^{12} – 4.5×10^{17}	239–2835	0.9–11.0	Mandal and Johnston (2006)
2.93–5.32	0.11–7.44	3.1×10^{13} – 2.0×10^{17}	226–889	1.7–6.75	Mandal and Dutta (2011)
1.7–5.6	0.13–26.7	3.55×10^{11} – 2.84×10^{17}	107–1515	1.3–11.83	Rapolu and Mandal (2014)
3.3–4.9	3.2–13.6	1.02×10^{14} – 3.4×10^{16}	233–857	2.11–6.51	Kumar <i>et al.</i> (2014)
2.05–5.52	0.1–14.4	1.5×10^{12} – 2.4×10^{17}	139.1–933.9	1.4–9.3	Kumar <i>et al.</i> (2015)
3.5–5.7	6.84–29.98	2.0×10^{14} – 6.3×10^{17}	168–2100	0.62–8.18	Trivedi and Parvez (2015)

Johnston (2006) found that the values of M_o show scatter above $10^{14.5}$ N-m for the Bhuj aftershocks. Kumar *et al.* (2014) studied the SPs of 34 earthquakes of M_w 3.3–4.9 in the KRB, recorded by a network of Strong Motion Accelerographs (SMA). Their estimates of $\Delta\sigma$ values lie in the range 30–120 bars. Usually, the stress drop values for higher magnitude events are scattered in nature and more systematic for smaller events (Mandal and Johnston 2006). In the KRB, earthquakes are associated with all types of focal mechanisms; reverse faulting with a minor strike-slip component being the dominant one (Mandal 2008; Singh *et al.* 2016). In the SH, most of the earthquakes have strike-slip mechanisms (Singh *et al.* 2015).

In the present paper, our major goal is to understand the seismotectonics of the two geologically distinct contiguous regions. Improved data quality due to the dense seismological network has provided an opportunity to estimate the SPs and fault plane solutions and to gain new insights on the seismotectonics and earthquake generating processes, which we highlight in this paper.

2. Geology and seismotectonics

Gujarat is a western state of India, which covers an area of approximately 200,000 km^2 (500×400 km) between 20.0° – 24.5° N latitude and 68.0° – 74.5° E longitude. The Gujarat state consists of three distinct zones: Saurashtra, Mainland Gujarat

and Kachchh (figure 1a). The structural setting of Gujarat is controlled by two major Precambrian orogenic trends, i.e., the NE–SW Aravalli and the ENE–WSW Satpura trend. Reactivated movements along these trends gave rise to three important rift basins: (1) the Kachchh basin, (2) the Cambay basin, and (3) the Narmada basin (Merh 1995; GSI 2001).

The Kachchh and Saurashtra regions have distinct geological settings. The E–W oriented, slightly southerly tilted KRB is a half-graben structure. However, the entire basin can be viewed as an assembly of several sub-basins bound by the E–W oriented uplifts along several major faults, such as NPF, Island Belt Fault (IBF), Kachchh Mainland Fault (KMF), South Wagad Fault (SWF) and NKF and the plains in between (Biswas 1987). The block step faulting within the basin is a major structural feature that is indicative of compressional tectonics within the basin.

The horst structure of the southwest tilted Saurashtra peninsula is a quadrangular block, which is bound on all four sides by major tectonic boundaries (figure 1a). The western boundary fault, sub-parallel to the Dharwar trend in the east, cuts across the Saurashtra Arch, which extends to the southwestern fringe of the peninsula. The NNW–SSE trending Cambay graben and the extension of NNE–SSW trending Delhi–Aravalli trend within the peninsula are the major tectonic features. The Saurashtra peninsula is relatively flat and mostly covered with Deccan lava flows,

Figure 1. (a) Map showing major tectonic features and past earthquakes with Centroid-moment tensor (CMT) solutions in the study region. Geologically mapped major faults in the Kachchh region are the following: NPF: Nagar Parkar Fault, ABF: Allah Bund Fault, BF: Banni Fault, KMF: Kachchh Mainland Fault, NKF: North Kathiawar Fault, SWF: South Wagad Fault, GF: Gedi Fault, IBF: Island Belt Fault, and the NWF: North Wagad Fault. Triangles show the broadband seismic stations with their station code. Dotted red lines show the seismic zones II–V (BIS 2002). Inset: Location map of the study region. (b) Epicenters of earthquakes in the Kachchh Rift Basin during 2001–2011. Green star shows the 2001 Bhuj Earthquake (M_w 7.7). (c) Same as figure (b), but for Saurashtra and Mainland Gujarat.

albeit the presence of sedimentary sequences from Mesozoic and Quaternary in the northern and southern fringes (Merh 1995; Sheth *et al.* 2012). Other rock types within the Deccan volcanics are intrusive in the form of volcanic plugs and dike swarms; the major intrusive being the Mount Girnar complex (Paul *et al.* 1977). Using LANDSAT imagery and aerial photography data, Ramasamy (1995) reported existence of several east–west trending lineaments, radiating dike swarms, several Z-shaped, and S-shaped drag folds in the southeastern part of the Saurashtra peninsula.

3. Data

The Institute of Seismological Research (ISR) is operating a seismic network in Gujarat since August 2006 (figure 1a; Chopra *et al.* 2008b). The network comprises broadband seismographs (BBS) as well as Strong Motion Accelerographs (SMA). Sixty seismic stations are equipped with CMG 3T broadband sensors (BBS) connected to 24-bit CMG–DM24 Guralp digitizers. The digitizers are synchronized with GPS system for time logging. The BBS data are transmitted through VSAT to the ISR's central station at Gandhinagar, Gujarat.

