A review on out-of-sequence deformation in the Himalaya

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Abstract: Out-of-sequence deformation in the Himalaya has been caused mainly by thrusting. Out-of-sequence thrusts, usually north- to NE-dipping foreshear planes, occur inside the Sub-Himalaya (SH), Lesser Himalaya (LH) and Greater Himalayan Crystalline (GHC) sequences. Where absolute dates are available, the youngest slip within the SH occurred near the Janauri Anticline (India) at *c.* AD 1400–1460. The Munsiari Thrust (India) activated within the LH at *c.* 1–2 Ma and the Main Central Thrust zone in the Marsyandi valley (Nepal) in the GHC was formed during the Holocene (*c.* 0.3 ka). Except for the Riasi Thrust (Kashmir, India), the Paonta Thrust (Himachal Pradesh, India) in the Siwalik and the Tons Thrust (Garhwal region, India) within the Main Central Thrust zone, crustal shortening related to out-of-sequence thrusting in the Himalaya has been insignificant. The major litho-/stratigraphic contacts within the SH and the GHC at some places acted as out-of-sequence thrusts. Out-of-sequence thrusts in the SH have been detected mainly based on geomorphological observations. However, more quantitative geochronological studies have detected out-of-sequence thrusting from *c.* 22 Ma up to Holocene age in the GHC based on age jumps, especially within the Main Central Thrust zone. Crustal channel flow (specifically for the GHC) and/or the critical taper model with or without erosion can be used to explain the Himalayan out-of-sequence thrusts.

The Himalayan orogen consists of three lithotectonic units (Fig. 1). From south to north these are: (1) the Mid-Miocene to Mid-Pleistocene nonmarine coarsening-upwards sedimentary succession of the Siwalik Supergroup/Sub-Himalaya (SH); (2) the Proterozoic phyllites, slates, schists and gneisses of the Lesser Himalaya (LH); and (3) the schists and gneisses of the Higher Himalaya or the Greater Himalayan Crystalline (GHC) sequences. The Siwalik Supergroup is delimited by the Himalayan Frontal Thrust or the Main Frontal Thrust (MFT) in the south and by the Main Boundary Thrust (MBT) in the north. The contact between the LH and the GHC is the Main Central Thrust (MCT), which is either sharp or a 1–10 km thick zone (the MCT zone), with the MCT-Lower ($MCT_L =$ MCT1) at the south and MCT-Upper ($MCT_U =$ MCT2) at the north (review in Godin *et al.* 2006; Yin 2006; Mukherjee 2013*a*, *b*; Yakymchuk & Godin 2012). The MCT zone is a mélange of LH and GHC rocks. The northern boundary of the GHC is the South Tibetan Detachment System-Upper ($STDS_U$), which underwent a first top-to-the-SW ductile shear followed by top-to-the-NE extensional ductile deformation (review in Yin 2006). A second strand of extensional ductile shear zone occurs in some sections in the GHC and is referred to as the STDS-Lower ($STDS_L$) (Mukherjee & Koyi 2010a). Top-to-the-SW shear in the MCT_L occurred from 15 to 0.7 Ma and in the MCT_U from 25 to 14 Ma. Top-to-the-NE shear occurred in the $STDS_L$ from 24 to 12 Ma and in the $STDS_U$ from 19 to 14 Ma (review in Godin *et al.* 2006). The MCT zone assembled rocks with various P–T–t constraints (Imayama 2014). The MBT and the MFT sheared top-to-the-SW from 9–11 to <2.5 Ma, respectively (review in Thakur *et al.* 2014). Thus, from the MCT_U up to the MFT, deformation migrated towards the south/foreland side in an in-sequence manner. Crustal channel flow and/or a critical taper mechanism have been proposed to explain the tectonics of the GHC (Beaumont & Jamieson 2010). The MFT, MBT and MCT merge at depth into a gently dipping Main Himalayan Thrust (MHT)/Main Detachment Thrust (Yin 2006) that became 'locked' at *c.* 15–20 km depth (Ader *et al.* 2012). Cross-section balancing studies by Schelling *et al.* (1991) suggested that the MHT is *c.* 6 km deep in Siwalik, Nepal.

In a collisional orogen, the hinterland to foreland propagation of deformation is in-sequence deformation. A deviation from this is late-breaking deformation (Robinson 2008), breaching, or out-of-sequence deformation, which have been noted from several orogens such as the Alps (e.g. Castellarin & Cantelli 2000), Zagros (e.g. Agard *et al.* 2005) and the Himalaya (this work). Out-of-sequence deformation is most commonly manifested by thrusting, although strike-slip faulting, folding and fracturing are also possible.

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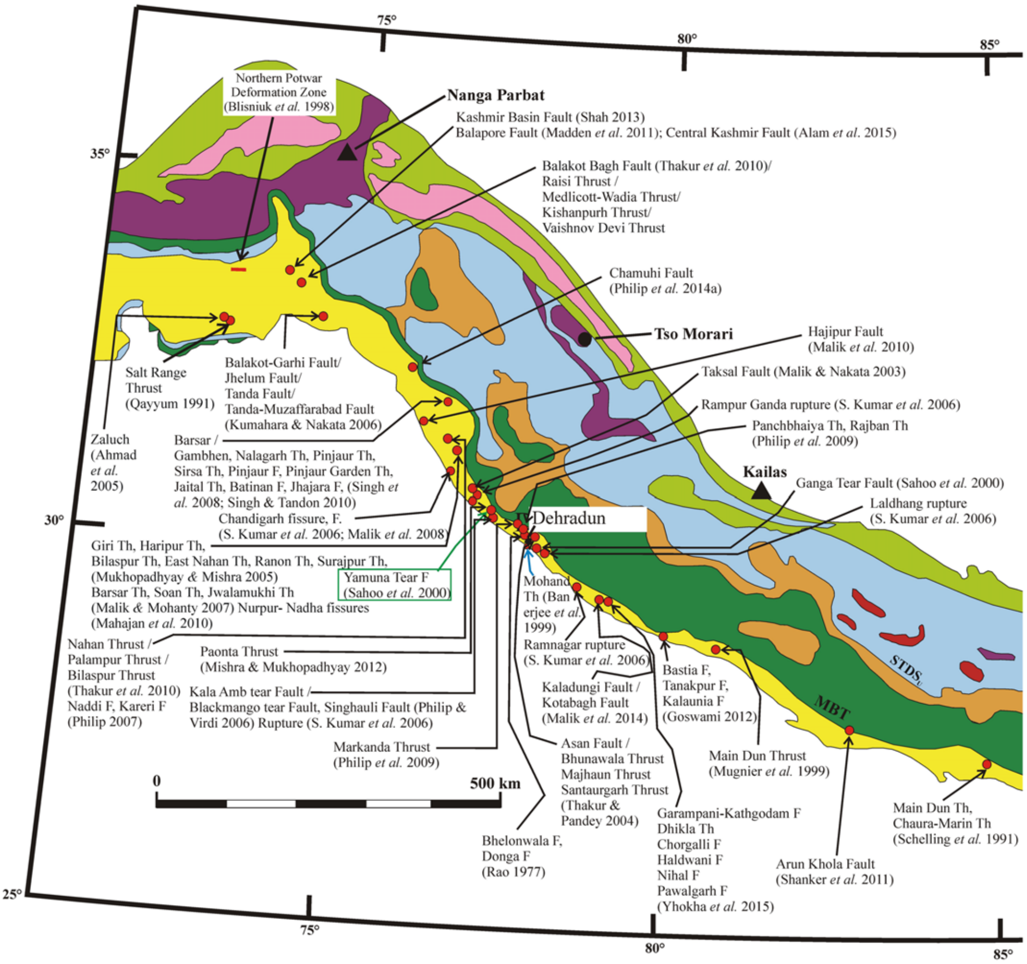
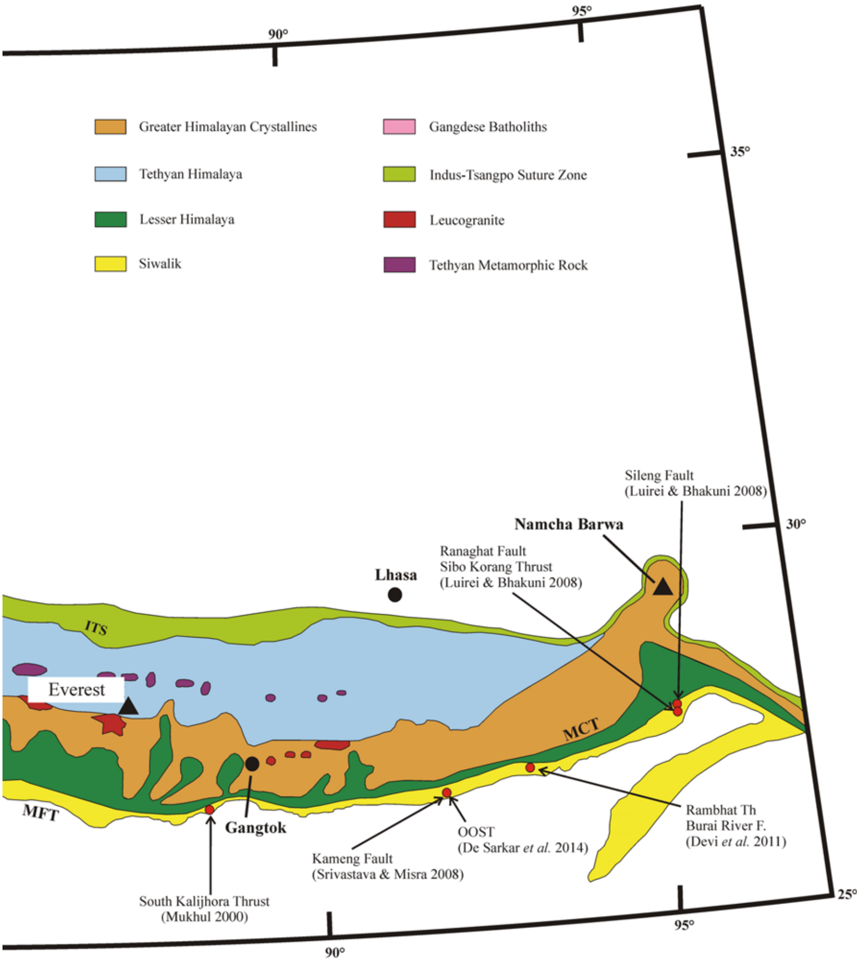


Fig. 1. The Himalayan orogen and its geological divisions. Reproduced from Zhang *et al.* (2015, fig. 1) with permission MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS_U, South Tibetan Detachment

Out-of-sequence thrusting develops favourably within a ductile regime in analogue models (Cotton & Koyi 2000). The reactivation of a thrust in a fold-and-thrust belt or thrust wedge can generate an out-of-sequence thrust. Conversely, an out-of-sequence thrust can also reactivate other thrusts (Mukhopadhyay & Mishra 1999). Out-of-sequence thrusts can be straight (Mukherjee *et al.* 2012), almost uniformly curved (Arita *et al.* 1997, fig. 1), or sigmoid-shaped in structural cross-sections (Park *et al.* 2000). Out-of-sequence thrusts may occur randomly in a deforming crustal wedge (Rajendran & Rajendran 2011). Such faults can generate from the ramp part of a fault system with a ramp-flat geometry (Rajendran & Rajendran 2011). Because the vergence of out-of-sequence thrusts is usually towards the foreland, it would prohibit subduction in a collisional orogen (Glessner *et al.* 2001). Major longitudinal fault zones in collisional orogens may have out-of-sequence deformation (St-Onge *et al.* 2006). Out-of-sequence thrusts have usually been observed to generate in the hanging-wall block of pre-existing thrusts and may cross-cut folds and faults in the other block (Searle *et al.* 1988). The documentation of such thrusts can lead to new tectonic models (Webb 2013).

Out-of-sequence thrusts in the SH and LH have been described in detail in terms of ‘active faults’ that may not have the same sense of slip as the older faults (see Nakata 1989 for an older review). Until the 1980s, Himalayan geologists were not very successful in finding out-of-sequence thrusts because of the vegetation cover (Nakata 1989). However, as remote sensing techniques have advanced,



from Elsevier. In this work, out-of-sequence thrusts within the Siwalik Himalaya are plotted from previous publications. System-Upper; ITS, Indus Tsangpo Suture.

there have been increasing reports of out-of-sequence thrusts from the Siwalik Himalaya (e.g. Philip *et al.* 2012). Out-of-sequence thrusts from the GHC and parts of the LH have been deciphered mainly from geochronological studies.

Studying out-of-sequence thrusts has several applied aspects because: (1) these are regions of (higher) seismicity (Park *et al.* 2000; Avouac *et al.* 2006); (2) these structures can entrap and preserve source rocks for hydrocarbons (Grelaud *et al.* 2002); and (3) they constitute an integral part of collisional orogens/fold-and-thrust belts (Molinaro *et al.* 2005). However, not all out-of-sequence thrusts are related to seismicity. For example, for the 4.0–1.5 Ma old Chaura/Sarahan Thrust in Himachal Pradesh, India (Jain *et al.* 2000), no earthquake record exists. Simpson (2010) considered out-of-sequence thrusting to be a ‘normal’ incident in thrust tectonics and Himalayan geologists have described such deformation from several sections of the Himalayan orogen over a vast geographical extent, sometimes along with genetic models. A number of reviews of Himalayan tectonics have been published (e.g. Nakata 1989; Yin & Harrison 2000; Jain *et al.* 2002, 2012; Gehrels *et al.* 2003; Yin 2006; Jain 2014). However, none of these discusses out-of-sequence thrusting separately in all the three sectors of the SH, LH and GHC.

This paper reviews out-of-sequence deformation and thrusting in the SH, LH and GHC, mainly in India, Nepal and Bhutan. Unless specified as normal or strike-slip faults, all the out-of-sequence thrusts described here are reverse faults. They usually dip towards the north to NE. Out-of-sequence thrusts in

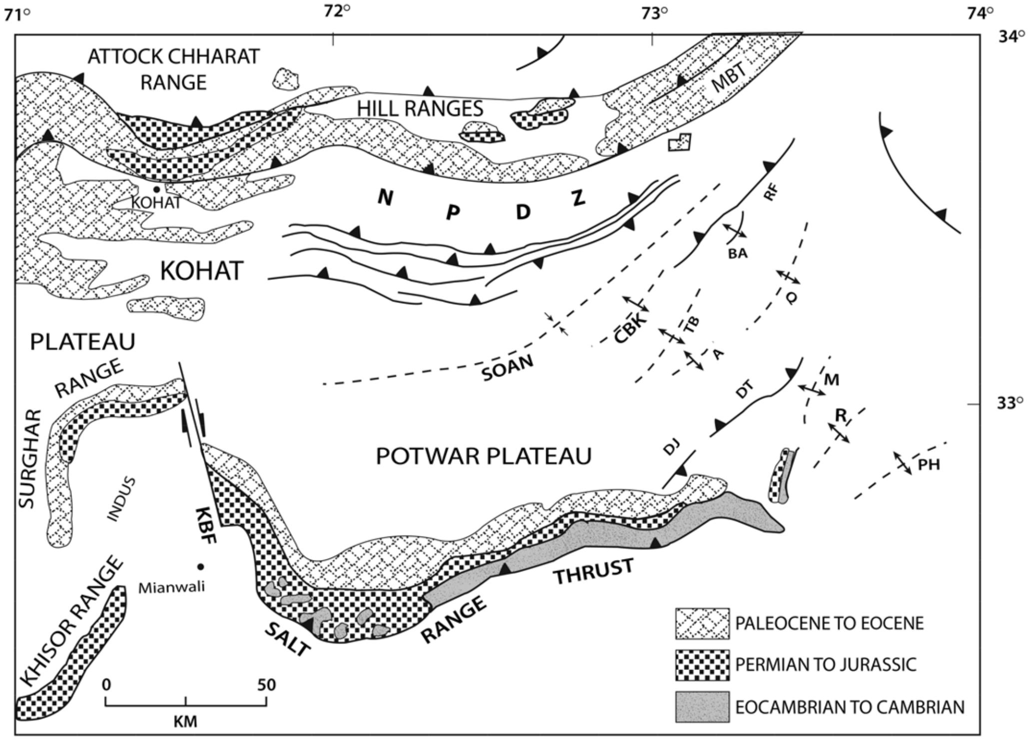


Fig. 2. Map of Salt Range and Potwar Plateau. Reproduced from Qayyum *et al.* (2014, fig. 1) with permission from Elsevier. NPDZ, Northern Potwar Deformed Zone; RF, Rawat Fault; CBK, Chak Beli Khan; BA, Buttar; TB, Tanwin Basin; A, Adhi; Q, Qazian; DT, Domeli Thrust; M, Mahesian; R, Rohtas; PH, Pabbi Hills; KBF, Kalabagh Fault, DJ, Dil Jabba Fault.

the Tethyan Himalaya (Murphy & Yin 2003), Tibet (Larson *et al.* 2010) and in the syntaxis were excluded from this study.

Out-of-sequence deformation in the Himalaya

Sub-Himalaya

Pakistan. The Salt Range region (Fig. 2) in Pakistan is characterized by syn-sedimentation out-of-sequence thrusting that occurred from 5 to 1.9 Ma. This led to *c.* 10 km of shortening and sequential synclines and anticlines in the Potwar basin (Qayyum 1991). In Pakistan, the deformation moved southwards after activation of the MBT. Blisniuk *et al.* (1998) established sedimentologically and structurally that deformation moved back in an out-of-sequence fashion into the Northern Potwar Deformation Zone.

The Muzaffarabad earthquake on 8 October 2005, close to the MBT in Pakistan, produced fractures and also a new N27W plane of slip (Champati Ray *et al.* 2005; see also Malik *et al.* 2007*a*). It also activated the Balakot–Garhi Fault of Kumahara & Nakata (2006), which includes the Jhelum Fault/Tanda Fault/Tanda–Muzaffarabad Fault (Aydan 2006)/Murree Thrust and the oblique-slip Muzaffarabad Fault (see also Champati Ray *et al.* 2009). The Balakot–Garhi Fault has a rupture interval of *c.* 3 kyr and vertical and horizontal slip rates of *c.* 1 and 2 mm a^{-1}, respectively (Kaneda *et al.* 2006). Note that seismic ruptures, most of which are near the MFT (Mugnier *et al.* 2011), have been reported to produce both in-sequence and out-of-sequence deformation (Mugnier *et al.* 2005). An interval in the uplift in the Early Pliocene of the Salt Range was linked with an out-of-sequence thrust (Burbank & Beck 1989). The fault constitutes a shallow crustal feature as the forelimb of the Zaluch Anticline seems to be an out-of-sequence thrust (Ahmad *et al.* 2005). Qayyum (1991) referred to an older out-of-sequence thrust in the Salt Range at *c.* 9 Ma and mentioned a few normal faults and back-thrusts produced in an out-of-sequence manner in this region. Qayyum (1991) proposed that the out-of-sequence thrusting in the Pakistan Himalaya developed in four steps.

