Article:

Larson, KP, Ambrose, TK, Webb, AAG et al. (2 more authors) (2015) Reconciling Himalayan midcrustal discontinuities: The Main Central thrust system. Earth and Planetary Science Letters, 429. 139 - 146. ISSN 0012-821X

https://doi.org/10.1016/j.epsl.2015.07.070

Elsevier Editorial System(tm) for Earth and Planetary Science Letters
Manuscript Draft

Manuscript Number: EPSL-D-15-00450R2

Title: RECONCILING HIMALAYAN MIDCRUSTAL DISCONTINUITIES: THE MAIN CENTRAL THRUST SYSTEM

Article Type: Letters

Keywords: Himalaya; Nepal; Main Central thrust; Kinematic evolution

Corresponding Author: Dr. Kyle P Larson, Ph.D.

Corresponding Author's Institution: University of British Columbia, Okanagan

First Author: Kyle P Larson, Ph.D.

Order of Authors: Kyle P Larson, Ph.D.; Tyler K Ambrose, M.Sc.; Alexander G Webb; John M Cottle, Ph.D.; Sudip Shrestha

Abstract: The occurrence of thrust-sense tectonometamorphic discontinuities within the exhumed Himalayan metamorphic core can be explained as part of the Main Central thrust system. This imbricate thrust structure, which significantly thickened the orogenic midcrustal core, comprises a series of thrust-sense faults that all merge into a single detachment. The existence of these various structures, and their potential for complex overprinting along the main detachment, may help explain the contention surrounding the definition, mapping, and interpretation of the Main Central thrust. The unique evolution of specific segments of the Main Central thrust system along the orogen is interpreted to be a reflection of the inherent basement structure and ramp position, and structural level of exposure of the mid-crust. This helps explain the variation in the timing and structural position of tectonometamorphic discontinuities along the length of the mountain belt.

RECONCILING HIMALAYAN MIDCRUSTAL DISCONTINUITIES: THE MAIN CENTRAL THRUST SYSTEM

Kyle P. Larson[1*], Tyler K. Ambrose[1,2], A. Alexander G. Webb[3], John M. Cottle[4], Sudip Shrestha[1]

[1]*Earth and Environmental Sciences, University of British Columbia Okanagan, FIP353-3247 University Way, Kelowna, British Columbia, V1V 1V7, Canada*

[2]*Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, UK*

[3]*School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK*

[4]*Department of Earth Science, University of California, Santa Barbara, Santa Barbara, California, 93106-9630, USA*

*corresponding author: kyle.larson@ubc.ca

Abstract

The occurrence of thrust-sense tectonometamorphic discontinuities within the exhumed Himalayan metamorphic core can be explained as part of the Main Central thrust system. This imbricate thrust structure, which significantly thickened the orogenic midcrustal core, comprises a series of thrust-sense faults that all merge into a single detachment. The existence of these various structures, and their potential for complex overprinting along the main detachment, may help explain the contention surrounding the definition, mapping, and interpretation of the Main Central thrust. The unique evolution of specific segments of the Main Central thrust system along the orogen is interpreted to be a reflection of the inherent basement structure and ramp position, and structural level of exposure of the mid-crust. This helps explain the variation in the timing and structural position of tectonometamorphic discontinuities along the length of the mountain belt.

1. Introduction

Investigation of the role the middle and lower crust plays during the development of orogenic belts has led to a better understanding of internal convergence accommodation processes. In the Himalaya, this type of investigation has recently demonstrated that the exhumed mid-crust, or Greater Himalayan sequence (GHS), which was previously thought to be relatively homogeneous and characterized by diffuse pervasive strain (e.g. Grujic et al., 1996; Jamieson et al., 1996; Searle et al., 2006; Larson et al., 2010), is actually cut internally by a number of cryptic, thrust-sense shear zones commonly referred to in the literature as tectonometamorphic discontinuities (e.g. Montomoli et al., 2014; Cottle et al. 2015). The GHS is characterized by amphibolite to granulite, and locally eclogite, facies metamorphism (Kohn, 2014), often with an inverted metamorphic sequence at its base (e.g. Mallett, 1875; Bordet, 1961; Gansser, 1964; Hashimoto et al., 1973; Arita, 1983). These rocks are thought to represent the metamorphosed and deformed equivalents of the former sedimentary wedge that was built upon the northern passive margin of India prior to collision with Asia and the closure of the Tethys ocean (Parrish and Hodges, 1996; Searle et al., 1997; Myrow et al., 2003; Murphy, 2007). Discontinuities within the GHS have been identified in various locations along the length of the orogen (Figure 1; Table 1), recognized mainly through abrupt breaks in pressure and temperature estimates and/or pressure-temperature-time ± deformation (P-T-t(-D)) paths (e.g. Carosi et al., 2010; Corrie and Kohn, 2011; Larson et al., 2013; Montomoli et al., 2013; Rubatto et al., 2013; Warren et al., 2014; Ambrose et al., 2015).

The discovery of these cryptic structures within the Himalaya has led to a transition away from geologic models that have either not accounted for deformation within the high-grade core (e.g. DeCelles et al., 2001; Robinson et al., 2006; Webb et al., 2007; Robinson, 2008), or implicitly assumed that deformation was diffuse and pervasive throughout its history (e.g. Searle and Szulc, 2005; Larson and Godin, 2009; Larson et al., 2010). The widespread recognition of thrust-sense faults within the GHS implies that deformation was localized on discrete structures for at least the later part of the finite strain history recorded by these rocks (Cottle et al., 2015). Moreover, it also indicates that the GHS has been significantly thickened (Montomoli et al., 2013; Larson and Cottle, 2014; Ambrose et al. 2015) and that shortening estimates made based on structural restorations (e.g. DeCelles et al., 2001; McQuarrie et al., 2008; 2014; Long et al., 2011a; Khanal and Robinson, 2013; Webb, 2013), which are acknowledged as minimums, may actually severely underestimate real shortening values.

As interpreted, these discontinuities have typically been classified into one of two end-member types: early (late Oligocene to earliest Miocene) in-sequence thrust structures (e.g. Carosi et al., 2010; Corrie and Kohn, 2011; Kohn et al., 2005; Larson et al., 2013; Montomoli et al., 2014; 2013) or late (middle Miocene) out-of-sequence thrust structures (e.g. Grujic et al., 2011; Warren et al., 2011a; 2014; Kellett and Grujic, 2012; Larson and Cottle, 2014). Attempts to reconcile the data characterizing the various tectonometamorphic discontinuities mapped along the Himalaya into a coherent kinematic model have been focused on, and informed primarily by, data from the early in-sequence structures (e.g. Montomoli et al., 2014). The majority of these types of structures have been identified near the middle of the exhumed midcrustal core in west-central Nepal (Carosi et al., 2010; Corrie and Kohn, 2011; Kohn et al., 2005; Montomoli et al., 2013), whereas discontinuities farther east are typically younger in age and occur as out-of-sequence thrusts structurally higher in the exhumed metamorphic core (Daniel et al., 2003; Grujic et al., 2011; Warren et al., 2011a; 2014). The existing kinematic models for the evolution of these structures are not compatible with the variability in the type of structure that occurs along the orogen (i.e. in or out-of-sequence), the differences in timing, or why the structures occur at different structural levels in different locations. This study attempts to elucidate the development of these discontinuities and their variability along and across the orogen as part of an integrated imbricate thrust system model.

