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FURTHER DATA ON ORTHO- AND CLINOPYROXENES FROM THE PYROXENE GRANULITES OF SWAT-KOHISTAN, NORTHERN PAKISTAN

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ABSTRACT

Microprobe analyses of pyroxenes from the pyroxene granulites of Swat-Kohistan are similar to their wet chemical analysis and the two sets of analysis yield similar temperature estimates. The pyroxenes are exsolved, but the exsolved pyroxene is similar in chemistry to its corresponding principal pyroxene, suggesting the attainment of physico-chemical equilibrium. The Mg/(Mg+Fe") ratios for the coexisting pyroxenes have been plotted and the implications of granulite facies metamorphosed noritic lenses in the amphibolite belt of Kohistan discussed.

INTRODUCTION

The Kohistan tectonic zone consists of a variety of volcanic and plutonic rocks and subordinate sediments, considered to represent a Cretaceous-Paleocene island arc sandwitched between the Indo-Pak and Karakoram plates (Tahirkheli *et. al.,* 1979; Tahirkheli and Jan, 1979; Bard *et. al.,* 1980; Andrews-Speed and Brookfield, 1982). The southern part of the Kohistan zone is occupied by the southern amphibolite belt consisting of (? oceanic) amphibolites with a complex mixture of other rocks. Emplaced towards the base of the amphibolites is a huge stratiform body, the Chilas Complex. It is 8 km thick and extends E–W for more than 300 km between central Dir and Nanga Parbat area. Isolated outcrops of such rocks occur further east near Kargil in Ladakh. Local bodies of these rocks are scattered in the southern amphibolite belt and the large Jijal complex, consisting of high-pressure ultramafic-mafic garnet granulites, may be a folded part of the Chilas Complex (Coward *et al.,* 1982).

Petrographic details of the Chilas complex have been presented from Dir (Chaudhry *et al.,* 1974), Swat and Indus Kohistan (Jan, 1977), and Thak Valley, Chilas (Shams, 1975). The complex is principally composed of norite with subordinate dunite, peridotite, pyroxenite, troctolite, gabbro, anorthosite and quartz diorite. These rocks seem to have been derived from a tholeiitic (Shams, 1975), or high alumina (calc-alkaline) magma of island arc-continental margin affinities (Jan, 1980; Jan and Kempe, 1973). The Chilas complex may have been intruded during the early phases (Early-Middle Cretaceous) of the development of Kohistan island arc and is a crucial unit of the arc (Jan, 1980). Honegger *et al.* (1982) suggest that the Kargil rocks (of the complex) represent the magma reservoir (cumulates) of the island arc volcanics in Ladakh.

The complex is isoclinally folded (Coward *et al.,* 1982) and metamorphosed in the pyroxene granulite facies (Jan, 1979, 1980). In a previous paper, Jan and Howie (1980) presented 41 wet chemical analyses of the coexisting ortho- and clinopyroxenes from the basic and intermedaite members of the granulites. These analyses were used in estimating the temperature of equilibration and, along with textural details, deciding about the igneous versus meta-igneous (granulite facies) nature of the rocks.

This paper presents only six representative microprobe analyses of the pyroxenes and their exsolved blobs in three rocks. For two of the rocks (337 and 592) no pyroxene analyses were given by Jan and Howie (1980) whilst the analyses of orthopyroxenes in 528 are included for comparison of the result by the two methods. Some additional amphibole, plagioclase, and biotite analyses are now available from the granulites in which pyroxenes have been analysed. These compositions have been used to present additional temperature estimates, along with the Mg/(Mg+Fe″) plots for the coexisting pyroxenes from the granulites of Swat Kohistan.

