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On the Metamorphism of the Eclogites and High-Grade Blueschists from the Penninic Terrane of the Tauern Window, Austria

By *Ch. Miller* (Innsbruck)*)

With 5 figures and 2 tables in the text

Abstract

Eclogites and high-grade blueschists in the Pennine terrane of the Tauern window, Austria, are associated with prasinites and calcareous clastics of the Mesozoic Peripheral Cover Sequence. The often nepheline-normative rocks are similar in mineralogy to the well-studied eclogites and glaucophaneschists from Zermatt-Saas Fee. The observed phase relationships are interpreted as representing an early Alpine high-pressure event (temperatures around 400–500° C and lithostatic pressures between 8–11 kb with fluid pressures possibly diluted by CO₂) and continuous adaptations to the greenschist-facies conditions prevailing during the main Alpine event.

INTRODUCTION

In the Eastern Alps the Pennine terrane exposed within the Tauern window consists of Hercynian sialic massifs surrounded by the partly allochthonous Paleozoic Inner and the Mesozoic Peripheral Cover Sequences (termed: Innere und Äussere Schieferhülle). These rocks were pervasively metamorphosed during Alpine time.

The occurrence of eclogites and eclogitic blueschists is restricted to a narrow and roughly east-west trending zone to the south of the old massifs, where they outcrop near the overthrust lower parts of the Peripheral Cover Sequence over a distance of about 30 km (Fig. 1). In this intensely tectonized area they form layers and lenses associated with rocks which have been metamorphosed to amphibolites, prasinites, serpentinites, garnet-mica-schists, calc-

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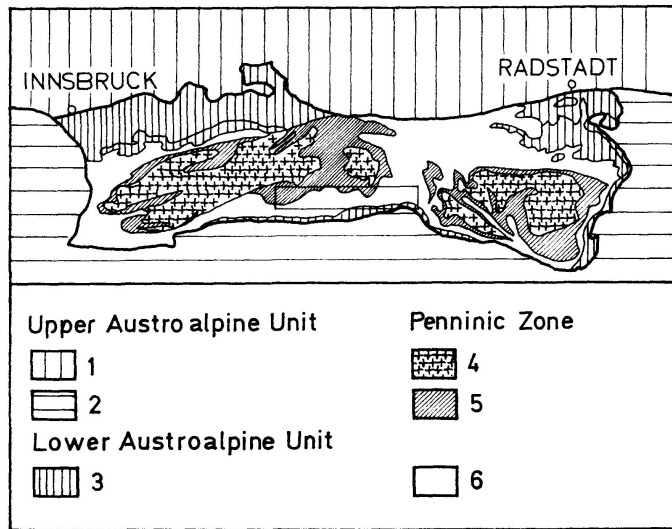


Fig. 1. Simplified geological map of the Tauern window to indicate area of eclogite occurrence. Explanations of symbols: 1 = Grauwackenzone + Northern Calcareous Alps; 2 = Crystalline Basement; 3 = Quartzphyllite + Mesozoic; 4 = Tauern Zentralgneis (old massifs); 5 = Paleozoic + Permo-triassic; 6 = Jurassic + Cretaceous (Bündnerschiefer, ophiolites).

schists, marbles and quartzites. According to CORNELIUS and CLAR (1939) and FRASL and FRANK (1966) the eclogitic and prasinitic rocks are derived from eugeosynclinal Jurassic to Lower Cretaceous mafic volcanics.

Although some petrographic and field data on these rocks are available, hardly any chemical data on rock and mineral compositions exist (SCHARBERT, 1954, RICHTER, 1973). More detailed investigations are needed to unravel the complicated metamorphic history of these rocks and the present paper also permits only a preliminary and tentative interpretation of the PT range of metamorphism.

PETROGRAPHY

The original lithology of the metabasic rocks and most of the primary features have been completely obliterated during deformation and metamorphism. Relict textures, however, indicate that some eclogites and prasinites represent igneous rocks. Features reminiscent of pillow breccias and pillow lavas were also noted in prasinites, but not yet definitely identified. Field relationships are very complicated, but it should be pointed out that eclogites + blueschists are nearly always in contact with calcareous micaschists.