2. Previous Interpretations

The current model proposed to explain the development of major thrust-sense tectonometamorphic discontinuities within the migmatitic rocks of the GHS suggest all such structures along the orogen are part of one feature, 'the High Himalayan Discontinuity' (Montomoli et al., 2014). In this model, the rocks in the hanging wall of the structure were initially metamorphosed deep in the hinterland and then thrust towards the foreland (Carosi et al., 2010; Corrie and Kohn, 2011; Montomoli et al., 2013). As hanging wall rocks were translated southward, metamorphism occurred in the overridden footwall (e.g. Pêcher, 1989; Harrison et al., 1997; Hubbard, 1996; Long et al., 2011b). Therefore, metamorphism in the footwall and hanging wall is expected to be diachronous with earlier, typically higher temperature metamorphism in the hanging wall and later, higher pressure metamorphism in the footwall (Figure 2; Montomoli et al., 2014). As interpreted, the development of the High Himalayan Discontinuity is thought to have occurred in the late Oligocene or earliest Miocene (Montomoli et al., 2014), at least partially coeval with motion along the South Tibetan detachment system, a top-to-the-north-sense structure marking the top of the GHS (Figure 2). After movement along the High Himalayan Discontinuity ceased, deformation migrated towards the foreland and down structural section initiating activation of the Main Central thrust (Figure 2; Montomoli et al., 2013).

This High Himalayan Discontinuity model was largely developed for structures observed in west-central Nepal. There, along the Himalayan front, the GHS can be very thin - only a few kilometers in structural thickness (e.g. locations 3 and 4 in Figure 1). This contrasts sharply with the GHS exposed in eastern Nepal and neighbouring regions where it is in excess of 30 km thick (e.g. locations 12-16 in Figure 1). In the High Himalayan Discontinuity model of Montomoli et al. (2014), a single structural break is interpreted to occur along the length of the orogen that connects recognized discontinuities. There are, however, incompatibilities between the various recognized structures in their timing of displacement and the structural level at which they occur. In Bhutan and adjacent NE India, for example, the Kahktang thrust and equivalents (Laya and Zimithang thrusts) were active near the top of the GHS in the mid-Miocene (Daniel et al., 2003; Grujic et al., 2011; Warren et al., 2011a; 2014), not near the middle of the GHS during the late Oligocene as the High Himalayan Discontinuity is interpreted to be in areas farther west (Carosi et al., 2010; Montomoli et al., 2013). Moreover, in contrast to the High Himalayan Discontinuity in the model of Montomoli et al. (2014), structures in the eastern Himalaya are interpreted as out-of-sequence thrust faults that post-date metamorphism in the footwall (e.g. Grujic et al. 2011; Warren et al. 2014). Similar interpretations have been made for an unnamed and undated structure in northern Sikkim, which has been tentatively correlated to the Laya thrust in nearby Bhutan (Rubatto et al., 2013). The only structure identified in the eastern Himalaya with apparently similar characteristics as the High Himalayan Discontinuity is the High Himal thrust (Goscombe et al., 2006; Imayama et al., 2012). The data used to infer timing of displacement on that structure, however, are entirely from the footwall of the fault and as such do not constrain metamorphism in the hanging wall or movement across it. Based on monazite petrochronology from both sides of the High Himal thrust in the Kanchenjunga region, Ambrose et al. (2015) reinterpreted the structure as an out-of-sequence thrust that was active between ca. 20 and 18 Ma and that the data Imayama et al. (2012) used to infer movement on the High Himal thrust actually mark a distinct, structurally lower, discontinuity. The Ambrose et al. (2015) study actually outline no less than five tectonometamorphic discontinuities in the Kanchenjunga region, which demonstrates the potential complexity of deformation within the GHS and calls further into question the interpretation of recognized discontinuities across the orogen as a single structure.

3. Development of the Main Central thrust system

The variability in timing, structural position, and number of discontinuities observed along the orogen requires the development of a new kinematic model. Recent studies have interpreted the development of thrust-sense structures in the GHS as part of a larger system (Larson and Cottle, 2014; He et al. 2015; Ambrose et al. 2015). The interpreted processes are similar to underplating thermal-kinematic models (e.g. Avouac, 2003; Bollinger et al. 2006; Herman et al. 2010) and inferred crustal thickening via duplexing (Murphy, 2007; Grandin et al. 2012; Cannon and Murphy, 2014) for material structurally below the GHS in the footwall of the Main Central thrust. In an imbricate thrust system model, differences in the kinematic evolution between spatially distinct areas may reflect changes in regional geology such as crustal ramp geometries and/or the initial thickness of the GHS protoliths. It also has important implications for the evolution of the Main Central thrust.

The definition, position, and kinematic significance of the Main Central thrust, a crustal scale, orogen-wide fault/shear zone, have been the subject of much debate (e.g. Upreti, 1999; Yin, 2006; Searle et al., 2008; Mottram et al., 2014) leading to various studies re-interpreting and potentially misinterpreting previously published data based on different definitions of the structure. A wireframe construction of the kinematic model presented herein (Figure 3) potentially sheds some light on why interpretations of the Main Central thrust have been so varied in its definition and mapped location (e.g. Upreti, 1999; Searle et al. 2008).

In the proposed kinematic model, the thickening and southward translation of the GHS is accomplished through the development of an imbricate thrust system with the sequential addition of material to the hanging wall (Figure 3A, B). The active fault in the area of subcretion, effectively the Main Central thrust, changes with each slice of material that is added. Once the former sole thrust is no longer active it becomes part of the over-riding plate, whereas the newly active structure becomes the sole thrust. The thrusts merge both up-dip and down-dip from the ramp. This results in the progressive overprinting of the various deformation histories along a single structure (the Main Central thrust) both towards the foreland and the hinterland (Figure 3C, D). This type of evolution for the Main Central thrust could result in significantly different geologic histories recorded in a region, depending on the structural level of exposure and other factors (see below) that may control kinematic history and potential thrust system development in that area.

The South Tibetan detachment system may allow early lateral ductile flow of the mid-crust (e.g. Jamieson et al. 2006) or wedging (e.g. Webb et al. 2007) of the mid-crust southward (Figure 3A). In the first case, the South Tibetan detachment system would accommodate channel flow before or during imbricate thrust stacking (Larson and Cottle, 2014); in the second possibility the South Tibetan detachment system would develop as a roof back-thrust of the imbricate system (He et al., 2015). In either case, movement along the structure ceases as the thrust system evolves.

4. Integrated Kinematic Model

Initial development of tectonometamorphic discontinuities within the GHS occurred at similar times across (at least) Nepal with the High Himalayan Discontinuity (Montomoli et al., 2014) initiating in the Dolpo region of west –central Nepal at ca. 26-27 Ma (Carosi et al., 2010; Montomoli et al., 2013) and the earliest structure initiating in the Kanchenjunga region between 31 and 26 Ma (Ambrose et al., 2015). In both areas, geochronology and P-T data indicate that over-thrusting of the hanging wall resulted in prograde metamorphism in the footwall (Montomoli et al., 2014; Ambrose et al., 2015). Following this early, shared history, the spatially distinct differential development of the Himalayan mid-crust may be related to regional geologic changes such as crustal ramp geometries, structural level of exposure, or the location of the brittle-ductile transition (e.g. Bollinger et al., 2006; Cannon and Murphy, 2014).

