Arc parallel extension in Higher and Lesser Himalayas, evidence from western Arunachal Himalaya, India

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The existence of E–W extensional features from northeast (NE) Himalaya is poorly documented. Our investigation in the western part of Arunachal Himalaya provides evidences of active Quaternary E–W arc-parallel extensional features in the Higher and Lesser Himalayas. They are represented by arc-perpendicular normal faults and arc-parallel sinistral strike-slip faults. We discuss the occurrences of these arc-parallel extensional features in terms of oblique convergence and radial expansion models. The partitioning of stress due to oblique convergence is argued based on evidences of left-lateral slip in NE-Himalaya, right-lateral slip in NW-Himalaya and absence of translation in the central part. The amount of arc-parallel extension in the hinterland regions is correlated to the amount of radial shortening in the foreland. The computation of arc-parallel extension in the NE Himalayan arc is carried out by defining a small-circle centered at $88^{\circ}39' \pm 0.7'E$ longitude and $33^{\circ}40' \pm 0.6'N$ latitude having a radius of 770.7 ± 15.1 km, for the segment between $92^{\circ}01'$ and $95^{\circ}16'E$ longitudes. The amount of arc-parallel extension estimated is ~ 110 km for the NE Himalayan segment. Our result agrees closely with the 104 km extension determined based on geodetically computed extension rate and age of initiation of rifting in southern Tibet.

1. Introduction

Intercontinental collision zones worldwide show common characteristics of horizontal shortening such as thickening of the crust and surface uplift. Crustal thickening often results in extension in the high elevated regions, while crustal shortening proceeds along the outer flanks of the uplifted ranges. Syntectonic extension in the high elevated Tibetan plateau and in the Himalayas is contemporaneous with crustal shortening in the foreland part, and constitutes an integral element of the mountain building phenomena (Burchfiel and Royden 1985; England and Houseman 1989; Murphy and Copeland 2005; Thiede *et al.* 2006). Various mechanisms and theories have been put forth to explain arc-parallel extension, however,

the evolution of both normal and translational fault systems still remains a matter of debate (e.g., Murphy *et al.* 2002; Selverstone 2005; Hintersberger *et al.* 2010). Extension related normal fault features have been documented extensively in the Tibetan Plateau, Higher Himalaya and from parts of Lesser Himalaya (Hintersberger *et al.* 2010 and references there in). Murphy and Copeland (2005), Jessup *et al.* (2008), Leloup *et al.* (2010) and Hintersberger *et al.* (2010) documented active north–south striking younger brittle extensional structures overprinting the previously generated crustal scale faults in northwest (NW) Himalaya. In the northeast (NE) Himalaya with the exception of the Cona–Oiga rift, which is largely restricted to southern Tibet, no extension related normal faults/graben or strike-slip faults

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Figure 1. Topographic map of Himalaya and southern Tibet showing active orogen-perpendicular NNE–SSW trending grabens and major strike slip faults (after Thiede *et al.* 2006; Jessup *et al.* 2008). GPS velocities are shown in dark blue arrows, while red arrows indicate convergence velocity (Zhang *et al.* 2004; Jade *et al.* 2007). The arc-perpendicular component is the light blue arrow and white arrow is arc-parallel extension and eastward extrusion of Tibet plateau is depicted by the yellow ellipse. White ellipse indicates the study area. Seven earthquake fault plane solutions are plotted in and around the study area (Source: <http://www.globalcent.org/> and Styron *et al.* 2011). Yellow arc is the segment of the small-circle describing Himalayan arc between 77.2° and 92.1°E longitudes defined by Bendick and Bilham (2001). Red arc is the proposed small-circle segment describing the NE Himalayan arc between 92°01' and 95°16'E longitudes. Numbers indicate arc-perpendicular rift initiation ages (Ma). Reference sources given in italics, (1) Harrison *et al.* (1995), (2) Stockli *et al.* (2002), (3) Coleman and Hodges (1995); Hurtado *et al.* (2001), (4) Lee *et al.* (2011) and (5) Murphy *et al.* (2002). ITSZ: Indus Tsangpo Suture Zone, STDS: South Tibetan Detachment System, HFT: Himalayan Frontal Thrust, WAH: Western Arunachal Himalaya and EAH: Eastern Arunachal Himalaya. Inset: Himalayan arc within red rectangle and location of study area within yellow rectangle in the DEM map of India.

have been reported. The NE Himalayan regions still remain largely unexplored. Most earlier tectonic studies in the NE regions were focused on understanding the arc-parallel thrusts and extension to understand the geodynamic evolution of the eastern syntaxial zone. In the present paper, we document Quaternary features that record the transition from shortening to extension in the Higher and Lesser Himalayas of western Arunachal Pradesh (figure 1). In light of the field evidences and timing, we discuss the probable cause for extension related features in the NE Himalaya.

