Geologische Rundschau **80/2** | 411–428 | Stuttgart 1991

Structural evolution and asymmetric uplift of the Nanga Parbat syntaxis, Pakistan Himalya

By PETER J. TRELOAR, London, GRAHAM J. POTTS, JOHN WHEELER, Liverpool and DAVID C. REX, Leeds*

With 15 figures

Zusammenfassung

Die Nanga Parbat Konvergenz im nordwestlichen Himalaya ist eine noch im Wachsen begriffene nach Norden streichende antiformale Struktur im Krustenmaßstab. In ihrem Inneren wurden Gneisse der Indischen Platte aus der Nähe der überschobenen Gesteine des Kohistan Inselbogens herausgehoben. Isotopen- und Spaltspurengeochronologie zeigen, daß das Heraushebungsmaß innerhalb der Konvergenz zu der heutigen Rate von > 6 mm/a angestiegen ist. Die Heraushebung hat sich angepaßt an die Kombination von initialer NW-vergenter Überschiebung auf den westlichen Konvergenzrand, die gefolgt wurde von einer krustalen Faltung und lateral von dextraler antithetischer Verwerfung des westlichen Randes. Diese Deckenüberschiebung, Faltung und Verwerfung ist das Resultat der Deformation des nordwestlichen Ausstriches der Himalaya-Hauptüberschiebung, wo sie in Wechselwirkung mit der SSE-vergenten Überschiebung des NW-Himalayas steht.

Abstract

The Nanga Parbat syntaxis, in the NW Himalaya, is a still growing crustal-scale north-trending antiformal structure in the core of which Indian Plate gneisses have been uplifted from beneath the overthrust rocks of the Kohistan island arc. Isotopic and fission track geochronology show that uplift rates within the syntaxis have increased to present day rates of > 6 mm/yr. Uplift has been accommodated by a combination of initial northwest verging thrusting on the western margin of the syntaxis, followed by crustal scale folding within the syntaxis and latterly by dextral reverse faulting on the western margin. This thrusting, folding and faulting is the effect of deformation at the northwestern lateral tips of the main Himalayan thrusts where they interfere with the south-southeast verging thrusts of the northwest Himalaya.

Résumé

La convergence du Nanga Parbat, dans le nord-ouest de l'Himalaya, est une structure antiforme d'orientation nord-sud, d'échelle crustale et toujours active; son cœur est occupé par des gneiss de la plaque indienne qui ont été soulevés à travers les roches charriées de l'arc insulaire du Kohistan. Les données géochronologiques obtenues à partir des isotopes et des traces de fission montrent que le taux de soulèvement a augmenté dans cette structure jusqu'à la valeur actuelle de plus de 6 mm/an. Le soulèvement s'est effectué par la combinaison d'un charriage initial, à vergence nord-ouest, sur la bordure ouest de la convergence, suivi d'un plissement d'échelle crustale dans la convergence et, latéralement, d'une fracturation par

Authors' addresses: P. J. TRELOAR, Dept. of Geology, Imperial College, London, SW7 2BP, U.K. (current address. School of Geological Sciences, Kingston Polytechnic, Kingston-upon-Thames, Surrey, KT1 2EE, U.K.), G. J. POTTS. J. WHEELER, Dept. of Earth Sciences, Liverpool University, Liverpool, L69 5BX, U.K. and D. C. REX, Dept. of Earth Sciences, Leeds University, Leeds, LS2 9JT, U.K.

Manuscript received: 31. 5. 1990; accepted: 22. 3. 1991

faille dextre inverse sur sa bordure ouest. Ce charriage, ce plissement et cette fracturation sont l'expression de la déformation à l'extrémité latérale nord-ouest des charriages principaux de l'Himalaya, où ils interfèrent avec les charriages à vergence sud- sud-est de l'Himalaya septentrional.

Краткое содержание

Конвергенция Панда Парбат в северозападных Гималаях является все еще расширяющейся и простирающейся на север антиформальной структурой в размерностях Земной коры. Гнейсы индостанской плиты, залегающие внутри ее, оказались поднятыми надвигами пород островной дуги Кигистан, расположенными вблизи. Данные, полученные при исследовании изотопного состава и следов трещин, указывают на то, что поднятие в конвергенции шло тогда с той же скоростью, что и сегодня, т.е. более 6 мм/а. Это поднятие соответствует исходному надвигу, проявляющему вергенцию на NW, на западном краю схождения, за которым следовало смятие пород в складки, и боковому правостороннему антиклинальному сбросу западного края. Названный надвиг кровли, смятие в складки и сброс являются следствием деформации северозападного простирания основного надвига Гималаев, где отмечается взаимодействие его с опрокинутым на SSE надвигом северозападных Гималаев.

Introduction

One of the characteristics of the NW Himalaya is the presence of large-scale north-trending antiformal structures which deform the main Himalayan thrusts and around which the regional Himalayan trend bends. Termed »syntaxes« by WADIA (1931, 1932) these are crustal scale structures developed during the last few million years, within the cores of which uplift rates may be high (ZEITLER, 1985) and absolute uplift amounts great. The largest two of the syntaxial folds are the Nanga Parbat and the Hazara syntaxes (Fig. 1). Of these the Nanga Parbat syntaxis deforms the collisional suture zone and the crystalline rocks of the Indian Plate internal zones. The Hazara syntaxis, described in detail by BOSSART et al. (1988), deforms recent thrusts and molasse sediments of the external zones. As these thrusts include the Main Boundary Thrust, movement along which was as recent as 5–8 Ma ago (BURBANK, 1983), growth of the syntaxis must post-date ca. 5 Ma. A study of the Himalayan syntaxes is obviously relevant to an understanding of the regional evolution of Himalayan tectonics. In addition such a study is relevant not only to our unterstanding of how large crustal scale structures grow, and the rates at which they do so, but also of the processes by which deep crustal rocks may be exhumed. In this paper we wish to address these problems through presenting new field and geochronological data from the Nanga Parbat syntaxis and by reviewing data already published in order to describe the evolution of the syntaxis, growth of which continues to the present.

Within the NW Himalaya the Indian and Asian Plates are separated by the Kohistan-Ladakh Island Arc complex. To the east, in India, this is known as the Ladakh complex, whereas to the west, in Pakistan, it is known as the Kohistan complex. The island arc, developed above the north dipping Tethyan subduction zone, forms a microplate that was the last exotic component to be accreted to the Asian Plate prior to Himalayan collision, being sutured to the Asian Plate along the Northern, or Shyok, Suture at ca. 100 Ma (TRELOAR et al., 1989a). Himalayan collision in North Pakistan was thus effectively between the island arc complex and the Indian Plate with the former thrust southwards onto India along the Main Mantle Thrust (MMT). The MMT is a north-dipping thrust fault which is the effective westward continuation of the Indus-Tsangpo Suture Zone.

Most of the deformation within the island arc rocks predates the Himalayan orogeny, during which they were carried passively southward along the MMT (TRELOAR et al., 1990). Within the Indian Plate the opposite is the case. During collision cover and basement sequences were decoupled (COWARD & BUTLER, 1985), the cover being stacked and imbricated in front of Kohistan and the decoupled basement, with only a thin slice of cover sediments, being subducted under Kohistan. Here basement thickness was approximately doubled (DUROY et al., 1989) by processes such as ductile shearing and thrusting and the development of recumbent folds and late backthrusts (TRELOAR et al., 1989b). In the Hazara and Swat districts (Fig. 1) metamorphism was synchronous with this early ductile deformation (TRELOAR et al., 1989c), the deformed and metamorphosed Indian plate rocks being subsequently stacked and imbricated within a post-metamorphic crustal scale thrust

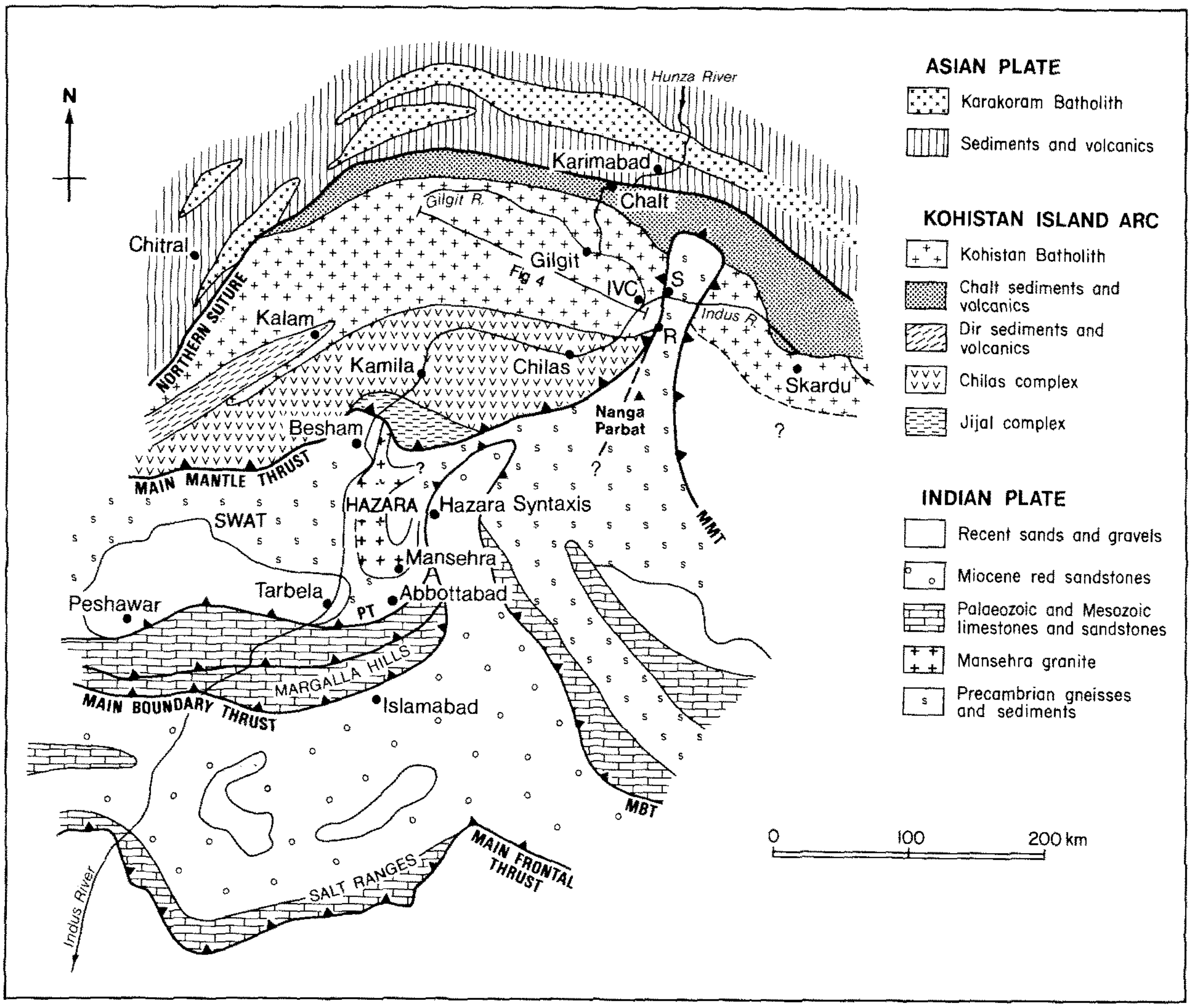

Fig. 1. Geological map of northern Pakistan showing the location of the Nanga Parbat and Hazara syntaxes, the separation of the Indian and Asian plates by the Kohistan island arc, and line of section for figure 4. R – Raikot; S – Sassi; PT – Panjal Thrust; MBT – Main Boundary Thrust.

stack which involved limited re-imbrication of the cover and basement sequences.

