Precollision tilt of crustal blocks in rifted island arcs: 
Structural evidence from the Kohistan Arc

Jean-Pierre Burg,1 Oliver Jagoutz,1,2 Hamid Dawood,3 and S. Shahid Hussain3

Received 16 April 2005; revised 9 June 2006; accepted 20 July 2006; published 7 October 2006.

[1] We describe results from field and microstructural investigations in the unusually large Chilas plutonic complex, which was emplaced within the Mesozoic Kohistan island arc (northern Pakistan). Magmatic and deformational fabrics of the Chilas gabbronorite are concordant with magmatic fabrics of associated gabbros, diorites, and tonalites and show that this reportedly huge intrusion is composed of juxtaposed plutonic bodies with predominantly SSW dipping flow structures over the northeastern part of the complex, which turn to SW-NE striking, subvertical attitudes to the west. Evidence for multiple intrusions includes concordant and discordant intrusive and/or mylonitic contacts between gabbronorites and associated rocks. Owing to structural and kinematic consistency, we attribute transitions from magmatic to more localized mylonitic fabrics to higher finite strain (and/or strain rate) produced from drag of magma against its margin. We discuss this structural pattern and conclude that the Chilas gabbronorite emplaced incrementally into generally south dipping listric faults that dominated arc extension about 85 Ma. In addition, several sets of hornblende pegmatite indicate that brittle deformation occurred in the presence of residual melt during consolidation of the main body. The latest pegmatitic set is composed of variably striking, vertical extensional veins that show no relationship to the magmatic fabric. We argue that the original attitude of these veins, along with that of the enclosing Chilas Complex, has been mostly preserved. We hypothesize that the northward dip of the southern side of the Kohistan is inherited from late Cretaceous rotation of crustal blocks in the hanging wall of the listric faults. Citation: Burg, J.-P., O. Jagoutz, H. Dawood, and S. S. Hussain (2006), Precollision tilt of crustal blocks in rifted island arcs: Structural evidence from the Kohistan Arc, Tectonics, 25, TC5005, doi:10.1029/2005TC001835.

1. Introduction

[2] The Kohistan Terrane in NE Pakistan (Figure 1) is regarded as a fossil island arc obducted between the collided Indian and Asian plates [Tahirkheli et al., 1979; Bard et al., 1980]. Owing to the quality of exposures, the Kohistan offers an unrivalled opportunity to investigate the structure of an island arc and related subduction processes [e.g., Bard, 1983b; Treloar et al., 1996]. In particular, numerous time markers in the form of intrusive bodies make the Kohistan an exceptional place to study the significance of magmatic structures in the deep crust of an arc system. [3] We present results from field-based studies and thin section observation within the gabbronoritic-ultramafic Chilas Complex, away from the tilted western limb of the crustal-scale Nanga Parbat antiform (Figure 1) [Butler et al., 1992]. Emphasis is placed on magmatic structures [Balk, 1937; Marre, 1982; Vernon, 2000] and pegmatite veins. Magmatic foliation and lineation suggest that the gabbronorite is an internally sheeted pluton with steeply dipping internal and external contacts. Regional analysis further suggests that it emplaced into a predominantly southwest dipping extensional zone with a dextral transtension zone to the west. We argue that this part of the Kohistan has preserved a near-original orientation since the emplacement of subvertical pegmatite veins that cut the flow-related structures during late brittle stages of magma consolidation. If this hypothesis is verified, the north dipping attitude of the southern Kohistan may reflect late Cretaceous tilting of southern (oceanward) parts of the Arc, a theoretically possible event on a south dipping, crustal-scale listric fault.