2. Geological setting of the study area

Arunachal Himalaya is the easternmost part of the Himalayan range trending ENE–WSW turning

to NE–SW further east (figures 1 and 2). The Main Central Thrust or Se La thrust in Arunachal Pradesh has been correlated with Thimpu thrust in Bhutan and Darjeeling thrust in Darjeeling–Sikkim Himalaya (Valdiya 1980). The Arunachal Himalaya is divided into western and eastern domains by the Siang window (figure 1) (Singh and Chowdhary 1990; Acharyya 1998; Ding *et al.* 2001; Zeitler *et al.* 2001).

The study area in the western Arunachal Himalaya exposes three major sub-parallel north-dipping regional thrusts; from south to north they are Himalayan Frontal Thrust (HFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) (figure 2). The HFT places molasse deposits of the Siwalik Formation over the Brahmaputra plain. The foreland Siwalik Group in the Arunachal Himalaya consisting of the Dafla,

Figure 2. Geological map of western Arunachal Pradesh (modified after Kumar 1997; Bhattacharjee and Nandy 2007; Goswami *et al.* 2009; Yin *et al.* 2010) shows distribution of the different stratigraphic units in the area. Structural data based on traverses from Bhalukpong–Tawang and Tawang–Zimithang. STD: South Tibetan Detachment, KT: Kakthang Thrust, ZT: Zimithang Thrust, LLW: Lum-La Window, MCT: Main Central Thrust, MBT: Main Boundary Thrust, HFT: Himalayan Frontal Thrust, BT: Bhalukpong Thrust.

Subansiri and Kimin Formation is bound between the MBT and HFT (figure 2) (Kumar 1997). The Lesser Himalayan sequence (LHS) lies in the hanging wall of the MBT and consists of varied rock types from south to north. In the south, marine and plant fossil bearing Permian Gondwana rocks are overlain by low-grade metamorphites of Tenga Formation and mylonitic gneiss. The garnet-kyanite-sillimanite schist of Dirang Formation lies thrust along Bomidilla Thrust (BT). The LHS is overthrust by the Greater Himalayan sequence (GHS) along the MCT. The Greater Himalayan Crystalline Complex is separated from Tethyan Himalaya by South Tibetan Detachment (STD) Fault which is a north dipping normal fault (figure 1). The Greater Himalayan Crystalline Complex in the Arunachal Himalaya consists of high grade migmatites, paragneiss, augen gneiss, amphibolites and Tertiary Leucogranites (Bhattacharjee and Nandy 2007; Kumar 1997; Goswami et al. 2009). The Tethyan sequence is not exposed in the study area. The GHS also host several MCT tectonic windows represented by lithologies equivalent of Dirang Formation. The present paper focuses on the western part of Arunachal Himalaya.

3. Arc parallel extension

3.1 Higher Himalaya (Zimithang valley)

The Himalayan–Tibetan orogen hosts numerous major active normal fault systems and grabens documenting general E–W extension that are distributed most extensively in the southern Tibetan plateau (figure 1). Most of them show strike at several places normal to the trend of the orogen (Molnar and Tapponnier 1978; Ni and York 1978; Armijo et al. 1986; Molnar and Lyon-Caen 1988; Ratschbacher et al. 1994). Fault plane solutions of earthquakes from Himalaya document thrust-related radial shortening, while the Tibetan region shows extension-related pure normal faulting both in shallow and deeper crustal levels (Molnar and Chen 1983; Ni and Barazangi 1984; Seeber and Armbruster 1984). Geodetic results of Banerjee and Bürgmann (2002) reveal active E–W extension both in the internal parts of Himalaya and Tethyan region.

The N–S striking extensional faults and associated grabens are not only pervasive in the southern Tibet, but are also extensively developed in the Higher Himalayan zone along the entire orogen (figure 1). Most of the extensional features cut across earlier structures. These extensional structural features occur either as isolated normal faults or as linked graben systems (Armijo et al. 1986;

Molnar and Lyon-Caen 1988; Ratschbacher et al. 1994; Murphy et al. 2002; Thiede et al. 2006). A recent paper by Hintersberger et al. (2010) documented active E–W extension throughout the NW Indian Himalaya. Their data indicate that the extension is not limited to the higher parts of the Himalaya, but is also found in the lower elevation regions as low as 1500 m.

