

Structural evolution of the footwall of the Indus Suture in Malakand (N Pakistan) during the Himalayan collision

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Received 7 February 2005; accepted 21 July 2005

Abstract

We report new data on the geometry and kinematics of structures in the rocks of the Indian Plate below the Indus Suture in the area of Malakand (N Pakistan). The study area forms part of the exposed northwestern promontory of the Indian Plate indenting Eurasia to form the Himalayan orogenic belt. Earlier widespread structures (i.e. regional foliation and lineation) are consistent with an approximate N–S convergence direction, in coincidence with the movement direction of the Indian Plate. Younger structures, such as NNE trending open folds that laterally become syntaxes (i.e. Besham or Nanga-Parbat), and relatively minor E–W dextral strike-slip shear zones, are related to a regional tectonic shortening direction subparallel to the trend of the suture. These folds are radial to the northwestern corner of the Indian Plate and contemporaneous with the general bulk N–S convergence. It is only very recently in the structural record that the irregular outline of the Indian Plate played a role in determining the orientation of new structures during its indentation. The structural pattern presents similarities to arcuate megastructures in ancient collisional orogens, such as the Ibero-Armorican arc of the Variscan belt in Europe, where indentation tectonics, as well as post-orogenic oroclinal folding, are invoked to explain the present curvature.

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Keywords: Collisional tectonics; Arcuate megastructures; Himalaya; kinematics; Ibero-Armorican arc

1. Introduction

Arcuate megastructures are a common feature in active collisional orogens, such as the Alpine or the Himalayan Belt (e.g. Argand, 1916), and in ancient orogens, such as the Variscan-Appalachian Orogen (Matte and Ribeiro, 1975; Ries and Shackleton, 1976; Matte and Burg, 1981). They coincide with the irregular outlines of plate boundaries and are often related to significant differences in the mechanical behaviour of the plates in collision (e.g. Tapponnier et al., 1986; Vauchez et al., 1994). In

studying the structural evolution of present day orogens, we expect to gather ideas that may help to understand the tectonic evolution of their ancient equivalents. With this in mind, we have made structural observations in the area of Malakand, in N Pakistan (Fig. 1), where some rocks of the leading edge of the Indian Plate were deformed during the Kohistan Island Arc-India collision, and are now exposed below the main suture (i.e. Indus Suture). The main aspect of our contribution is to emphasise that earlier ductile structures, including widespread foliation and lineation, in addition to more localised deformation in shear zones separating rock units, indicate approximately N–S stretching and shearing, which contrasts with younger overprinting N–S trending upright folds, suggesting E–W shortening. This pattern of orthogonally overprinting structures has also been described in the inner part of Ibero-Armorican Arc (e.g. Julivert and Marcos, 1973), formed in a rather similar geodynamic setting. We discuss

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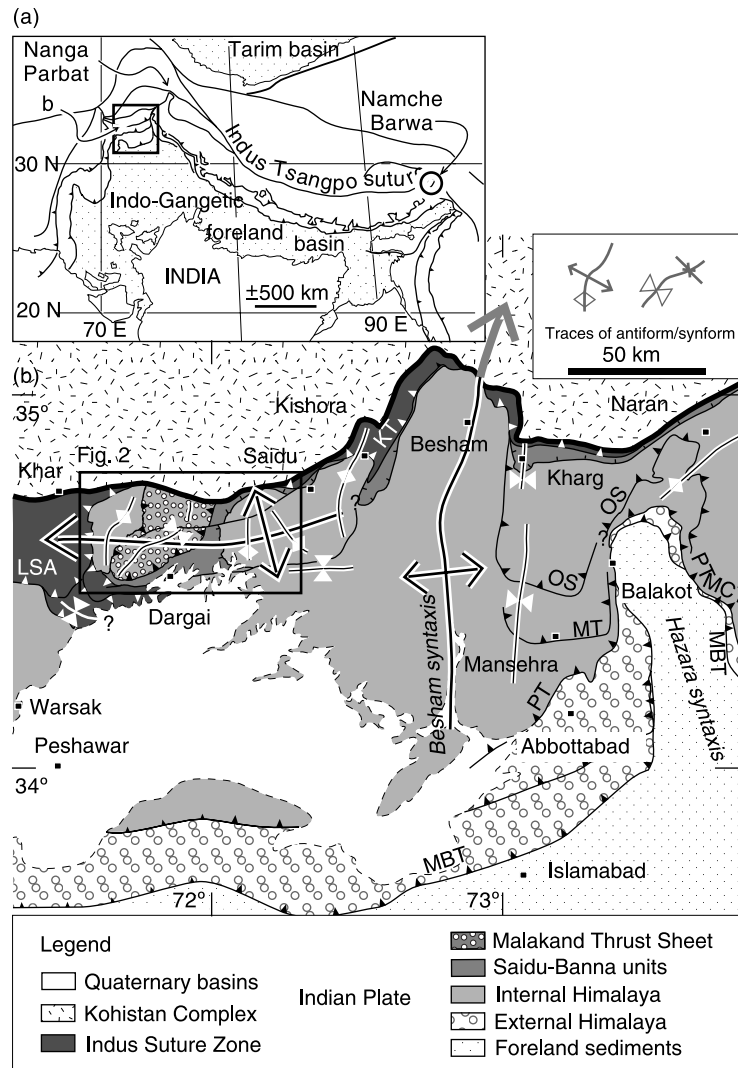


Fig. 1. Regional geological context of the study area in Lower Swat, N Pakistan. (a) shows the general tectonic setting in the Himalayan orogen (modified from Burg and Podladchikov, 1999). The synthetic tectonic map (b) is based on Coward et al., (1988) and DiPietro et al. (2000). LSA is the Lower Swat Antiform, MBT is the Main Boundary Thrust, MCT the Main Central Thrust, PT the Panjal Thrust, MT Manshera Thrust, OS the Oghi Shear and KT the Kishora Thrust.

the relationship between the kinematics of structures and the general and/or regional tectonics.

2. Tectonic evolution of the Indus Suture in N Pakistan

The Indus Suture in the Western Himalayas separates the Kohistan Island Arc to the north from the Indian Plate to the south (Gansser, 1964; Bard, 1983) (Fig. 1(a)). In Lower Swat, west of the Besham syntaxis (Fig. 1(b)), the suture is a north-dipping deformation zone (Bard, 1983; Coward et al., 1987; Lawrence et al., 1989; DiPietro et al., 2000). Its history is complex (see review in e.g. DiPietro et al., 2000). Blueschist facies metamorphism (Shams, 1972; Desio, 1977) in suture-related rocks, dated to the Late Cretaceous (70–90 Ma; Shams, 1980; Maluski and Matte, 1984; Anczkiewicz et al., 2000), indicate that it was a zone of subduction at that time, ceasing with the emplacement of

the Kohistan Island Arc onto the Indian Plate (Bard, 1983). Ongoing subduction and extensive deformation in the footwall led to the development of a pervasive tectonic fabric in amphibolite facies conditions in the pre-Tertiary basement rocks of the Indian Plate during the Eocene (Maluski and Matte, 1984; Treloar et al., 1989c; DiPietro, 1991; Chamberlain and Zeitler, 1996). This foliation is contemporaneous with high pressure metamorphism in rocks of Indian affinity (Tonarini et al., 1993). This episode of generalised deformation coincides with the 45–55 Ma decrease and later steady rate of northward motion of the Indian Plate towards Eurasia, as recorded in paleomagnetic anomalies in the Indian oceanic crust (Patriat and Achahe, 1984; Dewey et al., 1989; Treloar and Coward, 1991; Klootwijk et al., 1992). At the end of the Oligocene and the beginning of the Miocene (from 26 Ma on), extensional structures formed in the Himalayas and southern Tibet, still under general N–S plate convergence (Burg et al., 1984;

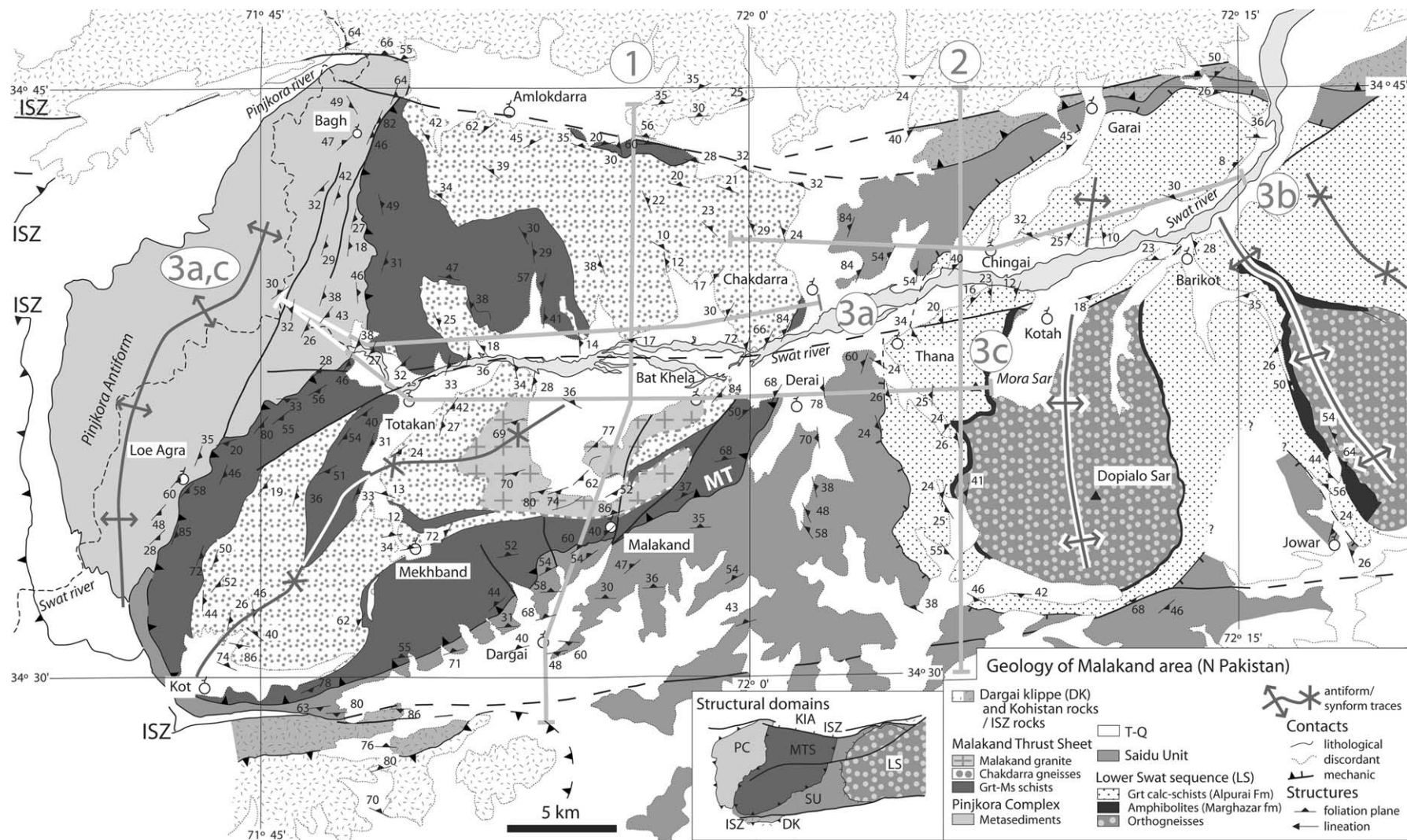


Fig. 2. Geological map of the Malakand area. The geology is based on detailed maps from Butt et al. (1980), Hussain et al. (1984), Ahmad and Lawrence (1992), Chaudhry and Ghazanfar (1993), in reviews by Chaudhry et al. (1997a,b), Kazmi and Jan (1997), Ghazanfar and Chaudhry (1999), DiPietro et al. (2000) and our own data. Next to the legend there is a sketch map showing the structural domains of the study area as they have been defined in the text: KIA is the Kohistan Island Arc, ISZ is the Indus Suture Zone, MTS is the Malakand Thrust Sheet, PC is the Pinjkora Complex, DK is the Dargai Klippe, LS is the Lower Swat sequence, MT is the Malakand Thrust and SU is the Saidu Unit.

