Available online at www.sciencedirect.com

ScienceDirect

Solid Earth Sciences 3 (2018) 67−80

www.elsevier.com/locate/SESCI

Oblique slip faulting associated with evolving central Indo-Burmese region from Early Pleistocene deformational sequences

Raghupratim Rakshit [a], Devojit Bezbaruah [a], Bubul Bharali [b,*]

[a] Dept. of Applied Geology, Dibrugarh University, Assam, India
[b] Dept. of Geology, Pachhunga University College, Mizoram, India

Received 25 March 2018; revised 17 April 2018; accepted 19 April 2018
Available online 7 May 2018

Abstract

The Indo-Burmese Ranges (IBR) marks as the boundary between the rigid Burmese Plate and the north-easterly moving, obliquely converging Indian plate. This results in upliftment of Mizoram fold belt alongside of IBR, in the eastern most part of the Indian subcontinent. NS trending fault generated fold belt appears around the region due to the NE stress component from Indian plate movement. There are many linear tectonic features formed due to this process. On the eastern margin of the fold belt in the greater elevated part of IBR, E−W and NW−SE lineament patterns intersect the NS lineaments, and deformed the ridges obliquely to create complex geotectonic settings. In this study, a pristine attempt has been made to understand the geodynamic evolutionary mechanisms for the area to reveal the cause for such surficial convolutions. The arcuate subduction zone along the IBR causes the slab to flex and bend at depth. This relates to differential dipping of the slab and the greater dip surface occurred beneath the study area. The easterly dipping slab can accommodate great amount of sediments and therefore the region having maximum dip upholds the highest Tertiary sediment thickness, above the basement. Champhai district of Mizoram, India had been considered for this study as it has in the zone of convergence with highest slab dip underneath. The surface exposures have sufficient neotectonic evidences which inferred the signs from Early Pleistocene neotectonic to present active tectonic deformational history. Sequential offset of the antecedent rivers carries the signatures of the varying stress component within them. The geodynamic processes produce some tectonic features through the mode of earthquake generation. Epicentral plots and focal mechanism solutions for the area indicate seismic activity associated with the thrust and oblique strike-slip movement along with their correlation for the lineament distribution. The evolutionary model indicates syn-tectonic upliftment of the study area along with evolving IBR during Late Oligocene thrusting events. A Paleo-lake adjacent to the Champhai town is believed to be the source of some northerly flowing rivers that was located on the ridge. Late Pleistocene seismic events produce some contractional strike-slip faults that later transformed to oblique slip component that shaped the area. This study is also important for understanding the earthquake events and related deformation pattern in IBR. This also might be used to locate potential geohazard sites for safer construction as well as to understand the petroleum migration pathways.

Keywords: Oblique slip; Indo-Burmese range; Slab bending; Focal mechanism

---

1. Introduction

The voyage of Indian plate ends up when it collided with the Eurasian plate during Eocene in the North and later with Burmese plate, which is an elongated tectonic block bounded by Sagaing fault, in the east (Curray et al., 1979). The later event is still believed to be active and results in evolution of folded Indo-Burmese Ranges (IBR) in the eastern margin of the Indian subcontinent. The subduction of Indian plate has been studied by means of seismic, geodetic and GPS methods, from where this process was regarded as active (Verma et al., 1976; Chandra, 1975; Mukhopadhyay and Dasgupta, 1988; Satyabala, 1998; Dasgupta et al., 2003; Copley and McKenzie, 2007; Steckler et al., 2008; Kumar et al., 2015), slow (Le Dain et al., 1984; Ni

---

* Corresponding author.
E-mail address: bubulearth@gmail.com (B. Bharali).

Peer review under responsibility of Guangzhou Institute of Geochemistry.

https://doi.org/10.1016/j.sesci.2018.04.002

et al., 1989; Chen and Molnar, 1990) or inactive (Rao and Kumar, 1999; Gahalaut et al., 2013). In this arcuate plate boundary, the fold belt continues south ward from low hills of western Myanmar near 25° N through Naga Hills to broad ranges near 16° N, and then transitioning into Sumatra-Andaman oceanic subduction zone (Wang et al., 2014; Kumar et al., 2015; Steckler et al., 2016). The upliftment rate of IBR is varied depending on the distance from the plate boundary and position in the arcuate belt. This is caused by the differential stress component associated with the Indian plate motion from Late Eocene. In its course, the cold subducting part of Indian plate is flexed paralleling to the IBR results in buckling of the slab at depth. This process generates intraplate stresses that cause seismic events. The subducted plate shows maximum dip between 23° N and 25° N latitudes which fall around Mizoram Fold belt region in eastern most part of India (Kumar et al., 2015). The fault-propagating folded hills of IBR comprising Oligocene and Miocene rocks, are also transected by strike-slip faults that are shaping the deformed NS trending hill ranges (Ghosh et al., 2016). In such complex setting to understand topographic expression of the tectonic features, seismicity and therefore revealing the proper sub-surface deformational pattern with respect to the subduction is very important.

Lineament patterns are the best tool that can be utilized for producing enough evidences of deformation from the topographic variations with local and regional context. Regional stress component gets sequentially embedded in the lithounits either as shear deformation or associated with fractural features by brittle offsets. Compressional stress caused upliftment of this fold belt and other faulting events had caused offsets of the beds to accommodate the differential motion among the blocks. This is the fact which acts as a rule of similar lineament patterns associated with stress components that work as topographic modifier. In this study the origin of the research problem is based on the change in orientation of local lineaments that were varied from the regional patterns in the study area. Moreover, the newly formed lineaments were superimposed over the older lineaments and therefore the rock beds also show different attitudes rather than regional orientation. Nonetheless this infers the presence of active tectonics in the region which can be verified by both geomorphic markers (river offsets, pull-apart basin etc.) and seismotectonics study (epicentral plot, focal plane mechanism etc.).

In the eastern most Champhai district of Mizoram state which fall under IBR, we found such distinct localized lineament variation bounded by active tectonic features. Therefore, the morpho-dynamic evolution in the eastern edge of Mizoram Fold belt near India–Myanmar international border has been studied in this present context. The differential upliftment results in greater elevated Champhai plateau rather than western outer edges of the hill range, even though subducting Indian slab is dipping towards east. The basement is around 16 km beneath Champhai, which is greater than the estimated average depth of 12 km for Mizoram (Ghosh and Dasgupta, 2013).

The study area comprises Tertiary sedimentary rocks where the Barail Group of rocks thrusted over the Bhuban Formation rocks of Surma Group (Nandy et al., 1983). The argillaceous facies are easily erodible compare to the arenaceous facies in the area (Fig. 1). The evolution of fold belt along with syntectonic thrusting events and the later generation strike-slip faults with few small scale normal faults are inferred in the satellite imagery that were also observed during extensive field investigations. These surface expressions are clear indication of the Neo-tectonic and active tectonic processes. To identify the extent of these features digital elevation model (30 m) had been used. Lineament study and their correlation with geology of the area can provide important information about the stress component, major and minor fault systems and crustal activities. They are also relevant with subsurface fractures which can be the potential migration conduits for the hydrocarbon believed to be present in the Oligocene-Miocene source rocks or even the Eocene shales present in the subsurface under the study area (Ghosh and Dasgupta, 2013). The lineament study is also important for the possible hydro-power and civil engineering constructions (Olgen, 2004). For lineament analysis manual technique is followed as it provides greater control, and allows to choose the scale for analyzing the data (Ramli et al., 2010; Caran et al., 1982). Lineament density analysis is done by producing lineament map showing concentrations of the lineaments over the area. Intersection of the lineaments of different generations are observed, as they produce criss-cross patterns. Many rivers, streams follow these major (>3 km in length) and minor (<3 km) lineaments as they preserve and transform depending on the deformational events (Burbank and Anderson, 2012; Yeats et al., 1997). Strike-slip faults have a different geomorphic expression than thrust and normal faults; combination of these deformational forces can create somehow oblique distortion of crustal blocks. These kinematic changes can be quantified by measuring the offset of the major antecedent rivers.