In the KRB, the aftershock activity of the 2001 Bhuj earthquake is continuing, with the occurrence of several moderate earthquakes (figure 1b). Besides the aftershock activity, several fold increase in seismicity along many other faults in KRB and SH could be due to stress perturbation caused by the 2001 Bhuj mainshock. However, the seismicity has not increased relatively along the Cambay Basin or Narmada zone or in other parts of the Mainland (Rastogi *et al.* 2014). In the SH, it is observed that seismicity (figure 1c) mostly follows heavy rainfall during the Indian summer monsoon (Singh *et al.* 2015). In this study, we used about 250 (M_w 1.6–5.0) events that occurred in the SH during 2006–2007 and 450 (M_w 1.3–4.8) events from KRB during 2002–2009. In addition, data of about 300 early aftershocks during August 2002–November 2004 recorded by the National Geophysical Research Institute (NGRI) Seismic Network consisting of eight BBS and ten SMA (Mandal *et al.* 2006; Sairam 2012) are also used. The seismographs recorded data in a continuous mode at 100 sps, while the accelerographs have been operated in a trigger mode with a sampling frequency of 200 Hz and a trigger level of

0.00195 gal. However, the NGRI network is confined to the KRB only.

The seismic noise levels are estimated for all the seismic stations in terms of the power spectral density (figures 2–6) and compared with the new global high and low noise models (Peterson 1993). Our calculations show that the day and night-time noise levels are similar, without varying with the time of the day. This is because our seismic stations are away from artificial noise sources like traffic, industrial and cultural noise. The noise levels at hard rock sites are found to be smaller in comparison to those of soft rock or sediment sites (figures 2–6). The noise levels at the Quaternary sediment sites are found to be larger compared to those at sites located on other geological formations. The Deccan trap sites show lesser noise levels, while sites on Jurassic, Cretaceous, and Tertiary formations show moderate noise levels. An earlier study by Kumar *et al.* (2012) using data from 14 broadband seismic stations revealed that stations on soft soils are noisier. A careful comparison between the previous seismic noise level analysis based on data from limited stations and the present analysis with larger amount of data recorded by more seismograph stations for longer duration, provides detailed information about the background noise level of the Gujarat seismic network. The current results can be used to evaluate the quality of data at the seismic stations and estimate the threshold magnitude detection capabilities.

4. Methodology

4.1 Estimation of source parameters

In this study, spectral analysis of the transverse component waveforms (S_H) is performed using the SEISAN software (Havskov and Ottemoller 1999), to estimate the SPs of earthquakes in the KRB and SH regions. The Fast Fourier Transform is utilized to compute displacement spectra of the instrument corrected S_H -wave data, which are subsequently accounted for the near-surface attenuation (K value), geometrical spreading and inelastic attenuation effects. A frequency dependent $Q = 102f^{0.98}$ (Mandal *et al.* 2004a) is used to correct for the inelastic attenuation effects. Subsequently, the low-frequency levels and high-frequency spectral decays are determined by fitting

Figure 2. Estimated seismic noise levels at broadband seismograph (BBS) stations on Quaternary sediments. The BBS stations are CHO: Chobari; DUD: Dudhai; GAN: Gandhinagar; JAG: Jhagadia; LKD: Lakadiya; RAD: Radhanpur and VAD: Vadodara.

Figure 3. Estimated seismic noise levels at BBS stations on Cretaceous rocks. The BBS stations are DES: Deshalpar; SUR: Surendranagar; TAP: Tapar and VAM: Vamka.

Figure 4. Calculated seismic noise levels at BBS stations on tertiary rocks. The BBS stations are DWK: Dwarka; MTP: Madhapar and SUV: Suvai.

Figure 5. Seismic noise levels at BBS stations on Deccan traps rocks. The BBS stations are AMR: Amerali; BHV: Bhachau; MTR: Matapar; RAJ: Rajkot; SIP: Sipu; UKA: Ukai; UNA: Una and VAL: Valsad.

Figure 6. Seismic noise levels at BBS Stations on Jurassic rocks. The BBS stations are BAD: Badalgarh; DHV: Dholavira; KAV: Khavda; LOD: Lodrani and NGR: Nagor.

of two straight lines to the spectra, in a logarithmic form, i.e., ω^{-2} source spectra (Brune 1970). The corner frequency is obtained from the intersecting point of these two straight lines. Samples of typical displacement spectra are shown in figures 7 and 8.

Following Brune (1970) circular source model, the observed displacement spectrum for an epicentral distance (d) and hypocentral depth (h) can be written as:

$$d(f) = A(r, h) * D(f) * \frac{M_o * R_{\theta\theta}}{4 * \pi * \rho * \beta^3 [1 + (f^2/f_c^2)]} \quad (1)$$

where f_c is the corner frequency, M_o is the seismic moment, and r is the hypocentral distance, $R_{\theta\theta}$ is the mean radiation pattern factor (0.55), ρ (2700 kg/m³) is the density, β is the S-wave velocity (3600 m/s) and $A(r, h)$ is the geometrical spreading. Since geometrical spreading depends on the hypocentral distance r and depth h , the spreading effects are accounted using the relations of $A(r, h) = 1/r$ for $r < 100$ km and $A(r, h) = 1/(100 * r)^{1/2}$ for $r > 100$ km (Herrmann and Kijko 1983; Herrmann 1985). According to

Brune's (1970) circular source model, $D(f)$ is the diminution function due to inelastic attenuation that can be written as:

$$D(f) = P(f) * \exp\left(-\frac{\pi * f * t}{Q(f)}\right) \quad (2)$$

where $P(f) = \exp(-\pi * \kappa * f)$ is meant for near-surface attenuation (Singh et al. 1982). The inelastic attenuation parameter $Q(f)$ accounts for attenuation of seismic waves along the travel path. $Q(f)$ can be written in terms of frequency dependent quality factor (Q_0) as $Q(f) = Q_0 f^n$. In this study, a frequency dependent relation, $Q(f) = 102 * f^{0.98}$ (Mandal et al. 2004a) is used for correcting the attenuation effects.

