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

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**Please see next page for abstract.**

**Abstract** Out-of-sequence deformation in the Himalaya has been mainly by thrusting. Out-of-sequence thrusts (OOSTs), usually N/NE dipping foreshear planes, occur inside the Sub-Himalaya (SH), Lesser Himalaya (LH) and Greater Himalayan Crystallines (GHC). Where absolute dates are available, the youngest slip within the SH is near the Janauri anticline (India) at ~ 1400- 1460 AD, within the LH is the Munsiari Thrust (India) at ~ 1-2 Ma, and in GHC is the Main Central Thrust Zone in Marsyandi valley (Nepal) during Holocene (~ 0.3 ka). Except the Riasi Thrust (Kashmir, India), the Paonta Thrust (Himachal Pradesh, India) in the Siwalik, the Tons Thrust (Garhwal region, India) within the MCZ Zone, crustal shortening related to OOST in the Himalaya has been insignificant. The major litho-/stratigraphic contacts within the SH and the GHC at places acted as an OOST. OOST in the SH were detected mainly based on geomorphological observations. On the other hand, more quantitative geochronologic studies detect ~ 22 Ma up to Holocene OOST in the GHC based on age jump, especially within the MCT Zone. Crustal channel flow (specifically for the GHC) and/or critical taper model with or without erosion explain the Himalayan OOSTs. 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 up to Arunachal Pradesh (India) in east. Other than faulting, 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-, Lesser Himalaya (LH) and Greater Himalayan Crystallines (GHC) consist of several out-of-sequence thrusts (OOSTs) that usually strike NW and dip NE. OOSTs (in the Himalaya) have been recognized by (i) they cut across recent sediments, (ii) geomorphic indicators e.g. landslides, (iii) trials in cross-section balancing exercises, (iv) disparity in geochronologic age across a tectonic plane. The first three techniques have been more applied on Siwalik, whereas the fourth method has been worked more profusely in the GHC. Some of the OOSTs in Salt Range (Pakistan) and Barsar Thrust and Majhaur Thrust in the Indian Siwalik are backthrusts. Rates of crustal shortening related to OOSTs usually are trivial compared to Himalayan tectonics. Notwithstanding, the Riasi Thrust is an OOST that seems to be accommodated significant crustal shortening. OOSTs can either be surface breaking (South Kalijhora Thrust in Darjeeling, India) or blind ('SjBt' in Himachal Predesh, India), can have gentle, moderate or steep dip, and may have an in-sequene deformation history with or without associated drag folds. Out-of-sequence faulting can display oblique slip (Muzaffarabad Fault: Siwalik, Pakistan; possibly Garampani-Kathgodam Fault: Siwalik, India), normal faulting (e.g. Singhauli Fault in Siwalik: Himachal Pradesh, India; Salt Range: Pakistan), strike slip (Ganga- and Yamuna Tear Fault in Siwalik, near Dehradun, India), and significant dip slip component (Tamar Khola Thrust, GHC, Nepal). Single OOSTs, such as the Kala Amb Fault, Pinjaur Garden Fault, Hajipur Fault (Himachal Pradesh), Munsiary Thrust (Uttarakhand, India), and Main Dun Thrust in LH and the Physiographic Transition from the MCT Zone (Nepal), on higher resolution reveals more than one strands of coeval/different activation timings. The Siwalik Himalaya along the Himalayan trend varies in critical taper condition. Intensity of deformation along individual OOST can vary along its length, such as the Medlicott-Wadia Thrust and the Main Dun Thrust. Temporal variation of slip rate of OOST is also deciphered for the Medlicott-Wadia Thrust, and varied slip along the Kathgodam-Garampani Fault.

At places in between the Upper- and the Lower Siwalik (e.g. Paonta Thrust, Pinjaur Thrust and Nahan/Nalagarh Thrust in Himachal Pradesh, Chaura-Marin Thrust in Nepal, South Kalijhora Thrust in Darjeeling, India), between the Upper- and the Middle Siwalik (e.g. Soan Thrust in Himachal Pradesh, Ramghat Thrust in Arunachal Pradesh, India), between Lower Siwalik and alluvium (e.g. Nalagarh Thrust:L Himachal Pradesh, India), the upper- and the lower LH (Bari- Gad Kali -Gandaki Fault), and between the upper GHC and lower GHC (Zimithang Thrust in Arunachal Pradesh, India) defines the OOST. Lithological contacts in different units of the Himalaya thus favourably acted as the OOST at few places, which is common in many other regional shear zones (Gerbi et al. 2015’s review). However, such thrusting amongst major lithologic division does not exist everywhere in the Siwalik. For example, the structural cross- section along Dun valley does not have any thrust between Upper- and Middle, and between the Middle- and the Lower Siwalik (see fig. 4 of Thakur and Pandey 2004). Secondly, the Chamuhi Fault (Himachal Pradesh, India) developed wholly inside the Upper Siwalik unit. Additionally, due to litho-facies variation along the Himalayan trend, not all the major- lithologic/stratigraphic contacts can be traced continuously. Finally, the contact between the GHCU and the GHCL in Nepal is the pre-India-Eurasia collisional Higher Himalayan Detachment (HHD), which is quite different from OOST. OOST within the GHC has been reported from 13 or more spot locations in various Himalayan sections. Except few sections, The MCT Zone reactivated/acted like OOST as discrete thrusts, deciphered most notably from the Marsyandi valley in Nepal. OOSTs of unconstrained mechanisms exist as the contact between domes/windows ans klippens with GHC and LH. The deepest exhumation of the hanging wall block of the OOST in GHC has been around Kakhtang. OOST in GHC links in a complicated way with the deformation of the GHC and also the LH, and spans ~ 22 Ma up to the Holocene. OOST in the GHC has been deciphered noting (significant) age jump of rocks across the Himalayan trend. However, the jump has also been explained by duplexing mechanism. Secondly, whether any age jump really exists has also been questioned. Whether duplexing was followed by OOST has remained uncertain. While Robert et al. (2011) and Grandin et al. (2012) almost negated OOST in the GHC, Kohn et al. (2001) from an alternate petrologic study supported the OOST activity within the GHC.

One would expect higher shear strain near the OOST in Siwalik, SH and GHC. Such a quantitative study is yet to be undertaken. However, even if higher strain is obtained near a tectonic plane/zone, it cannot act as an independent proof for OOST. This is because pre- Himalayan/pre-Collisional ductile shearing (as in Montomoli et al. 2013) might be the other possibility.

Erosion and crustal shortening during channel flow can produce age jump in the GHC, hence can explain OOST in GHC (Beaumont et al. 2007). On the other hand, Mukherjee et al. (2012) analogue modeled GHC's channel flow, same as restricted channel flow of Wang et al.’s (2013) and Hollister and Grujic’s (2006) mechanism, where OOST generated without any erosion of the extruded material. Whether OOST can form for a weak channel flow in some Himalayan section is yet to be explored though models. OOST can also be explained easily by critical taper mechanism with or without enhanced erosion. Recent finding of OOST of STDSU indicates more complicated tectonics of the GHC.

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