In this study these neotectonic events have been analysed by following the methods of Wang et al. (2014). Tectonic features that are exposed in the surface or their presence identified in geomorphic ambiguities are results of seismotectonics interacting in the plate boundary systems. In this paper, we aim to find out the actual relationship between crustal and plate boundary deformational settings, that imposed the morpho-dynamic evolution of this part of the IBR; as evident by variation in orientation of lineaments. This result also enhances our understanding of the active tectonics in the region which can be further analysed to predict the future large earthquakes. To understand this stress model the results of lineament study and neotectonic signatures are correlated with earthquake focal mechanisms of the region and for the study area, and then compile the results into a holistic framework. We used the data from Incorporated Research Institutions in Seismology (IRIS) and the Global Centroid-Moment-Tensor (CMT) project as they are easily available and can provide information from different stations which enhance the accuracy of the study. The earthquake events in the region are mostly associated with the subducting slab slipping along the megathrust and upper plate structures, which absorb some of the India-Sunda plate

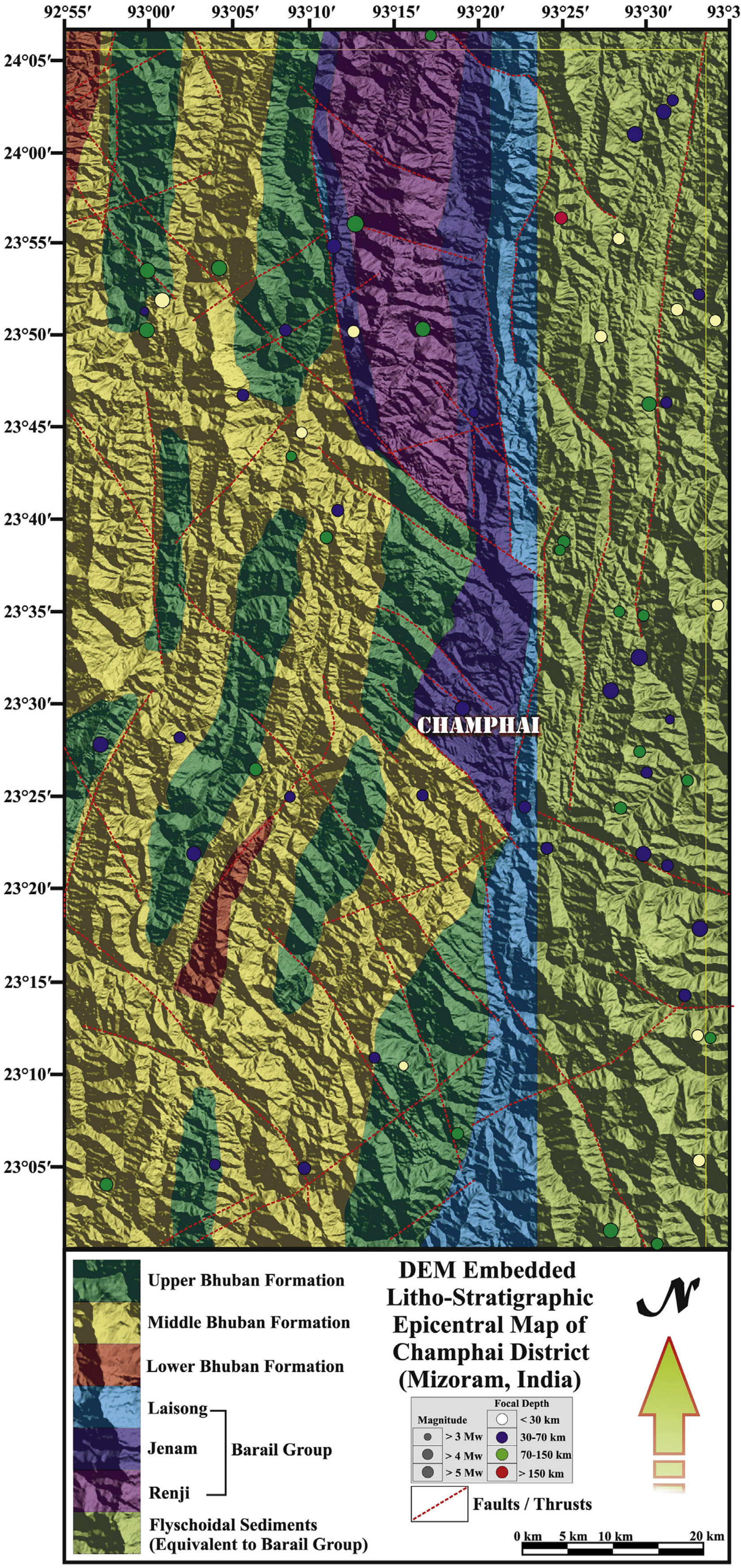

Fig. 1. Regional geological map around Champhai (modified after Bhaduri (2011); Morley and Searle (2017)).

motion (Nielsen et al., 2004; Socquet et al., 2006). The rest of the accumulating stress are released as oblique strike-slip motion as observed in the study area. The eastward dipping of the slab also confirms from the decreasing values of regional gravity anomalies from east to west inferring the variations in basement depth for the region (Nettleton, 1971). This entire slab is seismogenic and if the blind megathrust is failed at once it can produce an earthquake of a magnitude in the range Mw 8.6 to 8.9 (Blaser et al., 2010). The scarcity of published geologic, seismic and geodetic information of this part of IBR limits this pristine effort to some extent. Nonetheless, the regional GPS data across IBR has been studied to understand the Principle Displacement Zone (PDZ) with respect to the NE stress component due to Indian Plate motion. Recent geodetic studies reveal westward movement of the IBR about 14 mm/yr relative to the Indian plate (Gahalaut et al., 2013; Steckler et al., 2013). This slab section subducting with maximum dip at depth steered by the Indian plate motion although around upper crustal region westward stress component deforming with oblique slip movement due to different faulting mechanisms associated with them.

2. Regional tectonic settings

Evolution of IBR took place during the Oligocene time due to the convergence and oblique subduction of the Indian plate beneath the Burmese plate, with an eastward dipping slab is still seismogenic that could be extended down to 160 km (Brunnschweiler, 1966; Copley and McKenzie, 2007). Subducting slab is deformed by along the arc compression and downdip extension as result of slab pull forces and buckling at depth (Kumar et al., 2015). The characteristics of northern IBR is quite different from its southern part as the convergence changes from continental to oceanic subduction; with gradual transition observed in the central part. This part of IBR holds signatures of both the regions and has its own unique tectonic and geologic settings (Fig. 2). The area is bounded by many active fault systems, among which Dauki Fault and Naga Thrust is present in north and Gumti Fault in north-west region; Kaladan Fault, Chittagong Coastal Fault in the west and Kabaw-Sagaing Fault system in the east. In the IBR region, Churachandpur-Mao Fault (CMF) is another important aseismic strike-slip fault, that has not been associated with any historical rupture events (Szeliga et al., 2010); although can trigger minor to moderate earthquakes (Lienkaemper et al., 1991). The fault has resulted from the differential motion occurred due to confrontation between westward motion of the IBR and uplifting Shillong block. The eastward dipping Kabaw Fault has potential to generate Mw 8.4 earthquake if it were to fail all at once. Although this could only happen once in a millennium as the slip rate is only few mm/yr (Socquet et al., 2006; Steckler et al., 2008). Naga thrust is capable of producing an Mw 8.5 to 8.7 earthquake and the right-lateral Sagaing fault can trigger the maximum magnitudes of Mw 7 to 8 earthquakes (Wang et al., 2014). Northern IBR experiences less number of moderate to strong earthquakes as the active subduction has been seized beneath the Naga Hills (Steckler et al., 2008). Apart from these active faults the blind megathrust could produce strong earthquake if it fails all at once. This is also a possible scenario along with rupture of two to three faults as some historical incidents like 1964 Alaskan earthquake (Plafker, 1965) and the 1762 Arakan earthquake (Wang et al., 2013) strongly supports the facts.

The Tertiary sediments were deposited in the basin developed during plate convergence are uplifted due to folding and thrusting events. The development of IBR along with Mizoram Fold belt began in the Late Cretaceous (Nandy et al., 1983). The basement under the Mizoram area is believed to comprises

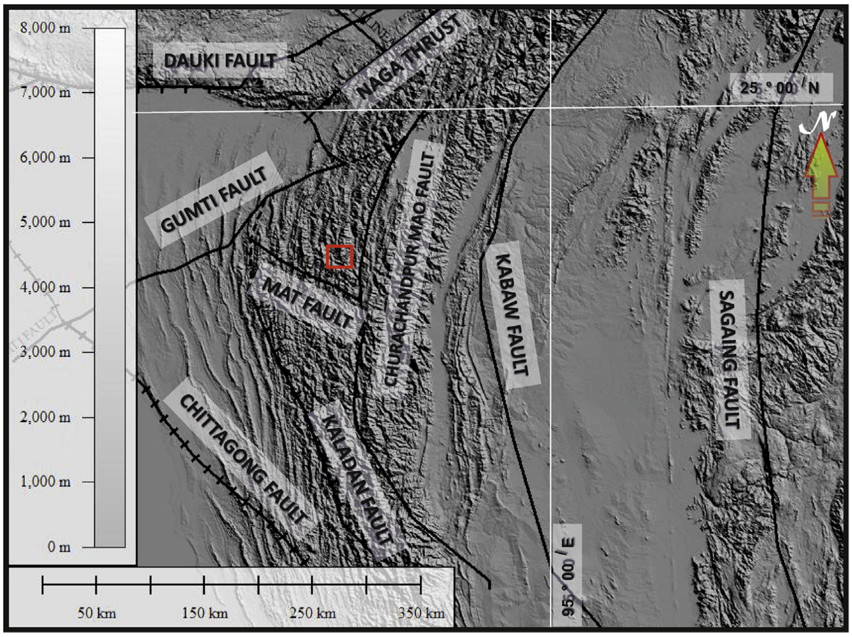

Fig. 2. Regional tectonic setting which have the influence on the study area; modified after Bhaduri (2011) & Morley and Searle (2017).

