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Three-Stage Metamorphic History of a Whiteschist from Sar e Sang, Afghanistan, as Part of a Former Evaporite Deposit

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Abstract. Small volumes (in the cm^3 range) of a talc-kyanite schist exhibit mosaic equilibria characterized by mineral assemblages conventionally attributed to vastly different pressure temperature conditions of metamorphism. On the basis of petrographic and microprobe studies these assemblages are attributed to three consecutive stages of metamorphism of a chemically exceptional rock composition falling largely into the model system $MgO-Al_2O_3-SiO_2-H_2O$. Stage 1 typified by Mg chlorite-quartz-talc and some paragonite was followed during stage 2 by talc-kyanite, Mg gedrite-quartz, and the growth of large dravites. In stage 3 pure Mg cordierite formed with or without corundum and/or talc, and kyanite was partly converted into sillimanite. Pressures and temperature during this final stage of metamorphism were probably near 5–6 kb, 640° C.

The preservation of this succession of mineral assemblages related to each other through isochemical reactions suggests that the main factors governing the metamorphic history of this whitheschist were compositional changes of the coexisting fluids with time, whereas pressure temperature variations may be subordinate. In the Sar e Sang area such chemical variations of the metamorphic fluids are probably caused by progressive metamorphism and mobilization of a former evaporite deposit.

Microprobe analyses of the phases gedrite *and* talc indicate variable degrees of sodium incorporation into these phases according to the substitution NaAl→Si.

1. Introduction

In recent years a number of rocks have been discovered throughout the world that have aroused the interest of petrologists because of their unusual, highly magnesium and aluminous, bulk chemistry falling largely into the system $MgO-Al_2O_3-SiO_2-H_2O$ (e.g. McKie, 1959; Chinner and Sweatman, 1968; Vràna and

Barr, 1972; Kulke and Schreyer, 1973). While the derivation of such bulk compositions represents a petrogenetical problem of its own, another feature of these rocks seems to be even more important from the general geologic point of view: In virtually all cases these rocks appeared to show evidence of high pressures of crystallization, at least during one stage of their metamorphic history, due to the occurrence of characteristic mineral pairs that are known from experiment to be stable only above certain minimum pressures (Schreyer and Seifert, 1969; Newton, 1972; Kleppa and Newton, 1975). One of these characteristic mineral pairs stable at high water pressures, i.e. *talc-kyanite*, was chosen by Schreyer (1973, 1974) to represent the type mineralogy of a rock named *whiteschist* which appears to occur in some areas even on a regional scale.

Salient geological and petrographic features of the whiteschists from Sar e Sang, Afghanistan, were already reported by Kulke and Schreyer (1973). These schists occur as layers within a stratigraphically continuous talc-bearing series located near the base of the marble unit which carries the famous lapis lazuli deposits. In a cooperative program between the Universities of Bochum, Germany, and Kabul, Afghanistan, more work is presently being conducted to study the regional extension and tectonics of the whiteschists and their neighboring rocks.

In the present paper the emphasis is laid upon the detailed mineralogy and mineral chemistry of two adjacent whiteschist samples (Nos. SSg 42 and 42a) which were already used in the preliminary description by Kulke and Schreyer (1973). One particularly intriguing problem, the occurrence of sapphirine with a peraluminous composition, has been dealt with in a separate note including a crystal chemical discussion (Schreyer and Abraham, 1975). The results reported here cast new light on the metamorphic history of this unusual rock which must be understood as part of a former evaporite deposit.

2. Chemistry

The results of a bulk chemical analysis of one of the whiteschist samples (No. SSg 42) consisting essentially of talc and kyanite are given in Table 1 and show that more than 98 weight per cent of the rock fall into the system $MgO-Al_2O_3-SiO_2-H_2O$. The most prominent impurity is Na_2O, whereas iron is extremely low for a pelitic schist. Much of this iron is likely to be present in the accessory phase *pyrite*, or in limonite replacing pyrite. Sulfur was not determined.

The chemical composition of this whiteschist has been plotted in a projection of the system $MgO-Al_2O_3-SiO_2-H_2O$ (Fig. 1) where it lies very close to the tie line talc-kyanite in good agreement with its mineralogical composition (Kulke and Schreyer, 1973). A chemical analysis of the gedrite-bearing whiteschist (42a) was not feasible due to small sample size in relation to the coarse grain size, especially of kyanite.

A compilation of chemical analyses on other whiteschists is given by Schreyer (1977) together with a discussion of the possible origin of these unusual bulk compositions as mudstones of evaporite deposits.

Table 1. Chemical composition of whiteschist from Sar e Sang, Afghanistan (sample no. SSg 42)

	Sar e Sang whiteschist		
	Weight%		Mol%
SiO_2	56.2	56.2	50.45
TiO_2	0.3		
B_2O_3	0.34		
Al_2O_3	16.0	16.0	8.46
Fe_2O_3	0.3		
FeO	0.1		
MnO	<0.01		
MgO	22.9	22.9	30.62
CaO	0.10		
Na_2O	0.6		
K_2O	0.2		
Li_2O	0.01		
P_2O_5	<0.02		
H_2O*	3.5	3.5	10.47
	100.55	98.6	100.00

* Total includes 0.28% H_2O^-

3. Petrography

The general appearance of the coarse grained Sar e Sang whiteschist containing kyanite prisms up to 5 cm long has been summarized and pictured by Kulke and Schreyer (1973, Fig. 1). For the present purpose it is necessary to repeat that two sets of mineral assemblages were found that have formed at different stages during the metamorphic history of the schist:

During an earlier stage attributed to high-pressure metamorphism generally coarse grained minerals formed: Kyanite, talc, and gedrite. *Kyanites* now showing

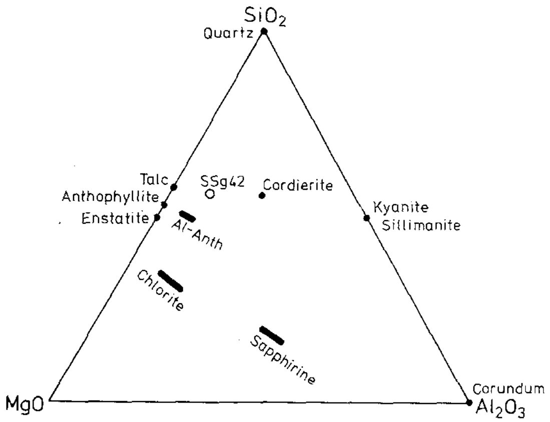

Fig. 1. Ternary plot of the model system $MgO-Al_2O_3-SiO_2(-H_2O)$ showing crystalline phases relevant to the mineralogy of the Sar e Sang whiteschist. Al-Anth stands for aluminous anthophyllites (Yoder, 1971). Open circle indicates the chemical compositions of a Sar e Sang whiteschist, sample SSg 42