The calculated S-wave displacement spectrum can be written as:

$$\begin{aligned} D(f, t) &= \frac{\Omega_o}{[1 + (f^2/f_c^2)]} \\ &= \frac{M_o * F * R_{\theta\theta}}{4 * \pi * \rho * R * \beta^3 * \left[1 + \frac{f^2}{f_c^2}\right]}. \end{aligned} \quad (3)$$

This spectrum is used to obtain low-frequency amplitude level (Ω_o) and corner frequency (f_c).

Figure 7. Estimated S_H -wave spectra of an earthquake magnitude of 5.0, which occurred on November 6, 2007 in the Saurashtra Horst. SPs of this earthquake are estimated at eight BBS stations.

Figure 8. Estimated S_H -wave spectra at different seismic stations for an earthquake magnitude of 4.2, which occurred on March 1, 2008 in the KRB.

Then, the other SPs are estimated from the following relations

$$\begin{aligned} \text{Seismic moment } (M_o) \\ = \frac{4\pi\rho R\beta^3}{FR_{\theta\theta}}\Omega_o \quad (\text{Brune 1970}) \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Source radius } (r) \\ = (0.37 \times \beta) / f_c \quad (\text{Brune 1970}) \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Stress drop } (\Delta\sigma) \\ = \frac{7}{16} \times \frac{M_o}{r^3} \quad (\text{Borok 1959}) \end{aligned} \quad (6)$$

$$\begin{aligned} M_w = \frac{2}{3} \times \log_{10}(M_o) - 6.06 \\ (\text{Hanks and Kanamori 1979}) \end{aligned} \quad (7)$$

where f_c is in Hz, r is in m, M_o is in N-m, $\Delta\sigma$ is in MPa and F is the free surface effect, whose value is chosen as 2.

4.2 Error estimation of source parameters

The uncertainties in the SPs estimates are studied by calculating the mean and standard deviation of f_c , M_o , and $\Delta\sigma$ (table 3). In our study, the average values of f_c , M_o , and $\Delta\sigma$ for each earthquake are estimated following the formula of Archuleta *et al.* (1982)

$$\bar{x} = \text{antilog} \left(\frac{1}{n} \sum_{i=1}^n \log x_i \right) \quad (8)$$

where the variable x is f_c or M_o .

The average source radius ($\bar{r}$) is determined utilizing the following equation

$$\bar{r} = \frac{1}{n} \sum_{i=1}^n r_i \quad (9)$$

where n is the number of seismic stations.

The standard deviation can be estimated utilizing the following equation

$$sd(\log \bar{x}) = \left(\frac{1}{n-1} \sum_{i=1}^n [\log x_i - \log \bar{x}]^2 \right)^{1/2} \quad (10)$$

where the variable ' x ' is f_c or M_o .

The multiplicative error factor Ex can be determined following the formula of Archuleta *et al.* (1982)

$$Ex = \text{antilog}\{sd[\log(x)]\}. \quad (11)$$

Table 3. Estimated source parameters of earthquakes in the Kachchh Rift Basin and Saurashtra horst in the present study.

M_w	$\Delta\sigma$ (MPa)	Standard deviation of $\Delta\sigma$	M_o (N-m)	Standard deviation of M_o	r (m)	Standard deviation of r (m)	f_c (Hz)	Standard deviation of f_c (Hz)	Study regions
1.3–4.8	0.06–16.62	0.10–3.42	1.24×10^{11} – 4.1×10^{16}	0.05–0.28	100–840	6–75	1.6–13.1	0.1–0.6	Kachchh rift basin
1.6–5.0	4.8–10.2	0.02–2.32	7.8×10^{11} – 4.0×10^{16}	0.1–0.31	195–1480	2–45	1.0–8.9	0.03–0.4	Saurashtra horst

Finally, the standard deviation of $\Delta\sigma$ is estimated following the scheme of [Fletcher et al. \(1984\)](#) utilizing the equation

$$\sigma_{\text{std}} = \Delta\sigma \left\{ \left[\left(\frac{\sigma_m}{M_o} \right)^2 + 9 \left(\frac{\sigma_r}{r} \right)^2 \right] \right\}^{1/2} \quad (12)$$

where σ_{std} , σ_r and σ_m are the standard deviations of $\Delta\sigma$, r and M_o , respectively.

4.3 Empirical relationships for the study regions

Empirical relations for M_o vs. f_c , M_o vs. r , and M_o vs. $\Delta\sigma$, for both KRB and SH regions, were obtained by leastsquare fitting (figure 9a–d; equations 13–21). For the KRB, these relationships are obtained for different sets of magnitude ranges, viz., for M_w 1.5–3.8 and for $M_w \geq 3.9$, since events of this region show a gap at about M_w 3.8.

