Active transverse faulting within underthrust Indian crust beneath the Sikkim Himalaya

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SUMMARY

Deep focus earthquakes within the underthrust Indian lower crust beneath the Himalaya occur in very specific regions and have distinct source characteristics. The study of the source mechanisms of these earthquakes provides valuable constraints on the kinematics of deformation of the underthrust Indian Plate, and its influence on the active deformation of the overlying Himalayan wedge. One of the most significant regions of these deep focus earthquakes is beneath the Sikkim and Bhutan Himalaya. We study the source characteristics of the 2011 September 18 (Mw 6.9) deep focus Sikkim main shock and its major aftershocks using global, regional and local waveform data. We determined the focal mechanism of the main shock using moment tensor inversion of global P and SH waveforms, and ascertained the earthquake fault plane using rupture directivity from regional P-wave spectra. The main shock originated at 53 ± 4 km depth and ruptured at least 20 km thickness of the underthrust Indian lower crust. Faulting occurred on a near-vertical dextral strike-slip fault oriented NW-SE (strike 127°, dip 81° and rake 167°), oblique to the local strike of the Himalayan arc. The rupture initiated from the SE end of the fault and propagated to the northwest. The main shock was followed by 20 small-to-moderate aftershocks (mb > 3.0), which we relocated using phase arrival times. We computed the focal mechanisms of the larger ones (mb ≥ 3.5) using local waveform inversion. We find that all aftershocks originated SE of the main shock, between depths of 12 and 50 km, and have dominantly strike-slip mechanisms. Our results, combined with the source mechanisms of earthquakes from previous studies, reveals that the entire underthrust Indian crust is seismogenic and deforms by dextral strike-slip motion on oblique structures beneath the Sikkim and Bhutan Himalaya. These active oblique structures with transverse motion possibly mark the western boundary of the clockwise rotating ‘microplates’ in northeast India observed from GPS geodesy.

Key words: Earthquake source observations; Seismicity and tectonics; Continental tectonics: strike-slip and transform; Rheology: crust and lithosphere.

1 INTRODUCTION

Earthquakes beneath the Himalaya are distributed in three distinct zones: (1) within the Himalayan wedge, (2) along the plane of detachment (also referred to as the Main Himalayan Thrust—MHT) separating the underthrusting Indian Plate from the overriding Himalayan wedge and (3) within the underthrust Indian Plate. Earthquakes in each of these zones have distinctive source characteristics and provide important insights into the tectonics of continent-continent collision and the rheology of the continental lithosphere.

First, the most common among the three zones are earthquakes within the Himalayan wedge. These occur throughout the arc, are small-to-moderate in size, shallow focus (depth <20 km) and originate between the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). Precisely determined locations of these events show that they lie within the hanging wall of the MHT, and are concentrated around the zone where the MCT splays from the MHT (Monsalve et al. 2006; Mitra et al. 2014). The northern limit of these earthquakes coincides with the ‘locking line’—demarcating the transition between interseismic locking and aseismic creep on the plane of detachment. The second zone of earthquakes are along the plane of detachment and are megathrust events with magnitudes (Mw) greater than 8 and recurrence intervals of a few to several hundred years (Bilham et al. 2001; Avouac et al. 2006; Kumar et al. 2006, 2010). These earthquakes accommodate a major component of the convergence between India and Tibet.
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Figure 1. (a) Map of Himalayan earthquakes \((m_b > 4.5)\) taken from ISC reviewed catalogues (http://www.isc.ac.uk/iscbulletin/search/catalogue/) and colour coded by depth. The depth uncertainty for the plotted events are usually ±10 km. (b) Topographic map of the Sikkim Himalaya [boxed in (a)] with the USGS focal mechanism (red focal mechanism) of the 2011 September 18 Sikkim main shock \((M_w 6.9)\) and the epicentral location of the aftershocks (white circles). The number above the beach ball is the USGS hypocentral depth of the main shock. The aftershocks have been relocated using phase data from global and local network of stations (plotted as white triangles). The uncertainty in their locations are plotted as black error bars.