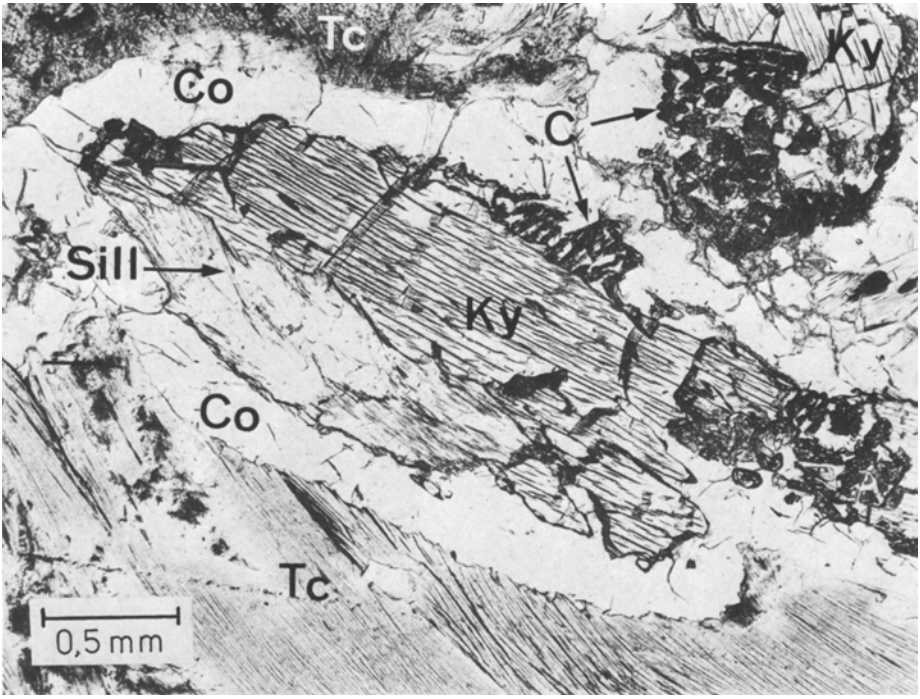

Fig. 2. Microphotograph of reaction zone between kyanite (*Ky*) and talc (*Tc*) with newly grown cordierite (*Co*) and corundum (*C*). Kyanite is partly converted into sillimanite (Sill). Sample 42, Sar e Sang, plane polarized light

signs of superficial corrosion were undoubtedly in direct contact with coarse flakes of *talc* following the schistosity that is generally contorted around the porphyroblastic, but often deformed kyanite prisms. In some layers of the schist poorer in talc, *gedrite* appears in prisms of several millimeters length which, however, are also corroded and may be surrounded by small, randomly oriented phyllosilicate flakes in *symplectitic intergrowth* with a tectosilicate. Most of the gedrites show a zonation with higher birefringence along the peripheries of the crystals. The gedrite-rich portions of the schist represented by sample No. 42a commonly contain also *quartz* which is otherwise rare. Gedrite and kyanite had mutual grain boundaries or were even intergrown in a complicated fashion during this stage of metamorphism.

In a *later stage* of metamorphism attributed by Kulke and Schreyer (1973) to lower confining pressures fine grained *cordierite* was formed consistently along the grain boundaries between kyanite and talc or kyanite and gedrite. This cordierite may be accompanied, in the case of silica-deficiency, by *corundum* or/and, as was discovered by microprobe work (Schreyer and Abraham, 1975), by very thin needles of *sapphirine*. A very similar occurrence of sapphirine in an apparently similar rock type from the Pamirs has previously been described by Zotov and Sidorenko (1968) in a paper which the present authors only recently came across. A typical mineral assemblage cordierite-corundum developed during this metamorphic stage in a zone between coarse talc and kyanite is shown as Fig. 2.

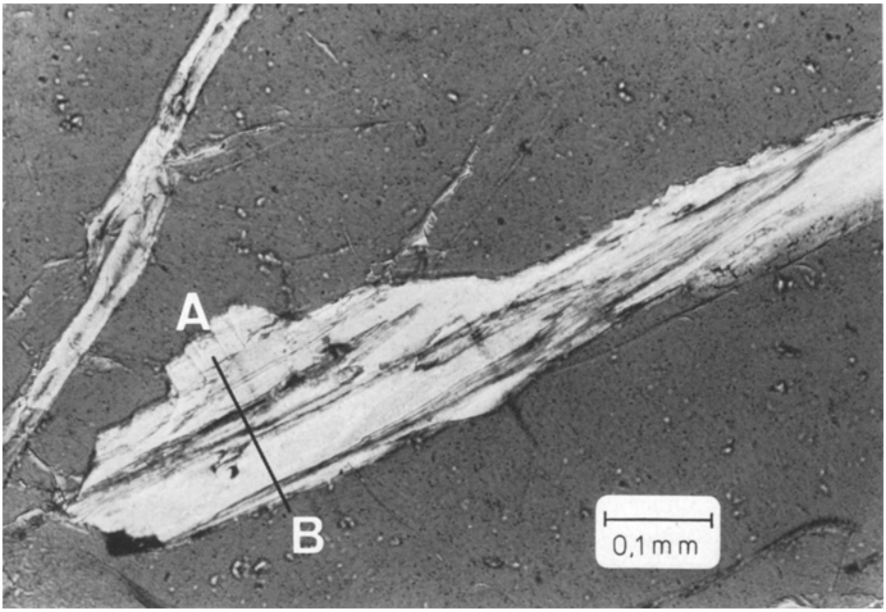

Fig. 3. Microphotograph of schistose inclusion within a large crystal of dravite (dark). The line A–B indicates the location of the microprobe scanning profile of Figure 4. Sar e Sang, whiteschist, sample 42. Crossed nicols

The newly formed minerals cordierite and corundum appear to coexist with the talc. *Sillimanite* occurs as a product of partial conversion of kyanite (Fig. 2) and is also attributed to the later stage of metamorphism. In rare cases *myrmekitic intergrowths* were found within the cordierite-bearing zones. Their characterization had to await microprobe analysis and will be discussed in a subsequent section (4.3.5.).

Additional minerals which are not as easily fitted into this two-stage scheme of crystallization are: Coarse euhedral *tourmaline* (dravite), *phlogopite*, and *sodic plagioclase*. *Rutile*, *pyrite*, and *xenotime* with inclusions of *zircon* are common accessories.

On the basis of its grain size *dravite* appears to belong to the earlier stage of metamorphism. This is supported by the finding of a series of inclusions within the tourmaline crystals which differ significantly both in texture and mineralogy from the external portions of the rock. Most common are *small* kyanites which, however, lack the characteristic peripheral zones of cordierite ± corundum. Genetically most significant among the inclusions is a three-phase *assemblage of chlorite, talc, and quartz* exhibiting small grain size and a very pronounced lamination which is interpreted as schistosity (Fig. 3). Since neither the assemblage chlorite-talc-quartz nor this type of schistosity has been found outside the dravites, these inclusions are regarded as preserved relics of a metamorphic stage that is precedent even to the kyanite-talc-gedrite grade. – *Phlogopite* is optically indistinguishable from talc. X-ray studies and the microprobe work have revealed, however, that it is a rare component generally occurring in small flakes which may be associated with all other minerals found in the rock. It is assumed that, depending on the availability of K, phlogopite was present in the rock at all stages of metamorphism that can be distinguished. – *Plagioclase* is very rare, too, and can only with great difficulties be distinguished from cordierite or quartz with which it occurs. Because of the common coexistence of plagioclase with cordierite it is likely that the plagioclase formed during the late stage of metamorphism.