Empirical relationships for the SH region

$$\log_{10} M_o = 16.82 - 5.39 \log_{10} f_c \quad (13)$$

$$\log_{10} M_o = 4.13 \log_{10} r + 2.32 \quad (14)$$

$$\log_{10} \Delta\sigma = 0.62 \log_{10} M_o - 8.63. \quad (15)$$

Empirical relationships for the KRB region for M_w 1.5–3.8

$$\log_{10} M_o = 20.64 - 8.26 \log_{10} f_c \quad (16)$$

$$\log_{10} M_o = 6.95 \log_{10} r - 2.2 \quad (17)$$

$$\log_{10} \Delta\sigma = 0.59 \log_{10} M_o - 7.57. \quad (18)$$

Empirical relationships for the KRB region for $M_w \geq 3.9$

$$\log_{10} M_o = 16.95 - 3.77 \log_{10} f_c \quad (19)$$

$$\log_{10} M_o = 2.78 \log_{10} r + 7.8 \quad (20)$$

$$\log_{10} \Delta\sigma = 0.09 \log_{10} M_o - 0.4. \quad (21)$$

4.4 Estimation of focal mechanisms

The Isolated Asperity (ISOLA) software is used for performing moment tensor inversion modeling of the broadband waveforms of local and regional earthquakes ([Sokos and Zahradnik 2008](#)). ISOLA uses the iterative deconvolution scheme for multiple point sources, developed by [Zahradnik et al. \(2005\)](#). This method is based on an extension of the Kikuchi and Kanamori's (1991) method for local and regional earthquakes. In this method,

the Green's functions are computed at local and regional distances using the discrete wave number method of [Bouchon \(1981\)](#) and [Coutant \(1989\)](#). Thus, the method is appropriate for local as well as regional earthquakes. Primarily, a set of point source positions along a line are studied. Subsequently, the contribution from a main point source or sub-event is obtained and then the corresponding synthetics are subtracted from the data. Next, the residual waveform is inverted for another point source, and so on ([Zahradnik et al. 2005](#)). As the optimum source position of each sub-event is also to be retrieved, this makes the technique nonlinear. However, because the point sources are removed consecutively, one after another, each step has only two unknown parameters (source position and onset time), thus, contributing to the stability of the inversion ([Zahradnik et al. 2005](#)).

In the ISOLA software, a grid search in the area of the accurately located hypocenter is used to obtain the best position and origin time. The grid search provides the optimum sub-event position and time in terms of the absolute value of the correlation coefficient between the observed data and synthetics, which is calculated automatically during the least square inversion ([Dimri 1992](#); [Zahradnik et al. 2005](#)). On the best-fitting spatial-temporal position, the match between the observed and synthetic data is characterized by the overall variance reduction (over all stations and components) ([Zahradnik et al. 2005](#); [Mandal et al. 2009](#)).

We used band pass filtered (0.01–5.0 Hz) and instrumentally corrected velocity records as inputs for the ISOLA code. First, ISOLA integrates the input data for estimating the band-passed displacement, which is then used as input for moment tensor inversion. A four point band pass filter (0.05:0.055:0.08:0.1) is used for both observed and synthetic data. The amplitude response of this filter is flat between 0.025 and 0.08 Hz and cosine tapered between 0.05–0.055 and 0.08–0.1 Hz. The phase response of the filter is zero. It is important to note that all solutions obtained using ISOLA are close to the first approximation ([Zahradnik et al. 2005](#)).

Next, the instrumental corrections on the broadband seismograms are applied using an in-built utility in the ISOLA computer code. Finally, the corrected velocity traces from the origin time to 250 s, filtered between 0.01 and 5.0 Hz using a 4-pole band pass Butterworth filter, are later integrated to displacement. Finally, these displacement

Figure 9. Plotted SPs of the KRB and the SH regions between (a) f_c and M_w , (b) f_c and M_o , (c) M_o and $\Delta\sigma$, (d) r and M_o , (e) depth-wise distribution of stress drops. The large $\Delta\sigma$ values, mostly confined in 15–30 and 3–8 km depths, respectively in the KRB and SH.

traces are used as input data for the full waveform moment tensor inversion, using the velocity model of Mandal *et al.* (2006) for Green's function calculation.

In general, the seismic moment tensor is used to define the source mechanism of an earthquake. A moment tensor can then be decomposed into the isotropic and deviatoric parts. The isotropic part corresponds to a volume change in the source. The deviatoric part can be decomposed in turn into a Compensated Linear Vector Dipole (CLVD), accounting for non-elastic volume changes and a Double Couple (DC), describing elastic volume changes in the source. Isotropic represents the constant background stress level, while deviatoric represents perturbation in the stress regime.

5. Results and discussion

The SPs of earthquakes in the KRB and SH regions demonstrate that these two tectonic blocks have varied SPs (table 3). In the SH, the values of M_o , f_c , $\Delta\sigma$ and r for earthquakes of M_w 1.6–5.0 vary from 7.8×10^{11} to 4.0×10^{16} N-m, 1.0 to 8.9 Hz, 4.8 to 10.2 MPa and 195 to 1480 m, respectively (table 3; figure 9a–e). The 'K' value is estimated to be about 0.02. Estimated standard deviations of $\Delta\sigma$ and error factors of the M_o and f_c for $M_w \geq 3.5$ are listed in tables 3 and 4. The standard deviation of f_c varies from 0.03 to 0.4 Hz; r from 2.0 to 45.0 m (table 3). The estimated error factor of M_o ranges from 0.1 to 1.9 (table 4). The estimated standard deviations of $\Delta\sigma$ lie in the range of 0.02–2.32 MPa (table 4). The low standard deviations indicate that the estimated SPs are statistically well estimated. In the SH region, the magnitude dependency of f_c , $\Delta\sigma$, M_o and r can be seen from the relations between f_c vs. M_w , $\log_{10}(M_o)$ vs. $\log_{10}(\Delta\sigma)$, and $\log_{10}(r)$ vs. $\log_{10}(M_o)$, respectively (figure 9a–e, equations 13–21). The earthquake hypocenters are mainly confined to a depth range of 3–20 km. However, higher $\Delta\sigma$ (>2.0 MPa) values are found for earthquakes that occurred in the depth range of 3–10 km; $\Delta\sigma \sim 9.3$ MPa for an earthquake of M_w 4.9 and $\Delta\sigma \sim 10.2$ MPa for M_w 5.0, which suggests that the seismogenic layer is in the depth range of 3–10 km in the SH, which is also supported by previous studies (Yadav *et al.* 2011; Singh *et al.* 2015).

