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GEOLOGY AND GEODYNAMIC EVOLUTION OF THE HIMALAYAN COLLISION ZONE

PART 2

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HIGH-P METAMORPHIC ROCKS FROM THE HIMALAYA AND THEIR TECTONIC IMPLICATION- A REVIEW

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ABSTRACT

The suture zones bordering the Indian subcontinent on the E, N and W are characterized in several places by the occurrence of ophiolitic complexes and tectonic melanges. High-P metamorphic rocks have recently been discovered in the melanges in Burma, Naga Hills, southern Tibet, eastern and western Ladakh, Kohistan (Jijal, Allai, Shangla) and Khost (Afghanistan). The development of these rocks has an important bearing on the plate tectonics of the Himalaya.

The High-P metamorphic rocks belong to prehnite-pumpellyite, blueschist and high-P greenschist facies but extensive garnet-granulites have developed at 35 km depth in Jijal. In the Indus-Zangbo suture zone (IZS) the high-P metamorphism is complemented to the N by low- or medium-P metamorphism and calc-alkaline magmatism in Tibet, Ladakh as well as Kohistan. High-P metamorphism in Jijal has been dated at 104 Ma, in Shangla at 70-100 Ma and in western Ladakh during mid-Cretaceous. Elsewhere, the timing of the high-P metamorphism is not known but a Cretaceous age is inferred. Since collision along the IZS occurred during Eocene, the high-P metamorphism is therefore related to the northwards subduction of the neo-Tethyan lithosphere under Tibet or late Mesozoic magmatic arcs. The timing of high-P metamorphism coincides with the breakup of India from Gondwanaland and its rapid northwards movement, whereas the tectonic melanges may principally have formed during Eocene collision and obduction.

Keywords: High-P metamorphism; blueschists; greenschists; garnet-granulites; paired metamorphics belts; Himalaya.

INTRODUCTION

The Indus-Zangbo Suture (IZS) is commonly agreed upon to mark an important boundary along which the Indian plate was subducted underneath the Tibetan landmass (Powell and Conaghan, 1973; Gansser, 1980; Le Fort, 1975). In the Ladakh and Kohistan regions of western Himalaya-Karakoram, the IZS bifurcates into the Main Mantle Thrust (MMT) in the S and the Main Karakoram Thrust (MKT) in the N. The MMT and MKT enclose the Kohistan-Ladakh island arc, developed largely during the Cretaceous in response to northward intra-oceanic subduction (Tahirkheli and Jan, 1979; Klootwijk et al., 1979; Virdi, 1981a; Andrews-Speed and Brookfield, 1982; Coward et al., 1982, 1986; Honegger et al., 1982; Bard, 1983; Jan and Asif, 1983; Radhakrishna et al., 1984; Searle et al., 1987). The possibility of an island arc setup for the Gangdise belt, occurring N of the IZS in southern Tibet, has also been suggested (Shackleton, 1981).