Thus, on the basis of the new petrographic evidence, there are actually *three different stages* in the metamorphic history of the whiteschist that can be recognized:

Stage 1 preceding the growth of dravite is accompanied by *strong shearing* leading to narrowly spaced schistosity planes. Its characteristic mineral assemblage is *chlorite*, *quartz*, and *talc*, all three occurring in relatively *small grain size*. In Al-rich portions of the rock kyanite may have been present in small crystals substituting for talc in the above assemblage. Probably the accessories rutile, pyrite, xenotime, and zircon were already present at this stage.

Stage 2 took place under *continued deformation* and resulted in the growth of coarse crystals of *kyanite, talc, gedrite*, and *dravite* with or without quartz as a function of the local SiO_2 contents.

Stage 3 is a period of *static metamorphism* in which the phases *cordierite, sapphirine, corundum* and *sillimanite* developed.

For the sake of clarity all the minerals occurring in each of the two specimens studied are listed in Table 2 independent of their attribution to any of the metamorphic stages.

Table 2. Total mineral content of whiteschist samples from Sar e Sang, Afghanistan

SSg 42: Kyanite, talc, dravite, phlogopite, cordierite, corundum, sillimanite, clinochlore, quartz, paragonite, rutile, pyrite, xenotime, zircon

SSg 42a: Kyanite, gedrite, talc, quartz, phlogopite, cordierite, sapphirine, corundum, dravite, plagioclase, sillimanite, rutile, pyrite, xenotime, zircon

4. Mineralogy

In the Sar e Sang whiteschists with their finegrained relic mineral inclusions and reaction products detailed qualitative and quantitative microprobe work was essential for an understanding of the mineral equilibria prevailing during the various stages of their metamorphic history. Thus in the following not only the results of mineral analyses are reported but also the nature of some of the phyllosilicates as well as of finegrained intergrowths is clarified which through normal petrographic means could not be studied.

4.1. Minerals of Stage 1

Among the inclusions of the stage 1 minerals in dravite only an Mg-chlorite could unequivally be identified optically. Due to the optical similarity of colorless micas and talc the highly birefringent phyllosilicates required microprobe study.

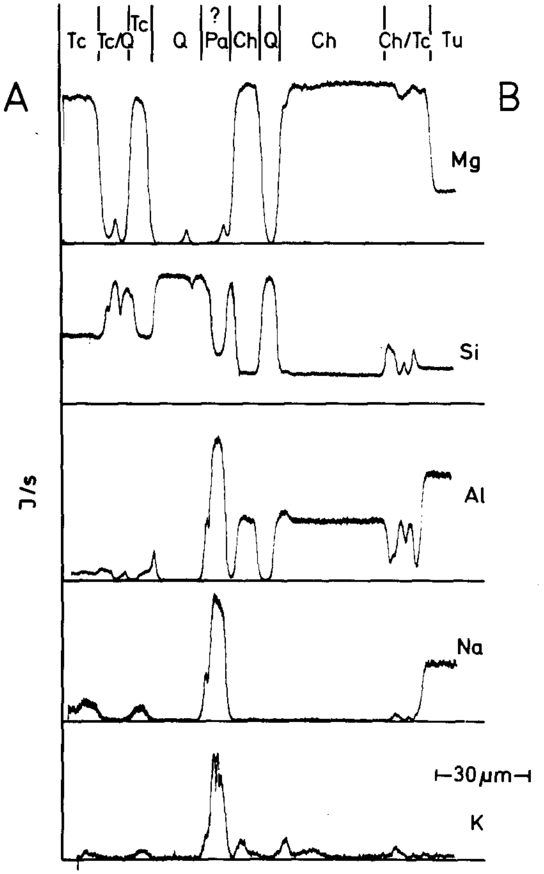

Fig. 4. Electron microprobe scanning profile A–B through schistose inclusions shown in Figure 3. I/s indicates impulses per seconds at scales that were different for the 5 elements measured. Abbreviations used at top: *Tc* talc, *Q* quartz, *Pa* paragonite, *Ch* chlorite, *Tu* dravite

Thus the finely schistose inclusion of Fig. 3 was identified to consist of *chlorite, quartz* and *talc* plus a trace of what appears to be white mica. On the basis of the scanning profile of Figure 4 the latter phase may be a potassic paragonite, although, because of the minute amount present, no quantitative analysis was possible. Figure 4 also shows that chlorite and talc may appear as an extremely intricate intergrowth which can hardly be resolved by the electron beam. The minerals of a second inclusion within the same dravite crystal were identified as bundles of *paragonite* surrounding a kyanite crystal of the composition $(Al_{1.99}Fe_{0.001})Si_{1.01}O_5$. The results of the quantitative microprobe analyses of phyllosilicate minerals included in dravites of sample 42 are compiled in Table 3.

4.1.1. Chlorite

The two analyses of chlorites (Chl 1–2) in Table 3 yield structural formulae close to that of clinochlore, $Mg_5Al[AlSi_3O_{10}](OH)_8$, but with characteristic excesses of Al following the substitution $Al[6]Al[4] \rightarrow MgSi$ thus demonstrating minor solid solution towards sheridanite (Tröger, 1969). The F-values, Fe/(Fe+Mg), of these chlorites amounting to 0.01 are extremely low.

Table 3. Microprobe analyses of phyllosilicates included within dravite of the whiteschist, Sar e Sang

	Chl 1		Chl 2		Tc 1		Tc 2		Pa 1		Pa 2	
SiO_2	29.29		29.35		60.61		60.04		47.80		47.72	
TiO_2	0		0		0.24		0.24		0		0	
Al_2O_3	21.49		20.13		2.52		2.35		37.38		36.40	
FeO^a	0.68		0.59		0.30		0.28		0.06		0.07	
MgO	32.95		33.47		30.26		30.26		0.91		1.12	
Na_2O	0		0		0.66		0.55		5.50		4.83	
K_2O	0		0		0.04		0.06		2.12		2.74	
	84.41		83.54		94.63		93.78		93.77		92.88	
Structural formulae:												
Oxygens:	28		28		22		22		22		22	
Si	5.61	8.00	5.68	8.00	7.75	8.00	7.75	8.00	6.19	8.00	6.25	8.00
Al IV	2.39		2.32		0.25		0.25		1.81		1.75	
Ti	0	11.97	0	12.03	0.02	6.12	0.02	6.13	0	4.09	0	4.10
Al VI	2.46		2.27		0.13		0.11		3.90		3.87	
Fe 2+	0.11		0.10		0.03		0.03		0.006		0.008	
Mg	9.40		9.66		5.77		5.82		0.18		0.22	
Na	0		0		0.16		0.14		1.38	1.73	1.23	1.69
K	0		0		0.006		0.01		0.35		0.46	