2. Kohistan Arc: Outline

[4] The Kohistan Arc originated during Jurassic Cretaceous times through north dipping subduction in the equatorial area of the Tethys Ocean [e.g., Yoshida et al., 1996; Zaman and Torii, 1999]. Three major units depict the gross organization of the arc complex. They are, from north to south (Figures 1 and 2):

[5] 1. The Kohistan Batholith, which is composed of numerous plutons and dikes of different age and chemistry originated over a time span of roughly 100 Ma [Pettersson and Windley, 1985, 1991]. Metasedimentary rocks (Yasin, Dir, and Jaglot groups) and metavolcanites (Chalt, Dras, Hunza and Shamran Volcanics) screen the younger plutons and unconformably cover some of the older magmatic units [Matsushita and Huzita, 1965; Pudsey, 1986; Khan et al., 1994; Pettersson and Treloar, 2004].
Figure 1. Sketch map of the Kohistan Arc, mostly based on original mapping and interpretation of multispectral Landsat 7 ETM+ satellite images. The Chilas Complex is restricted to gabbronorite, a lithological simplification that highlights the backbone location between the North Kohistan Batholith and the Southern Amphibolites. Bounding diorites and tonalites traditionally ascribed to the Chilas Complex and plutons of the Kohistan Batholith are being mapped in more detail.
2. The Chilas Complex is described as a >300 km long and up to 40 km thick mafic-ultramafic lopolith [Bard, 1983b; Khan et al., 1989, 1993]. It intruded at about 85 Ma [Zeitler et al., 1980; Schaltegger et al., 2002] and is attributed to within-arc extension, based on geochemical [Khan et al., 1989] and petrostructural evidence [Burg et al., 1998]. Crosscutting pegmatite dikes have a zircon U-Pb age of circa 83 Ma [Schaltegger et al., 2002]. Sm-Nd dating indicates cooling of the main gabbronorite below 600°C at about 70 Ma [Yamamoto and Nakamura, 1996; Ali et al., 2002]. The huge volume of the Chilas Complex, its location between two arc units with distinct tectonometamorphic histories and its association with arc rifting make it an important target for investigation. Our mapping, based on compositional differences recognized in the field and in thin sections and subsequent color differences on various channel combinations of satellite data, identified a multiple intrusion system, as previously envisaged by Jan and Howie [1980]. The Chilas Complex has intrusive contacts to the north with metasediments and metavolcanites (probably both belonging to the so-called Jaglot Group) and plutonic rocks (possibly belonging to the early magmatic phases of the Kohistan Batholith), and to the south with the southern amphibolites [Treloar et al., 1996; Searle et al., 1999].

3. Magmatic Structures in the Chilas Complex

3.1. Description

The gabbronorite is composed of plagioclase (labradorite to anorthite), clinopyroxene, orthopyroxene, accessory ilmenite, apatite and oxides and minor pargasitic hornblende rimming pyroxenes; the rock displays a predominantly granoblastic texture (grain size 1 to 5 mm). Euhedral to subhedral pyroxenes and plagioclase are locally preserved. Albite twinning within plagioclase is very common and typically parallel-sided; few tapered twins in cumulus crystals may reflect negligible deformation above the magma solidus, likely due to grain interaction at low melt fraction rather than superimposed regional strain (Figure 3). Lithological changes involve variable proportions of these main constituent minerals, olivine in ultramafic rocks and the occurrence of quartz and biotite in more evolved dioritic and tonalitic differentiates. Detailed petrography is given by Jan et al. [1984], and mineral chemistry is given by Khan et al. [1989].

The systematically north dipping attitude of foliations in the southern amphibolites and the bulk distribution of upper crustal rocks to the north of deeper crustal and mantle rocks has led to the conclusion that the whole Kohistan Arc Complex has been tilted by about 30° to the north during southward collision and obduction onto the Indian continent [Tahirkheli et al., 1979; Coward et al., 1982; Bard, 1983b; Coward et al., 1986]. We will question this interpretation and argue that obduction and subsequent arc-continent collision did not produce wholesale tilting of the Kohistan Arc.

3. Magmatic Structures in the Chilas Complex

3.1. Description

The gabbronorite is composed of plagioclase (labradorite to anorthite), clinopyroxene, orthopyroxene, accessory ilmenite, apatite and oxides and minor pargasitic hornblende rimming pyroxenes; the rock displays a predominantly granoblastic texture (grain size 1 to 5 mm). Euhedral to subhedral pyroxenes and plagioclase are locally preserved. Albite twinning within plagioclase is very common and typically parallel-sided; few tapered twins in cumulus crystals may reflect negligible deformation above the magma solidus, likely due to grain interaction at low melt fraction rather than superimposed regional strain (Figure 3). Lithological changes involve variable proportions of these main constituent minerals, olivine in ultramafic rocks and the occurrence of quartz and biotite in more evolved dioritic and tonalitic differentiates. Detailed petrography is given by Jan et al. [1984], and mineral chemistry is given by Khan et al. [1989].