Treloar et al., 1991; Burchfiel et al., 1992). These structures (e.g. the South-Tibetan Detachment, STD) allowed the extrusion of the High Himalayan rocks, while the Main Central Thrust (MCT) remained active at their base. In N Pakistan, the presence of the MCT is limited and arguable (Coward et al., 1988 Chaudhry and Ghazanfar, 1990; Chaudhry et al., 1997b; DiPietro et al., 1999); however, extensional structures in the Indus Suture Zone, denoting relative northward movement of the Kohistan Island Arc (KIA) after its emplacement on India, have already been described (Treloar et al., 1991; Burg et al., 1996; Vince and Treloar, 1996; Edwards et al., 2000). This movement, reworking the Indus Suture as a back-directed normal fault (i.e. a southerly directed major thrust reactivated as a normal fault downthrowing to the north), was active between 29 and 15 Ma (e.g. Anczkiewicz et al., 2001). It has been proposed that it was associated with the upward tectonic extrusion of a portion of the Indian Plate previously subducted under the KIA, facilitated by the simultaneous activity of the Panjal Thrust at the base (Chemenda et al., 1997; Anczkiewicz et al., 1998; Chemenda et al., 2000).

Zircon and apatite fission track ages indicate that no recordable differential cooling (i.e. vertical movement) across the Indus Suture has occurred since 20 Ma (Zeitler, 1985). However, the development of upright N–S trending folds, dextral strike-slip shear zones and faults in the Indian Plate, indicate that the region was not passively exhumed and uplifted.

3. Tectonic elements, stratigraphy and metamorphism

The rocks in the study area are subdivided into six tectonic units according to their composition and position in the tectonic pile (inset in Fig. 2). These subdivisions mostly follow the work of previous authors, but we indicate below in each subsection where this is not the case. The first three units: the Dargai Klippe, the Indus Suture Zone, and the Malakand Thrust Sheet (MTS), are composed of metamorphic rocks and are regarded as allochthonous thrust units. The other three: the Saidu Unit, the metamorphic rock sequence of Lower Swat, and the Pinjkora Complex, constitute the para-autochthonous (the Saidu Unit) and autochthonous parts of the thrust sheets, and belong to the Indian Plate.

Ultramafic rocks of the Dargai Klippe occupy the structurally uppermost position, immediately above the fault rocks of the Indus Suture. The suture rocks wrap around an antiform whose core exposes the other four units. Within it, the Malakand Thrust Sheet is the uppermost unit and constitutes a sheet thrust onto the Pinjkora Complex, also made of metamorphic rocks, and onto the lower grade rocks of the Saidu Unit. The sixth tectonic element is the pre-Tertiary metamorphic rock sequence of the Lower Swat, located beneath the Saidu Unit. We regard the Saidu Unit as para-autochthonous because of the difference in metamorphism and deformation from the overlying and underlying rock units, described below.

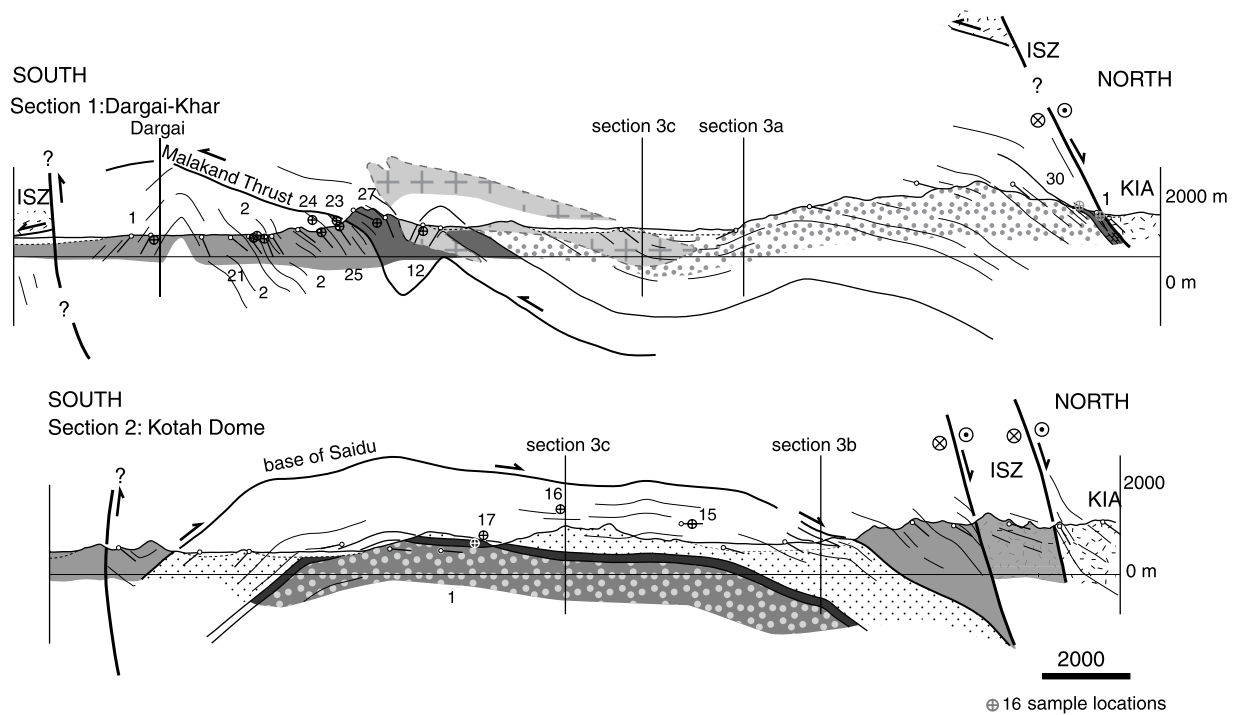


Fig. 3. South to north geological cross sections of the study area. Locations of the cross sections indicated in Fig. 2. The legend is the same as in the geological map in Fig. 2.

Our field observations extend from the Pinjkora River (W) to the town of Kotah on the bank of the Swat River (E) (Fig. 2). Our geological map, incorporates work from previous authors, which have been modified in places according to our own observations and information extracted from Landsat images. In the following sections, the geology of the Dargai Klippe and the fault rocks of the Indus Suture will be introduced briefly and extended the other four units, constituting the footwall of the suture.

3.1. The Dargai Klippe and the adjacent tectonites of the Indus Suture

The Dargai Klippe is a remnant of oceanic and mantle rocks emplaced on the Indian Plate (Tahirkheli et al., 1979). It is partially connected with the main trace of the Indus Suture, approximately 25 km to the north, around the western flank of the Pinjkora Antiform (Hussain et al., 1984; Lawrence et al., 1989). The ultramafic rocks have a steep compositional banding, defined by the orientation and relative abundance of pyroxene grains and pyroxenite dikes. To the north, talc-schists, derived tectonically from the ultramafic rocks, show a similar subvertical attitude.

Further north, the talc-schists are in contact with phyllonites, dipping steeply to the north. Phyllonitic units, mainly made of white mica, with less abundant sandstone layers show characteristic grey, green and purple colours. The strong deformation and their location between the ultramafic rocks and the underlying lower grade rocks to the north led us to interpret the ultramafic rocks as a klippe from the Indus Suture Zone (in agreement with Hussain et al., 1984). As seen on the geological map (Fig. 2) and in the cross sections (Fig. 3), both the ultramafics and the phyllonites are steeply dipping, a pattern likely to be related to subsequent folding and faulting, rather than to the original orientation of the thrust surface.

3.2. The Malakand thrust sheet (MTS)

The ‘Malakand slice’ is a thrust sheet originally defined by DiPietro et al. (2000). It includes amphibolite facies rocks to the west of Malakand, which are thrust along the Malakand Thrust (also Malakand Fault), over the lower grade rocks of the Saidu Unit (Fig. 2). The thrust, involving distributed deformation of both hanging- and footwall rocks, is outlined on the west by a band of quartzo-

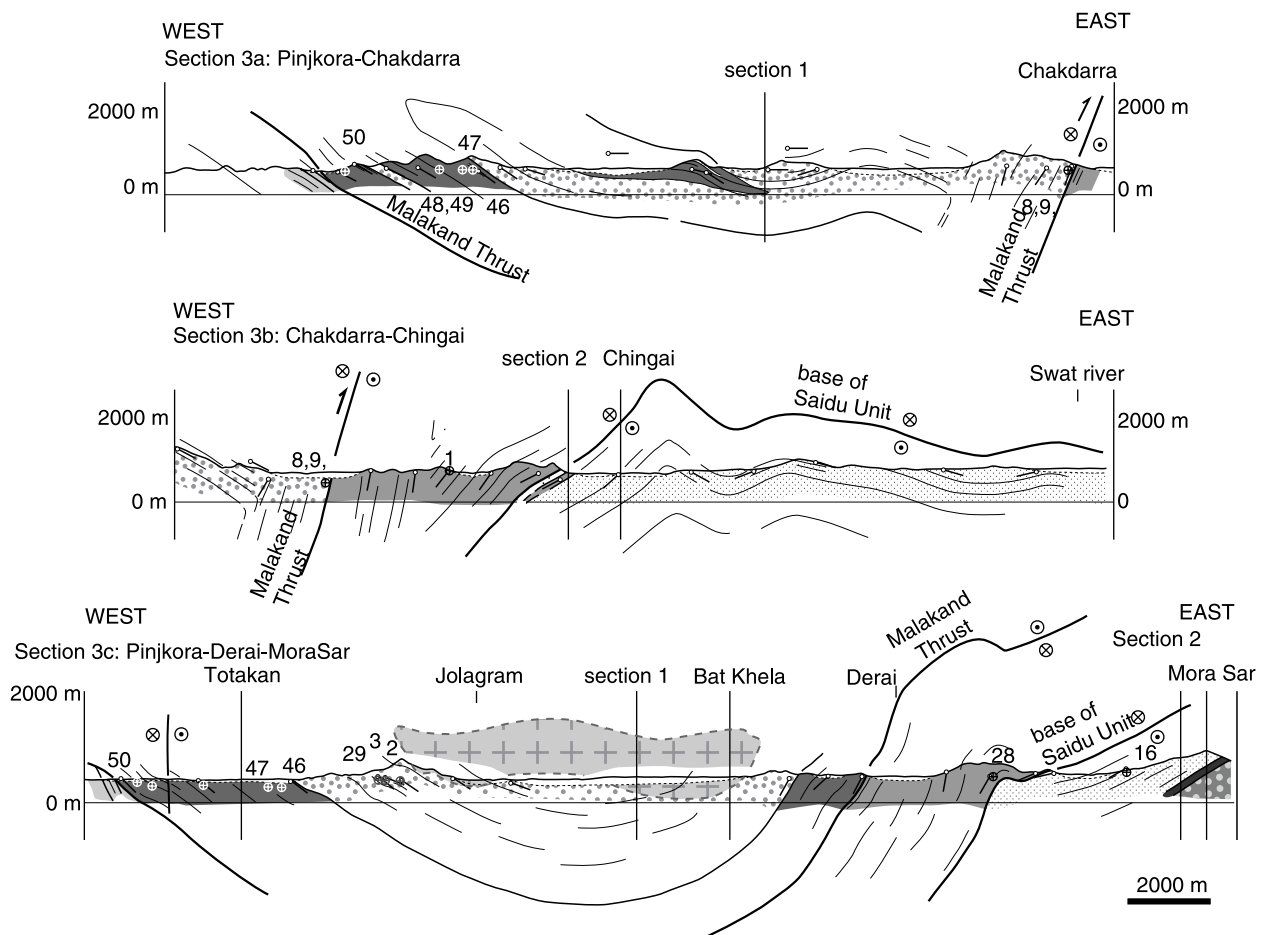


Fig. 4. West to east geological cross sections of the study area. Locations of the sections indicated in Fig. 2. The legend is the same as in the geological map in Fig. 2 and in Fig. 3.