[a] Total iron as FeO

4.1.2. Talc

The two talc analyses (Tc 1–2) of Table 3 were made on crystals directly adjacent to the chlorite of the inclusion within drawite. They are notable for their contents in Al and alkalies. It appears that all of the octahedrally coordinated Al and an equal amount of tetrahedral Al may be attributed to an Al[4]Al[4]→MgSi substitution as in aluminious talc (Fawcett and Yoder, 1966; Newton, 1972). The remaining tetrahedral Al can, on formalistic grounds, be linked with Na which is present in nearly equal amounts thus following a substitution NaAl[4]→Si. It is clear, however, that such substitution is not permissible in the crystal structure of talc which is free from layers occupied by large cations (Na, K) that typify the mica structures. Thus no solid solution should exist between ideal talc, $Mg_3Si_4O_{10}(OH)_2$, and the phase soda phlogopite, $NaMg_3[AlSi_3O_{10}](OH)_2$, which according to Carman (1974) exists under conditions of elevated temperatures and water pressures, but cannot be quenched to surface conditions. Recently Kulke (1976) has described a trioctahedral mica from an evaporite deposit in Algeria that is predominantly sodic. Thus it would seem possible that the "talc" phase formed during stage 1 of the metamorphic history of the whiteschist is actually a mixed-layer phyllosilicate of talc and small amounts of soda phlogopite. The analytical totals shown for talc in Table 3 are normal for this mineral and preclude the presence of large amounts of smectite (saponite) that may have anhydrous compositions along the join talc-soda phlogopite (Deer et al., 1962). The F-values, Fe/(Fe+Mg), of talc (0.005) are notably lower than those of chlorite.

4.1.3. Paragonite

The microprobe data of two portions (Pa 1–2) of the mineral paragonite present together with kyanite in an isolated inclusion within dravite are also listed in Table 3. Notable are the relatively high contents in the components muscovite, $KAl_2[AlSi_3O_{10}](OH)_2$, and Na-phengite, $NaAl_{1.5}Mg_{0.5}$

$[Al_{0.5}Si_{3.5}O_{10}](OH)_2$ which increase concomitantly from Pa 1 to Pa 2. The latter component, in particular, is rather unusual for dioctahedral sodium micas (Deer et al., 1962) and, when compared with the K analogues (Velde, 1965), might indicate high confining pressures and/or low temperatures. The high amounts of K incorporated in the paragonites analyzed here would, on the other hand, suggest relatively high temperatures.

The mica phase supposedly present in the inclusion shown in Figure 3 may, on the basis of the scanning profiles of Figure 4, have a similar composition as the paragonite analyzed here. If this were indeed true, that paragonite would occur in coexistence with quartz during stage 1 of the whiteschist metamorphism.

4.2. Minerals of Stage 2

Since the mineral phases formed during the second stage of metamorphism generally occur as coarse crystals there were only few problems of identification and thus hardly any surprizes during the microprobe work regarding unexpected phases. An analysis of a coarse *kyanite* crystal yielded the structural formula $(Al_{1.985}Fe_{0.002})Si_{1.009}O_5$. Results of analyses on the other minerals are complied in Table 4.

4.2.1. Talc

The two talc analyses reported in Table 4 are from a gedrite-free (Tc 3 from sample SSg 42) and from a gedrite-bearing (Tc 4 from sample 42a) portion of the whiteschist. Like the analyses Tc 1–2 of Table 3 they are characterized by considerable quantities of both Al and Na that seem to substitute in ideal talc according to the equations AlAl→MgSi and NaAl→Si.

Powder X-ray diffraction studies of the talc separated from sample 42 do not lend support to the presence of a mixed-layer phase between talc and soda phlogopite (see Sect. 4.1.2.). The lattice constants were determined from an indexed pattern run with KI as internal standard and refined using the computer program of Evans et al. (1963). For a triclinic cell (space group $C\bar{1}$) it follows: $a_0 = 5.298 \pm 0.002$ Å, $b_0 = 9.111 \pm 0.007$ Å; $c_0 = 9.492 \pm 0.001$ Å; $\alpha = 91°7' \pm 3'$; $\beta = 99°11' \pm 1'$; $\gamma = 90°10' \pm 2'$; $V_0 = 452.3 \pm 0.3$ Å^3. Compared to the lattice constants of a pure synthetic talc, $Mg_3Si_4O_{10}(OH)_2$, prepared by Fornefeld (1975) at 2 kb, 650° C and determined as $a_0 = 5.290 \pm 0.001$ Å, $b_0 = 9.163 \pm 0.002$ Å, $c_0 = 9.472 \pm 0.002$ Å, $\alpha = 90°49' \pm 2'$, $\beta = 99°3' \pm 3'$, $\gamma = 90°5' \pm 2'$, $V_0 = 453.4 \pm 0.15$ Å^3, there are differences in b_0 and c_0.

Despite the structural problem of a NaAl→Si substitution in talc (see 4.1.2.) it is interesting to note that the amounts of a soda phogopite component present in analyses Tc 1–4 (Tables 3 and 4) show clearly a positive correlation with the degree of Al-substitution according to the scheme AlAl→MgSi which is permissible in the talc structure and has been verified by experiment (Fawcett and Yoder, 1966; Newton, 1972). Such correlation is well known for the gedrite group of amphiboles (Robinson et al., 1971 and Sect. 4.2.2.). On these grounds one might hypothesize that the small amounts of Na present may perhaps be accomodated under certain pressure temperature conditions in other than interlayer positions of the phyllosilicate structure. One possible site seems to be within the tetrahedral layer in the centers of the (pseudo-) hexagonal rings. This position would be geometrically similar to the A-site of the amphibole structure.

A comparison of the two talc analyses of Table 4 indicates that the degree of substitution is considerably higher in the talc (Tc 4) of the gedrite-bearing whiteschist than in that (Tc 3) of the gedrite-free rock. This may be due to a somewhat higher Na concentration of the total rock chemistry in sample 42a leading to the coexistence of talc with the Na-bearing phase gedrite in that rock. It should also be noted that the substitution 2Al→3Mg affecting only octahedral talc sites is obviously of little importance in the Sar e Sang talc, although it is the major substitution in the talc of the yoderite whiteschist (McKie, 1959) and has also been verified experimentally (Newton, 1972).

Table 4. Microprobe analyses of minerals stable during stage 2 of metamorphism in whiteschist, Sar e Sang

	Tc 3		Tc 4		Ge 1		Ge 2		Dr 1		Phl 1	
SiO_2	61.28		59.35		49.01		54.21		37.19		42.38	
TiO_2	0		0.39		0.20		0.15		0		1.66	
B_2O_3	–		–		–		–		10.86[b]		–	
Al_2O_3	2.36		3.43		14.91		7.02		32.87		15.31	
FeO[a]	0.32		0.24		0.55		0.67		0.30		0.27	
MgO	30.34		30.16		28.62		31.80		11.58		26.09	
CaO	0		0		0.23		0.20		0.42		0	
Na_2O	0.33		0.88		1.46		0.63		2.61		0.76	
K_2O	0		0.03		0		0		0		7.71	
	94.63		94.48		94.98		94.68		95.83		94.18	
Structural formulae:												
Oxygens:	22		22		23		23		29		22	
Si	7.81	8.00	7.62	8.00	6.65	8.00	7.34	8.00	5.96		5.86	8.00
Al IV	0.19		0.38		1.35		0.66		–		2.14	
B	–		–		–		–		3.00		–	
Ti	0	6.04	0.04	6.20	0.02	7.31	0.02	7.18	0	9.88	0.17	5.94
Al VI	0.16		0.14		1.03		0.46		6.20		0.36	
Fe 2+	0.03		0.03		0.06		0.08		0.04		0.03	
Mg	5.77		5.77		5.79		6.42		2.76		5.38	
Ca	0		0		0.03		0.03		0.07		0	1.56
Na	0.08		0.22		0.38		0.17		0.81		0.20	
K	0		0.004		0		0		0		1.36	