Eclogites

Type 1: The massive rocks are coarse-grained and consist of green omphacite (4–9 mm), euhedral garnet (1–3 mm) and kyanite (0.5–1.5 mm). At their edges, the large omphacite crystals usually turn into an aggregate of fine-grained omphacite, amphibole ± paragonite, but oriented single crystal replacement by a subcalcic amphibole is also observed. Kyanite, if present, is marginally replaced by paragonite. Subhedral zoisite porphyroblasts sometimes occur, apparently forming at the same time as amphibole. Talc, rutile, quartz, apatite and pyrite are accessory minerals.

Type 2: The rocks are greenish-gray and dense with numerous garnet porphyroblasts less than 0.5 mm in diameter set in a very fine-grained, possibly cataclastic matrix of omphacite, kyanite, talc \pm glaucophane. Sometimes large (2–3 mm) grains of deformed omphacite are seen to have broken down into the groundmass association of omphacite 2 \pm glaucophane, whereas kyanite crystals are replaced by paragonite. Subsequently growth of subhedral poikiloblastic and randomly oriented zoisite must have occurred. Anhedronal quartz, rutile, pyrite \pm chalcopyrite are accessory minerals. Cross-cutting veins with the assemblages omphacite \pm quartz, talc + kyanite \pm Mg-chloritoid \pm quartz or kyanite \pm zoisite \pm quartz, with kyanite being frequently replaced by paragonite, are commonly associated with these rocks.

Type 3: The rocks are blue-green and dense with lenticular or streaky inhomogeneities due to differences in phase proportions. Fine-grained parts of granoblastic omphacite alternate with patches consisting of porphyroblastic garnets (2–3 mm) in a matrix of anhedronal omphacite, glaucophane, kyanite and zoisite and coarse-grained layers of either talc, kyanite and euhedral garnet or anhedronal breunnerite, garnet, zoisite, glaucophane, paragonite, omphacite, kyanite and talc. The paragenetic relationship between omphacite and glaucophane is ambiguous and if there is a replacement relation, the evidence is not always clearcut. Kyanite is often replaced by paragonite. Quartz, rutile and apatite are present as accessory minerals. Associated veins consist of glaucophane or omphacite or kyanite \pm paragonite + zoisite + quartz \pm dolomite.

Blueschists

Type 4: The rocks are fine-grained, foliated and conspicuously banded with compositional layering represented by the following associations: (1) clinozoisite/epidote + garnet + carbonates (dolomite or calcite) \pm quartz, (2) glaucophane + paragonite and/or phengite + clinozoisite + garnet, (3) glaucophane + garnet \pm omphacite. Accessories include rutile, apatite, pyrite and chalcopyrite. Omphacite, if present, may be partly replaced by glaucophane. Associated veins consist of clinozoisite + paragonite + quartz or dolomite + quartz + kyanite or quartz + calcite + rutile.

CHEMICAL COMPOSITION OF ROCKS AND MINERALS

For the purpose of comparing rock bulk compositions 30 samples were analyzed. The results, including 6 analyses previously determined by ANGEL (1954, 1957), SCHARBERT (1954) and RICHTER (1973) are plotted on various diagrams of Fig. 2 which clearly illustrates similarities in bulk composition between these rocks and basalts, respectively glaucophane schists and associated eclogites derived from basalts in other areas. 94% of the specimens analyzed are 01-normative and many are Ne-normative and hence critically under-saturated with respect to SiO_2 , showing affinities with alkali- and high-alumina basalts. But – contrary to the metamorphosed ophiolites of the Zermatt area (BEARTH, 1967, 1973) – only one of the samples has a $\text{CaO}/\text{Na}_2\text{O}$ ratio < 1.5 and thus a spilitic composition. Some variations in bulk chemistry could indicate admixture of tuffaceous material. According to PEARCE and CANN