In west-central Nepal, where the exposed GHS along the Himalayan front is as thin as 3 km (Le Fort et al., 1987; Carosi et al., 2007; 2010), deformation migrated structurally lower from the High Himalayan Discontinuity with the addition of the metamorphosed and deformed High Himalayan Discontinuity footwall (Figure 4; Carosi et al., 2010; Montomoli et al., 2013). Movement along the base of that imbricate, mapped as the Main Central thrust, occurred between ~19 and 13 Ma (Montomoli et al., 2013), post-dating local movement on the South Tibetan detachment system (Carosi et al., 2013). In eastern Nepal, where the exposed GHS is typically >30 km thick (e.g. Schelling, 1992), the development of the GHS was significantly different. Multiple imbricates were added to the Main Central thrust system between 24 and 20 Ma (Figure 4; Ambrose et al., 2015). The difference observed between the regions may reflect: 1) progressively deeper erosion levels (with respect to the crystalline core) from west to east across the orogeny (Webb et al. 2011), or 2) a more pronounced ramp structure in eastern Nepal that increased the volume of material accreted from the footwall. In the Kanchenjunga region, movement of the thrust sheets toward the foreland appears to have slowed by ~ 20 Ma. This may reflect encroachment of a significant change in footwall lithology leading to a change in fault geometry. Deformation then stepped out-of-sequence, towards the hinterland, cutting the previously imbricated GHS and driving deformation back towards the foreland (20 – 18 Ma). The location of the out-of-sequence thrust may be related to the position of the GHS above the main crustal ramp (e.g. Kellett et al., 2009; Warren et al., 2011a).

A similar history, with distinct timing, is postulated for the GHS of Bhutan and NE India. There, out-of-sequence thrusting occurs both significantly later (14-11 Ma) and farther toward the hinterland (Grujic et al., 2011; Warren et al., 2011a; 2014). This may reflect a similar lithologic change in the footwall encountered farther towards the foreland (Figure 4); the GHS moving along the basal detachment would take longer to encounter the effects of the forced change in fault geometry, thereby impeding its movement later than that in the Kanchenjunga region. Moreover, the GHS would have translated farther south by the time deformation slowed and out-of-sequence thrusting began. The resulting out-of-sequence thrust, located above the dominant crustal ramp (e.g. Kellett et al., 2009; Warren et al., 2011a), would have cut through the GHS later and higher up in the structural section (Figure 4).

Subsequent to the development of the Main Central thrust system in west-central Nepal, and the out-of-sequence thrust faults that cut the imbricate stack farther east, the GHS in all areas appear to have been largely exhumed through the development of the Lesser Himalayan duplex and concomitant erosion (e.g. DeCelles et al., 1998; McQuarrie et al., 2014; 2008; Robinson et al., 2001). The development of that duplex structure occurred at different times along the orogen corresponding to the time at which deformation was focused on different units in the down-going plate. In west-central Nepal, cooling of the GHS occurred between ca. 15 and 8 Ma; dominated by the earlier ages (Martin et al., 2014; Vannay and Hodges, 1996). Whereas exhumation and associated development of the Lesser Himalayan duplex in western Bhutan is much younger, with exhumation interpreted to have occurred between 9 Ma and the present day (McQuarrie et al., 2014).

A thrust imbricate model for the kinematic evolution of the GHS does not invalidate models of lateral midcrustal flow. ‘Channel’-type flow could occur during coeval movement along the Main Central thrust and South Tibetan detachment system, however, it would be relatively short-lived phenomena, with thrust imbrication being the dominant convergence accommodation process. Some published thermo-mechanical models (e.g. HT111; Jamieson et al. 2006) actually demonstrate vertical juxtaposition of formerly laterally adjacent rock units within the mid-crust during lateral transport, resulting in a similar final geometry to that presented herein. As modeled, however, the timing of juxtaposition and exhumation are not compatible with existing data.

5. Summary

The variation in the timing and structural position of tectonometamorphic discontinuities identified along the Himalaya is interpreted to reflect fundamental differences in the development of the Main Central thrust system. As described herein, these differences are interpreted reflect variations in the underlying basement/ramp structure of the basal detachment and perhaps structural level of exposure with respect to the mid-crust. This model is consistent with available along and across-strike geologic controls in the Himalaya and provides an integrated solution to help explain the occurrence and development of cryptic structures within an evolving orogenic midcrustal core.

6. Acknowledgements

This study was supported by a Natural Sciences and Engineering Research Council Discovery grant to K. Larson, a National Science Foundation grant (EAR-1119380) to J. Cottle, and a National Science Foundation grant (EAR-1322033) to A. Webb. The interpretations herein benefited from discussions with D. Kellett and R. Price. Reviews from M. Murphy and an anonymous reviewer and editorial handling by A. Yin improved the final manuscript.

7. Figure Captions:

Figure 1 – Simplified geologic map (after He et al., 2015) showing the spatial distributions of mapped tectonometamorphic discontinuities within the exhumed Himalayan mid-crust. See Table 1 for references corresponding to locations.

Figure 2 – Summary diagram of activity on the High Himalaya Discontinuity (HHD) and subsequently the Main Central Thrust (MCT) based on Montomoli et al. (2014). Movement of different particles demonstrates relative movement across the structures. Timing constraints are from western Nepal (Montomoli et al. 2013). STDS – South Tibetan detachment system.

Figure 3 – Evolution of the Main Central Thrust (MCT) system. The structure evolves such that the current floor thrust at any given time later becomes inactive as new material is incorporated into the thrust system. Motion along active structures is accommodated away from the site of addition along pre-existing faults potentially resulting in complex over-printing and/or protracted motion. Final exposure of the exhumed Himalayan metamorphic core above the Lesser Himalayan (LH) Duplex results in the surface exposure of a number the faults that comprise the Main Central Thrust system. Colors identify different discontinuities that in (D) merge up and down-dip into a single structure

(black) in present-day geometry. Throughout Himalayan development each would have been the Himalayan sole thrust. STDS – South Tibetan Detachment System.

Figure 4 – Conceptual development of the Main Central Thrust system at different points along the length of the orogen. See text for detailed discussion.

References

Ambrose, T., Larson, K.P., Guilmette, C., Cottle, J.M., Buckingham, H., Rai, S.M., n.d. Lateral extrusion, underplating, and out-of-sequence thrusting within the Himalayan metamorphic core, Kanchenjunga, Nepal. Lithosphere.

Ambrose, T.K., Larson, K.P., Guilmette, C., Cottle, J.M., Buckingham, H., Rai, S., 2015. Lateral extrusion, underplating, and out-of-sequence thrusting within the Himalayan metamorphic core, Kanchenjunga, Nepal. Lithosphere L437.1–24. doi:10.1130/L437.1

Arita, K., 1983. Origin of the inverted metamorphism of the lower Himalayas, central Nepal. Tectonophysics 95, 43–60.

Bollinger, L., Henry, Avouac, J.-P., 2006. Mountain building in the Nepal Himalaya: Thermal and kinematic model. Earth Planet Sc Lett 244.

Bordet, P., 1961. Recherches Géologiques dan l'Himalaya du Népal, Région du Makalu. C.N.R.S., Paris.

Cannon, J.M., Murphy, M.A., 2014. Active lower crustal deformation and Himalayan seismic hazard revealed by stream channels and regional geology. Tectonophysics 633, 34–42. doi:10.1016/j.tecto.2014.06.031

Carosi, R., Montomoli, C., Rubatto, D., Visonà, D., 2010. Late Oligocene high-temperature shear zones in the core of the Higher Himalayan Crystallines (Lower Dolpo, western Nepal). Tectonics 29, n/a–n/a. doi:10.1029/2008TC002400

Carosi, R., Montomoli, C., Rubatto, D., Visonà, D., 2013. Leucogranite intruding the South Tibetan Detachment in western Nepal: implications for exhumation models in the Himalayas. Terra Nova. doi:10.1111/ter.12062

Carosi, R., Montomoli, C., Visonà, D., 2007. A structural transect in the Lower Dolpo: Insights on the tectonic evolution of Western Nepal. Journal of Asian Earth Sciences 29, 407–423.

