Tectonic evolution of the Himalayan syntaxes – the view from
Nanga Parbat

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Abstract: Current tectonic understanding of the Nanga Parbat Haramosh massif (NPHM) is reviewed, developing new models for the structure and deformation of the Indian continental crust, its thermo-rheological evolution and relationship to surface processes. Comparisons are drawn with the Namche Barwa Gyala Peri massif (NBGPM) that cores an equivalent syntaxis at the NE termination of the Himalayan arc. Both massifs show exceptionally rapid active denudation and riverine down-cutting, identified from very young cooling ages measured from various thermochronometers. They also record relicts of high pressure metamorphic conditions that chart early tectonic burial. Initial exhumation was probably exclusively by tectonic processes but the young, and continuing emergence of these massifs reflects combined tectonic and surface processes. The feedback mechanisms implicit in aneurysm models may have been over-emphasised, especially the role of syn-kinematic granites as agents of rheological softening and strain localization. Patterns of distributed ductile deformation exhumed within the NPHM are consistent with models of orogen-wide gravitation flow with the syntaxes forming the lateral edges to the flow beneath the Himalayan arc.

Abrupt changes in the map-trend of orogenic belts and their component sutures, thrusts and folds – so-called syntaxes – are common to many parts of the Tethyan collision system. The purpose here is to review the tectonic evolution of the Himalayan syntaxes (Fig. 1). They include crust that is experiencing
exceptional exhumation rates that provide not only opportunities for relating the
rates of tectonic and surface processes but also ideal sites for deducing
deformation processes at various scales to understand deformation localization
in the crust. They also provide outcrop access to the most northern parts of the
Indian continental crust and thus can inform discussions on the deeper structure
of the main Himalayan belt. These themes are explored here. However, this
review also summarises detailed accounts of the basic geological relationships
and the deductions that can be drawn from them, especially for the Nanga Parbat
area. An underlying tenet here is that these relationships are fundamental for
establishing the tectonic evolution and thus for testing and exploring the
consequences of models not only those that link denudation to deformation of
the continental crust but also strive to explain the evolution of Himalayan orogen
as a whole. Without this information it is difficult to assess the uncertainties in
the applications of these models.

There are various explanations for the development of non-linear
orogenic systems (e.g. Carey 1955; Marshak 1988), as primary arcuate forms or
as quasi-linear belts that are subsequently bent, or are folded as they develop.
The modern mountain front in the western part of the Himalayan system
(Pakistan) contains various types. This front changes trend to form a re-entrant
from the western Salt Range, to the Trans-Indus Range (Fig. 1). This pattern can
be readily interpreted as a primary structure relating to the extent of
propagation of the basal detachment to the thrust system into the foreland,
reflecting in turn the subcrop of Cambrian-age halite (Butler et al. 1987).
Elsewhere the thrust front along the Kirthar and Sulaiman ranges (Fig. 1) may
reflect changes in the geometry of inherited basement rift structures in
controlling collision-related contractional tectonics (e.g. Coward 1994). Tectonic
rotations and local transverse folding of pre-existing structures may result from
interacting, doubly-vergent thrust systems within an overall zone of parallel
convergence (e.g. in the Eastern Salt Range; Butler et al. 1987). Thus the
mountain front has evolved in plan view.

While some syntaxes develop at or near the active mountain front, within
the main Himalayan chain there are much larger structures. It is these that form
the principal focus of this review. The Himalayan arc (Fig. 1) extends for 2500
km but terminates abruptly at each end at two major antiforms around which structures loop in map-pattern. These are the Himalayan syntaxes – cored by the Nanga Parbat-Haramosh massif (in the NW: NPHM) and the Namche Barwa – Gyala Peri massif (in the NE: NBGPM). They characterized by exceptionally fast rates of erosion and bed-rock exhumation, and consequently provide outcrops of levels of collided Indian continental crust that otherwise would lie deeply buried beneath their orogenic cover. The two districts have significantly different histories of geological research (Fig. 2) - reflecting their contrasting logistical challenges.

The NPHM (Fig. 3) has been accessible for almost a century, through a track network that serviced the frontier town of Gilgit. The terrain is exceptionally rugged, with some of the greatest relief on Earth, rising to the peaks of Nanga Parbat (8125m) and Haramosh (7397m; Figs. 3 and 4). The mountains are transected by deep gorges, including that of the Indus (Fig. 4c, d). Thus early geological research was chiefly allied to mountaineering expeditions, aimed at creating reconnaissance geological maps (e.g. Desio 1964).

Construction of the Karakoram Highway (KKH; Fig. 4c) through the 1960s and 70s allowed geologists, principally from Peshawar University, to create regional maps (e.g. Tahirkhieli and Jan 1978). The KKH opened to international visitors in 1979, which together with its offshoots further up the Indus gorge to Skardu (Fig. 4d) and up the Astor valley (Fig. 2), kick-started more detailed investigations of the NPHM. These western areas of the Greater Himalaya are relatively arid (e.g. Finlayson et al. 2002) and so provide exceptional outcrop. It has also benefitted being under a single administrative control (Pakistan). The SE portion of the NPHM, where its geological linkages into the main Himalayan arc can be established, lies on the original access (pre- Karakoram Highway) to Gilgit from the south. It is restricted due to proximity to the disputed Pakistan-Indian border. However, wider security to the whole region for international visitors has been difficult since 2001, especially so after the murder by a Taliban sect of eleven members of mountaineering expeditions to the Daimir face of Nanga Parbat in June 2013.

In contrast, the NBGPM lies within the Tibet Autonomous Region with access very strictly controlled by the Chinese authorities. Research activity has
accelerated over the past 18 years (Fig. 2), especially with the increased involvement of Chinese earth scientists. Unlike the western syntaxis, there is no equivalent to the KKH-Skardu road providing simple access for transects through the NBGPM – even if authority controls were relaxed. Both syntaxes are still significantly under-represented on geological maps - their internal structure and basement stratigraphy remains incompletely established. Yet the NPHM especially has been a testing ground for novel methods in quantifying tectono-geomorphological processes and rates, as reviewed below, but rarely have these methods been applied more broadly through their study areas. Consequently this review, as others before (e.g. Khan et al. 2000), should not be read as a definitive record but rather as a summary of a transient state of the art. The narrative here focuses primarily on NPHM but then draws comparisons with NBGPM.

The geology and history of research through the 20th century at Nanga Parbat, and more generally in the NW Himalayas, have been extensively reviewed by Khan et al. (2000). Research, especially relating to new fieldwork, has fallen away since then – with subsequent papers focussing on the young tectonic history of the NPHM – essentially building up on and examining the consequences of Zeitler et al.’s (2001) tectonic aneurysm model. This concept is developed from the notion that crustal shortening is balanced against the thickness of the crust and that syn-kinematic erosion permits crustal shortening to progress (e.g. Beaumont et al. 1992; Willett 1999). However, the aneurysm model incorporates the thermal consequences of rapid exhumation that drives a positive feedback between deformation and erosion. Exhumation elevates the transition from depth-dependent friction sliding (faulting) which effectively reduces not only the maximum but also the integrated strength of the deforming crust. Zeitler et al.’s (2001) model proposes that, if exhumation is rapid enough to drive decompression melting, the syn-kinematic crustal melts weaken the crust, focusing deformation further. This in turn accelerates deformation, generating faster uplift rates with concomitant accelerating erosion and exhumation. Thus syn-tectonic crustal melting is generally assumed to be the critical influence on the dynamics – a deduction common not only to the syntaxes but also to other parts of the Himalayan collision system. Both syntaxes have
become test-beds for developing analytical strategies for understanding the
interactions between Earth surface processes and the thermo-tectonic evolution
of the continental crust in collision belts.

**The pre-exhumation tectono-metamorphic evolution of the Nanga Parbat -
Haramosh Massif**

Although the principal modern interest in the NPHM lies in its Plio-Quaternary
history, understanding the aneurysm model and its limitations demands
understanding the precursor geology of the massif. As Whittington and Treloar
(2002) point out, the distribution and concentration of key reactants - muscovite
and biotite – will control the sites of decompression melting and leucogranite
genesis. The preceding burial and heating histories of the massif are also
important. These earlier parts of the geological history also have a bearing on the
development of the India-Asia collision in the NW Himalayas. There follow
discussions on the basement geology and pre-uplift structural history of the
massif that are concluded by examining implications for the early collision
history. These then provide information on the conditions that pertained at the
start of the late Neogene exhumation history, as discussed later.

**Basement structure**

That the heart of the NPHM contains abundant migmatitic gneisses (Fig. 5) has
been established since the early syntheses of Wadia (1919) who ascribed them
to the Archaean, in common with assumptions made for many high-grade
metamorphic terranes at the time. Misch (1949) demonstrated that the
migmatites, with cordierite-K-feldspar-sillimanite assemblages, pass laterally
into lower-grade metasediments on the flanks of the massif (Fig. 3). Since the
initial studies of gneiss types by Madin et al. (1989) in the 1980s, there have
been sporadic attempts to unravel basement geology at Nanga Parbat. Zeitler et
al. (1989) report ion microprobe U-Pb profiles in zircon with core ages of c
1850Ma and rims at 2.3-11Ma. In the absence of field relationships, relating
geochemical data from accessory phases to the structure, and therefore the
The tectonic evolution of the massif has been ambiguous (but see Crowley et al. 2009, discussed below). The challenge has been to establish how much of the basement structure relates to Himalayan tectonics and how much was inherited from the earlier crustal history of the Indian continent. The discovery of suites of mafic intrusions that cross-cut gneissic fabrics throughout the massif (Butler and Prior 1988a; Wheeler et al. 1995) indicates that the rocks experienced pre-Himalayan metamorphism (see discussion in Whittington et al. 2000). Treloar et al. (2000) conclude that the migmatitic fabrics in the heart of the massif are Precambrian in age (but see Crowley et al. 2009, discussed below).

Sr and Nd isotopic data show that the NPHM is assembled from pre-Himalayan metamorphic units (Argles et al. 2003) that correspond to the distinctive basement terrains (Lesser Himalayan, High Himalayan) of the main Himalayan belt. However, unlike the main Himalayas, at NPHM these different basement units do not lie in distinct Himalayan thrust sheets. No such structure can be mapped and indeed it is difficult, using field relationships alone, to establish which unit is which in the core of the massif. Around the flanks, non-migmatitic metasediments, chiefly biotite schists and psammites are cross-cut by biotite granites, commonly with large feldspars. These field relationships match those in the Hazara hills of the outer parts of the Pakistan Himalayas, where, late Proterozoic metasediments are intruded by 500-600Ma peraluminous granites (e.g. Baig et al. 1988). These granites (both in Hazara and NPHM) deform into augen-gneiss that can be mistaken for Proterozoic migmatitic gneiss. The massif may be one of the few regions that could resolve the pre-collisional structural relationships between various basement units on the northern margin of the Indian continent – but as yet these are unresolved. The margins of the NPHM are marked by a discontinuous veneer of metasediments without biotite granite intrusions and with distinctive marbles. These are speculatively correlated with the “Tethyan series” of cover sediments (Butler and Prior 1988a). That these units are not significantly interleaved with the basement units described above suggests that the NPHM contains little basement-cover imbrication of Himalayan age and therefore that it behaved as a coherent tectonic unit during the collision.