CHEMISTRY OF THE PYROXENES

Wet chemical analyses of minerals can suffer from a number of drawbacks such as a) zoning, b) impurities, c) exsolution on a fine scale, and d) mixing of exsolved lamellae and blobs of ortho- and clinopyroxenes with their corresponding principal phases which may chemically be quite different. For estimation of P-T conditions, microprobe analyses are, therefore, preferable over wet analyses. Therefore, pyroxene pairs in six rocks were analysed by microprobe, along with exsolved phases in three. Since the probe analyses are very similar to wet analyses in four of these (192, 193, 528, 592), therefore, no purpose will be served in presenting them. Pyroxenes in samples 337 and 587 were not analysed by Jan and Howie (1980) so their probe analyses are given in Table I, along with wet- and probe analyses of orthopyroxene in 528 for the sake of comparison.

The mircroprobe analyses generally have higher values for MgO, and lower for FeO^T, TiO_2 and, in the case of orthopyroxenes, CaO. Although the differences may well be due to two different analytical techniques, minor impurities of the other pyroxene as well as overestimation of CaO and TiO_2 in the wet analyses (or under estimation in probe data) might have had some contribution. Since Fe_2O_3 total was determined by atomic absorption and FeO by Wilson's (1955) method in the analyses presented by Jan and Howie (1980), it is likely that the lower FeO^T values in the microprobe analyses are either due to underestimation, or represent Fe-poor cores. Some excess in Fe may also be due to the small quantities of the finely exsolved hematitic blades in the pyroxenes concentrates wet chemically analysed. The important point is that the temperature estimates derived

TABLE 1. MICROPROBE ANALYSES OF SELECTED PYROXENES FROM THE PYROXENE GRANULITES

	SI 337 Opx	Sl 337 Exsol. Opx in Cpx	Sl 337 Cpx	Sk 587 Opx	Sk 528 Opx	Sk 528 Exsol. Opx in Cpx	Sk 528 Opx Wet anal.
SiO_2	50.23	50.60	50.09	50.20	51.14	50.05	50.85
Al_2O_3	3.49	3.25	4.40	3.85	2.87	2.65	2.89
TiO_2	0.08	0.05	0.33	0.25	0.05	0.05	0.25
FeO^T	27.29	27.55	11.90	25.74	23.14	21.30	21.25
MgO	17.62	17.84	11.13	18.11	21.59	19.96	20.12
MnO	0.68	0.65	0.35	0.62	0.51	0.59	0.54
CaO	0.57	0.40	20.52	0.29	0.59	1.21	1.04
Na_2O	0.09	0.00	0.72	0.01	0.04	0.05	0.03
K_2O	0.00	0.02	0.01	0.00	0.02	—	0.02
P_2O_5	0.01	0.00	0.02	0.03	0.01	0.02	—
Cr_2O_3	0.01	0.00	0.02	0.03	0.01	0.02	—
ZnO	0.06	0.03	0.00	0.00	0.07	—	—
TOTAL	100.20	100.40	99.47	99.13	100.03	95.88	99.78
NUMBER OF IONS ON THE BASIS OF SIX OXYGENS							
Si	1.916	1.926	1.894	1.918	1.908	1.946	1.910
Al[iv]	0.084	0.074	0.106	0.082	0.092	0.054	0.090
Σ	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Al[vi]	0.073	0.072	0.091	0.092	0.034	0.068	0.038
Fe″	0.858	0.877	0.328	0.823	0.659	0.693	0.668
Fe‴	0.013	0.000	0.048	0.000	0.062	0.000	0.079
Mg	1.002	1.012	0.627	1.031	1.200	1.157	1.127
Mn	0.022	0.021	0.011	0.020	0.016	0.019	0.017
Ti	0.002	0.001	0.009	0.008	0.001	0.001	0.007
Cr	0.000	0.000	0.001	0.001	0.001	0.001	—
Ca	0.023	0.016	0.832	0.012	0.024	0.050	0.042
Na	0.007	0.000	0.053	0.001	0.003	0.004	0.002
Σ	2.00	2.00	2.00	1.99	2.00	1.99	2.00
Mg	52.2	52.5	34.0	54.7	61.2	60.3	58.3
Fe	46.6	46.7	20.9	44.7	37.6	37.1	39.5
Ca	1.2	0.8	45.1	0.6	1.2	2.6	2.2

Fe expressed as total FeO in microprobe analyses. Fe^{2+} and Fe^{3+} in the formula recalculated such that the totals of Y and Z equal 2.00. Wet analysis of 528 Opx is after Jan and Howie (1980) and contains 2.79% Fe_2O_3 in total. Microprobe analyses by J.P. Bard. For details, see text.

