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HIGH–P ROCKS ALONG THE SUTURE ZONES AROUND INDO-PAKISTAN PLATE AND PHASE CHEMISTRY OF BLUESCHISTS FROM EASTERN LADAKH

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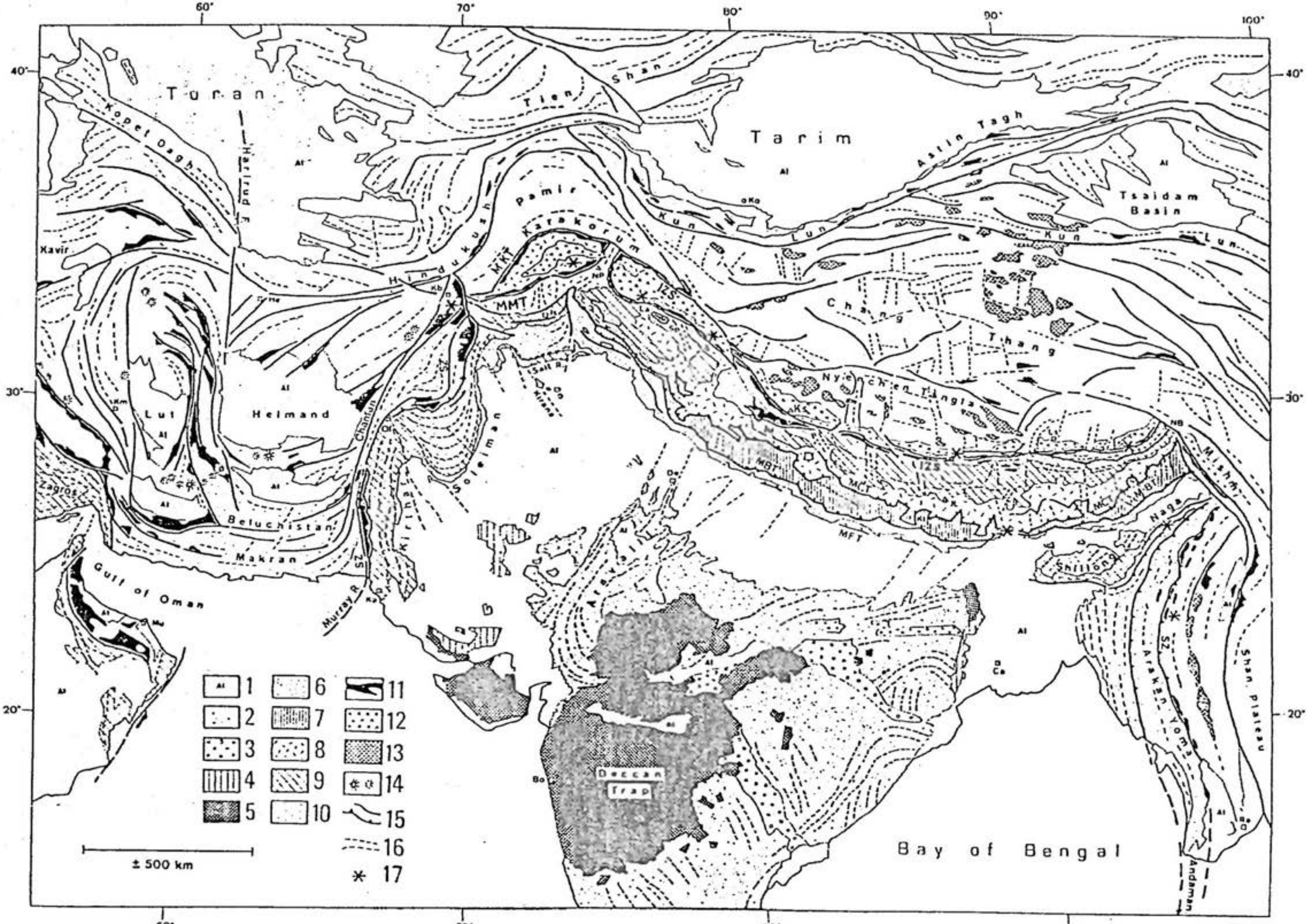
ABSTRACT

The Indus-Zangbo suture zone (IZS), the Indoburman suture zone and the Chaman Fault are the traces of major collisional boundaries between the Indo-Pakistan plate and Eurasian block, Gondwanic micro-continents or island arcs. These suture zones are characterized in several places by ophiolites and tectonic melanges. High-P metamorphic rocks, generally belonging to blueschist facies, have recently been discovered along the suture zones in Naga hills, southern Tibet, eastern and western Ladakh, Swat and Afghanistan. The high-P metamorphism probably occurred during the Late Cretaceous/Paleocene. In the IZS it is complemented by low- to medium-P metamorphism to the north, suggesting a northward dip for the subduction zone. Along the southern margin of the Kohistan arc near Jijal, immediately N of IZS, gabbroic rocks were metamorphosed to high-P garnet granulites at a depth of > 40 km about 100 m.y. ago.

Detailed investigations, based on whole rock- and 188 point analyses in three sections, suggest that metabasites in the eastern Ladakh ophiolite melange are ocean floor basalts metamorphosed under blueschist facies conditions. They are mineralogically similar to high-grade blueschists of other areas and contain sodic, sodic-calcic and calcic amphiboles, epidote, chlorite, albite, phengite, paragonite, garnet, quartz, rutile, calcite, and magnetite. The PT trajectory suggests that the metamorphic conditions culmiated around 370–480°C, 7-8 kbar and subsequent retrogression, possibly during uplift, took place at similar temperature but lower (6-4 kbar) pressure.



Turan
Kopet Dagh
Harirud F.
Tien Shan
Tarim
Altin Tagh
Tsaidam Basin
Kun Lun
Pamir
Karakorum
Hindukush
MKT
MMT
IZS
Chang Thang
Nyenchen Tangla
Salt R.
Kirana
Lut
Helmand
Chaman
Soleiman
Kirthar
Beluchistan
Makran
Zagros
Xavir
Gulf of Oman
Murray R.
MBT
MCT
MFT
Mishmi
Naga
Shillong
Aravalli
Deccan Trap
Arakan Yoma
Shan Plateau
Andaman
Bay of Bengal
± 500 km
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INTRODUCTION

This paper describes briefly the high-P metamorphic rocks of the Indus-Zangbo suture zone (IZS), the Khost ophiolite nappe, the Nagaland ophiolite belt, and of Assam, with details of the chemical mineralogy of those from the eastern Ladakh. The IZS is commonly agreed upon to mark an important boundary along which the Indo-Pakistan plate was subducted under the Tibetan landmass (Powell and Conaghan, 1973; Gansser, 1980a; Le Fort, 1975). In the Ladakh and Kohistan regions of western Himalaya-Karagoram, the IZS bifurcates into the Main Karakoram Thrust (MKT) and Main Mantle Thrust (MMT). The area between the MKT and MMT is considered to represent ancient island arc(s), developed largely during the Cretaceous in response to northwards intra-oceanic subduction (Tahirkheli *at al.,* 1979; Klootwijk *at al.,* 1979; Andrews-Speed and Brookfield, 1981; Honegger *at al.,* 1982; Bard, 1983; Jan and Asif, 1983). The possibility of an island are setup for the Gangdesi belt, occurring N of the IZS in southern Tibet, has also been suggested (Shackleton, 1981).

The IZS (including MKT and MMT) is marked by the occurrence of ophiolites and melanges and, like other examples of subduction, especially the circum-Pacific, has undergone widespread regional metamorphism (Fig. 1). High- and Low-P paired metamorphic belts have been recognized in southern Tibet (Zhang *et al.,* 1980), Ladakh (Virdi, 1981a) and Kohistan (Jan and Howie, 1981). Ophiolites and melanges/olistrosomes have also been reported along the western (Chaman transform fault) and eastern margins (Indo-Burmese zone) of the Indo-Pakistan plate (cf. Panayiotou, 1980). Several occurrences of high-P metamorphic rocks have been reported from the suture zones enclosing Indo-Pak: from Khost ophiolite nappe in Afghanistan (Tapponnier *et al.,* 1981; Guiraud *et al.,* in prep.), Burma (Mitchell, 1981), Nagaland (Agrawal and Kacker, 1980; Ghose and Singh, 1980), and IZS.

High-P metamorphic rocks along the IZS occur in Kohistan and Swat (Pakistan), eastern and western Ladakh (Kashmir), and southern Tibet. Amongst these only the Kohistan occurrences have been investigated in some detail. It is

Fig. 1. Geotectonics of the wider Himalaya region (after Gansser, 1980b), with locations of high–P rocks along the sutures around Indo-Pakistan plate. 1. Alluvial plain; 2. Pre-Gondwana basement, Indian Shield; 3. Gondwana sediments on Indian shield; 4. Mesozoic Platform sediments on Indian Shield; 5. Trap, Indian Shield; 6. Molasse type sediments (Siwaliks of Sub-Himalaya); 7. Lesser Himalaya; 8. Crystalline of High Himalaya; 9. Tethyan sediments (Platform); 10. Flysh facies; 11. Ophiolites incl. ophiolitic melanges and related pelagic sediments; 12. Transhimalayan plutons; 13. Tertiary and Quaternary Volcanics; 14. Quaternary Volcanoes; 15. Main thrust and faultzones; 16. Lineaments (fold axis, sec. faultzones, fracture zones); 17. High–P metamorphic rocks. Abbreviations: B. Bombay; Ca. Calcutta; De. Delhi; He. Herat; Is. Islamabad; Jl. Jolmo Lungma (Everest); Ju. Jungbwa nappe; K. Kabul; Ks. Kailas Mt.; Ka. Karachi; Kt. Kathmandu; K. Khotan; La. Ladakh; Ls. Lhasa; Mu. Muskat; NB. Namcha Barwa Mt.; NP. Nanga Parbat Mt.; Qt. Quetta; Ra. Rangun; Sp. Spongtang Klippe. Main structural units: SZ. Suture Zone (IZS. Indus-Zangbo Suture Zone; MKT. Main Karakoram Thrust; MMT. Main Mantle Thrust); MCT. Main Central Thrust; MBT. Main Boundary Thrust; MFT. Main Frontal Thrust; Outside wider Himalaya and Indian Shield only structural trends, ophiolites and volcanoes are shown.

expected that further search would reveal additional occurrences of such rocks in the IZS. In this paper, a summary of the high-P rocks is presented for the sake of a general review. Also, details of geochemistry from the eastern Ladakh occurrence are presented to postulate the tectonic environments and conditions of metamorphism.

(A) HIGH-PRESSURE METAMORPHIC ROCKS OF THE INDUS-ZANGBO SUTURE

The Garnet Granulites of The Jijal–Patan Complex, Kohistan

The Jijal-Patan complex covers an area of ~ 150 km^2 in NW Himalaya (35°5′ N, 72°55′ E). It consists of a wedge of high-P granulites with an up to 4 km thick slab of ultramafic rocks on their south along the MMT. The most abundant paragenesis consists of garnet+plagioclase+clinopyroxene+quartz+rutile±hornblende±epidote, but some are devoid of plagioclase and consist essentially of two or three of the mafic phases±orthopyroxene. The granulites are derived from a series of Early Cretaceous gabbros, troctolites, anorthositic rocks, pyroxenites and quartz diorites that may represent the Tethyan lower crust or, more probably, magmatic cumulates at the bottom of the Kohistan arc. The ultramafic slab consists of diopsidite, dunite, harzburgite, websterite and podiform chromitite representing a diapir or tectonic slab of the upper mantle.

The Jijal-Patan complex has undergone at least two phases each of deformation and progressive metamorphism. An early metamorphism produced two-pyroxene granulites at ~ 750°C, 6-8 kbar (Jan, unpublished data). This was followed by garnet granulite facies metamorphism (800–900°C, 12–14 khar; Jan and Howie, 1981; Bard, 1983) dated at 103 m.y. ago (Coward *et al.,* 1985). During uplift, the rocks were degranulitized locally, with overprints of amphibolite- and greenschist facies. Some hornblende, much epidote/zoisite, kyanite and paragonite (with 100 Na/(Na+K) up to 98.5; Jan *et al.,* 1982) were produced during ascent. Glaucophanic amphibole has recently been found in a secondary vein in pyrigarnites (M.A. Khan, pers. com.).

The complex appears to be a fault-bounded wedge in a vast terrane of dominantly ortho-amphibolites (see maps in Coward *et al.,* 1982; Bard, 1983). Twenty five kilometers to the southwest of Jijal, several "horizons" of garnet+clinopyroxene+plagioclase assemblage occur in banded amphibolites. PT estimates for these rocks are similar to those deduced for the Jijal-Patan granulites (Jan, unpubl. data) and significantly higher than those for the amphibolites. It is likely that the amphibolites 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 north of the IZS in Kohistan, followed by degranulitization during uplift. South of these are found high-P and low-T rocks discussed in the following section.

The Shangla (Swat) Blueschist

The Indo-Pakistan subcontinental sequence in the S of IZS in Swat is made up of twice metamorphosed schists, Cambrian granitic gneisses, and uncomformably 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. North of these melange group rocks occur amphibolites of the Kohistan arc thrust over the blueschist melange.