Kashmir (India). The Medlicott–Wadia Thrust (Fig. 3), a splay of the MHT that includes the Balakot–Bagh Fault/Jhelum Fault (Dunning *et al.* 2007), Riasi Thrust, Palampur Thrust, Bilaspur Thrust and Nahan Thrust in the Pakistani and Indian SH, activated during the Late Quaternary–Holocene (Thakur *et al.* 2010). Thakur *et al.* (2010, 2014) considered the Palampur Thrust to be the same as, or a continuation of, the Bilaspur Thrust. The Bilaspur Thrust separates deformed Subathu and Dharmsala units from Siwalik rocks at the south (Powell *et al.* 1998). Valdiya (1980) inferred the Kishanpurh Thrust in the Indian Himalaya and Hakhoo *et al.* (2011) inferred the Vaishnov Devi Thrust in the Jammu region in India to both be the same as the Riasi Thrust. Philip *et al.* (2009) recognized the Markanda Thrust near Dehradun to be a continuation of the Nahan Thrust. The Medlicott–Wadia Thrust dips 30–50° towards approximately north and meets the MHT at *c.* 10 km depth (Vassallo *et al.* 2015, fig. 1). The Kashmir earthquake of M_w 7.6 in 2005 acted near the Balakot–Bagh Fault (Pakistan) and created surface ruptures parallel to the fault (Kaneda *et al.* 2008). The shortening rate for the Balakot–Bagh Fault (Hussain *et al.* 2009) is *c.* 1.4–4.1 mm a^{-1}, which is thought to be insignificant in Himalayan tectonics (Kaneda *et al.* 2008). Shah (2013) reported that the Balakot–Bagh Fault might be a continuation of the Kashmir Basin Fault and the 60° NE-dipping Balapur/Balapore Fault. Vassallo *et al.* (2015) recently stated that the Kashmir Basin Fault is a back-thrust dipping SW. However, Shah (2015*a*) argued that this fault is a forethrust dipping NE. Madden *et al.* (2011) recognized the Balapore Fault by identifying scarps through remote sensing studies. Optically stimulated luminescence studies by Madden *et al.* (2011) also revealed that this fault slipped at *c.* 0.3–0.5 mm a^{-1}, activated repeatedly during 18.7–1.5, 38.4–33.4 and 40 ka, and was especially inactive at *c.* 50 ±3 ka. This fault accommodated insignificant crustal shortening. Based on remote sensing and field studies, Alam *et al.* (2015) recognized the Central Kashmir Fault as a continuation of the Kashmir Basin Fault for *c.* 165 km. Alam *et al.* (2015) recognized the Central Kashmir Fault as a NNW-trending dextral strike-slip fault. Shah (2015*b*), however, emphasized a dip-slip component of this fault. The NW-trending Balakot–Bagh Fault passes through both the LH and the SH. The fault cuts the MCT and the MBT, but not the MFT (Kaneda *et al.* 2008, fig. 1). A trace of

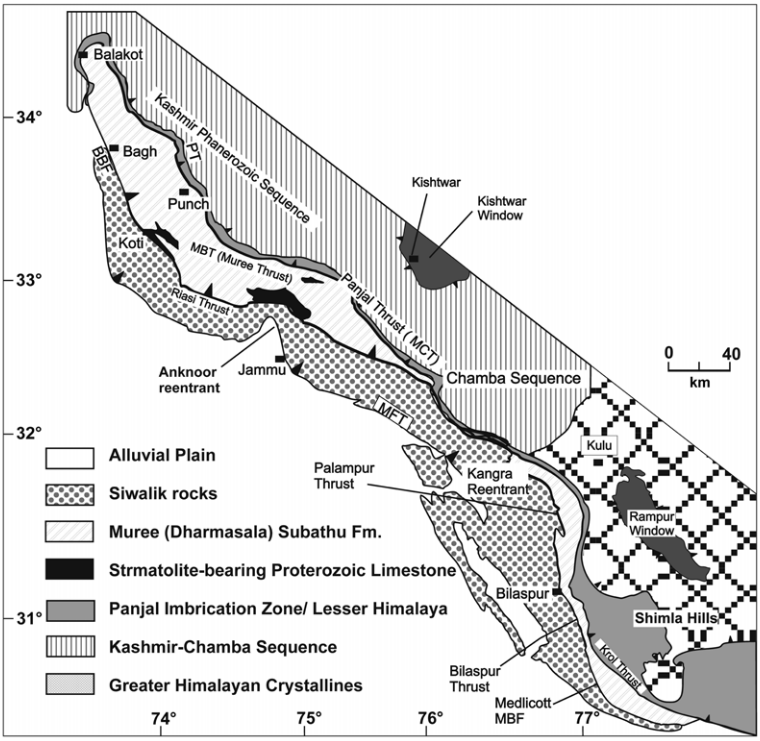


Fig. 3. Map of the NW Siwalik Himalaya. Reproduced from Thakur *et al.* (2010, fig. 1) with permission from Elsevier. BBF, Balakot–Bagh Fault; MFT, Main Frontal Thrust; PT, Palampur Thrust.

the Balakot–Bagh Fault, known as the Tanda Fault, cuts fluvial terraces. Thus it is inferred to have a Quaternary reactivation (review in Kaneda *et al.* 2008). The Riasi Thrust is *c.* 70 km long, dips 50° NE, and consists of the Main Riasi Thrust at the north (vertical separation: 272 m, uplift rate 5.0 ± 2.2 mm a^{-1}, slip rate 6.4 ± 2.9 mm a^{-1}, shortening rate 4.1 ± 1.9 mm a^{-1}) and the Riasi Frontal Thrust (shortening rate 8.8–4.4 mm a^{-1}, last rupture *c.* 450 yr ago) in the south (Gavillot 2011, 2014). The Riasi Thrust has taken care of 50% of crustal shortening since it came into existence (Gavillot 2014). This is the highest percentage of all the Himalayan out-of-sequence thrusts. A timing of *c.* 80–30 ka has been assigned to one of the two strands of the Riasi Thrust.

Webb (2013) described the Bilaspur and Palampur Thrusts as a ‘thrust system’. Gokarn *et al.* (2002) reported through magnetotelluric studies that the Palampur Thrust could be two thrust zones and that they reached *c.* 8 km depth. Webb (2013) designated the Bilaspur Thrust as an out-of-sequence thrust. Joshi & Kothyari (2010) referred to a slip deficit of 14 ± 1 mm a^{-1} for the Bilaspur Thrust deduced from a global positioning system study and predicted a major earthquake related to the Bilaspur Thrust in the future. Based on remote sensing and geochronological studies, Vignon *et al.* (2010) constrained the last activity of the Medlicott–Wadia Thrust to be between 35 and 30 ka, with a slip rate of 4.5–9 mm a^{-1}, and commented that it was more active in Riasi than in the Balakot area. This means that the activation of out-of-sequence thrusting varies along its trend, as has been reviewed by Mukherjee *et al.* (2009, 2012) from the GHC. Vassallo *et al.* (2015) estimated geochronologically a higher slip rate of 11.2 ± 3.8 mm a^{-1} for the Medlicott–Wadia Thrust for 24–12 ka. This means that this thrust changed its slip rate over time. Study from trenches revealed that the Medlicott–Wadia Thrust was characterized by seismicity (Vassallo *et al.* 2012). Based on findings to date, out-of-sequence thrusts/active faults are more numerous in the SH of the Kashmir Himalaya than elsewhere and hence deformation in the Kashmiri SH is more ubiquitous (review in Kundu *et al.* 2014).

Himachal Pradesh, Punjab and Haryana (India). Structural cross-section balancing by Mukhopadhyay & Mishra (1999) indicated that out-of-sequence deformation after in-sequence deformation can explain the structural geology of the Jwalamukhi section of the SH in Himachal Pradesh, India. Structural studies by Mishra & Mukhopadhyay (2012) from the SH and LH of Himachal Pradesh (India) also recognized out-of-sequence thrusts verging towards the hinterland after in-sequence deformation. These thrusts usually have low to moderate dips (<60°). The cataclasite- and gouge-bearing Paonta Thrust, an out-of-sequence thrust of unknown exact timing, juxtaposes the Lower Siwalik units over the Upper Siwalik unit (Mishra & Mukhopadhyay 2012). Cross-section balancing studies by Dubey *et al.* (2001) revealed 62% and 34 km of crustal shortening between the Paonta Thrust and the MBT (locally known as the Krol Thrust).

Steeply dipping and curved out-of-sequence thrust trajectories were found to be common (Mukhopadhyay & Mishra 1999). Eight local out-of-sequence thrusts were recognized from the SH in Himachal Pradesh (India), with slips varying from 1.8 to 7.3 km that segregated *c.* 32.6 km of slip into four ramps (Mukhopadhyay & Mishra 2005). These out-of-sequence thrusts are: the Nalagarh Thrust, the Haripur Thrust, the Bilaspur Thrust, the Surajpur Thrust, the East Nahan Thrust, the Ranon Thrust, the MBT and the Giri Thrust. No geochronological date is available for these thrusts and they were deduced solely from cross-section balancing studies (D.K. Mukhopadhyay pers. comm. 2015). Kumar *et al.* (2007) considered the Nahan Thrust (1) to be the same as, or a continuation of, the Nalagarh Thrust and (2) to demarcate the contact between the Lower Siwalik Subgroup and the Upper Siwalik Subgroup. However, Sharma & Kumar (2008) described the Nalagarh Thrust as the contact between the Lower Siwalik unit and the alluvium. Only the present-day (high) slip rate of the Nahan Thrust is available for these faults, which is *c.* 1 cm a^{-1} (Sinvhal *et al.* 1973). Philip *et al.* (2014*a*) recognized qualitatively repeated activation of the Nalagarh Thrust. However, these authors did not specify how many times this thrust had activated. Philip *et al.* (2014*a*) recognized strong ‘normal drag’ (Mukherjee 2014) of the hanging-wall block of the Nalagarh Thrust at a few places (Philip *et al.* 2014*a*, *b*, figs 4 & 5) that underwent *c.* 2.5 m slip. Discarding the liquefaction-related younger age, these authors concluded from luminescence dating that this thrust activated after 67.5 ± 8.4 ka.

Out-of-sequence thrusts dictated the geomorphology in one way (Mukhopadhyay & Mishra 1999). The folded Palampur Thrust demarcates the boundary between the Subathu and the Dharmsala rocks and, based on structural modelling by Mukhopadhyay & Mishra (1999), is an out-of-sequence thrust. Thrust planes that reactivate at one place in a thrust wedge might create an out-of-sequence thrust towards the foreland side (Mukhopadhyay & Mishra 1999). In cross-sectional models, an out-of-sequence thrust preceded by in-sequence deformation explains the tectonics of the Subathu area in Himachal Pradesh, such as the hanging-wall region of the Nalagarh Thrust, the Bilaspur horse, and reactivation of the Giri Thrust

(Mukhopadhyay & Mishra 2005). However, Searle (1986) inferred that cross-section balancing of terranes with out-of-sequence thrusts could be ambiguous. Therefore only geochronological dates can confirm that these are unquestionably out-of-sequence thrusts.

Malik & Mohanty (2007) recognized neotectonism from the Nalagarh Thrust, Barsar/Bursar Thrust, Jwalamukhi Thrust, Soan Thrust and Palampur Thrust from the Kangra region (Himachal Pradesh) based solely on geomorphological indicators. Hence these are considered as out-of-sequence thrusts even though the timings are unknown. Even in the absence of absolute timing, Dey *et al.* (2015) considered the Jwalamukhi Thrust to be an out-of-sequence thrust. This thrust controls the deposition of recent sediments in the Kangra re-entrant (Himachal Pradesh, India; Dey *et al.* 2015). The Barsar Thrust, which meets the Nalagarh Thrust approximately east of the location of Baddi (Philip *et al.* 2014*b*, fig. 2) (Fig. 4), is a back-structure (Dubey 2014) because it dips towards the south to SW. The Barsar and Nalagarh thrusts define mountain fronts in Pinjaur Dun (Singh & Tandon 2010). The folded bedrock near the Barsar Thrust with oppositely dipping limbs (Singh & Tandon 2010) is probably not related to the faulting.

Mukhopadhyay & Mishra (2005) also deciphered a phase of in-sequence thrusting of the Nalagarh Thrust. Thus the Nalagarh Thrust might have in-sequence activation followed by an out-of-sequence reactivation. Philip *et al.* (2011) deduced a 1.6 m vertical displacement, 2.5 m slip and 20 ka activation age of the Nalagarh Thrust from optically stimulated luminescence dating. The Soan Thrust activated in the Pleistocene and Holocene in the Kangra region of India and might be the surface expression of the M 7.8 seismicity in Kangra in 1905 (Husson *et al.* 2004; Hussain *et al.* 2009). The Soan Thrust separates Middle Siwalik rocks at the north from Upper Siwalik rocks at the south (Bhugarbh Vani 2014).

A set of faults that cuts the MFT includes the Singhauli Fault and the Kala Amb tear fault/Blackmango tear fault (Fig. 5) in the Middle Siwalik unit in Himachal Pradesh (Philip & Virdi 2006). Interestingly, the Singhauli Fault, which can be

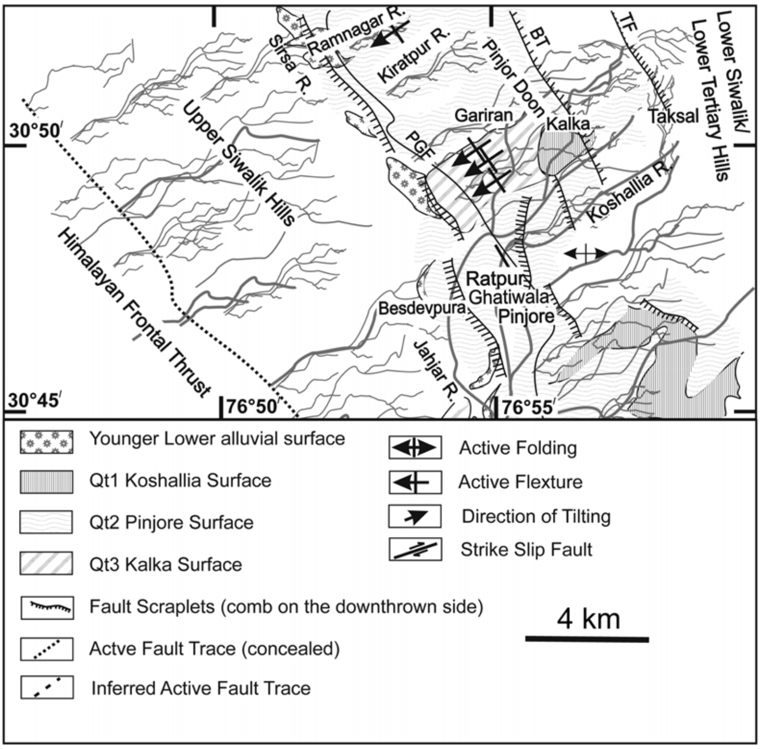


Fig. 4. A few out-of-sequence thrusts in and around Chandigarh (India). Reproduced from Malik & Nakata (2003, fig. 3) with permission. CF, Chandigarh Fault; HFF, Himalayan Frontal Fault (=Main Frontal Thrust); PGF, Pinjaur Garden Fault; BT, Barsat Thrust; TF, Taksal Fault.

traced for >4 km with an ENE trend in the west and an easterly trend in the east, is a normal fault and indicates several recent earthquakes (Philip 2011). Philip *et al.* (2012) subdivided the Kala Amb Fault into Fault 0, Fault I and Fault II. Although the first two faults acted coevally and yielded *c.* 12–16 m slip, Fault II acted during 5.8–2 ka (Philip *et al.* 2012). Note that: (1) the Kala Amb Fault and the Singhauli Fault do not intersect (therefore their relative time relation is unknown) – the former is located west of the latter; and (2) the Singhauli Fault cuts the Dhanaura Anticline, which is a drag fold related to the MFT similar to the Mohand Anticline between Dehradun and Roorkee. This indicates that this thrust is an out-of-sequence thrust. The second point matches with the expectation of Mishra & Mukhopadhyay (2012) in their balanced cross-sections from the Nahan Transect, Himachal Pradesh. Both the faults are oblique to the MFT and are associated with a number of characteristic geomorphological features (Philip & Virdi 2006; see also Valdiya 2001). A few WNW-trending normal faults have been reported, which are probably related to the Singhauli Fault (Philip & Virdi 2006). Malik & Nakata (2003) also reported the Taksal Fault, which has a right-lateral 2.8 mm a^{-1} slip rate and an associated pull-apart basin. The timing of surface rupture over a *c.* 285 km stretch at six locations from NW to SE (Chandigarh (Punjab state), Kala Amb, Rampur Ganda (Himachal Pradesh state), Lal Dhang and Ramnagar (Uttarakhand state, India)) ranges from AD 1200–1700 (S. Kumar *et al.* 2006) and marks *c.* 11–38 m displacement (S. Kumar *et al.* 2006). Philip (2011) also described the Bari Batauli, Nangal Jhandian and Majotu active fault systems from remote sensing studies. As their activation timings are not known, it is difficult to confirm whether those are also out-of-sequence faults.

Out-of-sequence thrusts in the SH commonly have fault-propagation folds in the hanging wall (see review in T. Singh *et al.* 2012). Mukhopadhyay & Mishra (2005) and Mishra & Mukhopadhyay (2012) replicated out-of-sequence thrusts in balanced cross-sections from the SH (India), along with fault-propagation folds. T. Singh *et al.* (2012) considered that the Nahan Salient is in a critical taper condition and that the Kangra and the Dehradun re-entrants are in sub-critical condition. Profound erosion in the Himalayan orogen can attain sub-critical conditions (Kohn 2008) in some portions.