Corrie, S.L., Kohn, M.J., 2011. Metamorphic history of the central Himalaya, Annapurna region, Nepal, and implications for tectonic models. Geol Soc Am Bull 123, 1863–1879. doi:10.1130/B30376.1

Cottle, J.M., Larson, K.P., Kellett, D.A., 2015. How does the mid-crust accommodate deformation in large, hot collisional orogens? A review of recent research in the Himalayan orogen. Journal of Structural Geology 78, 119-133. doi:10.1016/j.jsg.2015.06.008

Daniel, C.G., Hollister, L.S., Parrish, R.R., Grujic, D., 2003. Exhumation of the Main Central Thrust from lower crustal depths, Eastern Bhutan Himalaya. Journal of Metamorphic Geology 21, 317–334.

Davidson, Grujic, D., Hollister, L., Schmid, S.M., 1997. Metamorphic reactions related to decompression and synkinematic intrusion of leucogranite, High Himalayan Crystallines, Bhutan. Journal of Metamorphic Geology 15, 593–612.

DeCelles, P.G., Gehrels, G.E., Quade, J., Ojha, T., Kapp, P., Upreti, B.N., 1998. Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold-thrust belt, western Nepal. Geol Soc Am Bull 110, 2–21.

DeCelles, P.G., Robinson, D.M., Quade, J., Ojha, T.P., Garzione, C.N., Copeland, P., Upreti, B.N., 2001. Stratigraphy, structure, and tectonic evolution of the Himalayan fold-thrust belt in western Nepal. Tectonics 20, 487–509.

Fraser, G., Worley, B., Sandiford, M., 2000. High-precision geothermobarometry across the High Himalayan metamorphic sequence, Langtang Valley, Nepal. Journal of Metamorphic Geology 18, 665–681.

From, R., Larson, K.P., Cottle, J.M., 2014. Metamorphism and geochronology of the exhumed Himalayan midcrust, Likhu Khola region, east-central Nepal: Recognition of a tectonometamorphic discontinuity. Lithosphere 6, 361–376. doi:10.1130/L381.1

Gansser, A., 1964. Geology of the Himalayas. Interscience, London.

Godin, L., Parrish, R.R., Brown, R.L., Hodges, K.V., 2001. Crustal thickening leading to exhumation of the Himalayan Metamorphic core of central Nepal: Insight from U-Pb Geochronology and $^{40}Ar/^{39}Ar$ Thermochronology. Tectonics 20, 729–747.

Goscombe, B., Gray, D., Hand, M., 2006. Crustal architecture of the Himalayan metamorphic front in eastern Nepal. Gondwana Research 10, 232–255. doi:10.1016/j.gr.2006.05.003

Grandin, R., Doin, M.P., Bollinger, L., Pinel-Puyssegur, B., Ducret, G., Jolivet, R., Sapkota, S.N., 2012. Long-term growth of the Himalaya inferred from interseismic InSAR measurement. Geology 40, 1059–1062. doi:10.1130/G33154.1

Groppo, C., Rolfo, F., Lombardo, B., 2009. P-T Evolution across the Main Central Thrust Zone (Eastern Nepal): Hidden Discontinuities Revealed by Petrology. Journal of Petrology 50, 1149–1180. doi:10.1093/petrology/egp036

Grujic, D., Casey, M., Davidson, Hollister, L., Kündig, R., Pavlis, T.L., Schmid, S.M., 1996. Ductile extrusion of the Higher Himalayan Crystalline in Bhutan: evidence from quartz microfabrics. Tectonophysics 260, 21–43.

Grujic, D., Hollister, L., Parrish, R.R., 2002. Himalayan metamorphic sequence as an orogenic channel: insight from Bhutan. Earth Planet Sc Lett 198, 177–191.

Grujic, D., Warren, C., Wooden, J.L., 2011. Rapid synconvergent exhumation of Miocene-aged lower orogenic crust in the eastern Himalaya. Lithosphere 3, 346–366. doi:10.1130/L154.1

Harrison, T.M., Ryerson, F.J., Le Fort, P., Yin, A., Lovera, O.M., Catlos, E.J., 1997. A late Miocene-Pliocene origin for the Central Himalayan inverted metamorphism. Earth Planet Sc Lett 146, E1–E7.

Hashimoto, S., Ohta, Y., Akiba, C. (Eds.), 1973. Geology of the Nepal Himalayas. Saikon, Tokyo.

He, D., Webb, A., Larson, K.P., Martin, A.J., Schmitt, A.K., 2015. Extrusion vs. duplexing models of Himalayan mountain building 3: duplexing dominates from the

Oligocene to Present. International Geology Review 56, 1–27. doi:10.1080/00206814.2014.986669

Herman, F., Copeland, P., Avouac, J.-P., Bollinger, L., Mahéo, G., Le Fort, P., Rai, S.M., Foster, D., Pêcher, A., Stüwe, K., Henry, P., 2010. Exhumation, crustal deformation, and thermal structure of the Nepal Himalaya derived from the inversion of thermochronological and thermobarometric data and modeling of the topography. J. Geophys. Res. 115, B06407. doi:10.1029/2008JB006126

Hubbard, M., 1996. Ductile shear as a cause of inverted metamorphism: Example from the Nepal Himalaya. Journal of Geology 104, 493–499.

Imayama, T., Takeshita, T., Arita, K., 2010. Metamorphic P–T profile and P–T path discontinuity across the far-eastern Nepal Himalaya: investigation of channel flow models - IMAYAMA - 2010 - Journal of Metamorphic Geology - Wiley Online Library. … of Metamorphic Geology.

Imayama, T., Takeshita, T., Yi, K., Cho, D.-L., Kitajima, K., Tsutsumi, Y., Kayama, M., Nishido, H., Okumura, T., Yagi, K., Itaya, T., Sano, Y., 2012. Two-stage partial melting and contrasting cooling history within the Higher Himalayan Crystalline Sequence in the far-eastern Nepal Himalaya. Lithos 134-135, 1–22. doi:10.1016/j.lithos.2011.12.004

Jamieson, R.A., Beaumont, C., Hamilton, J., Fullsack, P., 1996. Tectonic assembly of inverted metamorphic sequences. Geology 24, 839–842.

Jamieson, R.A., Beaumont, C., Nguyen, M.H., Grujic, D., 2006. Provenance of the Greater Himalayan Sequence and associated rocks: predictions of channel flow models, in: Law, R.D., Searle, M.P., Godin, L (eds) Channel flow, ductile extrusion and exhumation in Continental collision zones. Geological Society, London, Special Publications, 268, 165-182.

Jessup, M.J., Cottle, J.M., Searle, M.P., Law, R.D., Newell, D.L., Tracy, R.J., Waters, D.J., 2008. P-T-t-D paths of Everest Series schist, Nepal. Journal of Metamorphic Geology 26, 717–739. doi:10.1111/jmg.2008.26.issue-7

Kellett, D.A., Grujic, D., 2012. New insight into the South Tibetan detachment system: Not a single progressive deformation. Tectonics 31. doi:10.1029/2011TC002957

Kellett, D.A., Grujic, D., Erdmann, S., 2009. Miocene structural reorganization of the South Tibetan detachment, eastern Himalaya: Implications for continental collision. Lithosphere 1, 259–281. doi:10.1130/L56.1

Khanal, S., Robinson, D.M., 2013. Upper crustal shortening and forward modeling of the Himalayan thrust belt along the Budhi-Gandaki River, central Nepal. International Journal of Earth Sciences. doi:10.1007/s00531-013-0889-1

Kohn, M.J., 2008. P-T-t data from central Nepal support critical taper and repudiate large-scale channel flow of the Greater Himalayan Sequence. Geol Soc Am Bull 120, 259–273. doi:10.1130/B26252.1

Kohn, M.J., 2014. Himalayan Metamorphism and Its Tectonic Implications. Annual Review of Earth and Planetary Sciences 42, 381–419. doi:10.1146/annurev-earth-060313-055005

Kohn, M.J., Catlos, E.J., Ryerson, F.J., Harrison, T.M., 2001. Pressure-temperature-time path discontinuity in the Main Central thrust zone, central Nepal. Geology 29, 571–574.