The blueschist melange is composed of large dismembered masses (up to 6 km in extent) of metavolcanics and phyllites with smaller lensoid masses of serpentinite, metagabbro, metadolerite, metagraywacke, metachert and marble; some rocks contain piemontite (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 (Eocene) limestone blocks. $^{39}Ar/^{40}Ar$ ages of 75–80 m.y. on phengite and glaucophane (Maluski and Matte, 1984) and an 84 m.y. K/Ar date on muscovite (Shams, 1980) suggest that the rocks were metamorphosed during the Late Cretaceous.

The petrography of the rocks has been presented by Shams (1972, 1980), Jan *et al.* (1981) and Kazmi *et al.* (1984). Amongst the typical minerals suggesting high-P and low-T metamorphism, jadeitic pyroxene has been reported from Shangla (Guiraud *et al.*, in prep.) and aragonite from Mingora (Davies, 1982); phengite is common but lawsonite has not been found. Blue amphibole (glaucophane to crossite) occurs in blueschists, metagraywackes and, rarely, metacherts and pure calcite rocks. Jan *et al.* (1981) suggested that the blueschists were metamorphosed at about 7 kbar and 380°C, with a possibly higher T overprinting as suggested by garnet-bearing veins.

Three types of zoned amphibole (calcic, sodic-calcic, and sodic) have been reported in the Shangla rocks. Thus, Guiraud *et al.* (in prep.) suggested oscillatory transition between glucophane-bearing greenschist facies and epidote amphibolite facies, with a negative gradient of – 70° to – 65°C/km. According to them, the highest pressure assemblage formed at 8 kbar, 320°C and the lowest at ~ 6 kbar and 500°C. The high-P metamorphism in Shangla has been related to subduction by some and obduction by others (for details consult the references cited and Bard, 1983).

In Alai Kohistan, across the Indus to the NE of Shangla and SE of Jijal, Majid and Shah (1985) have discovered a thick melange zone separating amphibolites of the Kohistan arc from gneisses of the Indo-Pakistan plate. The melange consists of ultramafic and volcanic rocks, greenschists, metagraywackes, limestone and cherts. One of the metagraywackes contains quartz, phengite, chlorite, alkali amphibole, plagioclase, epidote, apatite, carbonate and opaque mineral(s). Microprobe analyses show that the pistacite content of the epidote ranges from 17.9 (core) to 19.8 (margin), and the MgO+FeO content of the phengites from 8.2 to 10.0. The sodic amphibole is zoned with cores of glaucophane and margins of crossite.

High-P and Low-T Rocks of Southern Tibet

The ophiolite belt along the Zangbo suture is tens of kilometers in width and extends for over 1000 km in an E–W direction, running westwards into the Indus suture zone. The ophiolitic rocks have been described by Haoruo and Wanming (1980), Shackleton (1983) and Zhou *et al.* (1982). They contain Late Triassic and unconformably overlying Late Cretaceous radiolarian siliceous rocks, pillow lavas, flysch and other pelagic sediments. During Paleogene, the main basic and ultrabasic (tectonized harzburgite) masses were tectonically emplaced in great magnitude. The Xigaze ophiolite in Tibet is unusual in having no gabbro zone and a sill, rather than a dyke, complex (Nicholas *et al.,* 1981). Along the northern margin of the ophiolites occur the calc-alkaline rocks of the Gangdise belt, possibly an ancient island are (Shackleton, 1981). 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 south are also tectonic.

High-P metamorphic rocks have recently been reported from the Zangbo suture in southern Tibet, however, details are scanty. Zhang, Zhang and Li (1980) studied the white micas from metamorphic rocks of the suture zone near the great bend in the Zangbo river, SE Tibet. The b_0 values of the micas and their chemical composition, especially MgO content, were regarded to be suggestive of high-P metamorphism; however, blueschists have so far not been found there. Xiao and Gao (1982) reported stilpnomelane-bearing and alkali amphibole-stilpnomelane greenschists from southern Tibet. Three microprobe analyses suggest that one alkali amphibole is intermediate between crossite and magnesio-riebeckite, and two are intermediate between glaucophane and tremolite (barroisite). The eixstance of a parallel metamorphic belt of low-P facies series to the north of the high-P belt in SE Tibet has been reported by Zhang, Li and Li (1980).

(B) BLUESCHIST FACIES ROCKS OF AFGHANISTAN, ASSAM AND NAGALAND

Along the suture/thrust zones bordering western, northern and eastern margins of the Indo-Pakistan plate, three areas of blueschist facies metamorphism have been recognized. Although, these occurrences do not belong strictly to the Indus-Zangbo suture zone, they are described here briefly for the sake of completing a review of high-P metamorphic rocks around the Indo-Pak plate.

Blueschist Facies rocks of Khost, Afghanistan

The Khost ophiolite nappe is a northerly continuation of the Muslimbagh and Waziristan ophiolite massifs delineating the western suture of the Indo-Pak Plate. The Khost ophiolite, occurring about 140 km SE of Kabul, consists of dismantled harzburgites, gabbros, dolerites and pillow lavas. These are tectonically overlain by a thick (2500 m) sequence of pelagic sediments. These include, from bottom to top: red and grey radiolarian cherts, fine-grained limestones interbedded with carbonate turbidites and some sandstones and micro-conglomerates. The sediments are thought to have been deposited on oceanic crust and micropaleontological evidence points to a Triassic to Upper Jurassic age (Tapponier *et al.*, 1981). The entire pelagic sequence is thrust SE on top of the ophiolites, but some volcanic tuffs and exotic blocks of shallow marine limestones (Middle Cretaceous) occur between the two.

High-P metamorphic rocks have been recognized in two zones, 25 km WSW and 50 km NNE of Khost over a few square kilometers. In the locality to the WSW of Khost, an epizonal sequence of paragonite-phengite-garnet-bearing mica-schists with pink marbles, and green and/or blue-green horblende-bearing amphibolites are found. Those to the NE of Khost comprise metagraywackes with phengite, chlorite, and scarce glaucophane and crossite. Some basic meta-tuffs consist of blue-green amphibole (40%), white mica, epidote, sphene, chlorite, calcite and magnetite. Guiraud *et al.* (in prep.) list several other lithologies. They found the amphiboles to be zoned from hornblendic cores to actinolitic margins through glaucophane/crossite. They concluded that the rocks passed successively through epidite-amphibolite facies (470 ± 25°C, 6.5 ± 0.5 kbar), blueschist facies (385 ± 35°C, 7.5 ± 0.5 kbar) and greenschist facies conditions.

Blueschist Facies Rocks of the Eastern Himalaya, Assam

Sinha Roy (1975) described 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 south of the IZS, this interesting occurrence merits some description. Sinha Roy (1975) noted a temporal and spatial relation between the 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 Precambrian/Proterozoic and show three episodes of deformation.

Metagraywackes in the lower and intermediate structural levels consist of quartz + plagioclase + sericite + chlorite + sphene ± microcline ± epidote ± lawsonite ± stilpnomelane ± phengite ± pumpellyite ± (?) 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 is considered to have been overprinted on the Precambrian rocks during Tertiary, a more extensive time interval than 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 (foothill and inner belts) are the manifestations of collision between the Indian landmass and the 'microcontinents'. 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 km^2 Naga Hill ophiolite belt extends discontinuously for more than 200 km in a NE–SW direction. The ophiolites were emplaced during the Upper Cretaceous/Lower Eocene along the suture zone between the Indian and Chinese plates (Agrawal and Cacker, 1981; Singh and Srivastava, 1981). These comprise a variety of lithologies: amphibolite, serpentinite, harzburgite, pyroxenite, gabbro, diorite, basalt, spilite, agglomerate, tuff, talc-serpentine schist, glaucophane schist and quartz chlorite-sericite schist which, at places, are intermingled with oceanic sediments (limestone, chert, graywacke, tuff and phyllite). The ophiolite belt is tectonically bounded on the east by a continental crustal block consisting of sheared granite, quartzite, limestone, quartz-sericite schist and phyllite, and on the west by a group of para-autochthonous flyschoid sediments (Upper Cretaceous to Eocene).

The ophiolite bodies are dismembered and occur as steeply inclined narrow scheets ranging from a few to a few tens of kilometer 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 (Upper Cretaceous-Lower Eocene), is thought to be responsible for the development of blueschist facies parageneses (Singh and Srivastava, 1981). The blueschists, associated with quartz-chlorite-sericite schists (Ghose and Singh, 1980) consist of the following parageneses :

i) glaucophane-actinolite-lawsonite-epidote-quartz-opaque
ii) glaucophane-actinolite-epidote-chlorite-opaque
iii) glaucophane-aragonite-epidote-opaque

(C) BLUESCHIST FACIES ROCKS OF EASTERN LADAKH

Blueschist facies rocks were reported from the Indus suture zone near Sumdo (33°10′ N, 78°31′ E), west of Tibetan border in eastern Ladakh (Virdi *et. al.*, 1977). Although the Ladakh region has been investigated by a number of workers, detailed maps of the blueschists and associated rocks are unavai'able. From north to south, the following litho-tectonic set up is seen in the Indus suture zone of eastern Ladakh (Virdi *et al.,* 1977, Virdi, 1981a, 1981b; Kumar, 1981; Sharma and Gupta, 1983; Thakur and Bhat, 1983):

Ladakh plutonic complex (Creto- Tertiary)
——— Unconformity ———
Kargil Formation (Neogene sediments)
——— Tectonic Contact ———
Indus Formation (Arc-trench gap sediments, Mid. Cret–Early Olig)
——— Chunglung Thrust ———
Zildat – Sumdo Ophiolite Melange
——— Zildat Thrust ———
Tso-Morari crystalline complex (Paleozoic)

The Zildat ophiolite melange consists of tectonic slices of greenschists, conglomerates, garnet-mica schists, amygdaloidal basalt, agglomerate and interbedded slate and limestone, together with a mixedup jumble of lanses and blocks of Gretaceous limestone, serpentinite, peridotite, and glaucophane schist. North of the melange occur a lower zone of ultramafic rocks, 5 km thick; a gabbro zone with dykes; and an upper zone of island arc volcanics with pillows towards the top and overlain by interbedded chert, jasper, tuff and clastic rocks. These three zones, upto 8 km thick, constitute a thrust slab between the Indus Fm. to the north and Zildat ophiolite melange to the south (Thakur and Bhat, 1983).

Blueschists occur within the melange both near and away from the Zildat fault zone. (Virdi, 1981b), and Kumar (1981) reports the occurrence of altered eclogite bodies (garnet amphibolite according to Virdi, 1982b) in the serpentinite near the fault. The ophiolite, in the opinion of the present author, probably represents the Jurassic-Cretaceous crust-upper mantle of the meso or neo-Tehhys. Kumar (1981) thinks that high-P metamorphism started in Jurassic and "was quite intense during Upper Cretaceous to Early Tertiary". However, Virdi (1981b) regards it to be post-Cretaceous, possibly Eocene-Oligocene.

Blueschist has also been reported in northeast of Pashkyum (70°16′ E, 34°30′ N), in western Ladakh, some 250 km to the west of the above occurrence (Frank *et al.,* 1977). The blueschist here also occurs in a zone consisting of tectonic melange; the associated rocks being tectonized ultramafics, gabbro, diabase, volcanics (some representing tectonic slices of calc-alkaline Dras volcanics), red radiolarites, cherts, and siliceous schists, phyllite, mica schists and gneisses. The glaucophane schist consists of a prekinematic assemblage of weakly zoned, often broken, crossitic glaucophane, ankerite, stilpnomelane, epidote and albite. This assemblage has been overprinted by syn– to post-kinematic chlorite (replacing glaucophane along cracks), calcite and actinolite (Frank *et al.,* 1977). Further details of the blueschist facies rocks are not known and the remaining description is restricted only to those from eastern Ladakh.

Petrography of Blueschists from Eastern Ladakh

The following mineral assemblages were reported in the blueschists of eastern Ladakh by Virdi *et al.* (1977) and Virdi (1981a):

(1) Glaucophane–quartz–albite–carbonates–epidote–actinolite–rutile

(2) Glaucophane–quartz–white micas–epidote–opaque minerals

(3) Glaucophane–quartz–stilpnomelane–albite–epidote–opaque minerals

(4) Glaucophane–quartz–stilpnomelane–white micas–epidote–garnet

(5) Glaucophane–lawsonite–quartz–garnet–epidote–sphane–rutile

The associated pelitic schists, according to Virdi (1981a), consist of quartz+albite+epidote or calcite+muscovite±chlorite, with lawsonite in rare cases.

Only three samples of blueschists were studied in detail during the present course of investigation. All three are metabasites composed of amphiboles, epidote, chlorite, white micas, albite, garnet, and small amounts of magnetite (three microprobe analyses), rutile, calcite and quartz. The rocks are fine-grained but garnet, glaucophane and epidote may form porphyroblasts reaching 2mm in size. Sample L1 does not display schistosity, is coarser grained than the other two, and contains local pools rich in white mica, albite and quartz. Sample L2 is midly schistose with a higher proportion of sodic-calcic and calcic amphibole, and chlorite along shear bands. Sample L3 is distinctly schistose and contains a higher amount of sodic-calcic and calcic amphibole than the other two. It appears that these amphiboles and some chlorite in the samples are syntectonic and grew after the formation of glaucophane. Mineral zoning and replacement is common. Rutile may have secondary sphene margins, and clinozoisite may be zoned, or patchily replaced, by epidote. The sodic amphibole shows progressive outward zoning from glaucophane to crossite. Bluey green barroisite and actinolitic amphibole may zone or replace the alkali amphibole, especially along margins. In rare grains, barroisitic margins have outer zones of actinolitic amphibole. Some grains are entirely made up of either of these two; these may represent completely replaced grains of sodic amphibole. The sequence of formation of the three amphiboles appears to be: glaucophane-crossite, barroisite, actinolite.