Although extensional structures in the NW Himalaya are well documented, the NE Himalaya still remains poorly documented. The major orogen perpendicular N–S striking normal faults in the eastern part of southern Tibet and NE Himalaya are the Yadong–Gulu rift, which extends into the Higher Himalaya in Bhutan and the Cona–Oiga rift that extends into the Higher Himalayas of western Arunachal Pradesh (figure 1). The Cona–Oiga rift is about 120 km long and trends $\sim 12^\circ\text{N}$. It lies between 89° and 92°E longitudes and between $27^\circ 40'$ and 31°N latitudes. It cuts the STD to the south and extends across the Yarlung Tsangpo Fault into the eastern Gangdese batholith zone to the north. The Cona–Oiga rift consists of three independent grabens. The southernmost Cona graben has a maximum width of ~ 10 km and tapers at its southern end into the Arunachal Higher Himalaya (figure 1). The normal fault is located on the western margin of the basin and dips towards east. Two large earthquakes of M7.5 and M7.0 have occurred at the northern Cona in 1806 and southern Oiga in 1915, respectively (Zhong-hai et al. 2008).

In the present study, analysis of 30 m SRTM image first revealed an approximately north–south trending normal fault feature west of Cona rift. During our field investigation, this normal fault (F_1) was observed close to Zimithang trending NNE–SSW and dipping west (figure 1). The F_1 fault forms a half graben in the western side of the Cona rift close to its southern termination end in western Arunachal Pradesh (figures 1 and 3a, b). Similar to Cona rift, fault F_1 also cuts across the South Tibetan Detachment system (figure 1). The F_1 half graben is about 60 km long and 7 km wide. This half graben seems to have collapsed within into another N–S trending smaller graben of ~ 2.5 km long and 2 km wide and is bound by faults F_2 (figure 3b). Both the F_1 half graben and F_2 related graben have developed within the augen gneisses of Higher Himalaya. The F_2 faults related graben at its southern end is bound by E–W trending vertical normal fault represented by the F_3 fault scarp close to Zimithang. The scarp is ~ 100 m high and extends for about ~ 1 km along E–W (figure 3b and c). The northern end of the graben is also bound by a similar fault (F_4) trending ENE–WSW, however is accompanied by sinistral slip (figure 3b). None of the north and south

Figure 3. (a) Google-earth satellite image at Zimithang depicting the sudden change in the behaviour of the drainage pattern. Area within red ellipse is enlarged and demonstrated in (b). (b) Google-earth satellite image at Zimithang depicting arc-parallel extensional N-S trending half graben flanked by west dipping fault F_1 (location shown in figure 1). The small graben is flanked by the F_2 faults and bound at its southern end by north dipping normal fault (F_3), the northern end is flanked by normal cum sinistral fault (F_4), (c) vertical scarp face of the F_3 fault in the eastern bank of the river, and (d) channel showing abrupt break in the river morphology from braided type drainage to constricted bouldery channel in the downstream. Locations of (c) and (d) are shown in (b) with arrows indicating the photo direction.

bounding E–W faults (F_3 and F_4) cut across the main fault F_1 . A drastic change in river morphology is observed where the river crosses the fault F_3 . The narrow stretch of ~ 2.5 km broad south flowing anastomosing river with several sand bars abruptly changes its morphology to a narrow river channel constricted by large boulders (figure 3b–d) close to the fault F_3 . Similarly at the northern end close to fault F_4 , a constricted boulder laden channel in the north flows into a broad channel in the south. The stretch of anastomosing channel is observed only between fault F_3 and F_4 (figure 3b).

The Cona–Oiga rift cuts across STD and extends for only few kilometers towards south (Zhong-hai *et al.* 2008). However, the fault F_1 in the western Arunachal cuts across the STD and extends further south close to MCT (figure 1). We interpret that the E–W trending faults F_3 and F_4 have formed due to the collapse between the N–S trending faults F_2 . The extensional faulting resulted in the formation of linear graben that is geomorphologically represented as broad anastomosing channel seen presently. The graben formation might have resulted in the formation of an elongated lake damming at its northern and southern ends by faults F_3 and F_4 . However, the continued uplift of the Higher Himalaya provided greater slope towards south resulting in abandoning of lake and formation of anastomosing channel seen presently. The geomorphic evidences thus indicate periodic reactivation of E–W extension. Such reactivated extensional features were earlier documented by Armijo *et al.* (1986) in the southern Tibet. Low temperature thermochronological studies on migmatites from the E–W river valley in Tawang revealed Apatite Fission Track (AFT) exhumation age of ~ 1 Ma (De Sarkar *et al.* 2012). The Zimithang study area being only 30 km north-west of Tawang, we presume that the Zimithang zone might also have experienced similar exhumation history. This implies that the smaller graben formation at Zimithang might have occurred sometimes during Late Quaternary period post ~ 1 Ma. The formation of Zimithang graben in stages is represented schematically in figure 4.

