

Polarity of the subduction system responsible for the Cretaceous Kohistan island arc terrane, N. Pakistan: geochemical and structural constraints

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ABSTRACT: *The Kohistan island arc terrane of N. Pakistan has experienced multiple collisions, resulting in obliteration of the subduction system responsible for its creation. Indirect evidence, based on structural vergences and across-the-arc variations in trace elements (Ti, Zr, Nb, and P) have been combined to interpret the nature of the subduction zones responsible for Kohistan in terms of their location and polarity (i.e., dip direction). Geochemical investigations, from north to south, in the Chalt volcanics, the Chilas complex and the Kamila amphibolite belt indicate a systematic increase in high-field strength elements from north to south. These variations indicate an overall decrease in the degree of melting or degree of source-region depletion, which in either case, give a facing direction for the arc terrane towards north. The structural vergences in the northern parts of the Kohistan terrane are also consistent with a south dipping subduction zone located to its north. Using these observations, a tectonic model is proposed for the origin of Kohistan terrane on a south-dipping subduction zone located at its northern margin. The subduction switched to the southern margin of the arc terrane soon after the Kohistan-Karakoram collision with a reverse polarity (i.e., dip direction towards the north). The model has been tested in the light of modern examples of arc-continent collisions in SW Pacific ocean.*

INTRODUCTION

The Kohistan terrane of northern Pakistan is widely believed to represent crust of an accreted intraoceanic island arc of Cretaceous age trapped in the collision-related Himalaya-Karakoram mountains (Tahirkheli et al., 1979; Coward et al., 1986). The terrane is bounded by suture zones of regional extent at its northern and southern sides believed to have formed by obliteration of ancient oceanic basins. Since its first recognition as an island arc terrane (Tahirkheli et al., 1976), it is assumed that the arc was built on a subduction zone located to its south with a dip direction (i.e., polarity) to the north (Jan & Khan, 1981, 1983; Petterson & Windley, 1985, 1991;

Coward et al., 1985, 1987; DeBon & LeFort, 1987). Despite the fact that 95 Ma and older pre-collision granites in the Karakoram batholith (LeFort et al., 1983) require a separate north-dipping subduction zone at the southern margin of the Karakoram plate, the oceanic basin between Kohistan and Karakoram plate is interpreted to be not more than a marginal basin of back-arc type (Pudsey, 1986; Virdi, 1992).

In this paper we focus on subduction system responsible for the Kohistan terrane in terms of age span, relative location and polarity. As is a case with all collisional belts, Kohistan does not preserve direct evidence about the pre-collisional

geometry of its parental subduction zones. Our reconstruction is, therefore, based on structural and geochemical evidence obtained from within the Kohistan terrane. Moores and Twiss (1995), using relatively modern examples of collision tectonic in the Circum-pacific region, have demonstrated that structural vergences associated with the suture zones reflect polarity of the parental subduction zones. Likewise the igneous rocks in island arcs are considered to have compositional variations which correlate with depth of the subducting plate (Kuno, 1959; Dickson & Hatherton, 1967; Sugimura, 1973). This has potential for inferring the dip direction in ancient

subduction zones (Taylor et al., 1992). We have explored both these aspects, and propose that 1) Kohistan was initiated and grew in its intraoceanic span of life at a south-dipping subduction zone located to its north and 2) the subduction was shifted to a north-dipping subduction zone located to the south of the arc terrane at the time of Kohistan-Karakoram collision.

REGIONAL GEOLOGICAL SETTING

The Kohistan terrane in northern Pakistan is bounded by Shyok suture in the north and the Indus suture in the south (Fig. 1). Sedimentary