The presence of epidote, garnet, rutile, sodic-calcic and calcic amphibole, the absence of pumpellyite, aragonite and jadeite, and the paucity of lawsonite are noteworthy features of the Ladakh rocks. Such parageneses in other areas have been regarded to have formed under high-grade blueschist facies conditions (cf. Coleman and Lee, 1963; Coleman, 1967, Taylor and Coleman, 1968; Brothers, 1974; Ernst and Seki, 1967; Ernst, 1977). But in comparison with some high-grade blueschists, e.g. the Alps, the absence of omphacite is noteworthy.

GEOCHEMISTRY OF THE EASTERN LADAKH BLUESCHISTS

Bulk Rock Chemistry

Major and trace element XRF analyses of two metabasites are presented in Table 1. Both the samples contain unusually high total alkalis and Na/Ca

TABLE 1. XRF ANALYSES OF LADAKH BLUESCHISTS

	L1	L3		L1	L3
SiO_2	49.44	51.19	Ba	79	102
TiO_2	0.85	0.96	Ce	25	27
Al_2O_3	15.48	13.31	Co	85	82
Fe_2O_3	11.59	12.16	Cr	397	522
MnO	0.44	0.44	Ni	126	113
MgO	7.97	8.84	Nb	5	5
CaO	7.46	6.70	Sr	229	184
Na_2O	4.38	4.50	Rb	21	23
K_2O	1.02	1.15	Y	23	22
P_2O_5	0.02	0.02			
TOTAL	98.65	99.27			

* Total iron expressed as Fe_2O_3 — Analysis: S. Hamidullah

ratios, and are spilitic in nature. Plots of TiO_2, Ba, and Na against Fe*/MgO fall in the overlapping fields of abyssal tholeiites and island arc basalts (cf. Miyashiro, 1975). However, their Al_2O_3 *vs.* TiO_2 (Sun *et al.,* 1979), Ti *vs.* Cr, Cr *vs.* Y, Cr *vs.* Ce/Y, Ni *vs.* Y, Ti/Cr *vs.* Ni and Ti/Y *vs.* Nb/Y plots (Pearce, 1975, 1982, and unpublished data) characterise them as mid-oceanic ridge/ocean floor basalts. This conclusion is in harmony with their occurrence in an ophiolitic melange.

The high values of Cr, Ni, and atomic $Mg/(Mg+Fe^{2+})$ ratios ($\sim$ 0.6) suggest that the rocks have not experienced much fractionation and are close to primary magma composition. The high alkali content of the samples, therefore, may be due to interaction with sea water (i.e. metasomatism). It is to be kept in mind, however, that analyses of only two small samples may not be sufficient to reach accurate conclusion.

Phase Chemistry

A total of 188 points were analysed for the major and minor elements in the three samples by wavelength dispersive system on Joel Superprobe JCX-703. Suitable standards and a computerised programme involving ZAF correction was used. The voltage was kept at 15 KV, specimen current at 120×10^{-7} Amp and a counting time of 15 seconds.

Chlorite. Eleven analysed points are plotted on Hey (1954) diagram in Fig. 2; five representative analyses are given in Table 2. The analyses show a limited variation in Si (5.5 to 6.2) and have constant Fe/(Fe+Mg) ratios of 0.35; they classify as picnochlorite and ripidolite. Although chlorite may have grown in two generations, no distinction can be made on the basis of chemistry. However, analyses of a chlorite grown clearly after garnet is only slightly lower in the Fe/Fe+Mg) ratio.

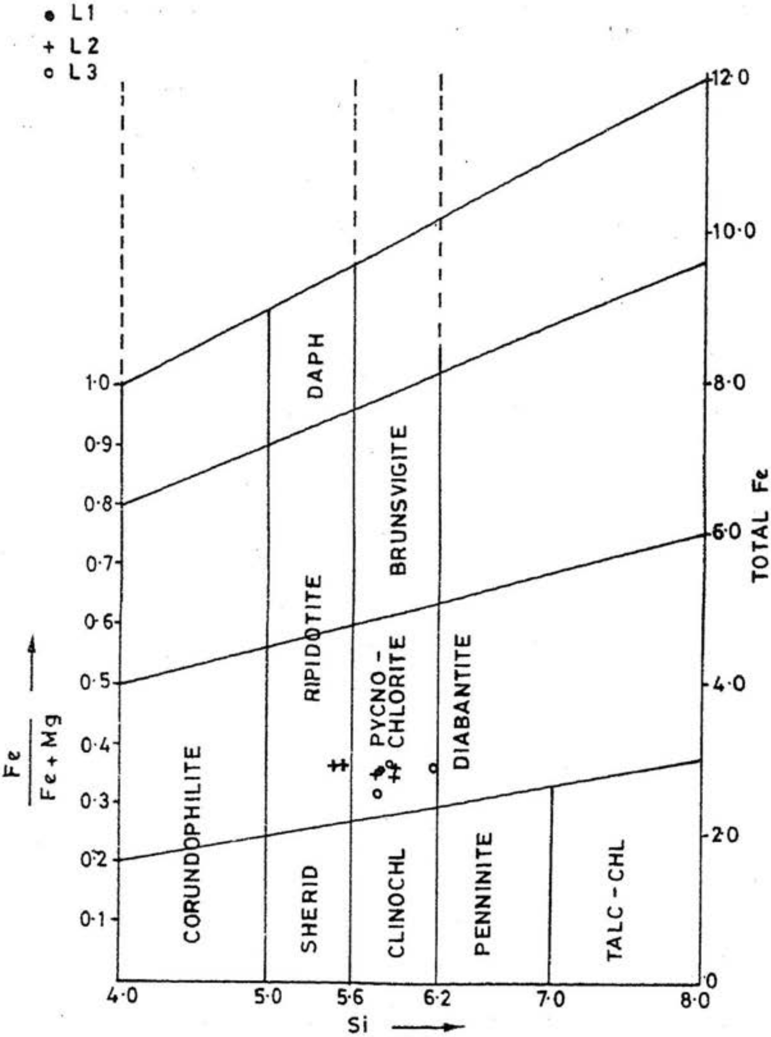

Fig. 2. **Classification of the chlorite analyses on Hey (1954) diagram. Two analyses are left out for clarity. Key: Filled circles represent analyses from sample L1, crosses from L2, and open circles from L3.**

An increase in the Mg/Fe ratio with increasing metamorphic grade has been demonstrated in the laboratory experiments and in the naturally occurring chlorites (Ernst, 1972; Cooper, 1972). However, Ramsay (1973) found a stronger compositional rather than grade control on the Mg/Fe ratio. The constancy of this ratio in the Ladakh chlorites may reflect compositional control but there is a possibility that the later formed chlorite grew at temperatures similar to those of the earlier formed chlorite.

TABLE 2. REPRESENTATIVE ANALYSES OF CHLORITE

	L1	L2	L2	L3	L3*
SiO_2	30.60	29.23	26.51	28.87	27.99
TiO_2	0.04	0.04	0.00	0.08	0.00
Al_2O_3	19.82	18.24	21.29	17.06	19.49
FeOt	17.78	20.43	19.09	20.16	16.71
MnO	0.48	0.47	0.52	0.63	0.99
MgO	17.75	20.44	18.83	19.65	19.92
CaO	0.00	0.19	0.09	0.02	0.08
Na_2O	1.09	0.03	0.01	0.00	0.03
TOTAL	87.56	89.07	86.34	86.47	85.21
	NUMBER OF IONS BASED ON 28 OXYGENS				
Si	6.160	5.888	5.488	6.000	5.802
Al	4.703	4.332	5.197	4.178	4.763
Ti	0.005	0.005	0.000	0.011	0.000
Fe	2.993	3.444	3.307	3.506	2.898
Mn	0.083	0.078	0.090	0.112	0.174
Mg	5.327	6.140	5.810	6.087	6.157
Ca	0.000	0.042	0.019	0.006	0.020
Na	0.426	0.011	0.005	0.000	0.011
Z	8.00	8.00	8.00	8.00	8.00
Y	11.70	11.94	11.92	11.90	11.98

* Chlorite after garnet; the remainder are independent grains.

Epidote. Seven of the 26 point analyses of epidote in the three rocks are presented in Table 3. The principal variation in the chemistry is caused by Al–Fe^{3+} substitutioin (Fig. 3). The pistacite ($Ps=100\ Fe^{3+}/Fe^{3+}+Al$) of the analyses ranges from 11.4 to 29.7 and, therefore, all belong to the clino-zoisite-epidote series (cf. Holdaway, 1972). Epidotes from the blueschists of Shangla, Kohistan, have higher Ps values (24 to 30 according to Guiraud *et al.*, in prep). Like those of the blueschists in Taiwan (Lieu *et al.*, 1975), many epidote grains show iron--enriched outer zones. This, coupled with the increase in Fe^{3+} content of the blue amphibole margin in Ladakh may suggest an increase in fO_2.

The recalculation of analyses on the basis of 12(O) allows a small entry (0.1) of Al in tetrahedral site and a deficiency of Ca in the octahedral site. The total MnO content of the analyses is uniformly low with a range of 0.0 to 0.5 %; most analyses contain 0.13 to 0.35 % MnO. It is not clear whether the manganese is in bivalent or trivalent state. The Fe-enriched margins of epidote contain more manganese than the cores possibly due to increasing oxygen fugacity with time during the blueschist facies recrystallization. Compared to epidote, the chlorite analyses contain slightly higher Mn, whereas the garnet is enriched in Mn

TABLE 3. REPRESENTATIVE ANALYSES OF EPIDOTE

	L1 Centre	L1 Margin	L1 Independent	L2 Replacing	L2 Replaced	L3 Centre	L3 Margin
SiO_2	39.44	37.73	39.65	38.23	39.85	39.11	38.52
TiO_2	0.25	0.04	0.31	0.18	0.09	0.18	0.00
Al_2O_3	26.50	21.55	27.95	21.31	28.10	27.66	23.49
Fe_2O_3*	8.65	14.10	6.22	14.10	6.21	5.80	11.01
MnO	0.08	0.46	0.18	0.19	0.15	0.27	0.51
MgO	0.05	0.00	0.07	0.00	0.05	0.08	0.00
CaO	25.07	24.49	24.79	24.42	23.95	25.00	23.97
Na_2O	0.00	0.00	0.02	0.03	00.00	0.00	0.01
TOTAL	100.04	98.37	99.19	98.46	98.40	98.10	97.51
NUMBER OF ATOMS PER 12 OXYGENS							
Si	2.906	2.899	2.918	2.928	2.944	2.913	2.942
Al	2.302	1.952	2.425	1.924	2.448	2.429	2.115
Ti	0.014	0.002	0.017	0.010	0.005	0.010	0.000
Fe^{3+}	0.479	0.815	0.345	0.813	0.345	0.325	0.633
Mn	0.005	0.000	0.011	0.012	0.009	0.017	0.033
Mg	0.005	0.000	0.008	0.000	0.005	0.009	0.000
Ca	1.979	2.016	1.955	2.004	1.896	1.996	1.961
Na	0.000	0.000	0.003	0.005	0.000	0.000	0.002
Ps	17.2	29.5	12.5	29.7	12.4	11.8	23.0

* Total iron as Fe_2O_3 $\quad$ $Ps = 100\ Fe^{3+}/(Fe^{3+} + Al)$

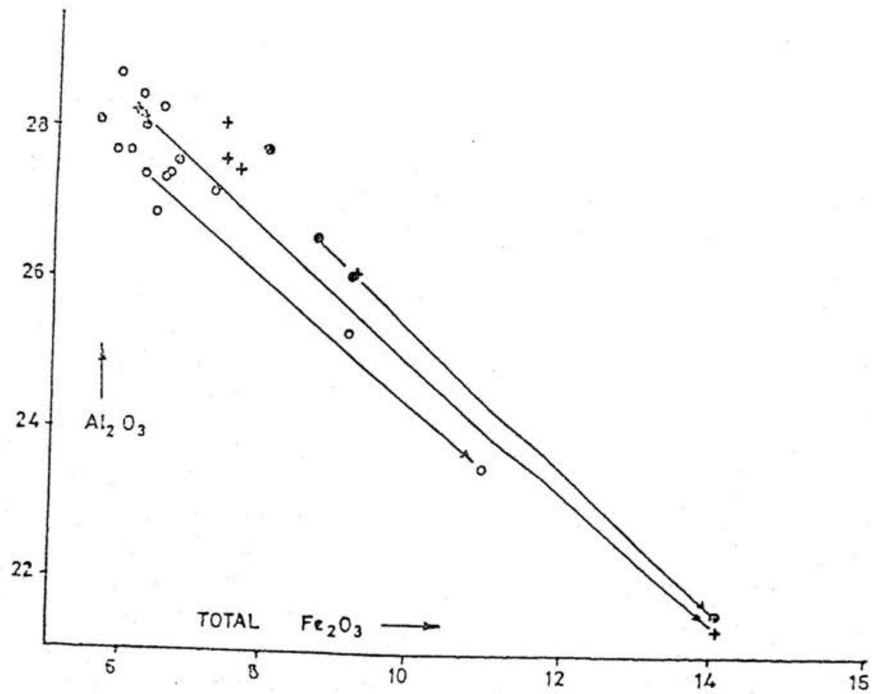

Fig. 3. Al_2O_3 *vs.* total Fe_2O_3 (oxide percentages) in epidote analyses. Arrows point towards outer zones. Symbols as in Fig. 2.