Yin *et al.* (2010) considered Kakthang–Zimithang thrust as a regional out-of-sequence thrust in the hanging wall of MCT. The Kakthang thrust in Bhutan is considered out of sequence based on the youngest age of 12.5 ± 0.4 Ma crystallization age from Khula Kangri granite (Edwards and Harrison 1997). According to Yin *et al.* (2010), the Kakthang thrust extends from Sikkim through Bhutan up to the central Arunachal Himalaya. Since the thrust passes through the Zimithang village, it was called as Khakthang–Zimithang thrust. The geomorphic

Figure 4. Schematic model of Zimithang graben formation. (a) Formation of F_1 half graben caused by arc-parallel extension, (b) initiation of F_2 graben formation due to collapse of F_1 half graben, post 1 Ma and (c) widening of the graben and formation of $\sim$ E–W bounding faults (F_3 and F_4) due to lake subsidence (see text for complete details). The broken lines along with the sense of movement on the front face of the block diagram (b and c) represent basin formation only within the small graben.

evidences discussed above on the drainage morphology change at Zimithang do not support the fault to be a thrust. The uplift of the hanging wall would have resulted in deep incision by the south flowing river. However, the field evidences indicate linear basin formation. In the DEM and geological map of Grujic *et al.* (2006) and

Goswami *et al.* (2009), the Khakthang–Zimithang fault is shown passing south of Zimithang.

3.2 Lesser Himalaya (Dirang valley)

Most of the extensional structures shown in figure 1 are located around prominent morphological features such as the grabens. To document the pervasive distribution of these extensional structures in the Lesser Himalayas, we analysed incised fluvial terrace deposits. In the eastern Himalaya, the MCT can be traced almost continuously from Nepal, Sikkim and Bhutan to the eastern Himalayan syntaxis in Arunachal Pradesh (Gansser 1964, 1983; Mohan *et al.* 1989; Singh and Chowdhary 1990; Kumar 1997; Ding *et al.* 2001). In contrast

to the broad shear zone in Bhutan, the MCT zone is exposed as contact between overlying sillimanite-kyanite migmatite, sillimanite-kyanite schist and underlying garnet-staurolite schist, phyllite, quartzite rocks in western Arunachal Pradesh (Singh and Chowdhary 1990; Goswami *et al.* 2009). During our investigation of fluvial terrace deposits south of MCT, a normal listric fault was observed at Dirang on a partially exposed face of a fluvial terrace deposit (figure 5a). To expose the fault trace, the face was scarped and cleaned. However, bottom part of the fault could not be exposed properly fearing collapse of the wall itself thereby affecting human settlement over the deposit. The incised terrace from the river valley is ~45 m in height. The fault strikes $\sim 320^\circ$ and dips 20° – 25°

Figure 5. (a) Normal fault exposed within the Quaternary fluvial terrace at Dirang. Inset of stereogram shows the orientation of fault, (b) Google-earth satellite image of the area showing N–S gully erosional feature (F–F) along which the river makes a turn, (c) lineament map of the area. The location of normal fault is shown in (b) and (c), and (d) rose diagram of the lineament trends, showing majority of lineaments trending N–S attributed to the features related to E–W extension.

due SW. The displacement, measured along the trace of the fault plane between the marker beds consisting of medium grained sand at the opposite sides of the fault, is 7.2 m. The fault cuts through the upper exposed surface consisting of coarse debris flow deposit. The exposed scarp section shows cross stratified medium sand layer at the bottom, followed by a 1.2 m thick trough cross bedded medium grained sand layer with gravels, overlain by 0.8 m thick layer of fine sand and further by gravel bed of similar thickness as the fine sand layer (figure 5a). The upper thickest deposit is represented by a bouldary-gravel bed, consisting of large gneissic boulders. The largest boulder size is ~ 0.4 m. The lateral extension of this Quaternary fault into the Dirang quartzite was precluded due to thick vegetation in the entire area.