The Nanga Parbat syntaxis (Fig. 2) is a structural half window within the core of which highly deformed Indian Plate basement gneisses of a high metamorphic grade are uplifted from underneath the volcanic rocks of the Kohistan complex. The magnitude, rate and recent nature of this uplift was shown by Zeitler (1985) on the basis of zircon and apatite fission track ages. These are significantly younger within the syntaxis than within Kohistan with a particularly marked break across the western margin (Fig. 3). Detailed Ar-Ar and K-Ar amphibole and mica geochronology from both Kohistan and the syntaxis (Chamberlain et al., 1989; Treloar et al., 1989a; Zeitler et al., 1989) also show a systematic decrease in cooling ages across Kohistan with much younger ages within the syntaxis itself (Fig. 4).

There can be no doubt that the young ages within the syntaxis record recent, and continuing, uplift and associated exhumation. The localised nature of this uplift is shown by the elevation of the mountains within the syntaxis. At 8126 m Nanga Parbat towers over the surrounding areas of Kohistan. The rapid rate of uplift and erosion is shown by both the deeply incised nature of the drainage system and the dramatic form of the topography. Where it flows across the syntaxis the Indus river is at an elevation of about 2000 m, a relief contrast with the summit of Nanga Parbat of > 6000 m.

Although the fact of rapid and recent uplift is now well established, the structures by which this

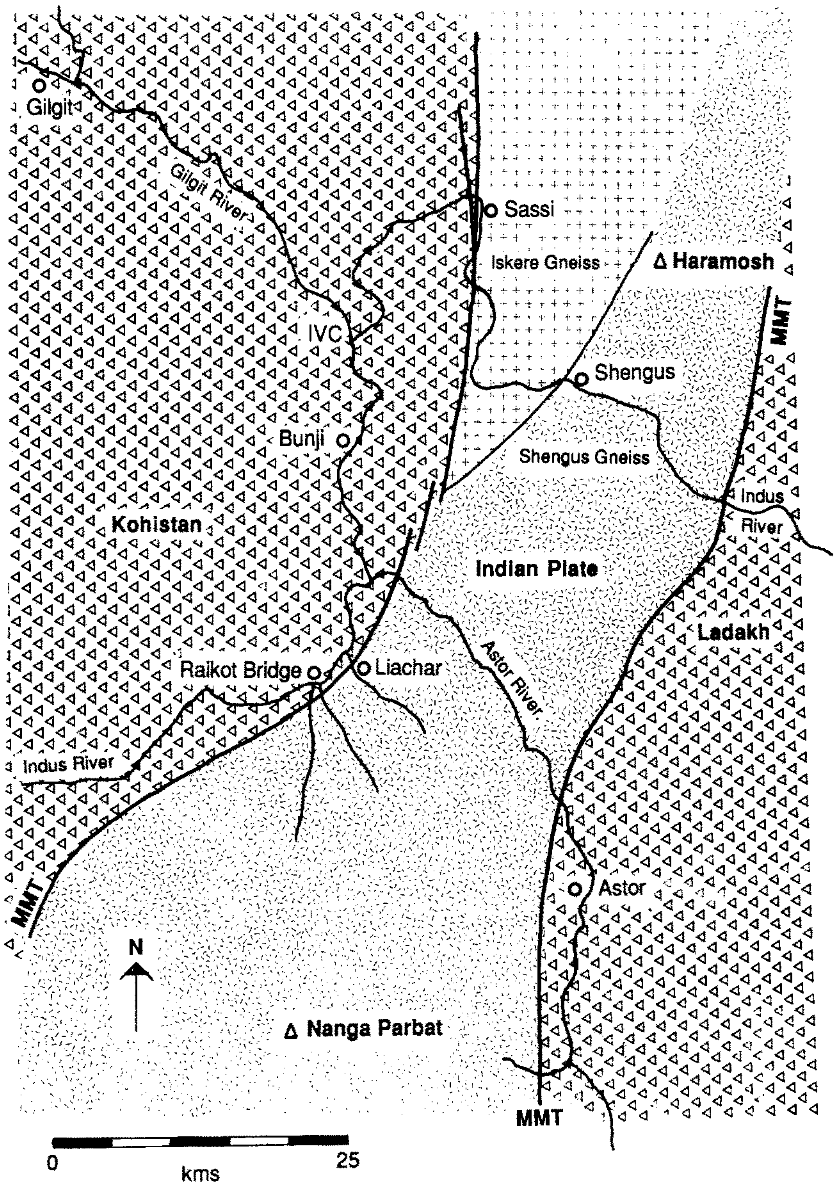

Fig. 2. Simplified map of the internal geology and bounding faults of the Nanga Parbat syntaxis (after MADIN et al., 1989).

uplift is accommodated are not so well constrained. A number of mechanisms have been suggested for the growth of the NW Himalayan syntaxes including crustal scale folding (COWARD et al., 1986), dextral oblique reverse faulting coupled with large scale folding (MADIN et al., 1989; BUTLER et al., 1989) and an antiformal stacking of thrust sheets caused by a rotation of thrust directions (BOSSART et al., 1988). Within the Nanga Parbat syntaxis, on the basis of a reconnaissance traverse, COWARD (1989) and COWARD et al. (1986) showed the internal structure to be that of a buckle-type antiformal fold with a half wavelength of over 30 km and an amplitude of 25 or more km. By contrast, MADIN et al. (1989) argued that uplift was accommodated along the western margin of the syntaxis along what they termed the Raikot Fault, a steeply dipping oblique-slip dextral reverse fault which offsets the MMT. BUTLER and PRIOR (1988a, b) and BUTLER et al. (1989) have also described the western margin of the syntaxis and, although recognising the dextral strike-slip component, describe a more complex structural zone, involving northwest directed thrusting as well. The eastern margin of the syntaxis is less well known although VERPLANK et al. (1985) suggest it to be an east-side down normal fault termed the Stak Fault which they interpret as cutting out the MMT altogether.

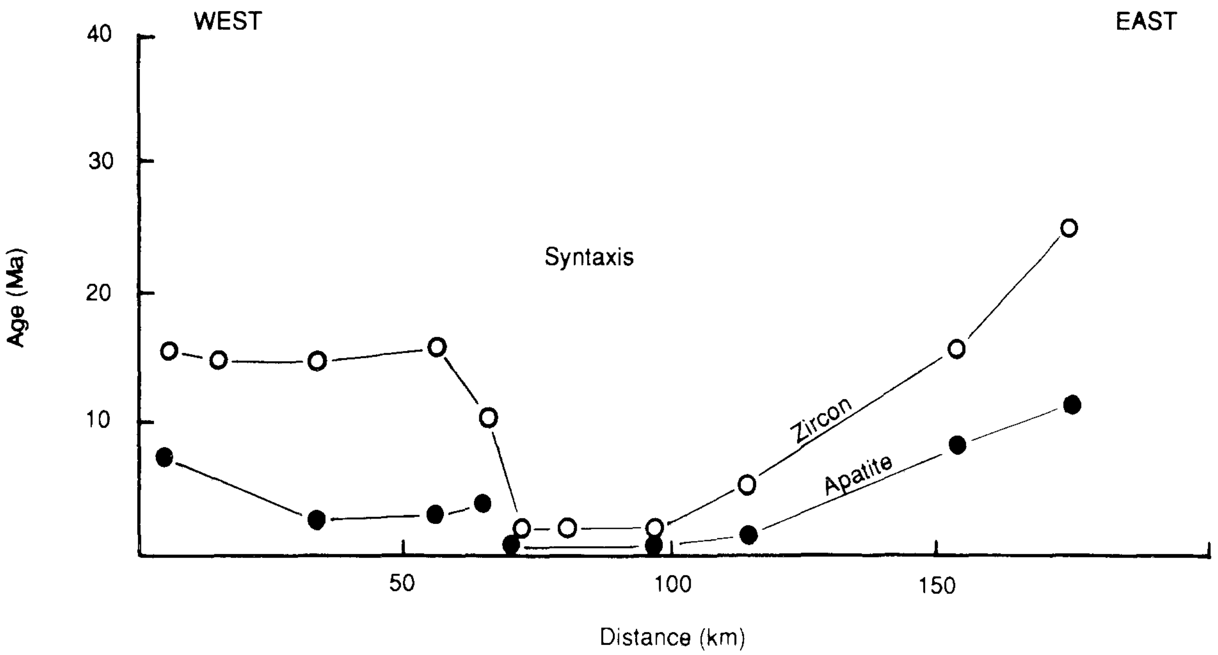

Fig. 3. Fission track profile (from ZEITLER, 1985) across the Nanga Parbat syntaxis.