Relationship with Kohistan-Ladakh arc
At the present outcrop level, the boundary between the NPHM and the surrounding Kohistan-Ladakh arc terrain is composite – in part defined by cataclastic faults signifying young deformation together with significantly earlier ductile structures. This early ductile structure was correlated with the Main Mantle Thrust (MMT), the southern suture of the Kohistan-Ladakh arc with the Indian continental crust defined 150 km WSW of Nanga Parbat (e.g. Tahirkheli and Jan 1979). It has been recognized in the Indus gorge (Butler and Prior 1988a), along the northern plunge termination of the massif (Fig. 6a; Butler et al. 1992; Pognante et al. 1993) and along its eastern margin (Fig. 6b; Argles 2000). It is an amphibolite facies shear zone, many hundreds of metres thick (Fig. 6a). In its hangingwall in the western Indus gorge (Fig. 6c), the shear zone deforms suites of granite sheets (the Confluence and Parri suites of George et al. 1993). Away from the shear zone these form cross-cutting networks but they are sheared, boudinaged and tightly folded in the shear zone (Fig. 6d,e). Ubiquitous top-to SSE kinematics are displayed by these deformed Kohistan rocks (Fig. 63). The same kinematics are displayed by shear bands and asymmetric boudinage in the deformed metasediments of the NPHM in the footwall (Fig. 6f). Argles (2000) notes the equivalent kinematics, represented as right-lateral shear, along the steep eastern margin of NPHM in the upper Astor valley.

The Confluence and Parri granite sheets were derived from a juvenile arc source, without contamination from Indian continent rocks. They comprise two distinct suites, one dated at 50-32 Ma and a younger Rb-enriched set dated as early Miocene (c. 26 Ma). That these intrusions are deformed into the ductile shear zone dates this structure was active until at least 26 Ma. The shear zone cannot be the original suture between the Indian continent and the Kohistan-Ladakh arc and is therefore not the MMT as defined elsewhere to the west (cf. Butler and Prior 1988a). Butler et al. (1992) termed the structure the *Phuparash Shear Zone* – a name used here to designate the amphibolite-facies tectonic contact between the Kohistan arc terrain and rocks of the Indian continent now preserved in the NPHM but which predates the late exhumation of the massif. The geochemistry of the Confluence and Parri granites places a limit on the northward extent of the NW Indian continent beneath the leading edge of the
amalgamated Asian continent prior to Miocene times. This is discussed further below.

Tectonic burial of the Indian continental crust

The NPHM is best known for its HT/LP metamorphism reflected in extensive development of migmatites. The preserved PT- conditions of these rocks are presented in two transects through the massif (Fig. 7a,b) and these are discussed later. However, the interleaved metasedimentary and meta-igneous rocks (the ‘Layered Unit’ of Butler et al. 1992) of the northern part of NPHM locally preserve eclogitic assemblages within metabasic rocks (Pognante et al. 1993). Termed the "Stak eclogites", they record peak conditions of c 2.5 GPa, c 750C (Lanari et al. 2013; Fig. 7c). They are extensively overprinted by amphibolite facies mineral assemblages (c 0.7 GPa, 650C) that have all but obliterated the eclogitic assemblages. These HP conditions were likely far more widespread through the massif. Kouketsu et al. (2016) report U-Pb zircon ages that tentatively date the thermal overprint at 36-28 Ma, broadly in the range of ages for the thermal maximum in NPHM of Foster et al. (2002). They contrast these results with those obtained from the coesite-bearing eclogites of the Kaghan valley (c 100 km SW of the Stak eclogites), where peak conditions of c 3 GPa and 700C were achieved at c 45-47 Ma, and the rocks exhumed to the mid crust by c 44 Ma. Thus rather than be rapidly exhumed, the NPHM resided longer at lower crustal levels than the Kaghan eclogites. The thermal consequences of this extended residence may explain the sparse preservation of HP assemblages in the massif.

Early Himalayan tectonic history of NPHM

The igneous history of Kohistan and the tectono-metamorphic history of the NPHM raise issues for the evolution of the NW Himalayas. These can be represented on scaled cross-sections (Fig. 8). The Stak eclogites – preserved in the outermost metasediments of the NPHM - suggests that the Indian crust upon which these rocks lay was subducted beneath the frontal (southern) part of the
Kohistan arc terrain. A similar setting is presumed for the genesis of the Kaghan eclogites. The Stak eclogites achieved peak pressures before c 36 Ma – potentially as early as 45-47 Ma if burial was synchronous with that of the Kaghan eclogites. Uplift and partial unloading of the Stak eclogites to c 07 GPa by 36-28 Ma requires removal of some of the overburden. This is broadly contemporaneous with granite genesis in the now-overlying Kohistan arc terrain. But granite genesis and eclogite exhumation initially must have been spatially separated – the Kohistan granites show no contamination by Indian continental crust. Their juxtaposition, and much of the displacement on the Phuparash shear zone, must be rather late. Note that the shear zone omits the lower part of the Kohistan arc terrain and therefore contributes to exhumation of the Stak eclogites by tectonic processes.

Thus before the younger tectonic episodes that saw it exhumed to the surface, the NPHM resided in the lower part of a duplicated crustal stack, capped by the residual Kohistan arc terrain. The tectonic contact between the Indian continental crust of the massif and arc terrain above was the Phuparash Shear Zone. It was from this position, with its cover series buried at c 30 km depth, that the NPHM was exhumed during late Neogene times. The cross-section gives a direct measure of the burial state of the Indian continental crust, and by inference, the rocks preserved at outcrop in the NPHM. The shallow parts of the Indian crust (the “layered unit” of Butler et al. (1992)) lay at 0.7 GPa, with the underlying crust at correspondingly higher pressures. Presumably temperatures in this buried Indian crust were c 650 – 750 C, gradually warming into the onset of exhumation tectonics.

Tectonics, metamorphism and melting: the exhumation of the Nanga Parbat – Haramosh Massif

Various interpretations for the current structure of the NPHM have been proposed (Fig. 9). Note that all these recognize the broadly antiformal structure to the massif depicted by the trace of the tectonic contact between the massif and the structurally-overlying Kohistan Arc Terrain. This contact is generally termed the Main Mantle Thrust and is labelled as such on Fig. 9 in accordance with the
original authors. However, as discussed above, this structure is better given an alternative name (the Phuparaash Shear Zone) as it is a distinctly younger shear zone to the MMT in its type area some 150km SW of Nanga Parbat.

Based on the Indus gorge transect, Coward (1985) defined the broad antiformal structure of the massif, an interpretation followed by more detailed structural studies by Wheeler et al. (1995; Fig. 9a). Upright folding was also proposed for the internal structure of the massif along the Astor valley transect by Argles and Edwards (2002). Burg and Podladchikov (2000) developed numerical models to investigate crustal scale buckling and crustal strength in syntaxes. These models predict uplift of the Moho beneath the NPHM.

Based on structural studies along the western margin of the massif, Butler and Prior (1988b) argued that the massif was carried on a NW-directed ductile-to-brittle thrust zone (the Liachar Thrust; Fig. 9b). Their NW-SE oriented section (Butler et al. 1988) through the Chongra district predicted uplift of the massif’s thermal structure together with hydrothermal activity focused on the Liachar thrust. It is this structure that overprints the earlier tectonic contact with the Kohistan Arc Terrain. In contrast, the eastern margin of the massif was predicted to simply be marked by the early ductile shear zone (MMT/Phuparash Shear Zone) between the Kohistan Arc terrain and the Indian continental crust.

Regional geological studies around the entire Nanga Parbat area led Schneider et al. (1999; Fig. 9c) to propose that the massif was uplifted on two opposed thrust-sense shear zones – the NW-directed Daimir shear (essentially the lateral continuation of the Liachar structure of Butler and Prior 1988b) and the SE-directed Rupal shear zone. This defines a “pop-up” structure, an interpretation that lies at the heart of Zeitler et al.’s (2001) aneurysm model for positive feedback in crustal deformation. This model requires the Rupal and Diamir Shear Zones to be broadly contemporaneous – and certainly active during leucogranite genesis and exhumation. Syn-kinematic granite melt emplaced into both shear zones is inferred to reduce their strength thereby focusing further deformation.

Butler et al. (2002) argued that the role of localized shear zones in accommodating uplift of the massif had been exaggerated and that deformation was largely achieved by vertical stretching, distributed through the heart of the
massif. This model is invoked by Crowley et al. (2009) to explain the localized
uplift and exhumation of the heart of the massif.

Thus although interpretations show the massif to have a broadly
antiformal structure, they vary in consideration of which structures within the
massif relate to its exhumation and which were developed in earlier Himalayan
deformation (or be part of pre-collisional Indian continental geology). These
issues, and the merits of the various models, are discussed below after reviewing
structural observations and other geological data.

Geophysical constraints

The deep structure of the NPHM and adjacent regions has been determined
geophysically. Gravity anomalies suggest a relatively smooth Moho across the
syntaxis, at a depth of 65-70 km (Tiwari et al. 2015). This is broadly consistent
with the crustal thickness determined from teleseismic receiver functions to the
east of the syntaxis (Rai et al. 2006). There is no indication of the upwarped
Moho predicted by the numerical models of crustal buckling developed by Burg
and Podladchikov (2000). This model is therefore inappropriate to explain the
crustal structure.

Magnetotelluric profiling by Park and Mackie (2000) show the crust
beneath Nanga Parbat to have high resistivity from which they conclude that it is
dry and restitie, without any discernable in-situ melt. In contrast the uppermost
few km are more conductive – interpreted as revealing a weakly connected,
fracture-hosted network if aqueous fluid. This is consistent with the prediction
of Butler et al. (1988; Fig. 9b). Fluid inclusion studies of synkinematic veins by
Craw et al. (1994) subsequently established the hydrothermal system, driven by
meteoric water from the mountain peaks in the heart of the massif. They
proposed that the system penetrated to c 5 km. This depth lies slightly above the
zone of microseismicity mapped by Meltzer et al. (2001), This indicates that the
“brittle-ductile” transition along the Liachar thrust zone lies significantly
shallower than that schematically illustrated by Butler et al. (1988; Fig. 9b).