(Avouac 2003). Finally, earthquakes within the underthrust Indian Plate have deep focus (≥40 km) and are observed to occur in specific regions beneath the Himalaya, for example Sikkim and northwestern Himalaya (Craig et al. 2012, Fig. 1a). These earthquakes are rare, and originate at depths well below the typical seismic–aseismic transition, as observed in most seismically active continental regions (e.g. 15–20 km; \(T \sim 350\, ^\circ\)C) (Chen & Molnar 1983), implying that the brittle–ductile transition is anomalously deep in this region. The depth distribution of these earthquakes has been extensively studied, given their significance in understanding the rheology of the continents (Jackson et al. 2008) and have been used to support contrasting views about the strength of the continental lithosphere (Chen & Molnar 1983; Maggi et al. 2000; Chen & Yang 2004; Jackson et al. 2004; Monsalve et al. 2006; Priestley et al. 2008). The presence of dry granulite-facies rocks in the underthrust lower Indian crust has been invoked to explain the occurrence of these deep earthquakes at temperatures of up to \(\sim 600\, ^\circ\)C (Jackson et al. 2008). However, the mechanism of faulting, for these events, have been sparsely studied; its relationship to the deformation of the Indian Plate is poorly understood, and its influence, if any, on the deformation of the Himalayan wedge is unknown.

We present new results for the source mechanism and source directivity of the 2011 September 18 deep focus Sikkim earthquake \((M_w 6.9)\); and source relocation and mechanisms of its major aftershocks \((m_b \geq 3.5)\) (Fig. 1b and Table 1). We then combine our results with the source mechanisms of previous deep earthquakes \((m_b > 6)\) beneath the Sikkim–Bhutan Himalaya and southern Tibet, to understand the kinematics of the underthrusting Indian Plate and its relationship to the active deformation of the overlying crust.

<table>
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<tr>
<th>No.</th>
<th>Event date (dd/mm/year)</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>Depth (km)</th>
<th>Mag</th>
<th>Strike (°)</th>
<th>Dip (°)</th>
<th>Rake (°)</th>
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<td>78</td>
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<td>65</td>
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<td>88.790</td>
<td>26.00</td>
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<td>75</td>
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Himalayan fold thrust belt. Finally, we discuss the implications of our results for the active tectonics of the eastern Himalayan Plate boundary system.

2 DATA

We use waveform data from three different sources for this study. First, for the source mechanism of the Sikkim mainshock, we use broadband teleseismic data from Global Digital Seismic Network (GDSN) stations, obtained from the Incorporated Research Institutions in Seismology (IRIS) Data Management Center (DMC). Secondly, for the rupture directivity of the Sikkim main shock, we use broadband data from both GDSN stations and from Indian Meteorological Department (IMD) stations. The IMD broadband stations are equipped with Trillium-240 seismometers (flat velocity response between 240 s and 50 Hz), Taurus digitizers and GPS time devices. Third, for the source mechanism of aftershocks, we use local waveform data recorded by a temporary network of stations operated by us in the Sikkim Himalaya (see Fig. 1b). These stations were funded by the Deep Continental Studies Program of Department of Science and Technology, India. The broadband seismograph system at GTOK consists of CMG-3TD seismometer, with flat velocity response between 120 s and 50 Hz. NAMC, RABN, YUMT, MANG and CHTG stations had CMG-3ESPCD broadband seismometer with flat velocity response between 60 s and 100 Hz. All these stations were equipped with CMG-DCM/EAM data loggers and were operated on continuous mode, recording data at 100 samples per second. The recorded data was time stamped with GPS synchronization.

3 SOURCE MECHANISM OF THE SIKKIM MAIN SHOCK USING GLOBAL P- AND SH-WAVEFORM INVERSION

We model the source mechanism of the Sikkim main shock using broad-band teleseismic waveform data from 43 GDSN stations, in the epicentral distance range of 30°–80° (Fig. 2). The waveform data have been deconvolved from their respective instrument response, and subsequently reconvolved with a filter to reproduce the 15–100 s response of the long-period WWSSN instruments, in which the earthquake approximates a point source. We window the P and SH waveforms on the vertical and tangential components, respectively. The windowed waveforms are modelled using the moment tensor inversion algorithm of McCaffrey & Abers (1988) to estimate the strike and dip of the nodal plane(s), rake of the slip vector(s), centroid depth and the variation of moment release with time (the source–time function). The seismic moment is given by the integral of the moment time function with the computed Green’s functions for direct arrivals (P or S), near-source reflections (pP, sP or sS) and multiples. As the waveform amplitude and shape are nonlinearly related to the source parameters, we iteratively perturbed the source parameters toward minimizing the misfit. The source time function is defined using a series of overlapping isosceles triangles of fixed half-width duration. Further details of the methodology are given in Nabelek (1984) and McCaffrey & Nabelek (1987).