The main gabbronorite displays a spectrum of fabrics ranging from primary igneous to secondary metamorphic/tectonic fabrics. We call primary structures those that formed in the presence of melt at above and subsolidus conditions during magma cooling and solidification; their description developed below is based on structural and textural criteria already summarized by other authors [e.g., Hutton, 1988; Paterson et al., 1989; Vernon, 2000]. Sec-
Secondary fabrics include shear zones, rare pseudotachylites and foliated areas that have undergone ductile deformation easy to identify where it cuts across primary textural and structural elements. In thin section, evidence for moderate to strong solid-state deformation includes undulatory extinction of minerals, subgrains, mechanical (tapered) twins in plagioclase, bending of pyroxenes, plagioclase and their alteration products and small intergranular aggregates of polygonal plagioclase grains in the more strongly deformed rocks. Mineral associations indicate a wide range of shear zones formed from subsolidus conditions to greenschist facies retrogression both within and along the walls of the Chilas Complex. As discussed below, some shear zones were active during consolidation of the Chilas Complex. Other shear zones reflect later deformation.

We first concentrate on orientation data of primary igneous fabrics as identified from both field and microscopic observation. Primary fabrics consist of structures ranging from faint mineral preferred orientation in otherwise massive, homogeneous rocks (Figure 4) to centimeter-decimeter thick composition layers (Figure 5a) particularly prominent in the vicinity of elongated, generally concordant ultrabasic bodies [Jan et al., 1984]. The absence of pervasive crystal-plasticity features in conventional thin sections (Figures 3 and 4) indicates that even pronounced layering with slump folds and geopetal structures [Khan et al., 1989; Sawada et al., 1994] represents planar concentration domains inherited from magmatic processes; discrete and local signs of solid-state overprint (mostly feeble undulose extension and perhaps some tapered twins in plagioclase) reflect very weak deformation that can be ignored here because this weak deformation is often late magmatic, as indicated by crosscutting and discrete melt veins (Figure 3). Slump folds typically display no axial plane foliation and the mineral shear preferred orientations turn with the folded layering. In places, rhythmically interlayered lithologies show syndeposition faults, erosional contacts, trough layering, cross-bedding and magmatic breccias (Figure 6). These “turbidite-like” structures with “synsedimentary” faults and slump folds in the Chilas Complex are evidence for dynamic, repeated magmatic currents rather than quiet, subvertical crystal settling under the influence of gravity on a horizontal magma floor [e.g., McBirney and Nicolas, 1997]. In particular, a nondynamic process would not explain erosional contacts and the opposite, symmetrical “geopetal” directions that can be deduced from layers oblique to the boundaries of the gabbronorite on either sides of ultramafic bodies [Coward et al., 1986; Burg et al., 1998]. Crosscutting relationships observed in such structures may be small-scale analogs of map-scale discordance of foliation trajectories in zones where neither lithological contrast, nor shear zone nor fault is apparent (Figure 7). In any case, they reveal internal magmatic contacts that become undetectable along strike, away from layered and truncated zones. Consequently, it is sometimes difficult to identify places where the magmatic fabric is parallel, oblique or crosscuts internal contacts. This difficulty suggests that either layering is local, and there was no notice-
able chilling between large intrusions, or that posttruncation annealing that homogenized the granoblastic texture found in many places (Figures 3 and 4) has also obscured internal contacts. Mapping cryptic, recrystallized contacts between magma batches with similar composition is a challenge in large batholiths. In the Chilas Complex, more investigation is needed to separate places where the magmatic fabric formed before, during and after individual internal contacts. Yet, relevant to this work, turbidite-like structures, multiple magmatic fabrics and outcrop- to map-scale crosscutting relationships between variable lithologies indicate together that the gabbronorite is a multiple magma complex accumulated through repeated injections of magma pulses of similar composition. They further indicate that tonalitic and dioritic magmas tend to be younger than the main gabbro-norite. On this matter, our mapping revealed that much of the outer margins of the Chilas Complex are composed of tonalitic “dikes” intruding the wall rocks (Figures 1 and 2).