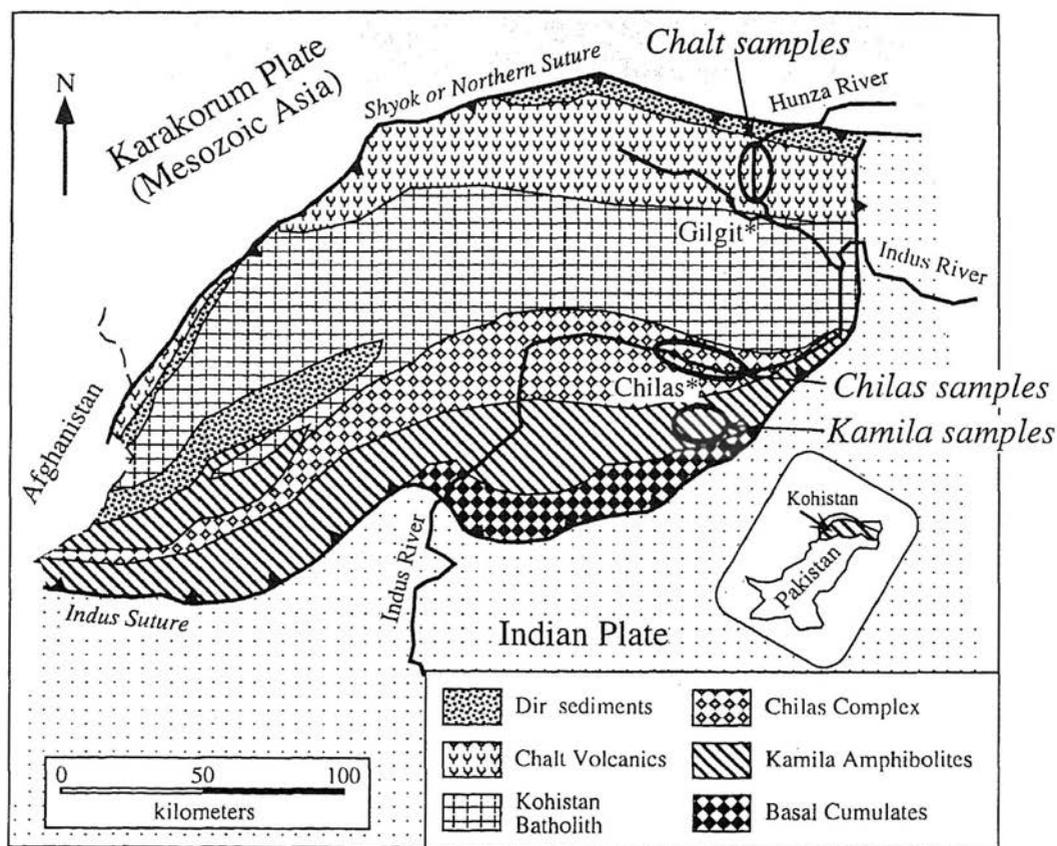


Fig. 1. Generalised geological map of Kohistan arc terrane, Pakistan (modified after Tahirkheli & Jan, 1979; Coward et al., 1986).

sequences preserved in its northern parts suggest that the intraoceanic phase of the island arc terrane started in Early Cretaceous (Aptian-Albian Yasin Group, Pudsey, 1986). Ar^{40}/Ar^{39} and Rb/Sr age data (Pettersson & Windley, 1985; Treloar et al., 1989) suggest that bulk of the igneous rocks related with this stage of arc development formed between 120 and 90 Ma. The island arc experienced its first collision at its northern margin with the Karakoram plate at 90-80 Ma, to become an Andean-type continental margin (Pettersson & Windley, 1985). The terrane went through its second collision during Early Eocene when it was welded to the Indian plate (Tahirikheli, 1983; Sullivan et al., 1993).

The intraoceanic phase of the Kohistan terrane, which we focus on in this paper, comprises five units, from south to north, 1) Basal ultramafic-mafic cumulates, 2) Kamila amphibolite belt, 3) Chilas complex, 4) Gilgit gneisses and Chalt volcanics and 5) Yasin Group of sediments. Much of the Kohistan batholith was intruded subsequently during the continental-margin stage of arc growth (Pettersson & Windley, 1985), and is not dealt with in this paper. The geochemical evidence presented in this paper comes from Chalt volcanics, the Chilas complex and Kamila amphibolite belt.

The Kamila amphibolite belt comprises two varieties of amphibolites; 1) homogeneous, medium-coarse grained amphibolites and 2) fine-grained banded or homogeneous amphibolites. Jan (1988) interpreted the medium-coarse grained variety to have derived from a plutonic gabbroic-diorite precursor, while the fine-grained variety was considered to have formed from a volcanic protolith. On the basis of whole-rock geochemistry, Khan et al. (1993) identified two varieties in the metavolcanic amphibolites, E- and D-type. The E-type

amphibolites were found to contain a relatively enriched content of high-field strength elements (HFSE) and a moderate to heavy rare-earth elements. These amphibolites resemble greatly with mid-oceanic ridge basalts. The D-type amphibolites are depleted in HFSE compared to large-ion lithophile elements, and have a composition which is typical of subduction-related island arc magmas.

The Chilas complex occupies a central position in the Kohistan terrane to the north of the Kamila amphibolite belt. Khan et al. (1989) described two association of rocks from the Chilas complex; an ultramafic-mafic-anorthosite association (UMA) and a main gabbro-norite association (MGA). The latter, comprising gabbros, gabbro-norites, norites and hypersthene diorites, makes by far the bulk of the complex. This association defines a calc-alkaline suite which ranges in its silica content between 51-59% and compares with the island-arc non-cumulates of Beard (1986). Significant mineralogical differences exist between the UMA (plagioclase An_{83-99} , olivine and Cr-spinel present) and MGA (plagioclase An_{40-64} , olivine-Cr-spinel absent, and magnetite-ilmenite present). The rocks of the MGA are characterised by distinct chemical characteristics of convergent-margin magmas, like strong positive spikes for Ba, K and Sr, negative Nb anomaly, modest light rare-earth element enrichment ($Ce/Yb = 2 - 3.5$) and a rare-earth content of about 10x chondrites. These rocks are estimated to have cooled and equilibrated under conditions of pyroxene granulite, estimated at 750° to 850° and 5-6.5 kb (Jan & Howie, 1981; Bard, 1983).

The Chalt volcanics occupy a ~30 km wide belt along the northern parts of the Kohistan terrane. The lower parts of the sequence comprises volcaniclastic sediments metamorphosed to high-grade gneisses (the Gilgit Formation of T. Khan et al., 1994). The

uppermost part of the volcanics is interbedded with the sediments of Aptian-Albian Yasin Group (Pudsey, 1986). Abundance of pillowed sequences suggest subaqueous eruption. A significant compositional difference is observed along strike, with high-Mg suite encountered in the Hunza valley and a low- to intermediate Mg calc-alkaline sequence found to the west. Boninite is common in the Hunza valley section along with some tholeiitic basalts and abundant felsic lavas.