Optically Stimulated Luminescence (OSL) dating of upper coarse debris deposits was done to fix a lower time bound of the faulting event as OSL age of sediment gives the depositional age. Sediment sample was collected in a metal pipe from ~ 1 m below the surface. Sample preparation was done under restricted light condition following the standard protocol. Equivalent dose (De) was estimated following SAR (single aliquote regenerative dose) protocol proposed by Murray and Wintle (2000, 2003). OSL signals were recorded at 125°C for 100 s through UV filter and a $^{90}\text{Sr}/^{90}\text{Y}$ beta source was used for irradiation. Equivalent dose (De) of the sample was 19 ± 1.4 Gy and uranium, thorium and potassium concentration of the sample gave annual dose rate of 5126 ± 483 Gy/ka. The OSL age of the sample was estimated as 3.5 ± 0.2 ka. The depositional age indicates the normal faulting event to be post 3.5 ka.

One of the characteristic geomorphologic features observed on extending Quaternary fault trace as shown in figure 5(b) is that the Bichom River is deflected close to the trend of the fault at Dirang from its original course. The river enters the fault zone and turns parallel to the normal fault trace and flows down and finally returns to its original flow direction. The trend of the Quaternary extensional fault and the trace of deflected stream also reveal extensive N–S gully erosional features north and south of MCT (F–F in figure 5b). We interpret these features to have developed as a result of the E–W extension. Similar extensional features were also reported recently by Hintersberger et al. (2010) in the NW Himalaya based on satellite imagery.

While the N–S extensional features documented here are only two of the sporadic evidences in the western part of Arunachal Himalayas, the pervasive presence of similar features in the central and NW Himalaya (Hintersberger et al. 2010) indicate that such features may not be uncommon in NE Himalayas.

4. Discussion

4.1 Cause for arc-parallel extension

Normal faults at Zimithang indicate dominant E–W extension, while Dirang show ENE–WSW extension. Tectonic models explaining the formation mechanism of orogen-perpendicular graben in the Himalayan orogen includes:

- active east–west extension in Tibet to gravitational failure due to attainment of high elevation and spreading of its thick crust, called as the *Lateral Extrusion model* (Tapponnier and Molnar 1976; Molnar and Tapponnier 1978; Tapponnier et al. 1982; Valli et al. 2007, 2008),
- extension in response to conjugate strike slip fault and eastward extrusion of Tibet (Armijo et al. 1986),
- extension due to outward radial expansion of the Himalayan thrust front, called the *radial expansion or spreading model* (Seeber and Armbruster 1984; Molnar and Lyon-Caen 1988; Seeber and Pecher 1998; Murphy and Copeland 2005),
- extension related to arcuate geometry of the subduction zone, called the *oroclinal bending model* (Klootwijk et al. 1985; Ratschbacher et al. 1994),
- extension attributed to rapid uplift of the Tibetan Plateau caused by convective removal of the lower mantle lithosphere (England and Houseman 1989; Royden et al. 1997),
- E–W extension in southern Tibet is argued as reflection of the local boundary conditions such as oblique convergence between India and Asia, called the *oblique convergence model* (McCaffrey and Nabelek 1998),
- extension due to Tertiary mantle upwelling in eastern Asia and thermal weakening of the lithosphere (Yin 2000),
- extension on account of mass accumulation and dissipation process (Hodges et al. 2001),
- extensional features attributed to local extension to metamorphic dome formation (Aoya et al. 2005), and
- extension in NW Himalaya driven by collapse of Tibetan Plateau (Hintersberger et al. 2010).

The various above models thus reveal that a concrete and viable explanation to the extensional features in both Tibet and Himalaya still remains enigmatic and subject of considerable debate. There are still large unexplored regions in NE Himalayas. A comprehensive database of extensional features along the entire NE Himalayas will be of great importance to test the viability of existing and new theories that might arise. However, evidences provided in the present study are discussed based on the oblique convergence and radial expansion models only, as most of the

extensional features can best be explained by these models.