Late Himalayan metamorphism and granites
The NPHM contains some of the World’s youngest collision-related granites (Zeitler et al. 1993), as reviewed extensively by Whittington and co-workers (Whittington et al. 1999; Whittington and Treloar 2002). Collectively these leucogranites have formed the cornerstones to Zeitler et al’s (2001) aneurysm model and its derivatives (e.g. Koons et al. 2002) and are generally assumed to have substantially weakened the crust. The leucogranites have various forms. Almost all are feldspar-quartz rocks with white mica and tourmaline and they form different types of intrusion (Fig. 10). There are few km-sized intrusions with cm-mm grain-sizes (Fig. 10a, shown on Fig. 3). However, the massif is riddled with m-10sm width leucogranite sheets (e.g. Fig. 10b), most of which are coarsely pegmatitic. One of these, near Tato village, yielded a crystallization age of 0.7 Ma (Crowley et al. 2009). Where studied (Butler et al. 1992; Whittington et al. 1999), the plutons yield high Rb-Sr ratios and very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that collectively imply vapour-absent, muscovite melting of a metapelite source. Similar values are obtained for the leucogranite pegmatites. Whittington and Treloar (2002) propose the reaction:

$$22 \text{ Muscovite} + 7 \text{ Plagioclase} + 8 \text{ Quartz} = 25 \text{ melt} + 3 \text{ K-feldspar} + 5 \text{ Sillimanite} + 2 \text{ Biotite}$$

Melt volumes are controlled by the proportion of muscovite in the source, with the mass of leucogranite generated by this reaction only slightly more than that of the muscovite consumed by the reaction.

Relating leucogranites to migmatitic source-areas within the massif is difficult: the poly-metamorphic history of the Indian crust renders establishing the pattern of Himalayan metamorphism within the NPHM especially challenging. Poage et al. (2000) compile a range of P-T estimates, chiefly from metapelites, that confirm the general trend noted by early workers, of high peak temperatures in the heart of the massif passing out to lower temperature rocks on the margins. In contrast peak pressures are lower in the heart, increasing to the margins (Fig. 7). The antiformal structure of the NPHM means that the present heart of the massif was more deeply buried than its margins prior to exhumation. Therefore the preserved metamorphic conditions were not
achieved synchronously: Poage et al. (2000) suggest that the heart of the massif has experienced younger HT/LP overprinting.

Butler et al. (1997) point out that the migmatites currently at outcrop in the NPHM are unlikely to be the main source for the leucogranites – because the main migmatitic fabrics are cross-cut by pre-Himalayan mafic dykes. Certainly the Tato pluton has Sr-isotopic values outside those of adjacent metasediments (Whittington et al. 1999). Consequently Whittington et al. (1999) argue that their source remains buried and that the melt migrated several km up through the crust to be emplaced in the plutons and arrays of leucogranite pegmatite.

However, the Tato-upper Raikhot area (Fig. 3) show secondary migmatitic textures (Fig. 10d). Crowley et al. (2009) propose the vapour-absent biotite melting reaction:

\[ \text{Biotite+Sillimanite+Plagioclase+Quartz = Cordierite+Garnet+K-feldspar+melt} \]

These melts only migrate very short distances, if at all, as the crystallization of cordierite takes water and thus increases the viscosity of the residual melt. These in situ migmatites yield peak temperatures of 730 °C (±30 °C) at 350 MPa (±30 MPa) while the formation of garnet-cordierite melts suggests conditions of 720 °C (±20 °C) at 500 MPa (±30 MPa). Monzaite crystallization ages for these rocks yield ages of 1660 ± 15 ka, interpreted as the date of these peak conditions.

The Nanga Parbat area therefore charts two distinct melting processes, which operated synchronously but at different crustal levels (Whittington and Treloar 2002). Both involve decompression and therefore relate to the exhumation of the NPHM. Thus melting relates to denudation.

**Geomorphology and thermochronology**

Key to the denudation of the Nanga Parbat massif and its surroundings is the Indus river and its tributaries. The erosive power of these systems retains the rivers at remarkably low elevations. At Raikhot (Fig. 3) the Indus is just 1100m above sea level, with the summit of Nanga Parbat (8125m) just 21 km away (Fig. 4a). The combined influence of glaciation and catastrophic rock slope failures
governed by the relief and maximum elevations deliver sediment to the river system (e.g. Hewitt 2009). Rivers then transport the load away from the mountains, freeing the lower slopes for the receipt of the erosional products of further glaciation and slope failure.

The NPHM has been a test-bed for applying thermochronological and geomorphological methods in the understanding of active tectonics in mountain belts. These include the early application of multi-mineral fission track studies to quantify patterns of low-temperature cooling (Zeitler et al. 1982; Zeitler 1985) and the use of cosmogenic ($^{10}$Be, $^{26}$Al) exposure age dating to chart bedrock erosion (Leland et al. 1997). These studies have focused on the Indus gorge, which provides a natural transect through the massif. Leland et al. (1997) argue that incision rates on the Indus have increased from c 4-6 m/ka at 27-65ka to 10-14 m/ka in the past 7ka, where it passes through the NPHM, significantly faster than to the east. This zone of enhanced down-cutting matches the young fission track ages obtained from apatite and zircon (Zeitler et al. 1982; Fig. 11) that imply cooling rates of up to 120 °C/Myr for the Indus gorge. The fission track data are asymmetric, with fastest cooling at the western end of the Indus gorge, just upstream from the confluence with the Gilgit River.

Ar-Ar isotopic data from amphiboles and white mica have been obtained widely around the massif (Treloar et al. 2000; Schneider et al. 2001) – again largely aimed at resolving the pattern of cooling from which the denudation history might be deduced. Similarly, perched terraces and dissected strath levels have been mapped through the Nanga Parbat area and tentatively correlated with the glacial history of the NW Himalayas to estimate valley down-cutting rates (e.g. Schroder and Bishop 2000). All of these methods have problems. It is now realized that geomorphological rate estimates depend upon the observation time-scale, ignorance of which introduces significant bias (DiBiase 2014). Argon isotopes can be unreliable chronometers where radiogenic argon can be incorporated into minerals, to be expected in metamorphic terrains (e.g. Warren et al. 2012). And simply relating palaeo-thermal data to unroofing depends upon palaeo-geotherm, which in active, rapidly denuding locations may be challenging to resolve (e.g. Whittington 1996). Notwithstanding these limitations, these quantitative methods yield results that are broadly consistent with the time-
averaged exhumation rates deduced from regional cross-sections and as
deduced by qualitative analysis of the original fission track data from the Indus
gorge (Zeitler et al. 1982; Fig. 11).

Young/active structures on the western margin of the massif

Active deformation at NPHM is indicated by microseismicity, apparently
restricted to the top 5km of the crust (Meltzer et al. 2001). Recent work has
identified right-lateral focal mechanism on the western margin, together with
weak normal faulting in the interior of the massif (Mukhopadhyay et al. 2011).
GPS-derived velocity fields do not resolve any net convergence across the massif
as a whole (Jouanne et al. 2014), albeit based on a very short observation
window of 4-5 years. There is a residual weak E-W convergence of the heart of
the massif relative to Kohistan of 2-7mm/a, apparently accommodated on the
western margin of the massif. There is no detectable convergence across the
eastern margin. Jouanne et al. (2014) argue that the active seismicity and
geodetic strain represent dominantly vertical flow of the NPHM relative to its
surroundings with weak E-W contraction matched by weak extension in the
heart of the massif.

Relating active deformation structures and their structural kinematics to
vertical motions within the NPHM is obviously fundamental to understanding
tectonic processes. Yet there is significant confusion in the literature concerning
the nomenclature of faults and shear zones associated with the NPHM, especially
along the western margin (reviewed by Butler 2000). Lawrence and Ghauri
(1983) coined the term “Raikhot Fault” and this has been adopted for the entire
western bounding structure of the NPHM by Madin et al. (1989) and some others
since (e.g. Jouanne et al. 2014). In the author’s view this obscures tectonic
understanding as it conflates different structures of different ages that coincide
only locally but otherwise diverge around the massif. Furthermore, the original
structure interpreted by Lawrence and Ghauri (1983) is part of a major landslip
(Butler and Prior 1988b; Butler et al. 1988; Hewitt 2009) and has no continuity
into the bedrock. Consequently, the more precise terminology of Butler (2000) is
followed here.
The most prominent active structure is the *Liachar Thrust* (Butler and Prior 1988b) that carries highly sheared gneisses with leucogranite sheets onto unconsolidated sands and gravels of the Indus valley (Fig. 12a). It is probable that seismicity on this structure at depth triggered the array of catastrophic landslips, including the 1840-41 events that dammed the Indus (Butler et al. 1988; Hewitt 2009; Fig. 4c). There are arrays of related faults developed in both the footwall and hangingwall to the Liachar Thrust, with distinct orientations and character that may relate to the orientation of host rock fabrics (Butler et al. 2008).

Along with the Liachar Thrust, there are significant north-south trended cataclastic structures, many of which show strike-slip kinematics (Butler et al. 1989). These may be traced north to the Indus gorge (e.g. Madin et al. 1989) to link into the *Shahbatot fault* system (Fig. 12b; Butler et al. 1989). Collectively the cataclastic system accommodates transpression, with NW-SE contraction together with right lateral strike-slip.

Brittle deformation is strongly focused along the western margin of the massif, and this is reflected in the original thermo-chronological studies that show asymmetric cooling (Zeitler et al. 1982). However, the thermochronology and down-cutting estimates are from the Indus gorge – where the neotectonic structure is RL strike-slip, not reverse – as assumed by Leland et al. (1998). The strike-slip regime may however be rather young – and overprint earlier contractual structures – which could explain why the nick-point on the Indus is not situated at the active fault strand but is 30 km upstream (Leland et al. 1998). The offset could reflect upstream migration following a local switch in tectonic kinematics.

**A new cross-section**

A new cross-section through the NPHM is presented (Fig. 13) which shows active surface-breaking faulting to be restricted to the western margin of the massif. This is the Liachar Thrust. However, unlike earlier interpretations (Butler and Prior 1988b; Fig. 9b) the thrust zone is only developed near-surface. Deeper
parts of the massif, and the outcropping heart, contain near-vertical stretching strains (Butler et al. 2002).

The central challenge in elucidating the deformation structures that, along with denudation, have accommodated exhumation of the NPHM over the past few million years lies in discriminating these from earlier deformation. As Wheeler et al. (1993) point out, it is a standard problem in multi-deformed basement terrains. However, just as they use basic sheets to identify pre-Himalayan structures, syn-exhumation leucogranites may be used to identify exhumation-related structures (Fig. 10).