In the KRB region, the estimated M_o , f_c , $\Delta\sigma$ and r for the aftershocks in the range of M_w 1.3–4.8 vary from 1.24×10^{11} to 4.1×10^{16} N-m,

1.6–13.1 Hz, 0.06–16.62 MPa and 100–840 m, respectively (figure 9a–e). The estimated standard deviations of f_c , r and $\Delta\sigma$ are in the range of 0.1–0.6 Hz, 6–75 m and 0.1 to 3.42 MPa, respectively (table 3). The error factor of M_o estimates are found to be between 1.0 and 1.87 (table 4). The K value is found to be in the range of 0.025–0.03; this value correlates well with the 'K' value estimated earlier by Mandal and Johnston (2006). The large K value could be due to the thick top sedimentary layer in the KRB. Systematic magnitude dependencies of f_c , r , M_o and $\Delta\sigma$ are also seen from the relation between f_c vs. M_w , $\log_{10}(M_o)$ vs. $\log_{10}(\Delta\sigma)$, and $\log_{10}(r)$ vs. $\log_{10}(M_o)$, respectively (figure 9a–e). The $\log_{10}(M_o)$ vs. $\log_{10}(r)$ plot for the earthquakes of KRB shows a break in linear scaling between M_o and 'r' at $M_o = 10^{14.9}$ N-m (figure 9d), which is closer to $M_o \sim 10^{14.5}$ N-m observed by Mandal and Johnston (2006). Such type of break has not been observed for the other stable continental region earthquakes in the world (Mandal and Johnston 2006; Mandal and Dutta 2011). The large stress drops estimated by us are mainly confined to the main rupture zone of the 2001 Bhuj earthquake between 10 and 30 km depth (figure 9e), which probably suggests that the base of the seismogenic layer is lying at 30 km depth as also indicated by the larger $\Delta\sigma$ values (>15 MPa, figure 9e). It is noticed that in the KRB, seismicity extends down to a depth of 40 km (figure 9e) and in the SH down to a depth of 20 km only (figure 9e).

Furthermore, we estimated focal mechanism solutions of nine earthquakes of M_w 3.5–4.5, which occurred along the North Wagad Fault (NWF), Gedi fault (GF) and Gora Dungar fault (GDF). Among the nine events, six events are associated with the NWF, two events with the GF, one event with the GDF. Details of focal mechanism solutions of these selected events are given in table 5. For all the events in Kachchh, the nodal plane having a strike between NW–SE and E–W directions, with a dip towards the south, is considered as the fault plane, since it is consistent with the near east–west trending faults of the region. Most of the events show reverse mechanism with a minor strike-slip component (Mandal *et al.* 2007; Singh *et al.* 2016). However, one event along the NWF shows normal faulting with a minor strike-slip component. The estimated CMT solutions obtained in this study are consistent with those from previous studies (Mandal *et al.* 2007; Rao *et al.* 2013; Singh *et al.* 2016).

In the SH region, focal mechanism solutions of two earthquakes of M_w 4.0 and 5.3, which occurred

Table 4. Standard deviations and error estimations of source parameters of $M_w \geq 3.5$ of the KRB and SH.