Philip & Virdi (2006) traced several other thrusts in Pinjaur Dun within the SH. Singh *et al.* (2008) designated the Jhajara Fault as a now inactive out-of-sequence thrust based on an optically stimulated luminescence date of 55 ± 6 ka. The Jhajara Fault, like the Barsar Thrust, is characterized by fractured Siwalik rocks, fault gouge and breccia (Singh & Tandon 2010). This fault constitutes a zone of *c.* 520 m consisting of gouge and juxtaposes the Lower Siwalik unit against the Dun gravel (Singh *et al.* 2008). Singh *et al.* (2008) also (re)identified the Sirsa Fault, Pinjaur Garden Fault (see also

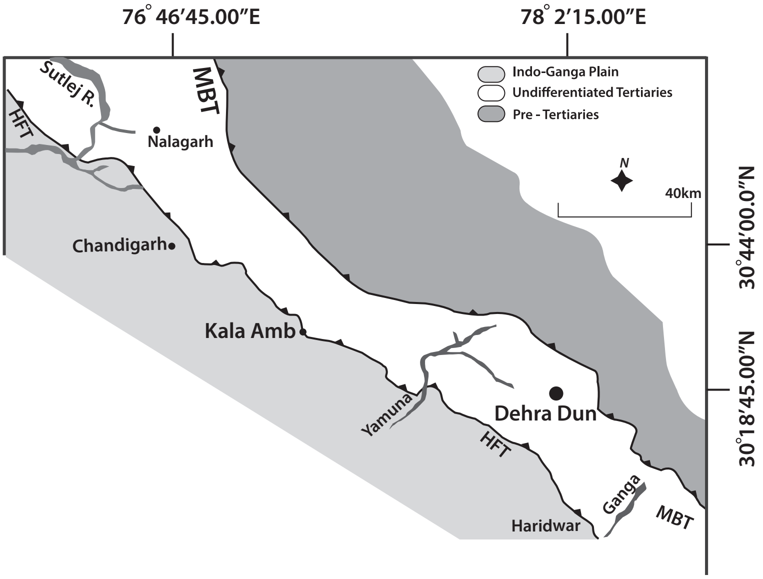


Fig. 5. Kala Amb region and the Kala Amb Tear Fault. Reproduced from Philip *et al.* (2012, fig. 2) with permission from Elsevier. HFT, Himalayan Frontal Thrust (same as the MFT); MBT, Main Boundary Thrust.

Malik & Mathew 2005), Pinjaur Thrust, Barsar–Gambhen and Nalagarh Thrust. Some of these faults are shown in Figure 4. Singh & Tandon (2010) further identified the Jaital Thrust and Batinan Fault and recognized their control on the geomorphology of their terrain.The Pinjaur Thrust is the contact between the Lower and the Upper Siwalik units (Singh & Tandon 2010). Some of these faults merge at different depths and one may be a splay of another (Singh & Tandon 2010, fig. 9). The fault zone between the Barsar Thrust and the Pinjaur Thrust cuts across Late Pleistocene–Holocene sediments (Singh & Tandon 2010). Geomorphologists (Singh *et al.* 2008; Singh & Tandon 2010) have not commented on whether they are all out-of-sequence thrusts, presumably because absolute dates are unavailable. Around 2 m displacement was reported for the Pinjaur Garden Fault (review, Verma & Bansal 2014). Malik *et al.* (2007*b*) identified two strands of the Pinjaur Garden Fault, F1 and F2, which they speculated might merge at a shallow depth.

The 1905 Kangra earthquake in India activated the NW-trending Naddi and Kareri active faults that dip approximately NE for more than 4 km (Philip 2007). The Kareri Fault could be a continuation of the Chandpur Fault near Dehradun (Tiwari *et al.* 2006). Philip (2007) did not report the amount of dip. The Naddi Active Fault is adjacent to the SW portion of Dal Lake in Kashmir, India. The rupture related to this seismicity is represented by the Jwalamukhi Thrust (Malik *et al.* 2010). These two faults are sub-parallel in one region and are at an angle elsewhere (Philip 2007). The Nurpur (NE of the Jwalamukhi Thrust) and the Nadha areas (Himachal Pradesh) developed fissures in the recent past and are out-of-sequence deformations (Mahajan *et al.* 2010). Malik *et al.* (2010) identified two 800–2600 year-old strands of the Hajipur Fault: HF1 and HF2 from the Hajipur region, NW India. The Hajipur Fault shows 7.5–8 m vertical displacement, a 7.6 ± 1.7 mm a^{-1} slip rate and a 25° dip (Malik *et al.* 2010). Studies using ground-penetrating radar revealed that the dip of the Hajipur Fault varies substantially and that it has four splays (Malik *et al.* 2012). Philip *et al.* (2009) recognized the Panchbhaiya Thrust to be still active and referred to the NW-trending Rajban Thrust, possibly another out-of-sequence thrust sub-parallel to the Panchbhaiya Thrust.

Delcaillau *et al.* (2006) decoded out-of-sequence (recent) folding of the *c.* 150 km long Chandigarh antiform and *c.* 50 km long Janauri pop-up antiform in Himachal Pradesh (Fig. 6). These authors relied on geomorphological indicators and the precise timing of these folding events is not known. Malik *et al.* (2008) detected the 'Chandigarh Fault', previously designated as the 'Chandigarh Fault System' (Malik *et al.* 2003), near the Indian city of Chandigarh. Two fault traces around 2–10 km long define the 20–46° dipping Chandigarh Fault with a 3.5 m displacement, 6.3 ± 2 mm a^{-1} slip rate and a 1.5 m vertical component of displacement (Malik *et al.* 2008). Two prominent sub-parallel faults constitute this fault system in both remote sensing images and in trench studies (Malik *et al.* 2003).

The Chamuhi Fault between the Soan Thrust and the MFT was seismically active after 51 ka, with 8–10 m throw and a fault scarp with a youngest age of 0.20 ka. It cut the hinge of the Janauri Antiform/Sukchainpur Anticline, displaced Holocene sediments, and is characterized by shattered pebbles (Bhugarbh Vani 2014; Philip *et al.* 2014*a*). This out-of-sequence thrust is probably linked with anticlines in the Siwalik rocks. A recent slip of 9.3 m at the margin of the Janauri fold was documented from a trench at Bhatpur and presumably occurred during AD 1400–1460 (Kumahara & Jayangondaperumal 2013).

Uttarakhand, Garhwal and Kumaun (India). Remote sensing studies led Rao (1977) to report strike-slip displacement on the Bhelonwala Fault, with limited yet unconstrained throw, and the Donga reverse fault with Holocene slip from the Dehradun valley. However, Srinivasan (2009) doubted fault identification based solely on remote sensing studies from this and other such areas in the thickly vegetated SH.

North of the Mohand Anticline, the approximately east–west-trending Asan Fault, Bhunawala Thrust, Majhaun Thrust and Santaurgarh Thrust occur from south to north (Fig. 7; Thakur & Pandey 2004; Thakur *et al.* 2007). The Asan Fault acted younger than 10 ka and the Bhunawala and Majhaun thrusts between 29 and 22 ka (reviewed in Thakur & Pandey 2004). The Mohand Thrust, a local name for the MFT south of Dehradun, India has been dated by thermoluminescence and infrared stimulated luminescence methods to have acted as an out-of-sequence thrust at *c.* 60 ka (Banerjee *et al.* 1999). T. Singh *et al.* (2012) suggested a rise of the SH induced by out-of-sequence thrusting from geomorphological studies in the western Himalaya, India (see also Devi *et al.* 2011). The Ganga and the Yamuna tear faults in Siwalik in the Haridwar and Dehradun regions in the NW Himalaya are also tectonically active (Sahoo *et al.* 2000). Recently Pandey & Pandey (2015) reported soft sediment deformation found in sediments aged 26–25 ka from channel-fill deposits of the Yamuna river near Dehradun (India).

In the Garhwal SH, Thakur & Pandey (2004) designated the Bhauwala Thrust, the Majhaun Thrust and the Asan Fault lying within the wedge of the MBT–MFT close to the Santaugarh Thrust

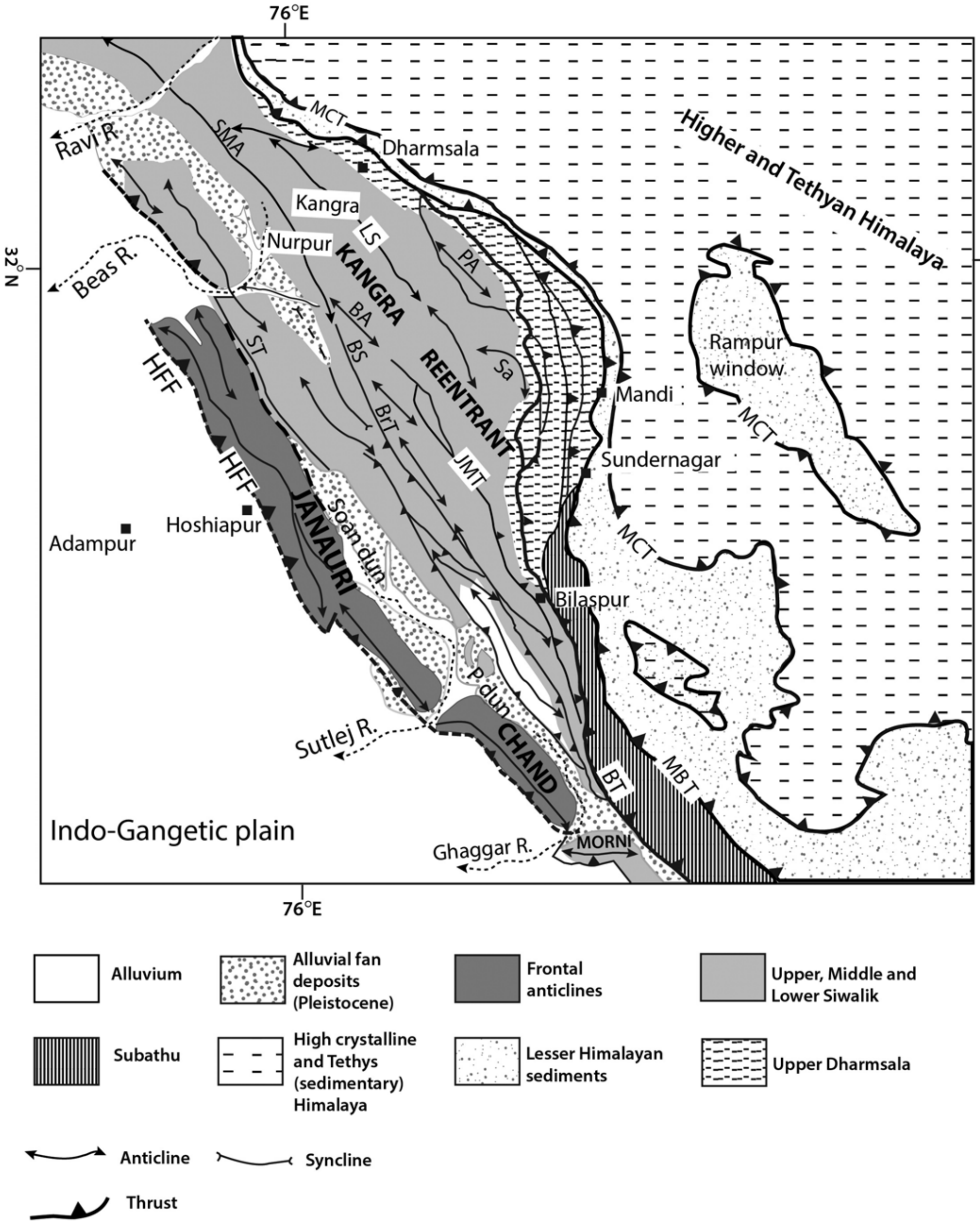


Fig. 6. Siwalik in NW India. MCT, Main Central Thrust; MBT, Main Boundary Thrust; HFF, Himalayan Frontal Fault; ST, Soan Thrust; BT, Bilaspur Thrust; BS, Balaru syncline; BrT, Barsar Thrust; LS, Lambargaon syncline; SA, Sarkaghat anticline; PA, Paror anticline; P dun, Pinjaur Dun; CHAND, Chandigarh anticline; SMA, Suruin-Mastgarh anticline; BA, Balh anticline; JMT, Jwalamukhi thrust. Reproduced from Delcaillau *et al.* (2006, fig. 1) with permission from Elsevier.

as four out-of-sequence thrusts. The Bhauwala Thrust is equivalent to the Main Dun Thrust in Nepal (R. Jayangondaperumal, pers. comm. 2015). The north- to NE-verging Majhaun Thrust is a back-thrust. The MFT, the Santaugarh Thrust and the Bhauwala Thrust (re)activated between 500 and 100, post-500 and 29–20 ka, respectively. The Majhaun Thrust activated during the initial stage

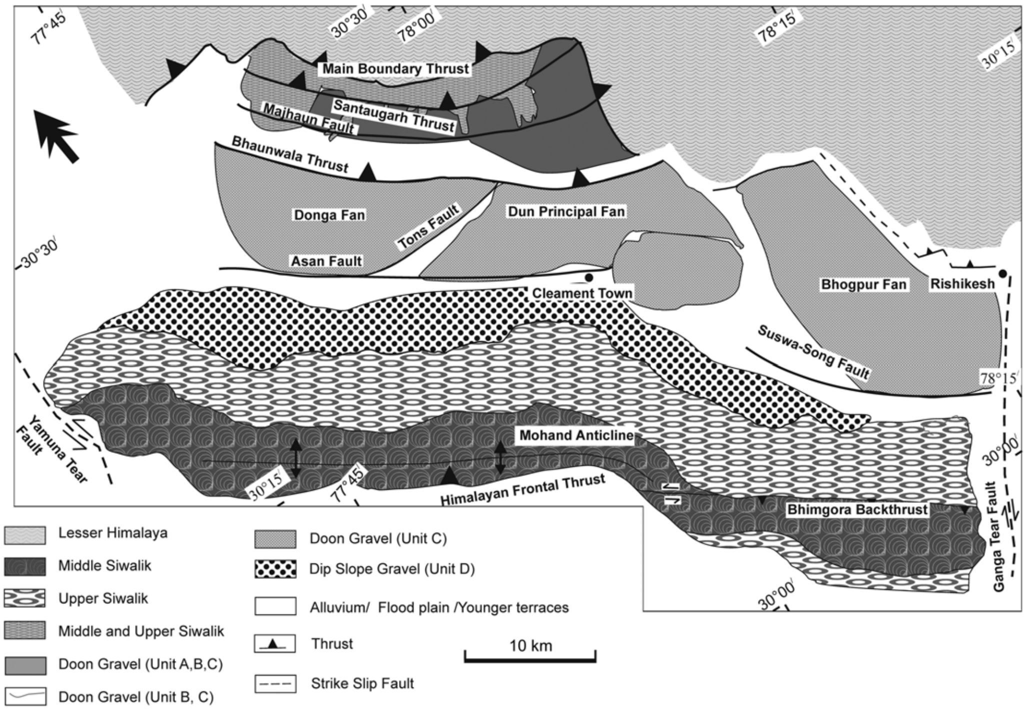


Fig. 7. Siwalik Himalaya showing a few out-of-sequence structures (and fan deposits). Reproduced from Thakur & Pandey (fig. 2, 2004) with permission.

of the Bhauwala Thrust (Thakur & Pandey 2004). Of these out-of-sequence thrusts, the Asan Fault is most conspicuous gemorphologically because it displaced the Asan River (Thakur & Pandey 2004).

Goswami (2012) suspected, based on cross-cutting relationships, that the NNE-dipping Bastia Thrust within Uttar Pradesh and Uttarakhand Himalaya, a splay of the MBT, could be an out-of-sequence thrust. Likewise, the longitudinal Dhikla and Pawalgarh thrusts and the transverse Baru Fault that displaced the Pawalgarh Fault, the Nihal Fault and Chorgalli Fault that slipped the MFT, and the Haldwani Fault were also recognized (Yhokha *et al.* 2015). However, the absolute timing of these faults/thrusts is not known. Goswami (2012) recognized that the Dhikla and the Pawangarh thrusts produced a piggy-back basin in Kota Dun. Several unnamed active faults of unknown absolute ages are also present in this region (review in Yhokha *et al.* 2015). As Goswami (2012) also reported that the Tanakpur and Kalaunia faults of unknown timing cut the Bastia Fault, the former two are also out-of-sequence thrusts.

Yhokha *et al.* (2015), based on remote sensing studies, have reported the approximately north- and NNE-trending Garampani–Kathgodam Fault that underwent deformation during 2008–2010. The Garampani–Kathgodam Fault seems to be an oblique-slip fault with variable slip along its length (Yhokha *et al.* 2015). It extends >100 km, passes through both the LH and SH, and has displaced the Ramgarh Thrust, the MBT and the MFT (Yhokha *et al.* 2015). Its eastern block subsided compared with the western block (Yhokha *et al.* 2015). Mishra *et al.* (2013) reported *c.* 5–4 Ma reactivation of the Kumaun MBT based on deformation in the SH. Malik *et al.* (2014) determined the geomorphologically out-of-sequence thrust/active nature of the Kaladungi and Kotabagh faults from the Kumaun Himalaya (Fig. 8). Other than Malik *et al.* (2014), no other reported research exists on these two faults. Note that the Tanakpur Fault, the Kalaunia Fault, the Chorgalli Fault, the Garampani–Kathgodam Fault, the Haldwani Fault and the Nihal Fault also continue in the Ganga foreland basin (Goswami & Deopa 2015; Yhokha *et al.* 2015).

Interestingly, the contact between the Lower and Middle Siwalik has been marked as the Mangoli Thrust, which is an imbricate of the MFT (Srivastava & Mitra 1994). However, publications do not state clearly whether it is an out-of-sequence thrust. A continuation of this fault, known as the Sarpa Dhuli Dhikala Thrust/Sarpduli Dhikala

Thrust, however, is known to be active (Singh *et al.* 1976). Goswami & Pant (2008*a*) believed that the Dhikala Thrust passes between the Lower and Upper Siwalik.