Kohn, M.J., Wieland, M.S., Parkinson, C.D., Upreti, B.N., 2005. Five generations of monazite in Langtang gneisses: implications for chronology of the Himalayan metamorphic core. Journal of Metamorphic Geology 23. doi:10.1111/j.1525-1314.2005.00584.x

Larson, K.P., Cottle, J.M., 2014. Midcrustal discontinuities and the assembly of the Himalayan midcrust. Tectonics. doi:10.1002/(ISSN)1944-9194

Larson, K.P., Gervais, F., Kellett, D.A., 2013. A P–T–t–D discontinuity in east-central Nepal: Implications for the evolution of the Himalayan mid-crust. Lithos 179, 275–292. doi:10.1016/j.lithos.2013.08.012

Larson, K.P., Godin, L., 2009. Kinematics of the Greater Himalayan sequence, Dhaulagiri Himal: implications for the structural framework of central Nepal. Journal of the Geological Society 166, 25–43. doi:10.1144/0016-76492007-180

Larson, K.P., Godin, L., Price, R.A., 2010. Relationships between displacement and distortion in orogens: Linking the Himalayan foreland and hinterland in central Nepal. Geol Soc Am Bull 122, 1116–1134. doi:10.1130/B30073.1

Larson, K.P., Cottle, J.M., Godin, L., 2011. Petrochronologic record of metamorphism and melting in the upper Greater Himalayan sequence, Manaslu-Himal Chuli Himalaya, west-central Nepal. Lithosphere 3, 379–392. doi:10.1130/L149.1

Le Fort, P., Cuney, M., Deniel, C., France-Lanord, C., Sheppard, S.M., Upreti, B.N., Vidal, P., 1987. Crustal generation of the Himalayan leucogranites. Tectonophysics 134.

Long, S.P., McQuarrie, N., Tobgay, T., Grujic, D., 2011a. Geometry and crustal shortening of the Himalayan fold-thrust belt, eastern and central Bhutan. Geological Society of America Bulletin 123. doi:10.1130/B30203.1

Long, S.P., McQuarrie, N., Tobgay, T., Hawthorne, J., 2011b. Quantifying internal strain and deformation temperature in the eastern Himalaya, Bhutan: Implications for the evolution of strain in thrust sheets. Journal of Structural Geology 33, 579–608. doi:10.1016/j.jsg.2010.12.011

Mallett, F.R., 1875. On the geology and Mineral Resources of the Dárjíling District and the western Duára, Memoirs of the Geological Survey of India.

Martin, A.J., Ganguly, J., DeCelles, P.G., 2010. Metamorphism of Greater and Lesser Himalayan rocks exposed in the Modi Khola valley, central Nepal. Contrib Mineral Petr 159, 203–223. doi:10.1007/s00410-009-0424-3

Martin, A.J., Copeland, P., Benowitz, J.A., 2014. Muscovite $^{40}Ar/^{39}Ar$ ages help reveal the Neogene tectonic evolution of the southern Annapurna Range, central Nepal. Geological Society London Special Publications 412, SP412.5. doi:10.1144/SP412.5

McQuarrie, N., Robinson, D.M., Long, S.P., Tobgay, T., Grujic, D., Gehrels, G.E., Ducea, M., 2008. Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system. Earth Planet Sc Lett 272, 105–117. doi:10.1016/j.epsl.2008.04.030

McQuarrie, N., Tobgay, T., Long, S.P., Reiners, P.W., Cosca, M.A., 2014. Variable exhumation rates and variable displacement rates: Documenting recent slowing of Himalayan shortening in western Bhutan. Earth Planet Sc Lett 386, 161–174. doi:10.1016/j.epsl.2013.10.045

Montomoli, C., Carosi, R., Iaccarino, S., 2014. Tectonometamorphic discontinuities in the Greater Himalayan Sequence: a local or a regional feature?, in: Mukherjee, S., van der Beek, P., Mukherjee, P.K. (Eds.), Tectonics of the Himalaya. Geological

Society of London, p. SP412.3. doi:10.1144/SP412.3

Montomoli, C., Iaccarino, S., Carosi, R., Langone, A., Visonà, D., 2013. Tectonometamorphic discontinuities within the Greater Himalayan Sequence in Western Nepal (Central Himalaya): Insights on the exhumation of crystalline rocks. Tectonophysics. doi:10.1016/j.tecto.2013.06.006

Mottram, C.M., Argles, T.W., Harris, N.B., Parrish, R.R., Horstwood, M.S.A., Warren, C., Gupta, S., 2014. Tectonic interleaving along the Main Central Thrust, Sikkim Himalaya. Journal of the Geological Society, London. doi:10.1144/jgs2013-064

Murphy, M.A., 2007. Isotopic characteristics of the Gurla Mandhata metamorphic core complex: Implications for the …. Geology.

Myrow, P.M., Hughes, N.C., Paulsen, T.S., Williams, I.S., Parcha, S.K., Thompson, K.R., Bowring, S., Peng, S.-C., Ahluwalia, 2003. Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction. Earth Planet Sc Lett 212, 433–441.

Parrish, R.R., Hodges, K.V., 1996. Isotopic constraints on the age and provenance of the Lesser and Greater Himalayan sequences,Nepalese Himalaya. Geol Soc Am Bull 108, 904–911.

Pearson, O.N., DeCelles, P.G., 2005. Structural geology and regional tectonic significance of the Ramgarh thrust, Himalayan fold-thrust belt of Nepal. Tectonics 24. doi:10.1029/2003TC001617

Pêcher, A., 1989. The Metamorphism in the Central Himalaya. Journal of Metamorphic Geology 7, 31–41.

Reddy, S.M., Searle, M.P., Massey, J.A., 1993, Structural evolution of the High Himalayan Gneiss sequence, Langtang Valley, Nepal. (*in* Himalayan Tectonics) Geological Society Speical Publications 74, 375-389.

Robinson, D.M., 2008. Forward modeling the kinematic sequence of the central Himalayan thrust belt, western Nepal. Geosphere 4, 785–801. doi:10.1130/GES00163.1

Robinson, D.M., DeCelles, P.G., Copeland, P., 2006. Tectonic evolution of the Himalayan thrust belt in western Nepal: Implications for channel flow models. GSA Bulletin 118, 865–885.

Robinson, D.M., DeCelles, P.G., Patchett, P.J., Garzione, C.N., 2001. The kinematic evolution of the Nepalese Himalaya interpreted from Nd isotopes. Earth Planet Sc Lett 192, 507–521.

Rubatto, D., Chakraborty, S., Dasgupta, S., 2013. Timescales of crustal melting in the Higher Himalayan Crystallines (Sikkim, Eastern Himalaya) inferred from trace element-constrained monazite and zircon chronology. Contrib Mineral Petr. doi:10.1007/s00410-012-0812-y

Schelling, D., 1992. The Tectonostratigraphy and Structure of the Eastern Nepal Himalaya. Tectonics 11, 925–943.

Searle, M.P., 1999. Extensional and compressional faults in the Everest-Lhotse massif, Khumbu Himalaya, Nepal. Journal of the Geological Society 156, 227–240.