[12] Locally abundant and clustered xenoliths of gabbroic to gabbronoritic composition, yet coarser grained than the host rock, are an important rock component aligned in the flow plane, which, along with the mineral lineation, is interpreted to constitute the magmatic fabric [Marre, 1982; Paterson et al., 1989]. The xenoliths are generally darker and finer grain than the host gabbronorite and locally display an earlier but likely rotated fabric that was not recorded in the gabbronorite. A strong line of evidence for xenolith alignment at subsolidus stage is the occurrence of boudinaged xenoliths and layers with plagioclase-rich veins, thus some melt, filling the interboudin space (Figure 5b).

[13] The magmatic fabric locally evolves into, and becomes overprinted by a solid-state fabric (Figure 5c) marked by internal elongation of crystals, including brittle boudinage of pyroxene and amphibole. This is particularly true for rare internal contacts defined by a few centimeter wide zone of solid-state deformation, on either side of which the magmatic foliation decreases away from the contact. Consistency of solid-state and magmatic foliations and lineations suggests that both were produced under the same kinematic/tectonic conditions during the last crystal-lization stages and flow increments of the gabbronorite. We attribute transitions from magmatic to more localized solid-state fabrics to higher finite strain (and/or strain rate) produced from drag of magma against its margin. This interpretation implies that at least some of the “metamorphic/tectonic” fabrics pertain to continued deformation during emplacement and cooling of the gabbronorite, which we assume to have in turn occurred under regional tectonics control. However, mylonite zones with stretching lineation directions different to mineral lineations in the gabbronorite likely signal tectonic overprint. This is particularly true for the southern border of the Chilas body. The high-temperature and coalescing mylonites there have a distinct, hornblende-rich microstructure, which reportedly bear downdip

---

**Figure 4.** Granular texture of the Chilas gabbronorite at GPS N35°26′09″; E073°49′36.1″. (left) Representative thin section cut parallel to mineral lineation and orthogonal to foliation, transmitted light. Grains have a weak preferred orientation defining the magmatic foliation (Sm). Opx is orthopyroxene, andfld is feldspar. (right) Ellipses of grain shape fabrics that were automatically measured using the intercept method [Launeau and Robin, 1996]. The average direction of these two fabrics fits the optically defined orientation of Sm.
Owing to the uncertainty in distinguishing ductile shear zones related to emplacement from those due to later regional deformation, we preferred to exclude measurements of solid-state fabrics from the data set discussed in this work. The meaning of the secondary fabric in relation to regional tectonics and/or magmatic history is beyond the scope of this work and may be developed later.

3.2. Interpretation

Magmatic structures develop during solidification of the magma under the influence of gravity, internal pressures and regional deformation. They are thus critical for understanding the emplacement setting of plutons, which in turn influences interpretations of the structures and metamorphism in the surrounding rocks [Berger and Pitcher, 1970; Paterson et al., 1989]. Viscous flow, ductile shearing and, ultimately, brittle fracture document the transition from ductile magma to brittle, crystallized rock. Prefull consolidation normal faults (Figure 5b), structurally and kinematically consistent with the fabrics of the surrounding rock, are found throughout the Chilas Complex. The plutonic bodies identified from field and satellite mapping as parts of the Chilas Complex have length >10 times longer than width, with long axes parallel to the trend of the complex. The width of the largest mapped bodies reaches a few thousand meters, which may be exaggerated by internal intrusions (hence dilation?). Contacts are mostly concordant with the mesoscopic layering, yet display local unconformities at both mesoscopic and map-scale, as described above. The stratiform shapes of these individual plutons and the generally steep contacts suggest imbrication and amalgamation of contiguous magmatic units, apparently emplaced in rapid succession in a sheeted-dike-like geometry, though deep in the magmatic arc. Such an arrangement does not imply that the elongated plutons were intruded in the same location, although they are confined to the long, narrow Chilas Complex (Figure 1). Magmatism within the complex may have migrated in one direction or had a random pattern. Geochronological work in progress favors a random pattern of mutually intrusive, nearly coeval and subparallel bodies.