feldspathic mylonites. In the proximity of the contact the foliation is parallel to the thrust on both sides, but on the map shows an angular discordance away from the thrust, also seen in the geological cross sections in Figs. 3 and 4. These structural observations do not support the interpretation of the Malakand thrust unit as it was initially interpreted by Di Pietro et al. (2000). We regard the rocks located further west (belonging here to the Pinjkora Complex), as a lower and separate tectonic unit to the ‘Malakand slice’.

The rocks of the MTS are comparable in lithology and metamorphism to the pre-Tertiary Lower Swat sequence located further to the east. However, no direct correlation has been made with them (DiPietro and Lawrence, 1991; DiPietro et al., 2000).

The lowermost lithological unit is comprised of garnet-rich schists, which alternate with carbonate-rich schists (commonly bearing garnet porphyroblasts), and thicker, metric-scale bands of impure marble (type localities are Totakan or Mekhband). Near the base of the unit, there are metric-scale layers of quartzite and, towards the structural top of the sequence, the rocks become more quartzofeldspathic and can be regarded as paragneisses. Scattered amphibolite layers are found within the metasediments. The metasediments show a well-developed foliation parallel to the lithological banding and parallel to the thrust zone at the base of the MTS. The schists contain garnet and biotite, which appear to be in equilibrium with the tectonic fabric, while in scattered amphibolites dark green amphibole defines the same foliation.

Above the schists are orthogneisses (at Chakdarra), composed mostly of quartz, K-feldspar (microcline), plagioclase and white mica. However, biotite-rich and amphibole-bearing granodioritic varieties are also found. A tectonic fabric is heterogeneously developed, from non-existent in the granodiorites (which are located in the middle of the main orthogneiss body), to well-developed in coarser grained rocks near the boundary of the orthogneiss to the north (e.g. in Amlokdarra), and strongly recrystallized in fine grained rocks, also in the outer parts of the gneiss body to the east (as in Chakdarra fort). At the lower contact, the orthogneisses interdigitate with the metasediments. Some lensoid laccoliths occur near this contact, isolated within the metasediments (Figs. 4 and 5(a)). The intrusive age from U–Pb in zircon grains of the orthogneiss is 278 ± 4 Ma (upper intercept, DiPietro and Isachsen, 2001). There are also U–Pb ages of 254–291 Ma from cores of zircons in the Malakand granite (Smith et al., 1994) that may be interpreted as having been derived from the host rocks, i.e. the orthogneisses. These Permian ages are in agreement with geochronological data from comparable Swat orthogneisses further to the east (Anczkiewicz et al., 2001).

The Malakand granite intruded both the metasediments and the orthogneisses (Figs. 2 and 3). It is a medium to coarse-grained granite showing no sign of ductile deformation (Maluski and Matte, 1984), although its outcrop is

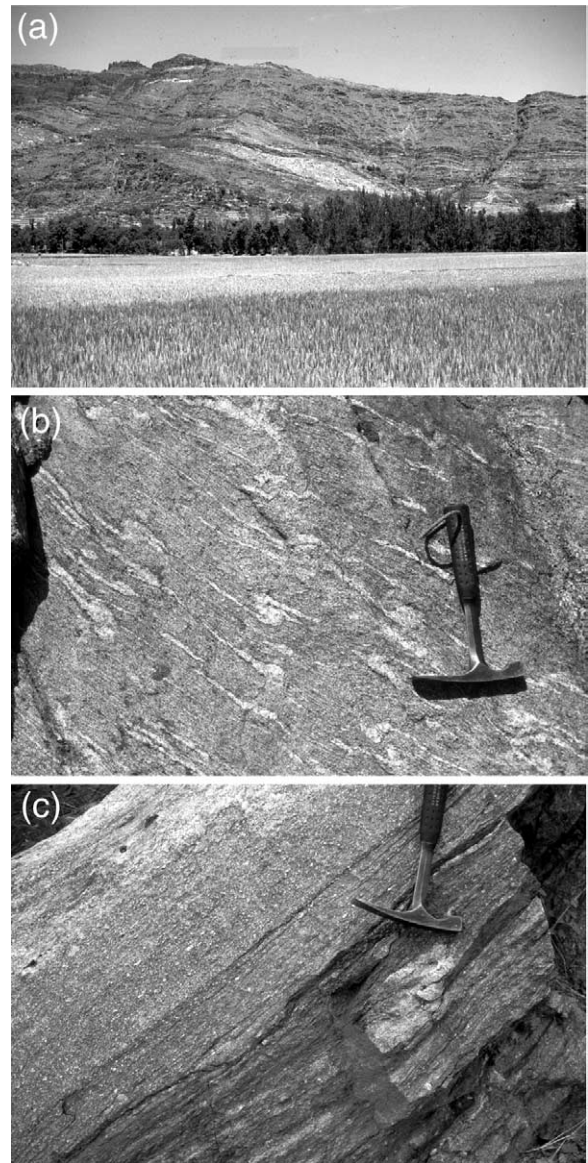


Fig. 5. Field appearance of some of the different lithological units described in the text: (a) deformed lensoid granitoid bodies of tens of meters in the upper part of the schists, below the contact with the Chakdarra orthogneiss, within the MTS; (b) migmatic gneisses forming part of the orthogneiss in the Dopialo Sar body; and (c) interlayered acid metavolcanics in the metasediments of the Pinjkora Complex. The hammer used as scale is 28 cm long.

slightly elongated parallel to the foliation of the host rocks (Fig. 2). The primary mineral assemblage is quartz, plagioclase, K-feldspar, muscovite and biotite with epidote, titanite, apatite, calcite, amphibole and opaques as common accessories (Hamidullah et al., 1986). It is spatially associated with fine-grained leucogranitic dikes that intrude the surrounding metasediments and orthogneisses. In places, dikes form dense networks or swarms rather than a single body, as shown in the map (the boundaries in the map (Fig. 2) and cross sections (Figs. 3 and 4) show the boundaries of these networks). As the granite is not seen

intruding the underlying rocks of the Saidu Unit, it is considered that its intrusion pre-dates the latest, most recent, thrusting episode of the MTS. Using $^{39}\text{Ar}/^{40}\text{Ar}$ techniques, the cooling age of the Malakand granite is approximately 23 Ma on muscovite (Maluski and Matte, 1984) and 24 Ma on biotite (Treloar et al., 1989c). Zircon and apatite fission track cooling ages are slightly younger, about 20 Ma (Zeitler et al., 1982). Using the U–Pb SHRIMP technique in zircon grains the intrusion of leucogranite dikes associated spatially with similar granites in other localities of Lower Swat is estimated to have occurred at 35 Ma (Zeitler and Chamberlain, 1991). Smith et al. (1994), obtained other U–Pb geochronological data from the Malakand granite indicating a range of core ages in zircons from 254–291 Ma with rims 47 ± 3 Ma. As already mentioned, the ages in the cores are very likely to indicate a component inherited from the host orthogneisses. The ages in the rims coincide with ages estimated for Himalayan metamorphism (Maluski and Matte, 1984; Treloar et al., 1989c; DiPietro, 1991; Chamberlain and Zeitler, 1996).

3.3. The Saidu Unit

This is a monotonous sedimentary sequence composed mainly of black and grey, often massive slates and phyllites,

containing millimetre to centimetre thick layers of carbonates and occasionally sandstones. Decametric marble layers to the north of the Swat river, East of Chingai (Fig. 2), have been reported previously (Ahmad and Lawrence, 1992). Metamorphism in these rocks is indicated only by the crystallization of white mica. The metamorphic grade is low enough to have preserved palynomorphs near Dargai (recognized by their shape, colour and their presence in areas rich in organic material: Sample mlk13 in Fig. 6(a)).

This lithological unit is sandwiched between the Malakand Thrust Sheet, above, and the pre-Tertiary metamorphic sequence of the Lower Swat below, both of which are of higher metamorphic grade (see upper cross section in Fig. 3). Elsewhere in N Pakistan these low grade rocks, comparable to the Banna Formation, are roofed by the Kishora Thrust, which corresponds to the base of the Indus Suture Zone (Treloar et al., 1989d; DiPietro et al., 2000). Although there is no evident tectonic contact with the underlying rocks, the difference in metamorphic grade suggests the omission of part of the metamorphic pile (Anczkiewicz et al., 1998). The same relationship with the underlying metamorphic rocks has been reported for the Banna Formation in Kharg, W of the Besham syntaxis (Treloar et al., 1989d; Vince and Treloar, 1996). These authors suggest that late normal faulting at the base of the