Searle, M.P., Simpson, R.L., Law, R.D., Parrish, R.R., Waters, D.J., 2003. The structural geometry, metamorphic and magmatic evolution of the Everest massif, High Himalaya of Nepal-South Tibet. Journal of the Geological Society 160, 345–366.

Searle, M.P., Law, R.D., Godin, L., Larson, K.P., Streule, M.J., Cottle, J.M., Jessup, M.J.,

2008. Defining the Himalayan Main Central Thrust in Nepal. Journal of the Geological Society 165, 523–534. doi:10.1144/0016-76492007-081

Searle, M.P., Law, R.D., Jessup, M.J., 2006. Crustal structure, restoration and evolution of the Greater Himalaya in Nepal-South Tibet: implications for channel flow and ductile extrusion of the middle crust, in:.

Searle, M.P., Szulc, A.G., 2005. Channel flow and ductile exrustion of the high Himalayan slab-the Kangchenjunga-Darjeeling profile, Sikkim Himalaya. Journal of Asian Earth Sciences 25, 173–185.

Simpson, R.L., Parrish, R.R., Searle, M.P., Waters, D.J., 2000. Two episodes of monazite crystallization during metamorphism and crustal melting in the Everest region of the Nepalese Himalaya. Geology 28, 403–406.

Spencer, C.J., Harris, R.A., Dorais, M.J., 2012. The metamorphism and exhumation of the Himalayan metamorphic core, eastern Garhwal region, India. Tectonics 31. doi:10.1029/2010TC002853

Swapp, S.M., Hollister, L.S., 1991. Inverted Metamorphism Within the Tibetan Slab of Bhutan - Evidence for a Tectonically Transported Heat-Source. The Canadian Mineralogist 29, 1019–1041.

Upreti, B.N., 1999. An overview of the stratigraphy and tectonics of the Nepal Himalaya. Journal of Asian Earth Sciences 17, 577–606. doi:10.1016/S1367-9120(99)00047-4

Vannay, J.-C., Hodges, K.V., 1996. Tectonometamorphic evolution of the Himalayan metamorphic core between the Annapurna and Dhaulagiri, central Nepal. Journal of Metamorphic Geology 14, 635–656.

Wang, J.M., Zhang, J.J., Wang, X.-X., 2013. Structural kinematics, metamorphic P-T profiles and zircon geochronology across the Greater Himalayan Crystalline Complex in south-central Tibet: implication for a revised channel flow. Journal of Metamorphic Geology 31, 607–628. doi:10.1111/jmg.12036

Wang, J., Zhang, J., Wei, C., Rai, S., Wang, M., Qian, J., 2015. Characterising the metamorphic discontinuity across the Main Central Thrust Zone of eastern-central Nepal. Journal of Asian Earth Sciences 1–67. doi:10.1016/j.jseaes.2015.01.027

Warren, C., Grujic, D., Kellett, D.A., Cottle, J.M., Jamieson, R.A., Ghalley, K.S., 2011a. Probing the depths of the India-Asia collision: U-Th-Pb monazite chronology of granulites from NW Bhutan. Tectonics 30, n/a–n/a. doi:10.1029/2010TC002738

Warren, C., Grujic, D., Cottle, J.M., ROGERS, N.W., 2011b. Constraining cooling histories: rutile and titanite chronology and diffusion modelling in NW Bhutan. Journal of Metamorphic Geology 30, 113–130. doi:10.1111/j.1525-1314.2011.00958.x

Warren, C., Singh, A.K., Roberts, N.M.W., Regis, D., Halton, A.M., Singh, R.B., 2014. Timing and conditions of peak metamorphism and cooling across the Zimithang Thrust, Arunachal Pradesh, India. Lithos 200-201, 94–110. doi:10.1016/j.lithos.2014.04.005

Webb, A.A.G., 2013. Preliminary balanced palinspastic reconstruction of Cenozoic deformation across the Himachal Himalaya (northwestern India). Geosphere 9, 572–587. doi:10.1130/GES00787.1

Webb, A.A.G., Yin, A., Harrison, T.M., Celerier, J., Burgess, W., 2007. The leading edge of the Greater Himalayan Crystalline complex revealed in the NW Indian Himalaya: Implications for the evolution of the Himalayan orogen. Geology 35, 955–958.

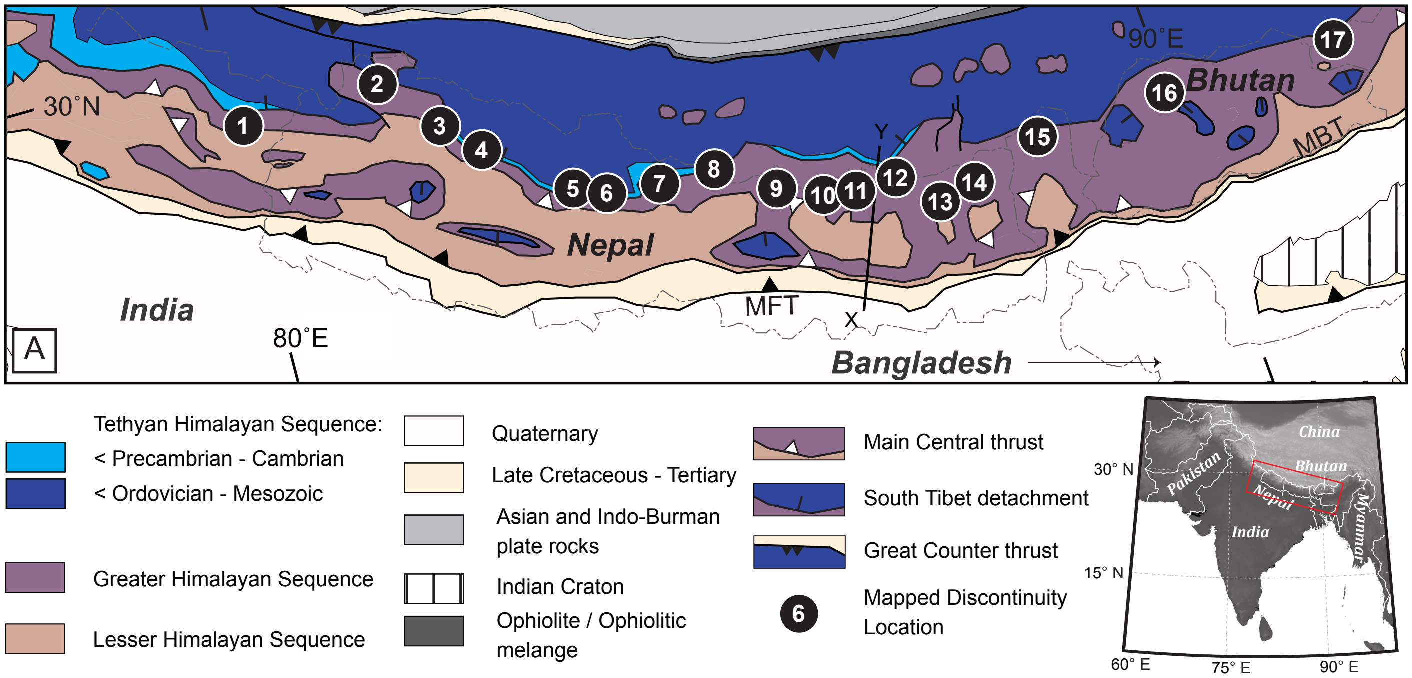
Yakymchuk, C., Godin, L., 2012. Coupled role of deformation and metamorphism in the construction of inverted metamorphic sequences: an example from far-northwest Nepal. Journal of Metamorphic Geology 30, 513–535.
Yin, A., 2006. Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth Science Reviews 76, 1–131.