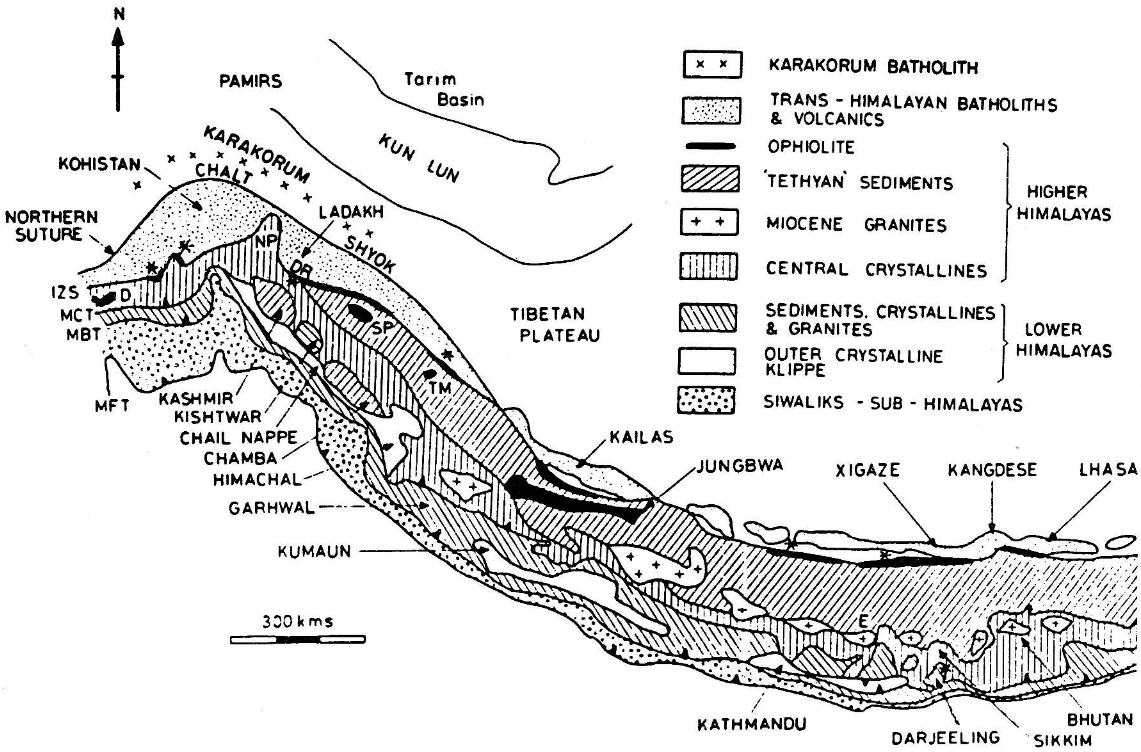

Fig.1. Tectonic map of the Himalaya (modified after Windley, 1984). Key. D- Dargai, DR- Dras, E- Everest, NP- Nanga Parbat, SP- Spongtang, TM- Tso Morari, IZS- Indus-Zangbo Suture, MCT- Main Central Thrust, MBT- Main Boundary Thrust, MFT- Main Frontal Thrust. Asterics show approximate location of high-P rocks along the IZS and near Darjeeling.

The IZS (including MKT and MMT) is marked by the occurrence of ophiolites, tectonic melanges/olistostromes and like other examples of subduction zones, especially the circum-Pacific, has undergone widespread regional metamorphism (Fig.1). High- and low- or intermediate-pressure paired metamorphic belts have been recognized in southern Tibet (Zhang, 1980), Ladakh (Virdi, 1981b) and Kohistan (Jan and Howie, 1981). Ophiolites and melanges have also been reported along the sutures on the western and eastern borders of the Indian plate (Dejong and Subhani, 1979; Moore et al., 1980; Agrawal and Kacker, 1980; Mitchell, 981; Jan et al., 1985).

Several occurrences of high-P metamorphic rocks have been reported along the suture zones enclosing the Indian subcontinent: Khost (Afghanistan), Jijal, Shangla, Allai (Kohistan), western and eastern Ladakh, southern Tibet, Assam, Nagaland, Burma. It is expected that further investigations would reveal additional occurrences of such rocks, especially along the IZS. In this paper, a summarized review of the petrology of the Himalayan high-P rocks is presented, followed by a discussion regarding their tectonic significance.

PETROLOGY OF THE HIGH-P METAMORPHIC ROCKS OF THE HIMALAYA

Garnet Granulites of the Jijal-Patan Complex, Kohistan

The Jijal-Patan complex covers an area of 150 sq km in the NW Himalaya (35° 5'N, 72° 55' E). It consists of a wedge of high-P garnet granulites with an up to 4 km thick slab of ultramafic rocks on their S, along the MMT (IZS) (Fig.2). The most abundant granulite paragenesis consists of garnet + plagioclase + clinopyroxene + quartz + rutile ± hornblende ± epidote ± scapolite, but some rocks are devoid of plagioclase and consist of two or three of the mafic phases ± orthopyroxene. The granulites are derived from a series of (?) Early Cretaceous gabbros, anorthositic and ultramafic rocks, and quartz diorites/tonalites that represent cumulates from the bottom part of the Kohistan island arc. The ultramafic mass consists of diopsidites, dunite, peridotites, websterite and podiform chromitites (high Cr/Cr + Al) representing cumulates to a primitive tholeiitic magma (Jan and Windley, in prep.). It is not clear whether the two represent a continuous cumulate sequence or two separate associations formed from independent pulses of a primitive and an evolved magma.

The Jijal-Patan complex has undergone at least two phases each of deformation and progressive metamorphism. The first episode of high-grade metamorphism is evidenced in two-pyroxene granulite relics equilibrated at 750 °C. 5.5 to 7.5 kbar (Jan, unpublished data). This was followed by garnet granulite facies metamorphism (800 °C, 10 kbar; Jan unpub. data; Jan and Howie ,1981; Bard, 1983). During ascent the rocks were degranulitized locally, especially along shear zones, with overprints of garnet amphibolite- and greenschist facies. Some hornblende and garnet, much epidote/zoisite, kyanite, and paragonite (with 100 Na/(Na + K) up to 98.5; Jan et al., 1982) were produced during uplift and erosion.