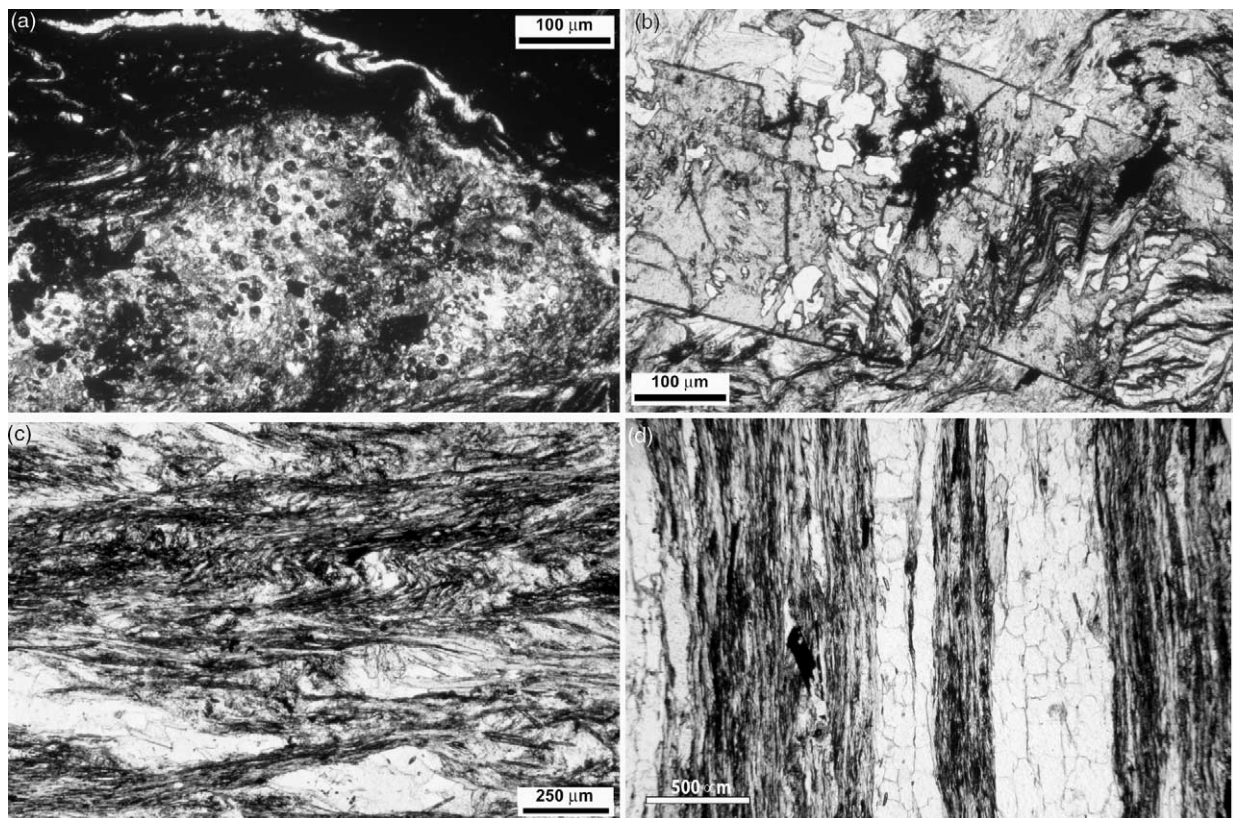


Fig. 6. Optical micrographs taken from the low-grade sediments of the saidu Unit (all in parallel polars): (a) shows likely remnants of palynomorphs in black shales; (b) illustrates the preservation of crenulation fabrics in white mica by the growth of porphyroblasts; (c) shows the crenulation cleavage observed in black shales and phyllites; and (d) a domainal foliation in the proximities of the Malakand Thrust is defined by the alternation of mica rich bands and quartz rich microlithons.

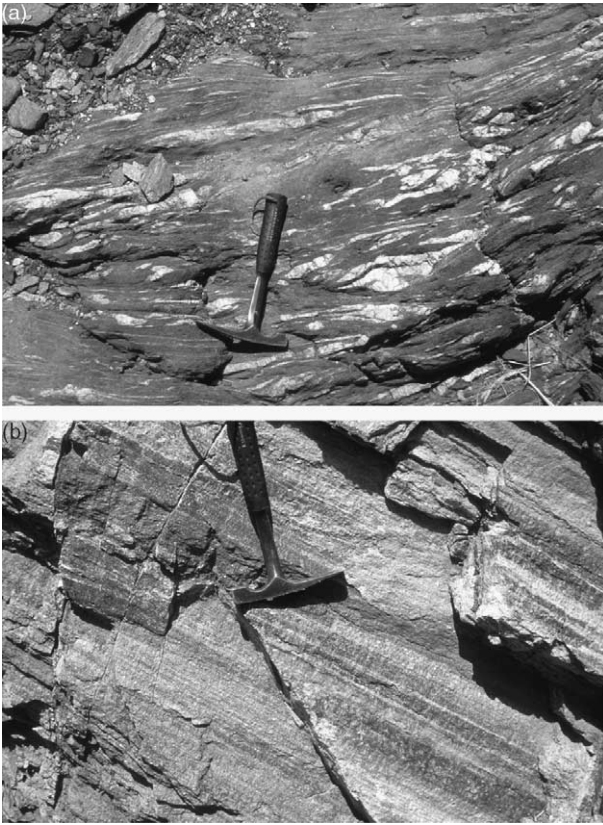


Fig. 7. Contrasting deformation features in tectonites at the base the MTS. (a) extensive precipitation of quartz veins within the phyllites from the Saidu Unit to the north of the Dargai Klippe (see Fig. 2 and cross sections in Fig. 3). (b) the well lineated mylonites developed near the thrust contact with the underlying rocks of the Pinjkora Complex. The hammer used as scale is 28 cm long.

Banna Formation placed low-grade rocks directly over higher grade rocks (Treloar et al., 1991; Vince and Treloar, 1996).

The structural and metamorphic features of the Saidu Unit where it is in contact with the MTS vary, as they are overprinted by shearing along the Malakand Thrust. Deformation associated with the initially 'ductile' thrusting has three major effects (Fig. 6). One is an apparent increase in metamorphic grade in the footwall, with the growth of white mica and pale green amphibole close to the thrust, and syn- to post-kinematic growth of chloritoid porphyroblasts containing microfolds (Fig. 6(b)). The second effect is the development of a tectonic banding composed of alternating quartz-rich and mica-rich layers (Fig. 6(c) and (d)). The third effect is pervasive quartz veining in the schists close to the shear zone, also evident in the contact with the Indus Suture Zone to the south of the study area (Fig. 7(a)).

3.4. Pre-Tertiary rock sequence of Lower Swat

Below the Saidu Unit in Malakand there are three lithostratigraphic units metamorphosed and deformed in the amphibolite facies, belonging to the pre-Tertiary Lower Swat sequence. They have been intensively studied in

surrounding regions by earlier authors (Lawrence et al., 1989; DiPietro, 1991; Pogue et al., 1992a; Pogue et al., 1992b; DiPietro et al., 1993; Chaudhry et al., 1997a; Kazmi and Jan, 1997; DiPietro et al., 1999; Ghazanfar and Chaudhry, 1999; Pogue et al., 1999). The orthogneisses, structurally at the base of the succession, are correlated with the Swat gneisses (Pogue et al., 1992a; Chaudhry et al., 1997a; DiPietro et al., 2000). They are characterised by centimetric K-feldspar porphyroclasts, in contrast with the finer grained orthogneiss in Chakdarra. Some migmatic textures affecting fine-grained gneisses are seen in the core of the mapped body (Fig. 5(b)). No age determinations are available for this particular body; however, a ca. 265 Ma intrusion age using U–Pb on zircons has been estimated in the Ilam augen gneiss located a few kilometres to the E, in the same structural and possibly the same stratigraphic position (Anczkiewicz et al., 2001; DiPietro and Isachsen, 2001).

Metasedimentary rocks rest on top of the orthogneisses. Amphibolite layers at the base are followed upwards by schists. Although the thickness of the amphibolites is variable, ranging from a few metres to tens of metres, the amphibolites are traceable at regional scale and are known as the Marghazar Formation (DiPietro, 1991). In other parts of the Swat the base is regarded as discordant over older, most likely Proterozoic rocks (DiPietro et al., 1993). The schists constitute a rather monotonous sequence made up predominantly of calcareous and garnet-bearing schists, relatively rich in centimetre to several tens of metres thick carbonate layers (type locality Thana), known also as the Alpurai Schists (Anczkiewicz et al., 1998) or the Kashala Formation (DiPietro, 1991). In the abundance of garnet porphyroblasts and the high carbonate content this unit resembles the metasediments seen in the MTS. The calculated pressure and temperature conditions in the Alpurai Schists during the main metamorphism are $625^{\circ}\text{C} \pm 50^{\circ}\text{C}$ and $0.7\text{--}1.1\text{ GPa}$ (Treloar et al., 1989b) and in the underlying Marghazar Formation are $630^{\circ}\text{C} \pm 43^{\circ}\text{C}$ and $1.03 \pm 0.15\text{ GPa}$ (DiPietro, 1991). Estimates from the same authors are higher for the underlying rocks further east in the Lower Swat, reaching up to $\sim 740^{\circ}\text{C}$ and 1.1 GPa . According to DiPietro et al. (1999), there is an equivalent rock unit to the south of Jowar of lower metamorphic grade, where Late Triassic conodonts have been reported (Pogue et al., 1992b). The same authors interpret these amphibolite facies rocks to be in continuity with the lower grade Nikanai Ghar and Saidu Formations (DiPietro et al., 1993; DiPietro et al., 1999).

Dikes of leucogranite, resembling the dikes spatially related to the Malakand granite, intrude the metamorphic rocks. They were dated at 35 Ma using U–Pb on zircons (Zeitler and Chamberlain, 1991).

3.5. The Pinjkora Complex

In the study area the structurally lowermost rocks appear in the core of the Pinjkora Antiform. Outcrops extend along

the river Swat and the river Pinjkora (also referred to as Panjkora), a tributary of the Swat. The sequence is composed predominantly of metasediments with some interlayered metavolcanites (Fig. 5(c)) and minor granite intrusions. In this survey, field observations were made in the structurally upper part of the sequence next to the contact with the overlying Malakand Thrust Sheet. In this part of the sequence, micaceous schists alternate with quartzitic schists and quartzites, although some metre-thick marble layers, decimetre to metre-thick amphibolites and black pelites are also found. Some of the amphibolites form boudins of decimetre size, surrounded by the tectonic foliation of the quartzo-feldspathic gneisses. However, the most outstanding feature is the frequent interlayering of quartzo-feldspathic gneisses (of probable volcanic or volcano-detritic origin) with metasediments, either metasandstones or schists (Fig. 5(c)). In most cases, the leucocratic gneisses are fine-grained and contain millimetre size K-feldspars and greyish-bluish quartz grains. They may represent meta-rhyolites.

The metasediments and the gneisses were metamorphosed in the amphibolite facies, as indicated by the appearance of garnet and biotite in schists and amphibolite. The major difference with the overlying metasediments is the abundance of amphibolite layers and black pelites. According to U–Pb dating in zircon grains in some of the metasediments, the sequence is dominantly of Early Proterozoic age (DiPietro and Isachsen, 2001); however these authors do not preclude the possibility that these ages were obtained from reworked grains.

4. Structure

We have identified six deformational structures. The regional foliation is pervasive and associated with the widespread ‘peak’ metamorphism. The remaining five structures overprint the regional foliation, but are relatively discrete structures. They are: the mechanical contact at the base of the Saidu Unit, the Malakand Thrust, the Lower Swat Antiform, the upright N-trending folds and the late strike-slip overprinting associated with the suture zone.

