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Searle, M, Avouac, J-P, Elliott, J orcid.org/0000-0003-2957-4596 et al. (1 more author) (2017) Ductile shearing to brittle thrusting along the Nepal Himalaya: Linking Miocene channel flow and critical wedge tectonics to 25th April 2015 Gorkha earthquake. Tectonophysics, 714-71. pp. 117-124. ISSN 0040-1951

https://doi.org/10.1016/j.tecto.2016.08.003

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Ductile shearing to brittle thrusting along the Nepal Himalaya: linking Miocene channel flow and critical wedge tectonics to 25th April 2015 Gorkha earthquake.

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ABSTRACT

The 25th April 2015 magnitude 7.8 Gorkha earthquake in Nepal ruptured the Main Himalayan thrust (MHT) for ~140 km east-west and ~50 km across strike. The earthquake nucleated at a depth of ~15-18 km approximating to the brittle-ductile transition and propagated east along the MHT but did not rupture to the surface, leaving half of the fault extent still locked beneath the Siwalik hills. Coseismic slip shows that motion is confined to the ramp-flat geometry of the MHT and there was no out-of-sequence movement along the Main Central Thrust (MCT). Below 20 km depth, the MHT is a creeping, aseismic ductile shear zone. Cumulated deformation over geological time has exhumed the deeper part of the Himalayan orogen which is now exposed in the Greater Himalaya revealing a tectonic history quite different from presently active tectonics. There, early Miocene structures, including the MCT, are almost entirely ductile, with deformation occurring at temperatures higher than ~400°C, and were active between ~22-16 Ma. Kyanite and sillimanite-grade gneisses and migmatites approximately 5-20 km thick in the core of the Greater Himalayan Sequence (GHS) together with leucogranite intrusions along the top of the GHS were extruded southward between ~22-15 Ma, concomitant with ages of partial melting. Thermobarometric constraints show that ductile extrusion of the GHS during the Miocene occurred at muscovite-dehydration temperatures ~650-775°C, and thus

brittle thrusting and critical taper models for GHS deformation are unrealistic. As partial melting and channel flow ceased at ~15 Ma, brittle thrusting and underplating associated with duplex formation occurred along the Lesser Himalaya passively uplifting the GHS.

INTRODUCTION

The Himalayan orogen is commonly interpreted as a crustal scale wedge, analogous to a critical taper (Yin and Harrison, 2000; Avouac, 2015; Bollinger et al., 2006), that formed as units detached from the underthrusting Indian plate were accreted to the southern margin of Tibet since the India-Asia collision started about 50 Ma ago (Figures, 1,2). The upper crust of the Himalaya is represented by the so-called Tethyan Himalaya, a sequence of Neo-Proterozoic to Cenozoic mainly sedimentary rocks showing intense folding and thrusting, crustal shortening and thickening, but generally not metamorphosed (Corfield and Searle, 2000). The middle crust is the Greater Himalayan Sequence (GHS) of highly metamorphosed and partially melted gneisses, migmatites and leucogranites all of which show Cenozoic metamorphism up to kyanite and sillimanite grade. Along the base of the GHS, metamorphic isograds are inverted along the Main Central Thrust zone (MCT) and along the upper contact isograds are right way-up beneath the South Tibetan Detachment (STD), an enigmatic low-angle, north-dipping normal fault (e.g. Burg and Chen, 1984; Searle, 2010, 2015; Law et al., 2011; Cottle et al., 2015a). The GHS was exhumed in the Oligocene - Miocene as a result of ductile shearing along the coeval MCT and STD ductile shear zones, by a process known as channel flow, the ductile extrusion of a mid-crustal layer of partially molten rocks (e.g. Beaumont et al., 2001; Grujic et al., 2002; Searle et al., 2003, 2010; Godin et al., 2006; Law et al., 2011; Cottle et al., 2015a,b). The southernmost and structurally lower part of the Himalaya is the Lesser Himalaya, comprising a series of south-vergent thrust sheets emplacing the Himalaya over the Siwalik foreland basin sediments along the Main Boundary Thrust (MBT).

This paper attempts to link the deformation in the Greater Himalayan hinterland (Early Eocene – Early Miocene metamorphism and deformation) to the Lesser Himalaya foreland critical wedge (mid-Miocene – Recent) to the active thrusting as exemplified by the 25th April 2015 Gorkha earthquake rupture. The geometry of the Main Himalayan Thrust (MHT), the basal detachment that ruptured during the 25th April 2015 Gorkha earthquake (Avouac et al., 2015; Elliott et al., 2016), is critical to the interpretation of the kinematic history the Himalaya.