We conceptually envision mantle-derived, basaltic magma [Jagoutz et al., 2006] intruding up the rifting arc in zones in which it is gravitationally stable. These extension-controlled zones were dominantly steep marginal parts of earlier, “dike-shaped” plutons. This intrusion style lasted at least until the emplacement of subparallel, <1 m thick, tens of meters long hornblende dikes (Figure 5d), which intrude each other and have developed up to hundreds meters thick and kilometers long packages with up to 100% dike frequency in several places amid the gabbronorite. Their map distribution and their relationships with the country rocks show that they were not formed by sidewall crystal-
lization in magma chambers [Jagoutz et al., 2006]. Hornblende and plagioclase crystals perpendicular to the walls of individual dikes and symmetrically organized on both sides of a median suture (Figure 5d) indicate opening and rapid infilling of subvertical fissures through, and parallel to the fabric of, earlier plutons.

[15] The magmatic foliation is generally parallel to the trend of the Chilas Complex, its internal layering and its contacts, and the mineral lineation plunges steeply (Figure 8). Steep “diking”, subvertical lineations and synmagmatic normal faults are consistent with the hypothesis that the Chilas Complex was emplaced in an extensional environment [Khan et al., 1993; Burg et al., 1998], even if synmagmatic normal faults often represent local instabilities for which regional control cannot be ignored, anyway. Two main areas are distinguished from the orientation of planar flow markers and foliations (Figure 9). The northern, Chilas-Kandiah area dips dominantly SSW, which implies that the Kohistan Batholith (our definition, i.e., the north Kohistan region) is the footwall and the southern amphibolites the hanging wall of the Chilas intrusion. The western, Kandiah-Dir area strikes SSW-NNE and is subvertical to WNW dipping. The facts that magmatic minerals are mostly undeformed (Figures 3 and 4) and that lineation directions are similar in both areas (Figure 8) suggest that the arcuate map view of the Chilas gabbro-norite (Figure 1) is primary rather than the result of folding of a consolidated planar body. If this assumption is correct, then the Chilas Complex represents a region where magmas filled fissure-like spaces created between the footwall Kohistan Batholith and the hanging wall Southern Amphibolite Belt. This interpretation does not imply that regional extensional faults should be

Figure 6. Structures reflecting dynamic, multiphase magmatic flow. (a) Erosional contact between two layered gabbro-norite batches. Arrow indicates magmatic foliation with nearly downdip amphibole and pyroxene lineation (GPS N35°26′10.0″; E074°07′36.2″). (b) Graded gabbro-norite layers with normal fault without fault-related mineral fabric. Rhythmic layering is attributed to “turbiditic” flow rather than quiet settling of crystals (GPS N34°24′27.9″; E074°08′41.4″). (c) Folded (black arrow, note the absence of axial plane foliation) and boudinaged (white arrow) layers in Chilas gabbro-norite (unmeasured GPS point). (d) Cross beds and deformed load casts (arrow) in Chilas gabbro-norite (near GPS N35°30′02.5″; E073°48′27.0″).

Figure 7. Internal contact in the gabbro-norite mapped between discordant foliation traces. Thalpan village is a few kilometers WNW of Chilas (Figure 1). Latitudes and longitudes specify the map location.
used to explain the origin of the entire arcuated Kohistan. Extensional faulting and magmatism may have taken advantage of older, arcuate structural trends as those usually seen in presently active arcs.