Year	Month	Date	HR	Min	Lat. (°N)	Long. (°E)	Depth (km)	M_w	M_o (N-m)	Error M_o	f_c (Hz)	Error f_c	r (m)	$\Delta\sigma$ (Mpa)	Sd $\Delta\sigma$	No. of stations	Region
2006	09	03	17	47	23.747	70.748	06.1	4.2	2.51E+15	1.58	2.43	1.14	551	08.3	3.42	4	KRB
2006	08	20	02	37	23.538	70.560	14.0	4.4	3.98E+15	1.63	2.22	1.07	597	10.7	2.25	3	KRB
2007	02	21	19	59	23.084	70.113	26.0	3.5	2.51E+14	1.87	4.47	1.11	298	04.6	1.42	4	KRB
2007	02	23	03	50	23.452	70.377	12.1	4.0	1.26E+15	1.84	2.95	1.02	448	06.9	0.53	3	KRB
2007	02	26	23	29	23.408	70.327	22.0	3.8	6.31E+14	1.47	3.41	1.05	389	05.7	0.83	5	KRB
2007	03	01	06	08	23.504	70.362	10.1	4.0	1.26E+15	1.59	3.24	1.07	409	09.3	1.87	3	KRB
2007	03	05	04	36	23.490	70.304	15.1	3.6	3.16E+14	1.32	4.26	1.08	312	05.8	1.30	4	KRB
2007	04	08	16	20	23.368	70.398	23.5	4.3	3.16E+15	1.30	2.54	1.01	521	11.0	0.38	3	KRB
2007	05	13	13	41	23.439	70.435	20.1	4.3	3.98E+15	1.72	2.60	1.03	508	15.3	1.53	4	KRB
2007	05	24	12	54	23.334	70.048	10.1	4.1	1.58E+15	1.58	2.87	1.04	461	08.7	1.07	5	KRB
2007	10	08	01	12	23.345	70.109	11.9	4.6	1.00E+16	1.14	1.91	1.03	692	15.9	1.42	4	KRB
2007	11	06	00	27	21.121	70.517	07.5	4.9	2.75E+16	1.70	1.23	1.12	1083	09.5	0.82	3	SH
2007	11	06	09	38	21.207	70.541	08.2	5.0	3.89E+16	1.48	1.13	1.08	1179	10.5	2.32	8	SH
2007	11	06	12	31	21.238	70.509	03.9	3.6	3.16E+14	1.26	3.30	1.05	404	02.1	0.32	4	SH
2007	11	06	15	53	21.140	70.555	08.7	3.7	5.01E+14	1.58	2.80	1.05	476	02.0	0.30	3	SH
2008	03	01	21	41	23.465	70.300	23.1	4.2	2.51E+15	1.65	2.49	1.07	533	08.3	1.73	4	KRB
2008	03	09	11	10	23.385	70.330	29.6	4.8	2.00E+16	1.34	1.58	1.03	839	16.6	1.42	5	KRB
2008	03	28	07	01	25.202	70.533	18.4	4.0	1.26E+15	1.38	3.78	1.00	350	14.2	0.21	3	KRB
2008	05	25	04	30	23.307	70.097	17.9	3.5	2.00E+14	1.36	5.95	1.04	222	09.4	1.04	4	KRB
2008	06	20	21	19	23.391	70.388	28.4	4.0	1.00E+15	1.64	3.69	1.07	360	12.4	2.70	5	KRB
2008	07	07	14	57	24.187	69.792	16.1	3.5	2.51E+14	1.28	4.42	1.03	300	04.6	0.47	4	KRB
2008	07	10	09	39	23.467	70.296	23.5	3.8	5.01E+14	1.56	3.39	1.12	394	04.8	1.68	5	KRB
2008	07	19	09	23	23.492	70.276	13.9	3.6	2.51E+14	1.38	4.71	1.07	282	06.3	1.38	5	KRB
2008	08	05	07	53	23.772	70.487	20.2	3.5	2.00E+14	1.26	4.89	1.07	271	05.1	1.05	3	KRB
2008	12	27	02	12	23.848	70.751	12.1	3.6	2.51E+14	1.44	3.99	1.13	336	03.6	1.35	5	KRB
2009	03	13	19	21	24.328	69.778	06.5	3.5	2.00E+14	1.18	4.84	1.05	274	04.9	0.67	3	KRB
2009	03	31	01	44	23.460	70.408	24.6	3.5	2.51E+14	1.87	4.54	1.17	297	04.8	2.18	4	KRB
2009	05	18	04	28	23.385	70.245	27.2	3.8	6.31E+14	1.79	4.04	1.13	331	08.4	3.02	5	KRB
2009	07	01	22	34	23.447	70.124	06.3	3.5	2.00E+14	1.22	4.92	1.04	269	05.1	0.58	3	KRB
2009	09	03	08	26	23.312	70.132	31.1	3.5	2.00E+14	1.52	4.51	1.13	296	04.2	1.60	4	KRB
2009	09	05	06	40	23.413	70.239	28.3	3.8	7.94E+14	1.71	4.25	1.09	313	12.3	2.98	4	KRB
2009	10	07	06	21	23.443	70.189	17.5	3.6	3.16E+14	1.69	4.18	1.15	320	05.2	2.05	3	KRB
2009	10	09	13	23	24.451	69.249	16.5	3.6	3.16E+14	1.35	3.86	1.10	345	03.9	1.09	4	KRB

Table 5. Calculated focal mechanism solutions of events in the KRB and Saurashtra regions.

Sl. no.	Str1	Dip1	Rake1	Str2	Dip2	Rake2	P-axis	P-plunge	T-axis	T-plunge	DC (%)	CLVD (%)	M_o (N-m)
1	127	79	110	245	22	30	201	31	60	52	50	50	2.05×10^{15}
2	305	43	104	106	49	77	205	3	314	80	97	3	3.04×10^{15}
3	246	56	20	145	74	144	199	11	100	36	82	17.6	1.01×10^{16}
4	158	69	137	267	51	28	216	11	115	45	63	37	3.16×10^{16}
5	136	45	98	305	45	82	40	0	131	48	67	33.5	4.37×10^{15}
6	354	25	-50	131	71	-107	17	60	234	24	69	31	5.04×10^{16}
7	342	74	175	74	85	16	207	8	299	15	61	39.5	9.07×10^{14}
8	82	46	-130	212	57	56	325	6	66	62	31	69	2.33×10^{15}
9	134	26	70	336	66	99	59	20	264	68	59	41.5	7.5×10^{15}
10	19	61	23	278	70	149	330	6	236	35	51	49	2.04×10^{15}
11	45	38	-31	160	72	-124	31	51	275	20	67	33	1.13×10^{16}
12	138	66	100	294	26	68	220	21	66	67	62	37.6	1.2×10^{16}
13	139	90	-180	49	90	0	4	0	94	0	87	13.4	1.3×10^{17}

along NW–SE trending lineaments, are estimated. The nodal plane which strikes in the NW–SE direction and dipping steeply towards south is considered as the fault plane, since it is consistent with the near NW–SE trending lineaments of the region (figure 10a–b). The CMT solution of an earthquake M_w 5.3 near Junagadh in 2011 shows a pure strike-slip mechanism, while the CMT solution of an earthquake M_w 4.0 near Jamnagar in 2006 reveals a reverse mechanism with a minor strike-slip component.