GEOCHEMISTRY: HIGH FIELD STRENGTH ELEMENT DISTRIBUTION

Three units i.e., Chalt volcanics, Chilas complex and Kamila amphibolites are selected here to reflect the north to south across-arc variations in the Kohistan terrane. General geochemistry of these suites has previously been presented (Petterson & Windley, 1991; Jan, 1988; Khan et al., 1989; 1993). In this paper, we restrict ourselves to those elements which reflect the levels of subduction component in their host rocks. As a general rule, subduction-related magmas are characterised by higher concentrations of large-ion lithophile elements (LILE; K, Rb, Ba, Sr, etc) and suppressed concentrations of high-field strength elements (HFSE; Zr, Ti, P, Y, and Nb) relative to N-type MORB (Saunders et al., 1980; Arculus & Powell, 1986). Considering that the rocks we are dealing with, in this paper, have undergone varying degrees of metamorphism in the range of greenschist- to pyroxene granulite facies, we refrain from using LILE for interpretation due to their known susceptibility to remobilisation during alteration and/or metamorphism. Instead we use the degree of depletion of the HFSE as a measure for the subduction component (Weaver et al., 1981).

The HFSE content of the three selected suites of rocks from Kohistan is portrayed graphi-

cally in Figure 2. All the four HFSE register minimum concentration in the Chalt volcanics and maximum in the Kamila E-type meta-volcanics. The Chilas complex and Kamila D-type meta-volcanics have concentrations intermediate between these two end members. These data clearly show that the HFSE are characterised by a distinct enrichment from north to south across the Kohistan arc terrane. Abundance of HFS elements in an intra-oceanic convergent margin increase from the forearc to the backarc, which reflects an overall decrease in the degree of melting or degree of source region depletion that gives a clear facing direction for the arc (Taylor et al., 1992). The HFSE evidence for Kohistan is very clear; considering only rocks with 48-59% SiO₂, the Chalt volcanics contain <0.3% TiO₂ and <30 ppm Zr. The Chilas complex samples contain 0.84 and 1.24% TiO₂ and 71 to 133 ppm Zr and the Kamila samples contain as much 2.25% TiO₂ and 149 ppm Zr. Such intra-arc variations are not uncommon and are associated with profiles from fore- through, active- to back-arc parts of island arcs. The across-arc variations in Kohistan are graphically presented and are compared with data for transects across the Izu-Bonin-Mariana intraoceanic arc system (Taylor et al., 1992) in Figure 3. This comparison clearly suggests that the intraoceanic Kohistan arc faced northwards above a S-dipping subduction zone, during its intraoceanic stage of evolution.

STRUCTURAL VERGENCES

The structural cross-section across the Kohistan terrane is marked by opposite vergences in its southern and northern parts (Fig. 4). Much of the Kohistan terrane between Indus confluence and the Shyok suture at Chalt is marked by strong upright to steeply south-dipping foliation. This foliation primarily represents the axial plane foliation associated with north-vergent isoclinal