Deformed leucogranite pegmatites are found throughout the Liachar shear zone indicating that it is a young structure (Fig. 10e-i; Butler and Prior 1988b). Likewise the heart of the massif around Tato village contains leucogranite seams that relate directly to boudin necks that indicate sub-vertical stretching occurred during exhumation (Fig. 10c; Butler et al. 2002). However, there are no such descriptions from the Rupal Shear Zone – although much of the critical ground lies on the inaccessible southern cliffs of Nanga Parbat. No leucogranites are described by Butler et al. (1992) for the Rama outcrops between Astor and Chongra peak. Therefore it is possible that the Rupal Shear Zone is not part of the exhumation of the massif. Furthermore, the Rupal Shear Zone does not cut the ductile shear zone on the eastern margin of the NPHM (the continuation of the Phuparash Shear Zone). A new interpretation is proposed here (Fig. 13), that the Rupal Shear Zone is an earlier Himalayan structure, unrelated to the recent exhumation of NPHM. In this model, it branches onto the Phuparash Shear Zone north of Astor village. Argles (2000) points out that this sector of the massif’s eastern margin has complex lateral variation so that rock units are difficult to correlate along strike. This would be expected if this area contains early thrust-sense shear zones that repeat stratigraphy. The general northward plunge on the massif allows inferred footwall rocks to crop out further south – marking a transition southwards into decreasing metamorphic grade. These metasedimentary cover may exist at depth beneath the Rupal Shear Zone, continuing beneath the summit of Nanga Parbat and thus may provide a buried source for leucogranites.
Beyond arguing that melt weakens the shear zones into which it has been emplaced, the aneurysm model, (Zeitler et al. 2001; Koons et al. 2002) does not explain the exhumation of hot rocks act to create or localize deformation onto specific structures. Their schematic illustration shows the structure of the NPHM as a “pop-up” bounded by two thrust-sense shear zones. Yet the chief site of exhumation and main area of anatexis is found within the massif, not simply within the shear zones. Widely distributed anatexis and thermal weakening might rather be expected to generate broad zones of deformation. This expectation is consistent with the kinematic model for crustal deformation at NPHM of Butler et al. (2002) who show general syn-magmatic vertical stretching. The localized shearing that evolves into cataclastic faulting along the western margin of NPHM is then simply a consequence of near-surface cooling.

The role of exhumation-related anatexis as a weakening mechanism is developed further by Crowley et al. (2009). They argue that “vertical channel-flow”, essentially the pure shear thickening model of Butler et al. (2002), was promoted by the vapour-absent breakdown first of muscovite and subsequently of biotite. They suggest that it was this additional reaction that decreased the effective viscosity of the crust beneath Nanga Parbat leading to in increase in strain rate that in turn drove faster uplift.

But is the generation of granitic melt itself sufficient to weaken the rocks within which it resides sufficiently to influence significantly the deformation? The aneurysm model is underpinned by the tacit assumption that the processes of anatexis and granite generation are weakening mechanisms for crustal deformation – a notion dating back at least to Hollister and Crawford (1986).

The leucogranite pegmatites of the Liachar shear zone are synkinematic. They cross-cut deformation fabrics but have deformed shapes consistent with top-to NW shearing (Fig. 10f, g, i). In many cases boudin necks show concentrations of quartz and other phases (e.g. Fig. 10h) indicative of structurally-controlled fractional crystallization. In these cases the composite pegmatite body must have deformed during its crystallization. Less-deformed parts of structures, including boudin bodies, are generally characterized by
preserving igneous crystallization textures with the only deformation structures represented by grain fracturing. Similarly, folded pegmatite bodies (Fig. 10 i) contain primary crystallization textures (Fig. 10j), commonly aligned in a manner akin on syntaxial crystal growth in hydrothermal veins. Most of the leucogranites within the NPHM simply cross-cut deformation fabrics. In the Liachar shear zone they show predominantly strong inclusion behavior (e.g. Passchier et al., 2005) – indicating that the presence of granite is a strengthening phenomenon. These observations are consistent with the notion that fully crystallized granites strengthen the continental crust (e.g. Neves et al., 1996; Brown, 2013).

For deformation to be melt-enhanced, crystallization rates for melts must be sufficiently slow to be able to accumulate significant tectonic strain and these melts must remain within the deforming rock volume. Observations in the Liachar Shear Zone (Fig. 10) indicate that the pegmatites deformed before full crystallization yet field relationships indicate that at all stages of deformation, the bodies behaved more competently than their surroundings. The implication is that crystallization initiated very rapidly upon final emplacement of the leucogranite melt and outpaced deformation. For these emplaced melts to be effective at weakening the Liachar Shear Zone they would need to have lower strength for time periods sufficient to accumulate significant strain. And this does not appear to have happened.

In contrast, very low melt concentrations that remain in situ in the migmatites of the heart of the massif, appear to focus local deformation (Fig. 10c). As Brown and Rushmer (1997) note, melt on grain boundary films can greatly reduce bulk viscosity and thus enhance deformation. However, larger melt fractions are effectively drained from migmatites in veins (e.g. Brown 2013). Thus for melting to enhance the host ductility it must remain in situ. And this may explain enhanced vertical stretching, rather than shearing on localized zones, being the primary deformation mechanism within the massif.

Thermo-rheological model.

Strength-depth curves for continental crust generally resolve two distinct domains: near-surface, depth-dependent deformation controlled by pressure-
sensitive friction slip (or cataclasis with grain-boundary sliding); and deeper, temperature sensitive creep (crystalline plasticity). The greatest strength in the crust is located at the cross-over between these two domains – the “brittle-ductile transition”. As Koons et al. (2002) note while quantifying the aneurysm model of Zeitler et al. (2001), raised isotherms effectively erode the frictional slip domain, thus reducing bulk strength of the crust beneath the Himalayan syntaxes. The thermal structure within the NPHM can be estimated using the PT estimates from Crowley et al. (2009; Fig. 14), with near isothermal decompression followed by very rapid cooling in the final few km of exhumation. The resultant thermal structure may be used to infer strength-depth relationships, using the approach of Handy (1999; inset, Fig. 14). Strain rates of c $10^{-12}$ (strains of 1-3 accumulated over c 1 Myr) are applied to a polymineralic, quartzo-feldspathic rock. This reveals the rather low strength of the upper crust (c 20km – 7 km), rapidly increasing at shallower depths. Using a typical friction coefficient ($\mu = 0.8$) yields at “brittle-ductile transition” at c 5km depth. Note that changing this coefficient to very low values (typical of fault lubricated by serpentinite, halite or swelling clays, none of which are appropriate to the NPHM) will only reduce the “brittle-ductile transition” to c 6 km.

The onset of cataclastic deformation at relatively high temperatures, illustrated on the thermo-rheological plot (Fig. 14) was inferred by Butler and Prior (1988b; Butler et al. 1988) and recognized as being unusual. Classical models of brittle-ductile shear zones (e.g. Sibson 1983) depict the transition to occur within the broad greenschist facies, at temperatures around 300 °C – 350 °C. The nucleation of earthquakes on these systems happens within a zone controlled by quartz ductility and phyllosilicate-influenced deformation. For the Liachar thrust, and presumably other cataclastic fault zones around the massif, the structure of the seismogenic zone may be significantly different from those inferred elsewhere. Regrettably the only microseismicity monitoring experiments conducted at Nanga Parbat to date (Meltzer et al. 2001) were of insufficient duration to explore this inference.

**Comparisons with Namche Barwa**
As research activity in the Nanga Parbat district has waned, so interest in the eastern syntaxis has increased. It too is dominated by two distinct mountain groups – Namche Barwa (7782m) and Gyal Peri (7294m) – and they are also separated by a deep river gorge, carrying the Yalung-Tsangpo river (Fig. 15). The NBGPM forms a structural half-window framed by the rocks of the Lhasa Block. Much of the original research is reviewed by Bracciali et al. (2016; compare with Zeitler et al. 2014). Burg et al. (1997, 1998) traced sheared serpentinites and mafics around the rim of the massif, correlating these with the rocks from the India-Asia suture zone, together with fabrics in the underlying migmatitic basement to propose the general antiformal structure of the massif. They also report young fission track ages and U-Th-Pb ages for zircons at c 3-4 Ma – indicative of young cooling for the NBGPM. These results are broadly comparable with NPHM and prompted research to develop and quantify Zeitler et al.’s (2001) tectonic aneurysm model. These researches, chiefly using thermochronological data together with quantitative estimates of riverine stream power and landforms, have become somewhat polarized: do rivers and role in erosion and sediment transport control the sites of crustal deformation (e.g. Finnegan et al. 2008) or does the deformation happen anyway and is simply enhanced at sites of rapid erosion and sediment transport (e.g. King et al. 2016)?

**The margins of the Namche Barwa – Gyal Peri Massif**

Based on the interpretations of the structures of its margins, the NBGPM has been described as forming a promontory of the Indian continent, indenting the Lhasa Block (e.g. Koons 1995; Ding et al. 2001). The margins of the massif contain strongly sheared rocks of various tectonic affinities. The western margin is largely defined by the *Dongjui-Milin Shear Zone*, a left-lateral structure (Xu et al. 2012). It deforms two-mica peraluminous granites, the final part of the Gangdese batholith and related intrusions, in the vicinity of Loulan (Fig. 15). The granites are dated at 29-23 Ma (Pan et al. 2012). So the shear zone is presumably not a structure dating from the original collision of the Indian continent. Palin et al. (2015) report a composite history of shearing along the NW margin of the massif, based on U-Th-Pb geochronology. The earliest shearing
is dated at 23.9 ± 0.7 Ma, with continued ductile deformation continuing to c 8 Ma. The eastern margin of the NBGPM is also bounded by strike-slip wrench shear – with right-lateral sense (Fig. 15) - variably termed the *Aniqiao-Mutuo* or *Medog shear zone* (e.g. Dong and Xu 2016). The age of this structure is not constrained by dated relationships with the Gangdese batholith. However, Dong and Xu (2016) report U-Pb zircon ages from the synkinematic rims of zircons at 29.4-28.6 Ma.

The two margins, east and west, of the NBGPM show opposed-sense wrench shear, but these bounding shear zones are considerably younger than the age of original collision between the Indian continent and the Lhasa Block. In this regard they may be similar to the Phuparash Shear Zone on the margins of the NPHM, a similarly relatively late feature in Himalayan tectonics. However, unlike NPHM, to date there are no structures described from the margins of the NBGPM that are equivalent to the Liachar Thrust-Shahbatot Fault system, discussed earlier, that accommodate the final part of the exhumation of the Indian crust in the heart of the syntaxis. Quanru et al. (2006) report cataclastic structures within the various bounding shear zones and infer that these are extensional structures. However, an extensive, coherent brittle fault network has yet to be described. Dong and Xu (2016) suggest shearing on the Medog shear zone culminated at temperatures in excess of 350 C. Thus bounding shear zones of the NBGPM developed at significant temperatures than those at NPHM and appear to have been frozen in during exhumation of the massif, rather than have evolved into shallow, cataclastic structures as at NPHM.