The complex appears to be a fault-bounded wedge in a vast terrain of dominantly ortho-amphibolites belonging to the Kohistan arc (see maps in Coward et al., 1982; Bard, 1983). It is separated from rocks of the Indian plate by the IZS. Twenty five kilometers to the SW of Jijal, several "horizons" of garnet + clinopyroxene + plagioclase assemblage occur in banded amphibolites. PT estimates based on mineral analyses on these rocks are similar to those deduced for the Jijal-Patan complex and significantly higher than those of the surrounding amphibolites (Jan, unpublished data). It is likely that the amphibolites here are retrograde in nature with relics of garnet granulites. Thus, there is a possibility that an extensive belt of high-P granulites developed in the N of the IZS, followed by degranulitization during uplift. The granulites owe their origin to deep burial (35 km) during subduction (Jan and Howie, 1981). A Sm/Nd mineral isochron age of 104 Ma (Coward et al., 1986) confirms the Cretaceous age of the Jijal garnet granulite facies metamorphism. Southwest of these are found high-P and low-T rocks and have been discussed subsequently.

Blueschists of Shangla and Allai Kohistan

The Indo-Pakistan subcontinental sequence S of IZS in Swat is made up of the twice metamorphosed schists, Cambrian granitic gneisses, and unconformably overlying once metamorphosed schists. The ophiolitic and associated rocks of the IZS have been divided into three units separated by thrusts (Kazmi et al., 1984). The Shangla blueschist melange is locally present in the north, followed southwards by greenschist melange and, finally, ophiolitic melange. The rocks were considered by Jan et al. (1981) to represent an oceanic trench assemblage. North of these melange group rocks occur amphibolites of the Kohistan arc thrust over the blueschist melange (Fig.2).

The blueschist melange consists of large dismembered masses (up to 6 km in extent) of metavolcanics and phyllites with smaller lensoid masses of serpentinite, talc-tremolite schists, metagabbros, metadolerite, metagraywacke, marble, and rare quartzitic rocks. Piemontite schists (± spessartine, margarite, Mn-chlorite) blocks were reported by Jan and Symes (1977). Kazmer et al. (1983) have reported fossils of Jurassic to Middle Cretaceous age from a limestone block but Guiraud et al. (in prep.) report also Nummulitic limestone blocks. Radiometric ages yield 100±20 Ma and 67±12 Ma for glaucophane (Maluski and Schaeffer, 1982), and 83.5±2 Ma (Maluski and Matte, 1984) and 84±1.7 Ma (Shams; 1980) for white mica. These dates suggest that high-P metamorphism was related to subduction, because collision is considered as Early Tertiary by Powell (1979) and Molnar 1986). The presence of Mesozoic and Eocene limestone blocks presumably record melange formation during obduction.

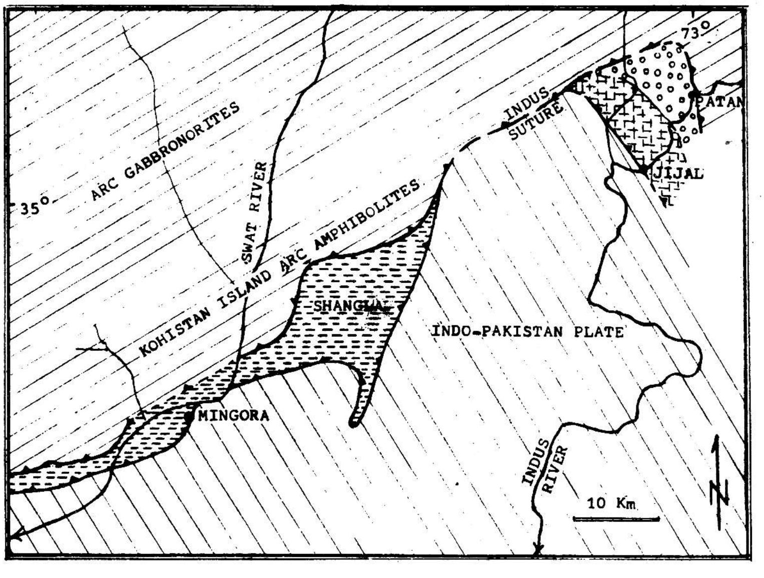

Fig.2. Simplified geotectonic map of the Indus-Zangbo Suture in Swat Kohistan. **Crosses**- Jijal upper mantle ultramafic rocks; **open circles**- High-P garnet granulites. Dashes show the high-P and low-T metamorphic belt of Shangla comprising tectonic melange with lenses of ophiolite and blueschist. (After Jan and Howie, 1981; Martin et al., 1962).

The petrography of the rocks has been presented by Shams (1972, 1980), Jan et al. (1981) and Kazmi et al. (1984). Blue amphibole (glaucophane, crossite) occurs in blueschists, metagraywackes and, rarely, metacherts and pure calcite rocks. Phengite is widespread in the rocks, jadeitic pyroxene occurs near Shangla (Guiraud et al., in prep.), and aragonite has been reported in some rocks near Mingora (Davies, 1962). Lawsonite has not been found but in Malam-Jaba area. A rare metabasite contains rhombic sections of porphyroblastic calcite that might be pseudomorphing lawsonite. Jan et al. (1981) thought that the blueschists were metamorphosed at about 7 kbar and 380 °C, with a possibly higher T overprinting as suggested by garnet-bearing veins.