In our analysis, we choose a two-layer velocity model (Table 2) for the source region, based on Acton et al. (2011), and the earthquake focus is placed within the second layer. We use a source time function comprising multiple elements with half-widths of 2 s. We read the P-wave arrival time from the broadband record to align the synthetic and observed waveforms. We choose a waveform window of 60 s to include the direct arrival and near-source reflected phases. The SH waveform is given half the weight in the inversions of the P waveform due to its larger amplitude. The observed seismograms are azimuthally weighted, giving less weight to seismograms from a cluster of stations compared to isolated ones. We used the USGS focal mechanism as the starting model for our inversion. The best-fitting source parameters are found by minimizing the misfit between the observed and synthetic waveforms (Fig. 2). Evenly distributed azimuthal coverage of stations for the P-waveform provides a tight constraint to the best-fitting solution. The near-source surface reflections constrain the depth of the earthquake.

The best fitting solution for the Sikkim main shock is a strike-slip earthquake on a near-vertical plane. The strike, dip and rake of the two nodal planes are (i) 219°, 78°, 9° and (ii) 127°, 81°, 167°, respectively. The hypocentral depth of the event is 53 km, the source rupture duration is ~10 s and the scalar seismic moment is $1.527 \times 10^{19}$ N m.

To obtain realistic uncertainties and examine trade-offs between the modelled parameters, we performed a number of tests. For all tests, we use $1\sigma$ bound as the uncertainty on the modelled parameter. First, we fix the depth of the earthquake to values bracketing the best-fitting solution and re-invert the waveform data for the other focal parameters, in order to estimate the depth uncertainty and its effect on the focal mechanism (Fig. 3a). The $1\sigma$ bound for the centroid depth is estimated to be ±4 km of its best fitting value, and the computed focal mechanism does not significantly trade-off with depth. The velocity model used for the source region (Acton et al. 2011) has an uncertainty of ~5 per cent in $V_S$ and would result in an additional estimated centroid depth uncertainty of ±2 km. Next, we examine the trade-off between strike, dip and rake by fixing a pair of these parameters around their best fitting values and re-inverting the data, allowing all other parameters to vary freely. The calculated misfit is contoured on a 2-D grid of the fixed parameters. This reveals the trade-off between the parameters and allows an estimation of the uncertainty. From the plots of the three different pairs, for example dip versus rake (Fig. 3b), dip versus strike (Fig. 3c) and rake versus strike (Fig. 3d), the estimated $1\sigma$ bound for rake is ±5° for dip is ±4° and for strike is ±6°.

4 RUPTURE DIRECTIVITY OF THE SIKKIM MAIN SHOCK

Modelling of source mechanism using far-field body wave displacement has an inherent ambiguity in discriminating between the fault plane and the auxiliary plane. In order to resolve this ambiguity, and uniquely determine the fault plane of the Sikkim main shock, we use rupture directivity effects. When an earthquake occurs, the fault (independent of its size) does not rupture at one instant. Generally, faulting nucleates at a point (focus), and the rupture propagates with a velocity close to the shear wave velocity of the medium. As a consequence, the frequency content of the resulting far field ground motion displays strong azimuthal dependence (Ben-Menahem 1961). A station in the direction of fault rupture propagation records a shorter duration, higher amplitude pulse (i.e.
a stronger ground motion) compared to a longer duration, lower amplitude pulse (i.e. weaker ground motion) in the diametrically opposite direction (Benioff 1955). This would result in enhancement of higher frequencies at the stations in the direction of rupture propagation, and the frequency spectrum of body waves will display the highest corner frequency. On the other hand, stations away from the rupture propagation direction will display the lowest corner frequency. Stations in azimuths between these two directions will have
intermediate corner frequency values. The effect of rupture directivity on pulse duration (width) is inversely proportional to that on the corner frequency.

In the absence of strong frequency dependent attenuation, Kane et al. (2013) has shown that this variation of corner frequency of the body wave displacement spectra with station azimuth can be used to determine the rupture directivity and hence discriminate between the fault and auxiliary plane. We adopt this method to determine the fault plane of the Sikkim main shock using the $P$-wave displacement spectra recorded at 80 GDSN stations and 20 IMD stations.