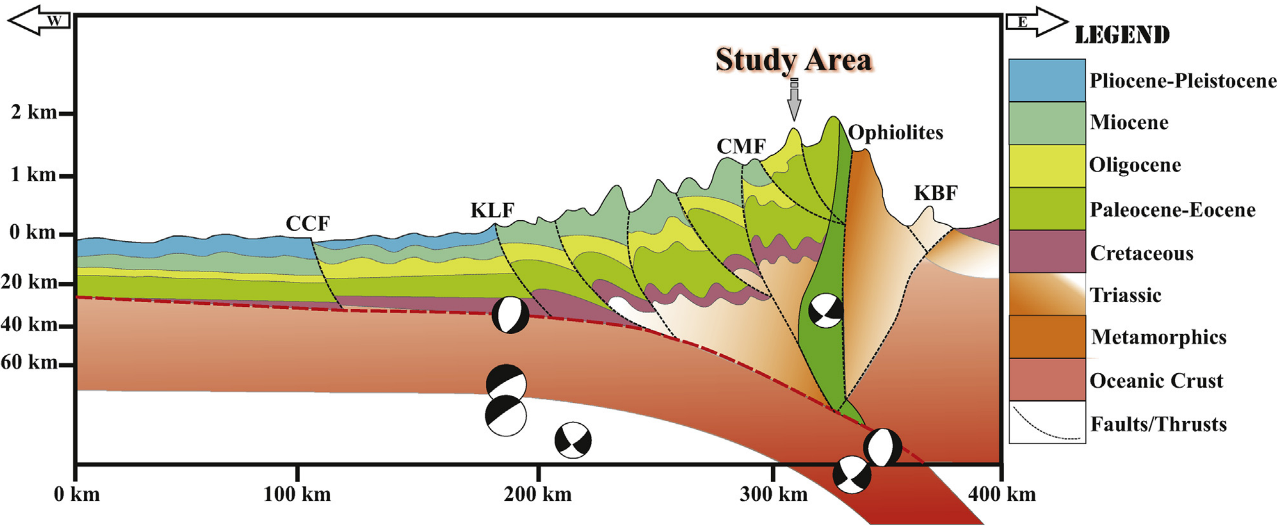

Fig. 3. Indian plate subduction process across IBR and associated focal mechanisms; modified after Searle et al. (2017).

Precambrian/Cambrian continental terrain as well as Cretaceous ophiolites (Fig. 3), which were set during the closure of the Tethys Ocean in the Late Cretaceous to Early Tertiary (Ghosh et al., 2016). The Cretaceous are unconformably overlain by Disang Group of Eocene-Paleocene age. During Late Eocene to Oligocene age, sediments of Laisong, Jenam and Renji Formations are deposited, together which comprises the Barail Group of rocks. The Miocene Surma sediments were deposited as Upper, Middle and Lower Bhuban adjacent to the uplifting IBR; along with Bokabil Formation in western margin during later phases in time. Further compression and upliftment of the area form a series of NS trending tight elongated fault-propagated folds, that are transected by later generation strike-slip faults.

3. Results and discussion

Lineament analysis is the first method towards discussing the tectonic control in any region. The lineament map for the area was produced from the manual extraction of the macro and micro lineaments. The density distribution (Fig. 4C) of the lineaments shows gridle shape in the quadrangle from 23°22' to 23°42'N in latitudes and 93°10' to 93°25'E in longitudes. The Rose diagram produced from the lineaments bearing, normalized for the major stress direction from the plate movements for the sake of illustration (Fig. 4A), indicate three sets of major trends, viz. NNE-SSW, NW–SE and E–W. The most of the lineaments show NW–SE and E–W trend. The lineaments were found to be aligned with NE–SW or NW–SE and associated with two NS thrusts that bound the Champhai block. Within this block, most of the macro and micro lineaments were associated with the WNW-ESE fault trend. On the basis of magnitude of the lineaments however the macro lineaments interpreted due to faulting whereas the micro lineaments are controlled by joints, minor faults or due to lithologic control in the region. Of the total lineaments delineated 37.96% are macro lineaments and 62.04% are micro lineaments; which further strengthen the fact of active tectonic deformations in the area. In Champhai plateau few antecedent rivers were observed in the satellite images and in DEM that are flowing through such features. Some interesting observations have been made during the analysis of the neotectonic signatures. One of them is that many streams and rivers like Tuipui, Tuichang and Tuivawl were flowing northwards before they follow the NW strike-slip faults to take the outer valleys around the block; and then deflected towards southwards regional stream flow-direction. The northward stream migration has been related to the Paleo-Lake near Champhai which feed the streams on its northern margin (Fig. 5). Champhai is supposed to be formed due to the faulting splay mechanism related with the NS thrusts. The evolution of the plateau and its associated lake which dried out in subsequent time period is also result of complex structural kinematics between exhumation and pull-apart basin formation. The detail mechanisms of these events are beyond the scope of the study and dealt with a different article by the authors. The oblique slip motion of the block along the inferred fault lines was observed as Tyao and Tuipui Rivers changes their course in a unique meander pattern and around the same Latitude (Fig. 6 & Fig. 7). The similar meandering was also observed for other two rivers situated in the western part of the block. Minute calculation for these offset meanders indicate that a NW–SE lineament which could be inferred as a later generation strike slip fault, possibly displaced the stretch of the block into an oblique slip motion (Table 1). The majority of these strike-slip faults are verified from geological investigations for the area. The ridges are formed due to compressional tectonics that uplifted the study area. The block was further shaped by dextral strike-slip faults with oblique slip component in a stress field that is bounded by NS oriented contractional regime. The simple shear model after (Twiss and Moores, 1992) with dextral slip motion can be used to illustrate the shear sense of these faults inferred by the morphologic study (Fig. 4B). Accordingly, NW–SE oriented ridge lines are

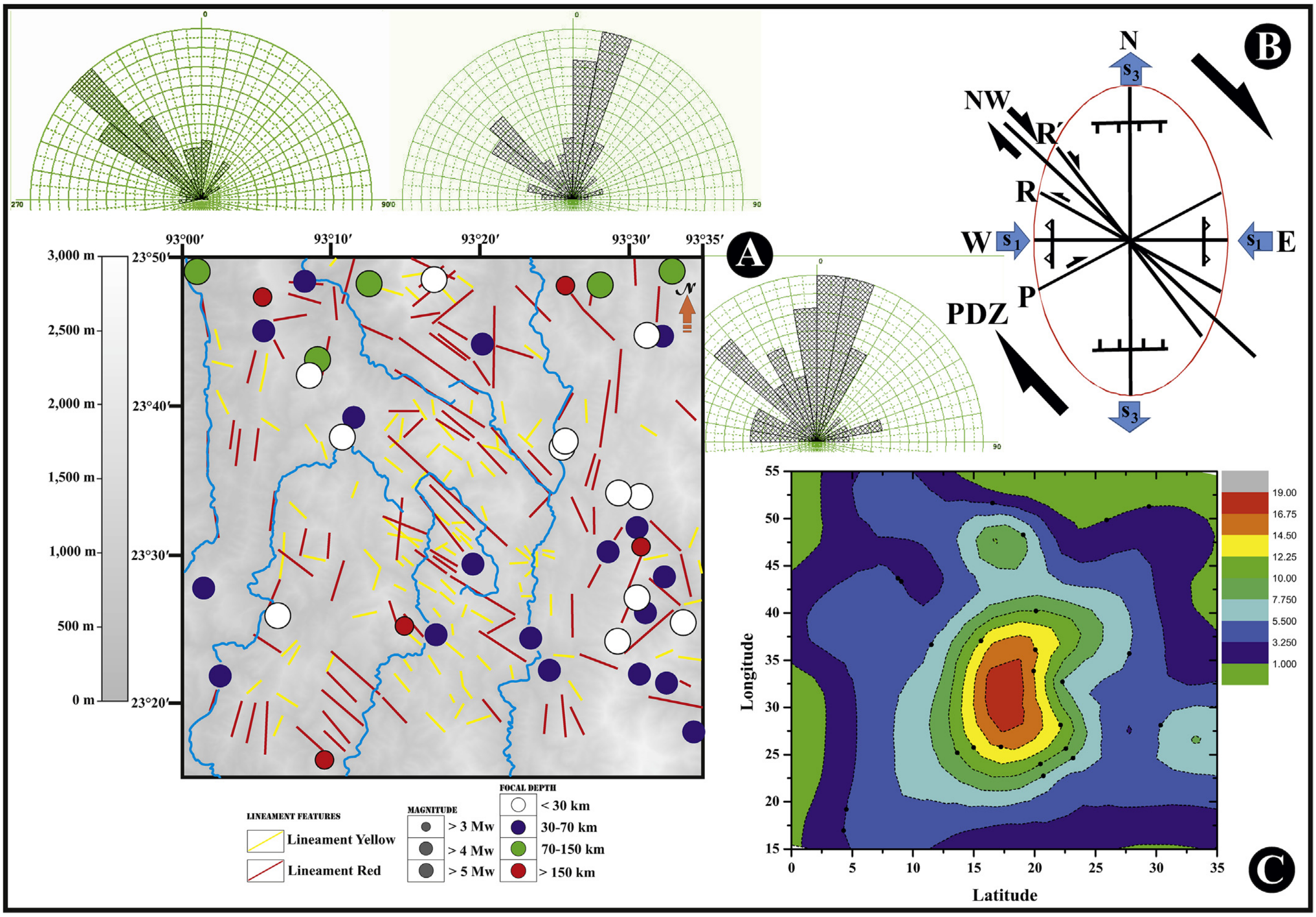

Fig. 4. Lineament and epicetral map along with Rose diagram from western, central and eastern part of map (A); Shear Model to illustrate deformational pattern (B) & Lineament frequency contouring diagram indicating more lineament variation in the central part (C).