Two major conflicts in Himalayan tectonics involve: (1) the discussion between proponents of Channel Flow along the Greater Himalaya (e.g. Beaumont et al. 2001; Grujic et al., 2002; Searle et al. 2003, 2006, 2010; Jessup et al., 2006; Godin et al., 2006; Streule et al., 2010) and proponents of the critical wedge taper model (e.g. DeCelles et al., 2001; Kohn et al., 2004; Kohn, 2008; Webb et al., 2011; He et al., 2015; Yu et al., 2015) (Figure 3), and (2) whether 'out-of sequence' thrusting has occurred in the past along the Main Central Thrust (e.g. Wobus et al., 2005, 2006) or not (e.g., Lavé and Avouac, 2001; Bollinger et al., 2006; Herman et al., 2010, Nadin and Martin, 2012).

The Langtang – Kathmandu profile across the Nepal Himalaya (Figs. 1,2) is a well-exposed and well-studied transect where the ductile and brittle structures have been mapped and there are P-T-t-D data (e.g. Reddy et al., 1993; Kohn, 2008). This was the area affected by the recent 25th April 2015 Gorkha earthquake and interpretation of the deep structure of the MHT during this earthquake (Avouac et al., 2015; Elliott et al., 2016) gives us a unique opportunity to correlate the geological history of older, deeper, hotter GHS rocks to Late Cenozoic brittle thrust faulting beneath the Lesser Himalaya, and active thrust faulting along the MHT as deduced from the 25th April 2015 Gorkha earthquake. To that effect, we use new field data from the Langtang area in combination with existing data from the literature to produce a geological cross-section across the range in the area of the Gorkha earthquake. Here we first review the critical taper and channel flow models and the geology of the Greater Himalayan Sequence before describing the Langtang – Kathmandu profile in more detail, relating the older Eocene-Early Miocene structures to the subsequent brittle thrust structures and the active tectonics deduced from the 25th April 2015 Gorkha earthquake.

THE CRITICAL TAPER MODEL, BRIEF OVERVIEW

The structural evolution of compressional mountain belts usually involves fold and thrust-related crustal shortening and thickening processes. Thrusts generally propagate in-sequence from hinterland to foreland, from deeper to shallower levels as thrusts progressively climb ramps and place older rocks over younger rocks (e.g. Dahlstrom, 1970; Elliott, 1976; Elliott and Johnson, 1980; Butler, 1987). Out-of-sequence thrusts can develop in the hangingwall of active thrusts but these, although fairly common (Morley, 1988), are not as important as in-sequence ('piggy-back') thrusts.

At the leading edge of a fold-thrust belt a 'critical taper' (e.g., Elliott, 1976; Davis et al., 1983; Dahlen et al., 1984; Dahlen, 1990) develops where material is continually added to the wedge by frontal accretion, or underplating (Figure 3). The shape of the critical wedge is governed by various factors including the composition and density of the deforming rock, the geometry and slope of the basal detachment, frictional stress along the basal thrust fault, convergence rate, erosion rate, and the nature of the backstop (e.g. Dahlen, 1984; Dahlen and Suppe, 1988; Malavielle, 2010). Whereas the pro-wedge side accommodates most of the crustal shortening, over-thickened wedges frequently result in backthrusts along the retro-wedge side. These doubly-vergent orogens for example the Western Alps (Schmidt et al., 1996; Willett et al., 1993) and the Western Himalaya (Corfield and Searle, 2000), show a central 'pop-up' structure, where thrusts fan around from the pro-wedge vergence direction to the retro-wedge backthrust vergence direction. Sandbox experiments generally support models of upper crustal, foreland-propagating thrust sequences (Koyi, 1995; Konstantinovskala and Malavieille, 2005; Graveleau et al., 2012).

In many analogue models the backstop along the trailing margin of critical wedges is frequently represented by a solid undeforming wall. Notable amongst these experiments are Cadell's (1888) vertical board or Dahlen's (1990) tractor pushing the deforming wedge up the basal slope. These models imply that the upper hangingwall is the main driving plate (the tractor), whereas in many mountain belts such as the Himalaya it is the lower down-going plate (India) that is the driving force, underplating beneath the backstop (Tibet). In principle it makes little or no difference whether the driving force is on the upper or lower plate. However, whereas most models assume the backstop to be rigid and undeforming, few models relate to ductile deforming backstops with high-temperature metamorphic or migmatitic rocks, as seen along the Greater Himalaya (e.g. Searle et al., 2003, 2006, 2010; Godin et al., 2006; Cottle et al., 2015).

