*Geol. Bull. Univ. Peshawar, Vol. 24, pp. 47-50, 1992*

# High-pressure veins in corona gabbros of Khwaza Khela, Kohistan

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ABSTRACT: *Gabbroic rocks of Khwaza Khela in the southern amphibolite belt of the Kohistan island arc preserve a record of thermal history from magmatic crystallization to high-pressure vein formation. The rocks formed from arc-related magma at about 1000°C, 3-4kb, probably during the Early Cretaceous. Subsequently calcic plagioclase and olivine reacted to form orthopyroxene + clinopyroxene + spinel ± tschermakite coronas at ~800°C, 6-8kb. The corona formation may have occurred in the early stages of the closure of the arc with the Karakoram plate (~95-102 Ma ago). Finally the rocks were subjected to high-pressure metamorphism which is reflected in thin quartzofeldspathic veins containing garnet, zoisite, paragonite and kyanite were formed at 500-600°C, 10-12kb. This paper presents petrography of these rocks and discusses the tectonic implications of the coronas and high-pressure veins which developed in response to cooling and crustal thickening.*

## INTRODUCTION

An extensive belt of amphibolites stretching for ~300km between the Nanga Parbat massif and Pak-Afghan border and attaining a width of ~50km, constitutes the southern part of the Kohistan island arc in northern Pakistan. The amphibolites consist essentially of hornblende and plagioclase or/and epidote. Quartz, opaque minerals, and sphene occur in minor amounts in most rocks, whereas garnet, clinopyroxene, micas, rutile, kyanite and a score of other minerals occur locally. In addition to amphibolites, the belt contains ultramafic and gabbroic rocks, quartz diorites, granites and trondhjemite (Jan, 1979; 1988). The amphibolites range from banded to homogeneous and are derived from volcanic and plutonic precursors. Major and trace element data suggest that the amphibolites have calc-alkaline, island arc-type chemical affinities (Jan, 1988). Gabbronorite relics occur throughout the amphibolite belt, especially to the north of Patan and south of Fatehpur. These resemble rocks of the Chilas complex forming the central part of the Kohistan arc (Khan et al., 1989). Near Khwaza Khela, only 5km from the suture, gabbroic relics contain sporadic garnetiferous quartzofeldspathic veins displaying high-pressure assemblages. These are briefly described in this paper.

High-pressure rocks occur intermittently along the entire length of the Indus suture and, along with ophiolites, mark traces of the collision boundries. Immediately to the south of the amphibolite belt across the Indus suture zone in Pakistan lies a complex of melanges in several places. In Shangla area blueschist-, greenschist-, and ophiolite melanges are separated by thrust faults (Kazmi et al., 1984). The blueschists have a minimum $Ar^{39}/Ar^{40}$ age of 75-80 Ma (Maluski and Matte, 1984) but, Spencer (pers. comm) suggests their metamorphism during Eocene. Jan et al. (1980) have assigned 410°C and 7kb $P_{H_2O}$ to the blueschists.

## PETROGRAPHY

### Host rock assemblage

The ~1km across Baba Dherai mound at Khwaza Khela occurs along the southern edge of the amphibolites. It is made up of gabbronorites, troctolites and small pods and layers of anorthosites and ultramafic rocks. The layers are generally thin (cm-scale to streaks) and may display rhythmic disposition and graded bedding. Mineral assemblages in these rocks were identified in thin sections and later confirmed by electron microprobe. Details of mineral chemistry will be published elsewhere.