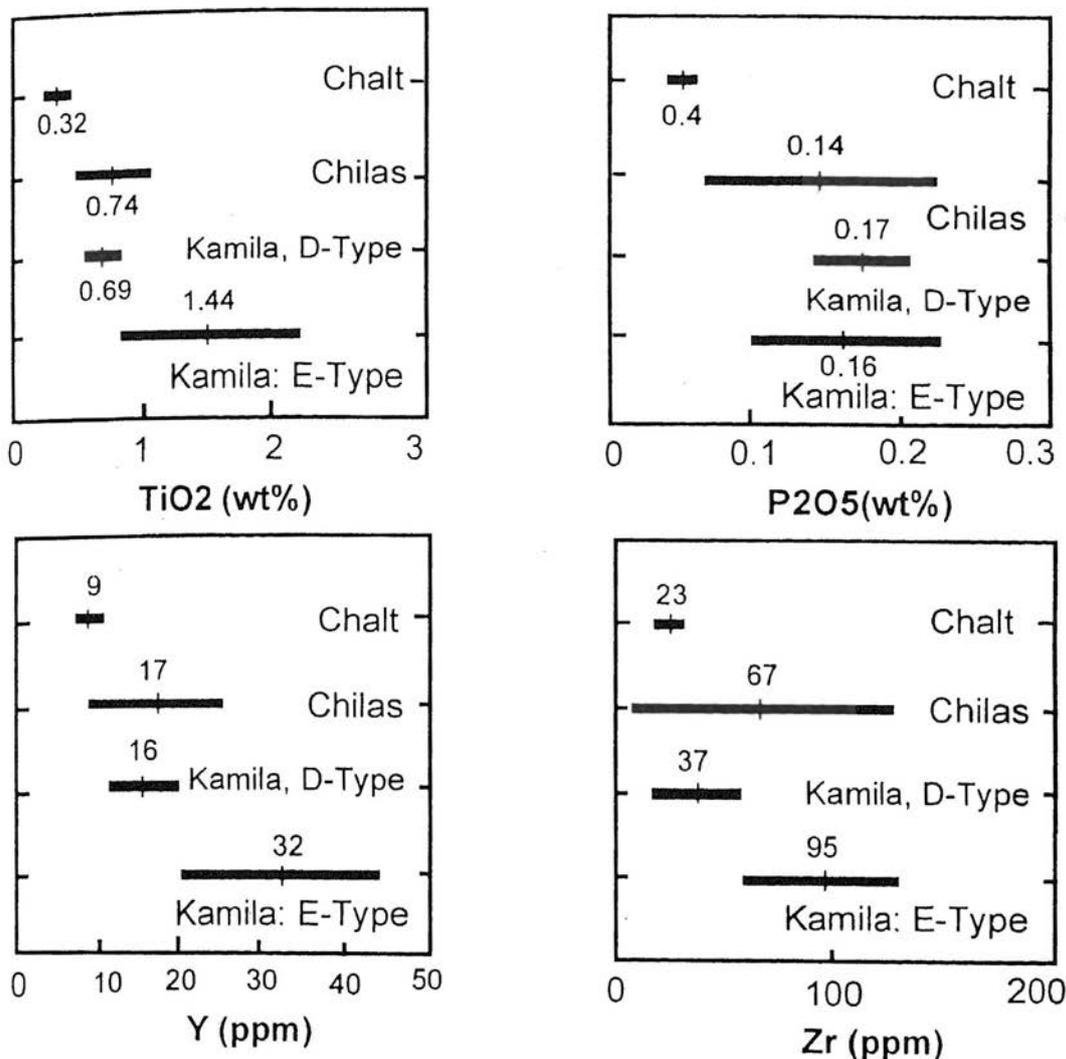


Fig. 2. Variations in HFSE (TiO_2 , P_2O_5 , Y and Zr) contents in terms of overall ranges and means across the arc from north to south (Chalt-Chilas-Kamila). Kohistan data sources follow: Chalt ($n = 41$), Petterson and Windley (1991), Luff and Windley (unpublished); Chilas ($n = 40$), Khan et al. (1989), Khan (unpublished); Kamila ($n = 37$) Khan et al. (1993), Khan (unpublished).

fold structures which themselves are associated with north-vergent shear zones and reverse faults. These north-vergent structures are strong enough to have completely upturned the stratigraphy in this part of the terrane. Gilgit Formation (schists/gneisses of volcaniclastic origin) locally approaching silliminite-facies regional

metamorphism, which was originally located at the base of the Chalt volcanics, now overlies them. Likewise the Chalt volcanics are thrust northwards to overlie the stratigraphically younger Yasin Group metasediments. Thus the Gilgit-Chalt transect in northern parts of the Kohistan terrane is marked by an

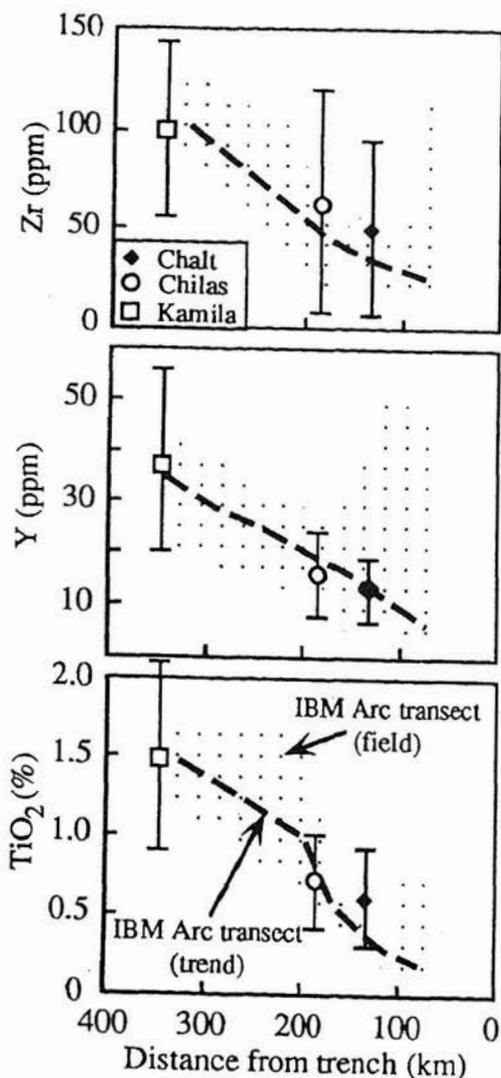


Fig. 3. Abundance of high field strength elements Zr, Y, and Ti for Kohistan intraoceanic phase igneous rocks, compared with data for transects across the Izu-Bonin-Mariana (IBM) intraoceanic-arc system, reported by Taylor et al. (1992). Stippled field encompasses all IBM data for samples, filtered for 3.5% <MgO> 15%; dashed line is our estimate of the best fit trend of the data. IBM arc system data indicates increasing HFSE concentrations with distance from the trench. Data for Kohistan samples includes mean ± 1 standard deviation. Positions of Chalt, Chilas and Kamila are shown to make the point that Kohistan HFSE data are most consistent with the sequence of units having the following order of increasing distance from the trench: Chalt, Chilas, and Kamila. This is consistent with a model for the formation of the Kohistan intraoceanic arc system over a south-dipping subduction zone.

upturned sequence with structures verging to the north. Coward et al. (1986) have published cross sections from Yasin and Ishkuman valleys with similar north-vergent structures in the northern parts of the Kohistan terrane.