Although different kinds of CMT solutions are found (figure 10a, table 5), they show two major trends. For most of the earthquakes, one of the nodal planes strikes in an east–west to northwest–southeast direction favoring a reverse mechanism with a minor right-lateral strike-slip component. The orientation of P-axis is nearly NNE–SSW, with some scatter (figure 10b). It implies that the estimated compressive stress direction being in the direction of Indian plate motion may cause a state of high compressive stress in different parts of the study regions.

Higher stress drops normally reflect material as well as structural heterogeneity, which is more evident in Kachchh compared to that in the SH. This is supported by more aftershock activity and thrust dominated right-lateral movement. Seismic tomographic studies in both the regions reveal why and how the structural heterogeneities control the earthquakes genesis (Kayal *et al.* 2002; Mandal *et al.* 2004b; Singh *et al.* 2012; Singh and Mishra 2015). Interestingly, the seismic activity in the SH has been drastically enhanced after the 2001 Bhuj earthquake, suggesting the reactivation of hidden seismogenic faults or creation of a new-seismic regime because of a long series of continued aftershock sequences of the Bhuj earthquake. Furthermore, the pattern of distribution of seismic velocity in Talala, SH and its association with aftershock occurrence provide seismological evidence for the neo-tectonics in the region, with a left-lateral strike-slip motion on the faults (Singh *et al.* 2013; Singh and Mishra 2015). The rate of occurrence of micro to moderate shallow earthquakes (≤ 20 km) enhances after heavy rainfall in the Indian summer monsoon period (Singh and Mishra 2015), which supports the explanation of pore collapse in the saturated subsurface rock matrix. The heavy rainfall raises the ground water table by 12–17 m in the observation wells, which was measured by the State Ground Water Department of Gujarat. In general, the rise of

Figure 10. (a) Estimated focal mechanism solutions in Kachchh, Saurashtra and Mainland Gujarat regions. Red coloured dots represent the events numbered 1–13. Open and black circles in the fault plane solutions represent T- and P-axes, respectively. Narmada Rift Basin (NRB), Cambay Rift Basin (CRB), KMF, SWF, NKF. (b) Rose diagram of the P-axis.

the groundwater table to about 10 m can induce stresses of the order of one bar (Singh and Mishra 2015). Thus, a stress change of 1–2 bars due to the rise in the groundwater table in the region can be considered sufficient to trigger small tremors along pre-existing critically stressed faults. The estimated lower stress drops may be caused due to triggering effect. Thus, we feel that the strike-slip mechanisms and relatively lower stress drops of the SH could be explained in terms of seismic failure on pre-existing small faults, such as the left-lateral strike-slip Umrethi fault at a shallow depth in the Talala region (Singh *et al.* 2015). A correlation of low-stress drop with strike-slip events is observed in the SH. In contrast, the high stress drops in the KRB are predominantly associated with the reverse with a slight component

of strike-slip mechanism. In the KRB, earthquakes near the epicenter of the 2001 mainshock primarily show reverse faulting mechanism (Mandal 2008; Singh *et al.* 2016). The surrounding earthquakes in the area, however, show predominantly strike-slip mechanisms (Rao *et al.* 2013; Singh *et al.* 2016).

We have obtained empirical relationships among M_o , f_c , r and $\Delta\sigma$ (equations 13–21), which are very important to understand the nature of self similarity of earthquakes (Kanamori and Anderson 1975; Hanks 1977). Our present study revealed $M_o \propto f_c^{-5.39}$ for the SH region (equation (13), figure 9b). Similarly, the two empirical relationships for the KRB are $M_o \propto f_c^{-8.26}$ and $M_o \propto f_c^{-3.77}$ for events between M_w 1.5–3.8 and $M_w \geq 3.9$ (equations 16 and 19, figure 9b), respectively. From these relations, it is inferred that

Table 6. Empirical relationship between M_o and f_c of the intraplate and interplate earthquakes of the Indian region.

Equation (N-m/s ³)	Earthquakes	M_w	References
$M_o f_c^3 = 7.6 \times 10^{16}$	Aftershocks of the 2001 Bhuj earthquakes	3.3–4.9	Kumar <i>et al.</i> (2014)
$M_o f_c^3 = 4.14 \times 10^{18}$	Aftershocks of the 2001 Bhuj earthquakes	2.93–5.32	Mandal and Dutta (2011)
$M_o f_c^{6.13} = 9 \times 10^{1617}$	Aftershocks of the 2001 Bhuj earthquakes	2.0–4.0	Kumar <i>et al.</i> (2015)
$M_o f_c^{9.748} = 10^{22}$	Aftershocks of the 2001 Bhuj earthquakes	4.0–5.2	Kumar <i>et al.</i> (2015)
$M_o \propto f^{-3.6}$	Earthquakes of Sikkim Himalaya	4.0–5.3	Hazarika and Kumar (2012)
$M_o f_c^{8.26} = 4.36 \times 10^{20}$	Aftershocks of the 2001 Bhuj earthquakes	1.5–4.0	In this study
$M_o f_c^{3.49} = 6.3 \times 10^{16}$	Aftershocks of the 2001 Bhuj earthquakes	4.0–5.2	In this study
$M_o f_c^{5.39} = 6.6 \times 10^{16}$	Earthquakes of the SH	1.6–5.0	In this study