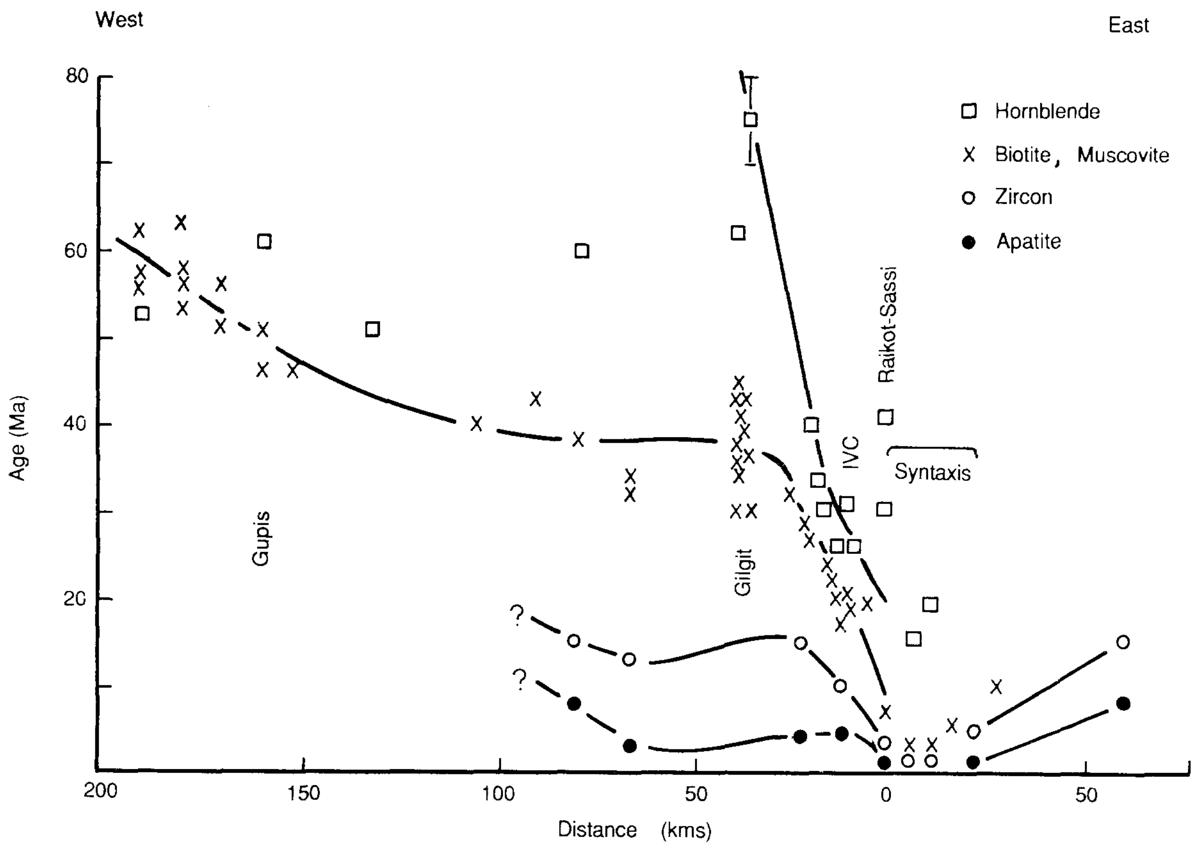

Fig. 4. Distance vs. time plot of K-Ar, Ar-Ar and fission track geochronological data across Kohistan showing both the decrease in ages towards the syntaxis and the much younger ages within it. IVC – Indus Valley Confluence (of the Indus and Gilgit Rivers).

These structural observations suggest uplift to be a combination of folding and faulting, although which is dominant and whether folding preceded faulting or not is uncertain. In an attempt to resolve this problem we will first briefly summarise data from the western margin and then detail the results of a recently completed traverse through the syntaxis along the Indus River gorge.

The Western margin of the Nanga Parbat syntaxis

The readily mapped section of the western margin extends approximately north-south from Sassi to Raikot (Fig. 5). This zone is marked by a complex suite of faults, thrusts and shears the character of which changes from north to south. In the south, at Raikot and Liachar, the major structure is a northwest verging thrust, the Liachar Thrust, in the hanging wall of which Indian plate rocks are being thrust back over Kohistan (Fig. 6). The earliest fabrics within the thrust zone are ductile shear fabrics formed at significant crustal depth. Thrusting appears to have continued from the formation of these earliest fabrics to the present day with a constant movement vector (BUTLER & PRIOR, 1988a, b). The present fault, as exposed at Liachar, is a brittle thrust that places Indian Plate gneisses directly onto recent Indus Valley alluvial sediments (OWEN, 1989).

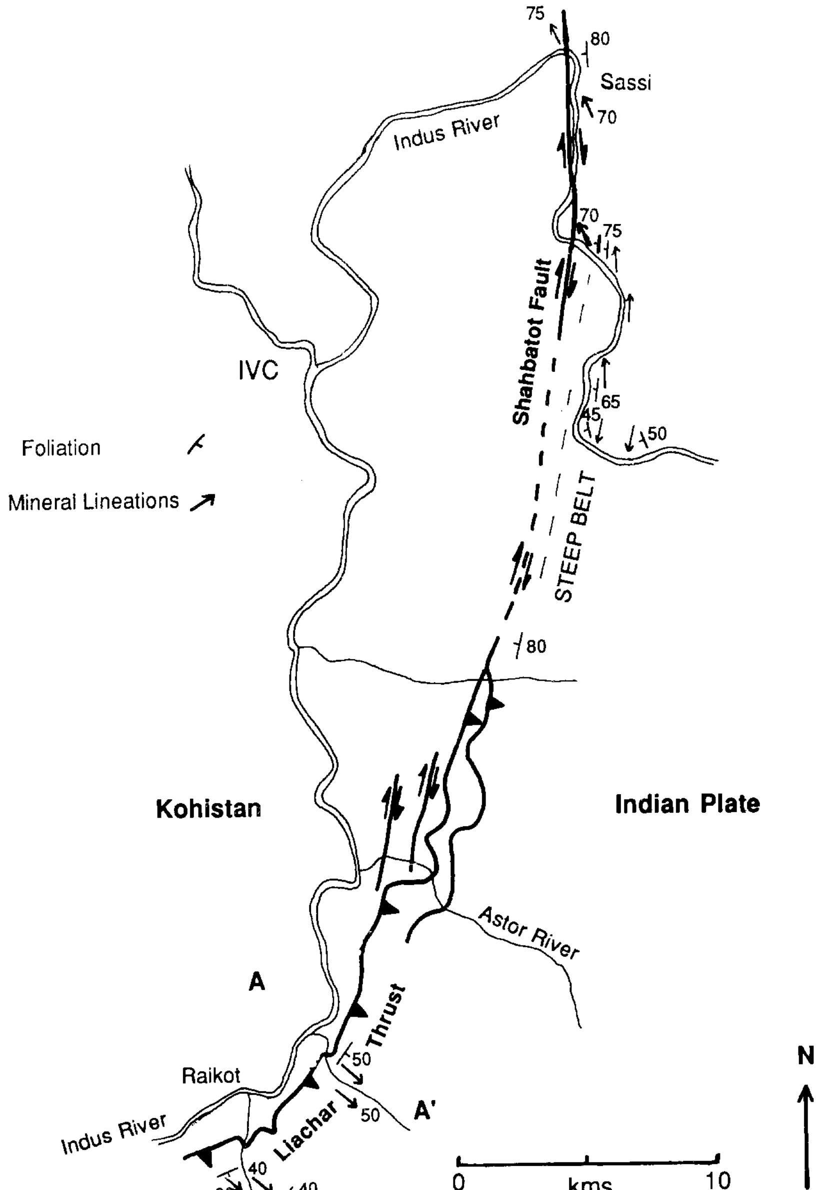

Fig. 5. Geology of the Raikot-Sassi fault zone along the western margin of the syntaxis (modified after BUTLER et al., 1989).

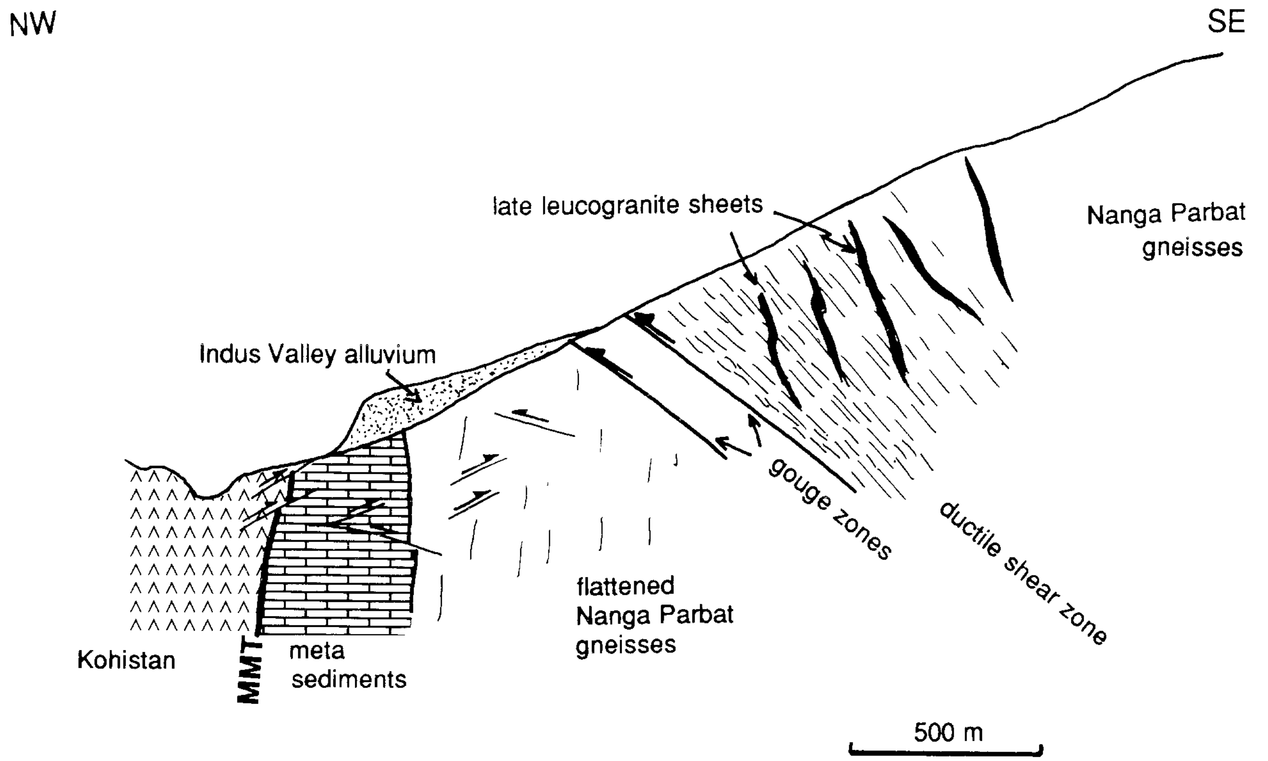

Fig. 6. Section across the Liachar thrust zone (A-A, Fig. 5) showing the northwest verging nature of the thrust with Indian Plate gneisses in its hanging wall and the vertical MMT sequence, unconformably overlain by recent Indus Valley alluvium, in the footwall. MMT – Main Mantle Thrust.

In the footwall of the Liachar Thrust the Indus Valley alluvium overlies a vertical sequence that includes the MMT. This is best exposed at Raikot where the north-striking MMT separates Kohistan amphibolites to the west from Indian plate gneisses. The MMT zone itself is a strongly sheared sequence of imbricated metasediments and Kohistan amphibolites. The metasediments, which include marbles, calcareous meta-psammites and coarse-grained garnet – kyanite bearing schists are Indian Plate cover sediments subducted and metamorphosed under Kohistan during initial stages of the Kohistan-India collision. These metasediments are similar in appearance and lithological diversity to the Alpurai schists (KAZMI et al., 1984) exposed immediately under the MMT in the Swat district (Fig. 1). TRELOAR et al. (1989b) have shown that prograde metamorphism in Swat was along a path of increasing pressure during active thickening and subduction of the Indian Plate under Kohistan.