4.1. Distributed deformation within the tectonic units: regional foliation and lineation

A tectonic fabric is present in the four footwall units. In the MTS, the Lower Swat sequence and the Pinjkora Complex the main foliation is parallel to the compositional banding. This foliation is defined by mineral assemblages such as biotite and garnet in pelites and dark green amphibole in basic rocks, which indicate that deformation occurred during amphibolite facies metamorphism. Estimates of pressure and temperature in the lowermost units of the Lower Swat sequence reach 600–700 °C and 0.9–1.1 GPa (DiPietro, 1991). A stretching lineation is in general weakly developed, being defined either by the elongation of deformed polycrystalline aggregates of quartz and feldspar in coarse-grained gneisses, by the elongation of pressure shadows nucleated from garnet porphyroblasts in schists (Fig. 8(a)), or by the

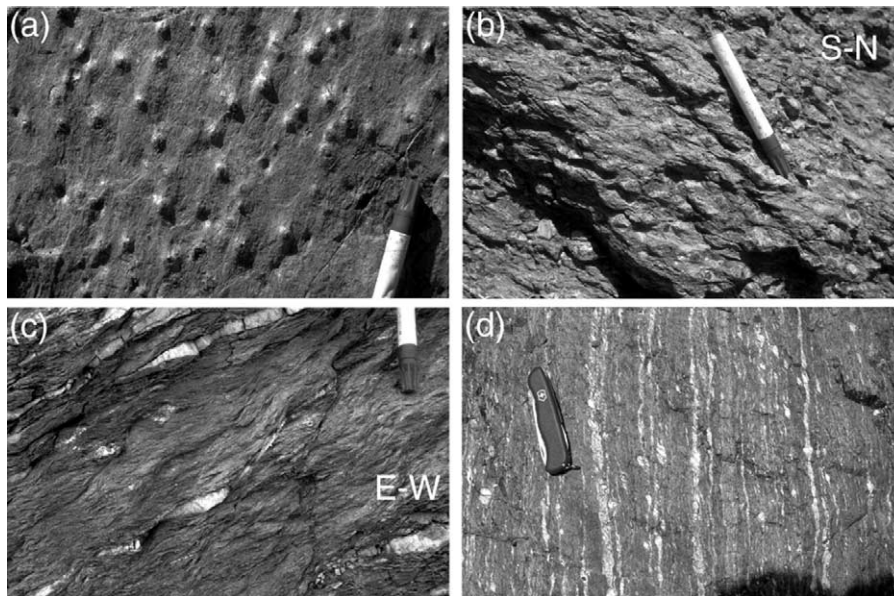


Fig. 8. Field photographs of kinematic criteria used in this work. (a) is lineation defined by elongated pressure shadows around garnet porphyroblasts in the foliation plane of garnet schists (within the MTS). (b) are the asymmetric pressure shadows and shear bands nucleated around garnet porphyroblasts indicating top-to-the-north sense of shear in the metasediments of the Lower Swat sequence. (c) the extensive shear bands developed in schists from the upper part of Pinjkora Antiform are interpreted to form as a consequence of the thrusting of the MTS. (d) kinematic criteria indicating dextral sense of shear in the metabasic rocks from the Indus Suture zone in the surroundings of Amlokdarra, a few metres away from the Indian Plate rocks. The pen and knife that are used as scales are approximately 15 and 10 cm long respectively.

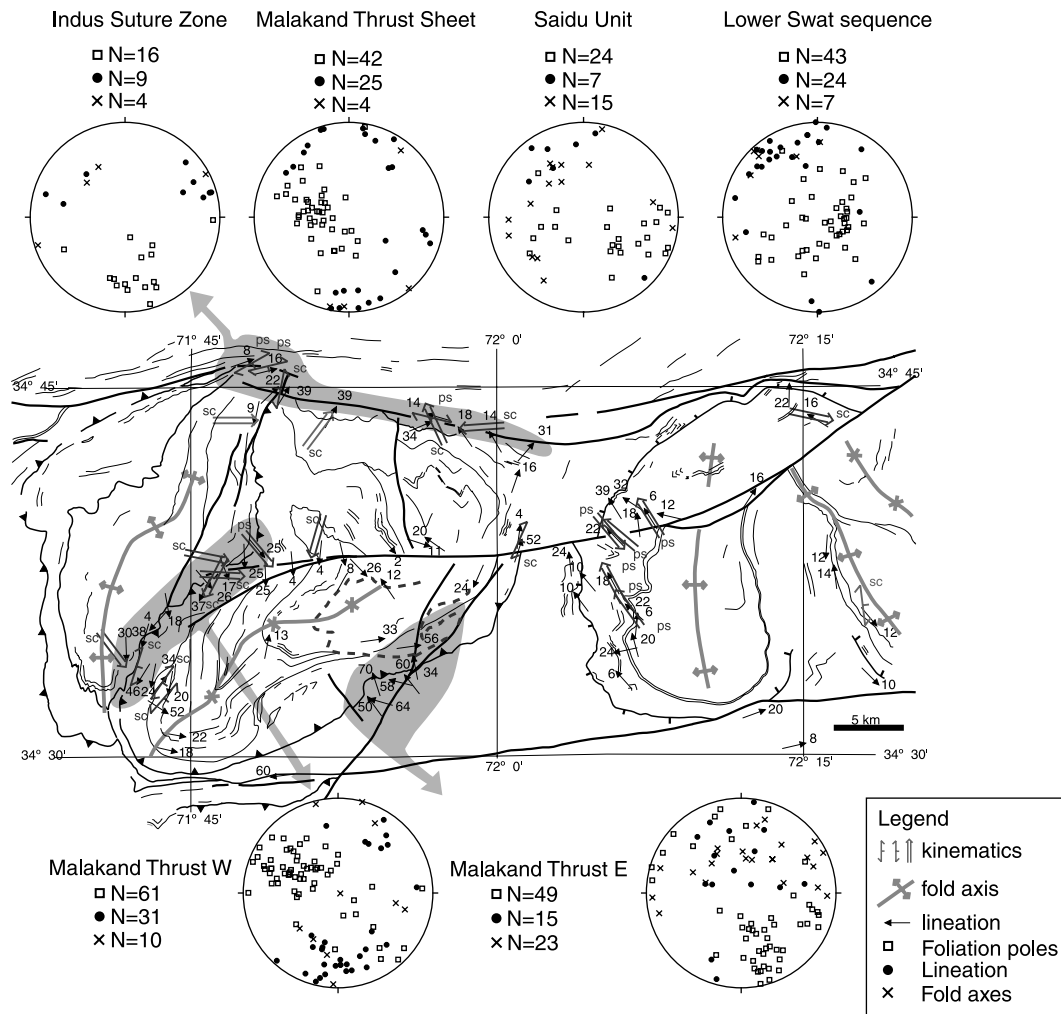


Fig. 9. Trend and distribution of kinematic criteria in the study area. The stereoplots show the foliation poles, lineation data and fold axes from the structural domains defined in the text and shown in the inset in Fig. 2, with the addition of the Malakand Thrust as a separate plot (data were recorded along the road from Dargai to Malakand on the eastern outcrop of the deformation zone and include observations in the Saidu Unit and the overlying garnet schists).

slight stretching of grains and porphyroblasts in paragneisses. Elongated minerals, such as the amphibole in the amphibolites, have a similar orientation to the stretching lineation. This lineation trends NNW in the MTS and the Lower Swat sequence (Fig. 9).

In contrast, the foliation in the Saidu Unit is defined by very small micas (hundreds of microns), which indicates a much lower metamorphic grade, and the concentration of opaque minerals (Fig. 6(c)). This fabric is oblique to bedding and crenulated by microfolds that eventually generate a tectonic banding near the Malakand Thrust (Fig. 6(d)). The stretching lineation is even weaker in these rocks, in which the intersection between bedding and the crenulation cleavage is usually dominant (and therefore has a different kinematic significance). This intersection lineation clusters broadly about a NNW direction (Fig. 9).

Foliation traces within the Saidu Unit become parallel to the thrust in the vicinity of the Malakand Thrust. The geological map suggests that the same relationship occurs

near the lower contact with the Lower Swat rocks (see the contact south of Thana in Fig. 2).

Garnet porphyroblasts in both allochthonous and autochthonous metamorphic rocks have an internal foliation, which is often curved and shows discontinuity with the external foliation (Treloar et al., 1989b; DiPietro and Lawrence, 1991). This internal fabric, which has not been investigated in the present work, may represent an earlier evolutionary stage of the external main foliation.

4.2. The base of the Saidu Unit and roof of the Lower Swat sequence

Fine grained phyllites, strongly crenulated in thin section, follow the base of the Saidu Unit in tectonic contact with the Lower Swat sequence (Fig. 6(c)). There is no evidence of cross-cutting relationships at the contact, as the foliation and crenulation in the hanging and footwall are sub-parallel; presumably the crenulation was formed in

relation to this contact. The difference in metamorphic grade between the underlying amphibolite facies and the hanging wall greenschists facies rocks, and the difference in deformation style suggest that a tectonic contact separates the two units (as noted further E by Anczkiewicz et al., 1998). This interpretation agrees at the regional scale with the observations made at the base of the Banna Formation, comparable with the Saidu Unit not only in lithology but also in its low metamorphic grade (Coward et al., 1988; Treloar et al., 1989a; Treloar et al., 1991; Vince and Treloar, 1996; Anczkiewicz et al., 1998). Note, however, that this contrasts with DiPietro and co-worker's interpretation (1993, 1999) who regard the rock sequence between Lower Swat and the Saidu Unit as continuous.

In the footwall and away from the contact, asymmetric pressure shadows on garnet porphyroblasts, widespread in the schists, indicate top-to-the-north sense of shear (Fig. 8(b)).

4.3. The Malakand Thrust

The foliation within the Malakand Thrust Sheet (MTS) is parallel to its base. Both foliation and the thrust are folded by a northeast trending synform (Fig. 9). On the eastern limb of this fold, the Malakand Thrust (MT on Fig. 2) defined by DiPietro et al. (2000) as the Malakand Fault separates the MTS from the overriding Saidu Unit. On the western limb, the Saidu Unit is absent and the MTS rest directly on rocks of the Pinjkora Complex. Here, the foliation in the Pinjkora Complex is parallel to the ductile thrust, marked by a band of quartzo-feldspathic mylonites.

Above the Saidu Unit, the contact is rather sharp but lacks clear kinematic criteria (see stereoplots in Fig. 9). Deformation affects several tens of metres of schists and is associated with grain size reduction and quartz veining. In the Pinjkora Complex, the contact is less discrete and the associated deformation band widens to include several tens of metres of hanging- and footwall rocks. In these rocks, asymmetric pressure shadows on garnet porphyroblasts and shear bands in schist layers (Fig. 8(c)) indicate south-eastwards sense of shear (see their distribution in map in Fig. 9).

4.4. The Lower Swat antiform

As shown in Fig. 1(b) the E–W antiform in Lower Swat extends for about 60–80 km parallel to the Indus Suture and has a half-wavelength of about 20 km. If we use the base of the thrust sheets of the tectonites in the suture zone as a reference surface, the core of the antiform extends from the Pinjkora River to Kishora. To the south it is followed by a synform, which is occupied in the west by tectonic slices from the suture and by a klippe of ultramafic rocks, the Dargai Klippe (Fig. 1(b)), and to the east, by Mesozoic rocks (see plate 1 in DiPietro et al., 1999).

The shared limb between the antiform-synform pair is partially faulted. Some minor faults have been reported in

the area around Jowar (Ahmad et al., 1987a; Ahmad et al., 1987b). There are no reliable markers to estimate the offsets of the faults, which may not exceed hundreds of meters. However, these faults coincide with a change in structural style, with predominant N–S trending folds to the north and E–W trending folds to the south. The predicted trace of the major fault in Fig. 2, connecting the geology around Jowar with the Dargai Klippe, also coincides approximately with a major pre-Himalayan fault responsible for changes in thicknesses and units in the pre-Mesozoic rock sequence (DiPietro et al., 1993).

4.5. North trending upright open folds

Further to the east, open upright folds that trend N–S on average in the Lower Swat are part of a regional suite that includes the Besham, Hazara and Nanga Parbat syntaxes, superimposed over all previous structures. With the exception of the large syntaxes (e.g. Nanga Parbat) and perhaps the Pinjkora Antiform, they seem to affect only Indian Plate rocks. In Malakand, the folds have a half-wavelength and an amplitude of several kilometres (Figs. 4 and 9) and affect Indian rocks within the Lower Swat antiform. Further south, folds trend E–W (Ahmad et al., 1987b; Ahmad and DiPietro, 2000).