The Kohistan terrane shows a change in the structural vergence at the Indus confluence. From here to the south, the structures verge towards the south. These include Jaglot syncline, the Kamila shear zone and the MMT (Fig. 4). Whereas the MMT and some of the south-vergent thrusts and folds are related with the Eocene India-Kohistan collision (Sullivan et al., 1993), the Jaglot syncline and the Kamila shear zone are as old as the Shyok suture and associated north-vergent structures in northern parts of Kohistan (Coward et al., 1986; Treloar et al., 1989, 1990).

Our understanding of the structures in Kohistan is grossly similar to that proposed by Coward et al. (1986), i.e., the Cretaceous-age divergent structures in Kohistan arc terrane were produced by collision at the site of the Shyok suture, while the south-vergent MMT and related structures of Eocene age in southern Kohistan formed by initiation of new structures and refolding of the earlier structures by the closure at the site of the Indus suture. We, however, add that the simple shunting together of

KOHISTAN TERRANE , N. PAKISTAN

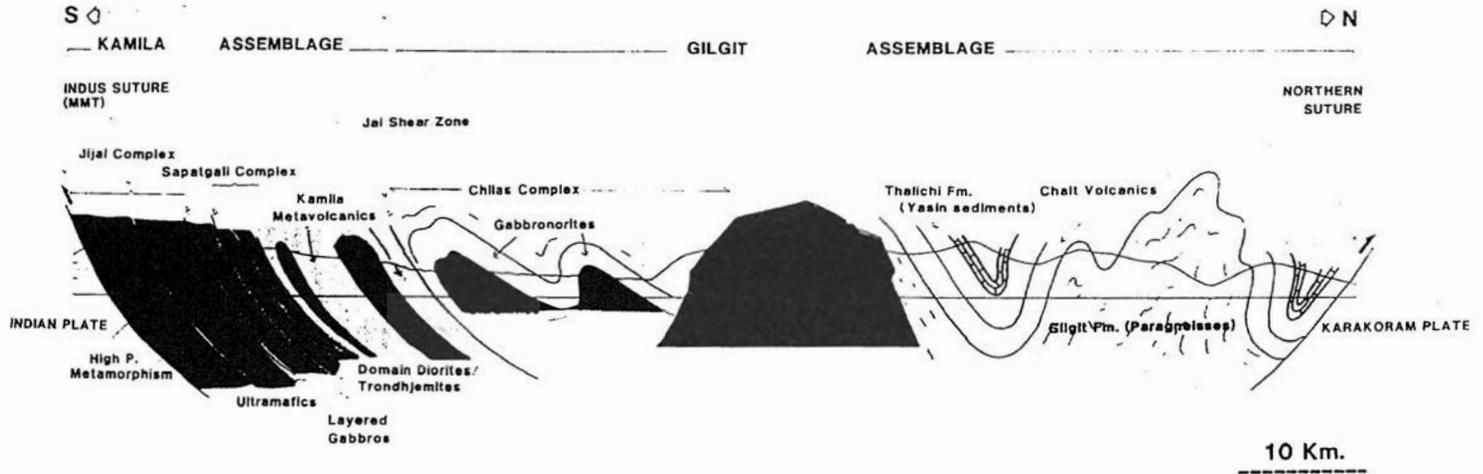


Fig. 4. A schematic structural cross section across the Kohistan terrane. Note that structures in northern parts of Kohistan verge towards north and those in middle and southern parts, verge towards south.