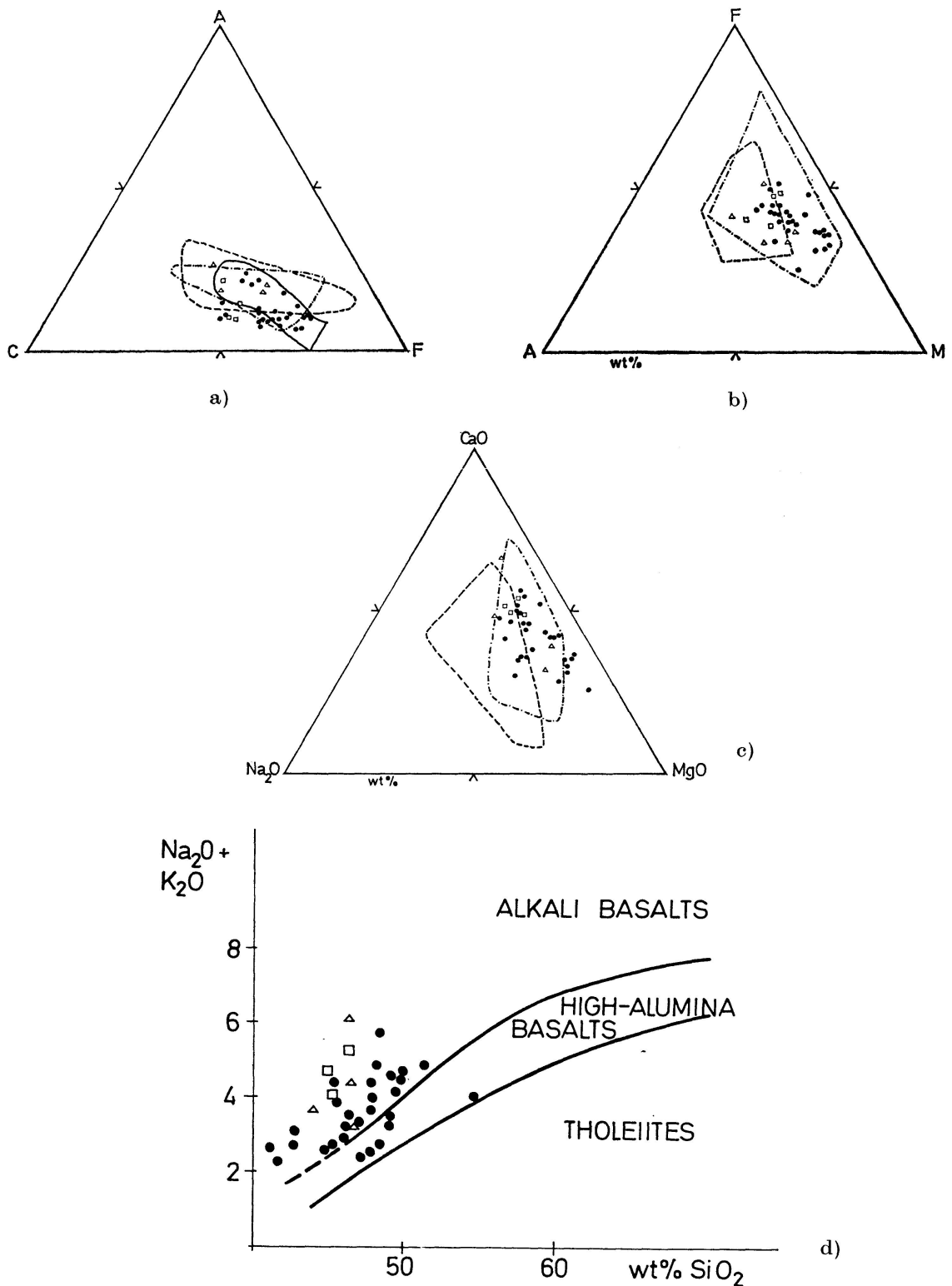
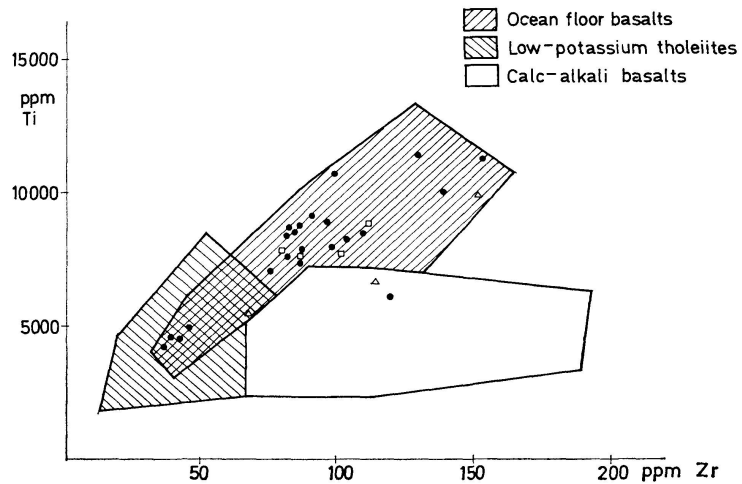