Gabbronorites, the predominant rocks in the area, are medium to coarse grained and contain high-presssure veins. Their primary

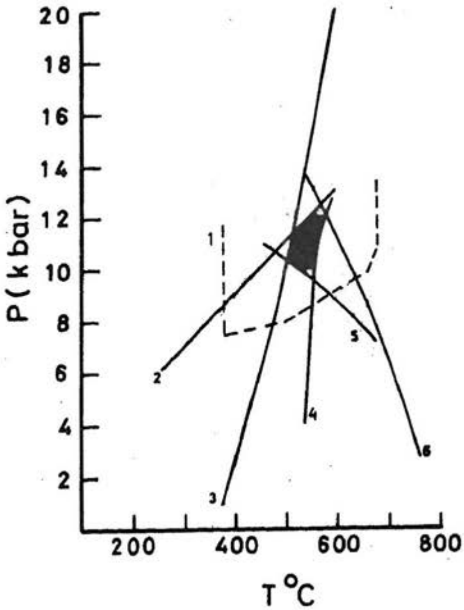


Fig. 1. Approximate conditions prevailing during the growth of the high-pressure veins in the Khwaza Khela metagabbros (shaded area). 1: margarite + plagioclase = paragonite + zoisite + quartz (Franz and Althaus, 1977), 2: calcite = aragonite (Forbes et al., 1984), 3: Diaspore = corundum + vapour (Chatterjee et al., 1984), 4: garnet + chlorite = staurolite + gedrite (Spear and Rumble, 1986), 5: margarite + quartz = zoisite + kyanite + vapour (Jenkin, 1984), 6: margarite = zoisite + kyanite + corundum + vapour (Halbach and Chatterjee, 1984).

mineralogy has been modified by post-magmatic processes including deformation, metamorphism, cooling and uplift. Relictual mineralogy comprises stout prismatic crystals of calcic bytownite, locally altered to scapolite, zoisite and clay minerals. It is either uniform in composition or shows very little core to margin variation. Orthopyroxene forms irregular or polygonal pleochroic crystals and classifies as enstatite ($En_{70}$). It is charged with dust and splinters of Fe-oxide and exsolved lamellae of clinopyroxene in a preferred orientation. Subordinate diopside occurs in textural equilibrium with orthopyroxene and as rare inclusions in garnet cores. Olivine ($Fo_{87}$), forming subhedral grains, contains streaks and dust of Fe-oxide and is marginally altered to chlorite. Brown pargasite of probable magmatic origin occurs sporadically in the rocks.

The olivine-bearing rocks of Khwaza Khela, like those of the Chilas complex (Jan et al., 1984), commonly display corona growths due to reaction between calcic plagioclase and olivine/orthopyroxene. These are high-temprature coronas consisting of shells with the disposition: olivine —> orthopyroxene-clinppyroxene-pleonaste (± tschermakite) <— plagioclase. Some coronas are made up only of clinopyroxene + pleonaste, but Arif et al. (1983) have also reported garnet + spinel in one rock. At lower temperature, probably during regional amphibolite facies metamorphism, plagioclase and pyroxene in some rocks reacted to produce thin coronas of amphibole and epidote.

### High-pressure vein assemblage

On the western flank, the Khwaza Khela gabbros contain thin (< 10 cm) sporadic veins of high-pressure assemblage. These veins are undeformed and consist of red poikiloblastic garnet (up to 5 cm) enclosed in a matrix of quartz, plagioclase, calcite, vermicular chlorite, paragonite, relict scapolite, and stout and accicular crystals of kyanite, pleochroic blue to pale in colour. The matrix material may project into or included by garnet poikiloblasts which may also contain rare inclusions of corundum and clinopyroxene in the cores. Veinlets containing plagioclase and subordinate amounts of carbonate, zoisite, chlorite, quartz, and corundum traverse the garnet. The plagioclase inclusions in garnet are far less calcic ($An_{25.5}$) than the primary plagioclase. Garnet is rich in almandine, but contains substantial amounts of pyrope and Ca-garnet components, possibly suggesting high pressure conditions.