(compare Table 6). The distribution of Mn between garnet and epidote is controlled by fugacity of oxygen (Stensrud, 1973); at hight fO_2, Mn^{3+} is preferentially accommodated in piemontite. Thus in addition to bulk control, the oxygen fugacity may not have been sufficiently high to allow the entry of much Mn in epidote.

Feldspar. Plagioclase feldspar, generally untwinned, is present in fair amount in the three samples. Twenty five spot analyses of plagioclase are uniformly low in Ca and K and are nearly pure albite. Sodic albite does not seem to be so typical of blueschists and is found commonly in prehnite-pumpellyite and zeolite facies rocks in several areas of the world (Coleman, 1967; Ernst, 1977). Analysis of a tiny grain in L3 suggests the presence of some microcline. However, this analysis is unusual in that it contains higher than normal amounts of FeO, MgO, CaO, and slightly lower amounts of K_2O and Al_2O_3 (see Table 4). It is possible that a thin film or edge of an amphibole grain interfered.

TABLE 4. REPRESENTATIVE FELDSPAR ANALYSES

	L1	L2	L3	L3
SiO_2	69.59	70.75	68.86	65.98
TiO_2	0.06	0.00	0.06	0.03
Al_2O_3	19.38	19.71	19.18	15.76
FeO*	0.21	0.08	0.06	2.26
MnO	0.04	0.04	0.00	0.09
MgO	0.16	0.03	0.00	1.88
CaO	0.31	0.22	0.25	1.35
Na_2O	10.05	10.73	10.90	0.49
K_2O	0.06	0.08	0.02	12.75
TOTAL	99.86	101.64	99.33	100.59
IONS PER 32 OXYGENS				
Si	12.096	12.098	12.065	12.086
Al	3.970	3.974	3.962	3.402
Ti	0.007	0.000	0.008	0.003
Fe^{2+}	0.037	0.013	0.008	0.346
Mn	0.005	0.005	0.000	0.013
Mg	0.042	0.007	0.000	0.515
Ca	0.058	0.040	0.046	0.266
Na	3.387	3.558	3.704	0.176
K	0.013	0.017	0.003	2.979
Z	16.07	16.07	16.03	15.49
X	3.55	3.64	3.77	4.30
Or	0.4	0.5	0.1	87.1
Ab	97.9	98.4	98.7	5.1
An	1.7	1.1	1.2	7.8

*Total iron as FeO

White Micas. Out of thirteen points analysed in white micas, five representative analyses are listed in Table 5. Four of the analyses are paragonite with 100 Na/(Na+K) between 72 and 83. The remainder are K-rich with sufficiently high amounts of Mg+Fe to be named phengites. The Ti and Mn contents of the analyses are small. Random point analyses suggest that samples L1 and L3 contain both the micas and sample 12 contains only phengite. Because of the fine grain-size and similar optical preoperties, textural relations could not be determined between the two types of mica.

An increase in Na and A1 with increasing T of metamorphism has been found in muscovites of the biotite zone metasediments occurring in NW Territories, Canada (Ramsay, 1973). Phengitic micas characteristically occur in high-P/Low-T rocks (Chopin and Maluski, 1980; Frey *et al.*, 1983). Coleman (1967) considered that accommodation of more phengite molecule in muscovite of California than in those of new Caledonia may reflect lower T or higher P_{H_2O}. Liou *et al.* (1975) reported Fe, Mg, and Si-rich phengites in the blueschists and high-Na paragonites in the epidote amphibolites of Taiwan. Thus there is a

TABLE 5. REPRESENTATIVE ANALYSES OF MICAS

	L1 Paragonite	L1 Phengite	L2 Phengite	L3 Phengite	L3 Paragonite
SiO_2	48.34	54.97	56.27	48.48	51.32
TiO_2	0.00	0.28	0.13	0.40	0.05
Al_2O_3	36.98	21.26	21.17	27.14	38.44
Fe_2O_3*	0.79	4.83	4.28	3.84	0.67
MnO	0.05	0.05	0.06	0.06	0.00
MgO	0.87	5.02	5.34	2.40	0.64
CaO	0.02	0.00	0.05	0.03	0.21
N_2O	4.96	0.04	0.04	0.73	5.57
K_2O	2.14	7.04	7.68	9.91	1.66
TOTAL	94.15	93.49	95.02	92.99	98.56
			IONS BASED ON 22 OXYGENS		
Si	6.248	7.309	7.369	6.641	6.314
Al	5.635	3.332	3.268	4.384	5.575
Ti	0.000	0.028	0.013	0.042	0.004
Fe^{3+}	0.077	0.484	0.422	0.396	0.062
Mn	0.005	0.005	0.006	0.006	0.000
Mg	0.168	0.995	1.042	0.490	0.119
Ca	0.003	0.000	0.006	0.004	0.026
Na	1.243	0.009	0.011	0.194	1.229
K	0.353	1.194	1.283	1.732	0.260

*Total iron expressed in ferric state

possibility that the paragonite in the Ladakh rocks developed later than the phengite at higher T or lower P_{H_2O}.

On the AKF diagram of Coleman (1987) showing the fields of white K-micas from greenschist-amphibolite and blueschist facies rocks, the Ladakh phengites plot just outside of the field of blueschists. The Ladakh analyses are lower in K; whether this is their chemical characteristic or is due to an under-estimation is not clear. Fig. 4, 5 and 6 show chemical variations in the mica analyses from Ladakh. The variation in total Fe_2O_3 and Na_2O against Al_2O_3 is shown in Fig. 4, together with the trends for white micas from Shirataki, Japan (Ernst, 1972) and Taiwan (Liou *et al.,* 1975). The Na variation is similar in the three but the slope of Fe in Ladakh samples is lower. This is compensated by the entry of more Mg in the Ladakh phengites.

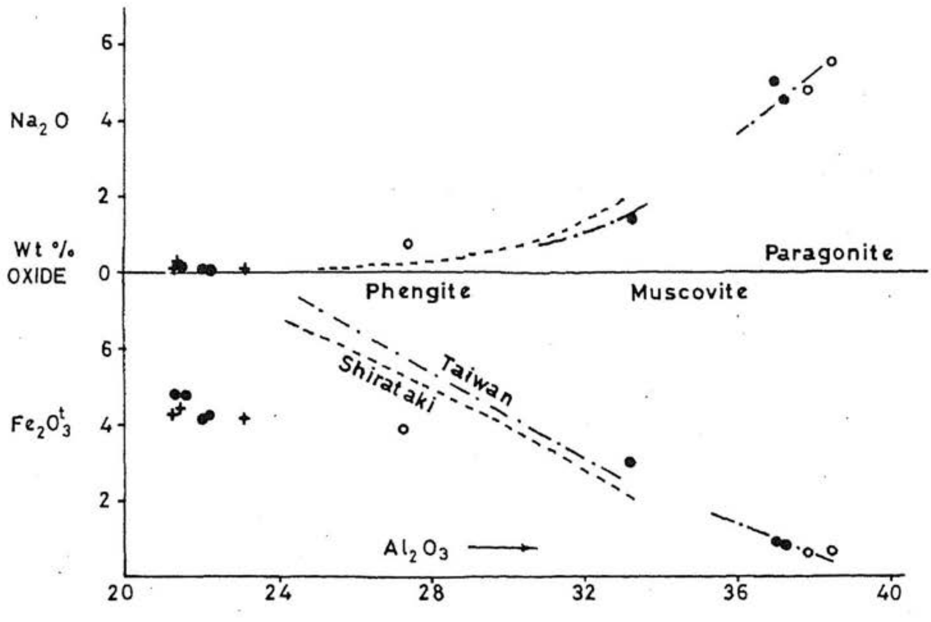

Fig. 4. $Na_2O-Al_2O_3$, and Fe_2O_3 (total)- Al_2O_3 plots showing compositional variations in the eastern Ladakh white micas. Variation trends of white micas from Shirataki district, Japan (Ernst, 1972), and Taiwan (Liou *et al.*, 1975) are drawn for comparison. Symbols as in Fig. 2.

The phengite content (Σ FeO*+MgO+MnO) of the micas shows a distinct negative correlation with the paragonite content (100 Na/(Na + K) of the micas (Fig. 5A). Celadonite-muscovite variation in the micas is displayed in Fig. 5 B and 6. In the former case, only K-rich micas have been plotted but in Fig. 6 the four paragonite analyses have also been plotted for comparison. Both the figures display that none of the K-rich micas plots as ideal muscovite and seven of them are rich in celadonite component. Fig. 6 also suggests that celadonite and phengite contents are not independent and increase together.

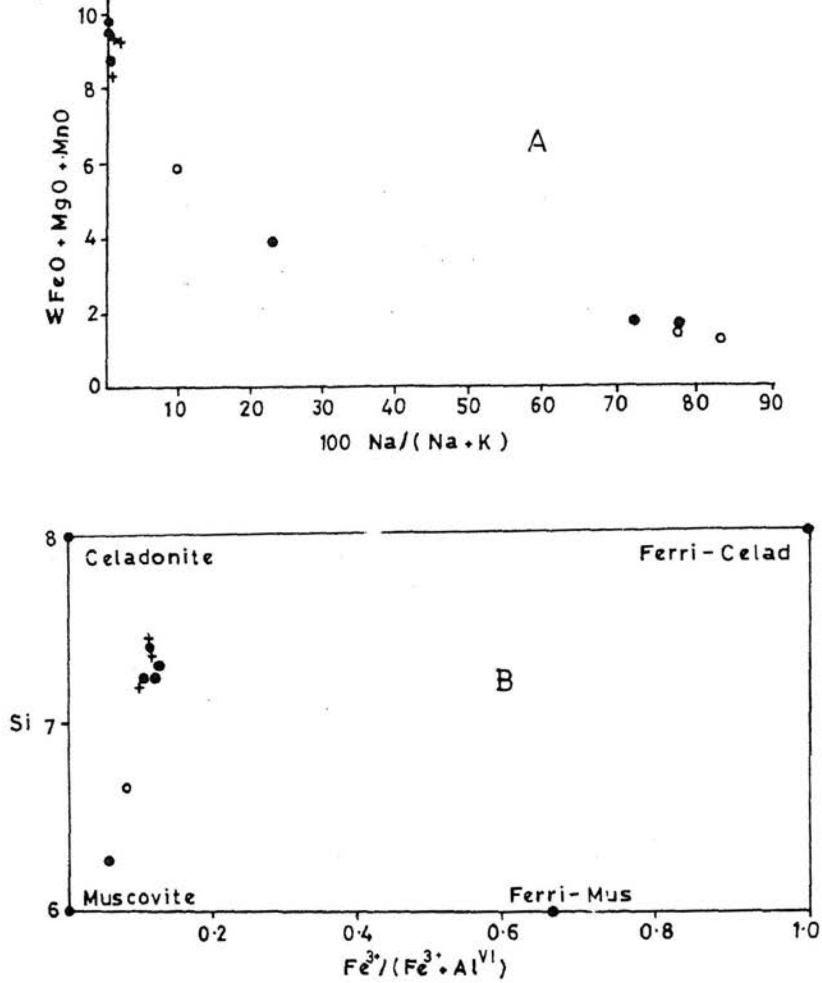

Fig. 5. A. Plots of Ladakh white micas showing a negative correlation between phengite and paragonite components.

B. Compositions of the analysed white K-micas plotted as a function of Si (Tschermak's substitution) and $Fe^{3+}/(Fe^{3+}+Al)$. Symbols as in Fig. 2.

Phengites have been extensively described in literature (cf. Cipriani *et al.*, 1971; Frey *et al.*, 1983). Ernst (1963) and Velde (1965) considered that the assemblage phengite + chlorite is stable at relatively high fluid pressure and lower temperature. White micas approaching normal muscovite form at higher temperature than phengite (Ernst, 1972; Liou *et al.*, 1975). Brown (1974) found that in the relatively high-P greenschists of Otage and low-P blueschists of

Cascades the white micas display a wide range and no systematic difference in the Si content. However, the experimental work of Velde (1965, 1967) and Massonne (1980; reported by Frey *et al.*, 1983) demonstrates that the celadonite content of white K-micas increases with P and decreases with T. The more recent field studies of Frey *et al.* (1983) in central Alps support the observation that phengitic micas with high silica content tend to occur in blueschist facies rocks.