The presence of three types of zoned amphiboles (calcic cores through sodic-calcic to sodic rims) in Shangla was thought by Guiraud et al. (in prep.) to be suggestive of oscillatory transition between glaucophane bearing greenschist- and epidote-amphibolite facies, with a negative gradient of -70 to -65 °C km. According to them, the highest pressure assemblage developed at 8 kbar, 320 °C and the lowest at 6 kbar and 500 °C.

In Allai Kohistan, across the Indus SE of Jijal and 30 km NE of Shangla, Majid and Shah (1985) have found a thick melange zone separating amphibolites of the Kohistan arc from gneisses of the Indian plate. The melange consists of ultramafic and volcanic rocks, greenschists, metagraywackes, limestone and chert. One metagraywacke contains quartz, phengite, chlorite, alkali amphibole, plagioclase, epidote, apatite, carbonate and opaque grains. Microprobe analyses suggest that the pistacite content of the epidote ranges from 17.9 (core) to 19.8 (margin), and the MgO + FeO content of the phengite ranges from 8.2 to 10.0%. The sodic amphibole is zoned with cores of glaucophane and margins of crossite.

Blueschists of Western Ladakh

Frank et al. (1977) first recorded these rocks along the Pushkyum thrust, to the east of Kargil. Honegger et al. (1989) reported the presence of such rocks in other places along the IZS in Ladakh, with details of those from western Ladakh. The blueschists occur as imbricated slices and blocks in Shergol melange between the Dras island arc volcanic thrust sheets to the north and the Lamayuru complex thrust sheets to the south. Other types of occurrences are also reported by these workers. The associated rocks consist of tectonized ultramafics (mostly serpentinized), gabbro, diabase (some rodingitized), volcanics (some representing tectonic slices of Dras), red radiolarites, cherts, oolitic limestone, siliceous schists, phyllite, mica schists, and gneisses. Calcareous schists forming the matrix of the melange consist of calcite, quartz, white mica and, rarely, stilpnomelane (Frank et al., 1977).

The petrography of the high-P metamorphic rocks and details of mineral chemistry have been presented by Honegger et al. (1989). The common mineral assemblages are: Metabasites containing alkali amphibole + sodic pyroxene + lawsonite + chlorite + titanite ± phengite ± albite ± stilpnomelane; metapelites consisting of alkali amphibole + lawsonite + phengite + chlorite + garnet + quartz ± stilpnomelane ± titanite ± albite, and alkali amphibole + lawsonite + phengite + quartz + albite ± garnet ± titanite ± chlorite; calcareous assemblages with alkali amphibole + phengite + aragonite/calcite

+ quartz ± stilpnomelane ± chlorite ± titanite.

The amphiboles range in composition from sodic-calcic to sodic, including solid solution of glaucophane-crossite-riebeckite. The omphacitic pyroxene contains 32 to 71 mole % jadeite. The garnets are zoned with cores containing up to 64 mole % spessartite and 13 mole % almandine, and rims with 2 mole % spessartite and 65 mole % almandine. Their grossular content ranges from 23 to 32 mole % but pyrope content remains constant at 1 to 4 %. The degree of phengite substitution in the white mica ranges from 3.3 to 3.8 and is strongly dependent on rock type and coexisting mineral phases for the lawsonite-bearing assemblages. The paragonite content of these phengites is less than 20 % for all samples and diminishes with increasing Si. The chlorites have a pycnochloritic composition with Al^{iv} and Al^{vi} contents comparable to those in prehnite-pumpellyite schists.

Geochemical investigations show the primary alkaline nature of the blueschist, which suggests an oceanic island or a transitional MORB type tectonic setting. K/Ar dating suggests middle Cretaceous metamorphism with temperatures of 350 to 420 °C and pressures around 9-11 kbar (Honegger et al., 1989). The presence of tectonic slices and blocks of Dras volcanics, and gneisses (? of the Indian plate) suggests that the melange may have formed during the late Cretaceous or, more likely, Early Tertiary, following the collision between the Indian plate and the Ladakh magmatic arc. Thus, like Kohistan and eastern Ladakh, here too the blueschist metamorphism appears to be related to the Cretaceous subduction of the neo-Tethyan Mesozoic crust before its closure during Eocene.