Nepal. Dhital (2015) referred the Kokhajor Fault to between Lower and Upper Siwalik. However, whether this thrust was produced in an out-of-sequence manner is unknown. In the western and far western Nepal Himalaya, a number of thrusts between the MBT and the MFT, i.e. within the SH, called the Main Dun Thrust (MDT) (Fig. 9) (Mugnier *et al.* 1999) have been described as 'a succession of laterally relayed thrusts propagating westward as ramp folds' (Husson *et al.* 2004, p. 117; see also Mugnier *et al.* 1999). The MDT dips at 40–50° (Mugnier *et al.* 2004). Clasts of quartz, calcite and clay minerals define the MDT fabrics, along with secondary shear planes and microbreccias. These formed either by seismic slip or cataclastic flow (Mugnier *et al.* 1998), as seen by the rotation of pebbles (Mugnier *et al.* 1994), but reliably indicate the shear sense (Mugnier *et al.* 2004). Mugnier *et al.* (1999) described them as MDT1 to MDT4 from east to west, presented their structures in detail, and referred a minimum of 6 km of slip for MDT3. The MDT slipped episodically and cumulatively by at least 8 km (Mugnier *et al.*

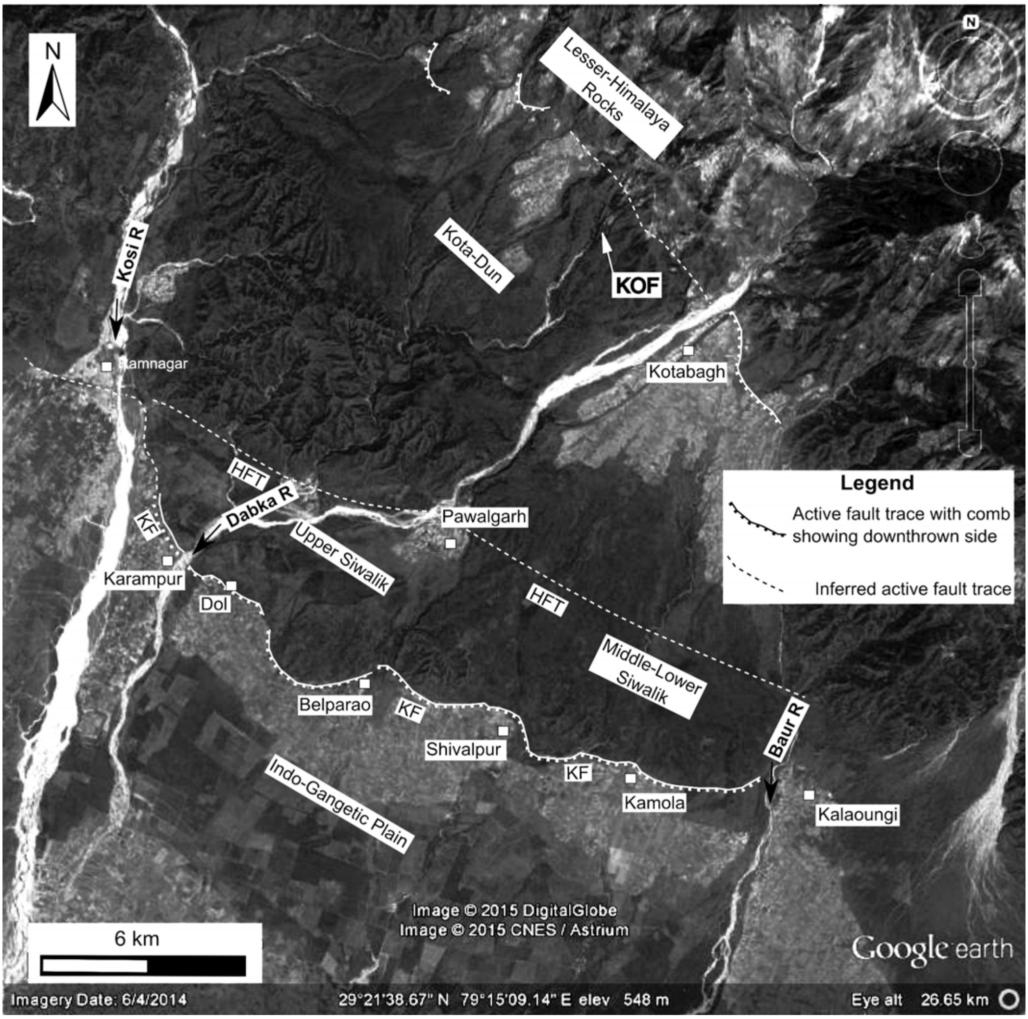


Fig. 8. Out-of-sequence thrusts around Kaladungi–Kotabagh area (Nainital). Quickbird image with 2.4 m resolution in the RGB bands. Source: http://www.satimagingcorp.com/satellite-sensors/quickbird/ (last accessed on 25 February 2015) This figure was prepared independently, following Malik *et al.* (2014, fig. 1), by Achyuta Ayan Misra (Indian Institute of Technology Bombay). KOF, Kotabagh Fault; KF, Kaladungi Fault; HFT, Himalayan Frontal Thrust.

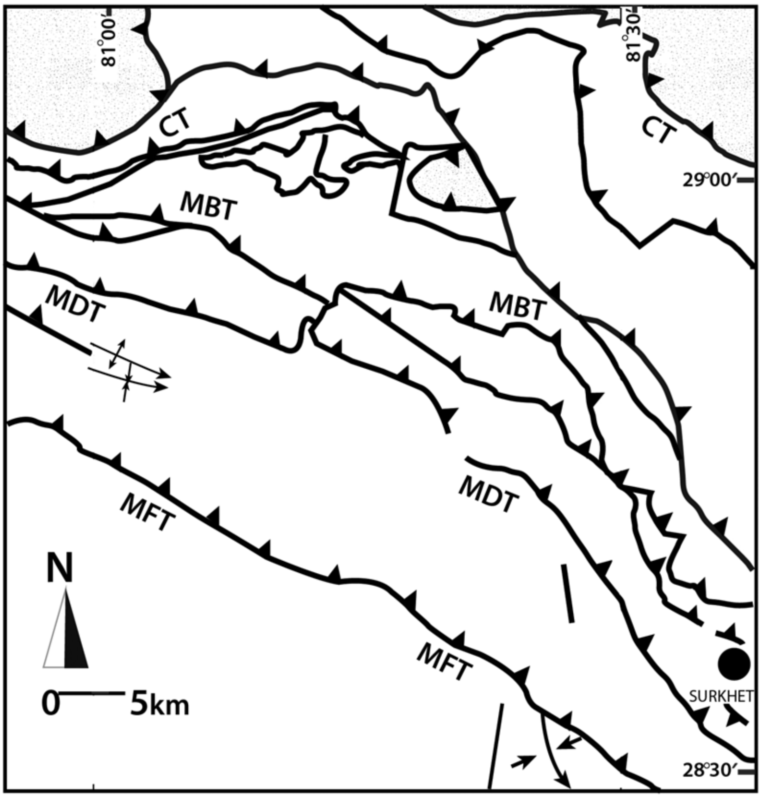


Fig. 9. Part of the Nepal Himalaya showing the Main Dun Thrust (MDT), MFT and MBT, with crystalline cores shown by hatching. Reproduced from Mugnier *et al.* (1998, fig. 2) with permission from Elsevier.

1998). Schelling *et al.* (1991) identified the MDT in Nepal in terms of the Chaura–Marin Thrust. Note this thrust is certainly different from the Chaura Thrust of Jain *et al.* (2000), demarcated in the GHC in Himachal Pradesh (also see Mukherjee *et al.* 2012). The Chaura–Marin Thrust trends N80W and demarcates the sandstone of the Lower Siwalik unit in the north and the Upper Siwalik conglomerates in the south; it is devoid of regional drag folds and thrust ramps (Schelling *et al.* 1991). Overall, the MBT slipped more slowly than the MDT and the MFT (Mugnier *et al.* 2004). The MDT1 underwent 32–40 km of shortening (Mugnier *et al.* 2004). A few metres of displacement have been deciphered from one of the three splays of the MDT2 and *c.* 23 m uplift from an external splay of the MDT (Mugnier *et al.* 2004). Some of these thrusts contain associated drag folds that are fault-propagation folds (Mugnier *et al.* 1999) of 'normal drag' geometries (Mukherjee 2014). Some of these folds and MDT faults are linked by strike-slip faults (Mugnier *et al.* 1999). Slip along one of the splay faults of the MDT exceeded 40 km (Mugnier *et al.* 1998). How individual strands of the MDT link with the MFT has remained indeterminate (Mugnier *et al.* 1998). When the MDT slipped, the MFT was possibly quiescent (Mugnier *et al.* 1998).

Using remote sensing images, Husson *et al.* (2004) also delineated the MDT in western Nepal. They predicted a greater slip for the MDT than the MFT from the compiled structural geology. However, previous authors have deduced (1) comparable slip rates of the MFT and the MDT of *c.* 7–10 mm a^{-1} in western Nepal and (2) significantly different slip rates in western Nepal of 21 mm a^{-1} for the MFT and 0 mm a^{-1} for the MDT (review in Husson *et al.* 2004). The latter conclusion is supported by the original structural work of Husson *et al.* (2004), which independently deduced these rates to be 17 and 2–3 mm a^{-1}. Undeformed sediments overlie the MDT in western Nepal, which indicates that the MDT stopped activating (review in Husson *et al.* 2004; also see Mugnier *et al.* 2004). Likewise, the MDT4 is capped by fluviatile sediments (Mugnier *et al.* 2004). The MDT in the Karnali splay most possibly underwent 40 m slip within 4–7 ka (Mugnier *et al.* 1998). Bollinger *et al.* (2014) described two strands of the MFT, the Patu Thrust and the Bardibas Thrust from east central Nepal, with recent slip rates of 8.5 ± 1.5 and 10–12 mm a^{-1}, respectively.

Chamlagain & Hayashi (2007) referred to three north-dipping active faults along the MBT, i.e. the *c.* 60 km long Arun–Arung Khola Fault, the Hetaunda Fault and the Udaipur Fault (see also Shanker *et al.* 2011), different from that in Tripura, India in the Himalayan syntaxis (Dey *et al.* 2009).

Darjeeling and Sikkim, India. The South Kalijhora Thrust sheared the Lower Siwalik unit over the Upper Siwalik unit (Fig. 10) (Mukul 2000). It is an out-of-sequence thrust, designated as a 'surface-breaking fault', that activated at *c.* 20 ka and affected the Tista River during 11.3 ± 1.3 to 1.4 ± 0.3 ka; it is still active (Mukul *et al.* 2007). Mukul *et al.* (2007) reported that the out-of-sequence thrust structures of the South Kalijhora Thrust overprinted the Himalayan structures; however, no detail was presented.

Arunachal Pradesh (India). Das (2004) concluded, based on lineament density, that the Siwalik units in Arunachal Pradesh (India) are more affected by recent tectonic activity than in Bhutan. Devi *et al.* (2011) documented the ENE-trending Ramghat Thrust with a late-phase right-lateral strike-slip movement and also the NNE-trending Burai River Fault as out-of-sequence thrusts in Arunachal Pradesh. The Middle Siwalik rocks are thrust over the Upper Siwalik rocks by the Ramghat Thrust (Devi *et al.* 2011). Luirei & Bhakuni (2008) referred to several 'active faults' from Arunachal Pradesh. These are the Ranaghat Fault, the Sampa Fault, the Sibo Korang Thrust and the Sileng Fault. However, the timings of their activations are unknown. De Sarkar *et al.* (2014) reported out-of-sequence thrusting of <1 ka age between Bhalukpong and Tipi villages from Siwalik in the eastern Himalaya. They deciphered a significantly high *c.* 12 mm a^{-1} slip rate and a *c.* 7 mm a^{-1} rate of shortening in the horizontal direction from this out-of-sequence thrust during the Holocene. De Sarkar *et al.* (2014) concluded that profound erosion and a critical taper condition produced this out-of-sequence thrust (see also Schuller *et al.* 2015). However, debate has not resolved about how far erosion can control the (Himalayan) tectonics (see brief review in Whipple 2014). Thus, genetic reasons or a kinematic model for the out-of-sequence thrusting in Siwalik are broad statements. Srivastava & Misra (2008) reported the approximately north–south-trending Kameng Fault, which created mainly unpaired terraces near Bhalukpong during the Holocene.

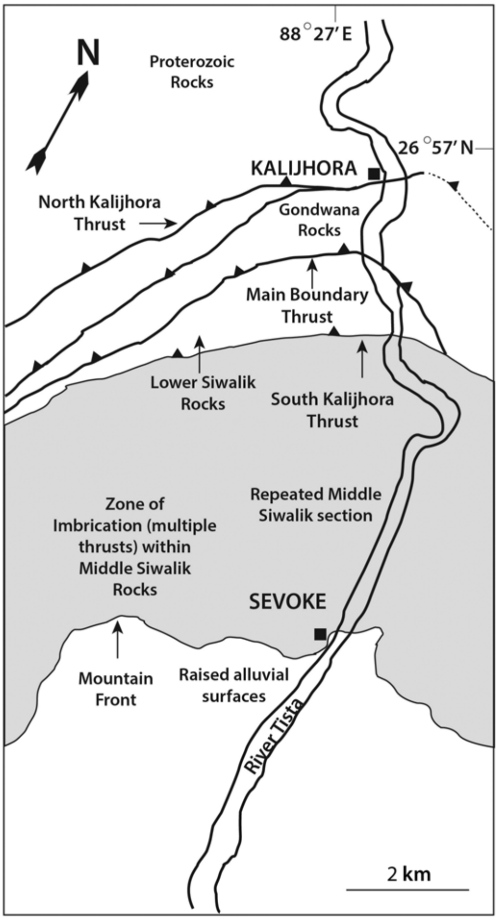


Fig. 10. Darjeeling section of the Siwalik Himalaya. Reproduced from Mukul (2000, fig. 16) with permission from Elsevier. The North and South Kalijhora Thrusts are shown.

Lesser Himalaya

Figure 11 shows the locations of out-of-sequence thrusts, compiled from previous publications, within the Lesser Himalaya.

Himachal Pradesh (India). Based on He and Ra isotopic data, Walia *et al.* (2008) determined the active nature of the Main Boundary Fault-2, a strand of the MBT, from the Dharmsala region. Using recent landslides near the MBT, Joshi & Bhatt (2015) determined that Dehradun is active at present.

Uttarakhand, Garhwal and Kumaun (India). Out-of-sequence thrusting in the LH cut off some of the LH rock units in the western Indian sector (Mukhopadhyay & Mishra 1999). Ray & Srivastava

(2010) referred to the North Almora Thrust (Fig. 12), which demarcates one of the boundaries of the Almora Klippe, as an out-of-sequence thrust. Igneous and detrital zircon data and epsilon Nd values from the Almora Klippe indicate that it is GHC and the Almora Thrust is considered as the MCT (Mandal *et al.* 2014). Alternatively, the North Almora Thrust may be an intra-GHC thrust (Khanal *et al.* 2014). GHC rocks in the Dadeldhura Klippe, which is the eastern continuation of the Almora Klippe, cooled to below *c.* 350 °C, are interpreted to indicate the time at which the trailing part of the klippe passed through the Ar closure temperature (DeCelles *et al.* 2001). This indicates that the thrust fault is not an out-of-sequence thrust, but may have experienced some brittle faulting after it was emplaced (Mandal 2014). Srivastava & Mitra (1996) stated that the Almora Klippe was emplaced during the Late Eocene. Brittle faults <5 km long, which could be out-of-sequence thrusts, were simulated in cross-section balancing studies north of the Almora Klippe (Mandal 2014).

Kothyari (2007) considered the North Almora Thrust to be still active as it affects recent sediments in addition to a number of critical geomorphological resultant features (see also Sati *et al.* 2007). Kothyari (2007) also noted that the NW-trending right-lateral strike-slip Ramganga Fault is the outcome of the North Almora Thrust. Therefore the North Almora Thrust can be considered as an out-of-sequence thrust.

A NW–SE zone of profound erosion in the Mandakani river valley, within the MCT and the Almora Thrust, was identified by Vaidyanathan *et al.* (2002) in the Garhwal Himalaya. However, whether this erosion was sufficient to produce (any) out-of-sequence thrusting is not known. This paper reviews erosion as a possible mechanism of out-of-sequence thrusting. Morell *et al.* (2012) has documented ≤2 ka old regional tilting towards the NE around Uttarkashi (Uttarakhand, India) in the northern portion of the LH, correlated with a possible surface-breaking out-of-sequence thrust.

Banerjee *et al.* (1999), in the Kumaun Himalaya, reported out-of-sequence thrust activity in the Nainital region at *c.* 40 ka at the Nainital Fault and the Sleepy Hollow Fault, and at the MBT *c.* 70 ka. Around 10–30 m vertical displacement of terraces was observed in the Nainital region (see also Kothyari *et al.* 2010). The Bhikiyasain Fault is a steeply dipping/sub-vertical transverse neotectonic fault from the Almora region of unknown exact timing (Goswami & Pant 2008*b*). From field studies around the Batalghat region, Mehta & Sanwal (2011) recognized NNE-trending oblique transverse normal faults south to the South Almora Thrust that offset Quaternary sediments by *c.* 1.5 m.

Nepal. Either nearly straight or lobate out-of-sequence thrusts/active faults <100 km long exist in Nepal Himalaya along and near the MBT (Nakata 1989). The following were reported specifically by Nakata (1989) from the LH: (1) the Matiali Fault (=MBT) defined by surface mounds, a bifurcation from the Gorubathan Fault in Darjeeling, average slip rate 1 m per 1000 years; (2) the Chalsa Fault (=MFT?) with *c.* 20 m vertical displacement; and (3) the Surkhet–Ghorahi Fault, traceable for *c.* 120 km and with 35 m vertical displacement – this fault is recognizable in remote sensing images.

Paudel & Arita (2000) designated the Phalebas Fault (Fig. 13), with activity prior to the Pliocene, as an out-of-sequence thrust inside the LH in the Nepal Himalaya because it cuts the Jajarkot Klippe and the Kathmandu Klippe. Upreti *et al.* (1980) opined that the Phalebas Thrust is equivalent to the Chail Thrust in the NW Indian Himalaya and is the same as the Lame Deorail Reverse Fault in Kumaun. The Bari-Gad Kali Fault/Bari-Gad Kali Gandaki Fault that separates the upper from the lower LH cuts the Phalebas Thrust (Upreti *et al.* 1980), hence the former is also an out-of-sequence thrust. Not all LH sections are divisible into lower and upper units. Thus, the continuation of the Bari-Gad Kali Gandaki out-of-sequence fault may not exist.

Near the Kathmandu region in Nepal, the seismically active Trisuli–Likhu Fault is a continuation of Sun Kose Fault/Sun Kosi Fault/Rosi Khola Fault that lies within the MCT zone (Arita *et al.* 1997). The Trisuli–Likhu Fault and the Bari-Gad Kali Fault have been considered as out-of-sequence thrusts, based presumably on the observation that they cut the fabrics of the MCT zone and the GHC rocks. These areas underwent *c.* 10 km of shortening and uplift rates increase significantly across them (Arita *et al.* 1997). However, the timings of the Trisuli–Likhu Fault and the Bari-Gad Kali Fault are unconstrained (Arita *et al.* 1997; also see Schelling 1992). Based on indirect geoscientific evidence, Arita *et al.* (1997) considered the timing of these out-of-sequence thrusts to be 10–7.5 Ma. Arita *et al.* (1997) postulated that uplift related to the out-of-sequence thrust, in the case of the Trisuli–Likhu Fault/Sun Kose Fault, was linked with the northwards shear of the Indian plate along the MHT. Not all river sections in the LH and GHC contain out-of-sequence thrusting, e.g. in the Budhi–Gandaki section (Khanal & Robinson 2013).