At Raikot and Liachar, therefore, the tectonic history is of initial southward thrusting of Kohistan onto India, associated with metamorphism of the Indian plate cover sediments in the MMT footwall. Subsequently the MMT was rotated into the vertical in the footwall of the northwest verging Liachar Thrust along which Indian plate rocks are carried back over Kohistan. That this thrust has a lengthy history and accommodates substantial uplift is shown by the progression through time from ductile through to brittle fabrics and the reworking of the earliest ductile fabrics by the latest brittle ones. For much of this period the fault zone has been the locus of hydrothermal activity. Fractures and shears within the shear zone are frequently coated with mats of hydrothermal biotite and the site of the presently active fault is marked, south of Raikot, by hot springs.

Timing of movement along the Liachar Thrust can be deduced from muscovite ages from granite sheets that cut the earliest ductile shear fabrics. These muscovites have K-Ar ages of 7.8–9.2 Ma which give a minimum age for the onset of shearing (D. C. REX and P. J. TRELOAR, unpublished data).

To the north, at Sassi, a lengthy period of deformation can also be recognised with early ductile deformation continuing into a more brittle regime. Here the shear fabrics dip steeply to the west. Shear criteria, ranging from ductile shear band fabrics to brittle offsets of veins and passive markers, have an oblique dextral sense of movement, east-side up on vertical surfaces. Stretching lineations plunge towards the north. Of these, the earliest lineations, invariably ductile, have a steep plunge with later lineations, which encompass a change from ductile through to brittle movements, having an increasingly shallow plunge, implying that the strike slip component of movement became more important through time (Fig. 7). Indeed, BUTLER & PRIOR (1988a, b) and BUTLER et al. (1989) have shown that the strike slip movement was initiated in the north and has migrated southwards, progressively interfering with the northwest verging thrusts.

This zone of shearing and faulting at Sassi, termed the Shahbatot Fault by BUTLER et al. (1989) separates Kohistan amphibolites to the west from Indian Plate biotite orthogneisses. An extensive sequence of marbles and mica schists outcrop within the fault zone. As at Raikot these are interpreted as Indian plate cover sediments which originally formed part of the MMT zone sequence and which have been reworked by the Shahbatot Fault. It is thus clearly incorrect to state that the MMT does not outcrop along the western margin of the Nanga Parbat syntaxis having been cut out and displaced by the structures there (LAWRENCE & GHAURI, 1983; MADIN et al. 1989). Rather the MMT is present along much of the length of the Raikot-Sassi fault Zone, albeit extensively deformed by later shears.

The Raikot-Sassi fault zone, which marks the western margin of the Nanga Parbat syntaxis, is clearly the locus of substantial east-side up movement, with an increasingly important dextral component, developed over a period of at least 9 Ma.

An east-west section across the syntaxis

a) lithology

Within the syntaxis the Indian Plate rocks can be divided into two (Fig. 2) – the orthogneiss

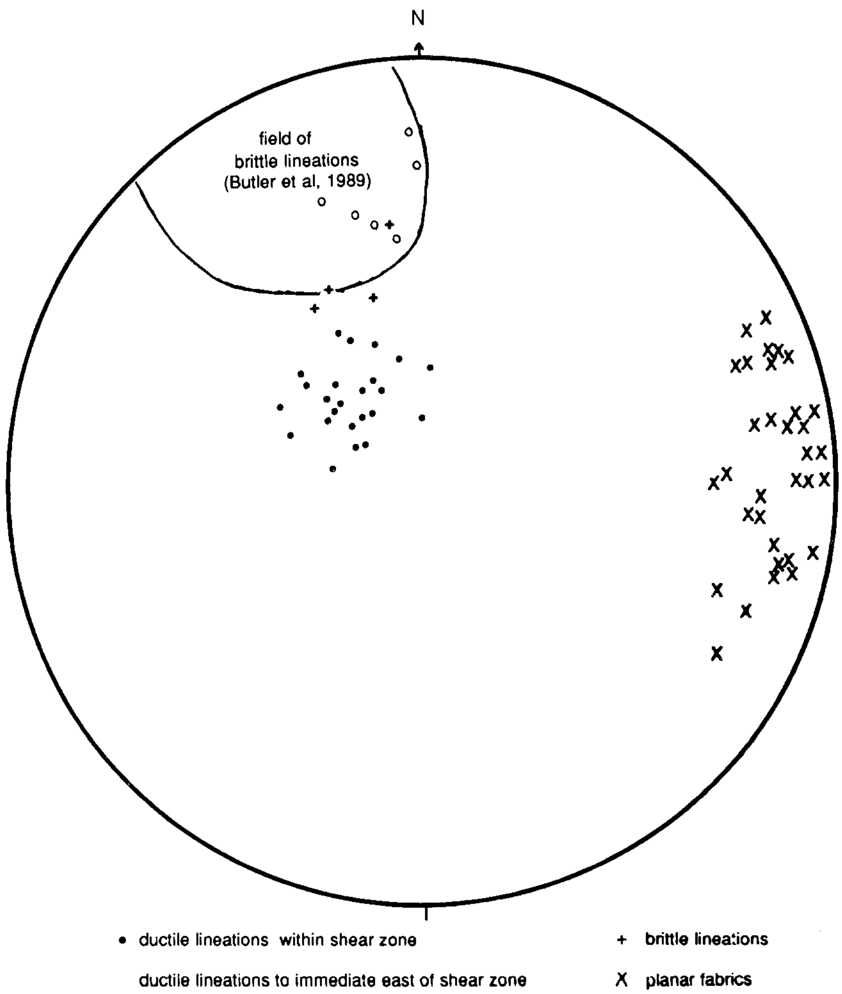

Fig. 7. Stretching lineation data for the northern part of the Raikot-Sassi fault zone showing the steeper plunge of the ductile than the later brittle lineations. The field of brittle lineation data is from BUTLER et al. (1989).

dominated Iskere Gneiss to the west and the paragneiss dominated Shengus Gneiss to the east (MADIN et al., 1989). Our mapping shows the Iskere Gneiss to be largely formed of biotite gneisses often with a migmatitic character. Although much of these gneisses are probably of igneous origin a number of calc-silicate pods and layers are present. The rocks are essentially quartz-plagioclase-orthoclase-biotite gneisses with some muscovite. Garnet is rarely present and kyanite has only been recorded from one pelite horizon. ZEITLER et al. (1989) dated zircons from the Iskere Gneiss at about 1850 Ma. Similar ages are recorded the Besham gneisses of North Pakistan (TRELOAR et al., 1989a) as well as from basement gneisses elsewhere in the Himalaya (BHANOT et al., 1977; TRIVEDI et al., 1984; VALDIYA, 1988) and we interpret the Iskere Gneiss as being essentially a basement orthogneiss sequence.

The Shengus Gneiss is a highly deformed supracrustal series of paragneisses interlayered with deformed biotite-rich orthogneisses. The latter yield an age of about 500 Ma (ZEITLER et al., 1989) similar to that of the Mansehra Granite exposed south of the MMT in the Hazara district (LE FORT et al., 1970). The paragneisses are dominated by kyanite (or sillimanite) – garnet – biotite – plagioclase – orthoclase – quartz bearing lithologies as well as numerous diopside – garnet – plagioclase bearing calc-silicate pods and lenses. The rocks are coarse grained with garnets frequently up to 1 cm in diameter. Veinlets and segregations of anatectic melt are distributed throughout the sequence. CHAMBERLAIN et al. (1989a, b) showed that metamorphism, to pressures of about 8 kbar, was along paths of increasing pressure probably during subduction of the leading edge of the Indian plate under Kohistan-Ladakh. We interpret the Shengus Gneiss as being a cover to the Iskere Gneiss and correlate it with the Tanawal Formation – Mansehra Granite series of the Hazara region (TRELOAR et al., 1989c). The contact between the Iskere and Shengus Gneisses is marked by a band of strongly foliated and very platy sillimanite bearing mylonites although this has been modified by later brittle faulting.

A variety of igneous sheets cut the Indian Plate gneisses. Amphibolite (meta-dolerite) dykes with an intense fine-grained highly strained internal fabric, often with strongly sheared and lineated contacts, are transposed into sub-parallelism with the regional tectonic fabric in both the Iskere and Shengus Gneisses. That many of the dykes show discordant relationships to banding within the country rock gneisses show that, although the sheets predated the main phase regional fabrics, their emplacement postdated an earlier deformation that could be Proterozoic or later in age. Undeformed garnet-tourmaline bearing leucogranite and pegmatite sheets cut the Shengus gneiss and postdate the main shear fabrics.

Three extensively boudinaged bands of amphibolite occur near to the eastern margin of the syntaxis. These are interpreted as slices of island arc metabasic rocks imbricated within the Indian plate gneisses in the footwall of the MMT.

b) Deformation

Maps of the Indus Gorge section showing foliation and lineation patterns are shown in Figure 8. The regional foliation is an intense ductile fabric, often mylonitic in character. Pervasive stretching lineations are contained within the fabric surface. Within much of the syntaxis these plunge gently towards either the north or south (Fig. 9). By contrast, within the Ladakh sequence to the east of the syntaxis and within the slices of island arc material imbricated within the Shengus Gneiss they plunge towards the northeast. Lineation intensity varies. In places the rocks are true L-tectonites. Elsewhere L-S relationships vary, with the development of both L-S and S-tectonites.

Although primary metamorphic fabrics are preserved in places they have generally been extensively reworked by the regional shear fabrics. This reworking involved the cataclasis of garnet and kyanite and the development of quartz ribbons. The shear fabrics anastomose around relic garnet and feldspar porphyroclasts. Most of the microstructures related to this shearing have subsequently been annealed and recrystallised with the quartz ribbon fabrics in particular now showing good granoblastic polygonised fabrics with much of the evidence for deformation mechanisms destroyed.