earthquakes of the KRB and SH do not follow the law of self similarity (Mandal and Dutta 2011; Kumar *et al.* 2015). However, the study of Kumar *et al.* (2014), shows self similarity for the earthquakes of M_w 3.3–4.9. The difference in the nature may be due to different size of events and non-consideration of the break in source parameters (Kumar *et al.* 2015). Similarly, Hazarika and Kumar (2012) reported that earthquakes in Sikkim Himalaya do not show self similarity. From table 6, it is observed that most of the intraplate and interplate earthquakes within the Indian subcontinent do not follow self similarity. We have developed empirical relationships between M_o and r , which show that $M_o \propto r^{4.13}$ for events in the SH region (equation 14, figure 9c), while $M_o \propto r^{6.95}$ (for $M_w \sim 1.5$ –3.8) and $M_o \propto r^{2.78}$ (for $M_w \geq 3.9$) for earthquakes in the KRB (equations 17 and 20, figure 9c). It is observed that the source radius of the SH events is higher than those for the KRB earthquakes (figure 9c). The relationship between $\Delta\sigma$ and M_o shows that $\Delta\sigma \propto M_o^{0.62}$ for the SH events (equation 15, figure 9d), while $\Delta\sigma \propto M_o^{0.59}$ (for $M_w \sim 1.5$ –3.8) and $\Delta\sigma \propto M_o^{0.09}$ (for $M_w \geq 3.9$) for the KRB earthquakes (equations 18 and 21, figure 9d). It is noticed that earthquakes in KRB have higher stress drop values compared to the quakes in SH region.

Furthermore, we compared the SPs of earthquakes in the KRB and SH regions with other intraplate and interplate earthquakes of the Indian subcontinent (table 7). Several researchers

determined stress drops of different earthquakes in the Indian region, such as the 1993 Latur (M_w 6.2), 1997 Jabalpur (M_w 5.8), Koyna earthquake sequence and interplate earthquakes. Estimates show that stress drops vary between 2 and 25 MPa for most of the earthquakes in the Indian region (table 7), which are supported by results from this study. It is interesting to note that the estimated M_o and $\Delta\sigma$ values of the SH events show values nearly similar to the shocks in the Koyna region known for reservoir triggered seismicity (Mandal *et al.* 1998). The values of the 2001 Bhuj aftershocks are found to be slightly larger than those for the SH events and reservoir triggered Koyna events (figure 9d; tables 3 and 7). It is believed that the SPs of the Koyna and SH regions are similar in nature. The seismicity in the Koyna and Saurashtra regions is reservoir induced and monsoon-induced, respectively (Gupta 1985; Singh and Mishra 2015). For an M_w 4.8 Kachchh earthquake, the $\Delta\sigma$ is estimated to be about 16.6 MPa while the $\Delta\sigma$ for a similar size Saurashtra event of M_w 4.8 is found 10.2 MPa. Nevertheless, the estimated $\Delta\sigma$ values are significantly varied in both regions, probably due to several reasons such as variability in the source geometry, rupture speed, focal depth, local wave velocities, and also uncertainty in the corner frequency (Huang *et al.* 2017). The higher $\Delta\sigma$ values associated with the KRB events could be attributed to the presence of high velocity mafic intrusive bodies at deeper depths (Mandal *et al.* 2004b; Singh *et al.* 2012; Rastogi *et al.* 2014).

Table 7. Calculated stress drops of the intraplate and interplate earthquakes in the Indian region.

Stress drop ($\Delta\sigma$) MPa	Earthquake	Intraplate/ interplate	Magnitude/ M_w	References
0.03–19	The Koyna earthquakes (1994–1997)	Intraplate	1.5–4.7	Mandal <i>et al.</i> (1998)
3–26	The Koyna earthquakes (2005–2012)	Intraplate	3.5–5.2	Yadav <i>et al.</i> (2013)
19	The 2005 Koyna earthquake	Intraplate	5.1	Kumar <i>et al.</i> (2006)
7	The 1993 Latur earthquake	Intraplate	6.2	Baumbach <i>et al.</i> (1994)
4	The 1991 Uttarkashi earthquake	Interplate	6.8	Singh <i>et al.</i> (2003)
0.03–3.37	The Kumaon Himalaya earthquakes (2005–2008)	Interplate	2.7–4.5	Sivaram <i>et al.</i> (2013)
15	The 1999 Chamoli earthquake	Interplate	6.5	Singh <i>et al.</i> (2003)
20	The 1997 Jabalpur earthquake	Intraplate	5.8	Singh <i>et al.</i> (2003)

6. Conclusions

We analyzed the SPs of small to moderate earthquakes in the Kachchh and Saurashtra regions recorded by the Gujarat seismic network over a period of seven years from 2002 to 2009. Results reveal higher stress drops in Kachchh probably due to strong material heterogeneity at the brittle-ductile transition zone, associated with the intra-continental Kachchh failed rift basin. On the other hand, the present study suggests that earthquakes in the SH region that occur within a depth of 20 km are associated with lower stress drops. The estimated M_o and $\Delta\sigma$ values in the KRB are slightly larger than those observed for similar magnitude events in Koyna and SH. However, the values are similar in Koyna and Saurashtra. The estimated ' K ', and stress drop values provide a better understating of the seismic characteristics of different seismogenic structures and are useful for risk evaluation in different segments. In general, low-stress drops are observed for regions associated with strike-slip motion.

Acknowledgements

We sincerely thank the Editor-in-Chief and the two anonymous reviewers for their constructive comments that improved the manuscript. We are also grateful to the Technical staff of ISR, Gandhinagar for their support. BS is thankful to B K Rastogi, Ex-Director General, ISR and Prantik Mandal, NGRI, Hyderabad for their valuable suggestions and discussions. The study was partially supported by Department of Science and Technology (DST), Government of Gujarat and the Ministry of Earth Science, New Delhi, India.

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Corresponding editor: N V CHALAPATHI RAO