The Pinjkora Antiform constitutes the westernmost of these N-trending folds in the study area (Fig. 2). In contrast to other folds of the same size in Lower Swat (see DiPietro et al., 2000), it does seem to bend the Indus Suture slightly.

4.6. The Indus Suture and its associated structures

The boundary between the Indian Plate and the Kohistan Island Arc, corresponding to the Indus Suture, puts the Pinjkora Complex in direct contact with rocks with Kohistan affinities, in their only exposed segment in the study area. The different tectonites, commonly associated with the suture zone and the remaining units in the tectonic pile seen in Indian domains, are absent. The high grade rocks in the hanging-wall (the Kamila Amphibolites of Tahirkheli, 1979) display a strong ductile fabric with a stretching lineation plunging 10° on average to the ENE (Fig. 9). The sense of shear inferred from asymmetric pressure shadows on feldspar 'clasts' (Fig. 8(d)) and shear bands in the surroundings of Amlokdarra (location in Fig. 2) indicate dextral strike-slip movement, which is consistent with the map deflection of several geological contacts north of the suture.

In outcrop, the faulted suture dips steeply to the north. Foliation deflections of a km scale reflected in the cross sections (Fig. 3), suggest at least two distinct offset components: dip-slip normal faulting and dextral strike-slip. Lineations plunging ENE at least 10° indicate an oblique offset, implying that the strike-slip overprint has an associated normal component. At this stage, we cannot evaluate if this normal component causes the deflection of

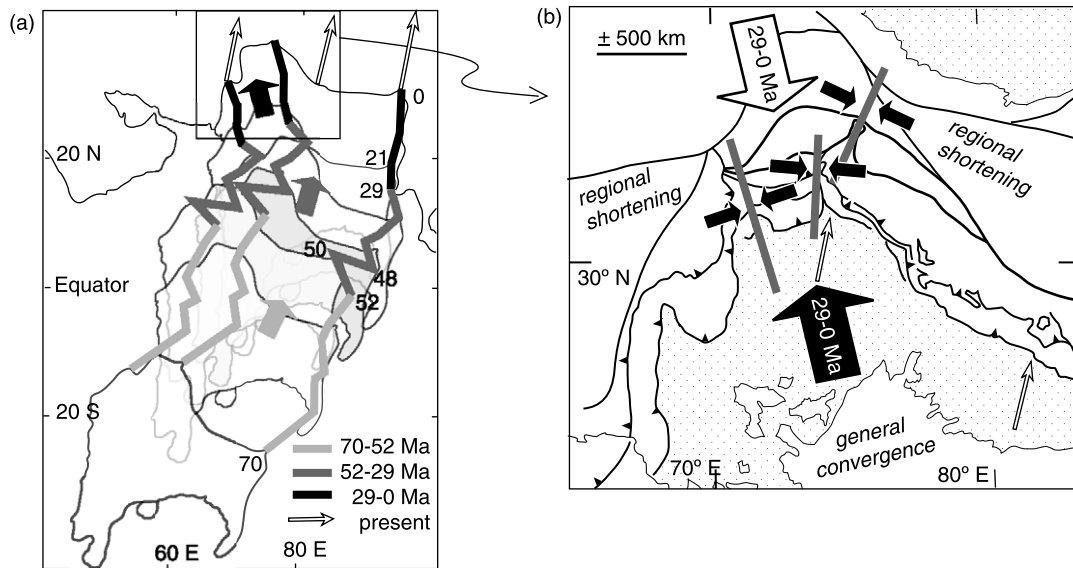


Fig. 10. (a) Summary of the movement path of the Indian Plate heading towards Eurasia, as recorded on paleomagnetic anomalies in the Indian Ocean. Fig. based on Patriat and Achache (1984) and Dewey et al. (1989). (b) Orientation of shortening directions in Western Himalaya inferred from plate convergence and from fold orientations. Present-day movement directions of Indian Plate are taken from De Mets et al. (1990).

geological markers that are seen in the N–S geological cross sections as well as in the map, or if it relates to a separate event.

On map view an unexposed fault is inferred to occur to the south of the suture, producing dextral offsets of the lithological contacts for hundreds of meters (see Figs. 2 and 9). This fault has similar characteristics to the faulted suture and may be an associated secondary structure. It runs along the Swat river valley and probably is responsible for the clockwise rotation of the synform affecting the MTS (see Fig. 9), as well as producing the bend in the Pinjkora Antiform as seen on the map (Fig. 2).

5. Discussion on the structural evolution during the collision

5.1. Structures formed during general N–S convergence

Structures that indicate tectonic transport in a N–S orientation have been ordered according to their overprinting relationships. We have also taken into consideration their metamorphic grade, their distribution in the study area and their relationships with neighbouring regions. The oldest structure is the regional foliation, which is widespread and bears a weak stretching lineation plunging on average to the NNW in all tectonic units in the footwall of the suture. Similar lineation patterns, in term of relative development and orientation, have been described from Malakand and neighbouring areas by other authors (King, 1964; DiPietro and Lawrence, 1991; Anczkiewicz et al., 1998; DiPietro et al., 2000) and are consistent with regional

trends on a larger scale (Maluski and Matte, 1984; Coward et al., 1986; Treloar et al., 1989b; Edwards et al., 2000).

In the Lower Swat sequence, peak PT conditions of the mineral assemblage in equilibrium with the foliation fall in the range 600–700 °C and 0.9–1.1 GPa (DiPietro, 1991). According to the field and preliminary petrographic observations, this may also be the case in the rocks from the Pinjkora Complex and the Malakand Thrust Sheet (MTS) (although further detailed work is required). The development of this pervasive fabric in Indian Plate rocks at a regional scale is constrained geochronologically by the peak high pressure metamorphism and by the intrusion of later undeformed leucogranites. In N Pakistan this is estimated to have occurred between 47 and 24 Ma. During this period of time, the movement path of the Indian Plate with respect to Eurasia averaged a northward direction; (Coward et al., 1988; Dewey et al., 1989) (Fig. 10(a)). Overall, the movement pattern is consistent with the orientation pattern in the stretching lineation associated with the regional foliation (Fig. 9). Thus, in agreement with previous authors, we suggest that this lineation indicates shearing and the tectonic transport direction during plate convergence.

The Malakand Thrust places high grade Himalayan rocks overriding lower grade ones (the Saidu Unit or equivalent Banna Units), which are the highest tectonic unit below the high pressure and low temperature rocks, and thus modifies the normal metamorphic sequence of tectonic units in the footwall of the Indus Suture. According to the emplacement sequence of thrusts established in other parts of N Pakistan, to the east of the Besham syntaxis, the Malakand Thrust represents a second generation thrust, or an out-of-sequence thrust (Coward et al., 1988; Treloar

et al., 1989b; Treloar et al., 1991). With the available data, the emplacement relationships between the MTS, the Dargai Klippe and the thrust sheets related to the suture itself (whether it cuts or it is been cut by them, both interpretation geometries are possible in cross sections in Fig. 3) are not clear.

In contrast to the observations of Lawrence and co-workers (Lawrence et al., 1989; DiPietro and Lawrence, 1991; DiPietro et al., 1993), in our study area we have no evidence of Indian rocks forming large northward plunging and westward verging recumbent folds, not in the MTS, the Lower Swat sequence, nor in the Pinjkora Complex. The evidence of these authors for such folds is restricted to the contact between the ‘Swat’ orthogneisses and the Marghazar Formation (the amphibolites), where fingers of orthogneiss within the Marghazar Formation and overlying schists led them to propose very ductile folding of the orthogneisses within the metasediments (see Fig. 5 in DiPietro et al., 1993). However, the foliation in the gneisses and schists does not bend around the supposed fold hinges. The contact may have been an intrusive one with primary digitations, as observed in the MTS along the contact of the Chakdarra orthogneisses with their host metasediments. There, ‘elongated inclusions’ of orthogneisses within the metasediments, do not correspond to folds, but to sills along layering which were boudinaged during subsequent regional deformation (see Fig. 5(a)).

We have already given indirect evidence of normal shearing with ductile deformation and tectonic transport towards the NNW related to the unroofing of the metamorphic sequence in Lower Swat. We infer that this shearing was associated with the northward movement of the Kohistan Complex, above (Burg et al., 1996), although it indirectly accommodates part of the exhumation and later emplacement of a slice of Indian Plate rocks in its footwall, now further south. At a later stage, it would have favoured the development of the gentle Lower Swat antiform. In the context of general N–S convergence this broad fold responded to the bending produced by the extrusion of a slice beneath it (Chemenda et al., 1997; Anczkiewicz et al., 1998).

5.2. Regional E–W shortening

Upright folds, trending on average N–S, and dextral strike-slip shear zones, oriented approximately E–W, deform the older structures (Fig. 1). In contrast to the earlier structures, they indicate overall E–W shortening (Fig. 10(b)). A dramatic change in the movement direction of India with respect to Asia can be ruled out as the cause of this change in shortening direction, as India’s wander path implies at most a 17° anticlockwise rotation since 27 Ma (Fig. 10, Dewey et al., 1989). The initial boundary conditions of the collision were determined by the irregular margins of the plates, related in the first place to the curved geometry of the plate boundaries in collision (McCaffrey

and Nabelek, 1998; Seeber and Pêcher, 1998). This initial geometry must have imposed an heterogeneous strain pattern (Houseman and England, 1993), which in N Pakistan was accommodated regionally by E–W shortening, contemporaneously with the general N–S convergence accommodated further south in the foreland-fold-and-thrust belt (Coward et al., 1986; McCaffrey and Nabelek, 1998; Seeber and Pêcher, 1998; Schneider et al., 1999).

Numerical models of the indentation of India suggest that there is significant crustal thickening at these particular locations, i.e. the Nanga Parbat and Namche Barwa syntaxes (Houseman and England, 1993). Using different approaches, two different mechanisms have been suggested to accommodate the thickening: buckling of the whole lithosphere, tested in two-dimensional finite-element models (Burg and Podladchikov, 1999), and widespread ductile deformation at the regional scale producing vertical thickening and extrusion (Butler et al., 2002) or pop-ups (Schneider et al., 1999). Note that these approaches are not incompatible, and that in these models, remarkably, regional shortening is at ca. 90° to general shortening, and to the plate convergence direction (Fig. 10(b)).

6. Remarks on the development of arcuate mega-structures

At this point, one may look back at ancient orogens for comparison with similar tectonic settings. Matte (1986, 1991) has already suggested similarities between the Western Himalayas and the Ibero-Armorican Arc (IAA) in the Variscan Belt of Europe. This orogen formed as a consequence of the collision between Gondwana and Laurentia (e.g. Martínez-Catalán et al., 1997). One of its most outstanding features is the IAA, produced by the indentation of the Gondwanan Iberian Plate into the microplates to the east of Laurentia, producing on map view a very similar looking tectonic pattern to the Himalaya (see fig. 11 in Matte, 1986). The presence of radial folds in the core of the arc, in rocks of the foreland fold-and-thrust belt of Northern Spain (Julivert and Marcos, 1973), indicated that local shortening direction was locally oriented at 90° to the plate convergence vector, from an E–W direction in present-day coordinates to a N–S orientation. An ongoing discussion concerning the development of this 180° orogenic arc is the possibility of separating the processes involved in its development, which occurred over a long period of time, from the Variscan collision itself, the subsequent opening of the Atlantic and finally Alpine deformation. The main problems are: when the arc started to develop; whether the collisional front was originally linear or slightly arcuate; and the extent to which different tectonic events contributed to the tightening of the arc. This has led to the suggestion that the stress regimes producing orthogonally overprinting structures were separate events

and correspond to different tectonic scenarios (Weil et al., 2001).