The station distribution provides a good azimuthal coverage. The recorded data is corrected for instrument response and integrated to obtain ground displacement. The $P$ wave is windowed on the vertical component and an equal length of seismogram from before the $P$ arrival is selected to examine the signal-to-noise ratio (SNR) of the $P$-wave signal. Both the time series are fast Fourier transformed to obtain the frequency spectrum. $P$-wave spectra with SNR greater than 2 are used to compute the corner frequency. Assuming a symmetric rupture, the displacement spectrum of the recorded $P$ wave at a given station is written as (Brune 1970):

$$D(f, t) = \frac{M_0}{4\pi} \frac{r}{t} \left(1 + \left(\frac{f}{f_0}\right)^2\right) G(\Delta, h) e^{-\pi f/(Q(f))},$$

where $M_0$ is the seismic moment, $t$ is the traveltime, $f$ is the frequency, $f_0$ is the corner frequency (intersection between segments of spectral amplitudes dependent on $\omega^0$ and $\omega^{-2}$), $\alpha$ is the $P$-wave velocity, $\rho$ is the crustal density at the source and $G(\Delta, h)$ is the geometrical spreading dependent on epicentral distance ($\Delta$) and earthquake focal depth ($h$) (and is taken as $1/R$ for body waves, where $R$ is the hypocentral distance). $Q(f)$ is the frequency dependent quality factor. The factor 0.6 accounts for average radiation
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Figure 4. Plot of fault rupture directivity for the Sikkim main shock. The analysis has been done using the P-waveform for 80 global stations within a radius of 40°. (a) Plot of P-wave spectra (scaled by amplitude) showing the increase in corner frequency for waveforms from stations 1 to 3 shown in (b). The stations are: 1 – Chiang Mai, Thailand (CHTO), 2 – Diego Garcia, Indian Ocean (DGAR) and 3 – Kashi, Xingjiang (KSH). The source spectra for the three stations, along with the best-fitting curve is plotted in (d), (e) and (f), respectively. (b) P-waveform first pulse displacement time series on vertical component showing the change in waveform shape from 1 (wide-low frequency) to 3 (narrow-high frequency). The fault ruptured towards station 3 and away from station 1. (c) Plot of all 80 stations P-wave spectra corner frequency ($f_0$) as a function of azimuth and epicentral distance (as size of circles). Stations 1, 2 and 3 used in (a) and (b) are labelled on the plot. A clear fault directivity is observed along 130°–310° direction, with the fault propagating along 310° azimuth and away from 130° azimuth. The strike of the corresponding fault plane is plotted as a vertical dashed line with 1σ uncertainty bounds. From this analysis we find the NW–SE nodal plane to be the fault plane of the Sikkim main shock. A histogram of $f_0$ values is plotted in the inset. The fault rupture area has been calculated for the maximum probable $f_0$ value.

In order to obtain $f_0$ from the observed P-wave spectra we use a grid search algorithm to search over a range of spectral amplitudes and $f_0$ values. For every pair of values we compute theoretical spectra of the form $\Omega_0/[1 + (f/f_0)^2]$. The best-fitting curve to the observed spectrum is obtained in a least-squares sense and the corresponding $f_0$ value is the corner frequency. We use this procedure to obtain the best fitting $f_0$ value for all the stations. The $f_0$ for each station is plotted against station azimuth to observe its azimuthal dependence (Fig. 4c). The plotted corner frequencies can be divided into three parts: (i) highest $f_0$ values between azimuths 315° and 335°; (ii) lowest $f_0$ values between azimuths 120° and 140° and (iii) intermediate $f_0$ values at all other azimuths. We select one station each from these three segments (designated as 1, 2 and 3) to compare the shape of the P-wave pulse (Fig. 4b), and their best-fitting spectra and corner frequencies (Figs 4a, d, e and f). The stations are: 1-Chiang Mai, Thailand (CHTO), 2-Diego Garcia, Indian Ocean (DGAR) and 3-Kashi, Xingjiang (KSH). We observe that station 3 has the sharpest pulse with the highest corner frequency, station 1 has the widest pulse with the lowest corner frequency and station 2 has intermediate values. We therefore conclude that the NW–SE striking plane is the fault plane and the earthquake rupture propagated from SE towards NW.