In the eastern half of the syntaxis, in the Shengus Gneiss, the foliations are folded around the asymmetric Bulache Antiform, a north plunging antiformal structure with a steeply dipping and attenuated eastern limb. There is a metamorphic asymmetry associated with this fold in that kyanite bearing rocks occur on its eastern limb and sillimanite bearing rocks in its core and on the western limb. This asymmetry may be explained if the sillimanite and kyanite rocks are separated by a shear zone that is folded by the antiformal structure. Within the western half of the syntaxis, within the

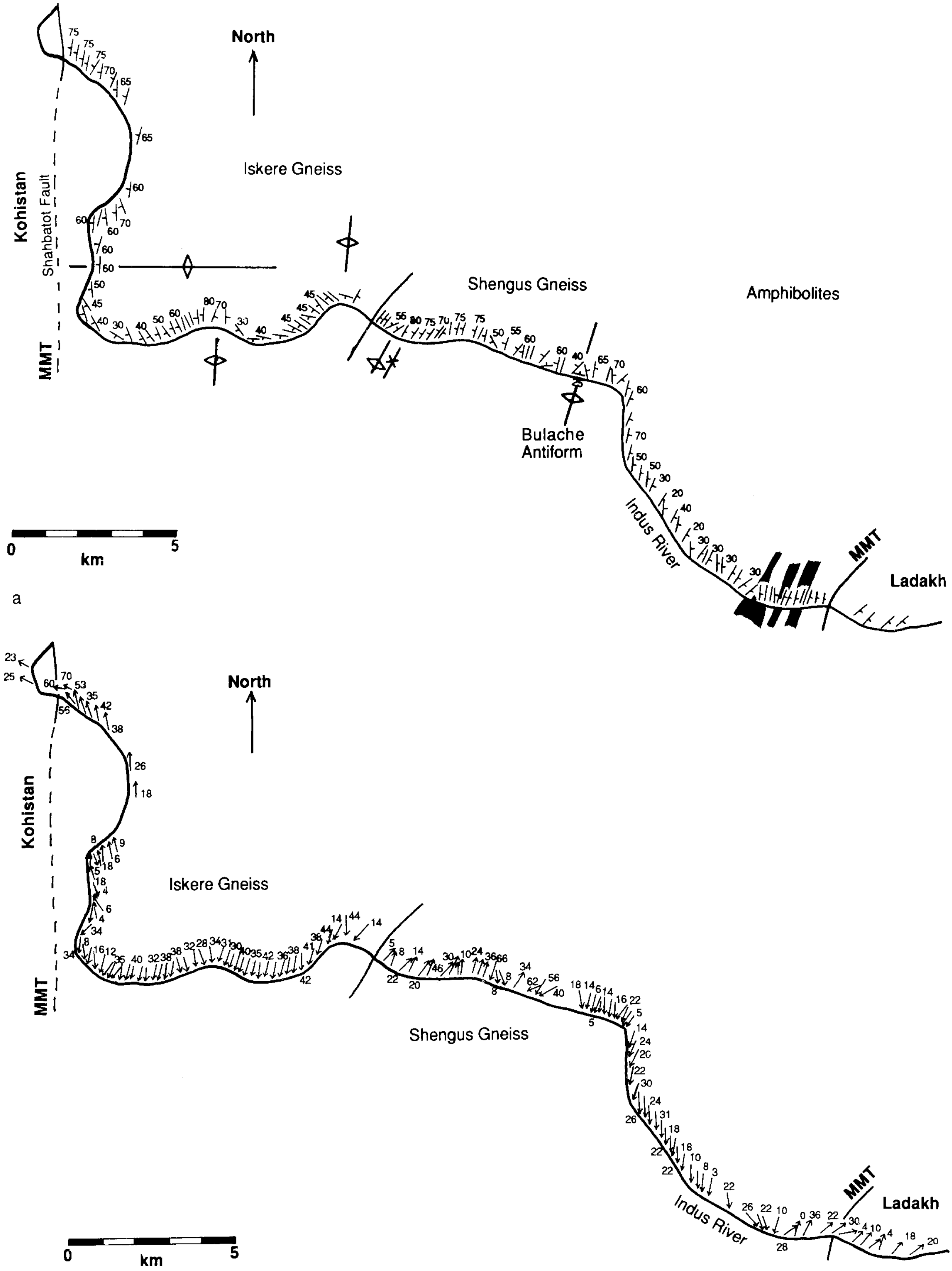

Fig. 8. a) foliation and b) lineation maps of the Indus Gorge section through the Nanga Parbat syntaxis.

Iskere Gneiss, the foliations are deformed both by a series of small wavelength small amplitude folds with northerly or northeasterly trends, and by an east-west trending flexure (Fig. 8).

Towards the western margin of the syntaxis the lineations plunge more steeply rotating from the horizontal towards a steep north westerly plunge. Here they are contained within a steeply west dipping ductile shear fabric with well developed S-C' shear bands, in which the C' surfaces dip steeply eastward and which record an east side up sense of displacement. This ductile L-S fabric represents the first, ductile, stage of movement along a trace now marked by the Shabatot Fault.

On the eastern margin the contact between the amphibolites of the Ladakh sequence and the Shengus paragneiss sequence is parallel to the regional fabric. The contact here is a sharp concordant one although folded by small wavelength north trending parasitic folds with sub-horizontal axial planes. Although there is evidence for some relatively small scale brittle faulting, we do not recognise the Stak fault of Verplank et al. (1985) and have found no evidence here that the MMT is significantly deformed or reworked other than having undergone an essentially passive steepening on the limb of the major north trending fold.

c) mineral cooling ages and timing of deformation

Some geochronological data (Fig. 10) are available from within the syntaxis (Zeitler, 1985; Zeitler et al., 1989; D. C. Rex, unpublished K-Ar data). Other than that the ages within the syntaxis are younger than those from outside (Figs. 3 and 4), the key features of these data are that i) mica Ar-Ar and K-Ar ages are older from within the eastern than the western part of the syntaxis, and ii) zircon and apatite ages within the western part are similar to those from within the Raikot-Sassi Fault Zone but older than those on the eastern margin. This disparity in ages between the eastern

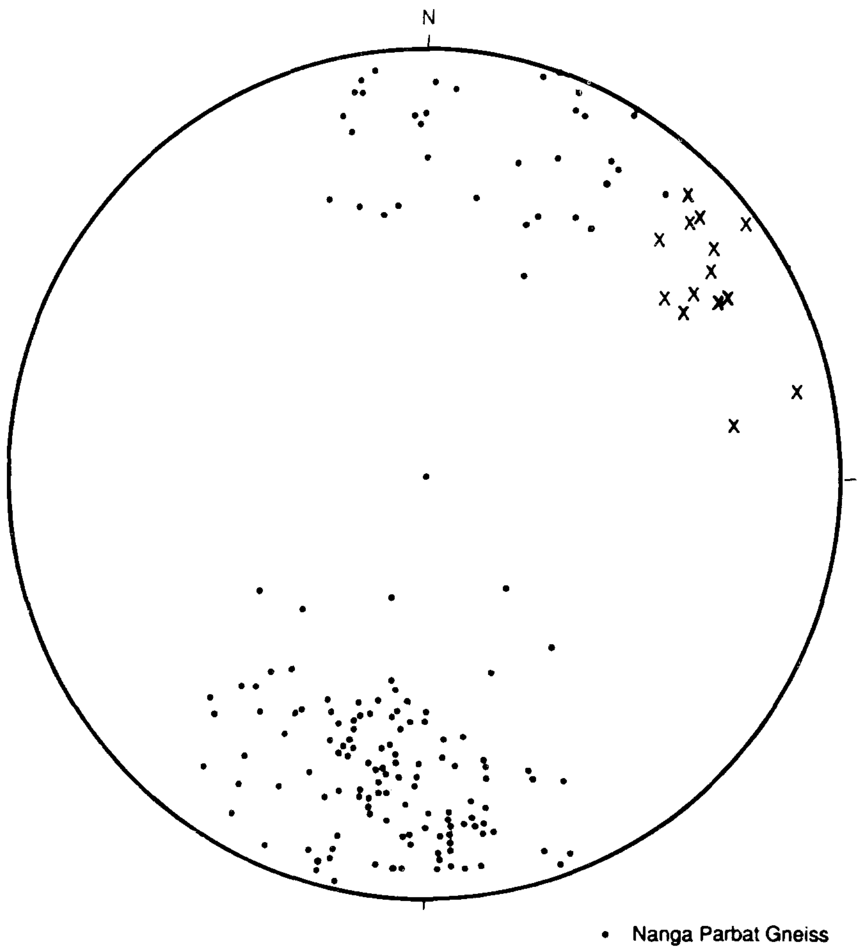

Fig. 9. Stretching lineation data from the Indus Gorge section. Crosses mark NE-plunging lineations within the Ladakh sequence to the east of the syntaxis and within slices of island arc material imbricated within the eastern part of the syntaxis.

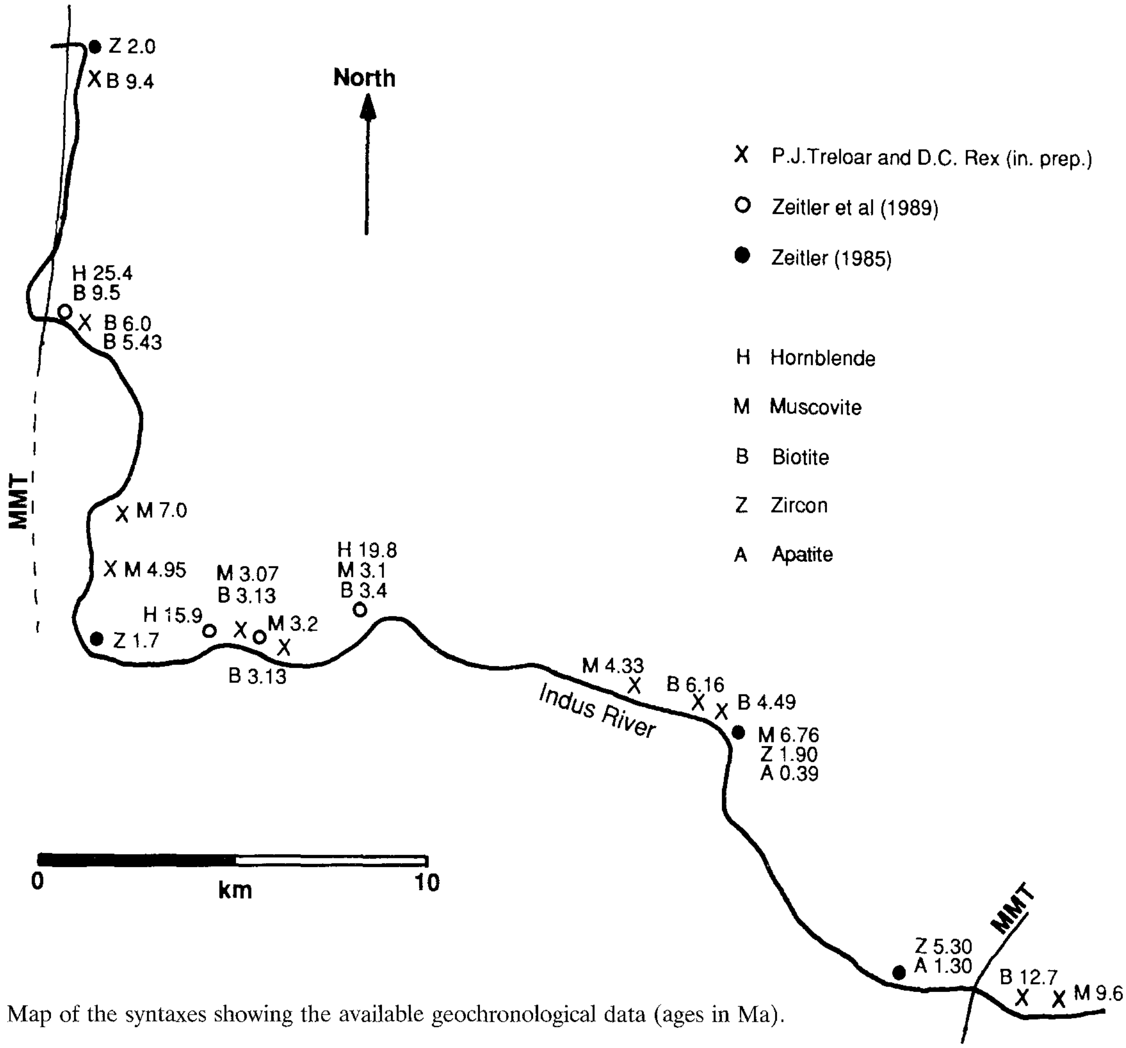

Fig. 10. Map of the syntaxes showing the available geochronological data (ages in Ma).

and western parts of the syntaxis is suggestive of differential uplift within the syntaxis. This could be explained by differences in the timing of growth of individual fold structures within the syntaxis, such as the Bulache Antiform.

d) Summary

The key structure within the Indus Gorge section through the syntaxis (Fig. 11) is the large north-plunging Bulache Antiform developed within the Shengus Gneiss. This structure, the largest of the north-trending folds, has a half wavelength of some 15 km and an estimated amplitude of 10 to 15 km, is a late structure which folds the regionally developed shear fabrics and is responsible for much of the localised uplift within the eastern half of the syntaxis.