The present structural evolution of the Himalayan syntaxes as general orogenic features indicates to Burg et al. (1997) that buckling is the most probable mechanism to accommodate a local stress regime that may have a different orientation from the overall direction of convergence. If this were an intrinsic tectonic feature of the indentation of protruding continental plates, then one may expect that some of the radial folds and the rotation of thrust emplacement directions in the core of the IAA (Pérez-Estáun et al., 1988) are a consequence of the indentation in itself, and not strictly associated with different scenarios or later events.

7. Conclusions

The northwestern corner of the Indian Plate, defining an orogenic arcuate megastructure within the Himalayan belt, constitutes an outstanding region for the study indentation tectonics during continental collision. Despite the size restrictions of the studied area we have been able to report a sequence of structures that depicts reasonably well nearly every aspect and stage of the India–Eurasia collision, which in neighbouring areas is overprinted by the latest events. Since the stratigraphy was already well known, we focussed our work on field observations of deformational structures, in particular in their kinematics and orientation. The major conclusion from our observations and from the regional geology is that we were able to separate two major tectonic stages during the Himalayan collision in this region: a first stage in which structures indicate shearing and shortening consistent with bulk N–S convergence, and a second stage in which structures form in relation to E–W shortening. This simplifies slightly, and perhaps clarifies, some of earlier tectonic interpretations for the structural evolution of the area in which structures were not associated with any tectonic event during collision. In addition to these considerations of regional significance, some other observations have been made with respect to comparable geodynamic scenarios in ancient orogens where wander paths and geometry of plates in collision are not so well constrained as in the Himalayan case. Further work dealing with the causes of strain heterogeneity frequently associated with collisional settings in present-day orogens will certainly have an impact in unravelling the tectonic processes and their application in the understanding of similar scenarios in ancient orogens.

Acknowledgements

Postdoctoral stay of SL-F in ETH-Zürich was funded by the Spanish ‘Ministerio de Educación, Cultura y Deporte’. Financial support for the field campaign in the spring of 2001

was provided by ETH project 0-20884-01 and the Swiss National Science Foundation project 20-61465.00. S.S.H. and H.D. wish to thank the Pakistan Museum of Natural History in Islamabad; MNC wishes to thank Punjab University for providing financial assistance for the field work. We acknowledge Mr Danish Mand in Mingora for the logistic support in Malakand. O. Jagoutz provided very helpful assistance combining data sets in Landsat images. A previous version of the manuscript was reviewed by P. Treloar. We thank D. Faulkner and J. Mecklenburgh for feedback on their reviews. We also acknowledge constructive criticism by M. Edward and by the editor, A.J. Barber.

References

- Ahmad, I., DiPietro, J.A., 2000. Analysis of folds south of Malakand and adjoining areas, North Pakistan, 15th Himalaya–Karakorum–Tibet Workshop. China University of Geosciences Publishing House, Beijing, China pp. 72–73.
- Ahmad, I., Lawrence, R.D., 1992. Structure and metamorphism of the Chakdara area NW of Swat river, Pakistan. *Geological Bulletin of the University of Peshawar* 25, 95–112.
- Ahmad, I., Ghauri Arif, A.K., Majid, M., Rosenberg, P.S., Lawrence, R.D., 1987a. Lithostratigraphy of the Karakar Pass section, south of the Main Mantle Thrust, Swat, N.W. Pakistan. *Geological Bulletin of the University of Peshawar* 20, 199–208.
- Ahmad, I., Majid, M., Ghauri, A.A.K., Rosenberg, P.S., Lawrence, R.D., 1987b. Evidence of multiple deformation in the rocks of Karakar Pass area, Swat, N.W. Pakistan. *Geological Bulletin of the University of Peshawar* 20, 189–198.
- Anczkiewicz, R., Burg, J.P., Hussain, S.S., Dawood, H., Ghazanfar, M., Chaudhry, M.N., 1998. Stratigraphy and structure of the Indus Suture in the lower Swat, Pakistan, NW Himalaya. *Journal of Asian Earth Sciences* 16, 225–238.
- Anczkiewicz, R., Burg, J.P., Villa, I.M., Meier, M., 2000. Late Cretaceous blueschist metamorphism in the Indus suture zone, Shangla region, Pakistan Himalaya. *Tectonophysics* 324 (1–2), 111–134.
- Anczkiewicz, R., Oberli, F., Burg, J.P., Villa, I.M., Gunther, D., Meier, M., 2001. Timing of normal faulting along the Indus Suture in Pakistan Himalaya and a case of major 231Pa/235U initial disequilibrium in zircon. *Earth and Planetary Science Letters* 191 (1–2), 101–114.
- Argand, E., 1916. Sur l’Arc des Alpes occidentales. *Eclogae Geologicae Helveticae* 14, 145–191.
- Bard, J.P., 1983. Metamorphism of an obducted island arc; example of the Kohistan Sequence (Pakistan) in the Himalayan collided range. *Earth and Planetary Science Letters* 65 (1), 133–144.
- Burchfiel, B.C., Zhiliang, C., Hodges, K.V., Yuping, L., Royden, L.H., Changrong, D., Jiene, X., 1992. The South Tibetan Detachment System, Himalayan Orogen: extension contemporaneous with and parallel to shortening in a collisional mountain belt. *Geological Society of America Special Paper* 269, 1–41.
- Burg, J.P., Podladchikov, Y., 1999. Lithospheric scale folding: numerical modelling and application to the Himalayan syntaxes. *International Journal of Earth Sciences* 88, 190–200.
- Burg, J.P., Brunel, M., Gapais, D., Chen, G.M., Liu, G.H., 1984. Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China). *Journal of Structural Geology* 6 (5), 535–542.
- Burg, J.-P., Chaudhry, M.N., Ghazanfar, M., Anczkiewicz, R., Spencer, D., 1996. Structural evidence for back sliding of the Kohistan Arc in the collisional system of Northwest Pakistan. *Geology* 24 (8), 739–742.

- Burg, J.P., Davy, P., Nievergelt, P., Oberli, F., Seward, D., Diao, Z., Meier, M., 1997. Exhumation during crustal folding in the Namche-Barwa syntaxis. *Terra Nova* 9 (2), 53–56.
- Butler, R.W.H., Casey, M., Lloyd, G.E., Bond, C.E., McDade, P., Shipton, Z., Jones, R., 2002. Vertical stretching and crustal thickening at Nanga Parbat, Pakistan Himalaya: A model for distributed continental deformation during mountain building. *Tectonics* 21 (4), 9 (DOI 10.1029/2001TC901022).
- Butt, K.A., Chaudhry, M.N., Ashraf, M., 1980. An interpretation of petro-tectonic assemblage west of Western Himalayan Syntaxis in Dir District and adjoining areas in Northern Pakistan. *Geological Bulletin of the University of Peshawar* 13, 79–86.
- Chamberlain, C.P., Zeitler, P.K., 1996. Assembly of the crystalline terranes of the northwestern Himalaya and Karakoram, northwestern Pakistan. In: Yin, A., Harrison, T.M. (Eds.), *The Tectonic Evolution of Asia*. Cambridge University Press, pp. 138–148.
- Chaudhry, M.N., Ghazanfar, M., 1990. Position of the Main Central Thrust in the tectonic framework of western Himalaya. *Tectonophysics* 174 (3–4), 321–329.
- Chaudhry, M.N., Ghazanfar, M., 1993. Some tectonostratigraphic observations on Northwest Himalaya. *Pakistan Journal of Geology* 1 (2), 1–19.
- Chaudhry, M.N., Ghazanfar, M., Spencer, D.A., Hussain, S.S., Dawood, H., 1997a. The Higher Himalaya in Pakistan—a tectonostratigraphic synopsis. *Geological Bulletin of the Punjab University*, 21–41, see also pages 31–32.
- Chaudhry, M.N., Spencer, D.A., Ghazanfar, M., Hussain, S.S., Dawood, H., 1997b. The location of the main central thrust in the Northwest Himalaya of Pakistan: tectonic implications. *Geological Bulletin of the Punjab University*, 1–19, see also pages 31–32.
- Chemenda, A.I., Matte, P., Sokolov, V., 1997. A model of Paleozoic obduction and exhumation of high-pressure/low temperature rocks in the southern Urals. *Tectonophysics* 276 (1–4), 217–227.
- Chemenda, A.I., Burg, J.P., Mattauer, M., 2000. Evolutionary model of the Himalaya-Tibet system; geopoem based on new modelling, geological and geophysical data. *Earth and Planetary Science Letters* 174 (3–4), 397–409.
- Coward, M.P., Windley, B.F., Broughton, R.D., Luff, I.W., Petterson, M.G., Pudsey, C.J., Rex, D.C., Asif Khan, M., 1986. Collision tectonics in NW Himalaya. In: Coward, M.P., Ries, A.C., (Eds.), *Collision Tectonics*, vol. 19. Geological Society of London Special Publication, pp. 203–219.
- Coward, M.P., Butler, R.W.H., Khan, M.A., Knipe, R.J., 1987. The tectonic history of Kohistan and its implications for Himalayan structure (Pakistan). *Journal of the Geological Society of London* 144 (3), 377–391.
- Coward, M.P., Butler, R.W.H., Chambers, A.F., Graham, R.H., Izatt, C.N., Khan, M.A., Knipe, R.J., Prior, D.J., Treloar, P.J., Williams, M.P., 1988. Folding and imbrication of the Indian crust during Himalayan collision. In: Shackleton, R.M., Dewey, J.F., Windley, B.F. (Eds.), *Tectonic Evolution of the Himalayas and Tibet Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences*, vol. 326, pp. 89–116.
- De Mets, C., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. *Geophysical Journal International* 101, 425–478.
- Desio, A., 1977. The occurrence of blueschists between the middle Indus and the Swat valleys as an evidence of subduction in northern Pakistan. *Rendiconti Accademia Nazionale dei Lincei* 52, 1–9.
- Dewey, J.F., Cande, S., Pitman, W.C., 1989. Tectonic evolution of the India/Eurasia collision zone. *Eclogae Geologicae Helvetiae* 82, 717–734.
- DiPietro, J.A., 1991. Metamorphic pressure–temperature conditions of Indian Plate rocks south of the main mantle thrust, Lower Swat, Pakistan. *Tectonics* 10 (4), 742–757.
- DiPietro, J.A., Isachsen, C.E., 2001. U–Pb zircon ages from the Indian plate in northwest Pakistan and their significance to Himalayan and pre-Himalayan geologic history. *Tectonics* 20 (4), 510–525.
- DiPietro, J.A., Lawrence, R.D., 1991. Himalayan structure and metamorphism south of the Main Mantle Thrust, Lower Swat, Pakistan. *Journal of Metamorphic Geology* 9 (4), 481–495.
- DiPietro, J.A., Pogue, K.R., Lawrence, R.D., Baig, M.S., Hussain, A., Ahmad, I., 1993. Stratigraphy south of the Main Mantle Thrust, lower Swat, Pakistan. In: Treloar, P.J., Searle, M. (Eds.), *Himalayan Tectonics*. Geological Society Special Publication, 74, London, UK, pp. 207–220.
- DiPietro, J.A., Pogue, K.R., Hussain, A., Ahmad, I., 1999. Geologic map of the Indus syntaxis and surrounding area, northwest Himalaya, Pakistan. In: Macfarlane, A., Sorkhabi, R.B., Quade, J. (Eds.), *Himalaya and Tibet: Mountain Roots to Mountain Tops*. Geological Society of America Special Paper 328, Boulder, CO, United States, pp. 159–178.
- DiPietro, J.A., Hussain, A., Ahmad, I., Khan, M.A., 2000. The Main Mantle Thrust in Pakistan; its character and extent Tectonics of the Nanga Parbat syntaxis and the western Himalaya. *Geological Society of London Special Publication*, pp. 375–393.
- Edwards, M.A., Kidd, W.S.F., Asif Khan, M., Schneider, D.A., 2000. In: Asif Khan, M., Treloar, P.J., Searle, M.P., Jan, M.Q. (Eds.), *Tectonics of the SW Margin of the Nanga-Parbat Haramosh Massif Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya*, Geological Society of London Special Publication, 170, pp. 77–100.
- Gansser, A., 1964. *Geology of the Himalayas*. Regional Geology Series. Interscience Publishers, London, New York.
- Ghazanfar, M., Chaudhry, M.N., 1999. Northwest Himalaya – Anatomy of a Collisional Belt, Punjab University-UNESCO Regional Postgraduate Training Course in Plate Tectonics 1999. Institute of Geology, Punjab University, Lahore, Pakistan pp. 1–47.
- Hamidullah, S., Jabeen, N., Bilqees, R., Jamil, K., 1986. Geology and petrology of the Malakand granite, gneiss and metasedimentary complex. *Geological Bulletin of the University of Peshawar* 19, 61–76.
- Houseman, G., England, P.C., 1993. Crustal thickening versus lateral expulsion in the Indian-Asian continental collision. *Journal of Geophysical Research* 98 (B7), 12233–12249.
- Hussain, S.S., Khan, T., Dawood, H., Khan, I., 1984. A note on Kot-Prang Ghar Melange and associated mineral occurrences. *Geological Bulletin of the University of Peshawar* 17, 61–68.
- Julivert, M., Marcos, A., 1973. Superimposed folding under flexural conditions in the Cantabrian Zone (Hercynian Cordillera, northwest Spain). *American Journal of Science* 273 (5), 353–375.
- Kazmi, A.H., Jan, M.Q., 1997. *Geology and Tectonics of Pakistan*. Graphic Publishers, Karachi, Pakistan.
- King, B.H., 1964. *The Structure and Petrology of Part of Lower Swat, West Pakistan, with Special Reference to the Origin of the Granitic Gneisses*. PhD Thesis, University of London.
- Klootwijk, C.T., Gee, J.S., Peirce, J.W., Smith, G.M., McFadden, P.L., 1992. An early India–Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121. *Geology* 20, 395–398.
- Lawrence, R.D., Kazmi, A.H., Snee, L.W., 1989. *Geological Setting of the Emerald Deposits of Pakistan; Geology, Gemology and Genesis*. Elite Publications/Van Nostrand Reinhold Co., Karachi/New York, pp. 13–38.
- Maluski, H., Matte, P., 1984. Ages of Alpine tectonometamorphic events in the northwestern Himalaya (northern Pakistan) by $^{39}\text{Ar}/^{40}\text{Ar}$ method. *Tectonics* 3 (1), 1–18.
- Martínez-Catalán, J.R., Arenas, R., Arenas, R., Díaz García, F., Abati, J., 1997. Variscan accretionary complex of Northwest Iberia; terrane correlation and succession of tectonothermal events. *Geology* 25 (12), 1103–1106.
- Matte, P., 1986. Tectonics and plate tectonics model for the Variscan Belt of Europe. *Tectonophysics* 126, 329–374.
- Matte, P., 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics* 196, 309–337.