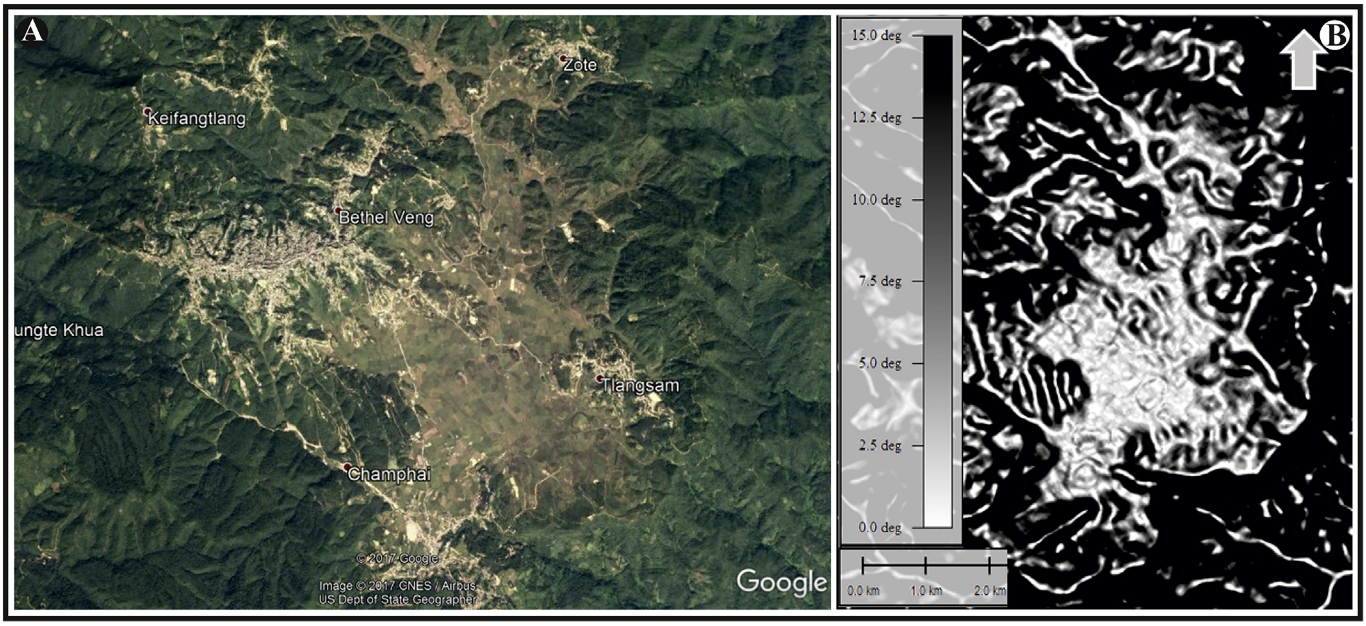

Fig. 5. Google Earth Image (Dec' 2017) of the Paleo-Lake (A) & The slope gradient DEM image of the area (B) clearly indicated the presence of a water body once existed in Champhai block.

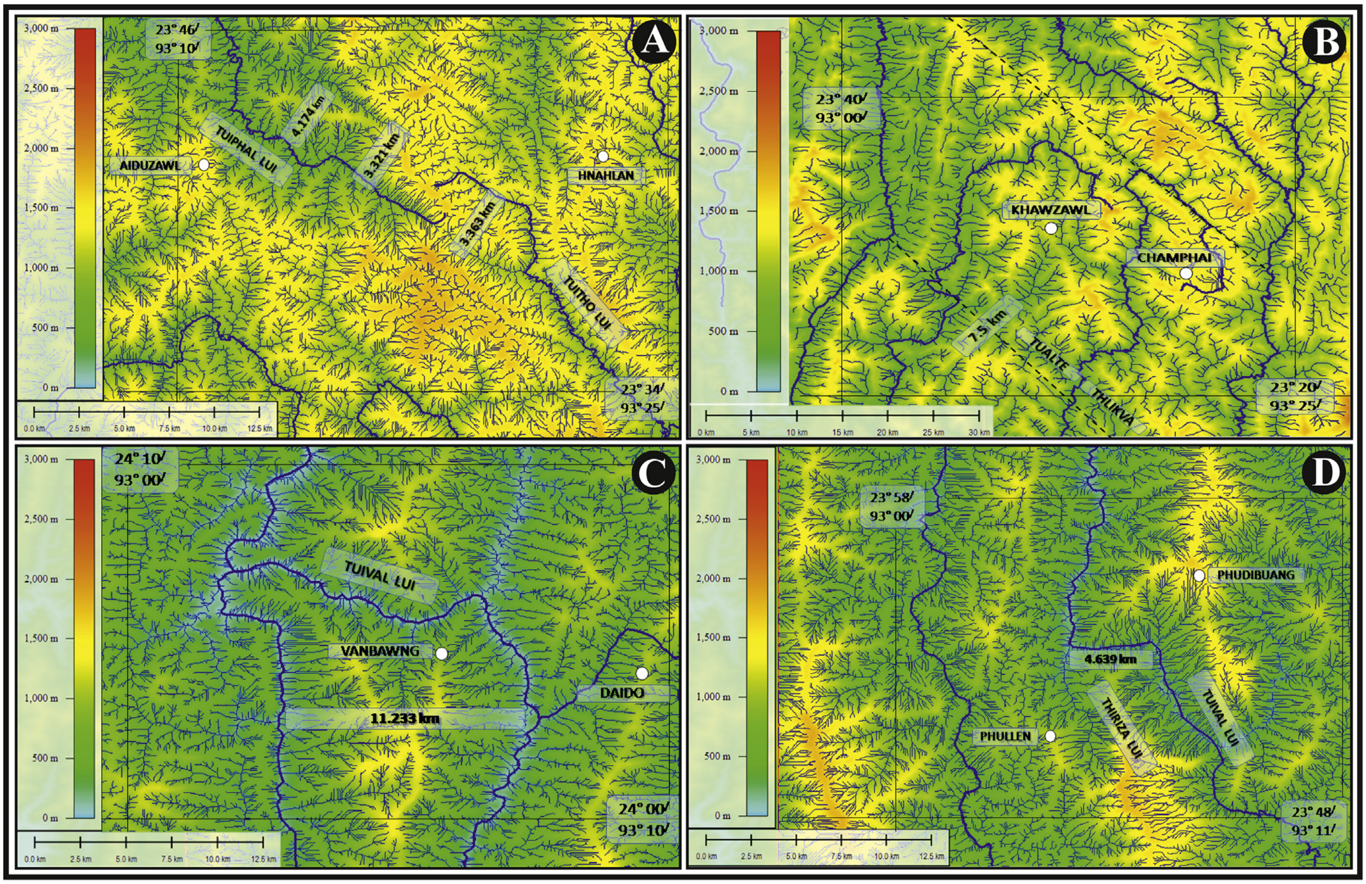

Fig. 6. Offset of antecedent rivers as observed in the satellite images around different section of the area.