The deformation-metamorphism history appears to be one of metamorphism, to upper amphibolite facies, along a path of increasing pressure followed by a period of intense shearing that discrupted the metamorphic pile and which involved the formation of the main phase foliations and lineations. This was followed by the folding of the foliation surfaces around the Bulache Antiform and other north trending folds. In many ways this is a similar chronology to that described to the southwest in the Hazara-Swat region where an early metamorphism synchronous with early ductile deformation, is post-dated by a period of crustal scale imbrication and stacking along ductile shear zones, the whole sequence being subsequently folded about large scale north plunging folds related to the growth of the Hazara syntaxis. If the Bulache antiform is unfolded it is clear that the Shengus Gneiss must structurally underlie the

Iskere gneiss, and that within the Shengus Gneiss sequence, the kyanite-bearing gneisses must structurally overlie the sillimanite-bearing gneisses (Fig. 11b). By analogy with the post-metamorphic re-imbrication of basement and cover in the Hazara region (Treloar et al., 1989c) this stacking of basement on top of its local cover, as well as the imbrication of island arc volcanics within Indian Plate paragneisses, should date from the period of post-metamorphic peak tectonic stacking and imbrication.

A further implication of the structural data is that none of the main ductile foliations or lineations within the core of the syntaxis are related to syntaxial development but are instead related to the thickening of the Indian plate under Kohistan. The only ductile fabrics and associated lineations associated with Nanga Parbat uplift are those developed within the Raikot-Sassi Fault Zone along the western margin.

Evolution of the Nanga Parbat syntaxis

On the basis of the structural and geochronological data a three phase evolution for the development of the syntaxis can be suggested. This evolution post-dates all the south-verging crustal stacking and thickening recorded within the core of the syntaxis by the ductile L-S fabrics.

The first uplift structures were ductile east-side up structures recorded within the Raikot-Sassi fault zone. These include early ductile movements within both the Liachar Thrust zone, and the Shahbatot Fault at Sassi (Fig. 12). Although early movement along these major ductile shear structures pre-dated 9 Ma it is not possible to say exactly when they initially became operative. However, the regional decrease in cooling ages across Kohistan suggests that the Nanga Parbat region may have already been one of a crustal scale arching prior to the initiation of thrusting (Treloar et al., 1989a). Movement along the western shears has been at least intermittently continuous since their initiation.

The disparity in ages between the eastern und western halves of the syntaxis dates the growth of the north-plunging fold developed within the Shengus Gneiss. As isotherms are essentially advected within the cores of rapidly growing large scale folds, cooling histories within them represent cooling that postdates folding and isotherm advection. Hence ages should be younger within the core of an antiformal fold than on its limbs. This is

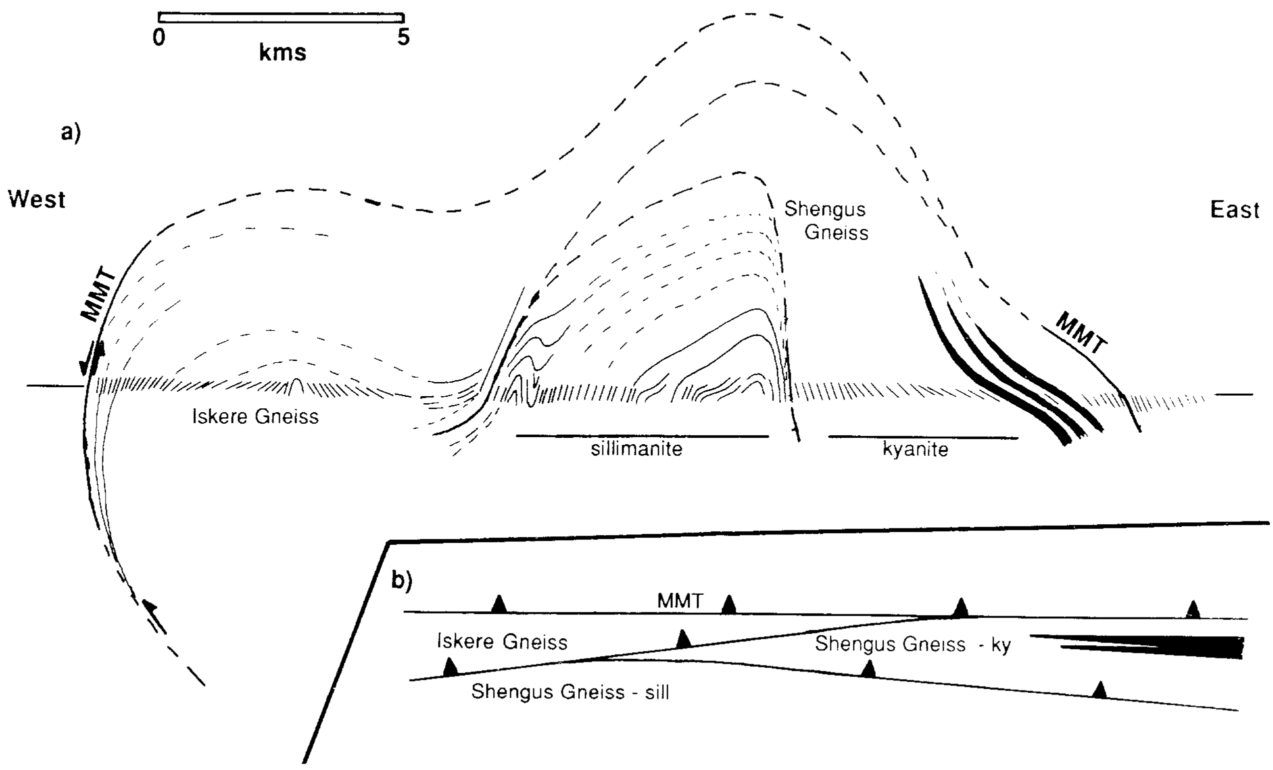

Fig. 11. Simplified cross section (down plunge projection) of the syntaxial structure derived from structural data collected along the Indus Gorge section. The inset shows a diagrammatic representation of the form of basement-cover imbrication that preceded the growth of the folds shown in the main section.

indeed the case within the Bulache Antiform, ages increasing outwards from the core towards its eastern limb and thus fold growth can be dated at about 4–5 Ma.

Subsequent to this, uplift transferred back onto the faults along the western margin. Zircon and apatite ages within the Raikot-Sassi Fault Zone and mica ages within the Iskere Gneiss date this uplift as commencing at about 3 Ma ago. The disparity in ages across the syntaxis, older in the east than the west, implies that the entire structure cannot have been uplifted passively within the hanging wall of the fault zone as simple advective cooling would have obliterated that disparity. Instead a degree of back rotation must have developed as the west side came up more rapidly than the east. During this period, deformation within the Raikot-Sassi Fault Zone became more brittle, with faulting in the north increasingly dominated by strike slip displacements.

Consequently we see a change in locus and style of uplift from dominantly northwest verging thrusting along the western margin prior to 10 Ma ago, through folding at about 5 Ma ago within the eastern half of the syntaxis, back to thrusting along the western margin at about 3 Ma together with a back rotation of the hanging wall rocks, with this thrusting becoming increasingly overprinted by dextral strike slip movement (Fig. 12). There is probably not a simple partitioning of deformation between thrusting and folding as, at stages, both may have operated together, although this analysis does suggest that thrusting and folding were dominant at different times. Although there is an apparently clear relationship between phases of folding and faulting along the Indus Gorge section, we would not wish to exclude the possibility of along strike variations especially in amplification rates, amounts and timing of fold growth and propagation. Considerable further fieldwork, allied to detailed geochronology, is required to establish over what scale the folding history may vary.

Total uplift within the syntaxis is hard to estimate given the problems of converting temperatures of cooling to depths within a geothermal gradient which reflects, in part at least, a tectonic advection of isotherms. ZEITLER (1985) calculated that uplift within the syntaxis has increased through the last 10 Ma to a present day rate of ca. 7 mm/year, with a total uplift over that time of > 8 km. Hornblende ages of 16 Ma from the Iskere Gneiss would suggest, for a geothermal gradient of 30–40°C/km, a total uplift within the syntaxis of no more than 14 ± 2 km since then. Although