Blueschists of Eastern Ladakh

Blueschist facies rocks here were found in the IZS near Sumdo (33° 15' N, 78° 27' E), to the west of Tibetan border (Virdi et al., 1977). From N to S, the following litho-tectonic set up is documented in the IZS zone of eastern Ladakh (Virdi et al., 1977; Virdi, 1981a, 1981b; Kumar, 1981; Thakur, 1981; Sharma and Gupta, 1983; Thakur and Bhat, 1983):

The ophiolite melange (Fig.3) consists of tectonic slices of greenschists, conglomerates, garnet-mica schists, amygdaloidal basalt, agglomerate and interbedded slate and limestone, together with a mixed up jumble of lenses and blocks of Cretaceous limestone, serpentinite, peridotite and glaucophane schists, as well as Dras volcanics (Thakur and Bhat, 1983). Kumar (1981) reported altered eclogite bodies in serpentinite near the Zildar thrust, but these have been considered garnet amphibolite by Virdi (1981b). Between the ophiolite melange and the Indus formation lies 8 km thick thrust slab consisting, from S to N, of a 5 km thick lower zone of ultramafic rocks, a gabbro zone with dykes, and an upper zone of volcanics with pillow lavas toward top and overlain by interbedded chert, jasper, tuff and clastic rocks (Thakur and Bhat, 1983).

Ladakh plutonic complex (Cret-Tertiary)

_________ Unconformity ____________

Kargil Formation (Neogene sediment)

___________ Tectonic Contact _________

Indus Formation (Mid Cret-Eocene arc-trench gap sediments)

____________ Chunglung Thrust ____________

Zildat-Sumdo ophiolite melange

____________ Zildat Thrust _______________

Tso-Morari crystalline complex (Paleozoic)

The mafic blueschist parageneses comprise glaucophane + epidote + quartz ±white mica±stilpnomelane± albite±garnet±rutile±carbonates ± actinolite± chlorite±lawsonite (rare). The associated schists consist of quartz + albite + epidote, and calcite + white mica±chlorite, with lawsonite in a few (Virdi et al., 1977; Virdi, 1981a). Detailed microprobe analyses (Jan, 1987) reveal that the amphibole is zoned with glaucophane cores, passing through crossite to barroistic and/or actinolitic margins, the epidote has a Ps range of 11 to 30 mole %, garnet shows a continuous increase in Fe/Mn towards the margin, and the white mica consists of phengi (up to 10% $Fe_2O_3 + MgO + MnO$) and paragonite. The blueschist paragenesis is thought to have formed at 370 to 480 °C, 7 to 8 kbar. The calcic amphibole and paragonite were overprinted during uplift and erosion at 6 to 4 kbar. The blueschist is chemically similar to oceanic basalts.

The presence of Cretaceous limestone blocks and Dras volcanics in the melange suggests its formation during late Cretaceous/Early Tertiary. If the garnet-mica schist blocks belong to the Indian plate, then melange formation would have taken place during the Early Tertiary collision. Since blueschist parageneses have not been reported in all the component lithologies of the melange, therefore, high-P metamorphism seems to predate the development of melange. Hence, the blueschist facies metamorphism here also can be related to the Cretaceous subduction of the neo-Tethyan lithosphere.

High-P, Low-T rocks of southern Tibet

The ophiolite belt along the Zangbo suture is tens of kilometers wide and extends E-W for over 1,000 km, running westwards into the Indus suture zone. The ophiolitic rocks have been described by Haoruo and Wanming (1980), Shackleton (1981), Zhou et al. (1982), and others. The ophiolites contain Late Cretaceous radiolarian siliceous rocks, flysch and other pelagic sediments in addition to pillow lavas. During Paleogene, the main basic and ultrabasic (tectonized harzburgite) masses were tectonically emplaced in great magnitude. The Xigaze ophiolite is one of the most important bodies along IZS and merits a brief mention. It is unusual in having a very small, nearly missing, amount of cumulate gabbros and a diabase sill rather than a dyke complex (Nicholas et al., 1981). Lead isotope investigation suggests that the tectonite harzburgite has much higher $^{207}Pb/^{204}Pb$ ratios, and is much older, than the overlying magmatic rocks considered to have crystallized 120 ± 10 Ma ago (Gopel et al., 1984).