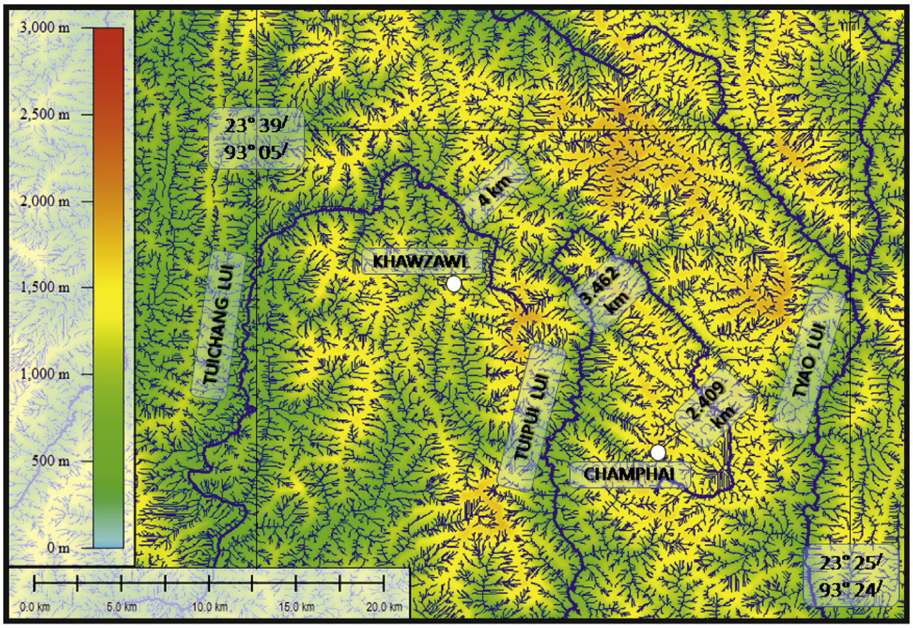

Fig. 7. River offset due to oblique motion as observed by variation in displacements along NW–SE around Champhai.

parallel to PDZ (equivalent to features formed due to ’tension gash’), NS running rivers and fold belt follow compressional reverse faults and WNW-ESE oriented streams and ridges following the macro lineament patterns correspond to the Riedel (i.e. R shear, first subsidiary fractures to occur, R generally build the most prominent lineaments) and Antithetic shears (R’ shear, with sense of displacement opposite to the primary movement). In accordance with the model, the

Table 1
Summary of age related to faulting process calculated based on the rate of slip and maximum fault offset for Champhai block (*after Gahalaut et al. (2013); Steckler et al. (2013)).

Fault name	Location of the outcrop		Possible fault mechanism involved	Maximum offset observed (in km)	Age (in Ma) of fault initiation based on slip rate*	
	Latitude	Longitude			Minimum (5 mm/yr)	Maximum (14 mm/yr)
Tualte-Thlikva	23°34′ to 23°46′ N	93°10′ to 93°25′ E	Contractional dextral strike slip motion	4.174	0.83	0.30
				3.321	0.66	0.24
				3.363	0.67	0.24
Tuival-Thiriza	23°53′ N	93°03′ to 93°06′ E	EW pure strike-slip	4.639	0.93	0.33
Tuival	24°02′ to 24°06′ N	92°58′ to 93°06′ E	Splaying of major thrust	11.233	2.25	0.80
Tualte-Thlikva	23°20′ to 23°40′ N	93°00′ to 93°25′ E	Oblique strike slip motion	7.5	1.50	0.54
Tuipui- Tuichang	23°30′ to 23°37′ N	93°11′ to 93°20′ E	Oblique thrusting	4.0	0.8	0.29
				3.462	0.69	0.25
				2.409	0.48	0.17

lineaments cross-cutting relationship with other features in the area, are synthetic shears (i.e. the P shear is symmetrically oriented to the R shear with respect to the fault plane). Such shearing senses were found to be less in number.

Geological attributes are also evolving in accordance with the changing structural controls in the area from Late Eocene. Though the older tectonic features were omitted or had been modified by the later generation tectonic features. Scarcity of the detailed research in the area, binds our effort to some extent as Neotectonic evidences could be modified to record only the latest deformations. Nonetheless, the results from the stream offset were correlated with the geologic evidences to understand the structural control over the area. The geologic map of the study area (Fig. 8) and particularly the NW–SE traverse section reveal that NS ridges were the result of thrusting events and rock beds associated with the anticline-syncline structures were folded and displaced. The strike of beds aligns to NS thrust on the western margin of the Champhai block which changes to NE–SW around 93°06'E in longitudes. Variations in bed attributes are also have similar relationship with the lineament pattern for this section. This is caused by the inferred synthetic faults that locally deforming the area. Synthetic faults in general are a type of minor faults whose sense of displacement is similar to the associated major fault present in the area. Western block margin to Tuipui River thrust the bedding strike follows roughly NS and NE–SW orientation, after which oblique strike slip component might result in transforming the orientation towards NW–SE as observed from major lineament patterns. Tuipui thrust is believed to be the lithologic contact between Bhuban and Barail rocks. The area from Champhai town to Tyao River thrust (International border) is highly deformed by the two strike-slip faults outcropped in the section. The field observation in this part also reveal such events in detail (Fig. 9). The EW stress component is now resulting in higher order antithetic faults generated due to the rigidity difference in the lithounits strained by oblique rotational motion.

Stress partitioning due to differential plate motion accumulated in the subsurface results in earthquake generation. Focal mechanism solutions of earthquakes are useful to understand the activity and deformational pattern in the subsurface. The dataset obtained from IRIS and CMT for 40 earthquake incidents were correlated with the lineament analysis, neotectonic features and fault systems around the region (Fig. 10). The corresponding epicenters were found to occur within a quadrangle from 23°00' to 24°10'N in latitude and 92°55' to 93°35'E in longitude. The earthquake occurrences recorded from 1970-onwards and more than 3 magnitude data are considered in the present context. The predominant fault systems observed in the region are reverse, strike-slip and normal types, although combinations of the types are more common. The 1st order upliftment processes was resulted from the NS oriented reverse faulting mechanism that are subsequently shifted to 2nd order NW–SE oblique strike-slip component. This is also evident from the distribution of focal mechanism solutions (Fig. 10). Such a beach–ball distribution suggests that the NS dip-slip reverse faults, NW–SE dextral strike-slip faults, and probable NE–SW strike-slip faults which might be associated with dextral slip motion; are present and their epicenters are directly associated with the faults and lineaments outcropped in the area. The slip motions delineated around different sections of the area are consistent with geological observations. The strike-slip component is dominating in this part of IBR which indicate EW extension rather than NE–SW compression. Earthquakes hypocenters are given from 10 km to 102 km inferring crustal to lithospheric depth (Table 2). Steckler et al. (2008) mentioned about different mechanisms associated with different depth ranges (Table 3). Moreover, they speculated that the detachment surface associated with Indian plate movement had produced megathrust earthquakes in the past and is capable of triggering such in the future. The arc-along convergence results in strain accumulation along the mega thrust beneath IBR. Although the movements at depth occur with a different failure mechanism than produce in the upper section of the plate. This supports the fact that the slip surface behaves as a transition zone from heterogenous upper part to comparatively homogenous lithosphere.

The stress component from N20°E motion of Indian plate along with westward rotational movement of IBR control the morphology and kinematics of the slip surfaces (Kumar et al., 2015; Steckler et al., 2016) due to the bending of the Indian

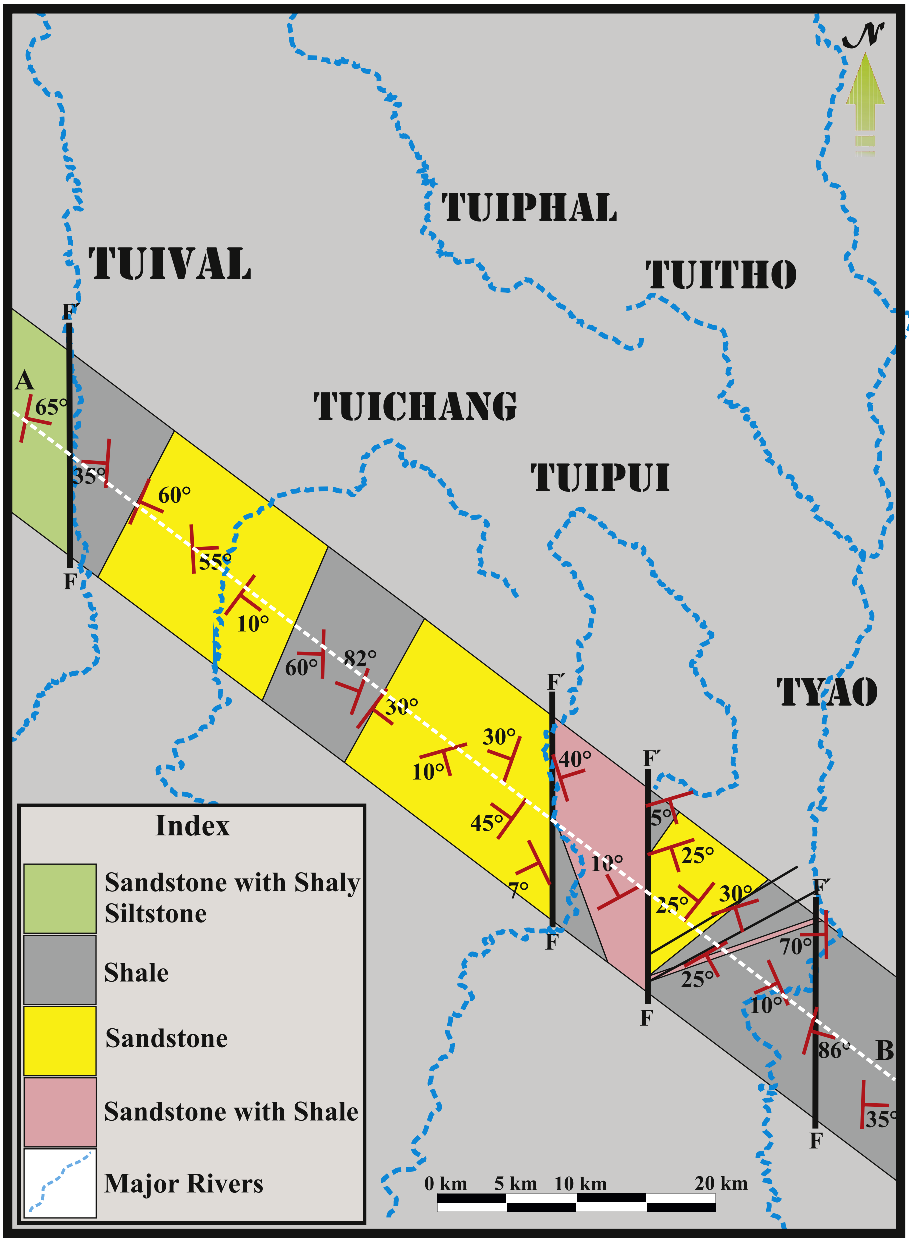

Fig. 8. Geological map of the traverse section across the study area.