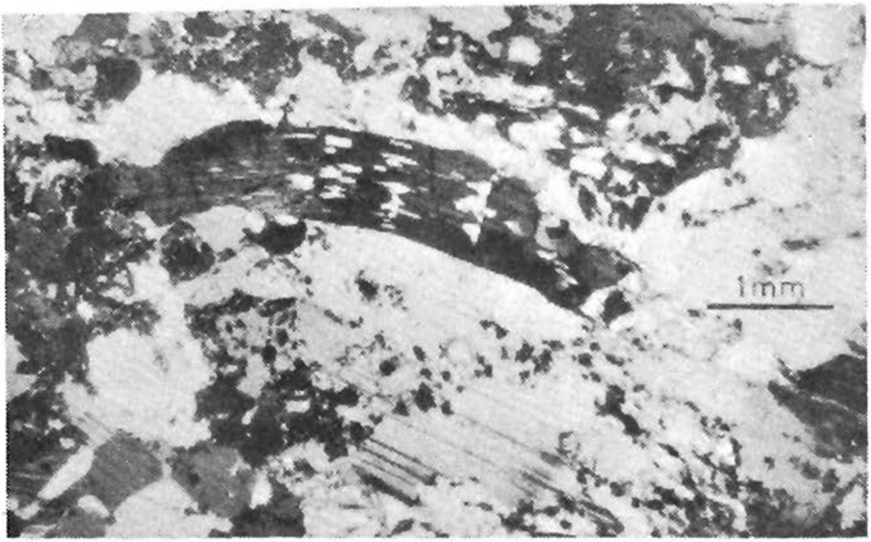

Fig. 1. Pyroxene granulite (528) with cloudy spots in plagioclase and bending in hypersthene. White blobs and short lamellae in the hypersthene are of exsolved clinopyroxene. They are clearly concentrated along axes of deformation in the host grain. Whether or not developed entirely during granulite facies metamorphism, the exsolved phase appears to have been concentrated as such during deformation that was probably synchronous with granulite facies metamorphism.

from the analyses by the two methods are quite similar and within the range of granulite facies metamorphism.

Analyses of the orthopyroxene in 528 show the general similarity of results obtained by microprobe and wet chemistry. Interesting is the phenomenon of exsolution displayed by both ortho- and clinopyroxenes. In addition to thin hematitic blades (Jan and Howie, 1980), the two pyroxenes contain discontinuous ("broken") lamellae, beeds, blobs, and lenses of the other pyroxene (Fig. 1). Petrographic details have been given for these by Jan (1979). It was thought that the chemistry of the exsolved pyroxene blobs would show substantial difference with that of its respective principal phase, however, microprobe analyses of exsolved orthopyroxenes closely match those of the principal orthopyroxenes in the two rocks studied for this purpose.

Analysis of the exsolved orthopyroxene in host clinopyroxene virtually duplicates that of the independent (and principal) orthopyroxene in rock 337, whilst those in 528 show only minor differences. Since the exsolved othopyroxene analysis in the latter rock is much too deficient in total, it is likely that SiO_2 and, especially, FeO and MgO are underestimated. The recalculated formulae for this and the major pyroxene phase are quite similar (see Table 1). It is concluded