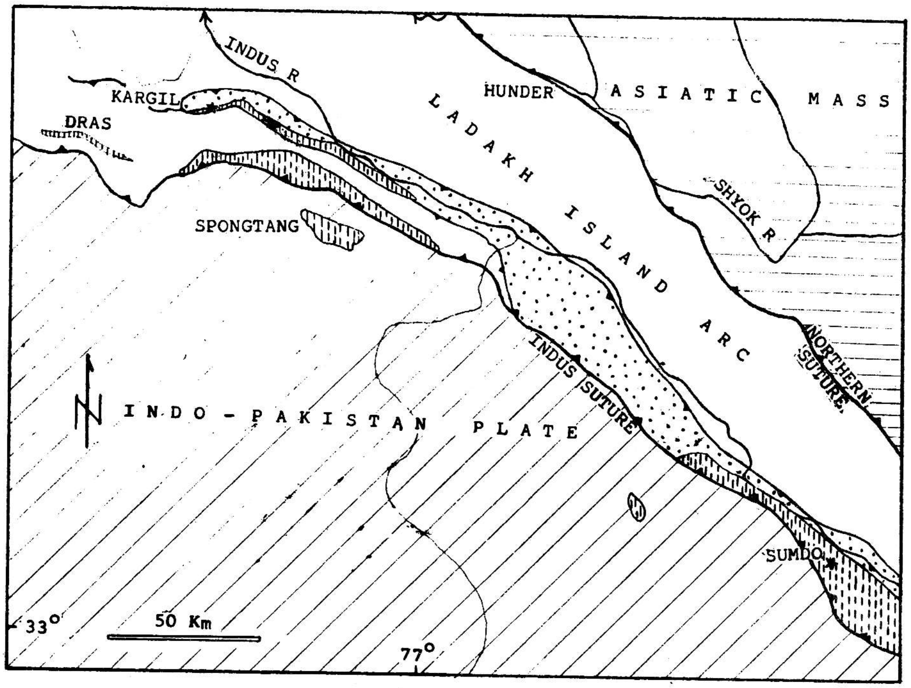

Fig.3. Simplified tectonic map of the Indus-Zangbo Suture in Ladakh (modified after Thakur, 1981). Dashes show ophiolites and melanges with local occurrences of blueschists (asterics) and dots are for arc-trench gap sediments.

To the north of the ophiolites occur the calc-alkaline rocks of the Gangdise belt (110 Ma and younger; Maluske et al., 1982). The southern margin of the ophiolite is represented by a tectonic ophiolite melange, followed southwards by a sedimentary tectonic melange at least 10 km wide. The contact of the two melanges and that of the sedimentary melange with the Tethyan metasediments to the S are tectonic (Shackleton, 1981).

A narrow and discontinuous belt of high- and medium-P rocks along the Yarlung-Zangbo suture belt in southern Tibet has recently been reported but the available data are scanty and fragmentary. Zhang et al. (1980) and Zhang et al. (1981) studied the white micas in these rocks. Their b_0 values and chemical composition, especially MgO content, were regarded to be suggestive of high-P metamorphic conditions, but typical blueschists have not been reported there as yet. The rocks belong to prehnite-pumpellyite and high-P greenschist facies conditions. Xiao and Gao (1982), however, described stilpnomelane-bearing and alkali amphibole-stilpnomelane greenschists in the Tsangpo suture melange near Sans Sang (60 km west of Shigatse). Three microprobe analyses show that one alkali amphibole is intermediate between crossite and magnesio-riebeckite, and two are intermediate between glaucophane and tremolite (? barroisite). These rocks are associated with Jurassic to lower Cretaceous cherts and volcanics, but the occurrence has been questioned by Burg et al. (1987).

The existence of a parallel metamorphic belt of low-P to the N of the high-P belt has been reported by Zhang et al. (1981). This (Gangdise) metamorphic belt is very extensive and of andalusite-sillimanite type. Zhang et al. (1981) think that the paired metamorphic belts were formed by rapid underthrusting of the Indian plate beneath the Eurasian plate during Late Cretaceous to Tertiary.

Blueschist facies rocks near Darjeeling, Assam

Sinha Roy (1975) reported these rocks in the Daling-Darjeeling thrust block near Sikkim-Bhutan border (88° 47' E, 27° 6' N). Although the rocks are located about 250 km to the S of IZS, this interesting occurrence merits description. Sinha Roy (1975) noted a temporal and spatial relation between blueschist facies rocks and structurally overlying Barrovian-type rocks, with a transition from blueschist facies in the lower structural level to greenschist facies in the overlying structural level. The Barrovian rocks show an inverted metamorphic zonal sequence from biotite to sillimanite grade. The metamorphic rocks are considered to be Precambrian/ Proterozoic and have undergone three episodes of deformation.

Metagraywackes in the lower and intermediate structural levels consist of quartz + plagioclase + sericite + chlorite + sphene ± microcline ± epidote ± lawsonite ± stilpnomelane ± (?) aragonite. Blueschists within the metagraywackes contain sodic amphibole + actinolite + stilpnomelane + epidote + sphene + plagioclase + quartz ± chlorite ± lawsonite. Based on optical properties, the sodic amphibole is considered to be intermediate between actinolite and glaucophane (? barroisite). PT estimates for the rocks are 300 to 400 °C, 5 to 7.5 kbar. The blueschist facies rocks show an upward passage to greenschist facies with a decrease in the modal abundance of sodic amphibole due to replacement by the greenschist facies minerals.