In the Himalaya during the period from initial collision at ~50 Ma to peak metamorphism during Early Miocene time the initial backstop was the Asian plate margin. During this period crustal folding and thrusting in the upper crust (Tethyan Himalaya) was accompanied by folding, shearing and high-grade metamorphism in the hot middle crust (Greater Himalayan Sequence; GHS). During the later stages of orogenesis (mid-Miocene to Recent) the later backstop was the GHS as the Lesser Himalayan thrust wedge was forming (Avouac, 2003, 2015; Bollinger et al., 2006; Searle, 2015; Cottle et al., 2015). Critical taper models have often been invoked to explain the large scale structure of various orogens (e.g., Davis et al, 1983) and the Himalaya in particular (e.g. Kohn, 2008; Robinson, 2008; Webb et al., 2011; He et al., 2015), but these studies have focussed mainly on the brittle structures across the Lesser Himalaya above the MBT and below the MCT. Above the lower MCT almost all deformation has occurred at higher temperatures in the ductile regime (e.g. Law et al., 2004, 2011; Jessup et al., 2006).

CHANNEL FLOW MODEL - GREATER HIMALAYAN SEQUENCE

The Greater Himalayan sequence (GHS) consists of a 10-30 km mid-crustal sequence of kyanite- and sillimanite-grade gneisses, migmatites and leucogranites formed from vapour-absent muscovite-dehydration melting of pelitic and psammitic protoliths during the Late Miocene (e.g. Godin et al., 2006; Jessup et al., 2006; Searle et al., 2010; Streule et al., 2010). These rocks are bounded along the base by the Main Central Thrust (MCT) where condensed metamorphic isograds show inverted P-T conditions and high ductile strain, and along the top by the South Tibetan Detachment (STD) where a right way-up isograd sequence also shows concomitant ductile general shear fabrics beneath a low-angle normal fault (Searle et al., 2003, 2006; Law et al., 2004, 2011; Jessup et al., 2006, 2008; Larson and Cottle, 2014). The channel flow hypothesis, defined as the ductile extrusion of partially molten mid-crust gneisses, migmatites and leucogranites, bounded by a crustal scale ductile shear zone and thrust below (MCT) and a low-angle normal fault and ductile shear above (STD), is constrained by numerous P-T-t-D profiles across the Nepal GHS notably from the Manaslu, Langtang, Everest, and Makalu sections (Searle et al., 2003, 2006; Law et al., 2004, 2011; Godin et al., 2006; Jessup et al., 2006, 2008; Streule et al., 2010; Cottle et al., 2015a). Structural-kinematic analysis combined with thermobarometry and U-Pb monazite geochronology shows that this mid-crustal slab was actively deforming at high temperatures and that the entire GHS mid-crustal slab was extruded at least 80-120 km southward during the Early Miocene.

The transition from ductile channel flow structures in the GHS to brittle Lesser Himalayan thrusting occurs within the MCT zone and is transitional both in space and time. The MCT is the prominent thrust plane that marks the southern boundary of Cenozoic metamorphic overprint (Searle et al., 2008). The precise location of the MCT remains controversial with several different locations reported, but it should be realised that thrust faults are 4-dimensional, following flats and ramps that cut up-section in the transport direction, merging with other thrusts along branch lines, and climbing from deep ductile to shallow brittle structures with time. Thus a single thrust fault can have different names as for example the MCT beneath the Ganesh-Langtang Himal, and Mahabharat thrust beneath the Kathmandu klippe (Figure 2).

Kinematic indicators across the GHS in the Langtang profile show top-south shearing along the lower part of the GHS within the sillimanite + K-feldspar migmatite zone and top-north ‘extensional’ fabrics along the upper part of the GHS. These ‘extensional’ fabrics occur in a wholly compressional environment and do not reflect any crustal or lithospheric extension. Instead they record the post-peak metamorphic exhumation path of high-grade rocks along the footwall of the STD. Metamorphic isograds along the upper part of the GHS show right way-up metamorphism. Linking the right way-up isograds beneath the STD to the inverted isograds above the MCT shows that the GHS rocks were extruded to the south, bounded by these two major ductile shear zones (i.e. Channel Flow).