[a] Total iron as FeO

[b] Calculated assuming 3.00 B per formula unit

4.2.2. Gedrite

Because the gedrites occurring in sample 42 are often conspicuously zoned two analyses are listed in Table 4, Ge 1 representing the wide optically homogenous interior, Ge 2 the thin, highly birefringent rim of a large single crystal. As it is not known whether the zonation is a primary growth feature during stage 2 of the metamorphic history, or due to a secondary alteration related to stage 3 mineral formation, the entire crystal chemical variation is discussed here. A concentration profile (Fig. 5) run across the zoned crystal for the elements Si, Al, Mg, and Na indicates that the two zones are very sharply separated from each other while they are nearly of homogenous chemistry within themselves. Analysis Ge 1 made at the center of the crystal is that of a *gedrite* exhibiting an intermediate degree of Na- and Al substitutions (compare Robinson et al., 1971). The ratio of the substitution NaAl→Si to AlAl→MgSi is about 1:3 as indicated by these authors. The rim of the gedrite crystal is conspicuously poorer in both Al and Na, so that the mineral name applying to analysis Ge 2 could actually be chosen as *anthophyllite* (see Deer et al., 1963). Yet is clear that the rim is sufficiently aluminous to fall within the compositional range in which coexistences between Al-poor anthophyllites and Al-rich gedrites are known (Robinson et al., 1971). Since no exsolution textures have been observed or analyzed in the present case, it must be concluded that the Al-poor gedrite rim formed under temperature conditions above those of the assumed anthophyllite-gedrite solvus. Compared to the magnesian gedrite described by Zotov and Sidorenko (1968) from an apparently similar rock in the Pamirs the degree of NaAl substitutions is similar, but the preponderance of Mg over Fe still higher: The F-values, Fe/(Mg+Fe), of the orthoamphiboles analyzed here (0.01) are close to that of an ideal Mg-gedrite. Yet they are still measurably higher than those of the coexisting talc (0.005 for Tc 4).

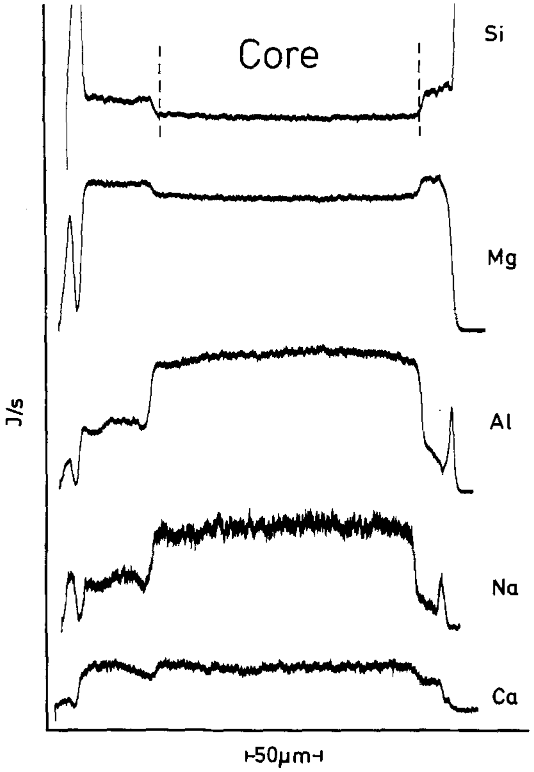

Fig. 5. Electron microbe scanning profile through zoned gedrite crystal. Note increase of Si and Mg from core to rim and concomitant decrease of Al and Na; see also Figure 8b–c. Sar e Sang whiteschist, sample 42a

4.2.3. Dravite

The coarse grained tourmalines occurring exclusively in sample 42 are of very uniform composition as shown by microprobe analyses on four different crystals. One of these analyses is included as Dr 1 in Table 4. Recalculation to the general chemical formula of tourmalines assuming 3 B-stoms per formula unit indicates that the composition is close to the ideal formula of dravite, $NaMg_3Al_6B_3Si_6O_{27}(OH,F)_4$. However, there is a consistent excess of Al and a deficiency both in (Mg+Fe) and Na which may be due to a substitution Al→NaMg. The theoretical end-member, $oMg_2AlAl_6B_3Si_6O_{27}(OH),F)_4$ derived from this substitution or similar phases may actually exist, since Na-free, pure MgAl-tourmalines can be synthesized in the laboratory (Rosenberg and Foit, 1975). On the basis of the F-value calculated (0.014) Fe is preferably partitioned into tourmaline relative to talc.

4.2.4. Phlogopite

The microprobe studies indicate that the phlogopites, which are optically indistinguishable from talc, are often intimately intergrown with the latter. Still more frequently small phlogopite flakes are spatially associated with gedrite both internally and externally. A phlogopite analysis from an inclusion in gedrite (sample 42a) is listed in Table 4 as Phl 1. The structural formula indicates a slightly eastonitic phlogopite with a small excess of octahedral Al and a notable deficiency in alkalies. The amount of soda phlogopite present in solid solution (some 13 mol%) is relatively low when compared to other phlogopites reported in the literature (see Carman, 1974).

4.3. Minerals and Mineral Intergrowths Formed during Stage 3

Mineral growth during the third and final stage of metamorphism is limited to relatively narrow reaction zones between the coarse crystals formed during stage 2. Therefore, the microprobe was indispensable for identifying the nature and determining the compositions of the newly formed finegrained reaction products. Analyses of corundum consistently proved it to be pure Al_2O_3. Other analyses are compiled in Table 5. Sillimanites formed at the expense of kyanite were not analyzed.

4.3.1. Cordierite

The cordierite grains that grew along the former grain boundaries of talc or gedrite versus kyanite or sillimanite have the composition of essentially *pure Mg-cordierite* (Co 1–2 of Table 5). This is the second find of pure end-member cordierite in nature (see Rossovsky, 1963; Schreyer, 1965).

Table 5. Microprobe analyses of minerals formed during stage 3 of whiteschist metamorphism, Sar e Sang

	Co 1	Co 2	Sa 1	Pl 1	Pl 2	Dr 2
SiO_2	50.30	49.95	11.28	62.01	63.36	37.30
TiO_2	0	0	0	0	0	0.52
B_2O_3	–	–	–	–	–	10.91[b]
Al_2O_3	33.12	33.95	68.64	22.83	22.34	33.25
FeO[a]	0.16	0	0	0	0	0.21
MgO	13.77	13.43	18.75	0	0	10.83
CaO	0	0	0	4.49	3.76	1.03
Na_2O	0.36	0.10	0	8.98	9.37	2.32
K	0	0	0	0.05	0.05	0
	97.71	97.43	98.67	98.36	98.88	96.37
Structural formulae:						
Oxygen	18	18	20	32	32	29
Si	5.03	4.99	1.31 } 6.00	11.15 } 15.99	11.30 } 16.00	5.94
Al IV	3.90	4.00	4.69	4.84	4.70	–
B	–	–	–	–	–	3.00
Ti	0	0	0	0	0	0.06
Al VI	–	–	4.72	–	–	6.24
Fe 2+	0.01	0	0	0	0	0.03
Mg	2.05 } 2.13	2.00 } 2.02	3.25 } 7.97	0 } 4.01	0 } 3.97	2.57 } 9.79
Ca	0	0	0	0.87	0.72	0.18
Na	0.07	0.02	0	3.13	3.24	0.71
K	0	0	0	0.01	0.01	0