The LH Ramgarh Thrust in Nepal continues in India as the Munsiari Thrust (Robinson & Pearson 2006), which cuts the MCT (Webb 2013). It is an out-of-sequence thrust as a young age of 4.3 Ma was determined from a quartzite within the Munsiari Thrust (Célérier *et al.* 2009*b*). Therefore the

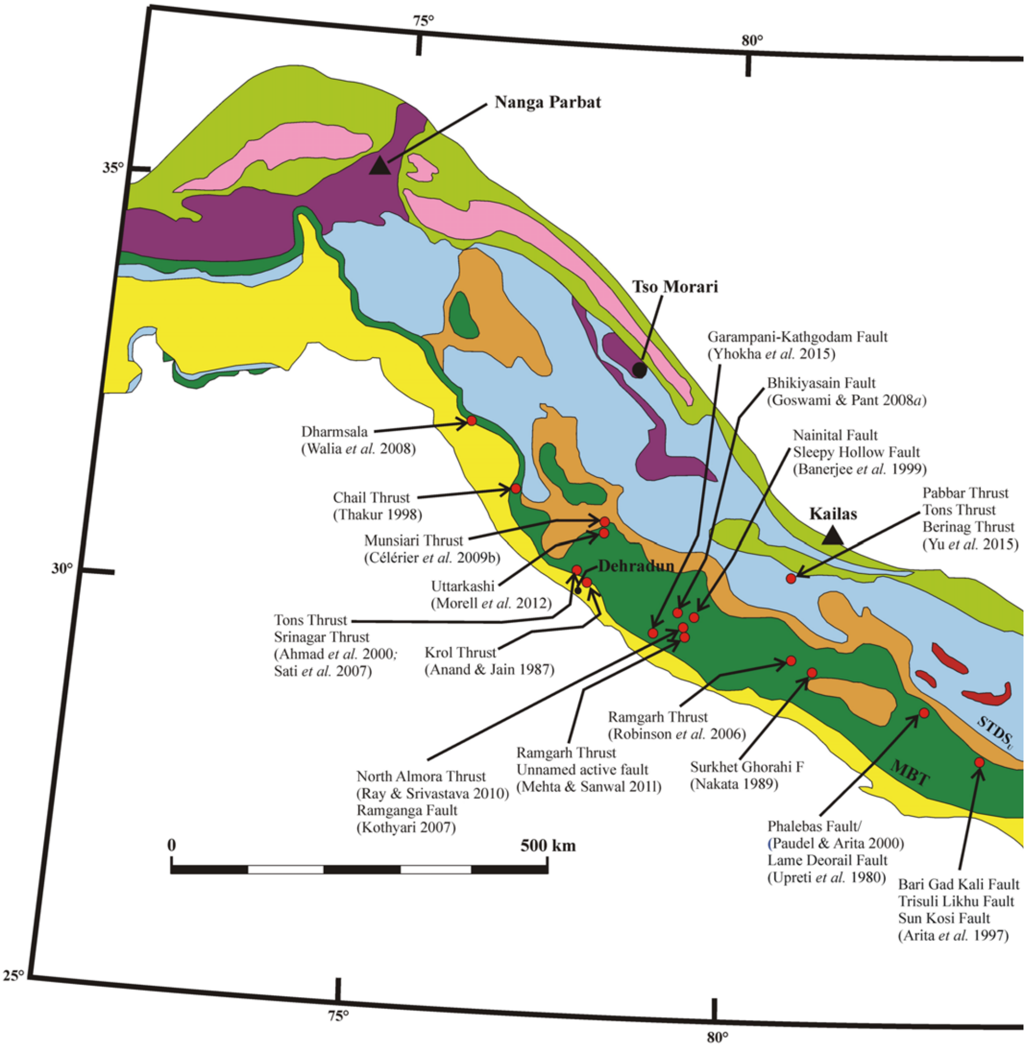
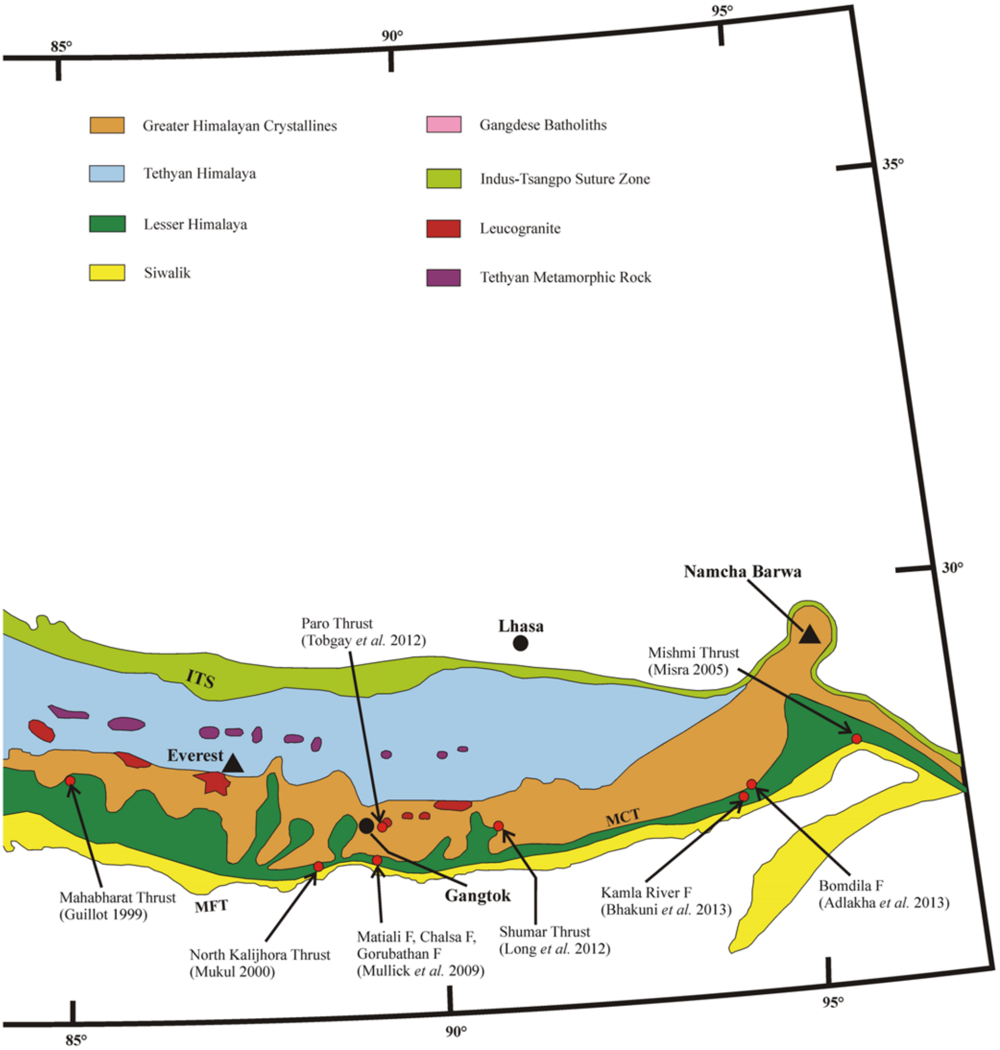


Fig. 11. Map of the Himalayan orogen. In this work, out-of-sequence thrusts within the Lesser Himalaya are plotted Main Frontal Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS$_U$, South Tibetan Detachment

Munsiari Thrust has a much younger age than the MBT (*c.* 9–11 Ma; see review in Thakur *et al.* 2014). Yu *et al.* (2015) reported 4–5 km heave of the Munsiari Thrust during its out-of-sequence activity. Webb (2013) reported a still younger 1–2 Ma age of activation from this thrust and stated that the Munsiari Thrust seems to be a sum of two thrust sheets (see also Draganits *et al.* 2014 for Pleistocene age reference). Rocks north of the Munsiari Thrust are part of a domain of underplating, seismicity, most abrupt topography and fastest incision and exhumation (Webb 2013 and references cited therein). Although previous workers (referred to in Webb 2013) considered the Kullu Window to be a product of the out-of-sequence thrust of the Munsiari Thrust, the cross-section balancing study of Webb (2013) proposed duplexing as an alternative mechanism. Webb (2013) determined *c.* 8 km of slip over the last 4–5 Ma for the Munsiari Thrust.

The Mahabharat Thrust (=MCT/sub-MCT structure: Johnson & Rogers 1997), related to the Kathmandu nappe, is a <22 Ma out-of-sequence thrust (Guillot 1999). Further east, no out-of-sequence thrust developed associated with the Rangit duplex (Bhattacharyya & Mitra 2009). Therefore the Himalayan duplexes are not invariably associated with out-of-sequence thrusts.



from previous publications. The map is reproduced from Zhang *et al.* (2015, fig. 1) with permission from Elsevier. MFT, System-Upper; ITS, Indus Tsangpo Suture.

Structural and geochronological studies by He *et al.* (2015) from the Nepal Himalaya concluded that the out-of-sequence thrust in the LH corresponds to $<10\%$ crustal shortening, even though overthrusting related to out-of-sequence thrusting can be proportionate (Robert *et al.* 2009, 2011). A minimum of 6 km of shortening along the MBT during 2.1–1.9 Ma occurred as an out-of-sequence thrust in the Nepal Himalaya (Burbank & Beck 1989).

Sikkim and Darjeeling (India) and Bhutan. From global positioning system studies, Mullick *et al.* (2009) estimated a shortening of 11.1 ± 1.5 mm a^{-1} together for the Gorubathan, Matiali, Chalsa and Baradighi faults and speculated the occurrence of an earthquake from the Darjjeeling Himalaya. Whether the North Kalijhora Thrust within the LH is an out-of-sequence thrust is indeterminate, although it has been correlated with the Ramgarh Thrust in Nepal and the Shumar Thrust in Bhutan (review in Mukul 2010). Structural studies by Tobgay *et al.* (2012) deduced *c.* 96 km crustal shortening related to the Shumar Thrust.

Arunachal Pradesh (India). Based on geomorphological features alone and no geochronological data, Bhakuni *et al.* (2013) determined the ENE-trending

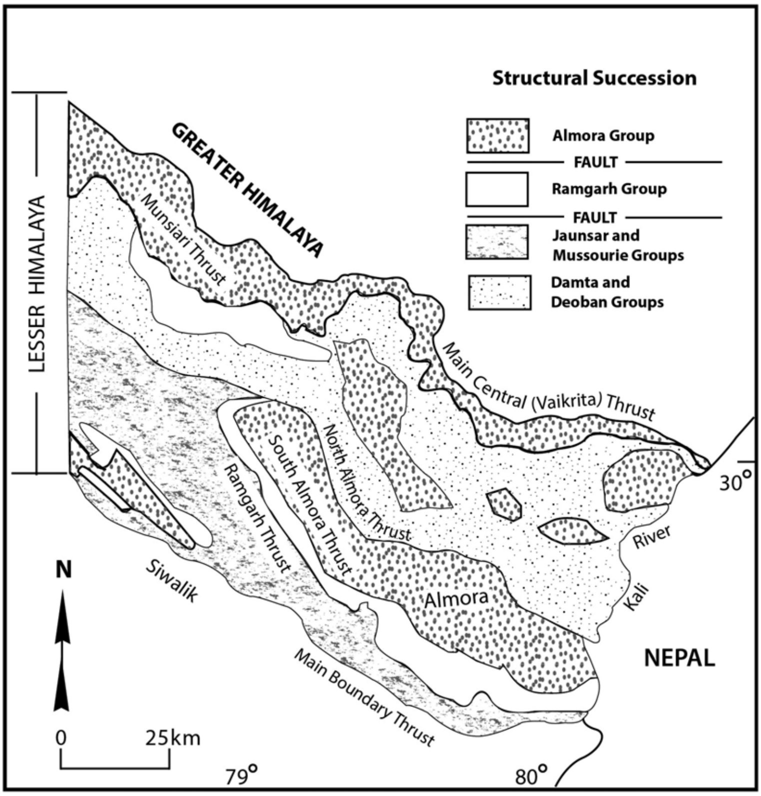


Fig. 12. Lesser Himalaya in the Kumaun section. Reproduced from Srivastava & Mitra (1996, fig. 1) with permission from Elsevier.

Kamla River Fault Zone as an out-of-sequence thrust in the LH in Arunachal Pradesh (India). A number of landslides were seen to occur parallel to this fault. Bhakuni *et al.* (2012) reported *c.* 10 Ma out-of-sequence thrusting of the Bomdila Thrust, which is equivalent to the Munsiari Thrust and the Paro Thrust (Valdiya 1980), in the Arunachal Himalaya. Adlakha *et al.* (2013) mentioned a further young ^{40}Ar–^{39}Ar age of 6–7 Ma for this thrust. The Mishmi Thrust, equivalent to the MBT determined from geomorphological studies, was reactivated (Misra & Singh 2002). Thus it seems to be an out-of-sequence thrust. However, absolute timing of its activation is not known.

Greater Himalayan Crystallines

Span of present review. Out-of-sequence thrusting within the GHC was activated from *c.* 22 Ma up to the Holocene (Grujic *et al.* 2011; Warren *et al.* 2011; review by Mukherjee *et al.* 2012; this work). Mukherjee *et al.* (2012) reviewed out-of-sequence thrusts from nine locations in the GHC from India, Nepal and Bhutan. A summary is presented in Table 1. Mukherjee *et al.* (2012) considered a single out-of-sequence thrust passing through these nine locations with different activation timings. Geoscientists have deciphered the out-of-sequence thrust in the GHC observed at isolated river sections as a continuous structure, such as the 'Kakhtang–Zimithang Thrust' (Yin *et al.* 2009) and the 'Laya–Kakhtang–Zimithang Thrust' (Warren *et al.* 2014). This is despite the fact that the continuity of out-of-sequence thrusts in collisional orogens has been debated (MacFarlane *et al.* 1992; Cannon 2011). In these considerations, the out-of-sequence thrust over regional extents does not demarcate the boundary between two specific lithologies. The relative position of the out-of-sequence thrust at specific valleys with respect to the MCT at the south and the $STDS_U$ at the north also vary (Mukherjee *et al.* 2012).

In their review, Mukherjee *et al.* (2012) missed the Tamar Khola Thrust in Nepal (Schelling & Arita 1991), the Laya Thrust in Bhutan (Warren *et al.* 2012) and the Balapur Fault in Kashmir, India

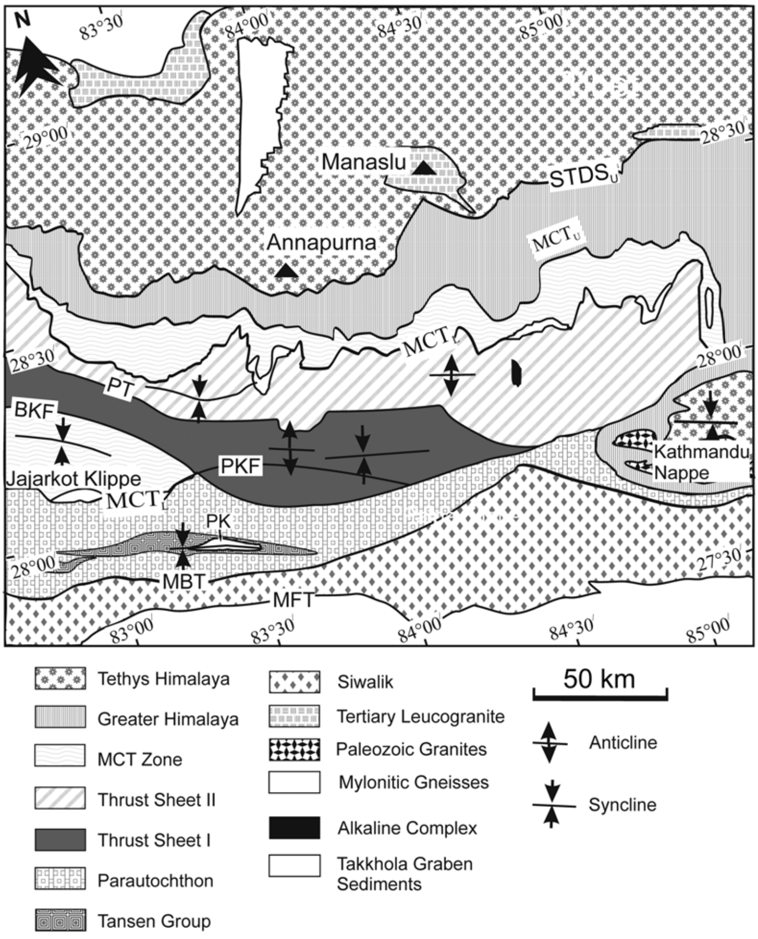


Fig. 13. Central Nepal Himalaya. Reproduced from Paudel & Arita (2000, fig. 2) with permission from Elsevier. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; PK, $\mathrm{MCT_L}$, Main Central Thrust-Lower; $\mathrm{MCT_U}$, Main Central Thrust-Upper; PKF, Pindi Khola Fault; BKF, Bari-Gad Kali Gandaki Fault; PT, Phelabas Thrust; $\mathrm{STDS_U}$, South Tibetan Detachment System-Upper.

(Ahmad & Bhatt 2012). In addition, the Nyalam Thrust in south-central Tibet (Wang *et al.* 2013) and the Kolbug Fault in Kashmir, India (B. Ahmad *et al.* 2014) were reported as out-of-sequence thrusts after Mukherjee *et al.* (2012) was published. Gururajan & Choudhuri (2003) reported reactivation of the Lohit Thrust from the Arunachal Himalaya. Thus, this thrust could be an out-of-sequence thrust. These new observations of the out-of-sequence thrusts are shown in Figure 14. New developments and issues about out-of-sequence thrusts within the GHC that were not covered in Mukherjee *et al.* (2012) are discussed in the following sections.

Pakistan. One or more out-of-sequence thrusts inside the MCT zone has been documented or proposed from the Pakistan Himalaya as the Panjal–Khairabad Thrust (=MCT; DiPietro & Pogue 2004); shear started in the Miocene and persisted in the Pliocene and Holocene.