The ductile MCT zone shows condensed metamorphic isograds from the sillimanite + K-feldspar isograd where partial melts first appear, down-section to ductile Munsiari Thrust that was active as young as 10.5 Ma (Kohn et al. 2004; Kohn, 2008). Beneath the Munsiari Thrust, the Lesser Himalaya are a sequence of relatively unmetamorphosed meta-sediments of Proterozoic-Paleozoic age, affected by only low-grade greenschist facies metamorphism during the Himalayan event. Whereas GHS deformation in the Early-Middle Miocene was almost entirely ductile, Lesser Himalayan deformation during Late Miocene – Pliocene time is more commonly brittle, involving foreland-propagating thrusts in upper crustal rocks.

LANGTANG – KATHMANDU HIMALAYAN PROFILE

A geological profile across the Langtang Himalaya from the Tibetan plateau across the Kathmandu klippe south to the Main Frontal thrust (MFT) is shown in Figure 2. The geology of the Langtang – Kathmandu Himalaya has been documented in past studies (e.g. Reddy et al., 1993; Massey et al., 1994; Johnson et al., 2001; Kohn et al., 2005; Kohn 2008; Webb et al., 2007, 2011). We use field structural data, metamorphic and thermobarometric data combined with U-Pb age data from these studies combined with more recent structural mapping in the Langtang valley (Dyke, Searle, unpublished data) to construct our cross-section (Fig. 2). We note that geometric 'rules' used to construct balanced and restored cross-section could apply along the Lesser Himalaya but cannot be used in the ductile deformed rocks above the MCT. The pervasive cleavage and schistosity observed in the Lesser Himalaya and Greater Himalaya units indeed attest to a probably large component of pure shear and possible volume changes during deformation. We therefore prefer an approach that is arguably less rigorous geometrically, but more faithful to the style of ductile structures observed in the field (Mount et al., 1990).

Figure 4 shows a restoration of the Langtang Himalaya to the Early Miocene when the GHS deformation, metamorphism and partial melting were active and widespread. The Greater Himalayan sequence (GHS) is comprised of high-grade metamorphic rocks, migmatites and leucogranites formed during the Early Miocene (~22-16 Ma). Metamorphic rocks of the GHS are bounded along the top by the low-angle, north-dipping normal fault, the South Tibetan Detachment (STD, and along the base by the Main Central Thrust (MCT), both of which were active during this time. The STD is exposed in southern Tibet above the Shisha Pangma leucogranite, dated by U-Pb xenotime and monazite at 20.2-17.3 Ma (Searle et al., 1997). The entire upper 5-10 km thickness of the GHS is composed of migmatitic sillimanite-K-feldspar grade pelite and psammite and leucogranites containing biotite, garnet, muscovite, tourmaline, and cordierite, commonly occurring as regional sills intruded parallel to the GHS schistosity (Reddy et al., 1993; Inger and Harris, 1993; Massey et al., 1994). At the highest structural level of the GHS, immediately beneath the ductile STD a ~4 km thick sill of biotite- garnet- and tourmaline-bearing leucogranite is exposed in southern Tibet (the Shisha Pangma leucogranite; Searle et al., 1997).

The Main Central Thrust and the structurally lower Munsiari thrust (MT) are associated with the inverted metamorphic sequence comprising sillimanite, kyanite, staurolite and garnet grade gneisses (Reddy et al., 1993; Massey et al., 1994; Jessup et al., 2006; Searle et al., 2008). U-Pb monazite dating demonstrates peak metamorphic ages decreasing progressively down-structural section from 21 ± 2 Ma in the sillimanite + K-feldspar migmatites at Langtang to 16 ± 1 Ma in the upper part of the MCT to 10.5 ± 0.5 Ma at the Munsiari Thrust (Kohn et al., 2005; Kohn, 2008). As expected from any regional metamorphic terrane undergoing crustal thickening, higher structural units reached peak metamorphic conditions earlier, and thrusting, crustal thickening and metamorphism propagated southwards. Thus higher structural units began cooling during exhumation at a time when structurally lower units were undergoing burial, heating and prograde metamorphism (c.f. England & Thompson, 1986).