[a] Total iron as FeO

[b] Calculated assuming 3.00 B per formula unit

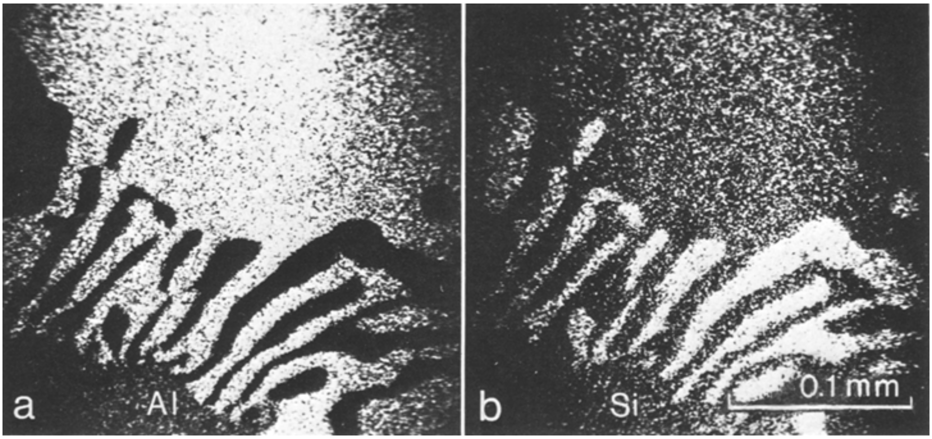

Fig. 6. Al- and Si-radiation pictures of myrmekitic intergrowth of quartz and cordierite surrounding gedrite (*Ge*). Sar e Sang whiteschist, sample 42a

The analytical totals leave room for some material other than alkalies that occupy positions with the structural channels of the mineral. On the other hand, the mean refractive index of the whiteschist cordierite was determined as 1.532 ± 0.001. Neglecting the small amounts of Na found analytically this indicates that only about one weight per cent of molecular H_2O may be present within the channel (see Schreyer and Yoder, 1964, Fig. 6). Unfortunately, the finegrained nature of cordierite and its intergrowth with other phases has precluded an analytical determination of the true nature and amounts of the channel-filling material. Whereas the formula of Co 2 is practically identical with the ideal cordierite stoichiometry, $Mg_2Al_4Si_5O_{18} \cdot X$, Co 1 contains some Na which may be linked to the framework by the substitution $NaMg \rightleftharpoons Al$, which is of importance in tourmaline (see Sect. 4.2.3.), in kornerupine (Seifert, 1975), and apparently also in some cordierites (Schreyer, 1965).

4.3.2. Sapphirine

The composition of the extremely fine needles of sapphirine formed preferably at the contact between gedrite and kyanite was found to be unusually Al-rich. In a previous paper (Schreyer and Abraham, 1975) arguments have been brought forward that this phase is actually an intermediate metastable product of crystallization preceding the growth of the stable assemblage corundum-cordierite. One of the sapphirine analyses is repeated in Table 5 as Sa 1. It coexists in sample 42a with the cordierite Co 2 (Table 5) and like the latter represents a true *Mg end member*.

4.3.3. Plagioclase

Plagioclase is an extremely rare mineral in the whiteschist, and it is confined to the gedrite-bearing portions. Its association with cordierite rims between gedrite and kyanite seems to indicate that its origin is related to the reaction between these two minerals, plagioclase accomodating the Na and Ca previously incorporated in gedrite (Table 4). This is supported by the two microprobe analyses of an inhomogenous plagioclase crystal given in Table 5 (Pl 1–2): Their Na/Ca ratios are rather similar to that of the NaAl-poor rim of the gedrite (cf. Table 4, Ge 2). The plagioclase compositions analyzed ($An_{21.6}$ for Pl 1; $An_{17.5}$ for Pl 2) fall within the peristerite range thus indicating a minimum temperature of some 500° C (Smith, 1972) for stage 3 of the whiteschist development. According to qualitative microprobe investigations plagioclase often includes small round grains of quartz which, however, never show any resemblance to those of myrmekites.

4.3.4. Dravite

In one case a small anhedral crystal of tourmaline was found within the cordierite rim separating kyanite and gedrite. Its analysis (Table 5, Dr 2) may be distinguished from those of the large euhedral crystals of stage 2 (Table 4, Dr 1) through small contents of TiO_2 which may be derived from the gedrite breakdown. The occurrence of tourmaline in the cordierite rim seems to indicate that boron was still mobile during stage 3 of the whiteschist metamorphism, dravite substituting in the presence of boron for cordierite and plagioclase.

4.3.5. Myrmekitic Intergrowth

The myrmekitic textures observed occasionally within the cordierite rims around gedrite were found through microprobe work to consist of minute worms of quartz in a matrix of Mg-cordierite (Fig. 6). They are thus distinct from the classical myrmekites (sensu strictu) representing intergrowths of quartz and sodic plagioclase (Becke, 1908). Since none of the mineral reactions invoked to have taken place during stage 3 of whiteschist metamorphism (see Sect. 5) produce free quartz—they often actually consume SiO_2— it is supposed that the myrmekite formed at the expense of a metastable silica-rich precursor phase of cordierite. Based on the experimental experience in the system $MgO-Al_2O_3-SiO_2$ such phases may either exhibit high quartz (Schreyer and Schairer, 1961) or osumilite-type structures (Schreyer and Schairer, 1962).

4.3.6. Phyllosilicate Symplectite

The petrographic observation that gedrites bordering against quartz are often surrounded by an optically indeterminate phyllosilicate-bearing symplectite was further investigated by microprobe techniques. The intergrowth was found to consist of minute *talc* platelets in a groundmass of *cordierite*

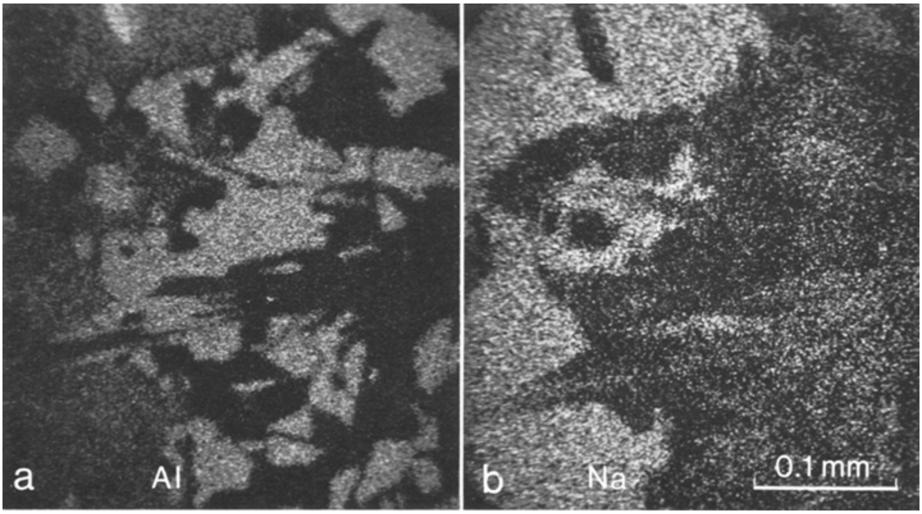

Fig. 7. Al- and Na-radiation pictures of finegrained symplectitic intergrowth of newly formed cordierite (light areas in a) and talc (black areas in a) surrounding a corroded crystal of gedrite in the left portion of both pictures. Sar e Sang whiteschist, sample 42a