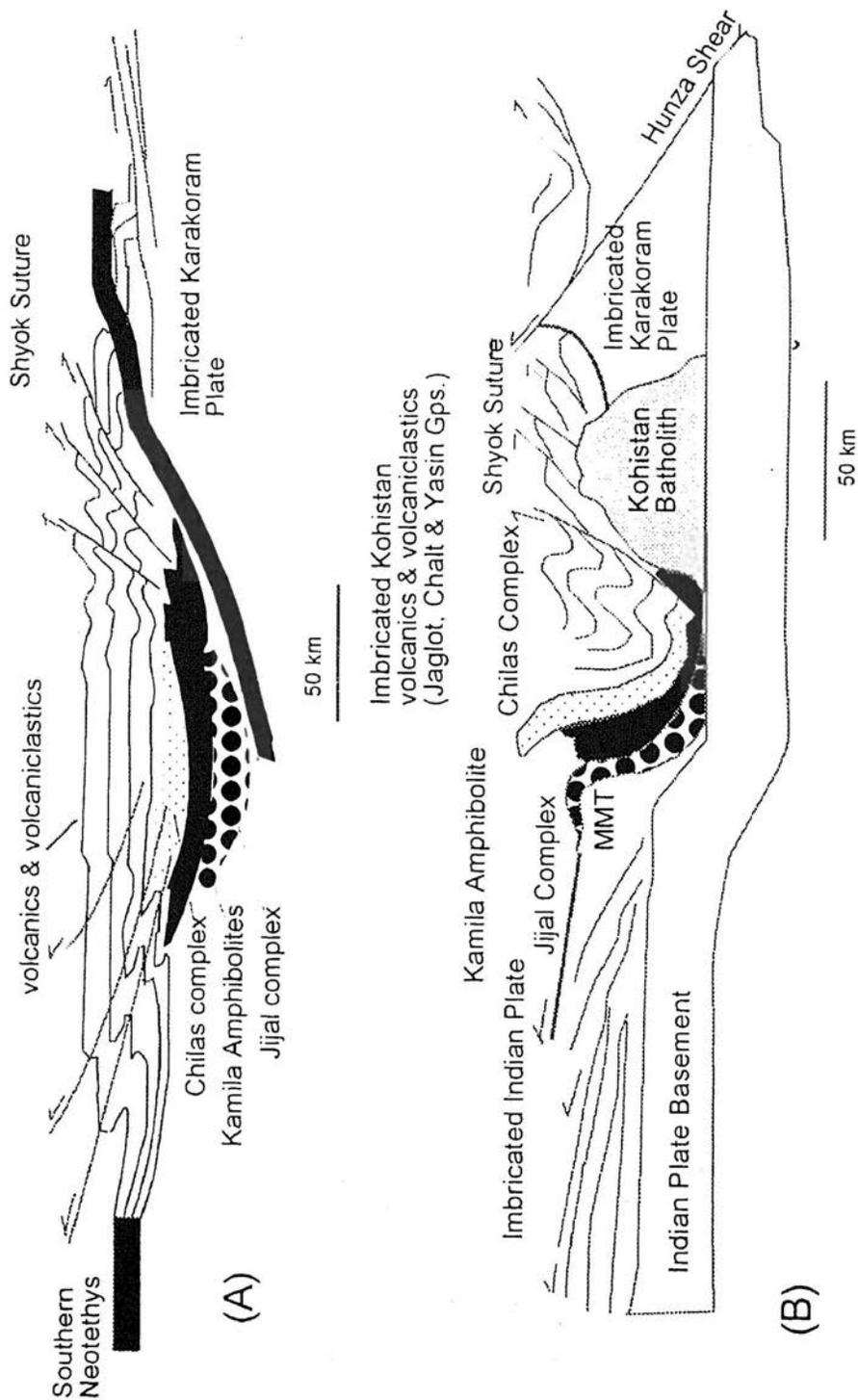


Fig. 5. Schematic model for the structural evolution of the Kohistan island arc highlighting the control of subduction zone vergence on the vergences of the structures in the island arc terranes and the at the continental margins.

Kohistan-Karakoram terranes (Pudsey, 1986; Coward et al., 1986) does not explain north-vergent structures in northern Kohistan. Rather they advocate their origin on a fault plane which was dipping southwards beneath them, probably related with a subduction zone of similar orientation (Fig. 5). The south-verging Jaglot syncline and the Kamila shear zone were related with the north-vergent structures in a pop-up geometry. A similar south-vergent fault structure at the arc-ocean boundary could have facilitated the initiation of the new subduction zone at the southern margin of Kohistan soon after the Kohistan-Karakoram collision (see later).

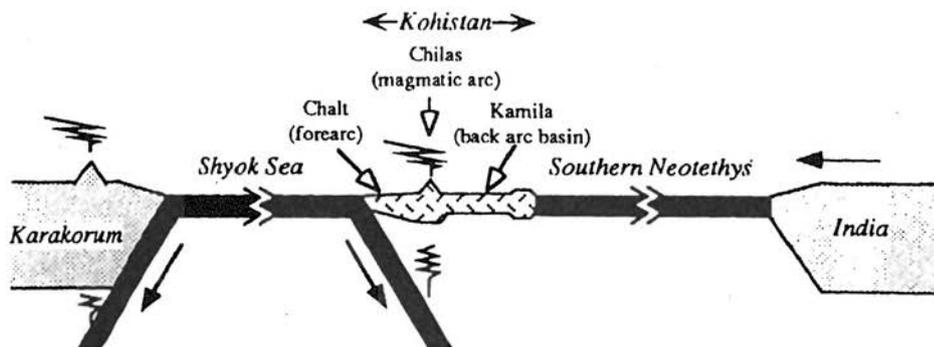
DISCUSSION

The Kohistan terrane has an unambiguous subduction-related origin (Pettersen & Windley, 1991; Khan et al., 1997). Yet, there has been no serious attempt to address the geometry of the subduction system responsible for its origin. Occurrences of boninites in the Chalt volcanics (Pettersen & Windley, 1991) and recognition of north-vergent structures in the Gilgit-Chalt segment of the Kohistan terrane (Coward et al., 1986) indicate that Kohistan could have formed at a south-dipping subduction zone located to its north. Further geochemical and structural data presented in this paper highlights this possibility. The tectonic model that we prefer is shown in Figure 6. Figure 6a shows the intraoceanic phase and features an ocean basin, "the Shyok ocean", between Karakoram and Kohistan. This ocean closed as a result of two subduction zones, one dipping north beneath Karakoram (parental to the Karakoram batholith) and the other dipping south beneath Kohistan. The closure of the Shyok ocean at around 90 Ma did not cease subduction-related magmatism in Kohistan nor there is any hiatus in marine-magnetic anomaly data con-

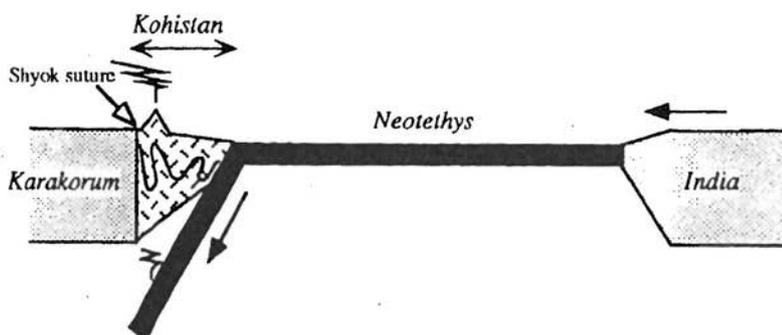
cerning India's northward motion during the Cretaceous. This would require switching of the subduction zone at the southern margin of Kohistan immediately after Kohistan-Karakoram collision. This new subduction zone dipped north on the south side of Kohistan (Fig. 6b) and gave rise to much of the Kohistan batholith and Dir-Shamran intermediate to felsic volcanics (Pettersen & Windley, 1985; Sullivan et al., 1993). In the following we address two principal aspects of this model.