Following Early Miocene partial melting and channel flow as constrained by ductile fabrics, metamorphic grade and U-Pb age data, brittle thrusts in general propagated down-structural section with time from the upper MCT to the Munsiari Thrust (MT) to the Ramgarh Thrust (RT, active ~10 Ma) to the Main Boundary Thrust (MBT, active from ~7-0 Ma) (Beyssac et al., 2004; Kohn, 2008). Rocks from the Kathmandu klippe show similar NeoProterozoic protolith ages, and similar metamorphic zircon ages (29-23 Ma) as the main GHS to the north and the two zones are hence correlated (Johnson et al., 2001; Searle et al., 2008; Khanal et al., 2014). The northern margin along the Galchhi shear zone shows that thrust movement occurred at >22.5 ± 2.3 Ma (Khanal et al., 2014), similar timing to the upper ductile MCT motion (Kohn et al., 2005) supporting the model of one continuous GHS with several intra-GHS ductile thrusts (Reddy et al., 1993; Larson and Cottle, 2014). The structural position beneath the Kathmandu metamorphic rocks, and top-to-south thrust-related kinematics show that the Galchhi shear zone is related to the ductile MCT (Johnson et al., 2001; Khanal et al., 2014) and not to the STD (Webb et al., 2011; He et al., 2015).

Structural dips of the low-grade Dhunche schists and the northern margin of the Kathmandu klippe suggest a thrust ramp at depth (Elliott et al., 2016). These thrust faults all splay off the basal detachment of the Main Himalayan Thrust (MHT), the master fault along which Indian plate rocks are underthrusting the Himalaya. Deformation across the GHS and south, at least as far as the MCT, was almost entirely ductile, reflecting deeper, hotter and earlier deformation events along the Himalaya whereas thrusting in the Lesser Himalaya was dominantly brittle, higher structural level and later in time.

The Kathmandu klippe is a basin-shaped klippe, or thrust sheet of GHS-type crystalline rocks with Lower Palaeozoic granites, but lacking the Miocene leucogranites of the GHS. The basal thrust, termed the Mahabharat thrust, is equivalent to the Munsiari thrust or lower MCT. Metamorphism in the Kathmandu klippe shows right way-up isograds above the local inversion along the MCT/Mahabharat thrust (Johnson et al., 2001). The rocks immediately surrounding the Kathmandu klippe belong to the Ramgargh thrust sheet comprising kyanite-garnet- and biotite-grade gneiss showing an inverted metamorphic sequence of the lower part of the GHS (Beyssac et al., 2004; Bollinger et al., 2004; Searle et al., 2008). These rocks have sometimes been referred to as 'Upper Lesser Himalaya' rocks but their protoliths, metamorphic grade and internal strain are similar to GHS rocks so we include them in the GHS. All rocks above the MCT/Munsiari thrust in the GHS have been affected by Miocene Himalayan metamorphism, whereas Lesser Himalayan rocks beneath have not (Searle et al., 2008). The right-way-up isograds in Kathmandu have been interpreted as part of the structurally higher limb of the extruding channel whereas the inverted isograds of the Ramgargh thrust sheet comprise the structurally lower limb of a southward closing fold of the GHS (Searle et al., 2008; Figure 4).

OLIGOCENE – EARLY MIOCENE MIOCENE CHANNEL FLOW

The Himalayan channel flow model is defined as a mid-crustal layer of low-viscosity, partially molten Indian plate crustal rocks extruding southward bounded by two major ductile shear zones, the MCT below and the STD above (Burg and Chen, 1984; Beaumont et al., 2001; Grujic et al., 2002; Searle et al., 2006, 2010; Godin et al., 2006). Geological, thermobarometric and geochronological constraints from the Langtang Himalaya match all the criteria required of the channel flow model. Kohn et al. (2005) and Kohn (2008) mapped the MCT profile up-section only as far as Langtang village (sillimanite isograd) where brittle overprinting of early ductile fabrics does occur, whereas the entire overlying 10-15 km thickness of GHS rocks up to the Shisha Pangma leucogranite and overlying STD (Reddy et al., 1993; Searle et al., 1997) are comprised entirely of ductily deformed migmatites and leucogranites.

The MCT shows a condensed sequence of metamorphic isograds from kyanite to biotite that are structurally inverted and associated with zones of high ductile strain (Jessup et al., 2006, 2008). The STD along the top of the GHS shows right way-up isograds, also condensed by a combination of pure shear and top-north simple shear (Law et al., 2004, 2011; Jessup et al., 2006, 2008). The STD wraps around the top of the 5 km thick leucogranite sill comprising the Shisha Pangma leucogranite in Tibet (Searle et al., 1997). In between the STD and MCT, the GHS shows approximately 20-30 km thickness of which the upper ~10 km is comprised entirely of sillimanite-K-feldspar grade migmatites, and leucogranites intruded dominantly as layer-parallel sills with a discontinuous ~4 km thick leucogranite sill (Shisha Pangma leucogranite) at the top. Deformation is entirely ductile throughout the GHS slab, although there are a few very rare later discrete brittle faults (Reddy et al., 1993).