(Fig. 7a, b). It is concluded that this symplectite was also formed during stage 3 of the whiteschist metamorphism through a reaction of gedrite with quartz. The sodium present in the gedrite is apparently incorporated both in the newly formed talc and cordierite (Fig. 7b). Although mutual grain boundaries between coarse talc of stage 2 and cordierite of stage 3 are very common in the whiteschist the coexistence of the two minerals in the newly formed symplectite indicates that the talc-cordierite assemblage is clearly stable during stage 3 of the whiteschist development. To the authors' knowledge this is the only recorded natural occurrence of this assemblage well known from experimental work (e.g. Fawcett and Yoder, 1966).

5. Petrogenetic Discussion

In Figure 8a–c the compatibility relations of analyzed mineral phases falling largely into the system $MgO-Al_2O_3-SiO_2-H_2O$ are summarized for the three consecutive stages of whiteschist metamorphism as derived through optical and microprobe work. Most impressive of all the changes occurring is the replacement of the chlorite-quartz tie-line of stage 1 (Fig. 8a) by talc-kyanite in stage 2

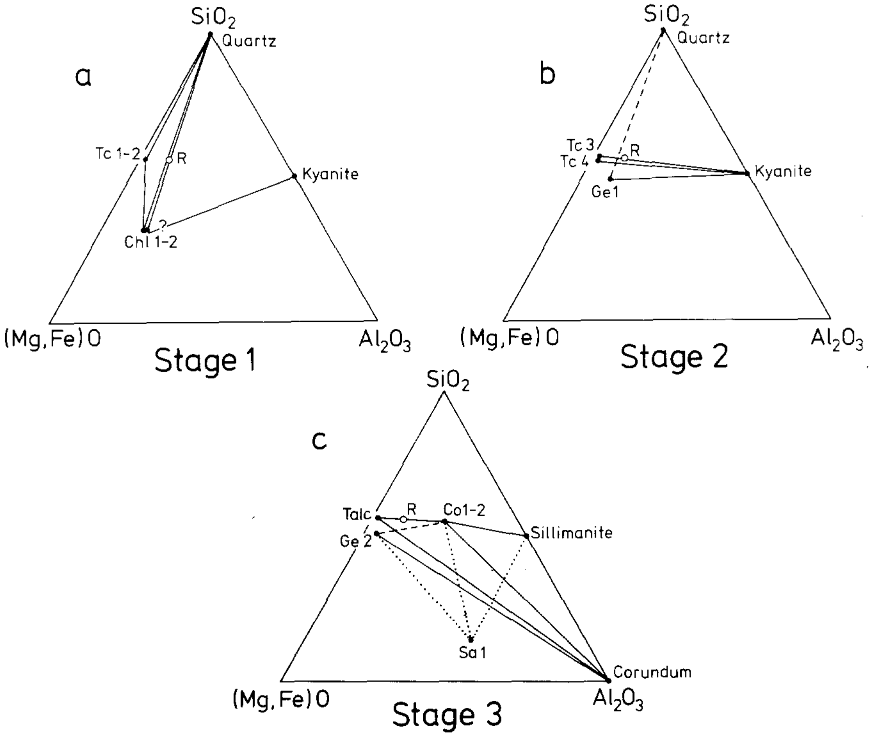

Fig. 8. Compilation of compatibility relations of minerals in the system $MgO-Al_2O_3-SiO_2-H_2O$ formed during three consecutive stages (a–c) of whiteschist metamorphism at Sar e Sang. Solid dots represent the microprobe analyses of minerals as listed and identified in Tables 3–5 and discussed in the text. Open circles labelled R give the bulk composition of sample 42 (Table 1). The extremely small amounts of total iron present in both mineral and rock analyses were taken as FeO and added to MgO. Solid tie lines are considered stable during the respective stages for compositions in the model system $MgO-Al_2O_3-SiO_2-H_2O$, whereas for the dashed tie lines of stages 2–3, though also stable, sodium is required as an additional component. The dotted tie lines of stage 3 show a metastable intermediate equilibrium (Schreyer and Abraham, 1975). Abbreviations: *Talc* talc, *Chl* chlorite, *Ge* gedrite, *Co* cordierite, *Sa* sapphirine

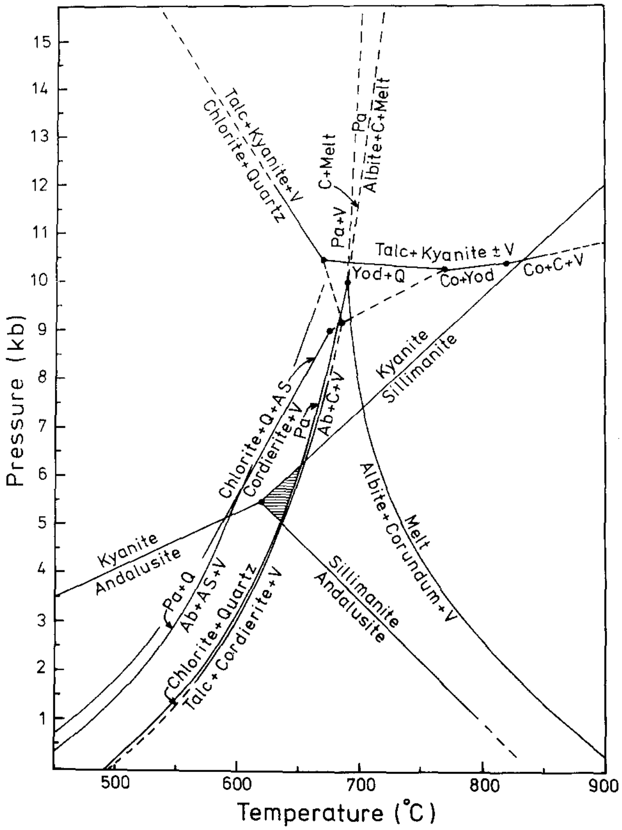

Fig. 9. Summarizing pressure temperature plot of some stability fields of minerals and mineral assemblages pertinent to the mineral succession observed in the Sar e Sang whiteschist. The data were taken from the following papers: Al_2SiO_5 polymorphs: Richardson et al. (1967); lower cordierite stability: Seifert and Schreyer (1970); paragonite-quartz: Chatterjee (1972); paragonite and its melting: Chatterjee (1970, 1974); chlorite-quartz at low pressures: Fawcett and Yoder (1966) extrapolated; chlorite-quartz at high pressures and talc-kyanite: Schreyer (1968) and Schreyer and Seifert (1969). The shaded area indicates pressure temperature conditions that are close to those prevailing during stage 3 of whiteschist metamorphism. Abbreviations: *Pa* paragonite, *Q* quartz, *AS* Al_2SiO_5, *Ab* albite, *C* corundum, *Co* cordierite, *Yod* yoderite, *V* vapor

(Fig. 8b), which is in turn replaced by cordierite-corundum in stage 3 (Fig. 8c). The compatibility relations of the orthoamphiboles shown by dashed tie-lines involve the presence of Na_2O as an additional component and, thus, only seemingly interfere with those of the pure system.