[16] The controversy we provoke centers on whether the internal magmatic fabrics reflect emplacement of a horizontal lopolith at the contact interface between sediments of the Kohistan Batholith and the southern amphibolites [Bard, 1983a; Jan et al., 1984; Khan et al., 1989, 1993] later tilted to the measured, steep attitude. We challenge this traditional interpretation from three types of arguments. First, tilt to near vertical, as would be the case with an upright, isoclinal fold of some tens of kilometers amplitude [Coward et al., 1987], is mechanically impossible and would involve intense, vertical foliation along the hinge zone. Such a foliation does not exist and the two theoretical limbs display lithologies and metamorphic grades that cannot be correlated, which is inconsistent with upright folding. Secondly, tilt of a thick crustal block around a horizontal axis is equally implausible owing to the lack of evidence for a vertical crustal sequence: sediments and volcanites are well documented on both sides of the Chilas Complex, as mentioned above. Thirdly, metamorphic pressures to the south (the floor of the supposed 30 km thick Chilas lopolith) should be about 1.0 GPa higher than those in the north (the eventual roof of the lopolith). Sediments and metavolcanites of the southern amphibolites have in places recrystallized in mid-grade to high-grade amphibolite facies conditions, which precludes a crustal pile of >30 km above them, and indicates that solid-state to brittle thrust zones along the southern boundary of the gabbronorite had a limited throw. Sediments and metavolcanites to the north have amphibolite facies parageneses. Plagioclase-garnet-biotite-quartz thermobarometry on a metapelite from the northern border of the Chilas Complex yielded peak metamorphic conditions of ∼0.7 GPa at ∼700°C [Jagoutz, 2004], in accordance with conditions calculated from the gabbronorite [Jan and Howie, 1980]. Pressure-temperature estimates on southern amphibolites range from 0.7 to 1.0 GPa at 650–850°C [Treloar and Rex, 1990; Anczkiewicz and Vance, 2000;
In addition, aluminum zoning in plagioclase and clinopyroxene shows that there is nearly no difference in thermobarometric history of rocks across the Chilas Complex [Yoshino and Okudaira, 2004]. We conclude that the interpretation of a large, originally horizontal lopolithic gabbronorite body is at odds with the geological information. It is also at odds with the classical view that the Kohistan Arc, including the Chilas Complex, has been tilted northward by about 30° after India–Kohistan collision [Bard, 1983b; Coward et al., 1987; Searle et al., 1999]. Indeed, if presently subvertical foliations and contacts are back-tilted southward to restore a near precollision attitude, then the Chilas Complex was dipping about 60°N. We deduce that the interpretation of a subhorizontal body is not defendable. We will now argue that the structural information contained in sets of hornblende-plagioclase pegmatite veins hints at the Chilas Complex being originally even steeper than the 60° dip estimate.

4. Hornblende-Plagioclase Pegmatite Veins

4.1. Description

Several sets of hornblende-plagioclase pegmatites occur throughout, yet heterogeneously in the Chilas Complex [Jan and Kempe, 1973; Ali et al., 2002]. The oldest set is composed of foliation-parallel and foliation and/or lineation-normal hornblende-plagioclase pegmatite veins that are in some cases foliated. These few centimeters to several meters thick veins typically represent cross and longitudinal joints that originated when the host gabbronorite magma cooled; the attitudes of such joints reflect local anisotropies during magma consolidation [Marre, 1982; Bergbauer and Martel, 1999]. They further indicate that brittle deformation began in the presence of residual melt during intrusion of the Chilas Complex and they consis-
tently yielded $^{39}$Ar/$^{40}$Ar ages of 80–90 Ma (D. Rex (personal communication, 1985), as cited by Coward et al. [1987] and Treloar et al. [1989]). Although hornblende Ar-Ar ages older than the 83–85 Ma emplacement age of the gabbro-norite are questionable, the 80 Ma age bracket places a bound to rapid cooling down to ca 500°C [Harrison, 1981]. Sm-Nd mineral ages older than host rock [Ali et al., 2002] probably result from isotopic mixing. Using strike variations as gauge of the ratio of magmatic to tectonic stresses [Delaney et al., 1986; Baer et al., 1994; Jolly and Sanderson, 1997] and the tensile strength of coarse norite [Hoek et al., 1998], we calculated a magma pressure of 0.2 to 0.3 GPa at a depth equivalent to 0.6–0.7 GPa.

We put aside these early pegmatite veins and, importantly to us, noted that they are cut by irregularly distributed and vertical swarms of thin (a few centimeters up to 20 cm) and long (more than 50 m) hornblende-bearing pegmatite dikes that bear no simple relationship to the magmatic fabric (Figure 10). We will discuss only these swarms of pegmatite veins, which, owing to their particularly high length/width ratio, are ascribed to postcrystallization brittle failure of the Chilas Complex. Yet, these swarms likely pertain to the latest consolidation stages of the Chilas Complex since they occur in the gabbro-norite only and their mineralogical composition is not different than that of previous veins.