**Internal structure and metamorphism of the Namche Barwa – Gyala Peri Massif**

As at Nanga Parbat, the NBGPM contains crystalline basement units, presumed to be derived from the Indian continent, which variably record a long and complex metamorphic and deformational history. These include leucogranite seams, though not as abundant as within the NPHM, dated as 3-10 Ma by Booth et al. (2009). These authors also recognize four other magmatic events within the NBGPM. Zhang et al. (2010) summarise metamorphic data for the massif. Garnet pyroxenites from along the Tsangpo gorge SW of Namche Barwa peak (Fig. 15)
record granulite metamorphism with pressures of 1.8 – 1.4 GPa. These HP granulites are preserved as dismembered pods within the Namche Barwa Complex and yield U-Pb ages from zircon rims of 38-32 Ma. Thus rocks now within the NBGPM were involved in thickening of the Indian continental crust at an early stage in Himalayan tectonics. The cores of zircons yield Proterozoic ages (Zhang et al. 2010), apparently clustering at 2.5 Ga, 1.6 Ga and 1.0 Ga. So, as at NPHM, rocks of the NBGPM record a long and complex geological history. Despite a few attempts to link geochronological and PT data deformation fabrics along the marginal shear zones (e.g. Palin et al. 2015) this is not been done within the massif as a whole. Tying in field relationships, including those between deformation fabrics and intrusions, is important for creating a mappable basement stratigraphy essential for relating structures to orogenic processes.

Burg et al. (1997, 1998) present cross-sections displaying the general antiformal structure of the massif and complex internal structure. However, the vertical exaggeration (10:1) on their sections renders problematic the interpretation of these structures. Booth et al. (2009) interpret the massif in similar fashion to Burg et al. – with south-vergent asymmetric folds (Fig. 16a). They also show a major shear zone that transects the massif just south of Namche Barwa peak – the Namla Thrust (Fig. 16a). For these workers this is an important structure that juxtaposes HT rocks in the north against lower-grade metasediments in the south. Subsequent work, illustrated by Xu et al. (2012) has modified this interpretation to include a series of tectonic slices, collectively termed the Namche Barwa Complex (Fig. 16b, c). However, the Namla Thrust retains a primary role in most models for the exhumation of the massif (see Bracciali et al. 2016 for review), with Zeitler et al. (2014) likening it to the Rupal Shear Zone at Nanga Parbat (as discussed above). Yet, as with the Rupal Shear Zone, the Namla Thrust at outcrop appears to have acted exclusively as a relatively high-temperature ductile structure. It is unclear how it might explain the distribution of cooling ages derived from low-temperature thermochronology.

Xu et al. (2012) report that the shear zones that contain the tectonic slices of the Namche Barwa Complex show variable kinematics, with both southward
and northward-directed shear senses. They propose that these relationships arise from pip-like exhumation of deeply buried Indian crust at around 40Ma. This mechanism has been invoked in other orogenic belts, most clearly in the Western Alps, to explain exhumation of eclogites through buoyancy-driven processes (e.g. Chamenda et al. 1995). Xu et al. (2012) also indicate that the Namche Barwa Complex is truncated against the bounding shear zones of the massif truncate not only structures of the Namche Barwa Complex but also of antiformal foliation trends in other parts of the massif. (Fig. 16b,c). These structural relationships are consistent with the geochronological constraints on the relative age of the various structures. Thus the exhumation of the NBGPM active at present is only part of a protracted structural and thermal history of the massif during Himalayan tectonics. This renders deductions of the geometric relationships of the massif to the form of the original collision especially problematic.

Thermochronology and active exhumation

The early studies of Burg et al. (1997) proposed that the Namche Barwa area had been exhumed from depths of c 30 km in the past 4 Myr, at a time-averaged rate of 7.5mm/yr. They compared this rate with fission track ages on zircon and apatite together with U-Th-Pb ages on xenotime, thorite and zircon. From these first data they argue for cooling rates of c 100 °C/Myr. In the past 20 years, Burg et al.’s (1997) initial work has spawned considerable efforts to refine the overall pattern, especially to establish the rates of down-cutting of the river gorges that cross the massif. Finnegan et al. (2008) report unpublished Ar-Ar (biotite) ages and a cluster of zircon fission track ages. Argon geochronology remains in general use, although the challenge remains to discriminate radiogenic argon inherited from basement degassing and thus to extract true cooling ages from micas. However, the overall pattern of apparently young Ar-Ar mica ages are consistent with results from an extensive variety of other thermochronological methods.

Following syntheses by Stewart et al. (2008) and Zeitler et al. (2014), recent results are collated and expanded by Tu et al. (2015), King et al. (2016)
and Yang et al. (2018). Samples from the Tsangpo gorge between the peaks of Gyali Peri and Namche Barwa, at elevations of c 2700m yield zircon (U-Th)/He ages of c 0.3 Ma (Stewart et al. 2008). Gneisses above the gorge (elevation of c 4 km) yield an apatite (U-Th-Sm)/He age of 1.5 ± 0.34 Ma (Yang et al. 2018). Tu et al. (2015) show that apatite fission track ages decrease with elevation up the flank of Namche Barwa peak. From this they conclude that enhanced Quaternary glaciation has driven increased exhumation rates. However, Yang et al. (2018) report ages along the Parlung as young as 0.18 ± 0.05 Ma for the apatite U-Th-Sm)/He system. They interpret the ages as the time samples cooled through 70 °C. It would appear then that denudation is especially rapid, exhuming recently cooled rocks through enhanced glaciation around the peaks and by rapid river down-cutting in the gorges.

Rather than use the thermochronological data to infer directly the cooling history for rocks of the eastern syntaxis, both King et al. (2016) and Yang et al. (2018) invert these data to test exhumation models. Both conclude that the locus of maximum denudation has migrated northwards through time. Within the spatial resolution of the existing samples, the current location of maximum rate of bedrock erosion lies just north of the outcrop of the NBGPM, along the Parlung river valley (Fig. 15). Presumably this in part reflects the capture of the Parlung drainage by the Tsangpo and the resultant rapid entrenchment of this drainage (e.g. Lang and Huntington 2014).

Attempts to deduce the record of denudation of the NBGPM during the Miocene have focused on the detrital record along the modern river valleys and within sedimentary basins south of the massif. Provenance studies based on detrital zircon U-Pb geochronology link source areas in the orogeny to ancestral foredeep (Siwalik) deposits of early Miocene and younger ages (Lang and Huntington 2014). These indicate that drainage from the Lhasa block flowed broadly across the Himalayas in the vicinity of the modern NBGPM from prior to the exhumation of the massif. Over time, and especially in the past 4 Myr, detritus from the NBGPM has increased in abundance. In modern sediments in the lower reaches of the Tsangpo river, over 50% is contributed from the massif, despite it accounting for >2% of the catchment (Bracciali et al. 2016).
The exhumation path

Zhang et al. (2015) summarise geochronological data within the context of the metamorphism. Additional data are provided by Palin et al. (2015). These can be linked to the low-temperature thermochronology discussed above. Bracciali et al. (2016) report U-Pb rutile ages from the massif of 1.4 Ma – implying that current bedrock was at 575 ± 75 C within the past 1-2 Ma. Syntheses stress the complex, pulsed history of exhumation of the metamorphic rocks outcropping along the margins and within the NBGPM. These results are summarized on Fig. 17. The challenge is to establish how far back the current tectonic regime, and its exhumation path, stretch back into the geochronological record.

If there is short wavelength differential vertical motion in the continental crust it should be manifest in the strain history and thus recorded by deformation structures. Unlike NPHM – there have been no systematic attempts to relate structures explicitly to the exhumation path, beyond definition of a few ductile shear zones. What structures are responsible for the rapid exhumation? Zeitler et al. (2014, following Booth et al. 2008) argue that the Nam La Thrust together with the northern tectonic boundary of the massif define a pop-up structure. As Bracciali et al. (2016) note, the current thermochronological data are difficult to interpret tectonically in the absence of descriptions of the structural geology of the massif. It is insufficient simply to assigning exhumation histories, especially those that reference the last few km of denudation, to tracts of gneisses thereby defining apparently distinct crustal blocks without also determining the kinematics of the low-temperature fault zones that would be required to bound them. As King et al. (2016) note and given the relief – perhaps the thermochronological data are not charting bedrock tectonics at all but merely the dynamic down-cutting associated with evolving drainage system. Given the relief (> 6km) and steep near-surface geothermal gradient (>100 C/km), implicit in the low-temperature thermochronology, simply reorganizing drainage can exhum rocks from temperatures approaching 600 °C without invoking any specifically focused crustal thickening.

Other syntaxes in the NW Himalayas
Various loop-shaped map patterns have been identified in the NW Himalayas, including the Besham syntaxis (Coward et al. 1988; Treloar et al. 1989) and other folded thrust systems (e.g. Greco and Spencer 1993). However, the most dramatic structure is the Hazara syntaxis (Fig. 18a), defined by the loop-shaped map pattern on the Main Boundary Thrust Zone. This structure straddles the de facto border between Pakistan and India making access especially difficult. Consequently there have been very few geological studies. Mapping and structural and stratigraphic data are provided by Bossart et al. (1988) and Greco and Spencer (1993), with stratigraphic data by Bossart and Ottiger (1989) and Critelli and Garzanti (1994). The general structure is an antiform, cored with Tertiary foredeep deposits of the Murree Formation. It is wrapped by thrust sheets that have been correlated with the Lesser Himalayan units to the SE (Greco and Spencer 1993), carried on the Main Boundary Thrust (Fig. 18a).

The Hazara syntaxis is generally interpreted to have formed by the superposition of the main Himalayan radial thrusting, here directed SW, upon the SSE-directed system in Pakistan (Coward et al. 1988). This has subsequently been supported by analyses of seismicity, including the devastating 2005 Kashmir earthquake (e.g. Avouac et al. 2006). Relocated aftershocks (Gibbons and Kvaerna 2017) define a buried continuation of the thrust NW of the Hazara syntaxis, leading to the Indus valley. The antiformal structure of the syntaxis is therefore readily interpreted to be the lateral tip fold to the Himalayan thrust front at depth (e.g. Coward et al. 1988).

The internal structure of the Hazara syntaxis is more complex than a simple antiform. The mapping of Bossart et al. (1988; Fig. 18b) reveals a strongly asymmetric structure so that the axial trace of the antiform is located on the SW margin of the fold, with a prominent SE plunge. The northern plunge and NE limb provides an exceptional stratigraphic section for the early Himalayan foredeep (Critelli and Garzanti 1994) that testify to the relatively low-relief of the early Himalayan chain. This changed so that by the early Miocene the foredeep was flooded with detritus, represented by the Siwaliks (see Burbank et al. 1996, for review). Unfolding the asymmetric anticline of the Hazara syntaxis reveals a lateral variation in the footwall to the Main Boundary Thrust. This
climbs section from west to east (Fig. 18c). The hangingwall also shows lateral
variation, with the Hazara Hills, to the west of the syntaxis, containing arrays of
heavily imbricated Phanerozoic supracrustals.