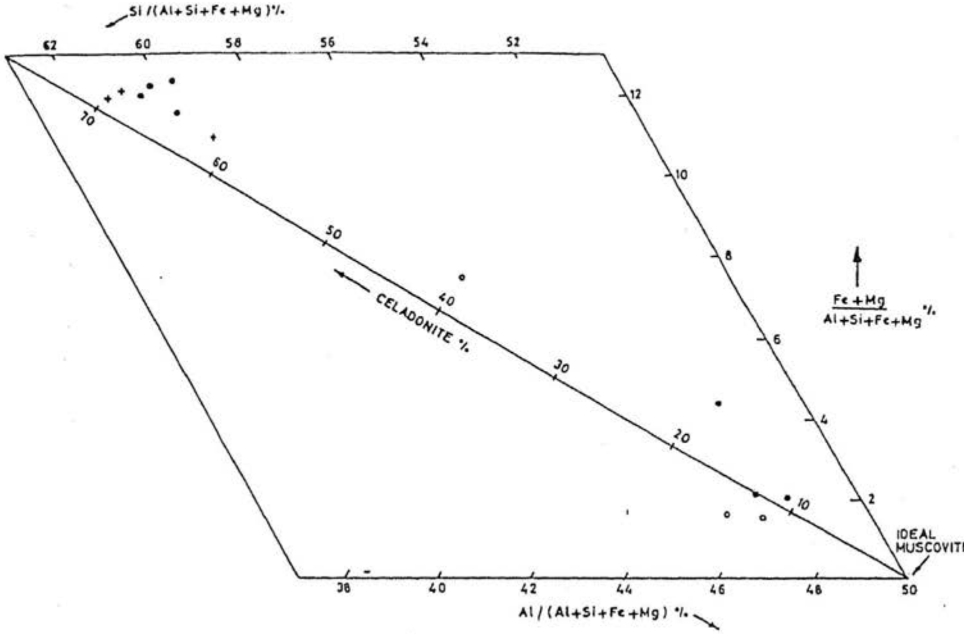

Fig. 6. Proportions of Si, Al, and Fe+Mg in white K-micas. Paragonite analyses are plotted only for Fe+Mg comparison. Symbols as in Fig. 2.

It can thus be concluded that the high phengite and celadonite components in the Ladakh micas reflect their formation under blueschist facies conditions. The lower Si and Mg+Fe contents of two micas and the occurrence of paragonite in two samp'es may suggest their adjustment to lower pressures or higher temperatures following the blueschist facies metamorphism.

Garnet. Garnet tends to be porphyroblastic in the three samples and is locally replaced by chlorite along fractures. In addition to 59 analyses on the largest porphyroblast (2 mm, in sample L3), eleven more points were analysed in six grains to study compositional zoning. Representative analyses are listed in Tab'e 6. The garnet is zoned with decreasing Mn and increasing Fe towards the margin. Magnesium remains constant and Ca tends to show a slight outward increase in some. A complete range in the 70 analysed points in terms of the garnet end-members is: almandine 45–57 %, spessartine 11–34 %, pyrope 4–7 %, and grossular 15–21 % (with two values of 25 % and three values extending down to 12 % in the largest porphyroblast).

TABLE 6. REPRESENTATIVE MICROPROBE ANALYSES OF GARNETS

	L1 Centre	L1 Margin	L2 Centre	L2 Margin	L3 Grn 1–C	L3 Grn 1–Mid
SiO_2	38.65	38.91	38.93	38.72	37.91	37.57
TiO_2	0.22	0.11	0.24	0.10	0.13	0.09
Al_2O_3	21.10	21.15	20.88	20.43	20.70	21.23
FeO	24.55	27.01	22.92	25.08	21.32	23.24
MnO	9.83	5.34	11.53	9.12	11.49	11.15
MgO	1.13	1.59	1.20	1.10	1.18	1.15
CaO	6.20	9.32	5.84	6.33	5.74	5.56
Na_2O	0.01	0.00	0.08	0.01	0.01	0.03
TOTAL	101.69	103.43	101.62	100.89	98.48	100.02
NUMBER OF ATOMS ON THE BASIS OF 24 OXYGENS						
Si	6.098	6.031	6.139	6.161	6.144	6.036
Al	3.924	3.864	3.881	3.830	3.955	4.020
Ti	0.026	0.012	0.029	0.012	0.017	0.010
Fe^{2+}	3.240	3.502	3.024	3.338	2.890	3.122
Mn	1.313	0.701	1.541	1.229	1.577	1.517
Mg	0.264	0.367	0.281	0.262	0.283	0.274
Ca	1.046	1.548	0.986	1.080	0.996	0.958
Na	0.002	0.000	0.024	0.003	0.002	0.009
Alm	55.3	57.2	51.9	56.5	50.3	53.2
Spes	22.4	11.5	26.4	20.8	27.4	25.8
Pyr	4.5	6.0	4.8	4.4	4.9	4.7
Gros	17.8	25.3	16.9	18.3	17.3	16.3

	L3 Grn 1–M	L3 Grn 2–C	L3 Grn 2–Mid	L3 Grn 2–M	L3 Grn 2--M
SiO_2	37.92	36.95	37.55	37.35	37.72
TiO_2	0.07	0.08	0.10	0.08	0.01
Al_2O_3	20.92	19.95	20.74	20.32	20.46
FeO	24.64	19.70	21.80	23.62	24.45
MnO	8.51	14.50	12.98	8.73	9.30
MgO	1.15	0.97	1.14	1.05	0.97
CaO	7.18	5.89	4.96	7.26	6.08
Na_2O	0.00	0.03	0.01	0.02	0.00
TOTAL	100.39	98.07	99.28	98.43	98.99
NUMBER OF ATOMS ON THE BASIS OF 24 OXYGENS					
Si	6.060	6.079	6.082	6.086	6.120
Al	3.941	3.871	3.960	3.905	3.912
Ti	0.010	0.010	0.014	0.010	0.002
Fe^{2+}	3.293	2.710	2.952	3.218	3.317
Mn	1.152	2.021	1.781	1.205	1.277
Mg	0.274	0.238	0.274	0.254	0.235
Ca	1.231	1.039	0.859	1.267	1.056
Na	0.000	0.009	0.003	0.005	0.000
Alm	56.4	45.1	50.3	54.1	56.4
Spes	19.7	33.6	30.4	20.2	21.7
Pyr	4.7	4.0	4.7	4.3	4.0
Gros	21.1	17.3	14.6	21.3	17.9

Total Fe as FeO. Abbreviations in Table 6 and 7: Grn = Grain; C = Centre; M = Margin; Mid = Middle

The Mg-Fe zoning pattern is similar to those reported in the garnets from type IV blueschists in California (Moore, 1984) and eclogites in Sanbagawa (Takasu, 1984). The zoning in the 2mm porphyroblast is shown in Fig. 7. Contours have been drawn for the spassartine and almandine components; the grossular moclacule does not show a systematic variation, neither does prope which has been ignored because of its small range.. The zoning is essentially simple with a smooth increase in Fe and decrease in Mn towards the margin instead of a sharp difference between core and margin. This may be suggestive of growth zoning produced by a continuous recation process (Tracey *et al.,* 1976; Ashworth and Evirgen, 1984). It seems that Mn preferentially fractionated into the earlier formed (i.e. cores of) garnet.

Ghent and Stout (1981) suggested that increasing pressure causes an increase in the Ca content of garnet. Whether the slight increase of Ca in the margins of some porphyroblasts in Ladakh is also due to an increase of pressure is not certain, because (1) outer zones in the other minerals do not point to an increase of P, (2) the detailed examination of the largest porphyroblast does not reveal an outward enrichment in Ca, and (3) the substantial outward increase in Fe and decrease in Mn, according to Miyashiro and Shido (1975), suggest an increase in T, or decrease in P or oxygen fugacity (Hsue, 1968).

The end-member compositions of the garnets are plotted in triangular diagrams in Fig. 8. Also plotted are the fields of garnets from California types III (low grade) and IV (high-grade) blueschists, and eclogites (cf. Coleman and Lee, 1963; Lee *et al.,* 1983). On the Alm+Spes—Gros—Pyr triangle (Fig. 8B), the Ladakh garnets plot along the margin of the field for those of type III rocks. On the Alm+Pyr—Spes—Gros diagram (Fig. 8A), many of the analyses plot in the field of type III rocks but the iron-rich margins extend into the field of type IV rocks. As such the garnets are similar to those of a high-grade exotic block of blueschists in the Franciscan complex (Moore, 1984).

Amphiboles. Amphiboles, together with epidote, are the most abundant components of the three samples. A total of 40 point analyses were performed in the three samples, 21 representative analyses are presented in Table 7. Following Leake (1978; but see also Muir Wood, 1980) total Fe was partitioned into Fe^{3+} and Fe^{2+} such that the sum of cations excluding Ca, Na and K equals 13. According to IMA momenclature (Leake, 1978), the analyses classify as glaucophane, crossite, barroisite, winchite, actinolite, actinolitic hornblende and one magnesio-hornblende. Zoning pattern and replacement textures suggest that alkali amphiboles was followed by sodic-calcic and, finally, calcic amphibole. Some grains are entirely made up of barroisite or actinolitic hornblende but these may have completely replaced the sodic amphibole.

Several workers have reported coexisting sodic and calcic amphiboles, especially in the Franciscan terrane (Coleman and Papike, 1968), and have attributed them to a miscibility gap at low temperature (Brown, 1974). Ernst (1979) found that in Valtourmanche and western Liguria in Alps, barroisitic

TABLE 7. REPRESENTATIVE AMPHIBOLE ANALYSES FROM LADAKH

	L1 Grn 1-C	L1 Grn 1-M	L1 Grn 2--C	L1 Grn 2-M	L1 Grn 3	L1 Grn 4	L2 Grn 1-C
SiO_2	58.61	59.39	59.45	59.54	57.74	51.06	56.27
TiO_2	0.13	0.00	0.13	0.03	0.07	0.14	0.04
Al_2O_3	9.80	6.34	10.90	10.54	1.09	10.52	8.54
Fe_2O_3	3.78	9.56	3.00	8.11	6.33	0.11	4.33
FeO	7.48	5.57	7.85	4.39	7.15	13.82	8.20
MnO	0.00	0.15	0.10	0.10	0.52	0.34	0.10
MgO	9.66	10.81	10.91	10.74	15.81	9.86	9.86
CaO	0.66	0.56	1.45	1.07	9.24	7.46	0.42
Na_2O	5.69	5.90	6.58	5.49	1.50	4.52	7.03
K_2O	0.00	0.00	0.00	0.00	0.00	0.17	0.00
TOTAL	95.81	98.28	100.37	100.01	99.45	97.98	94.79
			NUMBER OF IONS BASED ON 23 OXYGENS				
Si	8.127	8.131	7.923	7.910	8.000	7.336	8.014
Al^{IV}	0.000	0.000	0.077	0.090	0.000	0.664	0.000
Al^{VI}	1.602	1.023	1.635	1.560	0.178	1.118	1.434
Ti	0.014	0.000	0.013	0.003	0.007	0.015	0.004
Fe^{3+}	0.394	0.984	0.301	0.811	0.660	0.012	0.464
Fe^{2+}	0.867	0.638	0.874	0.488	0.828	1.660	0.977
Mn	0.000	0.017	0.011	0.012	0.061	0.041	0.012
Mg	1.996	2.205	2.167	2.126	3.264	2.111	2.093
Ca	0.098	0.082	0.207	0.152	1.372	1.148	0.064
Na	1.530	1.566	1.700	1.414	0.403	1.259	1.941
K	0.000	0.000	0.000	0.000	0.000	0.031	0.000
T	8.12	8.13	8.00	8.00	8.00	8.00	8.01
C	4.88	4.87	5.00	5.00	5.00	4.96	4.98
B	1.63	1.65	1.91	1.57	1.78	2.00	2.00
A	0.00	0.00	0.00	0.00	0.00	0.41	0.01
Name	Glau	Cross	Glau	Cross	Subcalcic Act	Barr	Glau

TABLE 7 CONTINUED

	L2 Grn 1–M	L2 1–Overgrowth	L2 Grn--2	L2 Grn–3	L2 Grn–4	L2 Grn--5	L3 Grn--1
SiO_2	58.08	51.26	58.08	47.22	56.66	53.06	51.37
TiO_2	0.00	0.22	0.10	0.00	0.00	0.08	0.05
Al_2O_3	9.35	6.16	7.99	7.40	6.24	3.72	3.83
Fe_2O_3	6.00	8.45	6.11	5.33	0.11	5.22	4.78
FeO	6.17	8.00	8.77	12.09	9.30	6.67	9.47
MnO	0.13	0.33	0.08	0.45	0.11	0.24	0.88
MgO	10.21	12.92	9.51	10.60	12.62	15.39	14.33
CaO	0.26	8.43	0.61	9.61	9.14	9.23	10.85
Na_2O	6.48	3.06	6.48	2.46	2.03	2.25	1.74
K_2O	0.00	0.00	0.00	0.10	0.00	0.00	0.17
TOTAL	96.68	98.83	97.73	95.26	96.21	95.86	97.47
				NUMBER OF IONS BASED ON 23 OXYGENS			
Si	8.023	7.301	8.055	7.118	7.999	7.652	7.458
Al^{IV}	0.000	0.699	0.000	0.882	0.001	0.348	0.542
Al^{VI}	1.522	0.335	1.306	0.433	1.038	0.284	0.114
Ti	0.000	0.024	0.010	0.000	0.000	0.009	0.005
Fe^{3+}	0.624	0.905	0.638	0.605	0.012	0.567	0.522
Fe^{2+}	0.713	0.953	1.017	1.524	1.098	0.804	1.150
Mn	0.015	0.040	0.009	0.057	0.013	0.029	0.108
Mg	2.102	2.742	1.965	2.381	2.655	3.307	3.100
Ca	0.038	1.286	0.091	1.552	1.382	1.426	1.688
Na	1.735	0.845	1.742	0.719	0.556	0.629	0.490
K	0.000	0.000	0.000	0.019	0.000	0.000	0.031
T	8.02	8.00	8.05	8.00	8.00	8.01	8.00
C	4.98	5.00	4.95	5.00	4.82	4.99	5.00
B	1.77	2.00	1.83	2.00	1.94	2.00	2.00
A	0.00	0.13	0.00	0.27	0.00	0.06	0.21
	Glau	Barr	Cross	Magnesio-Hbl	Subcalcic Act	Act	Actinolitic Hbl