From the above $f_0$ measurement, we use the most probable value of $f_0 = 0.125$ Hz (Fig. 4c inset), and estimate the fault radius (a) for a circular fault, given by Madariaga (1976): $a = 0.32\beta/f_0$; where $\beta$ is S-wave velocity. This yields a fault radius of 11.5 km and corresponding rupture area of 415 km$^2$ for the Sikkim main shock. Assuming fault rupture velocity of 0.9$\beta$ and using the source time function duration obtained from waveform inversion, we calculate the rupture length to be ~24 km. This is consistent with the fault diameter (~23 km) obtained from the corner frequency of the spectra. Using the seismic scalar moment ($M_0$) obtained from waveform inversion and the fault radius ($a$), we calculate the stress drop to be ~4.4 MPa.

5 SOURCE MECHANISM OF AFTERSHOCKS USING LOCAL WAVEFORM INVERSION

The Sikkim main shock was followed by 20 moderate aftershocks (3.0 < $m_b$ < 4.8) within the next week. We relocated these aftershocks and computed focal mechanisms of the larger ones ($m_b$ ≥ 3.5) to study the seismotectonics of the region. Aftershock relocation was done using the arrival time of body wave phases recorded by our local network of broadband stations, and using
International Seismological Center phase data for stations within 350 km radius of the Sikkim Himalaya. We use the iterative least squares approach of Geiger (1912) to minimize the residual between the observed and calculated arrival times of both P and S waves simultaneously at all stations. The relocated hypocentres have an accuracy of ±5 km in both the horizontal and vertical (Fig. 1b).

We compute the source mechanism of the 10 largest aftershocks using waveform inversion. As these events are of moderate magnitude ($M_o < 4.8$), and their recordings on the global network have poor signal-to-noise ratio, we therefore use data from the local network of stations in the Sikkim Himalaya. Three-component observed waveforms are corrected for instrument response and integrated to obtain ground displacement. The horizontal components are rotated using the backazimuth angle to obtain radial and transverse components. We employ the ‘cut and paste’ (CAP) method of (Zhao & Helmberger 1994), and window the P waveform on the vertical and radial components and the S waveform on the vertical, radial and transverse components. In order to remove unwanted high-frequency noise, and enhance the signal-to-noise ratio we frequency filter the waveform data. Depending on the frequency content of the P- and S-waves, we low pass filter the P waveform at 2 Hz and the S waveform at 0.8 Hz. This ensures that the wavelength of the filtered signal is greater than the rupture length and excludes high-frequency propagation effects. Our low pass filter at 0.8 Hz is greater than most contemporary works (Zhu & Helmberger 1996; Bhattacharya 2007; Torre et al. 2007), and our inclusion of higher frequency P waveform ensures a robust solution even with a few station recordings.

We use the method of Jost & Herrmann (1989) to calculate synthetic waveforms for a point source embedded within a 1-D velocity model (Table 2), taken from Acton et al. (2011). This method assumes a deviatoric moment tensor with a pure double couple source. The five independent elements of the moment tensor are calculated from the scalar seismic moment ($M_o$), strike ($\phi$), dip ($\delta$) and rake ($\lambda$) of the fault plane (Wang & Herrmann 1980; Jost & Herrmann 1989). We compute Green’s functions using the reflectivity method of Kind & Odom (1983), followed by the layer reduction formulation of Bhattacharya (1992). In this method the Green’s functions are represented as a linear combination of the basic synthetic displacements for three fundamental faults DD (45° downdip), DS (vertical dip-slip) and SS (strike-slip) and are computed for the vertical, radial and transverse components. The coefficients of these basic synthetic displacements are a function of the backazimuth. The source time function $s(t)$ is taken from Wang & Herrmann (1980) as follows:

$$2\pi s(t) = \begin{cases} 0.5(t/\tau)^2 & \text{for } 0 < t \leq \tau \\ -0.5(t/\tau)^2 + 2(t/\tau) - 1 & \text{for } \tau < t \leq 3\tau \\ 0.5(t/\tau)^2 - 4(t/\tau) + 8 & \text{for } 3\tau < t \leq 4\tau \\ 0 & \text{for } t \leq 0 \text{ and } t > 4\tau \end{cases} \quad (2)$$

where $4\tau$ is the source duration.

The synthetic displacement for the three components ($i = 1, 2, 3$) is a linear combination of the Green’s function and the moment tensor given as:

$$u_i = \sum_{j=1}^{5} G_{ij} M_j. \quad (3)$$

We use a grid search algorithm to search over all possible values of strike, dip and rake (0° $\leq \phi \leq 360°$, 0° $\leq \delta \leq 90°$ and $-90° \leq \lambda \leq 90°$) and compute synthetic seismogram for every integer value.