In an attempt at evaluating the compatibility relations deduced in Figure 8a to c in terms of physical conditions the relevant water pressure-temperature stability fields, as far as they have been determined experimentally, are summarized in the plot of Figure 9. It is obvious that the consecutive tie-line change chlorite-quartz→talc-kyanite→cordierite-corundum could best be explained through changes in the conditions of metamorphism from, for example, 6–10 kb P_{H_2O} and 500°–600° C during stage 1, to at least some 11 kb P_{H_2O} and about 700° C during stage 2, and, finally, again to lower water pressures, but at temperatures in excess of some 800° C during stage 3.

There are, however, serious objections against the simple picture outlined above, and they stem from the very fact that minerals and mineral assemblages formed during stage 1 have been preserved as inclusions within dravite throughout the later stages of whiteschist metamorphism. Thus it seems impossible that the bundles of paragonite assumed to form a separated subsystem by itself within the tourmaline can survive the temperature of some 800° C required for stage 3. One may argue that actually paragonite had been present as a hydrous melt during stage 3, and that it crystallized again during a still later period of cooling via the intermediate assemblage albite + corundum + H_2O. However, no optical or microprobe evidence could be detected in the inclusion for such "magmatic" and "postmagmatic" processes.

Perhaps still more enigmatic, in the light of the simple picture, would be the survival of the inclusions carrying the assemblage chlorite-quartz. It is hardly conceivable that this paragenesis included in tourmaline like in an externally heated pressure vessel should not show any signs of breakdown or mutual reaction when subjected to temperatures beyond 700°–800° C. The fact as evidenced by Figure 3 is that this assemblage retains relic textures of a low metamorphic grade that were completely destroyed in the external portions of the whiteschist fabric.

On the basis of the foregoing discussion and of the nature of the relevant stability fields of Figure 9 it must be concluded that the stages 2 and 3 of whiteschist metamorphism cannot be characterized by drastic increase in *temperature* versus stage 1: Metamorphic conditions during stages 2 and 3 must have remained within the stability fields of both chlorite-quartz and paragonite that have their maximum extension in the P_{H_2O}-T-diagram of Figure 9. Indeed, if the assemblage paragonite-quartz possibly present in one of the inclusions (Fig. 4) were accepted to be stable, the maximum temperatures attained would be still lower (Fig. 9).

Independent evidence concerning the pressure temperature conditions during stage 3 of whiteschist metamorphism is available through the partial conversion of kyanite into sillimanite. Taking this evidence in conjunction with that derived from inclusions in tourmaline the pressure temperature conditions during stage 3 must be assumed to lie in the small triangular portion of the sillimanite field (ruled in Fig. 9) just above the temperature of the Al_2SiO_5 triple point and limited by the paragonite breakdown curve, that is near 5–6 kb, 640° C. The latter curve might, for the present purpose, be shifted to very slightly higher temperatures due to the incorporation of some muscovite in solid solution (Chatterjee and Froese, 1975). The assemblage cordierite-corundum typical for stage 3 is also stable within most of this small area (Seifert, 1973). Although a lower pressure limit for the metamorphic conditions of stage 3 had never been postulated (Kulke and Schreyer, 1973) it seems surprising that the pressure range now envisaged is far below that of the equilibrium reaction talc + kyanite → cordierite + corundum in Figure 9. It is clear that maximum temperatures lying within the field of paragonite + quartz (!) would not allow the stable growth of sillimanite according to the experimental curves compiled in Figure 9. For consistency a lower temperature of the Al_2SiO_5 triple point would have to be assumed. However, with the meager analytical evidence at hand (Fig. 4 and Sect. 4.1.3) this line of reasoning cannot be followed convincingly at present.

A similar argument as that brought forward against high temperatures can also be valid for the *total pressure* prevailing during stage 2 of whiteschist metamorphism. Here the upper pressure limit of the field chlorite-quartz versus talc-kyanite lying in the range of 11–15 kb P_{H_2O} sets the absolute limit for the confining pressure endured by the whiteschist during stage 2, because it is also difficult to conceive that the large crystals of tourmaline could have prevented a transmission of a considerably higher external pressure onto minerals included within themselves. On the other hand, it seems possible that the reaction curve chlorite+quartz→talc+kyanite involving strong dehydration is by itself shifted towards lower pressure values under conditions of water pressures being less than total pressure (cf. Schreyer, 1977). If this is true, the assemblage talc-kyanite would not *necessarily* be indicative of confining pressures prevailing in 35–40 km depth or more as suggested by Schreyer (1973). More experimental and theoretical work will be necessary to clarify this point.

If changes in temperature and total pressure cannot solely be made responsible for the drastic changes in the mineralogy of the Sar e Sang whiteschists during their metamorphic history, what is their driving force? During recent field studies of the Sar e Sang area (Kulke, 1976) relic anhydrite and gypsum rocks were discovered. On the basis of this evidence it must be concluded that both the lapis lazuli deposits and the whiteschists are parts of a highly metamorphosed evaporite deposit that is now largely vanished due to melting and volatilization. In this genetic pattern it may be visualized that sedimentary pelitic layers of the salt deposit first underwent a period of metamorphism in which water pressures were relatively high and perhaps nearly equal to total pressure (stage 1). Subsequently, at higher grade, with the beginning mobilization of the salts, the metamorphic fluids became increasingly enriched in ions such as Na^+, Mg^{2+}, Cl^-, SO_4^{2-}, BO_3^{3-} etc., so that the water fugacity dropped considerably. This period perhaps represented by stage 2 of whiteschist metamorphism may thus also be characterized by strong metasomatism leading, for example, to the growth of dravite. The physical and/or chemical changes causing the final stage 3 of the whiteschist cannot be clearly defined as yet. The kyanite/sillimanite inversion requires an increase in temperature, or a decrease in pressure, or both; but changes in the composition of the coexisting gas phase may play an additional role for the formation of cordierite. The appearance of the assemblage talc-cordierite in the external portions of the rock during stage 3 (Fig. 7) as an alternative to the pair chlorite-quartz (Fawcett and Yoder, 1966) which is preserved as inclusions in tourmaline seems to indicate that water fugacity during stage 3 outside the tourmaline crystals was less than that within their inclusions.

In summary, it should be emphasized that a single thin section of a whiteschist from Sar e Sang contains mineral assemblages that would conventionally be attributed to the greenschist facies, the hornfels facies, and, in addition, also to the new high-pressure regime characterized by talc-kyanite (Schreyer, 1974). Their occurrence as mosaic equilibria over such small rock volumes suggests that they are largely governed by compositional changes of the coexisting metamorphic fluids with time, and, only to a lesser degree, by variations of temperature and total pressure.

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