Kashmir and Himachal Pradesh (India). Stephenson *et al.* (2000) ascertained that the MCT zone in the Zanskar section might have come from depth via an out-of-sequence thrust. Stephenson *et al.* (2001) deduced a 9.7 ± 0.2 Ma age of the MCT from the Kishtwar region, Kashmir, India. Many of the contacts between domes, windows and klippens in the LH and GHC with the country rocks have been stated to be out-of-sequence thrusts. For example, the east- and NE-dipping Kishtwar Thrust (Singh 2010, fig. 2), which breached from

Table 1 *Information on out-of-sequence thrusts in the Greater Himalayan Crystalline as compiled by Mukherjee* et al. *(2012)*

Location section	Bhutan	Nepal								Sutlej India	Arunachal, Pradesh, India
Local name of the out-of-sequence thrust (reference)	Kakhtang Thrust (Grujic *et al.* 1996, 2002 and references cited therein)	Carosi *et al.* (2010)	Khumbu Thrust (Searle 1999)	Modi Khola Shear Zone (Hodges *et al.* 1996)	Kalopani Shear Zone (Vannay & Hodges 1996)	High Himal Thrust (Goscombe *et al.* 2006)	Toijem Shear Zone (Carosi *et al.* 2007; see Carosi *et al.* 2010 for counter argument)	Central Nepal (Carosi *et al.* 2010)	Marsyandi valley (Wobus *et al.* 2003; Burbank 2005; review Harris 2007)	Chaura Thrust/ Sarahan Thrust (Jain *et al.* 2000; Chambers *et al.* 2008)	Zimithang Thrust (Yin *et al.* 2006)
Activation timing	14–10 Ma (but see scepticism in Yin 2006)	~15–13 Ma	–	22.5–18.5 Ma	–	–	At least between 25 and 17 Ma	22.5–18.5 Ma	Late Pliocene–Holocene	4.9–1.5 Ma (Jain *et al.* 2000)	–
Ratio of distance between MCTL to out-of-sequence thrust to that between out-of-sequence thrust and STDSU	1:1.15 (from fig. 1, Grujic *et al.* 2002); 1:0.71 (from fig. 5, Hollister & Grujic 2006)	–	1:0.67 (from fig. 6, Searle 1999)	1:0.19 (from fig. 10, Hodges *et al.* 1996)	1:0.3 (from fig. 3, Vannay & Hodges 1996)	1:0.96 (from fig. 2, Goscombe *et al.* 2006)	(from fig. 1b, Carosi *et al.* 2007)	–	–	1:0.75 (from fig. 1, Jain & Anand 1988; fig. 2,. Chambers *et al.* 2008)	*1:0.40 (from fig. 1, Yin *et al.* 2006)
Other data	Throw 10–20 km (Grujic *et al.* 2002); minimum displacement (net slip?) 33 km (McQuarrie *et al.* 2008)	–	−6 km (Searle 1999)	–	Throw similar to that at Chaura	Thickness: 100–400 m (Goscombe *et al.* 2006)	8 km of horizontal displacement (Carosi *et al.* 2010); thickness 50 m (Carosi *et al.* 2007); 40–50 km (Carosi *et al.* 2010)	–	–	Estimated throw 2.08 ± 0.68 km (Jain *et al.* 2000); average extrusion rate 0.6 mm a^{-1} (Jain *et al.* 2000)	Thickness 150 m (Yin *et al.* 2006)

the MCT and demarcates the western boundary between the LH Kishtwar Window rocks and the surrounding GHC, is an out-of-sequence thrust (Singh 2010).

Likewise, the boundary of the (Larji) Kulu Rampur Window (Himachal Pradesh, India) is an out-of-sequence thrust (Chamoli *et al.* 2011). The Jeori Wangtu Granite Gneiss Complex (Himachal Pradesh, India) inside the MCT zone underwent faulting. A continuation of this faulting in the Garhwal Himalaya is dated to be an out-of-sequence thrust (review in Miller *et al.* 2000). The Jhakri Thrust Zone, dipping *c.* 50° towards the NE and *c.* 15–17 km deep, demarcates a boundary of the Wangtoo Gneiss, similar to the Tons Thrust in Garhwal (Pandey & Virdi 2004). Pandey & Virdi (2004) determined a gradual increase in strain towards the Jhakri Thrust Zone based on microstructural studies. This is the only study where a strain gradient has been stated for the Himalaya in the context of out-of-sequence thrusting. However, the study is qualitative and demands quantitative confirmation.

The Balapur Fault is traceable for >40 km in the Rambiara basin of the Kashmir valley, has a 60°NE dip and 13 m of vertical separation (Ahmad & Bhat 2012). The Kolbug Fault, running sub-parallel to the Balapur Fault and mutually *c.* 8 km away, is also an out-of-sequence thrust that relates to the Budgam seismicity in 1963 (S. Ahmad *et al.* 2014).

Uttarakhand, Garhwal and Kumaun (India). In the Kumaun and Garhwal Himalaya in India, several sections of the MCT zone show reactivation based on quartz *c*-axis orientation (Bhattacharya & Weber 2004). However, the timings of reactivation for these sections are not known. Catlos *et al.* (2007) deduced 5.6–4.2 Ma monazite as the age of the out-of-sequence thrust of the MCT zone from the Garhwal Himalaya. Anand & Jain (1987) reported unconstrained recent tectonic activity in the MCT in the Tons valley and in the Krol Thrust near Dehradun based on soft sedimentary deformation structures.

Morell *et al.* (2015) identified a physiographic transition (UPT2) in Uttarakhand similar to the thoroughly studied PT2 in Nepal (discussed later). The UPT2 falls within the MCT zone and inside the Himalayan 'central seismic gap'. Using ^{10}Be studies, these authors deduced an average erosion rate of 0.2 mm a^{-1} south of the UPT2 and 0.6 mm a^{-1} north of the UPT2. No lithological change occurs across the UPT2. The line of ramp-flat transition obtained geophysically comes out as a line as a continuation of the UPT2 when projected on the map. Morell *et al.* (2015) concluded that the UPT2 is a surface manifestation of ramp-flat kinematics below the surface and they did not rule out out-of-sequence thrusting at the UPT2.

Yu *et al.* (2015) recognized (1) a *c.* 450 m thick top-to-the-SW sheared Pabbar Thrust, with *c.* 25 km displacement and a *c.* 3.5 km thick hanging-wall block, in between the Berinag and the Tons Thrust and (2) considered the Krol Thrust in the Mussourie hills near Dehradun (India) to also be equivalent to the Tons Thrust. Note that the Krol Thrust was earlier considered to be equivalent to the MBT (Yu *et al.* 2015). Ansari *et al.* (1976) estimated recent creep and strain from the Krol Thrust near Dehradun, but could not explain the cause. This recent creep seems to be due to the out-of-sequence activity of the Krol Thrust.

Based on apatite fission track (AFT) and zircon dates, the Vaikrita Thrust (=MCT$_U$) in the Goriganga section (India) shows present-day out-of-sequence activity, but not in the adjacent Dhauliganga valley (India) (Patel & Carter 2009). Based on this, Patel & Carter (2009) negated the link between erosion and deformation. P. Singh *et al.* (2012) also concluded an out-of-sequence thrust nature for the Vaikrita Thrust at *c.* 2.5 Ma and determined *c.* 0.3–0.9 Ma duplexing in the footwall of the MCT zone. They also concluded that, after a sequence of deformation from the MCT up to the MFT in the Pindari valley, an out-of-sequence thrust occurred in the Vaikrita Thrust. Harrison *et al.* (1999) considered the out-of-sequence thrust in the GHC in the Nepal Himalaya within 8–6 Ma as the MCT$_L$ and to be a part of the GHC tectonics (see also Upreti 1999). The MCT in NW Nepal reactivated as the Darma Fault, the Talphi Fault, the Tibrikot Fault and the Dhaulagiri Southwest Fault to give a fault system traceable for *c.* 170 km, but with an indeterminate fault dip.

Nepal and border regions. The Tamar Khola Thrust within the MCT zone, recognized as an out-of-sequence thrust, merges at depth with the MHT (Schelling & Arita 1991). Note that: (1) the hanging wall of the Tamar Khola Thrust is the GHC and the footwall is the Tamar Khola Window; (2) the Tamar Khola Thrust cuts the antiform developed in the ramp part of the MHT; (3) the Tamar Khola Thrust activated after the MBT; (4) the MCT terminates against the Tamar Khola Thrust at a single place, implying that the former activated before the latter; and (5) the latter thrust underwent *c.* 10 km dip-slip movement and has been projected up to *c.* 10 km depth (Schelling & Arita 1991).

Silver (2012) documented the out-of-sequence Dhaulagiri Transtension Zone that links the Tribrikot Fault with the Dhaulagiri Southwest Fault. This transtension zone offset Quaternary sediments, displays dextral (variable) slip and accommodated Himalayan strain (Silver 2012).

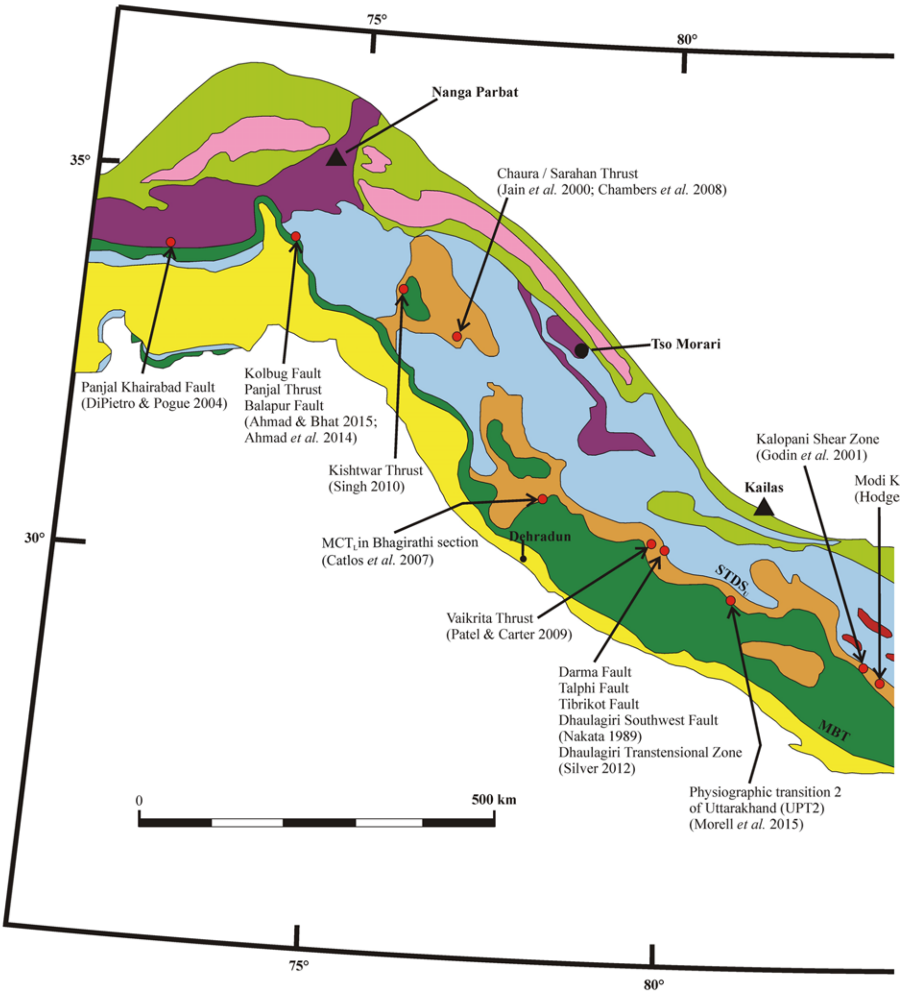
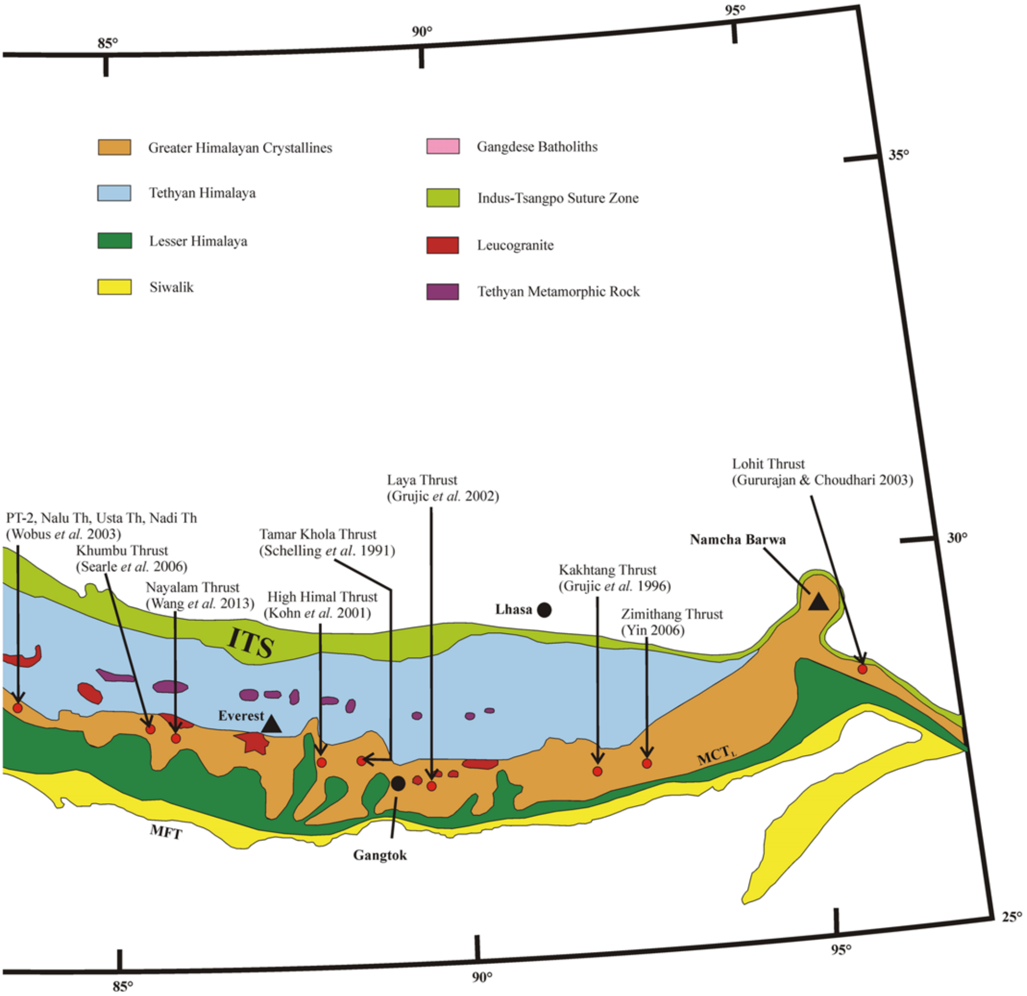


Fig. 14. Map of the Himalayan orogen. In this work, out-of-sequence thrusts within the Greater Himalayan Crystallines Elsevier. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; STDS$_U$, South Tibetan Transition in Uttarakhand.

The Bari–Gad Fault near the MCT in Nepal is an out-of-sequence thrust with 'right-lateral displacement with northward downthrow' (Nakata 1989). The MCT zone yielded a Late Miocene age in the Garhwal and Nepal Himalaya (review in Bollinger & Janots 2006) and elsewhere the age is 8–2 Ma (review in Célérier *et al.* 2009*b*). This timing partly coincides with the fastest sedimentation rates in the Siwalik (Gautam & Fujiwara 2000). The MCT reactivated in the Nepal Himalaya during 10–7.5 Ma (Antolin *et al.* 2013).

Around 5 km south to SW of Nyalam village, Wang *et al.* (2013) documented the 'Nyalam Thrust' within the GHC as an out-of-sequence thrust that acted at <14 Ma (Wang *et al.* 2013, fig. 11c). The timing (almost) matches with the first phase of low denudation of 0.27 mm a^{-1} in this part of the Himalaya during 15–6 Ma (Zheng *et al.* 2014).

The physiographic transition-2 (PT2) has been studied in great detail from the MCT zone in Nepal. The southern boundary of the PT2 is marked by a profound erosion rate and has been determined to be an out-of-sequence thrust (review in Adams *et al.* 2012) that differentially uplifted rocks across it during the Plio-Pleistocene (Hodges & Adams 2013), producing low relief to its south (Adams *et al.* 2012). Such a topography is independent of uplift of the hanging-wall block of the Kakhtang Thrust (Adams *et al.* 2012). Recently, however, McQuarrie & Ehlers (2015) postulated that the Kakhtang



are plotted from previous publications. The map is reproduced from Zhang *et al.* (2015), fig. 1 with permission from
Detachment Sustem-Upper; ITS, Indus Tsangpo Suture; Physiographic Transition in Nepal; UPT2, Physiographic

Thrust modulated the local topography. Geomorphological expressions as indicators of out-of-sequence thrusting have also been discussed for the PT2 from Nepal (McDermott *et al.* 2013). The entire PT2 can also be thought of as several out-of-sequence thrusts, such as the Nalu Thrust (=MCT), the Usta Thrust and the Nadi Thrust (Hodges *et al.* 2004). In particular, the shear fabric in the Nalu Thrust dates 4–3 Ma and together these thrusts absorbed Quaternary strain (Hodges *et al.* 2004). However, neither the strain nor the slip has been quantified (Pearson & DeCelles 2005). The out-of-sequence thrust within the MCT zone in the Nepal Himalaya, other than that documented as the PT2, is the Tamar Khola Thrust (Schelling & Arita 1991). Note that several authors questioned whether the PT2 is really an out-of-sequence thrust as the MFT in the Nepal Himalaya almost entirely accommodates the strain (review in Walsh *et al.* 2012).

Montomoli *et al.* (2013, 2014) determined the $\mathrm{GHC_U}$ and $\mathrm{GHC_L}$ contact to be a tectonometamorphic discontinuity: the Higher Himalayan Discontinuity (HHD). They determined that the HHD acted as a top-to-the-south/SW ductile shear zone prior to *c.* 25 Ma. Later Himalayan shortening (=the $\mathrm{D_2}$ deformation as referred to in Mukherjee & Koyi 2010b). Khanal *et al.* (2015) included the Langtang Thrust, the Toijem Shear Zone, the Mangri Shear Zone, the Bhanwua/Bhanua Thrust, the Sinua Thrust, the High Himal Thrust and possibly the Galchhi Shear Zone – all from the Nepal Himalaya – as the HHD. Ambrose (2014) considered the High Himal Thrust to be an out-of-sequence thrust activated at about 20 Ma. Larson & Cottle (2014) detected several discontinuities and tended to consider them as the HHD. Imayama (2014) preferred to also call the Nyalam Thrust an HHD. This appears incorrect as Wang *et al.* (2013), who designated the Nyalam Thrust clearly, stated that it occurred after the GHC had exhumed. Montomoli *et al.* (2014) re-designated the Toijem Shear Zone of 26–17 Ma activation in Nepal as an HHD, which the same group of researchers considered earlier as an out-of-sequence thrust (Carosi *et al.* 2007). The GHC in Bhutan also consists of a few metamorphic discontinuities (Regis *et al.* 2014), hence the HHD might also continue here. However, Yakymchuk & Godin (2012) considered the discontinuity in the NW Nepal GHC between its upper and lower parts to be an out-of-sequence thrust and not an HHD.