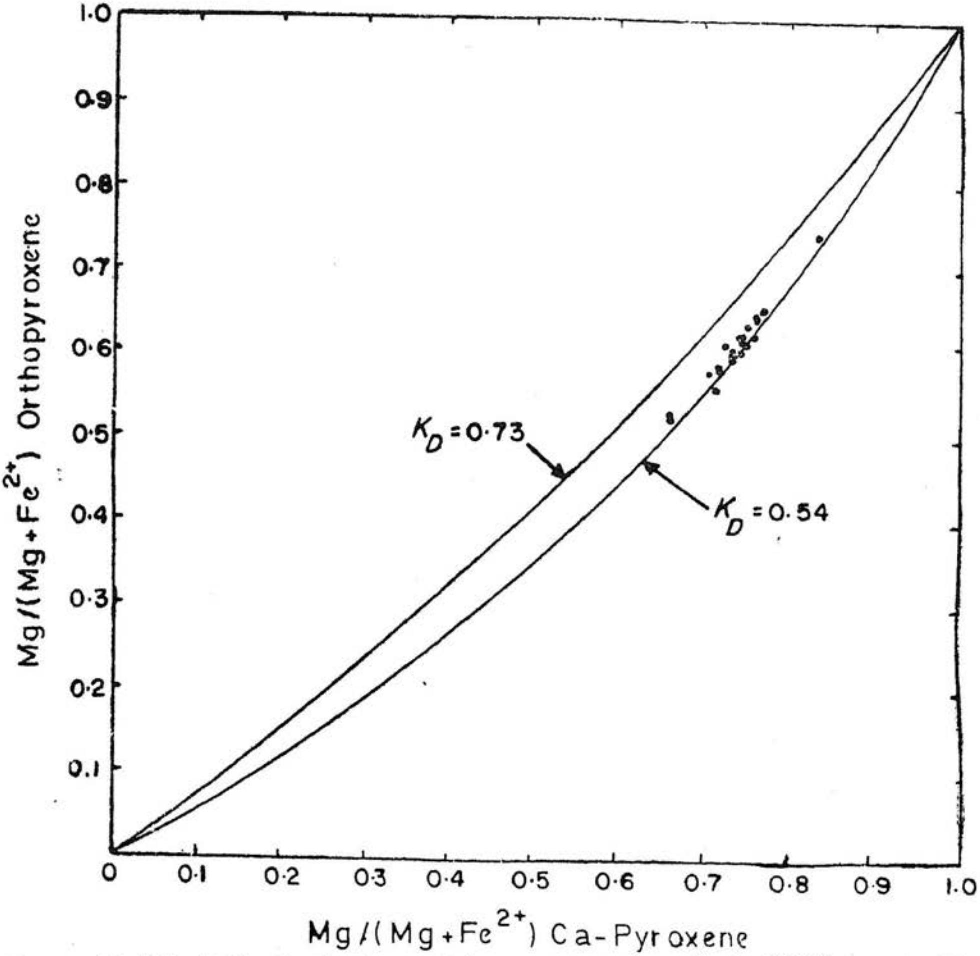

Fig. 2. Mg/(Mg+Fe″) plot for the coexisting pyroxenes from Swat Kohistan pyroxene granulites. The Mg-Fe distribution coefficient for metamorphic pyroxene pairs (0.54) is distinctly lower than that for igneous pairs (0.73) according to Kretz (1963). The Swat pyroxenes are clearly concentrated along the trend of metamorphic pyroxenes. For pyroxene analyses, see Jan and Howie (1980).

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that the close similarity of exsolved and independent principal corresponding pyroxene phases suggests close approximation to physico-chemical equilibrium, and that the wet analyses (Jan and Howie, 1980) of ortho- and clinopyroxenes have not been substantially affected by the incorporation of the corresponding exsolved phases, zoning, or impurities.

Figure 2 shows a plot of Mg/(Mg+Fe″) ratios of the coexisting pyroxene analyses from the pyroxene granulites of Swat Kohistan. Most of the analyses plot along or close to the distribution curve of metamorphic pyroxene pairs, and suggest that the pyroxenes have reached physico-chemical equilibrium under granulite facies metamorphism. Igneous pyroxenes, according to Kretz (1963), have higher K_DMg–Fe for ortho- and clinopyroxenes.