4.2. Interpretation

We interpret the near-vertical dip and dominantly NNW-SSE strike of the late and long/thin pegmatite vein swarms (Figure 11) to be their near-original attitude. This interpretation derives from the following line of thoughts.

Their remarkably planar shapes with very large length/width ratios and lack of (or very small) vein-parallel offsets of earlier structures indicate that these veins represent fluid-filled extensional fractures that formed when the Chilas magmas and hornblende-pegmatite veins in magmatic joints were solidified, yet still containing a very small melt fraction. Extensional fractures tend to open perpendicular to the least principal stress and dilate parallel to the maximum principal stress [Pollard and Johnston, 1973; Segall, 1984; Price and Cosgrove, 1990]. The nearly vertical attitude of the thin pegmatite veins thus suggests that the smallest principal stress under which they formed has a present-day horizontal orientation, orthogonal to their walls, and that the other two principal stresses lie in the present-day vertical plane. Is it coincidence after pretended rotation of the Kohistan Arc about a subhorizontal axis during collision and obduction? Vertical, long and narrow veins occur in parallel sets that have different strikes at different places (Figure 11); hence these sets would require different rotation axes (horizontal axes are necessarily parallel to the strike directions) which, by chance, would each have the ad hoc orientation to bring the individual vein sets to near-vertical dips. The regional continuity of host rock structures (magmatic foliations in particular) excludes the existence of separate blocks with multiple, horizontal rotation axes. An important corollary is that the vertical veins have not or little been rotated around horizontal axes since they formed as latest magmatic products of the Chilas intrusion; consequently, the magmatic structures measured in the host Chilas Complex, out of influence of the Nanga Parbat Syntaxis, are in a near-original attitude, eventual rotations around vertical axes excepted. As a matter of fact, the extensional nature of the Chilas Complex is theoretically consistent with a horizontal smallest principal stress [Price and Cosgrove, 1990], as deduced from the vertical vein sets. In addition, rare layers that are subhorizontal display sub-
vertical gravitational instabilities (Figure 12) whose geopetal nature also suggests that indeed those layers are in their near-original attitude.

5. Discussion

[21] The primarily arcuate trace of the Chilas Complex (Figure 1) accounts for a normal fault system (the Chilas-Kandiah area) and an extensional lateral ramp (the Dir-Kalam area), which is reminiscent of the map shape of listric fault systems with a neighboring transfer or transform fault [Hossack, 1984; Vendeville, 1991]. Owing to the >300 km length of gabbro-norite outcrops, the magmatic structures of juxtaposed plutons reported in this work document the curved shape of a within-arc extensional system on a lithospheric scale, an event that we tentatively attribute to slab rollback (Figure 12) [see also Treloar et al., 1996]. Indeed, we contend that a basal décollement zone existed at the time of extension because, in a synmagmatic system, faults and fissures cannot propagate into viscous magma that extends and expands in lithospheric horizons, as displayed on seismic models of active island arcs [Suyehiro et al., 1996; Holbrook et al., 1999]. A listric-like, flat-and-ramp geometry thus results from the connection between steep normal faults and the décollement level (see also the discussion for downward continuation of faults by Sibson [1983]). Whether the curved shape of the Chilas Complex expresses a crustal-scale listric geometry may still be disputed but the question does not exclude the fact that tilting of hanging wall blocks is an important feature of extensional systems [Kuszmir et al., 1991; McClay et al., 1991; Mauduit and Brun, 1998; Fort et al., 2004]. On a bulk south dipping extensional system, as proposed here for the Chilas body, one expects antithetic rotation resulting in a bulk northward dip of the hanging wall. We suggest that the general attitude of the southern amphibolites (Figure 2) is essentially inherited from extensional tilting, which took place while the Chilas Complex was emplaced at about 85 Ma (Figure 13). This working hypothesis is consistent with the fact that the Chilas gabbro-norite, which has arguably preserved its original dip, cuts the north dipping southern amphibolites on its southern boundary [Treloar et al., 1996]. This pre-India-Kohistan collision event, which could be the “yet unrecognized tectonic event” of Ringuette et al. [1999] responsible for partial exhumation of the base of the Kohistan Terrane, would also provide an explanation for the regionally distributed 39Ar/40Ar cooling/unroofing ages at 83–80 Ma, significantly older than the 60–50 Ma old India-Asia collision [Treloar et al., 1989, 1996]. Precollision tilting also explains how the basal Indus Suture climbs northward, from mantle peridotites to upper crustal sediments, up section of the southern amphibolites (Figures 1 and 2), while there is no obvious reason for this contact to be a back thrust between the two northward dipping sutures of the collisional system; the observed geometry reflects inherited inclination of the southern arc. Accepting that the southern Kohistan Complex was tilted before collision and kept its bulk orientation during later tectonics is further consistent with still flat-lying, 40–30 Ma old (Teru) lava flows in northwestern Kohistan [Danshwar et al., 2001; Petterson and Treloar, 2004] and analogue modeling of arc accretion, which do not involve much rotation during collision [Boutelier et al., 2003].