Structural mapping by Bossart et al. (1988) tracked cleavage through the
Hazara syntaxis. Strain studies reveal general flattening and the fabrics transect
the main anticline. These relationships demonstrate a significant component of
distributed strain to form the antiformal structure of the syntaxis – it does not
simply reflect differential uplift above a blind thrust (Fig. 18c). The strain
geometry is consistent with broadly NNW-SSE right lateral transpression.

Discussion: Why syntaxes?

There are various models for the structure of Himalayan syntaxes (Fig. 19). In
the aneurysm model (Zeitler et al. 2001; Fig. 19a), crustal structure is
represented by two opposed thrust shear zones with deformation apparently
focused by elevated near-surface temperatures and anatexis. There is a
coincidence of powerful rivers, high denudation and the location of the two main
syntaxial anticlines cored by the NPHM and NBGPM respectively. However, the
antiform of the Hazara syntaxis has formed but not amplified greatly. There are
no young metamorphic rocks in its core despite being crossed by large rivers
(Jhellum, Kaghan; Fig. 18). Indeed the lateral continuity of the Hazara fold and its
zone of seismicity passes to the Indus river yet there is no significant uplift here.
So it appears that, although denudation, effective erosion of strength-supporting
“brittle” upper crust and the uplift of weaker, hot rocks towards the surface is an
effective softening mechanism for crustal deformation, the location of this
defformation must have tectonic origins.

There are various models proposed for the tectonic processes. Some of
these follow Zeitler et al. (2001) and argue that uplift of the NPHM and NBGPM is
fault-controlled. Synthesising studies of earthquake distributions at both
terminations of the Himalayan arc, Mukhopadhyay et al. (2011; Fig. 19b) depict
NPHM as an upper crustal pop-up and thrust-detachments beneath the Hazara
syntaxis. In contrast Butler et al. (2002; Fig. 19c) argue that widespread
distributed strain in the NPHM implies crustal-scale vertical stretching with
thrust faults simply accommodating failure in the residual brittle “lid” of the
massif. The pattern of distributed deformation in the Hazara syntax, reported
by Bossart et al. (1988) and discussed above further support this model.
Distributed deformation models broadly build from the crustal folding models
for the antiforms of the syntaxes (Burg and Podladchikov 1999, 2000) – although
they do not rely on maintaining strong layers within the crust to act as buckling
instabilities. Distributed crustal deformation is also invoked by Palin et al. (2012;
Fig. 19d) beneath the NBGPM, passing up onto margin faults. However, they
suggest normal faulting rather than thrusting to accommodate upper crustal
exhumation.

Other deformation models attempt to place the Himalayan syntaxes in a
larger tectonic context. Ding et al. 2001) propose a combination of two
processes. One involves folding of the mantling thrust structures to the NBGPM
and the other envisages indentation of the massif into the Lhasa Block (Fig 19e).
Replumaz et al. (2012; Fig. 19f) present the results of sandbox analogue
modeling using two opposed oblique backstops. They create convergent thrust
systems that, where they interfere at the convergent apex, create oblique folds.
The model configuration is explicitly designed to mimic the thrust systems of the
NW Himalayas and northern Pakistan and thus to explain the Hazara syntaxis
and NPHM. This setting is also the target of numerical modeling by Whipp et al.
(2014; Fig. 19g) that create orogeny-parallel flow. This results from partitioning
oblique convergence, as happens in the western Himalayas, creating excess
crustal thickening and rapid uplift at the NW termination of the oblique
convergence zone.

A model for the syntaxes

The contention here is that the tectonic origins of the antiforms that lie at
the heart of the Himalayan syntaxes should be investigated in their broader
context. Various large scale numerical simulations and regional observations
inform this context. Numerical simulations of the evolution of the crustal
thickness of Tibet using the thin viscous sheet approximation (reviewed by
Houseman and England 1996) generate crustal thickness maxima adjacent to the
corners of an assumed rigid Indian continental indenter. However, the rigidity of
the Indian indenter in these models means that crustal deformation is exclusively restricted to the northern side of the India-Asia suture. But what if the leading edge of the Indian continent is not rigid?

The near-perfect shape of the Himalayan arc (Bendick and Bilham 2001) suggests that crustal deformation within the Himalayas is best described, on a large-scale, as a ductile continuum rather than be the product of complex thrust stacking. Copley (2012) argues that the Himalayan arc is the product of gravity-driven flow of relatively low-viscosity crust onto higher-viscosity (effectively rigid) foreland. Distributed strain is a feature of the NPHM and the core of the Hazara antiform. This suggests that the two folds form along the NW lateral margin to a zone of ductile strain beneath the Himalayan arc to the SE (Fig. 20).

Most cross-sections through the Himalayas emphasise the continuity to depth of major thrust systems upon which displacements are strongly localised. Copley’s (2012) model, adopted here (Fig. 20), suggests that the deep structure of the Himalayas is dominated by distributed strain. This dichotomy may be resolved if thrusting forms early and is being swept up by a southward-propagating strain wave. Copley (2012) considers the process to be a form of gravity spreading. The driver for this is most plausibly the overthickened continental crust of Tibet that is acting on the adjacent Indian crust, thickening this and collectively then driving further deformation out towards the foreland.

The timing of different parts of the tectonic history of the NPHM may be important here, within the Himalayan context. Even though India-Asia collision had occurred by c 52 Ma (see Green and Searle this volume), the main Himalayan syntaxes and their antiforms only formed within the past 10 Myr. First – the current juxtaposition of Kohistan arc on Indian crust was not achieved until the early Miocene – with movement on the Phuparash Shear Zone (Fig. 8) and it was from this configuration that the current tectonic regime developed. Given that, and the timing of high pressure in the Indian continental crust metamorphism dates to shortly after this time (Kouketsu et al. 2016), there is significant uncertainty as to the tectonic activity for the first half of Himalayan history (but see Treloar et al. this volume). It also renders linking the location of Himalayan syntaxes to the geometry of the Indian continent at the time of collision, and hence to original subduction geometry, especially uncertain. Nevertheless, the
leading edge of the Indian continental crust had been buried beneath the
southern edge of the Asian continent, presumably shortly after collision, as
recorded by the Kaghan eclogites (see Lanari et al. 2013). Peak temperatures of
650-750°C were achieved only after a further 20 Myr or longer, as is typical of
syn-orogenic (burial) metamorphism. Burial and radiogenic heating takes time
to warm and soften the Indian continental crust so that body forces created in
the thickened crust of Tibet are sufficient for it to yield. This means that the
Indian continent’s Argand number (as discussed by Houseman and England
1996), which quantifies the ability of lithosphere to support buoyancy forces
against imposed lateral (tectonic) forces, must vary with time.

Relating the geological history of the NPHM to the deformation model
presented here (Fig. 20) suggests that the modern extent of near perfect form of
the topographic arc is a rather young attribute of the Himalayas. It has taken 10s
Myr for sufficient volumes of the leading edge of the Indian continental crust to
become soft enough and thus to deform through widespread distributed strain.
This process is likely to be sensitive not only to the residence time of this crust
beneath tectonic overburden but also to its intrinsic heat production and
composition. It is interesting to note that the Himalayan arc does not define the
northern extent of the Indian continent. In northern Pakistan, west of the
syntaxes, there are major thrust systems that have stacked Indian continental
crust and translated upper crust towards SSE (e.g. Coward et al. 1988). Likewise,
Indian continental crust underlies the Assam syntaxis, east of the NBGPM. While
these areas may be less susceptible to body forces transmitted from thickened
Tibetan crust, it is also possible that both marginal areas beyond the syntaxes
may be dominated by continental crust with lower heat production and thus
have yet to warm sufficiently to deform by distributed crustal thickening.

Conclusions

The contribution has reviewed nearly four decades of geological research on the
syntaxes at the two ends of the Himalayan arc, containing the Nanga Parbat-
Haramosh massif and the Namche Barwa-Gyala Peri massif. Existing ideas and
data have been discussed alongside their importance for understanding not only
the early parts of the India-Asia collision but also how continental crust deforms in collision settings.

Nomenclature
There is significant confusion in the literature, especially in the western syntaxis about nomenclature – following a redundant approach of naming tectonic contacts on the basis of the units they juxtapose. The bounding ductile shear zone to the NPHM juxtaposes the Indian continental crust against the Kohistan arc. But it is erroneous to call this the Main Mantle Thrust (c.f. Butler and Prior 1988a and many others) as the contact is significantly younger than the MMT in its type area – it is a distinctly different structure - the Phuparash Shear Zone (Butler et al. 1992). Likewise, the tectonic contact along the western margin of the massif is sometimes conflated as a single “Raikhot Fault” (c.f. Madin et al. 1989) – even though the margin (Butler et al. 1989) includes segments of the (probable) Phuparash Shear Zone, a top-NNW thrust-shear zone (the Liachar Thrust) and a major strike slip system (the Shahbatot Fault). Retaining imprecise terminology obscures consideration of the structural relationships that are essential for understanding the geological evolution of the region.

Early Himalayan history
Both massifs comprise Indian continental crust that is juxtaposed against the southern margin of the northern Asian continent (the Kohistan arc in the west and the Lhasa Block in the east). Yet in neither case are these contacts the original suture: both were active several 10s Myr after collision. Earlier parts of the collision history are however recorded by both massifs. They contain rocks that originally resided in the Indian upper crust but which experienced HP metamorphic conditions relatively early in the Himalayan collision (at least 2.5 GPa at NPHM, Lanari et al. 2013; 1.8 GPa for NBGPM, Zhang et al. 2010). Their exhumation to lower crustal depths broadly while the now over-lying Kohistan-Lhasa crust was intruded by mantle-sourced granitoids (George et al. 1993; Pan et al. 2012), remains poorly understood.

Active exhumation: which structures are responsible for the tectonics?
Much recent activity has been aimed at relating quantifying near-surface cooling histories using various thermochronological tools, feeding this into models of denudation, mountain uplift and riverine down-cutting. Near surface cooling rates of over 100°C/Myr are recorded in both massifs (Zeitler et al., 1982; Burg et al. 1997). However, relating tectonic geomorphology to crustal-scale deformation and metamorphic processes is challenging in poly-metamorphic terrains such as the two massifs. Only the later part of their long and complex history relates to exhumation and the modern expression of the massifs and the tectonic significance of many ductile structures is ambiguous. Thus the Rupal Shear Zone at Nanga Parbat is more plausibly a pre-exhumation structure so that a description of the massif’s current structure as a pop-up is inaccurate (c.f. Schneider et al. 1999). Only the Liachar Thrust and shear zone (Butler & Prior 1988b; Butler 2000) shows the necessary combination of higher temperature shearing and cataclastic faulting. The exhumation is asymmetric, which accords the aneurysm model of Zeitler et al. (2001) as influenced by the distribution of rivers and erosion rates. Structures invoked in the eastern syntaxis to explain differential exhumation of the NBGPM have similar problems – illustrating the need for integrated structural mapping – admittedly difficult in the challenging landscape.