TABLE 7 CONTINUED

	L3 Grn 2–C	L3 Grn 2–M	L3 Grn--3	L3 Grn 4–C	L3 Grn 4–Mid	L3 Grn 4--M	L3 Ovrgr.
SiO_2	56.11	57.32	54.29	56.87	57.37	58.01	55.02
TiO_2	0.21	0.04	0.00	0.09	0.04	0.01	0.02
Al_2O_3	9.70	7.90	2.25	10.22	8.00	7.66	5.52
Fe_2O_3	3.89	8.56	3.00	3.67	4.89	6.45	2.33
FeO	8.26	5.56	8.10	8.05	8.48	6.83	11.29
MnO	0.20	0.10	0.51	0.09	0.11	0.16	0.45
MgO	9.61	10.22	16.20	9.86	10.06	10.55	11.34
CaO	1.43	0.59	11.03	1.42	1.37	0.88	6.18
Na_2O	6.02	5.92	1.09	6.06	6.08	6.21	3.57
K_2O	0.00	0.00	0.05	0.00	0.00	0.00	0.02
TOTAL	95.43	96.21	96.52	96.33	96.40	96.76	95.74
			NUMBER OF IONS BASED ON 23 OXYGENS				
Si	7.925	8.007	7.795	7.928	8.046	8.067	7.945
Al^{IV}	0.075	0.000	0.205	0.072	0.000	0.000	0.055
Al^{VI}	1.540	1.301	0.176	1.608	1.322	1.256	0.885
Ti	0.022	0.004	0.000	0.009	0.004	0.001	0.002
Fe^{3+}	0.413	0.899	0.324	0.385	0.516	0.674	0.254
Fe^{2+}	0.976	0.649	0.972	0.938	0.994	0.794	1.363
Mn	0.024	0.012	0.060	0.011	0.013	0.019	0.055
Mg	2.023	2.127	3.466	2.048	2.102	2.186	2.440
Ca	0.216	0.088	1.697	0.212	0.206	0.131	0.956
Na	1.648	1.603	0.303	1.638	1.653	1.674	0.999
K	0.000	0.000	0.009	0.000	0.000	0.000	0.003
T	8.00	8.01	8.00	8.00	8.05	8.07	8.00
C	5.00	4.99	5.00	5.00	4.95	4.93	5.00
B	1.94	1.69	2.00	1.85	1.86	1.80	1.96
A	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	Glau	Cross	Act	Glau	Glau	Cross	Winchite

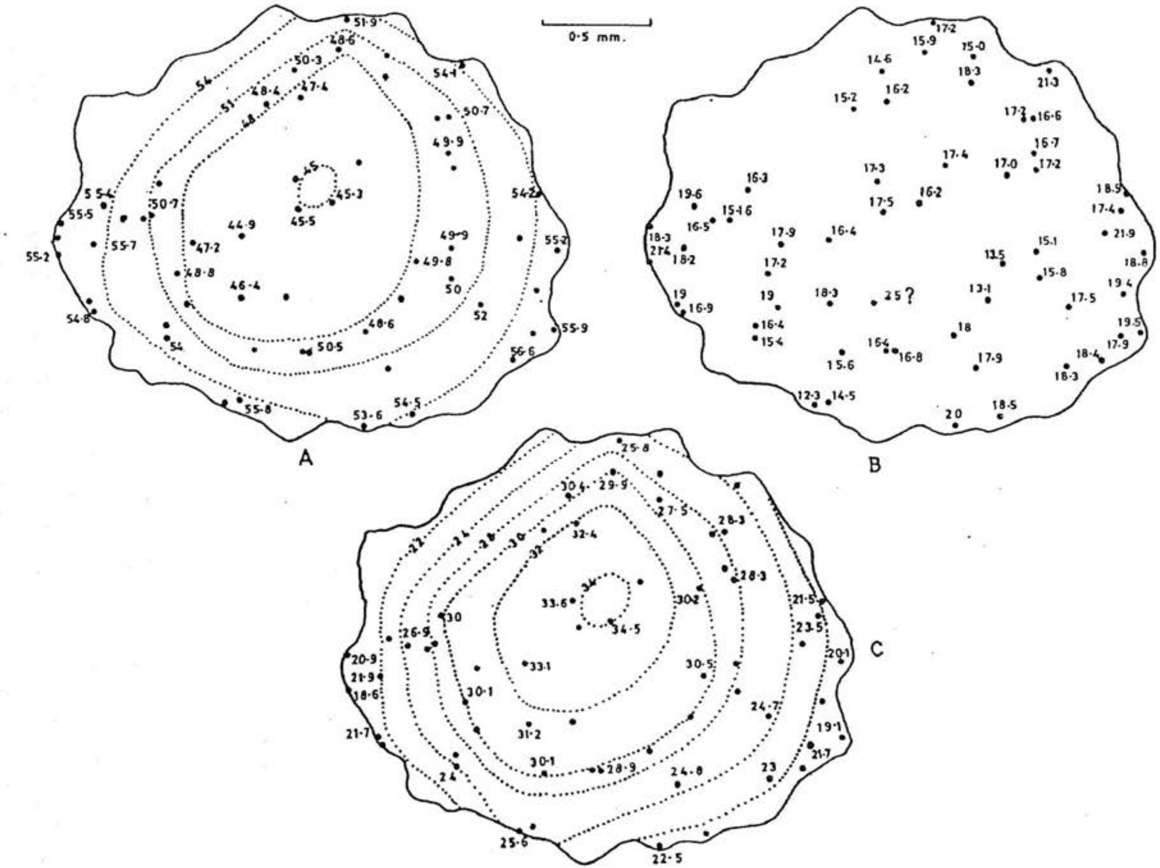

Fig. 7. Zoning pattern in terms of almandine (A), grossular (B) and spessartine (C) end-members in the largest garnet porphyroblast (sample L3). Pyrope values are not plotted because of their narrow range. Dots indicate locations of the points analyses and numbers are for mole % values. Some points are unnumbered for the sake of clarity. Mole % contours have been drawn for almandine and spessartine components; the grossular component does not show a systematic variation.

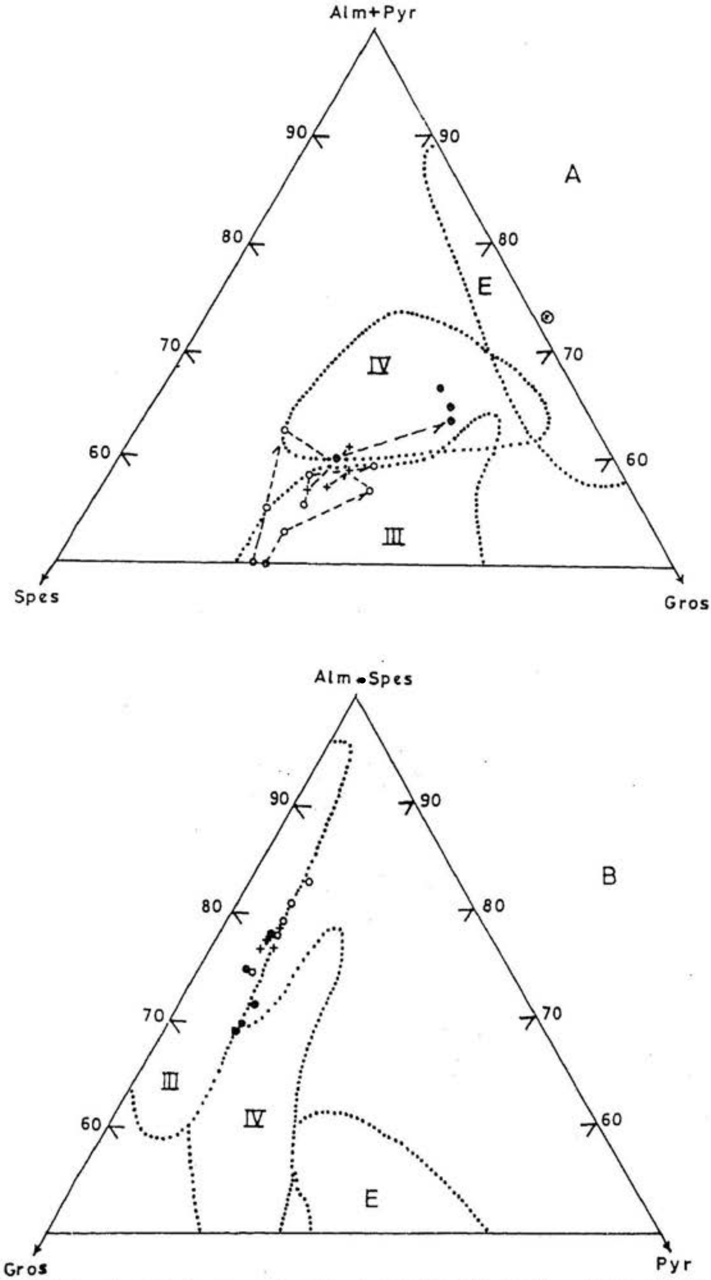

Fig. 8. Composition of garnet on mole % spessartine–(almandine+pyrope)–grossular (A) and grossular– (almandine+spessartine)–pyrope (B) triangles. Arrows in Fig. 8A point to outer zones. Compositional fields of garnets from types III and IV Franciscan glaucophane schists and eclogite (E) from Lee *et al.* (1963) are shown for comparison. Symbols as in Fig. 2.

ERRATA — Fig. 9, Line 2:
Please read 'riebeckite' for 'crossite'

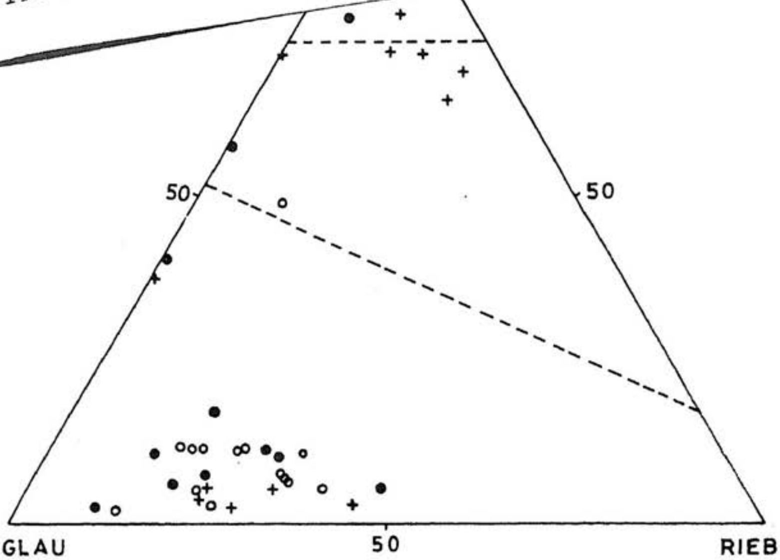

Fig. 9. Compositional variation of the Ladakh amphiboles in terms of actinolite–glaucophane–crossite components. Area between the dashed lines represents the miscibility gap found by Coleman (1967). Symbols as in Fig. 2.

interiors pass outwards into actinolitic rims. He thinks that the sodic amphibole in these areas and in the California high-grade tectonic blocks is probably not in equilibrium with barrosoitic amphibole but either grows earlier or later than the barroisite. The Ladakh amphiboles straddle the miscibility gap found between actinolite and calcic amphiboles of the Franciscan and New Caledonia by Coleman (1966). This (Fig. 9) and the textural features in the Ladakh samples suggest that the sodic, sodic-calcic and calcic amphiboles are not in equilibrium but have grown successively in response to changing P/T.

The analysed sodic amphiboles plot in glaucophane or crossite fields on Miyashiro diagram (Fig. 10). The overall range in 100 $Fe^{2+}/(Fe^{2+}+Mg)$ is 18.5 to 36 and that in 100 $Fe^{3+}/(Fe^{3+}+Al)$ 11 to 49 (except one analysis with a value of zero). In all the cases where cores and margine were analysed, the former turned out to be glaucophone and the latter crossite. The glaucophones plot in the area of the Franciscan sodic amphiboles but the crossites have lower $Fe^{2+}/(Fe^{2+}+Mg)$ ratios and plot outside the fields of those from Franciscan and Sanbagawa (Ernst *et al.*, 1970). The lower $Fe^{2+}/(Fe^{2+}+Mg)$ and higher $Fe^{3+}/(Fe^{3+}+Al)$ ratios in the crossite outer zones may suggest an increase in fO_2. The sodic amphidole analyses fall within the range of those from the blueschists of Alasaka (Forbes *et al.*, 1984).