Fig. 2. Variations in bulk chemistry for some eclogites + blueschists (●), eclogite-amphibolites (□) and prasinites (△) from the Pennine terrane of the Tauern window. The areas designated by the solid, dashed and dash-dotted lines in (a), (b) and (c) indicate the compositional range of basaltic rocks (NOCKOLDS, 1954) and metamorphosed mafic rocks from Zermatt-Saas Fee (BEARTH, 1967, 1971) and the Franciscan (ERNST et al., 1970) respectively.

Fig. 3. Ti/Zr discrimination diagram for basaltic rocks (Pearce and Cann, 1973). Symbols are identical with those in Fig. 2.



(1973) the distribution of the trace elements Ti and Zr as plotted on Fig. 3 would be consistent with an ocean-floor origin of these rocks. But the question, whether any large-scale metasomatism has been operating during formation of these rocks cannot be decided because of the absence of unmetamorphosed equivalents.

Garnet: Garnet is an essential phase in all Tauern eclogites and blueschists. In type 1, 3 and 4 rocks it is strongly zoned, with Ca, Mn, Fe enriched in the garnet-cores (av. 16.9 Py, 59.2 Alm, 21.7 Gross, 2.2 Spess) and Mg enriched in the rims (av. 27.5 Py, 52.00 Alm, 19.50 Gross, 1.00 Spess) as shown in Fig. 4. This summary of analytical data also indicates some compositional overlap with garnets in eclogites from other glaucophane-schist environments. All garnets (with the exception of those in type 2 rocks) contain numerous inclusions concentrated in the cores. These are in order of abundance: clinozoisite/epidote + white mica + green amphibole + chlorite + quartz + rutile ±

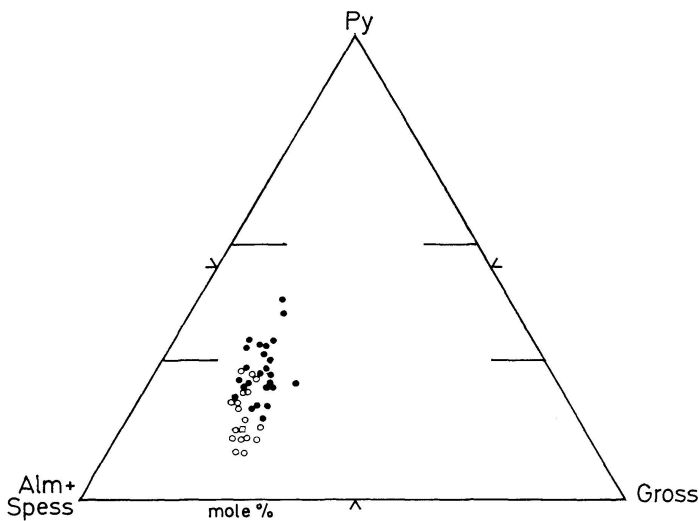


Fig. 4. Averaged microprobe analyses of garnet-cores (○) and -rims (●) from Tauern eclogites and blueschists. The open square indicates the garnet composition of an eclogite-amphibolite. Solid lines at 30 and 55 mole-% Py indicate garnet compositions in group-C and -B eclogites (COLEMAN et al., 1965).

apatite, carbonate and – observed but once – plagioclase. This inclusion mineralogy and the absence of the phases omphacite, kyanite and glaucophane possibly imply a pre-eclogite metamorphic mineral paragenesis.