The aneurysm model: the role of melt overplayed?

Despite the acquisition of exceptional high-resolution thermo-chronological data, there remains significant uncertainty on how the feedbacks and coupling between rapid erosion, resultant decompression melting and deformation actually work. Existing understanding of strength-depth relationships in the crust certainly imply that exhumation of hot rocks causes weakening, reducing the depth to which frictional sliding operates ahead of temperature-dependent creep processes (e.g. Koons et al. 2002). The aneurysm model (Zeitler et al. 2001, Koons et al. 2002) takes this further by assuming that syn-kinematic melts, formed by erosion-promoted decompression, are agents of softening. This then focuses further deformation in shear zones into which melt has been emplaced. However, once crystallized, coarse-grained feldspar-rich rocks (e.g. leucogranites) are strong. Thus softening effects will only occur while granites
are still effectively liquid. The coincidence of granites in shear zones is insufficient evidence of this – the granite bodies should show evidence of weak inclusion behavior if they influenced deformation while liquid. This is not the case for the Liachar shear zone at Nanga Parbat: the leucogranites show strong inclusion behavior. However, unmigrated melt, forming grain boundary networks, may serve to weaken migmatites (e.g. Brown and Rushmer 1997; Crowley et al. 2009) and these will be located in sites of rapid decompression with the appropriate reactants, not necessarily in active shear zones. Note however that these hot rocks will be weak anyway – compared with the load-bearing “brittle” (frictional sliding domain) upper crust so the effect of melt presence may be marginal rheologically. This discussion emphasizes the need for much more detailed investigation of crystallization rates vs deformation rates in deforming crust – an issue of far-greater impact than simply the tectonic evolution of the Himalaya syntaxes.

The aneurysm model: cause or effect?

Regardless of the specific softening mechanism, the aneurysm model suggests that surface processes are a primary control on the location of crustal deformation. Yet patterns of erosion and riverine down cutting derived from thermochronological data for the eastern syntaxis are not consistent with this model. (King et al. 2016) Furthermore, other crustal scale folds, such as the Hazara syntaxis have formed but not been amplified even though they are crossed by powerful rivers. At NPHM, the most rapid cooling rates are found in the north of the massif (Zeitler et al. 1982), where transected by the Indus gorge – yet the active structures here are dominated by strike-slip faults (Butler et al. 1989), not thrusts indicative of accelerated differential uplift. Thus the primary location and tectonic evolution of the main antiforms at the syntaxes appear not to be controlled by river systems. The feedback mechanisms implicit in the aneurysm model appear to be somewhat subdued, at least for these Himalayan examples.

A new tectonic model
Existing descriptions of the structure of the Himalayan syntaxes emphasise localized shear zones. However, both the NPHM and the Hazara examples show penetrative deformation fabrics (Bossart et al. 1988; Butler et al. 2002) that accommodate right lateral transpression. This is consistent with their location at the lateral edge to the Himalayan arc which is experiencing southward displacement (Coward et al. 1988). Distributed strains are unstudied in the NBGPM but might be predicted to accommodate left-lateral transpression.

It is proposed here that the exhumed distributed strain fabrics at NPHM are representative of the deformation style for the crust beneath the Himalayan arc. Distributed deformation at depth may then be propagating, with the Himalayan arc, southwards to the Indian foreland, in the manner proposed by Copley (2015), as a gravity current. Why this style of deformation is restricted laterally at the syntaxes is presently unclear. It may reflect lateral variations in the driving force or the propensity of the Indian continental crust to deform in this manner.

Quo vardis?

Despite the extensive research over recent years, albeit focused on eastern syntaxes, much more work is needed to address issues presented here. The challenges of tectonic geomorphology require more complete structural descriptions – tracing mapped and kinematically constrained structures from cataclastic fault zones into broader areas of distributed strain. There are abundant thermochronological tools to establish cooling histories down from 200 C. But tracing these histories into the structures demands direct dating of shear zone fabrics and intermediate temperature chronometers – a challenge given the constraints of isotopic systems, the very young and rapid rates of deformation and difficulties relating accessory phases to map-scale fabrics and kinematics. Building regional understanding is best served through establishing histories from integrated structural and metamorphic mapping at all scales. These are of course classic approaches in long-studied polymetamorphic terrains where relative geological histories were built – then calibrated by more elaborate geochronometers and petrology. Most of the data and compilations are open to many different interpretations – reflecting the uncertainty inherent in
much geological investigation. Consequently there remains considerable uncertainty in tectonic models for the Himalayan syntaxes and their constituent metamorphic massifs, including the one presented here.

Acknowledgements

I was introduced to the Himalayas by Mike Coward in the mid 1980s and remain indebted to him for inspiring a career studying orogenic tectonics. I also thank the numerous colleagues both from the UK and from Peshawar University who were companions on many field campaigns, especially around Nanga Parbat. Over the years this research has been variously supported by the UK’s Natural Environment Research Council and the Royal Society. Finally I thank Peter Treloar for inviting this contribution and for his patience while I put it together.

References


George, M.T., Harris, N.B.W. and Butler, R.W.H. 1993. The tectonic implications of contrasting post-collisional magmatism between the Kohistan island arc and the


differential bedrock uplift along the Indus River near Nanga Parbat, Pakistan
Himalaya, from $^{10}$Be and $^{26}$Al exposure age dating of bedrock straths. *Earth and

Madin, I. P., Lawrence, R. D. and Ur-Rehman, S. 1989. The northwestern Nanga
Parbat-Haramosh massif; evidence for crustal uplift of the northwestern corner

Marshak, S. 1988. Kinematics of orocline and arc formation in thin-skinned

characterization of an active metamorphic massif, Nanga Parbat, Pakistan


Mukhopahyay B., Acharyya, A., Bhattacharyya, D., Dasgupta, S. and Pande, P.
2011. Seismotectonics at the terminal ends of the Himalayan arc. *Geomatics,
Natural Hazards and Risk*, **2**, 159-181.

emplacement or magma-assisted nucleation of shear zones? Insights from

Palin, R.M., Searle, M.P., St Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood,
M.S.A., Parrish, R.R., Weller, O.M. 2015. Two-stage cooling history of politic and
semi-pelitic mylonite (sensu lato) from the Dongjiu-Milin shear zone, northwest


Replumaz, A., Vignon, V., Regard, V., Martinod, J. and Guerrero, N. 2012. East-west shortening during north-south convergence, example of the NW Himalayan...


Webb, A.A.G. 2013. Preliminary balanced palinspastic reconstruction of Cenozoic deformation across the Himachal Himalya (northwest India). *Geosphere*, 9, DOI: 10.1130/GES00787.1


Geology, 28, 719–733.


**Figure captions**

Figure 1. Location map for the Himalayan syntaxes. Modified after Webb (2013). Boxed areas: a – Fig. 3; b – Fig. 15; c – Fig. 18a).

Figure 2. Analysis of publications (peer-reviewed in international journals) grouped in two-year sample windows based on a search using GoogleScholar (October 2017) using the terms “Nanga Parbat massif” and “Namche Barwa massif”, filtered to show only those results based on geological/geomorphological field research. The peak in the Nanga Parbat results marks the publication of Geological Society Special Publication 170 (Khan et al. 2000).

Figure 3. Simplified geological map of the Nanga Parbat – Haramosh massif, re-interpreted from existing mapping (Butler et al. 1992, 2000; Schneider et al. 2001).

Figure 4. Photographs of the NPHM. a) looking south to Nanga Parbat from the ridge east of Darchan village (Fig. 3) showing the relief across the syntaxis. b) Rupal face and glacier. c) looking north up the Indus valley on the western flank of NPHM from above the mouth of the Raikhot valley (Fig. 3). d) looking down along the Indus gorge near Shengus village. e) aerial photograph (from c 5000m) looking to the summit of Nanga Parbat (slightly cloud-obscured) with Chongra in the foreground. f) aerial photograph of the west ridge of Haramosh. Note the layered series of rocks inclined to ESE on the summit right of the mountain.

Figure 5. Basement stratigraphy and rock-types for the Nanga Parbat Haramosh Massif. a) Interpreted rock relationships (unscaled); b) amphibolites in marbles, interpreted as a Tethyan cover succession with meta-basic intrusions, deformed into recumbent fold, Sassi area, Indus gorge (cliff height c 50m, looking west); c) metabasic intrusion cross-cutting ore-existing migmatitic fabric, both subsequently deformed. Indus gorge (compass scale); d) typical migmatites from the heart of the NPHM, fabrics probably of early Proterozoic age (Tato village, compass scale); e) biotite granite (with metasediment xenolith) from the upper
Rupal glacier (pencil is c. 15 cm long); f) view onto intrusive relationships of biotite granite across non-migmatitic metasediments (Tarshing Group of Butler et al. 2000 – visible cliff height c. 1200m).

Figure 6. The structure of the Phuparash Shear Zone, the ductile shear zone that juxtaposes the Kohistan arc against rocks of the Indian continent and commonly misrepresented as the Main Mantle Thrust (cf Butler and Prior 1988a). a) Seen in cliff section on the south wall of the Phuparash peaks (visible cliff height c. 2500m). b) in the south wall of the Indus gorge on the eastern margin of the NPHM (visible cliff height c. 300m). c) sketch section (after Butler and Prior 1988a) summarizing structural relationships in the Indus gorge on the western margin of the NPHM which demonstrate top-SSE shear sense. d) large-scale form of deformed granite sheets – the final magmatic component of the Kohistan arc. The visible cliff height is c. 250m. e) high strained part of the Phuparash shear zone with strongly attenuated granite sheets. Coin for scale. f) Asymmetrically boudinaged mafic sills within marbles, part of the “cover” series of the NPHM.

Figure 7. PT conditions paired in distance across the Nanga Parbat Haramosh Massif. a and b show transects for the Astor valley and Raikhot-Chongra-Astor village respectively (data from Poage et al. 2000). c) shows general PT- constraints for the massif, using the HP-LT conditions preserved in the Stak eclogites (Lanari et al. 2013) and the HT-LP conditions preserved in the upper Raikhot valley (Crowley et al. 2009).