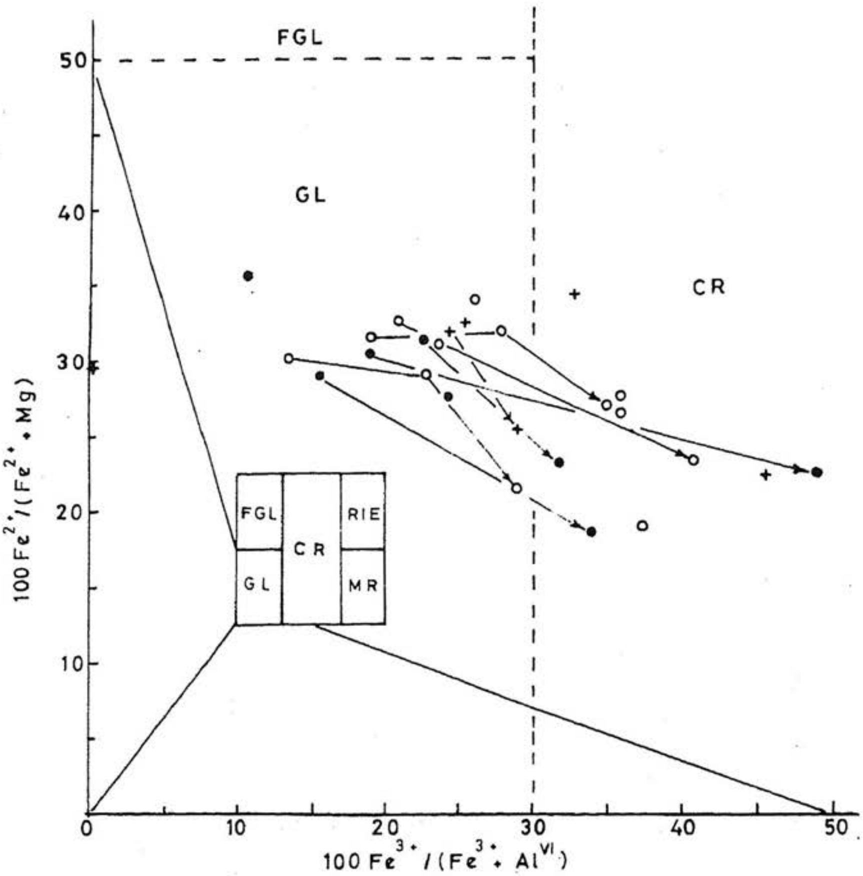

Fig. 10. Plot of the sodic amphibole analyses on Miyashiro diagram. Arrows point to outer zones. GL = glaucophane; FG = ferroglaucophane; CR = crossite; RIE = riebeckite; MR = magnesiorieb. All the analyses are confined to the fields of glaucophane and crossite. The latter have higher $Fe^{3+}/(Fe^{3+} + Al)$ and lower $Mg/(Mg + Fe^{2+})$ than the glaucophane cores. Symbols as in Fig. 2.

Zoned amphiboles in Franciscan (Ernst *et al.,* 1970), Taiwan (Liou *et al.,* 1975) and New Caledonia (Black, 1973; Brothers, 1974) have sodic amphibole margins around calcic amphibole cores. In Ladakh, as in Sangabawa (Ernst *et. al.,* 1970) and western Alps (Ernst, 1979), calcic outer zones grow around sodic cores. In Cascades, however, both types of zones have been found (Brown, 1974). With the help of several reactions, Muir Wood (1980) suggested that during progressive greenschist facies metamorphism a lowering of $Fe^{3+}/(Fe^{3+} + Al)$ causes the development of glaucophone margins around early formed crossite cores. The pressure stabilization limit is a function of cell volume. Pure glaucophone will occur the higher the metamorphic pressure, after the appearance of lawsonite and crossite marking the lowest pressure of blueschist facies metamorphism (Miyashire and Banno, 1958; Black, 1973; Brown, 1974; Muir Wood, 1980). It is thus, possible that early formed crossite in Ladakh was completely replaced by glaucophane during progressive metamorphism, followed by a drop of pressure during uplift when the present crossite, barroisitic and actinolitic amphiboles were produced. (It may, however, be mentioned that the occurrence of glaucophane without crossite cores is common in high-grade blueschists. It is not clear whether the sequence proposed by Muir-Wood applies for all rock compositions).

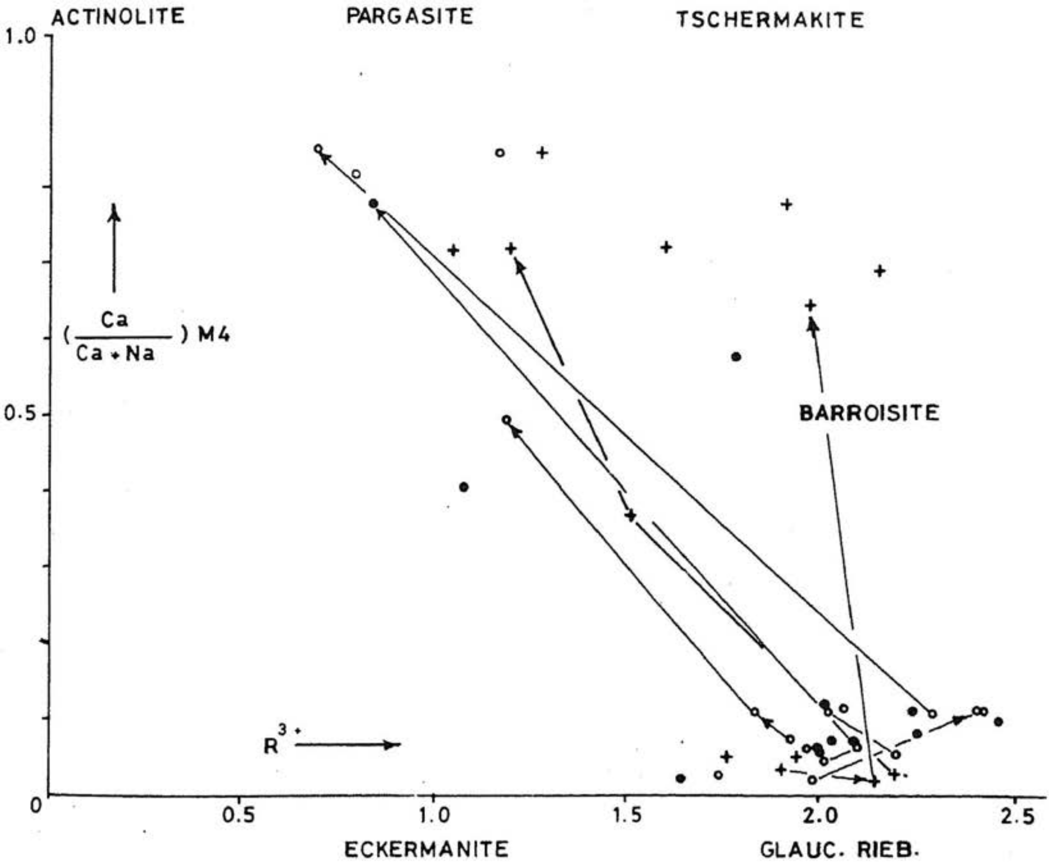

Fig. 11. **$Ca/(Ca+Na)$ M4 *vs.* R^{3+} plots of the Ladakh amphibole analyses. Arrows point to the outer zones or replacing amphibole. Not all the sodic-calcic and calcic amphibole grains have sodic cores due possibly to a complete replacement. Symbols as in Fig. 2.**

The $Ca/(Ca+Na)$ M4 *vs* R^{3+} plots of the analyses are shown in Fig. 11. The Ca amphiboles show a larger range in R^{3+} values and some sodic amphiboles display an increasing trend of $Ca/(Ca+Na)$ and decreasing R^{3+}

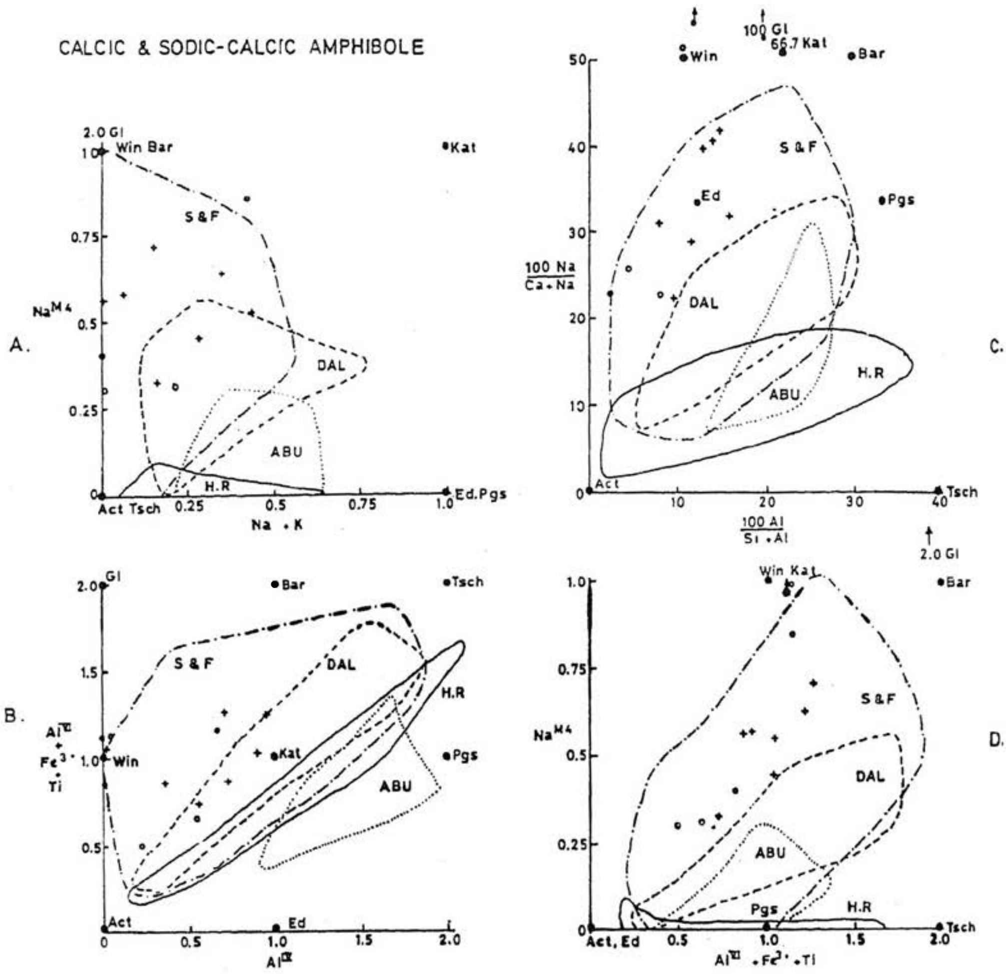

Fig. 12. **Chemical variations in the sodic-calcic and calcic amphibole analyses. Fields of amphiboles from high-P facies series terranes of Franciscan, California and Sanbagawa, Japan (S&F); medium-P terranes in Dalradian, Scotland (DAL) and Hast River, New Zealand (H.R.); and low-P, Abukuma terrane in Japan (ABU) are after Laird and Albee (1981). End-member compositions are indicated for actinolite, barroisite, edenite, glaucophane, kataphorite, pargasite, tschermakite, and winchite. Symbols as in Fig. 2.**

towards margins. "Tie lines" have been ignored between crossite and glaucophane for the sake of clarity, but those between the sodic cores and calcic margins broadly fo'low the pattern recorded in other high-P amphiboles (cf. Spear, 1982, p. 84). The more calcic margins generally have lower R^{3+} contents than their sodic cores and trend towards actinolite, pargasite and tschermakite end-members. The R^{3+} value of the sodic amphiboles cluster around 2.0, but their Ca+Na occupancy of the M4 site is a little less than 2.0 and A site is unoccupied (see Table 7).

Amphibole composition appears to be dependent upon facies series as well as metamorphic grade (Laird, 1982). Thus, amphiboles from Haast River, Abukuma, Dalradian, and Sanbagawa-Franciscan terranes occupy separate fields on Na M4 *vs.* (Na+K)A and $Al^{IV}+Fe^{3+}+Ti$, 100 Ca/(Ca+Na) *vs.* 100 Al/(Al+Si), and $Al^{VI}+Fe^{3+}+Ti$, *vs.* Al^{IV} plots (Laird and Albee, 1981). Compared to low-P terranes, amphiboles from high-P terranes have greater $Al^{IV}+Fe^{3+}+Ti$ for given values of Al^{IV}, and greater Na M4 for given values of (Na+K)A and $Al+Fe^{3+}+Ti$ (Fig. 12). Plots of the Ladakh amphiboles are confined to the field of high-P amphiboles from Franciscan and Sanbagawa, with only a few analyses plotting in the overlapping field of those from Dalradian (Fig. 12A and 12B).

Table 7 shows that the sodic amphibole analyses are characterised by a total lack of K ions, a vacant A site, and a small deficiency in B site. They have a small amount of Al^{IV}(mean = 0.004) and much higher Al^{VI}(1.0 to 1.7 with a mean of 1.44). The four barrosite analyses contain 0.00 to 0.03 K, 0.66 to 0.96 (mean 0.76) Al^{IV}, 0.21 to 1.12 (mean 0.52) $Al^{VI}$and 0.13 to 0.41 (mean 0.32) NaA+K. The two winchite analyses are intermediate between the sodic amphibole and barvoisite analyses. The seven calcic amphibole analyses have the values; K = 0.0 to 0.03, Al^{IV}= 0.0. to 0.88 (mean 0.36), Al^{VI}=0.1 to 1.0 (mean 0.35) and A = 0.0 to 0.27 (mean 0.010). The Ti, Mn and K values are uniformly low in all the analyses. The relative amounts of Al^{IV}, Al^{VI} and A-site occupancy in the sodic, sodic-calcic and calcic amphibole analyses are similar to those observed by Ernst (1979).