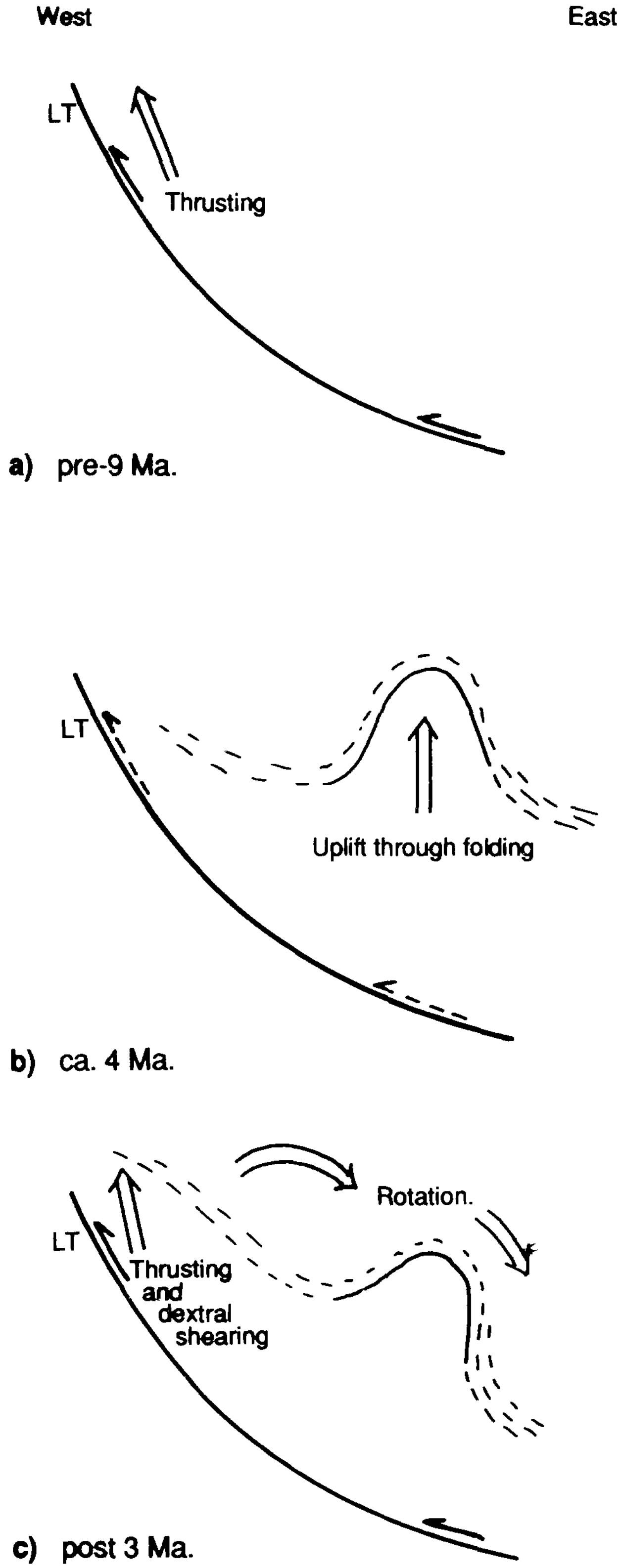

Fig. 12. Cartoons showing the three stages of syntaxial evolution. a) early (pre-9 Ma) thrusting on the western margin; b) later (ca. 4 Ma aged) folding within the core of the syntaxis; c) current dextral reverse faulting and thrusting on the western margin. LT – Liachar Thrust.

this gives a time-averaged uplift rate of ca. 1 cm/yr it is demonstrable that uplift rates have increased through time. Muscovite, zircon and apatite ages from within the Iskere Gneiss imply cooling of that sequence of ca. 350°C in 3 Ma, 200°C in 2 Ma and 120°C in 0.5 Ma. Even allowing for advection of isotherms and a consequent near surface steepening of the geothermal gradient this is consistent with increasing rates of uplift to the present day. How much of this uplift and associated exhumation is accommodated by folding and how much by oblique-slip faulting along the western margin is uncertain. Based on the offset of the Indus River across the Shahbatot Fault, MADIN et al. (1989) suggested a total Quaternary dextral displacement along the fault zone of 15 km. Given the oblique-slip nature of the fault zone, the plunge of the brittle slickensides would imply that the fault may accommodate up to 5 km of Quaternary uplift.

Regional controls of syntaxis growth

For the tectonic evolution of the NW Himalaya to be understood in detail, it is necessary that the tectonics of the syntaxes are also fully understood. The key to this problem lies in the recognition that the syntaxes lie in a zone of convergence marked by interference between the southwest-verging and southeast-striking thrusts of the main Himalayan chain and the south-southeast-verging and west-striking thrusts of north Pakistan (Fig. 13). The two thrust sequences cannot propagate indefinitely and how they interfere is the key to syntaxial growth.

Lineation data (BRUNEL, 1986) (Fig. 13) and fault plane solutions from seismic first motions on intermediate depth earthquakes (SEEBER et al., 1981) show an outward radial pattern of thrusting along the main Himalayan arc. KLOOTWIJK et al. (1985) have shown that this radial pattern is associated with both a decrease towards the west in the amount of displacement along the main Himalayan thrusts, and a westerly increase in Tertiary clockwise rotations. Such rotations would be consistent with the pinning of the main Himalayan thrusts at their western terminations. Similar rotations, although with an opposite anticlockwise sense, are recorded from the Potwar Plateau and Salt Range regions of the Pakistani thrust system to the east of the syntaxes (BURBANK & BECK, 1989).

Previous analyses of the Nanga Parbat fold (COWARD et al., 1986; BUTLER et al., 1989; MADIN et al., 1989) have suggested that it has grown

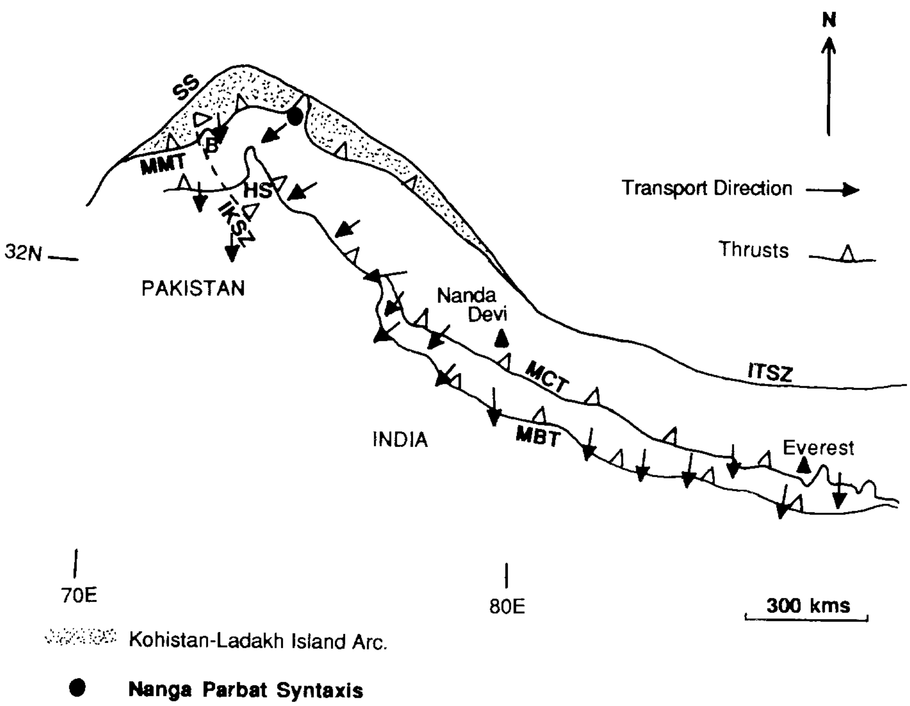

Fig. 13. Simplified structural map of the Himalayan arc showing the location of the northwestern syntaxes, the radial nature of the movement direction (after BRUNEL, 1986) that results in the thrust interferences in the northwestern part of the arc, and the location of the currently active Indus Kohistan Seismic Zone (IKSZ). MCT – Main Central Thrust; MBT – Main Boundary Thrust; SS – Shyok Suture; MMT – Main Mantle Thrust; B – Besham; HS – Hazara Syntaxis.

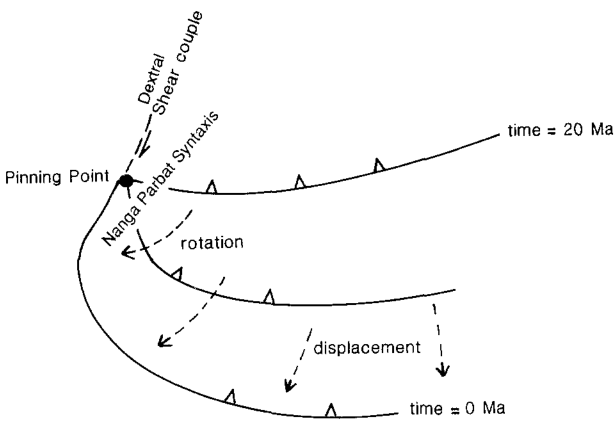

Fig. 14. Diagram showing the expected relationships between displacement amounts, rotations of movement direction, dextral shearing and crustal scale folding at the lateral teminations of the main Himalayan thrusts.

above the pinned lateral termination of a major Himalayan thrust, although not necessarily the Main Central Thrust. The most obvious predicted effects of this pinning are that strong local clockwise rotations should develop and that displacement amounts should increase to the east. This combination should generate both thrusting and strike-slip faulting. As a result of the local rotations, early thrusts should have a westerly or northwesterly vergence and the eastward increase in displacement amounts should generate a dextral shear couple near the pinning point (Fig. 14). Within the Nanga Parbat region this could result in the gradual overprinting of the marginal thrusts (i.e. the Liachar thrust) by dextral strike slip movements (i.e. the Shahbotat fault). Furthermore, the rotation of the shortening direction in the hanging wall (Fig. 14) would, if strain became distributed throughout the hanging wall rather than concentrated along the thrust, generate large scale antiformal folds such as are seen in the Nanga Parbat syntaxis. The combination of structures seen in the syntaxis would thus be consistent with deformation at the northwestern termination of a major Himalayan thrust currently cutting up through the south-southeast verging Pakistani thrust system. In other words, this reflects a reworking of early structures developed within the southeast-verging Pakistani thrust system by structures related to the main southwest-verging Himalayan thrusts.

By contrast, as a result of detailed structural analysis, BOSSART et al. (1988) showed that the Hazara syntaxis grew as a result of an anticlockwise rotation of thrust directions with a sinistral shear zone developed along the western margin of the syntaxis. Their interpretation implies that an early southwest-verging thrust stack, which forms part of the main Himalayan sequence and which contains internal evidence of earlier clockwise rotations (BOSSART et al., 1990), was reworked by a later south-verging set of thrusts which form part of the Pakistan thrust sequence (Fig. 15). This relationship between the two thrust sequences is the opposite to that seen in the Nanga Parbat syntaxis.