6. Conclusion

[22] Measurement of magmatic fabrics led to reevaluating the emplacement mechanisms that produced the Chilas Complex in the deep crust of the Kohistan paleoisland arc. Lithological and structural observations suggest that this gabbro-norite body was emplaced as a series of sequentially intruded, tabular plutons rather than as a single, enormously voluminous pulse of magma. The elongate shapes and concordant orientations of the plutons reflect exploitation of the spaces created during within-Kohistan Arc extension by multiple, coalescing, and subvertical intrusive sheets at about 85 Ma. These magmas were deformed in the process. An oceanward dipping rupture dominated extension and magma emplacement and compelled precollision tilt of the hanging wall crustal block, now represented by the southern amphibolites. This study illustrates three general points pertinent to present and past island arcs: (1) within-arc space can be made available for
the emplacement of magmas, so that the lower crust of an extended arc appears as a large-scale, “sheeted-dike-like” complex; (2) as a corollary there is no long-lived magma chamber of the size of the present-day Chilas Complex in the roots of island arcs; (3) rotation of large crustal blocks representing the hanging wall of lithospheric-scale listric fault zones may occur during the arc history and is responsible for older-than-collapse cooling/exhumation ages; and (4) precollision arc structures may be preserved in collision orogens but are unrelated to continental collision processes per se.

[23] Acknowledgments. The Swiss National Science Foundation supports our work (grants 20-49372.96 and 20-61465.00). L. Arbaret, J.-P. Brun, and P. Treloar provided critical and valuable comments on an early version of the paper. U. Gerber generated black and white, digital versions of photographs. We thank J. Martignole, R. B. Miller, and A. Yoshinobu for their constructive reviews that helped to significantly improve the manuscript. The Pakistan Museum of Natural History supports S.H. and H.D.

References


Hosack, J. R. (1984), The geometry of listric growths through early, mature and intra-arc rift formations for continental crustal growth, J. Geol. Mag., 131, 139 – 142.


Matsushita, S., and K. Huzita (1965), Geology of the Karakorum and Hindu Kush: Results of the Kyoto University Scientific Expedition to the Karakorum and Hindu Kush, 160 pp., Kyoto Univ. Press, Kyoto.


Ringuestu, L., et al. (1999), Magmatic crystallization, isobaric cooling, and decompression of the garnet-bearing assemblages of the Jijil sequence (Kohistan terrane, western Himalayas), Geology, 27, 139 – 142.


Schaltegger, U., et al. (2002), Multiple mantle sources during island arc magmatism: U-Pb and Hf isotopic evidence from the Kohistan arc complex, Pakistan, Terra Nova, 14, 461 – 468.


Treloar, P. J., and D. C. Rex (1990), Cooling and uplift histories of the crystalline stack of Indian Plate internal zones west of Nanga Parbat, Pakistan Himalaya, Tectonophysics, 180, 323–349.

Treloar, P. J., et al. (1989), 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, 881–909.