The misfit function between the observed and synthetic waveforms is computed using an L1 norm defined for the $k$th component as:

$$\text{misfit}_{kth\text{comp}} = \frac{1}{n} \sum_{j=1}^{n} |u_j^{obs} - u_j^{cal}|, \quad (4)$$

where $u_j$ is the amplitude at each sample point, $n$ is the number of stations, $l$ is the number of sample points in the waveform for each station and $k = 1, 2, 3$.

The values of $\phi, \delta$ and $\lambda$ corresponding to the minimum misfit gives the best fitting source mechanism. The uncertainty on the inverted model parameters is estimated as $1\sigma$ using the same procedure as for the Sikkim main shock. Results from the waveform-fitting algorithm for a $m_s$ 3.7 aftershock on 2011 September 18 are plotted on Fig. 5, with the corresponding uncertainty estimation shown in Fig. 6. All the aftershock data have been analysed in the same manner and the results are given in Table 1, and the focal mechanisms are plotted on Fig. 7.

6 DISCUSSION

6.1 Active transverse faulting beneath the Sikkim Himalaya

Our results for the source mechanism and rupture directivity of the Sikkim main shock show that the earthquake occurred on a near vertical fault plane, oriented NW–SE at a highly oblique angle to the Himalayan arc, and produced dextral strike-slip motion. This demonstrates that the underthrust Indian crust beneath the Sikkim Himalaya deforms by strike-slip motion on at least one active transverse structure. Fig. 7 shows previous large earthquakes (<7 magnitude) beneath southern Tibet (Zhu & Helmberger 1996; Ekström 1989) and the Bhutan Himalaya (Drukpa et al. 2006), which originated in the underthrust Indian lower crust and have similar strike-slip focal mechanisms. This set of earthquakes either ruptured segments of one large transverse fault or are on a set of juxtaposed transverse structures within the underthrust Indian Plate. From these earthquake mechanisms, it is evident that the underthrust Indian Plate beneath Sikkim and Bhutan Himalaya deforms by major strike-slip motion.

The aftershocks originated southeast of the Sikkim main shock (Fig. 7) and are distributed throughout the crust (Fig. 8) between depths of 12 and 50 km. This has also been observed in a separate study of the aftershock distribution following the 2011 Sikkim earthquake (Ravi Kumar et al. 2012). Comparing the seismicity distribution with the Moho depth, and with the geometry of the MHT (as determined by receiver function studies, Acton et al. 2011), we observe that the underthrust Indian crust beneath the Sikkim Himalaya is entirely seismogenic (Fig. 8). This attests to the presence of dry granulate within the underthrust Indian mid-to-lower crust (Jackson et al. 2004, 2008), capable of remaining seismogenic up to temperatures of ~600 °C (Lund et al. 2004). The spatial distribution and focal mechanism orientations of the aftershocks suggest that they occurred on other active structures within the crust, rather than on the same fault plane as the main shock, despite their similar mechanisms.

The observed deformation of the underthrust Indian crust, beneath Sikkim and Bhutan Himalaya, is influenced by a combination of factors; for example the resistive forces exerted on the Indian Plate by the Tibetan plateau (Copley et al. 2010) due to the changing geometry of the Indian Plate as it underthrust Tibet and the lithostatic pressure from the overlying material, the compressive stress...
6.2 Relationship to earthquakes within the Himalayan wedge