Sikkim. The MCT zone in Sikkim, characterized by ‘alternate shifts in epsilon Nd and zircon characters’ suggests an out-of-sequence thrust (Mottram *et al.* 2014), although again the timing of MCT activation is not clearly understood. On map view, one of the splays of the MCT cuts the latter and therefore defines an out-of-sequence thrust from the Darjeeling Himalaya (Searle & Szulc 2005).

Bhutan. Lesser Himalayan rocks of the Paro Window are bound by the Paro Thrust. Based on geochronological and cross-section balancing studies, McQuarrie *et al.* (2014) established that the Paro Thrust is an out-of-sequence thrust and that the Paro Window exhumed dominantly within 13–9 Ma. Cross-section balancing studies indicated ≥58 km displacement and *c.* 28 km shortening related to the Paro Thrust (Tobgay *et al.* 2012). Valdiya (1980) referred to the Paro Thrust as an equivalent of the Munsiari Thrust, the Jutogh Thrust and the Panjal Thrust in the west, and the Bomdila Thrust in the east.

Warren *et al.* (2011) referred to the Laya Thrust as another possible out-of-sequence thrust, which activated during *c.* 21–17 Ma (Grujic *et al.* 2011) or *c.* 14–10 Ma (Warren *et al.* 2011).

The Laya Thrust and the Kakhtang Thrust developed klippe to the south, with Tethyan rocks and the Chekha Formation inside them (Regis *et al.* 2014). McQuarrie *et al.* (2014) presented *c.* 2 Ma timing for the out-of-sequence thrust in the MCT and a *c.* 14 Ma monazite age for its in-sequence deformation from western Bhutan.

The Kakhtang Thrust has been considered to be one of the reasons for the increasing structural thickness of the GHC in this area (Wiesmayr & Grasemann 2002). Around 23–30 mm a^{-1} rate of exhumation of the hanging-wall block of the Kakhtang Thrust has recently been deciphered by McQuarrie & Ehlers (2015). The northern side of the Kakhtang Thrust eroded preferentially and the exact role of this thrust in exhuming the bedrock is unknown (Tshering 2007). It has also been explained less popularly as the tip of a blind thrust fault (reviewed in Hodges & Adams 2013). The Kakhtang Thrust cuts shear fabrics and isograds (Coutand *et al.* 2014), indicating that it is a much younger structure. Among all the exposures of out-of-sequence thrusts in the GHC, the hanging-wall rock of the Kakhtang Thrust consists uniquely of altered eclogites that exhumed from *c.* 70 km up to *c.* 20–30 km depth (review in Coutand *et al.* 2014). The presence of 15–13 Ma granulitized eclogites at the hanging-wall block of the Kakhtang Thrust (against older 21–18 Ma amphibolites in the footwall; Regis *et al.* 2014) indicates that the thrust exhumed at a rate of 10–44 mm a^{-1} along with slip of the STDS$_U$ (as referred to in Coutand *et al.* 2014). The out-of-sequence thrust in the GHC does not contain granulitized eclogites in any other river section. Thus, it appears that the deep exhumation at Kakhtang is a unique and localized feature.

Around 1–10% shortening (Meade 2010) for out-of-sequence thrusts in the GHC and 31–53 km specifically for the Kakhtang Thrust – merely 8–14% of the total Himalayan shortening – has been determined (Long *et al.* 2011). Despite several research papers on the Kakhtang Thrust, Cooper *et al.* (2013) considered the timing, displacement constraint and location of this thrust to be subjective. The relative timing of the out-of-sequence thrust in relation to peak metamorphism is generally unknown. Only at the Kalopani section can the out-of-sequence thrusting at the Kalopani Shear Zone be shown to occur after peak metamorphism (Godin 2003).

At a few locations, the top-to-the-south compression shear of the out-of-sequence thrust has been understood to be coeval with the top-to-the-NE extensional shear inside the STDS$_U$ and with duplexing of the LH. For example, in the eastern Himalaya the Kakhtang Thrust and the STDS$_U$ co-activated within 15–11 Ma (Long *et al.* 2012) or 15–9.5 Ma (Adams *et al.* 2012), leading to fault-bend folding of the hanging-wall block of the Kakhtang Thrust (Wiesmayr *et al.* 2002). Wiesmayr *et al.* (2002) considered that activation of the Kakhtang Thrust probably led to extensional shearing within the STDS$_U$. The dates of intrusions inside the Kakhtang Thrust bracket the upper age limit of the activation of the latter (Long *et al.* 2012).

Field observations of the Kakhtang Thrust, taken as the trace of the anatexis of the granite/second sillimanite isograd, cutting the $STDS_L$, indicates that the former post-dated the latter (Long *et al.* 2012). The PT2 in places coincides with the Kakhtang Thrust (Adams *et al.* 2012). No estimate of slip of the Kakhtang Thrust is available (Long *et al.* 2012). Instead of supporting a channel flow (Beaumont *et al.* 2001) induced by gravity, Long *et al.* (2012) indicated that the Kakhtang Thrust might build the critical taper condition. Adams *et al.* (2012) doubted the throw, the trace on the map and the activation timing of the Kakhtang Thrust. If this is so, commenting on its tectonic implication, such as in Long *et al.* (2012), is also questionable.

Arunachal Pradesh, India. Adlakha *et al.* (2013) postulated out-of-sequence thrusting within the MCT zone from the Arunachal Himalaya, where a crustal ramp might have played a role in exhumation. A recently obtained *c.* 7 Ma timing of the Zimithang Thrust (Warren *et al.* 2014) by the $^{40}Ar-^{39}Ar$ method proves that this thrust is indeed an out-of-sequence thrust. Yin *et al.* (2009) reported that the Zimithang Thrust, with N10E to N45W varying stretching lineations, also marks the boundary between mylonitized gneiss and garnet–biotite–quartzo-feldspathic gneiss. However, it is not clear from this paper whether this marks a first-order lithological boundary within the GHC. Yin *et al.* (2008) identified a >200 m thick top-to-the-south ductile shear zone in Geevan, east of Zimithang, as a continuation of the Zimithang Thrust.

Kinematics and genesis of out-of-sequence thrusting in the GHC. Out-of-sequence thrusting between the MCT and STDS has been the key driving mechanism of exhumation of the GHC since the Late Miocene–Pliocene (review in T. Singh *et al.* 2012). Out-of-sequence thrusting in the GHC was one of the factors in the exhumation and erosion of the Himalayan leucogranites located to the north. For example, the out-of-sequence thrust in the GHC in the Everest section, the Khumbu Thrust, uplifted, eroded and exhumed the Himalayan leucogranites to the north (Searle 1999). Edwards & Harrison (1997) reached a similar conclusion for the Khumbu Thrust and the leucogranites to its north in Bhutan.

The initiation of out-of-sequence thrusting in some GHC sections took place when deformation in the $STDS_U$ stopped (Kellett *et al.* 2009). Also, when the MBT activated, the MCT steepened from *c.* 7 to 30° and underwent out-of-sequence thrusting (review in Catlos *et al.* 2007). In the Bhutan Himalaya, the MBT activated at *c.* 10 Ma, presumably when the MCT and the Kakhtang Thrust stopped operating within the ductile regime (Coutand *et al.* 2014). $^{40}Ar-^{39}Ar$ and U–Pb dating led to the conclusion that, in Bhutan, the out-of-sequence thrusting in the GHC – the Kalopani Shear Zone – co-activated the local South Tibetan Detachment (Godin *et al.* 2001). The Kakhtang Thrust was also one of the reasons for the termination of the $STDS_L$ (Chambers *et al.* 2011). In contrast, Herman *et al.* (2010) modelled the out-of-sequence thrusting that developed after the STDS stopped and favoured occasional slip of the MCT.

In some cases, out-of-sequence thrusting in the GHC has been linked with tectonics and the deformation of both the LH and GHC. For example, (1) duplexing in the LH and cooling and folding of the GHC occurred simultaneously with Kakhtang thrusting (McQuarrie *et al.* 2008) and (2) kinking and doming north of the GHC link with out-of-sequence thrusting of the MCT (review in Godin 2003; Aikman *et al.* 2008). The low angle of rotation of the MHT coeval to or later than GHC extrusion can explain the out-of-sequence thrust. Thus, the out-of-sequence thrust within the GHC is linked in a complicated way with the GHC thrust wedges, whereby out-of-sequence thrusts keep developing in the hinterland while deformation propagates towards the foreland (review in Robinson & Pearson 2006). Khanal *et al.* (2014) viewed out-of-sequence thrusts in the Himalaya as ‘location specific unique complications’ in response to subsurface deformation.

Can the genesis of out-of-sequence thrusting proposed from one specific location of the GHC be applied to a different location? The Nyalam Thrust plots to the south to SW of the Nyalam Detachment/$STDS_U$ and inside the migmatitic GHC_U. The ‘Chaura Thrust’ (Jain *et al.* 2000) or ‘Sarahan Thrust’ (Chambers *et al.* 2008), on the other hand, falls inside the non-migmatitic lithology of the GHC_L. Therefore, the model of Carosi *et al.* (2007) (Fig. 15) cannot explain accurately the genesis of the Nyalam Thrust nor the Chaura Thrust; this could have been explained if the thrusts demarcated the contact between the GHC_U and the GHC_L. The Zimithang Thrust (Yin *et al.* 2006) demarcates the GHC_U and GHC_L contact in Bhutan and Arunachal Pradesh, respectively. The model of Carosi *et al.* (2007) might, therefore, work for the Zimithang Thrust.

In the case where the out-of-sequence thrust in the GHC is negated, this would result in tectonics becoming the single deciding factor in the structural geology of the GHC, not climatic or erosional factors (Pratt-Sitaula *et al.* 2009). Herman *et al.* (2010) compiled two ‘end-member models’ for Himalayan tectonics: (1) underplating of the Indian plate, activation of the MHT and duplexing (review in Robinson & Pearson 2006); and (2) underplating, MHT activity and out-of-sequence thrusting (see Arita & Ohira 2004), probably linked with mid-crustal

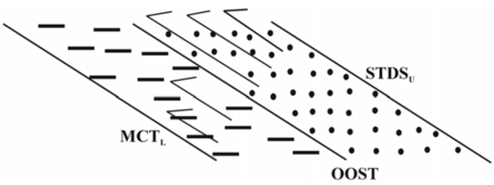


Fig. 15. When a shear zone with two broad lithologies is simple sheared, the softer right-hand part slips more than the harder left-hand part. An out-of-sequence thrust develops between the two lithologies.

channel flow (Mukherjee *et al.* 2012). Both the models excluded a role for far-field stress in the genesis of the out-of-sequence thrust (Huntington *et al.* 2006). The two models incorporate the thermochronological age jump across the inferred tectonic discontinuity.

Controversy exists about whether any age jump is really there (review in Caldwell *et al.* 2013). Buckingham (2014) showed a momentous jump in the AFT age from 1.3 to 2.4 Ma in eastern Nepal and favoured duplexing. Zeiger *et al.* (2015) reported no significant variation in zircon age across the Kakhtang Thrust. They therefore considered the Kakhtang Thrust to be a 'minor shear zone'. The authors, however, compiled ages across the Laya Thrust and showed *c.* 23–15 Ma south of the Laya Thrust and *c.* 15–11 Ma to the north. Wobus *et al.* (2006) considered both models to be correct and that the GHC initiated with underplating and duplexing, and then later underwent out-of-sequence thrusting. The problem in choosing the correct model from the two arises because the following six (tectonic) aspects of the GHC fit both the models: (1) its fast erosion; (2) its 4.4–6.8 mm a^{-1} rate of thrusting; (3) the reduced friction of the MHT (Herman *et al.* 2010); (4) several geomorphological expressions (McDermott *et al.* 2013); (5) disparity in the Ar–Ar age (Robl *et al.* 2008); and (6) the difference in AFT age (review in Caldwell *et al.* 2013) across the suspected out-of-sequence thrust. Note that the last point has not been accepted by all (reviews in Caldwell *et al.* 2013; Webb 2013). Aspect (3) does not match the opposite case, where high friction at the base can favour out-of-sequence thrusting. In addition, a few geomorphological indicators remain difficult to explain – for example, the knick zone in the Modi river in Nepal around the MCT zone could either indicate an out-of-sequence thrust or a combined effect of incision of the river and landslides (Nadin & Martin 2012), or even a ramp structure at depth (Pratt-Sitaula *et al.* 2009). Geophysical studies also remain inconclusive (Godard & Burbank 2011; and the imaging of the Munsiari Thrust by Caldwell *et al.* 2013).

Based on remote sensing and surface velocity studies, Grandin *et al.* (2012) negated out-of-sequence thrust activity at the physiographic transition as this would require a kinematically implausible steep 45–90° dip of the out-of-sequence thrust. Interestingly, Kohn *et al.* (2001), based on the P–T–t paths of metapelites in the MCT region in central Nepal, deduced a *c.* 8 Ma age for out-of-sequence thrust reactivation. This becomes proof, independent of geochronological methods, that the out-of-sequence thrust did occur in the MCT zone. This is despite the modelling results of Robert *et al.* (2011), which demand an unusually high temperature/geothermal gradient and faster overthrusting.

None of the out-of-sequence thrusts in the Quaternary requires a gently dipping (*c.* 20°) ramp beneath it. Note that Gavillot (2014) concluded geochronologically that climate forcing has no relation with erosion and exhumation in the Kashmir Himalaya. Based on thermochronological and thermobarometric data, Herman *et al.* (2010) also pointed out that the duplex model can explain the topographic disparity across the PT2. However, Hirschmiller *et al.* (2014) favoured a critical taper condition based on a morphological study of the orogen. Therefore, an out-of-sequence thrust could still be likely. On another aspect, Herman *et al.* (2010) pointed out that the LH klippes and windows cannot be explained by the out-of-sequence thrust model.

Neither of the two cases, duplexing and the out-of-sequence thrust, can explain all the geochronological data available from the Marsyandi valley in Nepal (discussed in Landry 2014). Landry (2014) still favoured the duplexing model because his mathematical model run for a time span equivalent to 10 Ma showed that the out-of-sequence thrust model demands >18 mm a^{-1} for the unusually high slip rate of the MCT. For comparison, (1) Nadin & Martin (2012) demonstrated from geochronological studies that no fault around the Modi river in central Nepal attained a slip rate of >4 mm a^{-1} in last 1 Ma and (2) both Herman *et al.* (2010) and Nadin & Martin (2012) found that the out-of-sequence thrust slipped at less than a few mm a^{-1} in Nepal. Their methodology of deduction was geochronology and analytical modelling.

An out-of-sequence thrust that acts for a short duration may not affect AFT age data across it (Robert *et al.* 2011). As geochronological approaches could not prove with certainty whether or not an out-of-sequence thrust exists inside the GHC, input from structural geology and metamorphic petrology might help to establish or refute the out-of-sequence thrust (Kellett *et al.* 2013). For example, presuming a Himalayan D$_2$ deformation of top-to-the-south/SW ductile shear at *c.* 25 Ma

(Mukherjee 2013*a*, *b*) gave a uniform shear strain, then a subsequent out-of-sequence thrust would be expected to give a higher magnitude of shear strain near the out-of-sequence thrust. If this is proved, it could be an important input to understanding the seismicity within the GHC (Herman *et al.* 2010).

Kellett *et al.* (2013) pointed out that if one of the strands of the South Tibetan Detachment acted as a passive roof structure, out-of-sequence thrusting is not required in the tectonics of the GHC. However, this argument does not negate the presence of an out-of-sequence thrust.

Erosion simultaneous to tectonics can facilitate out-of-sequence thrusting (Konstantinovskaia & Malavieille 2005). An out-of-sequence thrust can reduce the critical taper angle of a thrust wedge (Kellett *et al.* 2009). A possible enhanced erosion rate on the Himalayan wedge during 12–10 Ma was probably one of the reasons that the critical taper angle was reduced and a single out-of-sequence thrust developed inside the GHC at several places within the orogen (Kellett *et al.* 2009). Herman *et al.* (2010) pointed out that although the second model demands a much faster India–Eurasia convergence, a <1 mm a^{-1} slip rate and 30° dip of the MCT zone still revokes the out-of-sequence thrust model.

Thermal mechanical mid-crustal channel flow modelling by Beaumont *et al.* (2007) explained 2–0.9 Ma profound exhumation of a part of the GHC, guided by vigorous erosion under a pre-existing crustal shortening rate that reproduced the spatial trend of the cooling age variation of the prototype. This, in one way, supports erosion as a key factor of out-of-sequence thrusting in the GHC. Beaumont *et al.* (2007) modelled the coherent flow of the GHC where out-of-sequence thrusting remains unexplained (Warren *et al.* 2014). Out-of-sequence thrusting in the GHC was earlier considered to be a hindrance to crustal channel flow (review in Thakur 2013). As the rigour of channel flow may be milder in some Himalayan sections, e.g. the Annapurna–Dhaulagiri Himalaya, as determined by Parsons *et al.* (2014) from back-scattered electron diffraction studies, how far out-of-sequence thrusting can be produced in such cases remain uncertain.

By pushing a Newtonian fluid inside a horizontal channel and letting it extrude through a linked inclined channel equivalent to the GHC, Mukherjee *et al.* (2012) demonstrated that the fluid originally within the horizontal channel was extruded through the model GHC$_U$ (Fig. 16). The lower boundary of this part of the fluid defines a blind out-of-sequence thrust that reaches the surface (equivalent to a surface-breaking fault) much later. Neither erosion nor any thermal variability was exerted in these models, which were run with a single fluid. Therefore, the thermal reason for the restricted flow of Wang *et al.* (2013), the lithological heterogeneity of Carosi *et al.* (2007) and differential erosion (review in Harris 2007) are not essential for out-of-sequence thrusting. Thus, the out-of-sequence thrust developed as a result of fluid flow from a flat into a GHC ramp.