Although the Nanga Parbat syntaxis is continuing to uplift and evolve, there is evidence that a similar type of deformation is stepping southwestward. Earthquake fault plane solutions (SEEBER & ARMBRUSTER, 1979; JACKSON & YIELDING, 1983)

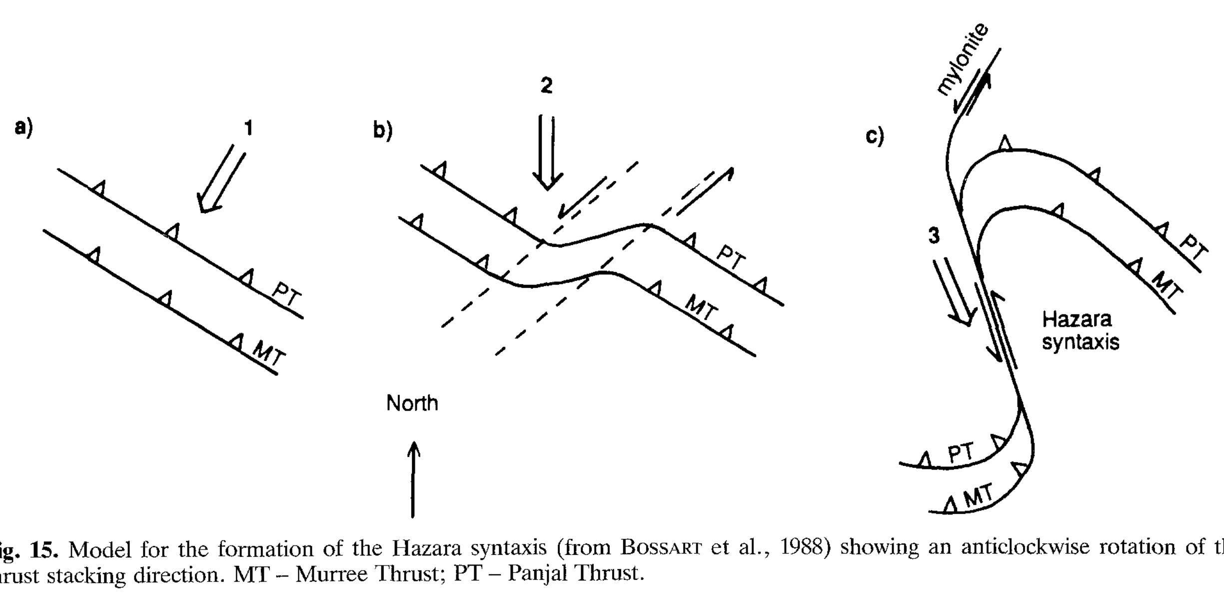

Fig. 15. Model for the formation of the Hazara syntaxis (from BOSSART et al., 1988) showing an anticlockwise rotation of the thrust stacking direction. MT – Murree Thrust; PT – Panjal Thrust.

document the presence of an active southwest-verging thrust, the Indus Kohistan Seismic Zone (Fig. 13), within the Swat-Hazara region. The Besham Antiform, within which apatite fission track ages (Zeitler, 1985) are younger than those in surrounding regions, has been interpreted (Treloar et al. 1989d) as a proto-syntaxis developing in the hanging wall of this structure which could represent a new thick skinned Himalayan thrust beginning to cut up through the south-verging Pakistani thrust stack.

The northwest Himalayan syntaxes thus represent a structural interference within a zone of convergence between two thrust systems. Different syntaxes represent different interference patterns. Some, such as Nanga Parbat and Besham, may represent essentially clockwise rotations with dextral strike slip marginal displacements as structures developed within the south-verging Pakistani thrusts stack are reworked by later structures that are part of the main southwest-verging Himalayan thrust system. Others, such as the Hazara syntaxis, may represent anticlockwise rotations with sinistral marginal displacements as south verging thrust movements rework earlier southwest verging thrusts stacks. Will one of these thrust directions ultimately become dominant? If so this may be the southwest-verging one which currently appears to be stepping farther to the southwest along structures such as the Indus Kohistan Seismic Zone.

Acknowledgements

Field work in Pakistan was supported by the UK Natural Environment Research Council, grant GR3/6113. Discussions with Rob Butler and Mike Coward are gratefully acknowledged.

References

Bhanot, V. B., Singh, V. P., Kansal, A. K. & Thakur, V. C. (1977): Early Proterozoic Rb-Sr whole rock age for the Central Crystalline Gneiss of the Higher Himalaya, Kumaun. – J. Geol. Soc. India, **18,** 90–91.

Bossart, P., Dietrich, D., Greco, A., Ottiger, R. & Ramsay, J. G. (1988): The tectonic structure of the Hazara-Kashmir Syntaxis, southern Himalayas, Pakistan. – Tectonics, **7,** 273–297.

–, Ottiger, R. & Heller, F. (1990): Rock magnetic properties and structural developments in the core of the Hazara-Kashmir Syntaxis, NE Pakistan. – Tectonics, **9,** 103–121.

Brunel, M. (1986): Ductile thrusting in the Himalayas: ductile thrusting and shear sense criteria. – Tectonics, **5,** 247–265.

Burbank, D. W. (1983): The chronology of intermontane basin development in the northwestern Himalaya and the evolution of the Northwest syntaxis. – Earth Planet. Sci. Letts., **64,** 77–92.

– & Beck, R. A. (1989): Early Pliocene uplift of the Salt Range; temporal constraints on thrust wedge development, northwest Himalaya, Pakistan. – Geol. Soc. Amer. Sp. Paper, **232,** 113–128.

Butler, R. W. H. & Prior, D. J. (1988a): Tectonics controls on the uplift of Nanga Parbat, Pakistan Himalayas. – Nature, **333,** 247–250.

– & Prior, D. J. (1988b): Anatomy of a continental subduction zone. – Geol. Rundschau, **77,** 239–255.

–, – & Knipe, R. J. (1989): Neotectonics of the Nanga Parbat syntaxis, Pakistan, and crustal stacking in the northwest Himalaya. – Earth Planet. Sci. Letts., **94,** 329–343.

Chamberlain, C. P., Zeitler, P. K. & Jan, M. Q. (1989a): The dynamics of the suture between the Kohistan island arc and the Indian Plate in the Himalaya of Pakistan. – J. Metamorphic. geol., **7,** 135–149.

–, Jan, M. Q. & Zeitler, P. K. (1989b): A pretrologic record of the collision between the Kohistan island arc and Indian plate, northwest Himalaya. – Geol. Soc. Amer. Sp. Paper, **232,** 23–32.

Coward, M. P. (1986): A section through the Nanga Parbat syntaxis, Indus valley, Kohistan. – Geol. Bull. Univ. Peshawar, **18,** 147–152.

– & Butler, R. W. H. (1985): Thrust tectonics and the deep structure of the Pakistan Himalaya. – Geology, **13,** 417–420.

–, Windley, B. F., Broughton, R. D., Luff, I. W., Petterson, M. G., Pudsey, C. J., Rex, D. C. & Khan, M. A. (1986): Collision tectonics in the NW Himalayas. – Geol. Soc. London. Sp. Publ., **19,** 203–219.

Duroy, Y., Farah, A. & Lillie, R. J. (1989): Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan. – Geol. Soc. Amer. Sp. Paper, **232,** 217–236.

Jackson, J. & Yielding, G. (1983): The seismicity of Kohistan, Pakistan: source studies of the Hamran (1972.9.3), Darel (1981.9.12) and Patan (1974.12.28) earthquakes. – Tectonophysics, **91,** 15–28.

Kazmi, A. H., Lawrence, R. D., Dawood, H., Snee, L. W. & Hussain, S. S. (1984): Geology of the Indus suture zone in the Mingora-Shangla area of Swat, N. Pakistan. – Geol. Bull. Univ. Peshawar., **17,** 127–144.

Klootwijk, C. T., Conaghan, P. J. & Powell, C. McA. (1985): The Himalayan arc; large scale continental subduction, oroclinal bending and backarc spreading. – Earth Planet. Sci. Lett., **75,** 167–183.

Lawrence, R. D. & Ghauri, A. A. K. (1983): Evidence of active faulting in Chilas district, northern Pakistan. – Geol. Bull. Univ. Peshawar, **16,** 185–186.

Le Fort, P., Debon, F. & Sonet, J. (1980): The Lesser Himalayan cordierite granite belt, typology and age of the pluton of Mansehra. – Pakistan. Geol. Bull. Univ. Peshawar, **13,** 51–62.

Madin, I. P., Lawrence, R. D. & Ur-Rehman, S. (1989): The northwestern Nanga Parbat – Haramosh massif: evidence for crustal uplift at the northwestern corner of the Indian craton. – Geol. Soc. Amer. Sp. Paper, **232,** 169–182.

OWEN, L. A. (1989): Neotectonics and glacial deformation in the Karakorum Mountains and Nanga Parbat Himalaya. – Tectonophysics, **163,** 227–265.

SEEBER, L. & ARMBRUSTER, J. G. (1979): Seismicity in the Hazara arc in northern Pakistan: decollement versus basement faulting. – In: Farah, A. and De Jong, K. (eds)., »Geodynamics of Pakistan«, Geol. Surv. Pakistan. Quetta., 131–142.

–, – & QUITTMEYER, R. C. (1981): Seismicity and continental subduction in the Himalayan arc. – Am. Geophys. Union. Geodyn. Ser., **5,** 215–242.

TRELOAR, P. J., REX, D. C., GUISE, P. G., COWARD, M. P., SEARLE, M. P., PETTERSON, M. G., WINDLEY, B. F., JAN, M. Q. & LUFF, I. W. (1989a): K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: constraints on the timing of collision, deformation, metamorphism and uplift. – Tectonics, **8,** 881–909.

–, COWARD, M. P., WILLIAMS, M. P. & KHAN, M. A. (1989b): Basement cover imbrication south of the Main Mantle Thrust, North Pakistan. – Geol. Soc. Amer. Sp. Paper, **232,** 137–152.

–, BROUGHTON, R. D., WILLIAMS, M. P., COWARD, M. P. & WINDLEY, B. F. (1989c): Deformation, metamorphism and imbrication of the Indian Plate south of the Main Mantle Thrust, North Pakistan. – J. Metamorphic Geol., **7,** 111–125.

–, WILLIAMS, M. P. & COWARD, M. P. (1989d): Metamorphism and crustal stacking in the north Indian Plate, North Pakistan. – Tectonophysics, **165,** 167–184.

–, BRODIE, K. H., COWARD, M. P., JAN, M. Q., KHAN, M. A., KNIPE, R. J., REX, D. C. & WILLIAMS, M. P. (1990): The evolution of the Kamila Shear Zone, Kohistan, Pakistan. – In: Salisbury, M. H. and Fountain, D. M. (eds). »Exposed sections through the deep crust«, Kluwer Academic Press, Amsterdam. NATO ASI Series C **317,** 175–214.

TRIVEDI, J. R., GOPALAN, K. & VALDIYA, K. S. (1984): Rb-Sr ages of granitic rocks within the Lesser Himalayan nappes, Kumaun, India. – J. Geol. Soc. India, **25,** 641–654.

VALDIYA, K. S. (1988): Tectonics and evolution of the central sector of the Himalaya. – Phil. Trans. Roy. Soc. London. Ser. A., **326,** 151–175.

VERPLANK, P. C., SNEE, L. W. & LUND, K. (1985): The boundary between the Nanga Parbat massif and Ladakh island arc terrane, northern Pakistan; a cross fault on the Main Mantle Thrust. – [abstract] EOS, **66,** 1074.

WADIA, D. N. (1931): The syntaxis of the northwest Himalaya: its rocks, tectonics and orogeny. – Rec. Geol. Surv. India, **65,** 189–220.

– (1932): Note on the geology of Nanga Parbat (Mt. Diamir) and adjoining portions of Chilas, Gilgit district, Kashmir. – Rec. Geol. Surv. India, **66,** 212–234.

ZEITLER, P. K. (1985): Cooling history of the NW Himalaya. – Tectonics, **4,** 127–151.

–, SUTTER, J. F., WILLIAMS, I. S., ZARTMAN, R. & TAHIRKELLI, R. A. K. (1989): Geochronology and temperature history of the Nanga Parbat – Haramosh massif, Pakistan. – Geol. Soc. Amer. Sp. Paper, **232,** 1–22.