4.2 Oblique convergence model

Structural and morphological features both at Zimithang and at Dirang reveal absence of evidences suggesting local doming. Within the Himalayan arc, both active normal and strike-slip faults are reported. The slip directions in general show arc-parallel characteristics, resulting in both arc-parallel extension and translation (Ratschbacher *et al.* 1994; Murphy and Copeland 2005; Murphy and Burgess 2006; Thiede *et al.* 2006; Li and Yin 2008). The orientation of three independent grabens of the Cona–Oiga rift indicates a dextral en-echelon pattern (figure 1); however, there exists no report on the basins north and south bounding faults. At Zimithang, F_4 fault associated with the north trending graben show left slip component along with dip slip (figure 3b). GPS vector data of Zhang *et al.* (2004) and Jade *et al.* (2007) with reference to Eurasia indicate that the geodetic vectors show normal orientation towards central and eastern parts of the Nepal Himalayan arc, while the convergence becomes progressively more oblique along the eastern Himalayan syntaxis (figure 1). Shen *et al.* (2005) and Allmendinger *et al.* (2007) have shown that the eastern Himalayan syntaxis show significant clockwise vertical axis rotation. The variation in convergence results in varying arc-parallel and arc-normal components relative to the Indian plate motion. The varying convergence would cause the total strain getting partitioned along the Himalayan arc into arc-normal shortening (thrusts), arc-parallel extension (rifts/normal faulting) and translation (strike-slip faults). The regional compressive stress direction turns from NE in the NW Himalaya, through north in the central Himalaya to NNW in NE Himalaya (figure 1). Extensional force acts perpendicular to the compressive force. Therefore, an arc-parallel extensional regime develops perpendicular to the direction of shortening.

We attribute the Zimithang graben, sinistral faulting and the evidence of normal faulting at Dirang as evidence of arc-parallel relieving of the strain in this region contemporaneous with the compressive phase. With regard to the earthquake focal mechanism, the seismic event B (figure 1) close to Bomdila in the year 1995 of $M_w \sim 5.4$ indicates dominant arc-parallel normal-slip component mechanism. The events A and C show strike slip components, while event D indicates dominant NW–SE contraction. The seismic events E and F reveal dip slip components close to STD, however, the event G at the syntaxial zone show $\sim$ N–S normal faulting associated with translation

movements. We presume that this is due to the sinistral movement at the eastern end of STD and dextral movement over the Jiali fault.

The Quaternary evidences at Zimithang and Dirang and the seismic events (B and G) reflects active arc-parallel extension mechanism along the strike of the eastern Himalayan arc, resulting in arc-perpendicular normal faulting and arc-parallel sinistral faulting. The left-slip faulting at Zimithang if accounted along with the extent of other left-slip fault zone in the eastern Himalaya, such as the dominant left-slip fault in the eastern syntaxial area (figure 1) of Namche Barwa (Burg *et al.* 1998; Ding *et al.* 2001) indicates that the eastern Himalaya shows distinct contrast to the right-slip deformation dominant in the north-western Himalaya (Karakoram fault in figure 1). The block model experiment of McCaffrey and Nabelek (1998) supports and demonstrates our interpretation of sinistral slip fault in the western Arunachal Himalaya. The block model experiment showed convincing evidences on the cause for radial slip vectors, arc-parallel translation and stretching occurring on account of oblique convergence. The oblique thrusting of India beneath the Himalayas and Tibet results in partitioning of the oblique convergence due to drag shear of the subducting plate. In the oblique convergence model, Indian plate motion, relative to Eurasian plate (red arrows), has an arc-normal component (blue arrows) and an arc-parallel component (white arrows) causing arc-parallel extension and along strike translations of the Himalaya (figure 1). These are manifested along the Himalayan arc as N–S extensional faulting and dextral slip faulting in NW Himalayas, absence of significant translational faults but presence of arc-perpendicular normal faults in central part of Nepal, sinistral slip faulting and normal faulting in the NE Himalayas (figure 1). The extension driven by the basal shear can affect the upper plate at any elevations (McCaffrey and Nabelek 1998).

4.3 Radial expansion model

The outward radial expansion or spreading model of the Himalayan arc (Murphy and Copeland 2005; Murphy *et al.* 2009) also provides satisfactory explanation towards the arc-parallel extension following arc-normal shortening. As thrust wedge propagates towards foreland developing new thrust at the front, contemporaneous arc-parallel extension occurs at the back. The vertical stress being minimum (thrust) in the foreland becomes maximum (normal fault) or intermediate (strike slip fault) in the hinterland part. The model states that the collisional arc expands radially outward along a single thrust without deforming the

underthrusting lithospheric plate, while the thrust front suffers extensive extension. In a system of multiple thrusts like Himalaya, extension will be more active in the hinterland regions and decrease towards the foreland, as older thrust sheets in the hinterland gets greater radial push and therefore, gets translated to maximum distance than the younger thrust sheets in the foreland, where the convergence exceed expansion. Thus, the zone of crustal shortening propagates towards foreland creating space for zone of crustal expansion in the hinterland.