Hollister & Grujic (2006) proposed pulsed channel flow of the Bhutanese GHC where the out-of-sequence thrust was involved as follows. The *c.* 12–10 Ma final pulse was confined within the GHC$_U$, between the Kakhtang Thrust in the south and the STDS$_U$ in the north. The reason for this restricted flow was not stated. Wang *et al.* (2013) postulated in their 'revised channel flow model' that partial melting for *c.* 26 Ma from *c.* 30 to 40 km depth near Nyalam (border of Nepal), south-central Tibet produced a southward 'long-lived channel flow' that exhumed the GHC. Denudation from the top and buoyant force from the bottom drove the channel by a 2–3 kbar km^{-1} pressure gradient in the lower GHC and <0.5 kbar km^{-1} in the

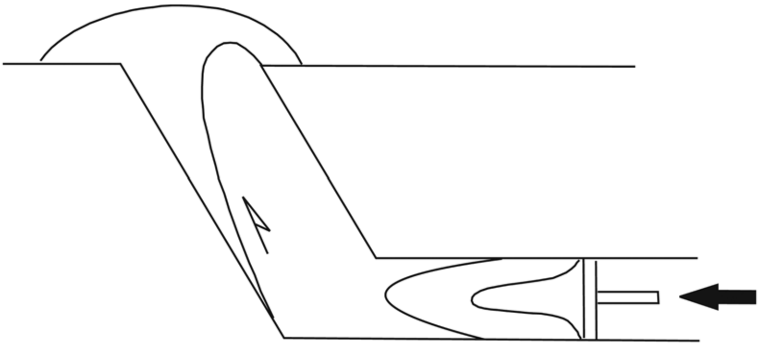


Fig. 16. On pushing a piston towards the left in a horizontal channel, the fluid inside extrudes through an inclined channel. Its lower boundary (half-arrow) defines an out-of-sequence thrust.

upper GHC. They conjectured that the MCT activated between 27 and 14 Ma and the melt extruded preferentially through the upper part of the GHC due to heat convection.

Out-of-sequence thrusting of Cenozoic age was postulated from the STDS (Yin 2006). An out-of-sequence thrust inside the STDS has been ascertained (review in Hurtado *et al.* 2001). Rana *et al.* (2013) deduced most convincingly from soft sedimentary deformation structures that the STDS in the Uttarakhand Himalaya activated during the Pleistocene–Holocene. Based on (U–Th)/He apatite and zircon thermochronology and field studies, McDermott *et al*. (2015) also recently deduced a Pleistocene reactivation of the STDS from the Annapurna–Dhaulagiri Region in Nepal. The deformation of the GHC, therefore, appears not to be simple and to be more prolonged than previously thought.

Hoth *et al.* (2007) expected out-of-sequence thrusting to develop within bivergent tectonic wedges. Interestingly, the GHC is now also viewed as a bivergent wedge with top-to-the-south/SW pro-shear (review in Yin 2006) and top-to-the-north/NE back-shear (Mukherjee 2013*a*). If this is so, we may expect an out-of-sequence thrust within the GHC.

Discussion

The leading models of Himalayan tectonics have, until now, not considered the out-of-sequence deformation in detail (Streule *et al.* 2010, fig. 2). However, the timing of out-of-sequence thrusting has been found to affect how the GHC deforms and exhumes in cross-section balance models (Gilmore *et al.* 2014). Out-of-sequence thrusting takes partial care of the shortening produced by the India–Eurasia collision (Mukul *et al.* 2007). By adding the slip rates of the two major thrusts and those of the out-of-sequence thrusts in between them, we can estimate the rate of shortening of this particular segment of the Himalayan unit (Mugnier *et al.* 2004).

Pratt-Situala *et al.* (2009) proposed that enhanced precipitation in the Himalaya was the key reason for profound erosion followed by out-of-sequence thrusting, leading to a sharp morphology. However, Cruz *et al.* (2010) considered that erosion was not an essential requirement for out-of-sequence thrusting. These authors acknowledged that the abrupt morphology could be produced by a ramp underneath.

Out-of-sequence thrusts have been designated as a zone of (strong) seismicity (Mugnier *et al.* 1998; Bilham & Ambraseys 2005; Mukul *et al.* 2007). The nearby region acts as the seismic gap (Mugnier *et al.* 1998). As out-of-sequence thrusts parallel nearby in-sequence thrusts in outcrop, deformation may localize within them, yielding strong seismicity (Vassallo *et al.* 2012). The presence of out-of-sequence thrusts in orogens most probably indicates seismicity associated with genesis (Kao & Chen 2000). The Chamoli earthquake in 1999 was considered to be related to an out-of-sequence thrust movement on the Himalaya (Mugnier *et al.* 2013 and references cited therein). Out-of-sequence thrusting decides how wide the rupture zone is in relation to the earthquake (Mugnier *et al.* 2005). The 1991 Uttarkashi and the 1999 Chamoli earthquakes ruptured and faulted close to the MHT in the subsurface. However, the width of the rupture zone in relation to the earthquake intensity was probably not studied. The seismicity in relation to out-of-sequence thrusts is confined most plausibly in ramps (Yeats & Thakur 1998). Ramping seems to control the Himalayan tectonics critically (Caldwell *et al.* 2013). Interestingly, Roux-Mallouf *et al.* (2015) inferred a ramp geometry for the MHT around the boundary between western Bhutan and Sikkim.

The MFT was reactivated, leading to sinking of the ground where it was blind (Valdiya 2003). The other manifestation of reactivation has been seismicity (such as the 1905 Dehradun earthquake) and a shift in the courses of rivers (Valdiya 2003). However, whether it is considered to be an out-of-sequence thrust is subjective, as no thrust exists south of the MFT. Another point to note is that no fault was produced or reactivated by earthquakes in Siwalik from 1803 to 1991 (Yeats *et al.* 1992).

Out-of-sequence thrusting, along with duplexing, can develop a critical wedge condition in the collisional orogen (Mukul *et al.* 2007) and strain partitioning (Husson *et al.* 2004). Slip transfer from one out-of-sequence thrust into the other has been determined by cross-section balancing (Mugnier *et al.* 1999). The (over)critical wedge condition might have been augmented by fast up-rise of the Tibetan Plateau (Huyghe *et al.* 2001). Out-of-sequence thrusting can develop prior to the critical taper condition (Thakur 2013), or after the steady state has been attained (Chalaron *et al.* 1995). Out-of-sequence thrusting can also maintain the critical taper situation (Cruz *et al.* 2010) and bring equilibrium to the wedge (review in Bollinger & Janots 2006). Alternatively, out-of-sequence thrusts can develop to maintain the critical taper condition and favour the foreland-ward propagation of thrusts (Robinson *et al.* 2006).

Whether channel flow or a critical taper mechanism works in the Himalaya has been contested. A number of studies have suggested that either (1) both channel flow and critical taper acted together (Beaumont & Jamieson 2010; Mukherjee 2013*a*, *b*), or (2) critical taper dominated (Hirschmiller *et al.* 2014). The presence of out-of-sequence thrusting in several sectors of the Himalaya suggests that some component of critical taper might be acting in this orogen.

Two-dimensional finite-element modelling of the tectonics of the Nepal Himalaya (Chamlagain & Hayashi 2007) revealed that normal faulting would be possible near the MBT. This might simulate normal faults around Singhauli (Haryana, India). Chamlagain & Hayashi (2007) did not specify whether such faults could be expected in the Siwalik or the LH. The mid-crustal ramp related to the MHT was found to be the key reason for such faulting.

Among the out-of-sequence thrusts in the Siwalik, LH and the GHC, the Nalagarh Thrust (Himachal Pradesh, India) and the MCT in Garhwal and (western) Nepal reveal a prior in-sequence deformation. This means that the out-of-sequence thrust can be reactivated along pre-existing planes of ductile/brittle shear. The Balapore Fault (Kashmir, India) and the Nalagarh Thrust (Himachal Pradesh, India) display multiple phases of out-of-sequence thrusting.

Few out-of-sequence thrusts developed as new thrust planes, e.g. the Bhauwala Thrust (Dehradun, India) and the Soan Thrust (Soan Dun, India). The other group of out-of-sequence thrusts developed presumably by reactivation of the pre-existing thrust planes, e.g. the out-of-sequence thrusts developed inside the MCT zone, such as the UPT2 (Uttarakhand, India) and the PT2 (Marsyandi valley, Nepal).

Webb (2013) deduced from cross-section balancing studies that the Tons Thrust is a continuation of the Berinag Thrust in Himachal Pradesh. Similarly, Yu *et al.* (2015) considered the Tons Thrust with >40 km displacement and the Berinag Thrust to be ‘contiguous structures’ and grouped them together as the ‘Berinag Tons Thrust’. Webb (2013) deduced from cross-section balancing studies that (1) crustal slices accreted near the Berinag/Tons Thrust, the Chaura Thrust and the Munsiari Thrust in the LH and the Higher Himalaya; (2) from *c.* 14 Ma onwards, these thrusts started developing; and (3) a total of *c.* 218 km of crustal shortening occurred that was related to these out-of-sequence thrusts. Webb (2013) deduced the timing of out-of-sequence thrusts in trials in cross-section balancing. Note that the Chaura Thrust has actually been dated to be active within 4.9–1.5 Ma (Jain *et al.* 2000). Ahmad *et al.* (2000) considered the LH Tons Thrust, with >80 km displacement (Yu & Webb 2012), locally known as the Srinagar Thrust, in the Garhwal Himalaya as an out-of-sequence thrust and correlated it with the Tamar Khola Thrust in Nepal.

The MCT (zone) has not yielded a conclusively young age, indicating out-of-sequence thrusting, at all locations, e.g. some parts of the Kisthwar region (Stephenson *et al.* 2001) and near the Mount Everest region in Nepal (review in MacFarlane *et al.* 1992). At several other sections, no data are available, e.g. in the Indian Dhauliganga section (Mukherjee 2010). In the Garhwal Himalaya, a gradation in cooling ages in the MCT zone negates the episodic nature of its out-of-sequence thrust (Célérier *et al.* 2009*a*, *b*). Out-of-sequence thrusts leading to klippens (Hodges & Adams 2013) have been understood, but the detailed mechanism has not been explained.

A number of studies have determined the neotectonics/out-of-sequence deformation within the Siwalik/LH/GHC, but did not pin-point exactly which fault(s) were active. A few of these include: (1) Singh (2007) from the Itanagar region of Siwalik in Arunachal Pradesh (India); (2) Virdi *et al.* (2006) from Siwalik in Bata and the Markanda river basins in Himachal Pradesh, where the region within the Nahan Thrust and the MBT tilted and the Bata Formation uplifted; (3) based on seismicity-related soft sedimentary deformation structures reported by Kundu *et al.* (2011) from the Siwalik in Darjeeling district, West Bengal, India; (4) the neotectonicly active GHC and LH in the Pindari valley (Bali *et al.* 2012); and (5) the landslide-prone MCT zone in the Bhagirathi river section from Maneri up to Bhatwari (Mathew *et al.* 2007). Saha *et al.* (2002) hinted that local thrusts can cause landslides in the Bhagirathi section, but did not provide a possible timing for the thrusting. Note that the Bata Thrust with 25–30 m throw has been recognized in Himachal Pradesh (Philip *et al.* 2009) and this could be the reason for the uplift of the Bata Formation.

Conclusions

The study of out-of-sequence deformation in collisional terrains is important in the context of seismicity, petroleum geoscience and tectonics. Thrusting is the most common manifestation of out-of-sequence deformation in the Himalaya, from Pakistan in the west to Arunachal Pradesh (India) in east. In addition to faulting, a less common mode of out-of-sequence deformation in the Himalaya has been fracturing related to earthquakes. Examples from India are from Nurpur, Nadha, Kala Amb and Rampur Ganda (Himachal Pradesh), Lal Dhang and Ramnagar (Uttarakhand) and Punjab.

The vast stretch of Siwalik, LH and GHC consists of several out-of-sequence thrusts that usually strike NW and dip NE. Out-of-sequence thrusts (in the Himalaya) have been recognized by the following features: (1) they cut across recent sediments;

(2) geomorphological indicators, e.g. landslides; (3) trials in cross-section balancing exercises; and (4) disparities in geochronological ages across a tectonic plane. The first three techniques have been applied in Siwalik, whereas the fourth method has been worked more profusely in the GHC.

Some of the out-of-sequence thrusts in the Salt Range (Pakistan) and the Barsar Thrust and Majhaur Thrust in the Indian Siwalik are backthrusts. The rates of crustal shortening related to out-of-sequence thrusts are usually trivial compared with Himalayan tectonics. Notwithstanding, the Riasi Thrust is an out-of-sequence thrust that seems to have accommodated significant crustal shortening. Out-of-sequence thrusts can either be surface-breaking (the South Kalijhora Thrust in Darjeeling, India) or blind (the SjBt in Himachal Pradesh, India), have a gentle, moderate or steep dip, and may have an in-sequence deformation history with or without associated drag folds. Out-of-sequence faulting can display an oblique-slip component (Muzaffarabad Fault, Siwalik, Pakistan; possibly the Garampani–Kathgodam Fault, Siwalik, India), normal faulting (e.g. the Singhauli Fault in Siwalik, Himachal Pradesh, India; the Salt Range, Pakistan), a strike-slip component (the Ganga and Yamuna Tear Fault in Siwalik, near Dehradun, India) and a significant dip-slip component (the Tamar Khola Thrust, GHC, Nepal). Single out-of-sequence thrusts, such as the Kala Amb Fault, Pinjaur Garden Fault, Hajipur Fault (Himachal Pradesh), Munsiari Thrust (Uttarakhand, India), the MDT in the LH and the physiographic transition from the MCT zone (Nepal) reveal, on higher resolution, more than one strand of coeval/different activation timings. The Siwalik Himalaya along the Himalayan trend varies in critical taper condition. The intensity of deformation along individual out-of-sequence thrusts can vary along its length, such as the Medlicott–Wadia Thrust and the MDT. Temporal variation of the slip rate of out-of-sequence thrusts has also been deciphered for the Medlicott–Wadia Thrust, in addition to varied slip along the Kathgodam–Garampani Fault.

At places the out-of-sequence thrust is defined between the Upper and Lower Siwalik (e.g. the Paonta Thrust, Pinjaur Thrust and Nahan/Nalagarh Thrust in Himachal Pradesh, the Chaura–Marin Thrust in Nepal and the South Kalijhora Thrust in Darjeeling, India), between the Upper and Middle Siwalik (e.g. the Soan Thrust in Himachal Pradesh, the Ramghat Thrust in Arunachal Pradesh, India), between the Lower Siwalik and alluvium (e.g. the Nalagarh Thrust, Himachal Pradesh, India), the upper and the lower LH (the Bari-Gad Kali Gandaki Fault) and between the upper GHC and lower GHC (the Zimithang Thrust in Arunachal Pradesh, India). Lithological contacts in different units of the Himalaya thus favourably acted as the out-of-sequence thrust in a few places, which is common in many other regional shear zones (review in Gerbi *et al.* 2015). However, such thrusting among major lithological divisions does not exist everywhere in the Siwalik. For example, the structural cross-section along the Dun valley does not have any thrust between the Upper and Middle, and between the Middle and the Lower Siwalik (Thakur & Pandey 2004, fig. 4). In addition, the Chamuhi Fault (Himachal Pradesh, India) developed wholly inside the Upper Siwalik unit. As a result of lithofacies variation along the Himalayan trend, not all the major lithological/stratigraphic contacts can be traced continuously. Finally, the contact between the GHC_U and the GHC_L in Nepal is the pre-India–Eurasia collisional Higher Himalayan Discontinuity, which is very different from an out-of-sequence thrust.

Out-of-sequence thrusting within the GHC has been reported from 13 or more spot locations in various Himalayan sections. Except for a few sections, the MCT zone reactivated or acted like an out-of-sequence thrust as a discrete thrust, deciphered most notably from the Marsyandi valley in Nepal. Out-of-sequence thrusts of unconstrained mechanisms exist as the contact between domes/windows and klippens with the GHC and LH.

The deepest exhumation of the hanging-wall block of the out-of-sequence thrust in the GHC has been around Kakhtang. The out-of-sequence thrust in the GHC links in a complicated way with the deformation of the GHC, and also the LH, and spans *c.* 22 Ma up to the Holocene. The out-of-sequence thrust in the GHC has been determined by noting the (significant) age jump of rocks across the Himalayan trend. However, the jump has also been explained by a duplexing mechanism. Whether any age jump really exists has also been questioned. Whether duplexing was followed by out-of-sequence thrusting has remained uncertain. Although Robert *et al.* (2011) and Grandin *et al.* (2012) almost negated out-of-sequence thrusting in the GHC, Kohn *et al.* (2001), using an alternative petrological study, supported out-of-sequence thrust activity within the GHC.

We would expect a higher shear strain near the out-of-sequence thrust in the Siwalik, LH and GHC. Such a quantitative study is yet to be undertaken. However, even if a higher strain is obtained near a tectonic plane/zone, it cannot act as independent proof for out-of-sequence thrusting. This is because pre-Himalayan/pre-collisional ductile shearing (as in Montomoli *et al.* 2013) might be another possibility. A few conventional structural geological studies exist across out-of-sequence thrusts, such as around the Chaura/Sarahan region in the GHC (e.g. Singh 1980; Singh & Jain 1993).

These studies do not indicate the presence of an out-of-sequence thrust.

Erosion and crustal shortening during channel flow can produce the age jumps in the GHC and hence can explain out-of-sequence thrusting in the GHC (Beaumont *et al.* 2007). On the other hand, Mukherjee *et al.* (2012) analogue-modelled the channel flow of the GHC, the same as the restricted channel flow in the mechanisms of Wang *et al.* (2013) and Hollister & Grujic (2006), where out-of-sequence thrusting was generated without any erosion of the extruded material. Whether out-of-sequence thrusting can form a weak channel flow in some Himalayan section is yet to be explored via modelling. Out-of-sequence thrusting can also be explained easily by the critical taper mechanism with or without enhanced erosion. Recent findings of out-of-sequence thrusts of the $STDS_U$ indicate more complicated tectonics in the GHC.

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Appendix A

The main acronyms used within the text are explained below. Additional acronyms may appear in figure captions and are explained there.

AFT	Apatite fission track
GHC	Greater Himalayan Crystalline
GHC_L	Greater Himalayan Crystalline-Lower
GHC_U	Greater Himalayan Crystalline-Upper
HHD	Higher Himalayan Discontinuity
LH	Lesser Himalaya
MBT	Main Boundary Thrust
MCT	Main Central Thrust
MCT_L	Main Central Thrust Lower
MCT_U	Main Central Thrust Upper
MDT	Main Dun Thrust
MFT	Main Frontal Thrust
MHT	Main Himalayan Thrust
PT2	Physiographic Transition-2
SH	Sub-Himalaya
STDS	South Tibetan Detachment System
$STDS_L$	South Tibetan Detachment System-Lower
$STDS_U$	South Tibetan Detachment System-Upper

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