## THERMOBAROMETRY AND TECTONIC IMPLICATIONS

The abundance of Khwaza Khela type relics and their derivative amphibolites lead to think that a large part of the southern amphibolite belt was initially made up of mafic plutonic rocks similar to those of the Chilas complex. These rocks formed beforethe southern belt was sheared, hydrated and amphibolitized between 85 and 102 Ma ago (Treloar et al., 1990). We regard that the thickness of the arc crust may not have exceeded 15km at the time of the emplacement of these gabbroic rocks. The primary anhydrous mineralogy of the Khwaza Khela rocks shows the crystallization, from an arc-related magma, of a very calcic plagioclase and olivine, which indicate pressures below 6kb. The probable depth of emplacement of less than 15km points to even lower pressures. It is likely that the rocks crystallized at 3-4kb and 1100-900°C.

During subsequent cooling, the anorthitic plagioclase and olivine reacted to form the corona assemblages. The growth of two pyroxenes and spinel ($\pm$ tschermakite) at the expense of olivine and anorthite, and the general absence of garnet in the coronas suggest pressures of 6 to 8kb (Frost, 1976; Green and Ringwood, 1972), and $P_{H2O} < P_{Total}$. These higher than the magmatic pressure estimates mean that the coronas developed during burial rather than exhumation (cf. Griffin and Heier, 1973). There are no significant differences in the compositions of the coronitic and independent pyroxene phases, suggesting the attainment of an overall equilibrium during the corona growth. Two-pyroxene thermometer of Wells (1977) and clinopyroxene-hornblende thermometer of Perchuk (1969) yield 800-820°C temperature estimates for the independent and corona assemblages.

It is interesting to note that temprature estimates of about 800°C have also been reported for the gabbronorite relics to the north of Patan (Jan, this vol.) and the Chilas complex (Jan & Howie, 1981), Quite likely, a major episode of equilibration under granulite facies conditions operated in the southern half of the Kohistan arc before the southern amphibolites were formed at least 85 Ma ago. The timing and cause of this high temprature equilibration is not clear but hornblendes from the Chilas complex have been dated at 80-103 Ma (Treloar et al., 1989). These dates coincide with those of suturing of the arc with the Karakoram plate (Petterson and Windley, 1985). The high temprature equilibration may therefore have taken place due to crustal thickening following the thrusting of the Karakoram plate onto the Kohistan arc, or even earlier due to growing thickness of the crust resulting from continued magmatism, provided the lower levels of the arc retained much of their heat.

The mineral paragenesis in the veins (garnet, zoisite, kyanite, paragonite, corundum, oligoclase, quartz, calcite) appears to be a continuum of this trend of increasing pressure and decreasing temprature. Some reactions relevant to the vein assemblage are shown in Figure 2: 1) margarite + plagioclase = paragonite + zoisite + quartz, 2) calcite = aragonite, 3) diaspore = corundum + vapour, 4) garnet + chlorite = staurolite + gedrite, 5) margarite + quartz = zoisite + kyanite + vapour, and 6) margarite = zoisite + kyanite + corundum + vapour. These quantify the pressure-temperature conditions of the veins at about 10-12kb, 510-570°C. Temperature estimates on garnet core and clinopyroxene inclusion are about 620°C (Ellis and Green, 1979), suggesting that the vein formation may have started at slightly higher temperature. It would, therefore, appear that continuous heat loss was taking place during the thickening/burial at the southern edge of the arc crust. The local presence of the high-pressure assemblage in veins and abundance of hydrous minerals reflect that fluid migration played an important role during their growth.

We conclude that the Khwaza Khela rocks display a continued history, from magmatic crystallization at 1100-900°C, 3-4kb, through corona growth at ~800°C, 6-8kb, to the development of veins at 510-600°C, 10-12kb. The coronas may have grown soon after collision with the Karakoram plate, and the high-pressure veins may have formed when the crust was sheared, imbricated and further thickened due to southward thrusting of the arc. Alternately, the veins may have developed when the southern edge of the arc was dragged down the subduction zone during initial collision with India, some 50 Ma ago (Patriat and Achache, 1984).

*Acknowledgements:* The cost of field work was defrayed by NSRDB grant ESC (24) to M.Q.J. Barkatullah is thanked for his assistance with microprobe analyses.

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