***Highlights (for review)**

Highlights

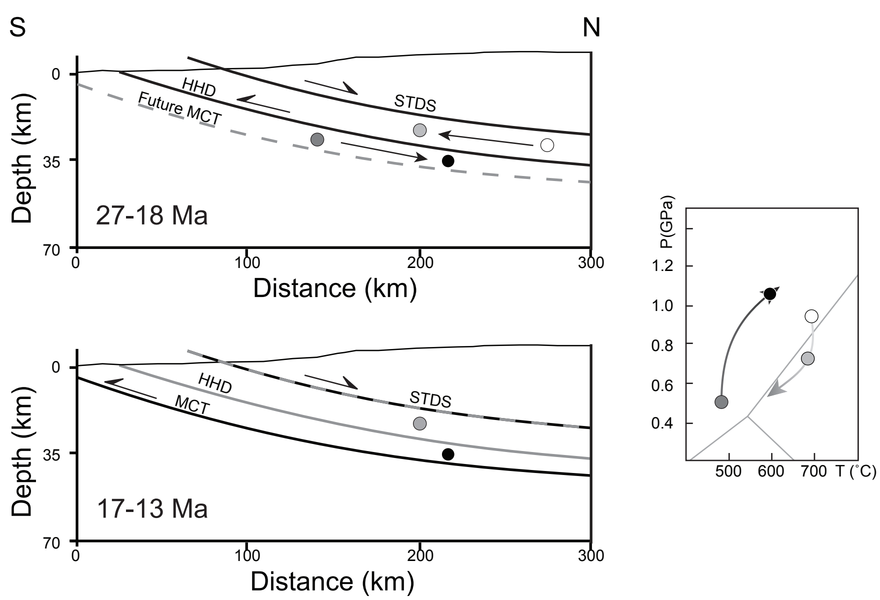
- Variable development of discontinuities is related to along strike changes
- The Main Central thrust system significantly thickened the mid-crust
- Complex overprinting during activity along the Main Central thrust is expected

Figure 1
Click here to download Figure: Figure 1.pdf



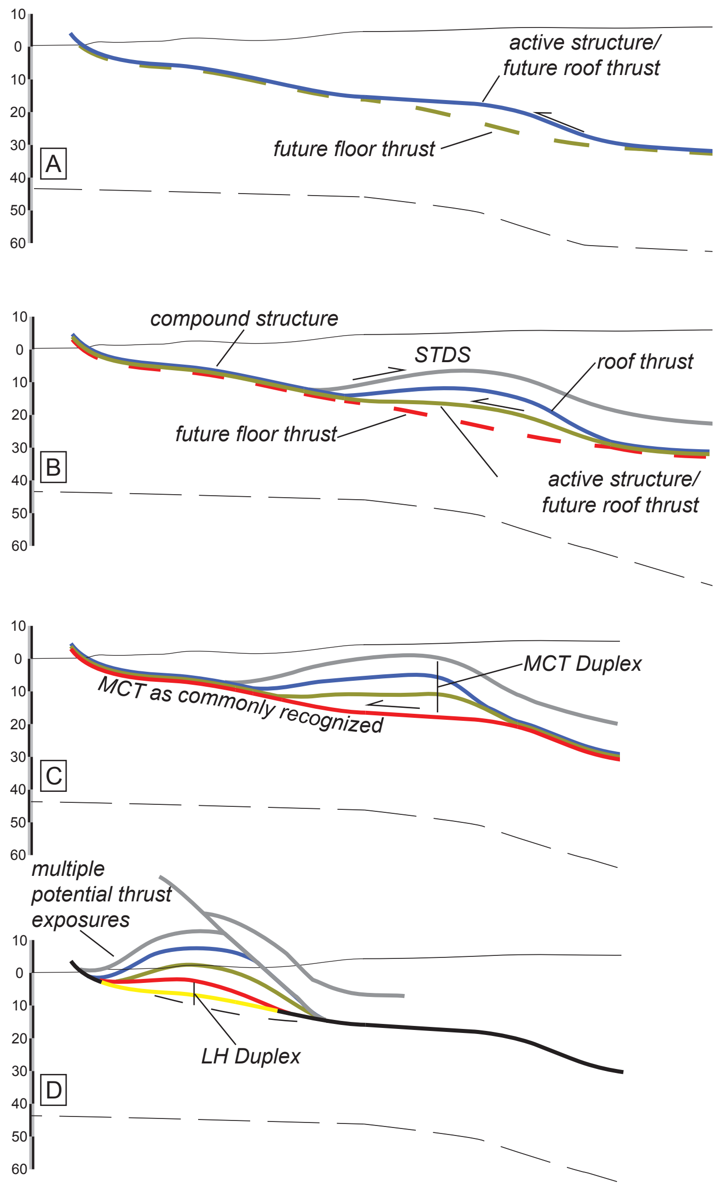
Larson et al., Fig. 1

Figure 2
Click here to download Figure: Figure 2.pdf



Larson et al., Fig. 2

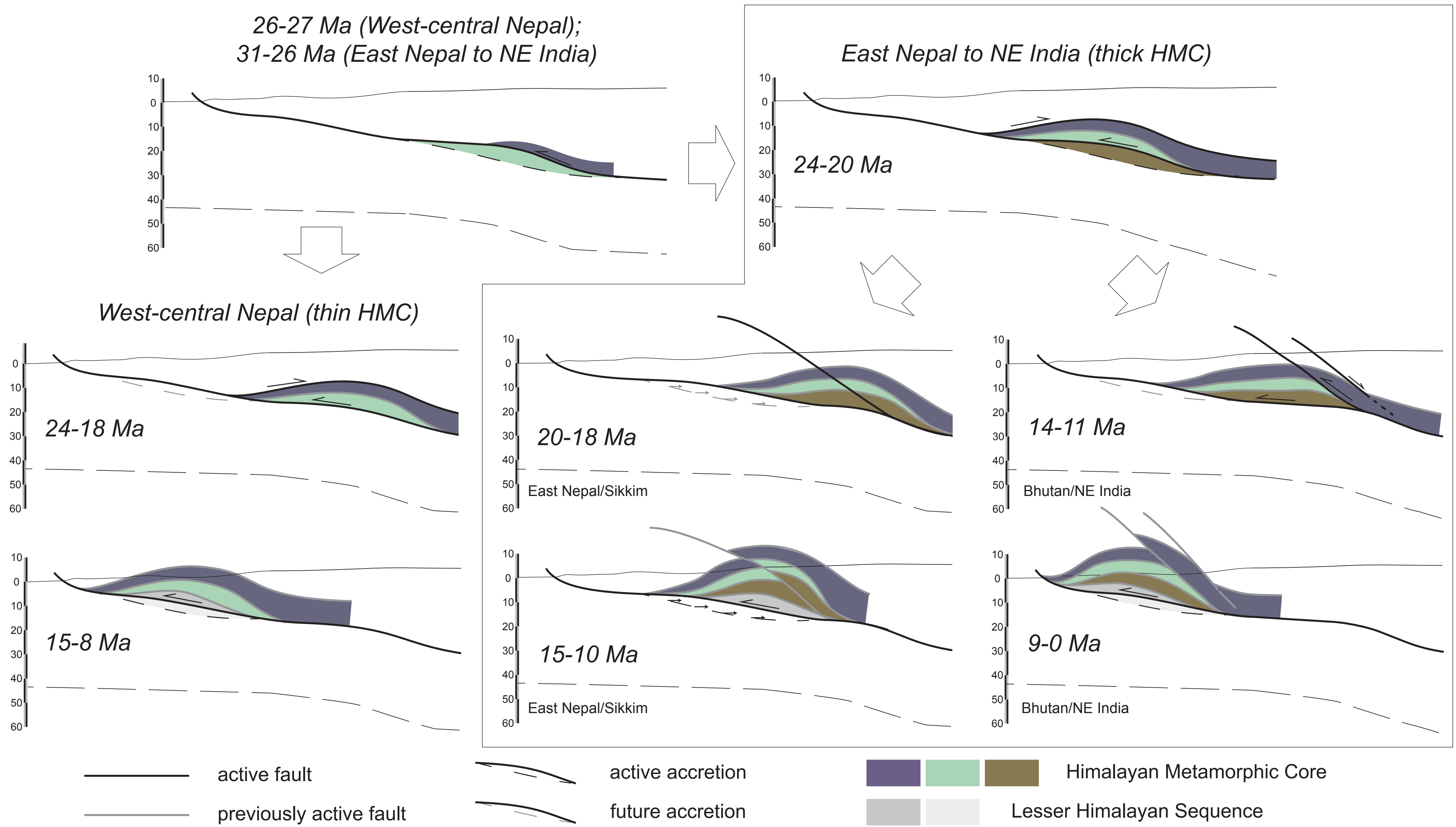
Figure 3
Click here to download Figure: Figure 3.pdf