Figure 8. Scaled schematic cross-sections showing the evolution (a-b in time) for the pre-exhumation history of the Nanga Parbat Haramosh Massif and its relationship to the Kohistan arc terrain. Compare the relative position of markers x, y and z. x – the current location of the hangingwall to the Phuparash shear zone in the Haramosh area. y – the eclogitic rocks (and their retrogressed equivalents) of the Indian continental crust. z – the leading edge of lower crust of the Kohistan arc – former hangingwall to the Main Mantle Thrust, now hidden by the overstepping Phuparash Shear Zone.
Figure 9. Competing interpretations of the internal structure of the Nanga Parbat – Haramosh Massif shown on cross-sections. a) shows the composite antiformal structure preserved along the Indus gorge deduced by Wheeler et al. (1995). b) illustrates the geometry of the Liachar Thrust and shear zone interpreted by Butler et al. (1988), based on a transect through Raikhot to Astor. c) Schneider et al.'s (2001) cross-section through the southern part of the massif illustrating the “pop-up” structure proposed by Schneider et al. (1999).

Figure 10. Field relationships of exhumation-related granites in the Nanga Parbat Haramosh Massif. a) the Jutial leucogranite pluton – equant feldspar-quartz–tourmaline granite, with margins discordant to host gneisses. b) far-migrated leucogranite pegmatites from the Indus gorge forming discordant sills, indicative of vertical stretching. c) locally sourced diffuse-margin leucogranite seams preferentially developed in boudin necks (Tato area). d) cordierite-bearing leucogranite seams forming web-arrays in boudin necks. The remaining images are from leucogranite pegmatites in the Liachar shear zone, lower Raikhot valley. e) apparently deformed pegmatite, cross-cutting sheared migmatitic gneisses and amphibolites. f) deflected pegmatite g) compositionally zoned margin to the pegmatite dismembered into the shear zone indicating structurally controlled fractional crystallization of the original melt. h) typical coarsely-crystalline but undeformed igneous texture within the pegmatite. i) folded pegmatite with coarse margin facies and deformed, quartz-rich interior facies (j).

Figure 11. Fission track profile across the Nanga Parbat Haramosh Massif along the Indus gorge transect (diagram after Butler et al. 1989; data from Zeitler et al. (1982)).

Figure 12. Exhumation-related deformation on the western margin of the Nanga Parbat Haramosh Massif, in the Raikhot valley and surroundings. a) cross-section showing deformation kinematics. b) the Liachar Thrust in its type locality, c 5 km NE of Raikhot Bridge (hillside c 2 km high). c) the lower Raikhot gorge, showing
a section through the Liachar Shear Zone. Main cataclastic fault indicated by pecked line. d) asymmetric feldspar augen and s-c fabrics in orthogneiss showing top-NW shear sense. e) symmetric feldspar augen (indicative of quasi-pure shear sub-vertical stretching) in orthogneiss in footwall to the Liachar thrust zone. f) conjugate shear zones (with local leucosome patches) developed in migmatites at Tato village.

Figure 13. Revised cross-section through the Nanga Parbat – Haramosh Massif.

Figure 14. Temperature-depth plot for the heart of the Nanga Parbat – Haramosh Massif. Inset: Strength-depth plot for the NPHM – based on interacting depth- and temperature-dependent deformation mechanisms. See text for information.

Figure 15. Simplified geological map of the Namche Barwa – Gyalaperi massif, modified after Booth et al. 2009. The zone of HP-UHP granulites is after Xu et al. (2012). The zone of maximum bedrock erosion is after King et al. (2016). The lines of section (A-A'; B-B'; C-C') are those shown in Fig. 16.

Figure 16. Cross-sections through the Namche Barwa – Gyalaperi massif (lines of section on Fig. 15). a) A-A': after Booth et al. (2009). b) B-B' and c) C-C' are after Xu et al. (2012).

Figure 17. Temperature-depth-time plots for rocks within the Namche Barwa – Gyalaperi massif, with data from Zhang et al. (2015). The numbers are ages of various parts of the paths. The two paths (green boxes, grey ellipse) are recorded by different parts of the "Namche Barwa gneisses" but the relationship between these sites is obscure.

Figure 18. a) Simplified sketch map of the thrust systems in the NW Himalayas. Overlain with the pattern of after-shocks, simplified from the analysis by seismicity Gibbons and Kvaerna (2017). b) Geological map of the Hazara syntaxis (simplified from Bossart et al. 1988). c) Fold model for Hazara syntaxis and
Figure 19. A review of models for the syntaxial anticlines (scales and orientations, or lack thereof, are after those shown by the source publication). a) the aneurysm model of Zeitler et al. (2001) relating erosion and sediment evacuation by rivers to enhanced exhumation, elevated near-surface temperatures and the consequent localization of deformation. b) Mukhopahyay et al.’s (2011) block model to show the relationship between the NPHM, Hazara syntaxis and earlier thrusts (MMT – Main Mantle Thrust, MBT – Main Boundary Thrust) together with their younger subsurface structure (RF – “Raikhot Fault”). c) The distributed deformation model of Butler et al. (2002) for the crustal structure beneath NPHM, seen in cross-section. d) Palin et al.’s (2015) cross-section interpretation of the relationship between crustal thickening beneath NBGPM and the major Himalayan thrust and shear zones (STD – South Tibetan Detachment, MCT – Main Central Thrust, MBT – Main Boundary Thrust, MFT – Main Frontal Thrust). e) Ding et al.’s (2001) model in plan-view for the indentation of the Asian continent (Lhasa Block) by the NBGPM that forms a promontory of the Indian continent. f) plan-view sketch based on the photographs of analogues experiments by Replumaz et al. (2012) showing antiform formation at the apex between convergent thrust systems. The brown lines formed an orthogonal grid before deformation and illustrate rotational strain. g) Output (plan-view) from numerical modeling of partitioned oblique convergence by Whipp et al. (2014).

Figure 21 – Schematic block diagram, viewed looking SW to show the interpretation presented here for the western syntaxes as the lateral edge to the Himalayan crustal gravity current proposed by Copley (2012). The thermal structure is illustrative and qualitative. Note that displacement on the Main Frontal Thrust passes back down dip into ductile strain accommodating vertical stretching and crustal shortening. This forms the leading edge of the ductile component to the gravity current. Right lateral compression characterizes the deep structure of the syntaxes, as exhumed within the NPHM.
The image is a map of the Himalayas and surrounding regions, highlighting geological features and time periods. The map includes the following key features:

- **Asian and Indo-Burman plate rocks**
- **Kohistan-Ladakh arc**
- **Indian basement in Himalayas**
- **Quaternary**
- **Late Cretaceous**
- **Cambro-Ordovician**
- **undifferentiated Indian craton**
- **sutures (or later faults that limit outcrop of Indian crust)**

The map indicates time periods such as:
- 1.0 - 0.5 Ga
- 1.8 - 1.0 Ga
- > 1.8 Ga

Geographical locations marked on the map include:
- Karachi
- Lahore
- Kathmandu

The map also includes a legend and a figure reference: **Figure 1**

Click here to download Figure Fig 1 locationmap.pdf
Figure 2
Indian basement

> 1.8 Ga

1.0 - 0.5 Ga

Kohistan-Ladakh arc

Indian Phanerozoic cover?

1.0 - 0.5 Ga

Indian basement

> 1.8 Ga

leucogranites

DLG - Daimir leucogranite;

JLG - Jutial leucogranite

TLG - Tato leucogranite

cordierite-bearing gneisses

early ductile contact (Kohistan onto Indian crust)

neotectonic shear and fault contact

Figure 3

Click here to download Figure Fig 3 NPHMmap.pdf
Figure 7

a) Astor valley

b) Raikhot

- Poage et al. 2000
- Lanari et al. 2013 - UHP peak
- Crowley et al. 2009
- amphibolite overprint

Stak eclogites
Heart of NPHM

Click here to download Figure Fig 7 NP_PT.pdf
Island Arc Amphibolites
Mainly orthogneiss
Mainly paragneiss

NW

Indus
Liachar Thrust
hot springs
fluid circulation

large earthquake generation zone
active ductile shear zone
estimated 300°C isotherm

NE

Mazeno Pass Pluton (1.4 Ma)
NANGA PARBAT

Diamir Shear
Rupal Shear

0 km
Kohistan Arc

V=H

Main Mantle Thrust in all sections

W

Liachar Thrust

sea level

c 20 km thrust uplift

estimated 300°C isotherm
hot springs
fluid circulation

large earthquake generation zone
active ductile shear zone

sea level

5 km

10 km

15 km

Main Mantle Thrust in all sections

V=H

Figure 9

Click here to download Figure Fig 9 NPsections.pdf
all photos (apart from a) viewed to S/SW

boudinaged amphibolite

augen gneiss

integrown magmatic feldspar and quartz

qz in boudin neck
tourmaline-rich banding
Chongra

branch between Rupal and Phuparash SZs

vertical stretching in heart of massif

FW synform for Rupal SZ - now downward facing

10 km

1.0 - 0.5 Ga

> 1.8 Ga

Kohistan-Ladakh arc

Indian Phanerozoic cover?

Indian basement
Figure 14

- **seismicity limit?**
- **onset cataclasis?**
- **potential granite genesis**
- **anatexis**
- **heart of massif** (Crowley et al. 2009)
- **“standardized” exhumation pathway**
- **margins**

- **μ = 0.8**
- **“brittle-ductile” transition**
- **rapid change in strength**

- Geotherm (c 120°C/km)
- Geotherm (c 1°C/km)

- **μ = 10^{-12}**
- **qz = 30%; fds = 70%**

- **“wet melt” break down**

Temperature (°C) and pressure (MPa) as a function of depth (km).

Click here to download Figure Fig 14 PT strength.pdf
erosion rate > 3km/Myr

NAMCHE BARWA
7782 m

GYALA PERI
7294 m

Duoxiong-La dome

Antiguo-Motuo shear zone

Figure 15
Click here to download Figure Fig 15 finalNamche Barwar geol map.pdf
Figure 16

Metamorphic evolution of the eastern Himalayan syntaxis

a) Ductile shear sense
- Sinistral strike-slip (red indicates reoriented early thrust fabric)
- Thrust/Normal
- Steeply plunging stretching lineation

b) Brittle shear sense
- Dextral strike-slip
- Sinistral strike-slip
- Normal slip
- Thrust slip

Indian crust with HP/UHP lenses

Greater Himalayan unit

Lhasa terrain

Namche Barwa complex

Nam-La Thrust

Indian basement

migmatites and mylonitic gneiss

Gyala Peri

Namche Barwa

Duoxiong-La dome

SSWNNE

20 km

v = h

20 km

ESEWNW

10 km

Granite

Ophiolite

Gneiss

migmatites

Thrust

Detachment

Right-lateral strike slip fault

Left-lateral strike slip fault

HP (UHP?) blocks

Aniqiao - Motuo shear zone

Dongjiu - Milin shear zone

Lhasa terrain
Figure 17

Click here to download Figure 17 Barwa PTt.pdf
Figure 18

Click here to download Figure Fig 18 Hazara.pdf