Figure 5 is a P-T diagram showing the PTt paths for the kyanite grade rocks in the lower GHS, after Kohn (2008) and PTt paths for the upper GHS rocks in sillimanite + K-feldspar grade migmatites, after Inger and Harris (1993). Also shown are the U-Pb monazite and xenotime ages from the Shisha Pangma leucogranite, the 4 km thick leucogranite sill forming the uppermost GHS in south Tibet immediately beneath the STD (Searle et al., 1997). U-Pb dating of monazites show that the MCT and STD ductile shear zones were active simultaneously during the Early Miocene from ~21-16 Ma in Langtang (Kohn et al., 2005), 23.6-~13 Ma in Sikkim (Kellett et al., 2013) and slightly younger in the Everest – Rongbuk profile down to 13-11 Ma (Cottle et al., 2009, 2015a). PT conditions across the GHS and structural criteria show that these rocks were formed by partial melting at 15-18 km depth more than 50-100 km north of the Himalaya and have been extruded southward bounded by the relatively rigid upper crust above (Tethyan zone) and lower crust beneath (Indian plate lower crust). The totally ductile nature of the deformation across the GHS, together with the abundance of mid-crustal partial melt is clearly incompatible with models involving whole crust brittle duplexing and critical taper (Kohn, 2008; Webb et al., 2011; He et al., 2015; Yu et al., 2015). A fundamental change to the tectonic regime occurred at ~15 Ma when mid-crustal granite melting along the GHS ceased and channel flow and ductile shearing along the MCT and STD zones also ended.

LATE MIOCENE – PLIOCENE THRUSTING (LESSER HIMALAYA)

Following Early Miocene mid-crustal melting and channel flow, the GHS cooled rapidly during exhumation and was being passively uplifted by underplating and duplex formation along the Lesser Himalaya (Bollinger et al., 2006). Since ~15 Ma Himalayan crustal shortening within the GHS had ended with cooling of the high grade metamorphic rocks and leucogranites, and shortening was taken up mainly frontal accretion, foreland-propagating brittle thrusting across the Lesser Himalaya and underplating processes (Avouac, 2015). The geometry of the wedge is governed by the balancing forces of frictional stress along the base (MHT) and stresses induced by the slope of the wedge (Davis et al., 1983; Dahlen, 1990). Continuing compression resulted in folding of earlier MCT-related thrusts and formation of klippen such as the Kathmandu klippe. It is likely that thrusting across the Lesser Himalaya propagated southwards from the Ramgargh thrust to the Main Boundary thrust with time. As younger thrusts became active, older thrusts were carried passively piggy-back in a normal foreland-directed 'piggy-back' thrust sequence. Modelling of thermochronological data shows that a simple foreland-propagating thrust duplex system can account for the inverse metamorphic gradient and to the development of mid-crust ramp and duplex (Bollinger et al., 2006). Underplating resulted in passive uplift of the GHS. Since about 2-1 Ma the Main Boundary Thrust (MBT) locked, and thrusting propagated south into the Siwalik molasse basin with active motion along the Main Dun thrust and the Main Frontal thrust (Lave and Avouac, 2000).

25TH APRIL 2015 GORKHA EARTHQUAKE

The epicentre of the 25th April 2015 Mw 7.8 Gorkha earthquake was located 80 km WNW of Kathmandu, with a hypocentral depth of ~15 km, the focal mechanism indicating thrusting on a sub-horizontal fault dipping at ~10^{o} north (Hayes et al., 2015; Avouac et al., 2015; Galetzka et al., 2015; Elliott et al., 2016). The earthquake caused over 8800 deaths and left more than 4 million people homeless. Two Mw 6.6-6.7 aftershocks occurred at either end of the rupture soon after and an even larger Mw 7.3 aftershock occurred at the northeastern end of the rupture 17 days later on 12th May 2015. The aftershocks reveal that the entire 140 x 50 km plane of the north-dipping MHT ruptured, propagating at a speed of almost 3 km/second

(Avouac et al., 2015; Fan and Shearer, 2015). Increase of elevation above the thrust ramp and northward tilting would be expected with any active south-vergent thrust fault. Interferometric Synthetic Aperture Radar (InSAR) data reveal up to 2 m of SSW motion and more than 1 m of uplift in the Kathmandu basin and region immediately to the north, whilst subsidence resulted in a 0.6 m decrease in elevation in the region to the north of the slip, roughly along the highest peaks 100 km along-strike west of Everest (Lindsey et al., 2015, Wang & Fialko, 2015; Elliott et al., 2016).