Nature of the ocean between Kohistan and Karakoram

The proposed location of the subduction zone(s) at the site of the Shyok suture requires that the Shyok ocean was a full-fledge ocean rather than a marginal (back-arc type) basin as suggested by Pudsey (1986). Khan et al. (1997), on the basis of recognition of DUPAL anomaly in the isotope data from Kamila amphibolite, Chilas complex and the Chalt volcanics have suggested that Kohistan initiated at a paleolatitude position at or to the south of equator. This paleopole position for Kohistan is supported by the recent paleomagnetic data from Kohistan (Yoshida et al., 1996). The abundant high-quality paleomagnetic data from the Lahasa plate (Chen, 1992), which is an eastern equivalent of the Karakoram plate, indicates a paleolatitude position at 10-15° N, suggesting that during the Cretaceous, Kohistan occurred a minimum of 1000 km and a maximum of 3000 km to the south of Karakoram. This implies that the Shyok sea was a full fledge ocean of Pacific type rather than a marginal basin of sea of Japan-type. Our vision of the Shyok sea in Cretaceous has a modern analogue in the Molucca Sea, south of Philippine. The Molucca Sea is closing as a result of west-dipping subduction beneath the Sangihe Arc to the west and east-dipping subduction beneath the Halmahera Arc to the east (Hamilton, 1978; Moore et al., 1981).



A) Kohistan - Intra-oceanic Phase - ca. 100 Ma



B) Kohistan - Andean Margin Phase - ca. 70 Ma

Fig. 6. Tectonic model for the evolution of Kohistan arc: a) Intraoceanic phase; India drifts northwards (left) due to closing of an ocean basin between Karakoram and Kohistan. Kohistan is on the same plate as India. Note positions of Chalt volcanics, Chilas complex, and the Kamila amphibolite, b) Andean phase; Kohistan has collided with Karakoram and a new, northward dipping subduction zone has formed on the south side of accreted Kohistan. India continues to move north.

Relocation and polarity reversal of the subduction system: modern examples from the Circum-Pacific region

An important aspect of the suggested model (Fig. 6) is the relocation of the subduction zone from the northern margin to the southern margin of the Kohistan terrane at the time of Kohistan-Karakoram collision. This is envisaged to be accompanied by reversal in the polarity i.e., change in dip direction of the subduction zone from southerly to northerly. The process involving jumping of the subduction zones from one

place to another and reversal in polarity to opposite directions may appear cumbersome. Modern subduction systems, such as those of Circum Pacific, which are passing through varying stages of collision, provide a wealth of data developing a useful criteria for interpreting obliterated subduction zones in ancient collisional belts. Hamilton (1978) and Moores and Twiss (1995), using the south-west Pacific region, point out that subduction zones can pass through a highly complex evolution when involved in multiple plate collisions. We pick two examples from the

south-western Pacific (Fig. 7A) to illustrate that the suggested relocation and polarity reversal of the subduction system in Kohistan is not unusual in plate tectonics.

The Ontong-Java plateau, north-east of Australia is an oceanic plateau accreted with the Solomon-Vanuatu island arc. The two are over-riding an active subduction zone located in the WSW (Fig. 7B). The geological evidence (Carney & MacFarlane, 1982; Cooper & Taylor, 1985), however, indicates that prior to Pliocene the Pacific plate carrying the plateau was being subducted towards the south-west beneath the Solomon-Vanuatu island arc. The plateau collided with the subduction zone, resulting in relocation of the subduction zone at its current position accompanied by a reversal in the polarity.

Another interesting example involving island arc-continent collision is provided by the New Guinea region at the NE margin of Australia. The Vanuatu-Solomon-Bismark subduction zone when approaches the eastern margin of Papua New Guinea merges with a SW vergent thrust which separates an island-arc ophiolite from the Papuan fold belt (Fig. 7B). This ophiolite was once a continuation of the Bismark island arc that lay above a north-dipping subduction zone and was thrust over the Australian continent when the continent collided with the subduction zone. This collision relocated the subduction zone to its current position to the north of the ophiolite with a reversed polarity. These examples show that relocation and reversal in polarity of subduction systems are processes not uncommon in regions undergoing multiple collisions.