- Matte, P., Burg, J.P., 1981. Sutures, thrusts and nappes in the Variscan Arc of western Europe; plate tectonic implications. In: McClay, K.R., Price, N.J. (Eds.), *Thrust and Nappe Tectonics*. Geological Society of London Special Publication, pp. 353–358.
- Matte, P., Ribeiro, A., 1975. Forme et réorientation de l'ellipsoïde de déformation dans la virgation hercynienne de Galice. Relations avec le plissement et hypothèses sur la genèse de l'arc ibéroarmoricain. *Comptes Rendus Academie des Sciences Paris* 280, 2825–2828.
- McCaffrey, R., Nabelek, J., 1998. Role of oblique convergence in the active deformation of the Himalayas and southern Tibet plateau. *Geology* 26 (8), 691–694.
- Patriat, P., Achache, J., 1984. India–Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. *Nature* 311, 615–621.
- Pérez-Estáun, A., Bastida, F., Alonso, J.L., Marquínez, J., Aller, J., Álvarez-Marrón, J., Marcos, A., Pulgar, J.A., 1988. A thin-skinned tectonics model for an arcuate fold and thrust belt; the Cantabrian Zone (Variscan Ibero-Armoricain Arc). *Tectonics* 7 (3), 517–537.
- Pogue, K.R., DiPietro, J.A., Khan, S.R., Hughes, S.S., Dilles, J.H., Lawrence, R.D., 1992a. Late Paleozoic rifting in northern Pakistan. *Tectonics* 11 (4), 871–883.
- Pogue, K.R., Wardlaw, B.R., Harris, A.G., Hussain, A., 1992b. Paleozoic and Mesozoic stratigraphy of the Peshawar Basin, Pakistan; correlations and implications. *Geological Society of America Bulletin* 104 (8), 915–927.
- Pogue, K.R., Hylland, M.D., Yeats, R.S., Khattak, W.U., Hussain, A., 1999. Stratigraphic and structural framework of Himalayan foothills, northern Pakistan. In: Macfarlane, A., Sorkhabi, R.B., Quade, J. (Eds.), *Himalaya and Tibet: Mountain Roots to Mountain Tops* Geological Society of America Special Paper, vol. 328, pp. 257–274.
- Ries, A.C., Shackleton, R.M., 1976. Patterns of strain variation in arcuate fold belts. *Philosophical Transactions of the Royal Society of London A* 283, 281–288.
- Schneider, D.A., Edwards, M.A., Kidd, W.S.F., Asif Khan, M., Seeber, L., Zeitler, P.K., 1999. Tectonics of Nanga Parbat, western Himalaya; synkinematic plutonism within the doubly vergent shear zones of a crustal-scale pop-up structure. *Geology* 27 (11), 999–1002.
- Seeber, L., Pécher, A., 1998. Strain partitioning along the Himalayan arc and the Nanga Parbat antiform. *Geology* 26 (9), 791–794.
- Shams, F.A., 1972. Glaucofane-bearing rocks from near Topsis, Swat—First record from Pakistan. *Pakistan Journal of Scientific Research* 24, 343–345.
- Shams, F.A., 1980. Origin of the Shangla Blueschists, Swat Himalaya, Pakistan. *Geological Bulletin of the University of Peshawar* 13, 67–70.
- Smith, H.A., Chamberlain, C.P., Zeitler, P.K., 1994. Timing and duration of Himalayan metamorphism within the Indian Plate, Northwest Himalaya, Pakistan. *Journal of Geology* 102 (5), 493–508.
- Tahirikheli, R.A.K., 1979. Geology of Kohistan and adjoining Eurasian and Indo-Pakistan continents, Pakistan. *Geological Bulletin of University Peshawar* 11, 1–30.
- Tahirikheli, R.A.K., Mattauer, M., Proust, F., Tapponnier, P. (Eds.), 1979. *The India–Eurasia Suture Zone in Northern Pakistan: Synthesis and Interpretation of Recent Data at Plate Scale Geodynamics of Pakistan*, Geological Survey of Pakistan, pp. 125–130.
- Tapponnier, P., Pelzer, B., Armijo, R., 1986. On the mechanics of the collision between India and Asia. In: Coward, M.P., Ries, A.C. (Eds.), *Collision Tectonics*, vol. 19. Geological Society Special Publication, pp. 115–157.
- Tonarini, S., Villa, I.M., Oberli, F., Meier, M., Spencer, D., A., Pognante, U., Ramsay, J.G., 1993. Eocene age of eclogite metamorphism in Pakistan Himalaya; implications for India–Eurasia collision. *Terra Nova* 5 (1), 13–20.
- Treloar, P.J., Coward, M.P., 1991. Indian Plate motion and shape; constraints on the geometry of the Himalayan Orogen. In: Pérez-Estáun, A., Coward, M.P. (Eds.), *Deformation and Plate Tectonics* Tectonophysics, vol. 191, pp. 189–198.
- Treloar, P.J., Broughton, R.D., Williams, M.P., Coward, M.P., Windley, B.F., 1989a. Deformation, metamorphism and imbrication of the Indian Plate, south of the Main Mantle Thrust, North Pakistan. *Journal of Metamorphic Geology* 7, 111–125.
- Treloar, P.J., Coward, M.P., Williams, M.P., Khan, M.A., 1989b. Basement-cover imbrication south of the Main Mantle Thrust, North Pakistan. In: Malinconico, L.L.J., Lillie, R.J. (Eds.), *Tectonics of the Western Himalayas* Geological Society of America Special Paper, vol. 232, pp. 137–152.
- Treloar, P.J., Rex, D.C., Guise, P.G., Coward, M.P., Searle, M.P., Windley, B.F., Petterson, M.G., Jan, M.Q., Luff, I.W., 1989c. K–Ar and Ar–Ar geochronology of the Himalayan collision in NW Pakistan; constraints on the timing of suturing, deformation, metamorphism and uplift. *Tectonics* 8 (4), 881–909.
- Treloar, P.J., Williams, M.P., Coward, M.P., 1989d. Metamorphism and crustal stacking in the North Indian Plate, North Pakistan. *Tectonophysics* 165 (1–4), 167–184.
- Treloar, P.J., Rex, D.C., Williams, M.P., 1991. The role of erosion and extension in unroofing the Indian Plate thrust stack, Pakistan Himalaya. *Geological Magazine* 128 (5), 465–478.
- Vaucher, A., Tommasi, A., Egydio-Silva, M., 1994. Self-indentation of a heterogeneous continental lithosphere. *Geology* 22 (11), 967.
- Vince, K.J., Treloar, P.J., 1996. Miocene, north-vergent extensional displacements along the Main Mantle Thrust, NW Himalaya, Pakistan. *Journal of the Geological Society of London* 153 (5), 677–680.
- Weil, A.B., Van der Voo, R., van der Pluijm, B.A., 2001. Oroclinal bending and evidence against the Pangea megashear: The Cantabria-Asturias arc (northern Spain). *Geology* 29 (11), 991–994.
- Zeitler, P.K., 1985. Cooling history of the NW Himalaya, Pakistan. *Tectonics* 4 (1), 127–151.
- Zeitler, P.K., Chamberlain, C.P., 1991. Petrogenetic and tectonic significance of young leucogranites from the northwestern Himalaya, Pakistan. *Tectonics* 10 (4), 729–741.
- Zeitler, P.K., Tahirikheli, R.A.K., Naeser, C.W., Johnson, N.M., 1982. Unroofing history of a suture zone in the Himalaya of Pakistan by means of fission-track annealing ages. *Earth and Planetary Science Letters* 57 (1), 227–240.