Larson et al., Fig. 3

Figure 4

Click here to download Figure: Figure 4.pdf



Larson et al., Fig. 4

Table 1

Click here to download Table: Table 1.xlsx

Table 1: Metamorphic and Geochronologic Contstraints Defining Interpreted Tectonometamorphic Discontinuities

Location (Figure 1)	*(Name),* Location	Footwall			Hanging Wall			PT Method	Shear Zone Age (Ma)	References
		P (GPa)	T (˚C)	Age (Ma)	P (GPa)	T (˚C)	Age (Ma)			
1	[1] Garhwal, NW India	0.7-1.2↑	~550	-	1.4-0.8↓	~750	-	ER+TE	-	Spencer et al., 2012
2	Karnali, NW Nepal	0.8-1.1↑	600-630	-	1.0-0.5↓	650-720	-	AvPT	-	Yakymchuk and Godin, 2012
3	*Mangri Shear Zone* , Mugu Karnali, W Nepal	0.9-1.1	665-700	*21-17*	0.7-0.8	690-700	*25-18*	ER	(*21-17*)	Montomoli et al., 2013
4	*Toijem Shear Zone* , Lower Dolpo, W Nepal	0.7-0.9↑	640-675	*43-33*	0.63	620-640	*29-17*	ER	(*26-17*)	Carosi et al., 2010
5	*Kalopani Shear Zone* , Annapurna, central Nepal	0.7	450-650	*35*	1.0	650-750	*34-35*	ER	(*23-15*)	Vannay and Hodges, 1996; Godin et al., 2001
6	*Bhanuwa Thrust* , Modi Khola, central Nepal	1.0-1.2	550-700	*33-24, 22-17*	1.1-1.4↓	700-775	*26-24, 23-21*	ER+TE	(*23-19*) *or* (16-	Martin et al., 2010; Corrie and Kohn, 2011; Martin et al., 2014
	Sinuwa Thrust , Modi Khola, central Nepal	1.1-1.4↓	700-775	*26-24, 23-21*	1.1-1.4↑	730-800	*32-27, 22-19*	ER+TE	(*27-19*)	Martin et al., 2010; Corrie and Kohn, 2011; Martin et al., 2014
7	[1] Manaslu-Himal Chuli, central Nepal	0.6-1.3↑	525-650↑	*21.5, 15-12*	1.1-0.30↓	640-675	*26-15*	ER	*~21*	Larson et al., 2010, 2011; Kohn et al., 2001
8	*Langtang Thrust* , Langtang, Nepal	0.75-1.0	680-800	*36-16, 15-13*	0.6-0.95	750-850	*31-21,19-16*	ER	(*20-16*)	Reddy et al., 1993; Fraser et al., 2000; Kohn et al., 2005; Kohn, 2008
9	*Nylam Thrust* , Bhote Kosi, Nepal	0.3-1.3↓	600-700	-	0.3-0.9↓	700-800	48-30, 19-14	ER	(*30-19*)	Wang et al., 2013
	[1] *Main Central Thrust* , Bhote Kosi, Nepal	0.8-1.0	620-650	-	0.9-1.5	660-720	-	PE	-	Wang et al., 2015
10	[1] *"Lower Discontinuity"* , Tama Kosi Region, Nepal	0.64-0.7	610-640	*10-8*	1.0-0.7↓	700-750	*23-19, 19-14*	PE	(*14-8*)	Larson et al., 2013; Larson and Cottle, 2014
	"Upper Discontinuity" , Tama Kosi Region, Nepal	1.0-0.7↓	700-750	*23-19, 19-14*	-	-	24-21, 19-16	PE	(22-19)	Larson and Cottle, 2014
11	Likhu Khola, Nepal	0.9-1.3↑	725-900	-	0.3-1.0↓	750-900	*27-23, 22-15*	AvPT	(*22-15*)	From et al., 2014
12	*Khumbu Thrust* , Everest Region, Nepal	0.4-0.6	600-700	*32-21*	-	-	*24*	AvPT, ER	-	Searle et al., 1999, 2003; Simpson et al. 2000; Jessup et al., 2008
13	*"Lower Discontinuity"* , Arun Region, Nepal	0.6-07	550	-	0.8-1.0↑	600-650↑	-	PE	-	Groppo et al., 2009
	"*Upper Discontinuity"* , Arun Region, Nepal	0.8-1.0↑	600-650↑	-	0.7-1.0↑	650-800↑	-	PE	-	Groppo et al., 2009
14	*High Himalayan Thrust* ,Tamor/Ghunsa, Kanchenjunga, Nepal	0.5-1.2↓	700-800	30-28, 27-18	0.6-0.4	700-850	-	AvPT, PE	~ 20	Goscombe et al., 2006; Imayama et al., 2010, 2012; Ambrose et al., 2015
	Kanchenjunga Duplex, Nepal				*multiple discontinuities/structures*					Ambrose et al., 2015
15	*"Age Discontinuity"* , Northern Sikkim	0.8	750-850	*31-28, 28-25, <25*	0.9	750-850	*26-23, 23-20, 20-17*	PE	-	Rubatto et al., 2013
16	*Laya-Kakhtang Thrust* , Bhutan	0.3-0.6	~650	*22-17*	0.8-1.0↑	750-800	*15-13*	ER	(*13*-10)	Swapp & Hollister 1991; Davidson et al., 1997; Grujic et al., 1996, 2002, 2011; Daniel et al., 2003; Warren et al., 2011a, b
17	*Zimithang Thrust,* NE India	0.8-09	535-715↓	*27-16*	-	535-630↑	*17-12*	ER, TB	(*12*-7)	Warren et al., 2014

[1]Indicates interpreted structure is equivalent to the 'MCT' of Jamieson et al. (2004). ↑ indicates an increase up structural section, ↓ indicates decreasing values up structural section. Where multiple age ranges are present, the first indicates prograde-path metamorphism, the second indicates retrograde-path/decompression metamorphism. In the one case were three ranges are given, the third range indicates late stage isobaric cooling. Parentheses indicate the ages are interpreted to bracket movement. Ages in italics are from monazite; underlined ages are from zircon, grey ages are from thermochronologic constraints. ER = 'traditional' exchange reaction and net transfer reaction thermobarometry; TE = thermodynamic equilibrium - based thermobarometry; AvPT = THERMOCALC-based thermobarometry; PE = Phase equilibria modelling-based thermobarometry; TB - titanium in biotite thermometry.