The blueschist facies metamorphism was overprinted on Precambrian rocks during Tertiary, a more extensive time interval that has been reported for high-P rocks typical of subduction zone complexes (Ernst, 1977). According to Sinha Roy (1975) " the frontal thrust belt comprising the Precambrian/Proterozoic rocks represents the basement nappes formed during the Himalayan orogeny (Tertiary) from the microcontinent, situated between the main landmass of India and northern Asia. Therefore, the major thrusts in these belts (foot hill and inner belts) are the manifestations of collision between the Indian landmass and the micro-continents. It is highly tempting to relate the high pressure metamorphism in these rocks to collisional tectonics although the exact mechanism is not clear".

Blueschists in the Naga Hill Ophiolite Belt

The 800 sq km Naga Hill ophiolite belt extends discontinuously for more than 200 km in a NE-SW direction. The ophiolites were emplaced during the Late Cretaceous/Early Eocene along the suture zone between the Indian and Chinese plates (Agrawal and Kacker, 1980; Singh and Srivastava, 1980). These comprise a variety of lithologies: amphibolite, serpentinite, harzburgite, pyroxenite, gabbro, diorite, basalt, spilite, agglomerate, tuff, talc-serpentine schist, glaucophane schist and quartz-chlorite schist which, at places are intercalated with oceanic sediments (limestone, chert, graywacke, tuff and phyllite). The ophiolite belt is tectonically bounded on the E by a continental crustal block consisting of sheared granite, quartzite, limestone, quartz-sericite schist and phyllite, and on the W by a group of para-autochthonous flyschoid sediments of Upper Cretaceous to

Eocene age (Fig.4).

The ophiolite bodies are dismembered and occur as steeply inclined sheets ranging from a few to a few tens of kilometers in length, in swarms arranged in en-echelon pattern. The ophiolite sequence ranges from meta-peridotites at the base to spilites and basalts at the top, through a cumulate section of dunite and gabbros. In a narrow melange zone 25 to 100 m thick, blueschists are associated with dismembered ophiolitic rocks in at least five localities. The first deformational episode, correlated with the first phase of the Himalayan orogeny (Late Cretaceous-Early Eocene), is thought to be responsible for the development of blueschist parageneses (Singh and Srivastava, 1980). The present author considers that high-P metamorphism took place during mid-Cretaceous subduction. The blueschists associated with quartz-chlorite-sericite schists (Ghosh and Singh, 1980) consist of the parageneses glaucophane + actinolite + epidote + opaque oxide ± lawsonite ± aragonite ± chlorite. Some rocks also contain phengite, garnet and/or omphacite. Microprobe and whole rock chemistry of this occurrence is in progress.

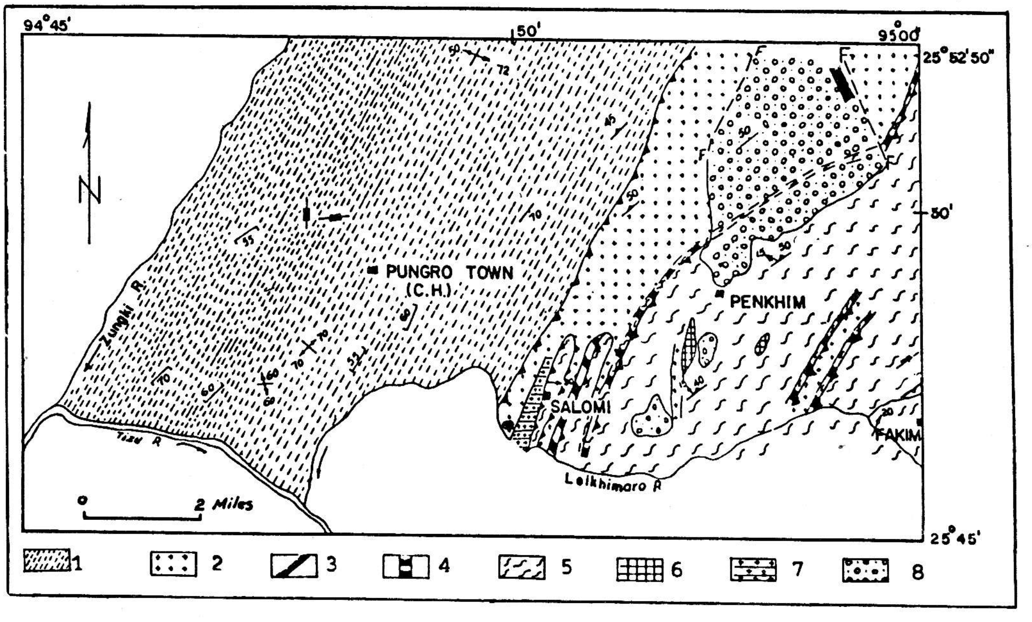

Fig.4. Geological map of the northern part of the Nagaland ophiolite belt (after Singh and Srivastava, 1980). 1 = Late Cretaceous-Eocene flysch (shale, slate and phyllite); 2 = Ophiolite sequence ranging from metamorphic peridotite at the base to spilites, basalts and pelagic sediments at the top through cumulate dunite and gabbros (Upper Cretaceous to Lower Eocene); 3 = Magnetite; 4 = Blueschists (? Upper Cretaceous); 5 = Chlorite-sericite ± quartz schists; 6 = Limestone; 7 = Tectonic Melange; 8 = Mio-Pliocene molasse (shale, graywacke, grit, conglomerate).