Table 2 shows temperature estimates for 337 and 587, along with those for 192, 193, 528, and 592. Some of the estimates for the latter four rocks were presented by Jan and Howie (1980) and these have been distinguished by asterics. Newly available analyses of biotite, amphibole and plagioclase in these rocks have enabled the writer to present additional estimates. The new estimates are in accord with those of Jan and Howie (1980) and confirm the conclusion regarding granulite facies metamorphism. Two interesting conclusions can be reached readily from Table 2: 1) the Wood-Banno (1973) and Wells (1977) models produce substantially higher temperatures for the Swat Kohistan pyroxene compositions. A similar situation was found for the Madras granulites by Weaver *et al.* (1978), and 2) the various methods of Perchuk (1966, 1968, 1969, 1977) yield exceedingly consistent results and are worthy of extensive application.

Whether the amphibole and, especially, biotite reached physico-chemical equilibrium with the pyroxenes (and with each other) is not clear. Textural evidence does not oppose equilibrium relation in the case of amphibole except in rock 337. However, the biotite may extend into and cut the pyroxene and thus appears to have grown later than pyroxene in a number of rocks (e.g. 192, 193). But despite such an opposing textural evidence, the Fe/Mg distribution between the biotites and coexisting ortho- and clionopyroxenes shows a systematic variation, suggesting approach to chemical equilibrium (Jan and Howie, in preparation). It should be kept in mind that even the presence of reaction textures does not necessarily imply disequilibrium (Ganguly, 1977). This is further suggested by the concordant temperature estimates involving biotite and the rest of the ferromagnesian silicates, unless the estimates are much too fortuitous and accidental.

Rocks 587 and 337 are of special interest and merit more description. The former (near Asrit) is an unusual type of granulite of Swat and is composed of bytownite, biotite, garnet, hypersthene, quartz (20%!), and small amounts of ore and secondary, muscovite, chlorite, talc and saussurite. This is the only granulite in the area which contains abundant garnet and biotite but no clinopyroxene. In thin section the mafic minerals in the rock may form large patches incorporating other minerals. Field data for this sample is not sufficiently clear but it occurs on the contact of a granite intrusion and noritic rocks and might be a hybrid rock metamorphosed in granulite faceis. Jan and Howie (1980) estimated pressures of 6 to 8 kbar for the pyroxene granulites of Swat-Kohistan. The biotite-garnet barometer of Perchuk (1977), however, gives a pressure estimate of about 8.8 kbar for rock 587.

Rock 337 (near Patan) forms a lens in the amphibolites that border the granulites on the south, the lens being about 30 km away from the main granulite belt. Such lenses, often amphibolitized marginally, occur sporadically throughout the amphibolite belt but their origin has yet not been clearly understood. Bard *et al.* (1980) suggested that these lenses are anhydrous assemblages formed during amphibolite facies metamorphism. Jan (1980), on the other hand, thought that their