The strike-slip deformation of the underthrusting Indian crust beneath the Sikkim and Bhutan Himalaya is notably different from the imbricate thrust faulting observed within the Himalayan wedge (Molnar 1984; Avouac 2003). Therefore, it is important to explore the possible relationship between the two. It is now well understood that the present-day convergence between India and Tibet is accommodated by underthrusting of the Indian Plate beneath the Himalaya and southern Tibet (Mitra et al. 2005; Schulte-Pelkum et al. 2005; Rai et al. 2006; Acton et al. 2011). This thrusting occurs by motion on the basal detachment, which separates the downgoing Indian Plate from the overriding Himalayan wedge. The shallow portion of this detachment is frictionally locked, accumulating strain as the two plates converge, while at depth it deforms by aseismic creep. During the period of strain accumulation, the overriding Himalayan wedge is stressed and undergoes readjustment by brittle faulting on pre-existing planes of weaknesses. These are observed as diffused micro-to-moderate seismicity within the Himalayan wedge (Monsalve et al. 2006), concentrated primarily between the MBT and MCT (Pandey et al. 1995; Mahesh et al. 2013; Mitra et al. 2014). Several workers have tried to associate this seismicity with pre-existing imbricate thrust faults within the Himalayan wedge (De & Kayal 2003, 2004), but with limited success. Due to the ongoing convergence, once the frictional limit on the basal detachment is exceeded, it slips to produce megathrust earthquakes ($M_w > 8$). These earthquakes typically break either the entire locked portion of the detachment, reaching very close to the surface (Avouac et al. 2006; Kumar et al. 2006, 2010), or its splays (e.g. MBT or MCT) as out of sequence thrusting (Wobus et al. 2005). The downgoing rigid Indian Plate does not actively participate in this deformation, except for producing the basal traction on a rigid base, a consequence of the ongoing convergence (Copley & Mckenzie 2007). However, the underthrusting Indian Plate deforms due to the vertical load exerted on it by the Himalaya and the resistive forces exerted on it by the transmitted to India from the continent–continent collision, and possibly the influence of stresses transferred across the MHT. This would result in reactivation of pre-existing structures which deform by strike-slip motion due to the oblique convergence between India and Tibet across the eastern Himalaya. Combined with observations of well estimated depth distributions of earthquakes in southern Tibet (Craig et al. 2012), we hypothesize that the Sikkim Himalaya possibly marks the transition, along the Himalayan arc, from arc normal convergence and thin skinned deformation observed in the central Himalaya (Avouac 2003) to oblique convergence and thick skinned deformation (involving the underthrusting Indian Plate) observed in northeast India (E of 88° latitude) (Billham & England 2001; Mitra et al. 2005; Clark & Bilham 2008).

Figure 5. Example of a local waveform inversion to estimate the focal mechanism of aftershocks. The plot shows the fit of observed (grey) and synthetic (black) waveforms (three-components) for recordings at three stations [GTK – (a) to (d), GTOK – (e) to (h) and RABN – (i) to (l)] and the estimated focal mechanism (m) for event no. 7 (Table 1). To obtain the best fitting focal mechanism we fit the observed $P$ waveform on vertical and radial components and the $S$ waveforms on vertical, radial and transverse components. We use two different frequency band for fitting the data. The $P$ waveform on the vertical is filtered between 0.1 and 2 Hz [(a), (e) and (i)], while the entire waveform (both $P$ and $S$) on all three components are filtered between 0.001 and 0.8 Hz [(b), (f) to (h); and (j) to (l)]. The minimum misfit focal mechanism is obtained by simultaneously fitting all the four waveforms for all stations. (m) Plot of the minimum-misfit solution focal mechanism with strike 90°, dip 65° and rake 25°.
Tibetan plateau. This deformation is distinct from the deformation of the Himalayan wedge and can occur as brittle failure within the underthrust Indian crust if it has relatively low temperatures (<600 °C) and is composed of dry granulite (Jackson et al. 2008). The Sikkim main shock attests to both of these inferences and has ruptured at least 20 km thickness of the seismogenic lower crust of the underthrust Indian Plate, if we assume an equidimensional fault rupture area. The major aftershocks originated southeast of the main shock and ruptured the entire underthrust Indian crust. However, this deformation did not propagate within the wedge except for the two farthest aftershocks, which are close to the basal detachment and have thrust mechanisms. In order to demonstrate the distinctiveness in the style of deformation of the underthrust Indian Plate to the deformation on or above the basal detachment, we modelled the source mechanism of the 2006 Phodong earthquake (which originated within the Himalayan wedge) using the same moment tensor inversion technique as described in Section 3. Comparing the focal mechanism and depths of the Sikkim main shock and its aftershocks to the 2006 Phodong earthquake (Figs 7 and 8) it is evident that the predominantly strike-slip mechanism of deformation in the underthrust Indian Plate is distinctly different from the pure thrust mechanism observed on or above the basal decollement.