Reconciling previous independent geological, geomorphological and geophysical datasets with the earthquake geodetic data supports a ~20° north-dipping ramp in the MHT beneath the northern part of the Kathmandu basin corresponding to steep dips in the Dhunche schists and the northern margin of the Kathmandu klippe (Fig. 2). The MHT follows a flat beneath the Kathmandu basin before rising to the surface beneath the Main Frontal Thrust (Lavé and Avouac, 2001; Elliott et al., 2016). The 2015 Gorkha earthquake rupture did not rupture to the surface as would be expected (Angster et al., 2015), similar to the 1833 Mw 7.7 earthquake, which also caused heavy damage in Kathmandu (Bilham, 1995, 2004), and instead only triggered minor surface slip on the Main Dun Thrust (Elliott et al., 2016). Other large earthquakes, such as the 1934 Mw 8.4 Bihar-Nepal earthquake, did break to the surface and resulted in 6 meters of slip (Bollinger et al., 2014). Geodetic InSAR, seismic and geological data can be combined to determine the shape and size of the MHT thrust fault plane, despite motion being blind. It is likely that the 25th April 2015 Gorkha earthquake may have nucleated close to the ductile-brittle transition at depths of 15-18 km (Avouac et al., 2015). Deeper motions were accommodated by ductile shear and aseismic creep. From evidence of the Gorkha earthquake it could be inferred that most deformation during Himalayan orogenesis beneath ~20 km depth was ductile, with aseismic creep and viscous flow processes dominating over critical taper brittle faulting.

DISCUSSION AND CONCLUSIONS

Geological and U-Pb zircon-monazite geochronological constraints from the Langtang – Kathmandu Himalaya are entirely compatible with Early Miocene (~22-16 Ma) channel flow, the southward extrusion of a mid-crustal layer of partially molten rocks (sillimanite + K-feldspar gneisses, migmatites and leucogranites) bounded by large-scale ductile shear zones below (top-south ductile MCT) and above (top-north, bottom south ductile STD). Both MCT and STD shear zones show high ductile strain, general shear (simple shear + pure shear), telescoping of metamorphic isograds, and were active concomitantly between ~22-15 Ma (Searle et al., 2003, 2006; Cottle et al., 2009, 2015a; Law et al., 2011). Peak metamorphic ages and shear zone thrusting both propagated southward and down structural-section with time. Deformation within the presently exposed GHS was entirely ductile, at temperatures high enough to induce partial melting. *In situ* melts accumulated into cracks and fissures and spread through hydraulic fracturing processes into sills (Searle et al., 2010). Sills transported the leucogranite melts laterally with occasional dykes feeding magma up to higher level sills. During this time period both ductile shear zones along the upper part of the MCT zone and the lower part of the STD zone were active.

Structurally below and to the south of the Munsiari Thrust (lower MCT zone), deformation is dominantly brittle with foreland propagating thrusting, evolving from the MCT zone (20-15 Ma) to the Munsiari-Ramgarh Thrust (15-10 Ma; Kohn et al., 2005) to the Main Boundary Thrust (7-0 Ma) to the active Main Frontal Thrust (MFT) with time. It is probable that the intersection of these pre-existing thrust structures with the MHT at depth forming branching lines had a structural control on the rupture propagation and arrest in the Gorkha earthquake (Elliott et al., 2016). The Kathmandu klippe with right way-up metamorphic isograds above the Mahabharat/MCT is interpreted as the southward extension of the GHS upper limb (Johnson et al., 2001; Searle et al., 2008; Khanal et al., 2014), whilst the Ramgargh thrust sheet ('lesser Himalaya' of Beyssac et al., 2004) is the lower limb showing inverted metamorphism. The PT conditions and timing of metamorphism in the Ramgargh thrust sheet are similar to those in the Munsiari thrust sheet and GHS and thus we map the MCT as underlying all the thrust sheets showing Cenozoic metamorphism. Since ~15 Ma the Himalaya has grown by underplating, foreland-propagating thrusting across the Lesser Himalaya and post-metamorphic shearing of underplated units.