lithosphere. The rotational movement causes a swirling effect around the region, results in NW–SE maximum stress for the study area and E–W maximum stress in the western part of the Fold-belt. CMF accommodate most of this rotational motion and therefore in the western edge of IBR, the NE stress component has greater effect (Kumar et al., 2015); whereas the EW and NW–SE stress field have major role in shaping the topography of the study area. From the GPS study around the Indian Fold belt indicate dextral motion of the area with the rate of displacement of about 18 mm/yr; although 5–14 mm/yr range has been assigned for the study area (Gahalaut et al., 2013). This range of displacement rate therefore be taken into consideration to find out the approximate age of initiation for studied strike-slip faults (Table 1). This methodology though has error in computation but is strong enough to delineate the period of such events (Wang et al., 2014). All the computed values infer that the second generation of strike-slip dominating deformational stage were initiated from Pleistocene time. This is most likely to be the result of post slab bending events that changed the morpho-dynamics of the region.

The earthquake focal solutions and neotectonic evidences provided sufficient inputs for defining the causative events that shaped the Champhai plateau. The evolutionary model indicates syn-tectonic upliftment of the study area along with evolving IBR during Late Oligocene-Miocene thrusting events (Fig. 11). This results in forming NS ridges that carries some low-order streams in them. Present Champhai town once had a lake on it, which might be located along the ridge line that was bounded by fault systems. Increase in elevation and denudational processes forced the lake to shrink continuously by the

Fig. 9. The View of Champhai Paleo-Lake (A), Pull apart basin drain by channels (B), Highly dipping beds (C), Fault patterns (view angle S30°W) are similar to regional faults (D), Present day Rih Dil lake (E) near Zokhawthar (Indo-Burma Border) & Vertical bedding near Rih Dil, Zokhawthar (F).

sediment deposition from the higher hilly parts. Continuous sedimentation was resulted in what could be describe as remains or imprints of this Paleo-Lake. The area bounded by later generation strike-slip faults, provided passage to the rivers to flow towards east or west till the edge of the block then they migrates southerly direction to follow the regional NS trend along the fault surfaces. During Late Pliocene the neotectonic activities swirled the NS features in clockwise rotational direction. This E–W stress component slowly overcomes the NE stress component of Indian plate motion to deform the features along NW–SE to WNW-ESE principle displacement zone. The northerly flowing rivers from the plateau region changed the course along the NW strike-slip faults. The NE–SW lineaments are the latest deformational zone and possible future ruptures may take place along this trend.

4. Conclusions

Champhai plateau is situated around the central IBR, where the sediment thickness is comparatively greater beneath the area than the western parts. This is because of greater depth and slope of the subducting slab in the arcuate subduction zone. The slab gets flexed and bends more near to this part of the IBR

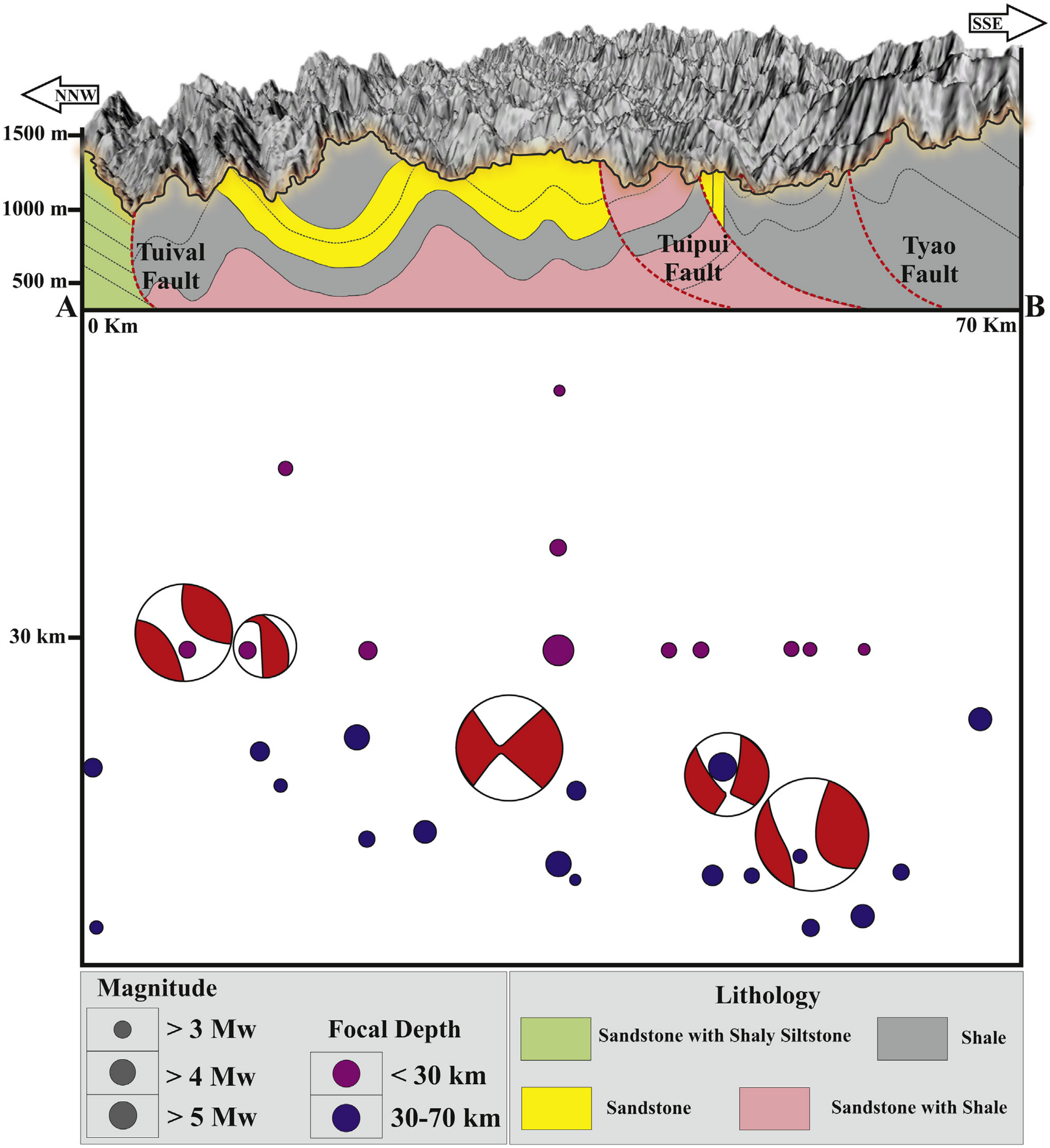

Fig. 10. Profile section of the study area with hypocentral distribution and few focal mechanism.

at depth (Fig. 12). This results in greater EW stress component rather than the stress accumulated due NE Indian Plate motion. The Champhai crustal block is therefore bounded by two strike-slip dominating low angle reverse faults, which are deforming at rate of approximately 14 mm/yr towards NW slip component. The streams and rivers that follow such fault system carries the evolutionary evidences that jolted the uplifting IBR. The geomorphic features observed in the area include: alignment of the streams on both sides of the drainage divide; comparatively straight river segment and associated stream patterns; offset or deflection of an incised river to some extent and then going back to previous trend or take another flow direction. These features are the direct indication of the presence of fault systems (Cronin et al., 1993; McCalpin, 1996; Burbank and Anderson, 2012). The offset values from different segments around the area infer that the neotectonic activities are completely controlled by tectonic evolution. The thrusting events from Late Miocene uplifted the Champhai

Table 2
Earthquake events (since 1970) and predominant focal mechanism of the study area in the quadrangle 23°15' to 23°50'N in Latitude and 93°00' to 93°35'E in Longitude.