It has been noted by a number of workers that Al^{VI} increase with pressure, and Al^{IV} and A-site occupancy with temperature of metamorphism (cf. Jan and Howie, 1982, for a review). The values for these in the Ladakh amphiboles may therefore suggest that following the development of glaucophane, a drop in P/T may have caused the growth of barroisitic amphibole and actinolitic hornblende. Brown (1977) devised a geobarometer based on Na M4 and Al^{IV} contents of amphibole. This geobarometer is not yet calibrated by experiment and the influence of temperature is not known. A plot of the Ladakh amphiboles (Fig. 13) suggests that the sodic amphiboles formed at about 7 kbar, sodic-calcic amphiboles at 6 kbar, and calcic amphiboles at 4 to 5 kbar.

Conditions of Metamorphism in eastern Ladakh

The high-P metamorphic rocks from Ladakh are devoid of prehnite, pumpellyite, aragonite and jadeite, but contain epidote, garnet and late-developed calcic amphibole. The three blueschist samples studied here also lack lawsonite, however, Virdi *et al.* (1977) report small quantities of this mineral in some metabasites and metasediments. Mineral assemblage in the Ladakh rocks is similar to blueschists from Taiwan (Liou *et al.,* 1975), Sanbagawa (Ernst and Seki, 1967) and the type IV blueschists in exotic blocks of the Franciscan complex (Coleman and Lee, 1963; Moore, 1984). These three examples are thought to have formed at higher temperatures and lower pressures than the insitu (type III) blueschists in the Franciscan (estimated at 200–300°C, 6–8 kbar according to Taylor and Coleman, 1968; Ernst, 1979).

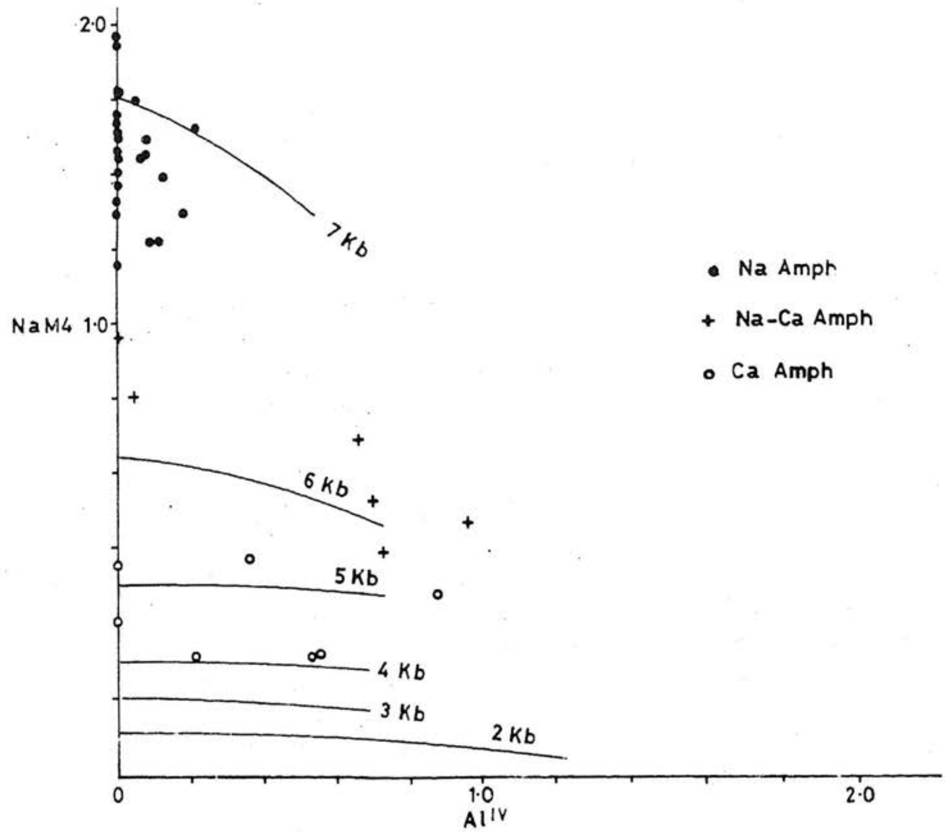

Fig. 13. NaM4 *vs.* Al^{IV} plots of sodic amphibole (filled circles), sodic-calcic amphibole (crosses), and calcic amphibole (open circles) analyses from the Ladakh blueschists. Tentative isobars are from Brown (1977).

Phase equilibria pertinent to the blueschists are plotted in Fig. 14. The recation Jd_{25} + Qtz → Ab (Moore, 1984), Ar → Cc (Johannes and Puhan, 1974), Pum + Chl + Qtz → Epi + Act + Fluid (Nitsch, 1971), Law + Ab → Par + Zoi (Holland, 1979; Heinrich and Althaus, 1980) and Plg + Mar → Par + Zoi + Qtz (Franz and Althaus, 1977) define metamorphic conditions for the Ladakh rocks (hatched area). The presence of minor lawsonite, and barroisitic zones around glaucophane suggest that the metamorphic peak temperatures ranged from the upper stability limit of lawsonite to that of glaucophane.

The estimated conditions for the glaucophane-stable assemblage are deducted to be 370 to 480°C and 7 to 8 kbar. That pressures were not lower at these temperatures is also indicated by the celadonite content of the phengite. The average Si content of seven phengite analyses is 7.3 suggesting a pressure of about 8 kbar at 400°C according to the work of Velde (1965). (The more recent data of Massonne, 1980 (in Frey *et al.*, 1983) yield anomalously high pressure estimates). A pressure of about 7 kbar is also obtained by the application of Na M4 *vs.* Al^{IV} method of Brown (1977).

During uplift, a lower pressure overprinting resulted in the development of barroisitic and, afterwards, actinolitic amphibole. The inferred PT conditions for these stages are 470° to 400°C, 6 to 4 kbar (stippled area in Fig. 14). These

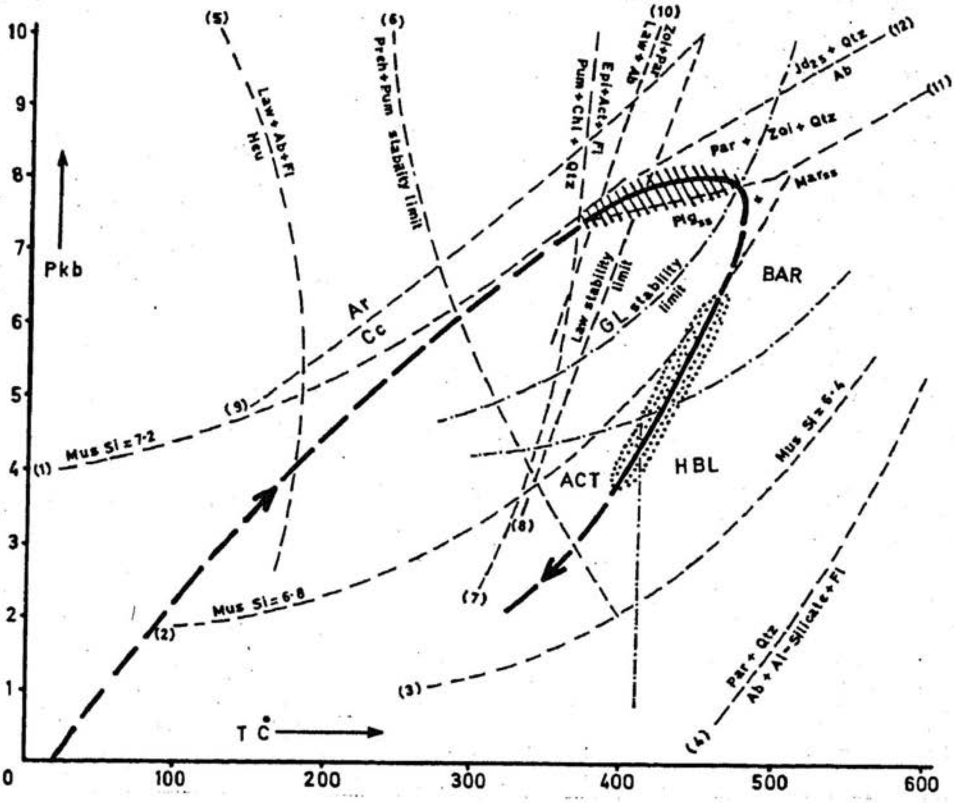

Fig. 14. PT conditions for high-P metamorphism in eastern Ladakh. Sources of data shown are: (1, 2, 3) Velde (1965); (4) Chatterjee (1972); (5) Nitsch (1968); (6. 7) Nitsch (1971); (8) Nitsch (1972); (9) Johannes and Puhan (1971); (10) Franz and Althause (1977); (11) Holland (1979); Heinrich and Althause (1980); (12) Moore (1984). Stability fields of galucophane, barroisite, hornblende and glaucophane adopted from Ernst (1979). Diagonally hatched area shows metamorphic conditions postulated for the blleschist facies climax and stippled area for the "lower presslre overprint". Thick arrowed curve is the tentative PT trajectory for the Ladakh blueschists.

estimates are based on the stability fields of the various amphiboles in PT grid (cf. Ernst, 1979) and the following reason. The sodic-calcic amphibole seems to have formed at ~6 kbar and the calcic amphiboles at 5 to 4 kbar (Fig. 13) according to the procedure of Brown (1977). It is assumed that the plagioclase reached equilibrium with the calcic amphibole and K-feldspar. Based on average value, the plagioclase-calcic amphibile pair yields a temperature of about 500°C by the model of Spear (1980) and <400°C by the method of Perchuk (1966) Two-feldspar geothermometry of Whitney and Stormer (1977) gives a temperature of ~440°C. Two phengitic micas have lower celadonite contents (Si=6.6 and 6.3) than the remainder; these values may record adujstment to lower pressures during uplift.

The decompression and thermal relexation of the PT trajectory in Fig. 14 is in accordance with the uplift and erosion model of England and Richardson (1977). The Ladakh rocks preserve much of the blueschist paragenesis; barroisitic and calcic amphiboles suggestive of epidote amphibolite and greenschist facies conditions are not developed intensely. Therefore, it is likely that the Ladakh blueschists were uplifted rather rapidly. The PT path for the most part is identical to that deduced for the rocks of the east central Shikoku area in Sanbagawa high-P metamorphic belt (Ernst, 1979). It was pointed out earlier that the blueschist parageneses in the two areas are more or less identical. However, the PT trajectory deduced by Guiraud *et al.* (in prep.) for similar paragenesis along the IZS near Shangla (Swat) is quite different.

CONCLUSION AND DISCUSSION

Like the present day subduction zones, especially the circum-Pacific, the Indus-Zangbo suture zone is characterized by the development of High-P metamorphic rocks. The suture is regarded as a major collisional boundary between India and Asia. At least half a dozen occurrences of high-P metamorphic rocks have been discovered over the past ten years and detailed investigations in the Himalaya-Tibet region may reveal additional occurrences. The high-P metamorphic rocks along the IZS have not surpassed the blueschist facies metamorphic conditions. However, in the Kohistan region of northern Pakistan, high-P garnet granulites have developed on an extensive scale at the expense of gabbroic rocks at 800–900°C, 12–14 kbar. The high-P metamorphic rocks of Khost and Nagaland, developed in suture zones bordering Indo-Pakistan plate on the west and east, respectively, also belong to the blueschist facies.

In Kohistan, Ladakh and southern Tibet, fossilized island arcs and paired metamorphic belts have been identified. In all three the low-P metamorphic belts and the magmatic arcs lie to the north of the high-P metamorphic belts. (Jan and Howie, 1981; Virdi, 1981a, 1981b, Zhang *et al.,* 1980; Zhou *et al.,* 1981). The Dras formation sedimentary rocks, occurring between the Ladakh magmatic arc to the north and ophiolitic malange to the south, have been recognised to be arc-trench gap type (Thakur and Bagati, 1983). These findings lend further support to the commonly held opinion that the Tethyan lithosphere subducted underneath the Tibetan landmass.

Sm-Nd dating suggests that the high-P granulites of Kohistan formed about 103±2 m.y. ago. K/Ar and $^{39}Ar/^{40}Ar$ ages on Shangla blueschist minerals range from 75 to 84 m.y. (The Shangla blueschists occur just to the south of the granulites from which they are separated by a thrust fault). Elsewhere along the IZS, the timing of the high-P metamorphism is not known but a Late Cretuceous to Early Tertiary age seems likely. Taking into consideration the various tectonic models (Andrews-Speed and Brook-field, 1981; Virdi, 1981b; Jan and Asif, 1983; Windly *et al.*, in press), the age of formation of the rocks could not have been much older (probably Late Jurassic to Cretaceous). The occurrence of Early Tertiary numulitic limestone blocks in the Shangla-Kabal area (Guiraud *et al.*, in prep.) may indicate the timing of obduction and melange formation. It can, therefore, be stated that high-P metamorphism in the IZS occurred within a few tens of million years of the deposition of the rocks. Some 250 km to the south of the IZS in Asam, however, (?) Early Tertiary collision between India and a microcontinent may have produced high P/T (blueschist facies) parageneses in Precambrian/Proterezoic rocks.

The Ladakh blueschists belong to a fault-bounded ophiolitic melange and their chemical characteristics are similar to ocean-floor volcanics. They were metamorphosed under high-grade blueschist facies conditions estimated at 370–480°C, 7–8 kbar. During obduction, lower pressure minerals were overprinted on the blueschist facies assemblage at 6 to 4 kbar when the temperature remained nearly the same. Sodic-calcic and calcic amphiboles, and some chlorite and white mica seem to have grown during ascent.

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