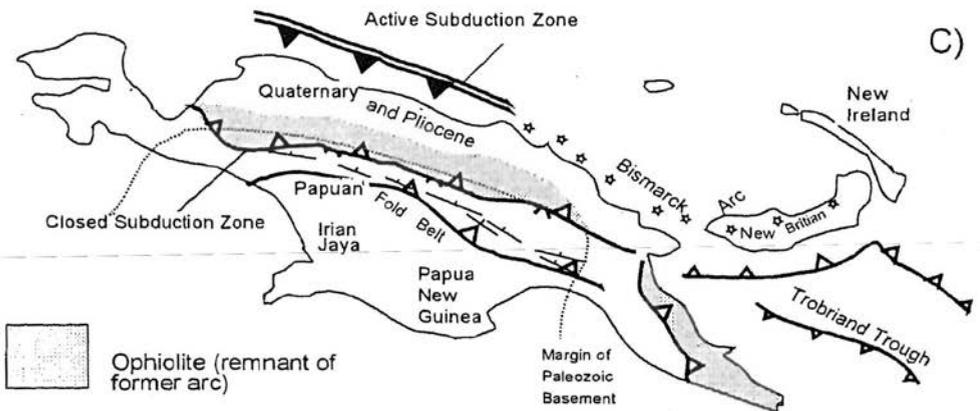
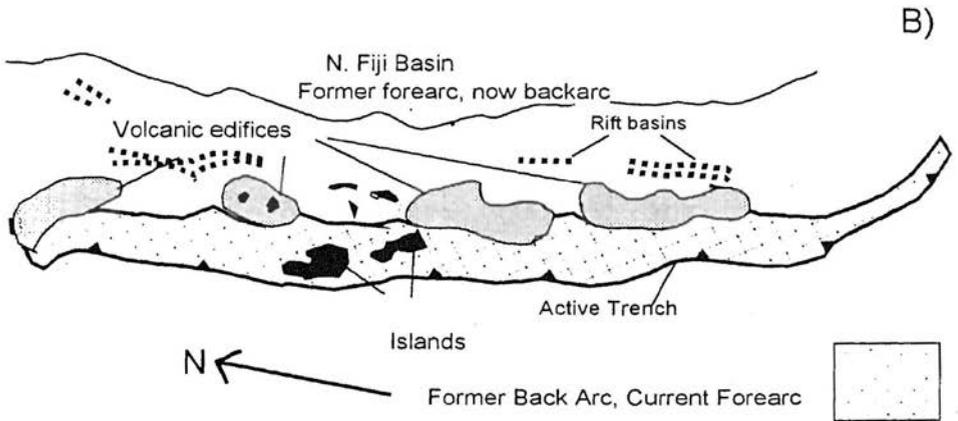
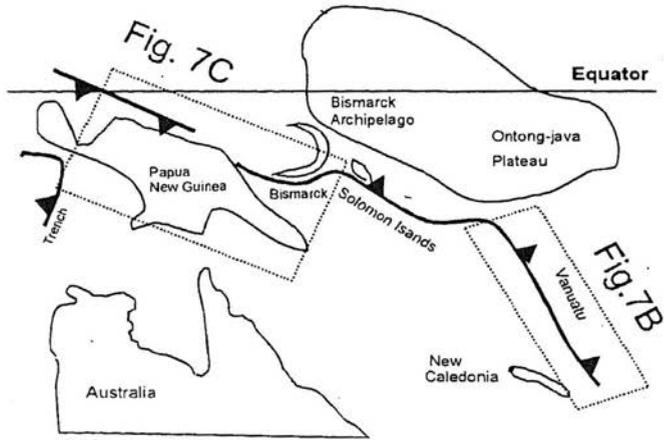
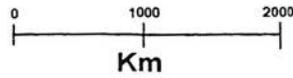
The comparison with modern examples of arc-continent collisions in SW Pacific region help to explain the sequence of collisional events involving Kohistan. In the previous models for Kohistan, subduction zone is always believed to

be located to the south of the arc, yet the first collision is known to have occurred at its northern margin at the site of Shyok suture (Tahirkheli, 1983; Petterson & Windley, 1985). The lack of ophiolites and blue schists in association with the Shyok suture is used as evidence for its marginal basin nature without having a subduction system associated with it. In both the examples cited above, the plate subducting beneath the arc was consumed first. By analogy, the first collision of the Kohistan terrane would have taken place at its southern margin and not at the Shyok suture. To have the first collision at the site of the Shyok suture, for which there is compelling geological evidence (Tahirkheli, 1983; Coward et al., 1986), the subduction zone responsible for Kohistan is required to have been located to its north rather than to its south as is suggested in the model proposed here.

CONCLUSIONS

Vergence of structures like folds and reverse faults and across-the-arc variations in high-field strength trace elements (Ti, Zr, Y etc.) in the Kohistan terrane of northern Pakistan are re-examined. These evidences are used to point out the likelihood that the Kohistan formed on a subduction zone that was located at its northern margin with dips southwards beneath the arc. The subduction zone jumped to the southern margin of the terrane soon after the closure at the site of the Shyok suture (i.e., ~90 Ma). Much of the subsequent Andean-stage of the evolution took place on this subduction zone which dipped towards the north.

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- Fig. 7. A) Plate tectonic map of SW Pacific (after Moores & Twiss, 1995).
 B) Map of the Solomon-Vanuatu arc, Southwest Pacific. The Pliocene subduction zone (now closed) was located north-northwest of the arc, which jumped to the south-western margin with a reversed polarity at the time of collision with Ontong-Java plateau (Carney & MacFarlane, 1982).
 C) Tectonic map of the New Guinea region. The ongoing collision is accompanied by relocation and polarity reversal in the subduction zone (after McCaffery et al., 1991).

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