Brittle thrusting in the Lesser Himalaya is exemplified by the 25th April 2015 Mw 7.8 Gorkha earthquake when the MHT ruptured ~140 km along strike and ~50 km across strike beneath central Nepal. The earthquake initiated at ~15-18 km depth and propagated toward the east and south but did not rupture to the surface. There is no evidence of out-of-sequence thrusting along the MCT but there is strong evidence of a frontal ramp beneath the northern margin of the Kathmandu klippe (Avouac et al., 2015; Elliott et al., 2016). Below 20 km depth deformation occurs by aseismic creep and this depth corresponds to the brittle-ductile transition. The clear implications of the geodetic, InSAR, and seismic data from the Gorkha earthquake are that brittle thrusting and duplexing can only occur in the upper 15-20 km of the crust, and throughout the GHS temperatures were far too high during the Miocene kyanite- and sillimanite-grade metamorphic event for brittle faulting. Thus, models involving brittle deformation and whole crust duplexing for the Greater Himalaya (Kohn, 2008; Webb et al., 2011; He et al., 2015; Yu et al., 2015) cannot be correct. Deformation in the Early Miocene mid-crust GHS was almost entirely ductile, viscous and flowing; deformation in the post-15 Ma upper crust Lesser Himalaya below the Munsiari Thrust (lower MCT zone) was dominated by brittle foreland-propagating thrusting and underplating analogous to the prediction of the critical taper model in presence of surface erosion (e.g., Konstantinovskaia and Malavielle, 2005). Rupture during the 25th April 2015 Gorkha earthquake is the latest manifestation of this process.

ACKNOWLEDGEMENTS

We thank two anonymous reviewers and editor Rich Briggs for comments that helped improve the manuscript. JRE is supported by the UK Natural Environmental Research Council (NERC) through the Looking Inside the Continents (LiCS) project (NE/K011006/1), the Earthquake without Frontiers (EwF) project (EwF_NE/J02001X/1_1), and the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET, http://comet.nerc.ac.uk).

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FIGURE CAPTIONS

Figure 1. Digital Elevation Model (DEM) of the central Nepal Himalaya, showing main structures metamorphic grade across the Langtang – Ganesh Himalaya. Greater Himalayan Sequence (dark green) includes amphibolite facies gneisses and schists, migmatites and leucogranites. ASTER GDEM is a product of METI and NASA.

Figure 2. Geological cross-section of the Langtang – Kathmandu Himalaya showing major structural units, metamorphic grade, thrust faults and extent of the rupture during the 25th April 2015 Gorkha earthquake.

Figure 3. Schematic representations of the Critical Taper (A) and Channel Flow (B) models for the Himalaya, after Cottle et al. (2015b). Early phase of channel tunnelling is depicted in C, and underplating beneath the MCT is shown in D; see text for sources and discussion. HMC refers to the Himalayan Metamorphic core.

Figure 4. Restored section of the Langtang – Kathmandu Himalaya to Early Miocene (~20 – 16 Ma) showing structures related to metamorphism and partial melting along the Greater Himalaya. Also shown are right way-up metamorphic isograds beneath the STD, inverted isograds along the MCT (kyanite, staurolite, garnet, biotite) and depths of the large Shisha Pangma leucogranite. Early Siwalik molasse deposits derived from erosion of the GHS unconformably overlie Palaeozoic and Proterozoic rocks of the future Lesser Himalaya. Younger than 16 Ma Lesser Himalayan thrusts are dashed. Depth to Moho is approximate.

Figure 5. Simplified P-T diagram showing the metamorphic conditions in the upper and lower Langtang GHS. The muscovite dehydration melting curve is from White et al. (2007), and the Al-silicate stability is taken from Holdaway and Mukhopadhyay (1993). Path A represents the P-T conditions of kyanite-garnet grade metamorphism in the lower GHS schists after Kohn (2008). Path B presents the conditions of the sillimanite-K-feldspar grade metamorphism in the upper GHS migmatites (Inger and Harris, 1993). The shaded area depicts the portion of the P-T path where partial melting occurred during Channel Flow. The peak conditions of both P-T paths were determined independently by phase thermobarometry and using the stable mineral assemblages. The U-Pb monazite age for melting of a lower GHS kyanite-gneiss is taken from Kohn (2005). The upper GHS Shisha Pangma U-Pb monazite and xenotime ages are from Searle et al. (1997), and represent timing of crystallisation of melt in a weakly foliated biotite-leucogranite and the main body of tourmaline-muscovite-leucogranite. The $^{40}Ar/^{39}Ar$ plateau age is from Searle et al. (1997), and implies that leucogranite emplacement was followed by high cooling rates and rapid exhumation of the GHS.