Hypocenter depth (in km)	No. of events occurred	Focal solutions (Beachball diagram)
<30	6	
30–70	28	
>70	6	

block to the present elevation, though denudation processes erode some part away in course of time. In this study the neotectonic features reveal that the last phases of NS thrusting took place during Early Pleistocene age. In later phases the EW stress accumulation become more active with clockwise rotational component. This results in many strike-slip faults with some oblique slip motion. Change in orientation of the mega thrusts increases the dextral strike-slip movement in the region. The rate of this movement decreases westward with minimal oblique slip as in Aizawl (capital of Mizoram state) is moving with the rate of 10 mm/yr toward Dhaka (Bangladesh) at present (Jade et al., 2007). The long term shortening rate of 5 mm/yr (Maurin and Rangin, 2009) for the Fold belt indicate differential motion was caused of the greater elevation of the Champhai block. The subducting Indian slab can trigger strong earthquakes and could initiate other crustal faults that are potential geohazards sites. The deep focus earthquakes initiate at more than 180 km depth are less frequent than shallow ruptures of greater significance (Engdahl and Villasenor, 2002; Allen et al., 2009). These events are actually responsible for the unique neotectonic expressions and could be used in proposing a geohazard potential zone; road and other engineering constructions and can reveal potential petroleum migration paths

Table 3
Earthquake hypocenter distribution and systematic variation in the focal mechanism at different depth beneath IBR (Steckler et al., 2008).

Depth (in km)	Associated fault mechanism	Nodal plane orientation	Important components
Shallow (27 to 31)	Predominantly thrust	Parallel to the strike of the subducting Indian plate	slip vectors point in the direction of ~E–W convergence
Intermediate (51 to 67)	Predominantly strike-slip	One plane oriented N–NE and the other towards E–SE.	Occurred within subducted Indian plate and results from fracturing of the plate under extensional stresses
Deep (76 to 108)	Predominantly thrust	Strike of the nodal planes are at high angle to the strike of the subducting Indian plate	The nodal planes are oriented perpendicular, while the slip vectors are sub-parallel, to the trend of the arc

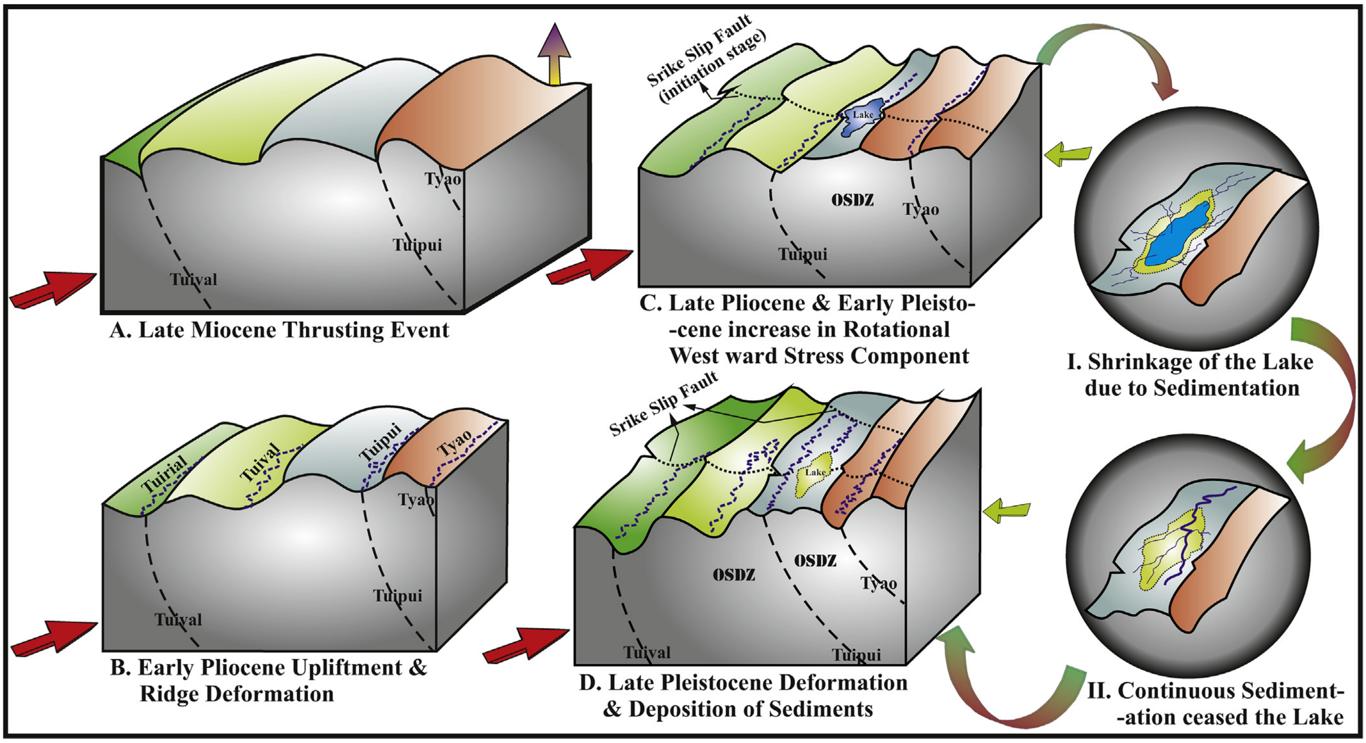

Fig. 11. Evolutionary model of the Champhai Block.

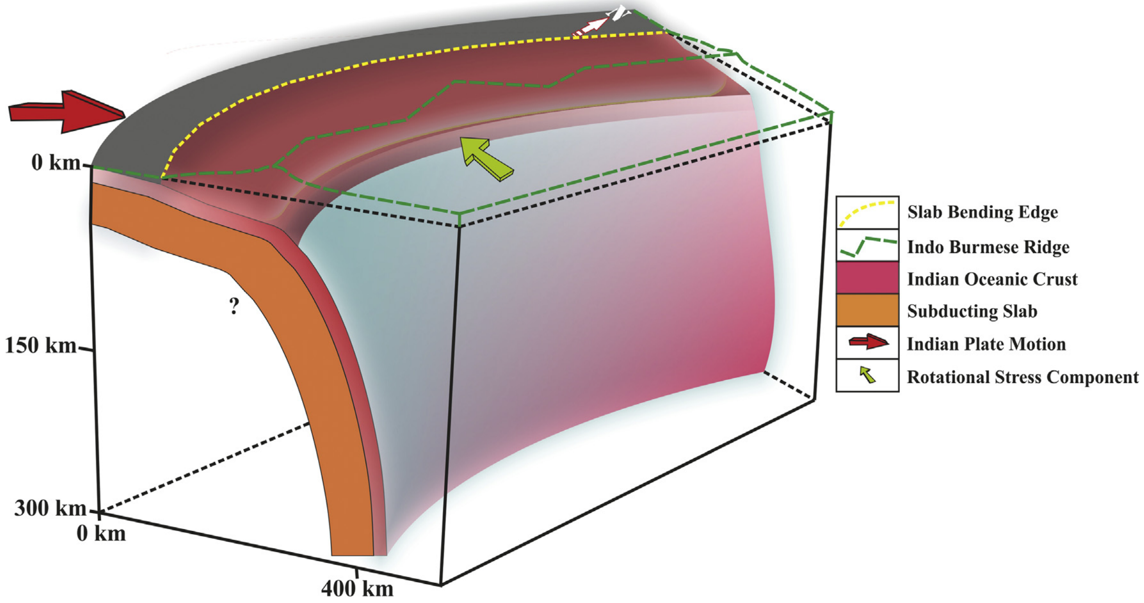

Fig. 12. Bending of the Indian slab causing the EW stress component around IBR; modified after Webb et al. (2017).

through minute fractures formed during active deformation in the area.

Acknowledgements

Seismograms for a part of this study have been downloaded from IRIS-DMC (http://www.ds.iris.edu/ds/nodes/dmc/) and Global CMT project (www.globalcmt.org). First author is also thankful to UGC (Govt. of India) for providing the scholarship. Gratitude towards Richard Lalrinzuala for his support during field study. Authors are thankful to the Editor-in-Chief and the anonymous reviewers for their critical reviewing which significantly contribute to the improvement of this article.

References

Allen, T.I., Marano, K.D., Earle, P.S., Wald, D.J., 2009. Pager-cat: a composite earthquake catalog for calibrating global fatality models. Seismol Res. Lett. 80 (1), 57–62.

Bhaduri, A., 2011. State Geological and Mineral Maps- Geological Survey of India. Miscellaneous Publication Series, pp. 1–2.

Blaser, L., Kruger, F., Ohrnberger, M., Scherbaum, F., 2010. Scaling relations of earthquake source parameter estimates with special focus on subduction environment. Bull. Seismol. Soc. Am. 100 (6), 2914–2926.

Brunnschweiler, R.O., 1966. On the geology of the Indoburman ranges. J. Geol. Soc. Aust. 13 (1), 137–194.

Burbank, D.W., Anderson, R.S., 2012. Tectonic Geomorphology. John Wiley & Sons.

Caran, S.C., Woodruff, C.M.J., Thompson, E.J., 1982. Lineament analysis and inference of geologic structure - examples from the Balcones/Ouachita trend of Texas. GCAGS Trans. Gulf Coast Assoc. Geol. Soc. 31, 59–69.