DISCUSSION

Like the circum-Pacific, the IZS is characterized by the development of high-P metamorphic rocks. Over half a dozen occurrences of these rocks have been discovered along the Indus-Zangbo and related sutures enclosing India. The high-P rocks have formed at low to moderately low temperatures (up to high-T blueschist facies) except the garnet granulites of Jijal. "The high-pressure metamorphic assemblages are thought to be generated near and beneath the trench in the upper 20-35 km of the descending slab, well below the base of most accretionary wedges" (Ernst, 1984).

The intimate association, in the IZS melanges, of blueschists with ophiolitic ultramafic and gabbroic rocks and blocks of limestone (Shangla; Naga land, west and east Ladakh), arc volcanics (west and east Ladakh), manganiferous schists (2.1% MnO) and (?) arc-derived clastic sediments (Shangla) suggest that the high-P metamorphism is related to oceanic trench environments as in California and elsewhere (Ernst, 1984; Dewey and Bird, 1971; Miyashiro, 1973). This conclusion is further corroborated by the occurrence of arc-trench gap sediments to the N of east Ladakh melange (Thakur and Bagati, 1983). Thus, the IZS must be the trace of a major collisional zone between India and northerly lying landmasses, and it should have played a major role in the Himalayan orogeny.

In Kohistan, Ladakh, and southern Tibet, magmatic arcs and paired metamorphic belts have been recognized. In all, the lower-P belts and subduction-related magmatic arcs lie to the N of the high-P rocks (Jan and Howie, 1981; Virdi, 1981a 1981b; Shackleton, 1981; Zhang, et al., 1981; Maluski et al., 1982; Zhaou et al., 1981). These findings and the occurrence of arc-trench gap sediments N of ophiolite melange in Ladakh lend additional support to the commonly held opinion that the neo-Tethyan lithosphere subducted northwards underneath the Tibetan mass and Kohistan-Ladakh arcs.

K/Ar and $^{39}Ar/^{40}Ar$ ages on minerals from blueschist facies rocks of Shangla (Kohistan) range from 70 to 100 Ma (Shams, 1980; Maluski and Schaeffer, 1982; Maluske and Matte, 1984), and the western Ladakh blueschists have radiometric age of mid-Cretaceous (Honegger et al., 1989). The high-P garnet granulite facies metamorphism in Jijal, NE of Shangla, has a Sm/Nd mineral isochron age of 104 Ma. (Coward et al., 1986). Elsewhere along the IZS the timing of high-P metamorphism is not clearly known but a Cretaceous age can be inferred by analogy to Shangla and western Ladakh. A Cretaceous age would mean that high-P metamorphism was induced by subduction in contrast to obduction because paleomagnetic data (Powell, 1979; Klootwijk et al., 1979; Molnar, 1986) suggest that collision between India and Tibet (or magmatic arcs) occurred during Eocene.

Fossil evidence and the proposed tectonic models suggest that arc magmatism in Kohistan and Ladakh started during Late Jurassic-Early Cretaceous (Ivanac et al., 1956; Andrews-Speed and Brookfield, 1982; Thakur, 1981; Coward et al., 1982, 1986; Honegger et al., 1982; Bard, 1983; Dietrich et al., 1983; Jan and Asif, 1983; Radhakrishna et al., 1984; Searle et al., 1987). By inference, the northwards subducted neo-Tethyan lithosphere should have originated by Late Jurassic. Thus, blueschist facies metamorphism in Ladakh and Kohistan may have occurred some 90 million years after the initiation of subduction and trench system. If this interval is realistic, it leads to two important conclusions: (1) that the spreading rate of the neo-Tethyan ocean was slow, and (2) that high-P (blueschist facies) metamorphism in Kohistan-Ladakh coincides with the rapid northward movement (15 cm/year) of India following its breakup from Africa in mid-Cretaceous (cf. Windley, 1984).

In the melanges along IZS, there are blocks of Nummulitic and/or Mesozoic limestones (Shangla and eastern Ladakh) and Cretaceous Dras volcanics (western and eastern Ladakh). Therefore, the melange formation may principally have taken place during Late Cretaceous or, more likely, Early Tertiary. This age coincides with the timing of collision between India and Kohistan-Ladakh arcs and may suggest that the melanges formed during obduction of the arc.

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