The amount of arc-parallel expansion is directly related to the amount of radial shortening. Murphy *et al.* (2009) proposed an equation to compute arc-parallel extension from the amount of arc-normal shortening. The magnitude of extension is expressed as:

$$E = R\alpha\pi/180 \quad (1)$$

where E is the amount of arc-parallel extension, R is the amount of arc-normal shortening and α is the angle of the arc segment taken into consideration.

Bendick and Bilham (2001) considered the shape of Himalayan arc as a small-circle centred at $92.1^\circ \pm 1.6^\circ$ E longitude and $42.4^\circ \pm 2.1^\circ$ N latitude with a radius of 1696 ± 55 km, which corresponds to an arc segment of 16.2° or 1800 km. However, this small-circle is applicable only for the arc segment between 77.2° and 92.1° E latitudes (figure 1, broken yellow line). They considered four independent datasets to compute a single curve for the Tibet–Himalaya collision arc. Independent best fit curves were computed based on parameters, viz., maximum relief, seismicity, regional stress and fluvial knick points. Change in relief is the product of interaction between uplift rate and fluvial incision rate. If incision rate is assumed constant all along the arc-normal profile, high relief directly manifests high uplift rate. Quantitative measurement from leveling data indicates that the locations of maximum relief and maximum vertical velocity are coincident, through which one of the best fit curve has been drawn by Bendick and Bilham (2001). According to them the principal stress direction is dominantly arc-normal in the southern part of the collision zone, while it is vertical in the northern part. In the southern part, minimum stress direction is vertical. Therefore, arc-normal compression represents thrust related structures in Himalaya indicating maximum vertical velocity of deformed particles. A small-circle was therefore, fitted to the shallow earthquake events along the Himalayan arc which show arc-normal compression. Vertical compressive stress is minimum (σ_3) in the south of Tibetan plateau while it is maximum (σ_1) within the plateau (Molnar and Lyon-Caen 1989). They proposed from the earthquake focal

mechanism data that the transition from minimum vertical stress (σ_3) to maximum vertical stress (σ_1) indicates the zone of continental collision which coincides to 4000 m contours. A small-circle was therefore, again drawn to fit the 4000 m contour in the Himalayan arc. River is considered as one of the best geomorphic indicator to tectonic activity. Fluvial knick points are the response of river related to active uplift in that area. Thus it also corresponds to the area of maximum vertical velocity. One independent small-circle was also drawn through the river knick points. Bendick and Bilham (2001) provided the final curve for the Himalayan arc after considering all the individual small-circles discussed above.

The NE Himalaya does not fall in the small-circle proposed by Bendick and Bilham (2001). Since the small-circle constructed based on topography show sudden divergence from the model arc due to Shillong Plateau, that accommodates large amounts of shortening, the small-circle proposed by Bendick and Bilham (2001) does not extend into the NE part of the Himalaya. Therefore, another small-circle is required to compute the NE Himalayan arc segment. We followed the criteria of state of stress suggested by Bendick and Bilham (2001) and fitted a small circle through 4000 m smoothed contour in the NE Himalayan region. The other data used by them were insufficient for the NE Himalaya to calculate an independent small circle; however, these meager data are qualitatively fitted well into the circle. We calculated circle equations through the contour points by keeping two end points of the contour fixed and varying the third in the middle and then took the mean of the centre and radius of those circles. The computed uncertainty is 1σ standard deviation of the data. We propose a best fit small-circle for the NE Himalaya which is defined by the centre at $88^\circ 39' \pm 0.7'$ E longitude and $33^\circ 40' \pm 0.6'$ N latitude and radius of 770.7 ± 15.1 km for the arc segment between $92^\circ 01'$ and $95^\circ 16'$ E longitudes (figure 1, broken red line).

Yin *et al.* (2010) estimated the Cenozoic shortening of minimum 315 km from the map relationship in the northeastern Himalaya from the lateral stretch between 92.6° and 94.7° E which falls within the 20° arc segment of the proposed NE Himalayan small-circle in the present paper. Taking this shortening into account along the 20° arc segment (figure 1), the amount of arc-parallel expansion computed based on equation (1) is 110 km. The rate of E–W extension in the southern Tibet is known from the geodetic study. Chen *et al.* (2004) illustrate that there is spatial non-uniformity in the extension pattern along the Himalayan arc and the rate of extension increases towards east. The extension rate computed between Lhasa and Gongbu