TABLE 2. TEMPERATURE ESTIMATES (C°) FOR THE PYROXENE GRANULITES

	SI 337	Sk 587	SI 192	SI 193	Sk 528	Sk 592	Model
1	837	—	886*	929*	907*	876*	Two pyroxene (Wood & Banno, 1973)
2	600	—	795*	665*	755*	735*	Two pyroxene (Perchuk and Vaganov, 1977)
3	880	—	905*	859*	939*	911*	Two pyroxene (Wells, 1977)
4	760	—	700*	720	730	—	Amphibole-Plagioclase (Perchuk, 1966)
5	725	—	800	650	690	—	Amphibole-Plagioclase (Spear, 1980)
6	660	—	780*	750	710	—	Amph-Cpx (mg) (Perchuk, 1969)
7	700	—	800*	765	780	—	Amphibole-Orthopyroxene (Perchuk, 1969)
8	690	—	750*	730*	690	725	Biotite-Clinopyroxene (Perchuk, 1969)
9	725	700	700*	740*	680	750	Biotite-Orthopyroxene (Perchuk, 1969)
10	—	720	—	—	—	—	Orthopyroxene-garnet (Perchuk, 1968)
11	—	750	—	—	—	—	Biotite-garnet (Thompson, 1976)
12	—	820	—	—	—	—	Bio-Gar (Ferry & Spear, 1978)
13	—	700	—	—	—	—	Biotite-garnet (Perchuk, 1977)
14	700	—	—	—	—	—	Clinopyroxene-Amphibole. Ca-alk distribution (Perchuk, 1968)
15	730	—	780	720	850	780	Two pyroxene (Dahl, 1980)
16	—	702	—	—	—	—	Gar-opx (Dahl, 1980)

mg=Mg/(Mg+Fe+Mn) ca=Ca/(Ca+Na+K)

* From Jan and Howie (1980).

Amphibole mg: 337 = 0.45, 192 = 0.61, 193 = 0.58, 528 = 0.60

ca: 337 = 0.71, 192 = 0.76, 193 = 0.71, 528 = 0.70

Plagioclase An: 337 = 57, 192 = 55, 193 = 45, 528 = 50

Biotite mg: 337 = 0.53, 587 = 0.60, 192 = 0.61, 193 = 0.53, 528 = 0.63, 592 = 0.57

Garnet mg: 587 = 0.31

metamorphic grade was substantially higher than the surrounding amphibolites and are probably remobilized granulite bodies from depth. Textural, mineralogical, and geochemical data suggest a genetic link between these lenses and the rocks of the granulite belt. The surrounding amphibolites are rocks of diverse nature (metamorphosed tuffs, flows, ultramafic rocks and basic to intermediate and acidic plutons, possibly representing an oceanic suite, and minor metasediments). Since temperature estimates for rock 337 are at least 100°C higher than those deduced for the rocks of the amphibolite belt (Jan, 1977), an amphibolite facies metamorphism for this and the other noritic granulite lenses should no more be considered valid. Thus there is a possibility that the lenses are alien bodies, either remobilized or tectonically incorporated in the amphibolites. Conversely, it is also possible. that the rocks of the amphibolite belt are completely re-equilibrated (retrogressively) during obduction, following an earlier phase of granulite facies metmorphism. In such a consideration, the noritic granulite lenses would represent relict anhydrous assemblages only marginally amphibolitized.

CONCLUSIONS

Microprobe analyses of some ortho- and clinopyroxenes from the pyroxene granulites of Swat Kohistan closely match their wet analyses presented by Jan and Howie (1980). There are minor differences in Mg, Fe, Ca, and Ti but the temperature estimates deduced from the two sets of analyses are similar. The pyroxenes are exsolved, the exsolvd material generally having similar composition to the principal corresponding pyroxene phase in the rocks. This is taken to suggest that close approximation to physico-chemical equilibrium was achieved during granulite facies metamorphism. The amphibole- and biotite-involving geothermometers yield granulite facies temperature estimates and, despite an opposing textural evidence in most rocks, the biotite may have attained a chemical equilibrium with the rest of the ferromagnesian silicates during granulite facies metamorphism. The suggestion that the Swat noritic rocks have been metamorphosed at temperatures of 750°–800°C is repeated. Since garnet is found exceedingly sparingly, it is likely that the operating pressures were not more than 8 kbar, except locally. Noritic lenses in the vast belt of amphibolites to the south of the granulite belt have undergone a higher grade of metamorphism than the surrounding rocks. Thus they may be remobilized or tectonically incorporated bodies. There also is the possibility that the entire amphibolite belt is degranulitized, i.e. recrystallized into amphibolite facies during obduction, following an earlier phase of granulite facies metamorphism.

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