Chandra, U., 1975. Seismicity, earthquake mechanisms and tectonics of Burma, 20 N-28 N. Geophys. J. Int. 40 (3), 367–381.

Chen, W.-P., Molnar, P., 1990. Source parameters of earthquakes and intraplate deformation beneath the Shillong plateau and the northern Indoburman ranges. J. Geophys. Res. 95 (B8), 12527.

Copley, A., McKenzie, D., 2007. Models of crustal flow in the India-Asia collision zone. Geophys. J. Int. 169 (2), 683–698.

Cronin, V.S., Schurter, G.J., Sverdrup, K.A., 1993. Preliminary landsat lineament analysis of the northern Nanga Parbat-haramosh Massif, northwest Himalaya. Geol. Soc. Lond. Spec. Publ. 74 (1), 193–206.

Curray, J.R., Moore, D.G., Lawver, L.A., Emmel, F.J., Raitt, R.W., Henry, M., Kieckhefer, R., 1979. Tectonics of the Andaman Sea and Burma: Convergent Margins.

Le Dain, A.Y., Tapponnier, P., Molnar, P., 1984. Active faulting and tectonics of Burma and surrounding regions. J. Geophys. Res. 89 (B1), 453–472.

Dasgupta, S., Mukhopadhyay, M., Bhattacharya, A., Jana, T.K., 2003. The geometry of the Burma Andaman subducting lithosphere. J. Seismol. 7 (2), 155–174.

Engdahl, E., Villasenor, A., 2002. Global seismicity: 1900-1999. In: Lee, W.H.K., et al. (Eds.), International Handbook of Earthquake Engineering and Seismology, 81A. Academic Press, Boston, Mass.

Gahalaut, V.K., Kundu, B., Laishram, S.S., Catherine, J., Kumar, A., Singh, M.D., Tiwari, R.P., Chadha, R.K., Samanta, S.K., Ambikapathy, A., Mahesh, P., Bansal, A., Narsaiah, M., 2013. Aseismic plate boundary in the Indo-Burmese wedge, northwest Sunda Arc. Geology 41 (2), 235–238.

Ghosh, G., Dasgupta, R., 2013. Interpretation of crustal structures using spectral analysis of gravity and magnetic data in Mizoram thrust belt area. South East Asian J. Sediment. Basin Res. 1, 38–41.

Ghosh, G.K., Dasgupta, R., Borthakur, A.N., Singh, S.N., 2016. Structural interpretation of gravity data as an aid in hydrocarbon exploration - a case study from Mizoram thrust belt, Assam-Arakan basin. J. Geophys. XXXVII (No. 3), 165–172.

Jade, S., Mukul, M., Bhattacharyya, A.K., Vijayan, M., Jaganathan, S., Kumar, A., Tiwari, R., Kumar, A., Kalita, S., Sahu, S., Krishna, A., Gupta, S., Murthy, M., Gaur, V., 2007. Estimates of interseismic deformation in Northeast India from GPS measurements. Earth Planet Sci. Lett. 263 (3–4), 221–234.

Kumar, A., Mitra, S., Suresh, G., 2015. Seismotectonics of the eastern Himalayan and indo-burman plate boundary systems. Tectonics 34 (11), 2279–2295.

Lienkaemper, J.J., Borchardt, G., Lisowski, M., 1991. Historic creep rate and potential for seismic slip along the Hayward Fault, California. J. Geophys. Res. 96 (B11), 18261–18283.

Maurin, T., Rangin, C., 2009. Structure and kinematics of the Indo-Burmese Wedge: recent and fast growth of the outer wedge. Tectonics 28 (2), 1–21.

McCalpin, J., 1996. Paleoseismology. Academic Press, San Diego, California.

Morley, C.K., Searle, M., 2017. Regional tectonics, structure and evolution of the Andaman Nicobar Islands from ophiolite formation and obduction to collision and back-arc spreading. Geol. Soc. Lond. Mem. 47, 51−74.

Mukhopadhyay, M., Dasgupta, S., 1988. Deep structure and tectonics of the Burmese arc: constraints from earthquake and gravity data. Tectonophysics 149 (3−4), 299−322.

Nandy, D.R., Gupta, S.D., Sarkar, K., Ganguly, A., 1983. Tectonic evolution of Tripura - Mizoram fold belt., Surma basin, north east India. Quart. J. Geol. Min. Met. Soc. India 35 (4), 186−194.

Nettleton, L., 1971. Elementary Gravity and Magnetic for Geologists and Seismologists. Society of Exploration Geophysicists (SEG), Tulsa, Oklahoma, USA.

Ni, J.F., Guzman-Speziale, M., Bevis, M., Holt, W.E., Wallace, T.C., Seager, W.R., 1989. Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone. Geology 17 (1), 68.

Nielsen, C., Chamot-Rooke, N., Rangin, C., 2004. From partial to full strain partitioning along the Indo-Burmese hyper-oblique subduction. Mar. Geol. 209 (1−4), 303−327.

Olgen, M.K., 2004. Determining lineaments and geomorphic features using landsat 5-tm data on the Lower Bakirçay Plain, Western Turkey. Aegean Geogr. J. 13, 47−57.

Plafker, G., 1965. Tectonic Deformation Associated with the 1964 Alaska Earthquake: the earthquake of 27 March 1964 resulted in observable crustal deformation of unprecedented areal extent. Science 148 (3678), 1675−1687.

Ramli, M.F., Yusof, N., Yusoff, M.K., Juahir, H., Shafri, H.Z.M., 2010. Lineament mapping and its application in landslide hazard assessment: a review. Bull. Eng. Geol. Environ. 69 (2), 215−233.

Rao, N.P., Kumar, M.R., 1999. Evidences for cessation of Indian plate subduction in the Burmese arc region. Geophys. Res. Lett. 26 (20), 3149−3152.

Satyabala, S.P., 1998. Subduction in the Indo-Burma region: is it still active? Geophys. Res. Lett. 25 (16), 3189−3192.

Searle, M.P., Morley, C.K., Waters, D.J., Gardiner, N.J., Htun, U.K., Than, Than Nu, Robb, L.J., 2017. Tectonic and metamorphic evolution of the mogok metamorphic and jade mines belts and ophiolitic terranes of Burma (Myanmar). Geol. Soc. Lond. Mem. 48, 261−293.

Socquet, A., Vigny, C., Chamot-Rooke, N., Simons, W., Rangin, C., Ambrosius, B., 2006. India and Sunda plates motion and deformation along their boundary in Myanmar determined by GPS. J. Geophys. Res. Solid Earth 111 (B5), 1−11.

Steckler, M.S., Akhter, S.H., Seeber, L., 2008. Collision of the Ganges Brahmaputra delta with the Burma arc: implications for earthquake hazard. Earth Planet Sci. Lett. 273 (3−4), 367−378.

Steckler, M.S., Mondal, D.R., Nooner, S.L., Akhter, S.H., Seeber, L., Bettadpur, S.V., Rangin, C., et al., 2013. GPS velocity field in Bangladesh: delta subsidence, seasonal water loading and shortening across the Burma Accretionary Prism and Shillong Massif. AGU Fall Meet. Abstr. 13.

Steckler, M.S., Mondal, D.R., Akhter, S.H., Seeber, L., Feng, L., Gale, J., Hill, E.M., Howe, M., 2016. Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges. Nat. Geosci. 9 (8), 615−618.

Szeliga, W., Hough, S., Martin, S., Bilham, R., 2010. Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762. Bull. Seismol. Soc. Am. 100 (2), 570−584.

Twiss, R.J., Moores, E.M., 1992. Structural Geology. Macmillan.

Verma, R., Mukhopadhyay, M., Ahluwalia, M., 1976. Earthquake mechanisms and tectonic features of Northern Burma. Tectonophysics 32 (3−4), 387−399.

Wang, Y., Shyu, J.B.H., Sieh, K., Chiang, H.-W., Wang, C.-C., Aung, T., Lin, Y.-n. N., Shen, C.-C., Min, S., Than, O., Lin, K.K., Tun, S.T., 2013. Permanent upper plate deformation in western Myanmar during the great 1762 earthquake: implications for neotectonic behavior of the northern Sunda megathrust. J. Geophys. Res. Solid Earth 118 (3), 1277−1303.

Wang, Y., Sieh, K., Tun, S.T., Lai, K.-Y., Myint, T., 2014. Active tectonics and earthquake potential of the Myanmar region. J. Geophys. Res. Solid Earth 119 (4), 3767−3822.

Webb, A.A.G., Guo, H., Clift, P.D., Husson, L., Muller, T., Costantino, D., Yin, A., Xu, Z., Cao, H., Wang, Q., 2017. The Himalaya in 3D: slab dynamics controlled mountain building and monsoon intensification. Lithosphere L636.1.

Yeats, R.S., Sieh, K.E., Allen, C.R., 1997. The Geology of Earthquakes. Oxford Univ. Press, Beijing, China.