(figure 1) is ~ 13 mm/yr (Chen *et al.* 2004). Timing of initiation of arc-parallel extension in the Himalaya and southern Tibet has been estimated by many authors. E–W extension in the south of Leo Pargil gneiss dome started at around 16 Ma revealed by $^{40}\text{Ar}/^{39}\text{Ar}$ age of synkinematic micas on a fault plane (Hintersberger *et al.* 2010). Lee *et al.* (2011) reported that the age of initiation of the Kung Co rift extension is ~ 12 –13 Ma based on zircon and apatite (U–Th)/He thermochronology. A range of 14–10 Ma has been suggested as the age of opening of the Thakkhola graben (Coleman and Hodges 1995; Garzione *et al.* 2000; Hurtado *et al.* 2001) in the western part of south Tibet. The onset of E–W extension across the Yadong–Gulu rift was postulated from the stratigraphic relationship with South Tibetan Detachment fault. STD cuts the Khula Kangri granite (12.5 Ma) and was activated until 10 Ma, which imply that the E–W extension probably started after 10 Ma (Edwards and Harrison 1997). Harrison *et al.* (1995) reported 8 Ma as the initiation age for Neogene extension of the plateau based on $^{40}\text{Ar}/^{39}\text{Ar}$ cooling age of Nyainqentanghla massif in the northwest of Yadong Gulu rift, while from the NE part of the Gulu rift, apatite (U–Th/He) thermochronology of the rocks from footwall suggest onset of extension around 7–5 Ma (Stockli *et al.* 2002). Due to the obliquity of India–Asia convergence, the arc-parallel extension in the southern Tibet and Himalaya initiated first in the western part and subsequently migrated towards east, as supported by the ages reported by various authors from different areas (figure 1). Thus, for the northeastern part of Himalaya, an age of ~ 8 Ma (Harrison *et al.* 1995) has been considered in the present study as the age of extension initiation. Based on the rate (~ 13 mm/yr) of arc-parallel extension reported by Chen *et al.* (2004) and age of 8 Ma as the initiation of extension (Harrison *et al.* 1995), imply a total extension of ~ 104 km. This corroborates closely with the amount (110 km) of extension calculated by the radial expansion model.

Analysis of the major lineaments in the study area (figure 5c) and its rose diagram (figure 5d) indicates that the first three higher frequencies fall in the trends of N–S, E–W and NW–SE respectively. The Himalayan range is mostly E–W trending while in the northeastern segment it turns towards ENE–WSW. Major thrusts, which create the high relief, run parallel to the Himalayan arc. Thus the E–W lineaments follow arc-parallel compressive structures. The N–S lineaments are evidences pointing towards the extensional features in the area.

The Quaternary arc-parallel extension evidences and mechanism suggested in the present paper indicate that there must be several pervasive

extension related features along the NE Himalaya. Towards the syntaxial zone, translation related arc-parallel extension would dominate over the combination of north trending rift/normal fault and translation in the western and central parts of the Arunachal Himalaya. Further field studies, structural mapping and chronology would extend more conclusive evidences to understand the effective mechanism dominant in the NE Himalayas in particular and Indo-Tibetan collision dynamics in general.

5. Conclusions

The present study enables following inferences:

- There exist pervasive extensional related features in the NE Himalaya, extending from Tibet to the Lesser Himalaya. The Quaternary evidences of arc-parallel extension at Zimithang as graben, sinistral faulting and the evidence of normal faulting at Dirang suggest arc-parallel relieving of the strain in this region. The oblique thrusting of India beneath the Himalayas and Tibet resulted in partitioning of the oblique convergence due to drag shear of the subducting plate. The variation in oblique convergence along the Himalayan arc have resulted in the partitioning of strain along the Himalayan arc into arc-normal shortening (thrusts) and arc-parallel extension (rifts/normal faulting) and translation (strike-slip faults).
- Thrust wedge propagation towards foreland resulted in new frontal thrusts, while contemporaneous arc-parallel extension occurred in the hinterland regions. The amount of arc-parallel expansion is directly related to the amount of radial shortening. Analysis of the NE Himalayan arc segment based on considering a separate small-circle defined by the centre at $88^{\circ}39' \pm 0.7^{\circ}\text{E}$ longitude and $33^{\circ}40' \pm 0.6^{\circ}\text{N}$ latitude and radius of 770.7 ± 15.1 km reveal that in the 20° arc segment the amount of arc-parallel expansion is ~ 110 km. This corroborates closely with the amount of extension ~ 104 km calculated based on the rate of E–W extension and Neogene extension age estimate. The arc-parallel extensional features in the western Arunachal Himalaya can be explained satisfactorily by the oblique convergence and radial expansion models. However, this may not be entirely true for the Tibetan Plateau.

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