6.3 Implications for regional tectonics

Our results have implications for the kinematics of deformation in the Eastern Himalayan Plate boundary system. Recent GPS geodetic data reveal clockwise rotation of two blocks (named Shillong and Assam blocks) in northeast India with respect to the Indian Plate (Vernant et al. 2014). These blocks are suggested to be bound by strike-slip faults, one of which is the dextral strike-slip Kopili fault separating the two blocks (figs 3 and 4 in Vernant et al. 2014). The western margin of the Shillong block has been assumed to be bound by a NW–SE trending transverse structure extending beneath the Sikkim-Bhutan Himalaya. The transverse dextral strike-slip fault which we study here, along with the previous earthquake faults beneath southern Tibet and Bhutan Himalaya (Table 1) possibly mark this western boundary of the Shillong block. This would explain the existence of an active transverse structure within the underthrust Indian Plate, and our results regarding the fault geometry and slip...
Figure 7. Map of the Sikkim Himalaya with plot of focal mechanisms for Sikkim main shock, aftershocks (black focal mechanisms – this study), the Phodong (2006) earthquake (dark grey focal mechanism - this study) and older events (light grey focal mechanisms) (Table 1). The numbers outside the focal mechanisms are depth of the events and the numbers inside correspond to the event number in Table 1. The size of the focal mechanisms are scaled by event magnitude. The Sikkim (local) network stations are plotted as grey triangles. Epicentral locations of the smaller aftershocks are plotted as open circles. The Himalayan thrust faults are plotted as bold lines and labelled in the plot (MBT—Main Boundary Thrust; MCT—Main Central Thrust; STDS—Southern Tibetan Detachment System). The dashed line demarcates the political boundary of India.

provide better constraints on kinematic models of deformation of the eastern Himalayan boundary system.

7 CONCLUSIONS

We studied the source characteristics of the 18th September ($M_w$ 6.9) deep focus Sikkim main shock and its major aftershocks to understand the kinematics of deformation of the underthrust Indian Plate beneath the Sikkim Himalaya and its influence, if any, on the active deformation of the overlying wedge. We determined the focal mechanism of the main shock using moment tensor inversion of global $P$ and $SH$ waveforms, and ascertained the earthquake fault plane using rupture directivity. We then relocated the major aftershocks ($m_b > 3.0$) using phase data and computed the focal mechanisms of the larger ones ($m_b \geq 3.5$) using local waveform inversion. Key findings from our study and its implications are as follows:

1. The Sikkim main shock originated at a depth of $53 \pm 4$ km and ruptured at least $20$ km thickness of the seismogenic lower crust of the underthrust Indian Plate beneath the Sikkim Himalaya.

2. The main shock fault plane is near vertical and oriented obliquely to the Himalayan arc, with dextral strike-slip motion attesting to an active transverse structure beneath the Sikkim Himalaya.
Figure 8. Cross-section along A–B (inset), parallel to the fault plane of the Sikkim main shock (Fig. 7). The focal mechanism of the main shock and its aftershocks are plotted in black. The size of the focal mechanisms are scaled according to their magnitude. The grey focal mechanism represents the Phodong (2006) earthquake which occurred above the MHT. The smaller aftershocks (mb < 3.5) are plotted as open circles. The uncertainty in location of the aftershocks are plotted as horizontal and vertical bars. The topography is projected along the profile (note the vertical exaggeration) and the outcrop of the major thrust faults (viz. MBT, MCT1 and MCT2) are shown by inverted triangles and their depth profiles plotted as dashed lines. The geometry of the MHT (dashed line) and Moho depths (plotted as black rectangles) has been taken from receiver function study of Acton et al. (2011). The Sikkim earthquake main shock and aftershocks occurred within the underthrust Indian crust.

3) The main shock rupture originated at the SE end of the fault and propagated in the NW direction. The dextral strike-slip faulting resulted in southeastward shift of the region underneath the Sikkim Himalaya relative to Nepal and propagation of stresses within the underthrust Indian Plate beneath Sikkim (Fig. 8).

4) All small-to-moderate aftershocks originated SE of the main shock, between depths of 12 and 50 km. Comparison with receiver function estimates of the depth to the Moho (Acton et al. 2011) shows that the entire crust beneath the Sikkim Himalaya is seismogenic.

5) Aftershock source mechanisms show dominant strike-slip faulting, possibly on pre-existing weak structures distributed throughout the underthrust Indian crust, rather than being on the main shock fault.

6) The underthrust Indian Plate beneath Sikkim and Bhutan Himalaya deforms by strike-slip faulting which is distinct from the thrust faulting observed in the overlying Himalayan wedge.

7) The active transverse strike-slip structure within the underthrust Indian Plate beneath the Sikkim Himalaya possibly defines the western boundary of the clockwise rotating 'microplates' in northeast India observed from GPS geodesy (Vernant et al. 2014).

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