Clinopyroxene: The chemical variation of the pyroxene is shown in Fig. 5 which also demonstrates a similarity in composition to clinopyroxenes from California group C eclogites (ESSENE and FYFE, 1967). They are relatively unzoned and characterized by a regular sodium content, averaging (12 samples)

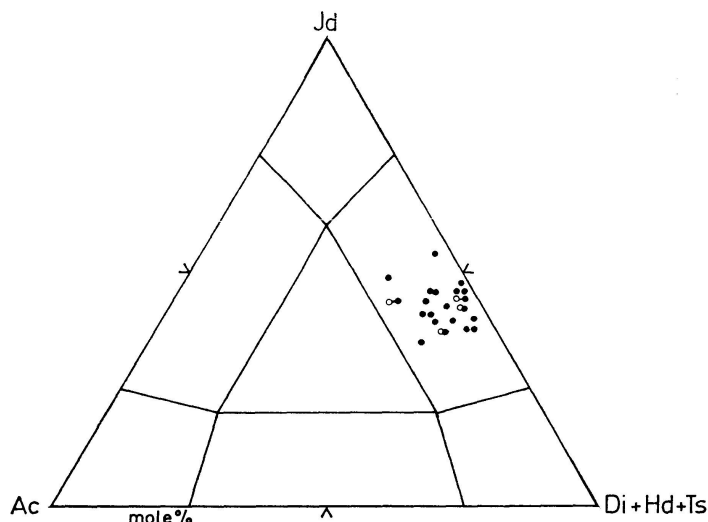


Fig. 5. Averaged microprobe analyses of omphacites from Tauern eclogites and blueschists, with open and solid circles indicating the extent of zonation observed. Terminology after ESSENE and FYFE (1967).

7.0 wt% Na_2O . The jadeite content was calculated from the analyses recast in atomic proportions relative to 6 oxygens as $\text{Jd} = \text{Al}^{\text{VI}} - \text{Al}^{\text{IV}}$ (for $\text{Si} + \text{Al}^{\text{IV}} = 2.00$) and assuming all Al in Jd and Ts. The Fe^3/Fe^2 -ratios were calculated from the analyses. The mean value thus obtained on matrix omphacites is 41 mole % jadeite and 6 mole % acmite. Further analytical work is needed to find out whether any significant compositional differences exist between the omphacites 1 and 2 and the omphacite occurring in veins.

Amphiboles: Amphiboles may occur either replacing single grains of omphacite, or as porphyroblasts subparallel to or cross-cutting the fine-grained matrix and containing inclusions of omphacite, kyanite, zoisite, rutile \pm talc, garnet, or as part of the granoblastic matrix with no textural evidence of disequilibrium. Of the 12 samples analyzed, 6 are *glaucophanes* proper, according to the classification of ERNST (1968), the range of $\text{Ca} \pm \text{K}$ substituting for Na in the X-group being 0.08–0.32 (Table 1). The rest could be described as *subcalcic hornblendes* ($\text{Ca} \pm \text{K} = 0.42\text{--}1.34$) or as Ca-glaucophanes (MOTTANA and EDGAR, 1969). All amphiboles are zoned, with Ca increasing towards the rim. Apparently there is a correlation between atomic Na in amphibole and the sodium content of the rock, but the significance of this has to be evaluated by further analyses.

Table 1. Average microprobe analyses of some Tauern eclogite phases

	Omphacite 157	Glaucophane 157	Paragonite 151	Phengite 235	Talc 188	Kyanite 188	Chloritoid 121
SiO ₂	56.52	60.04	48.84	51.28	62.01	37.10	24.57
TiO ₂	0.04	0.02	0.07	0.44	0.04	0.03	0.00
Al ₂ O ₃	10.16	11.08	38.50	27.90	0.54	62.70	43.14
Cr ₂ O ₃		0.03					0.02
Fe ₂ O ₃	1.32	1.89				0.47	
FeO	3.47	3.16	0.36	2.00	3.84		11.91
MgO	8.81	14.66	0.12	3.95	29.48	0.00	11.51
CaO	13.05	1.70	0.22	0.02	0.01	0.00	0.02
MnO	0.07	0.04	0.00	0.00	0.03	0.04	0.01
Na ₂ O	6.67	6.01	7.39	0.55		0.04	
K ₂ O		0.04	0.44	10.66			
Total	100.11	98.67	95.94	96.80	95.95	100.38	91.18

Atomic ratios

	0=6	0=23	0=22	0=22	0=22	0=20	0=12
Si	2.005	7.931	6.174	6.735	7.919	3.995	1.932
Ti	0.001	0.002	0.007	0.043	0.004	0.002	—
Al	0.425	1.726	5.738	4.321	0.081	7.960	4.000
Cr		0.003					0.001
Fe ³	0.035	0.188				0.038	
Fe ²	0.103	0.349	0.038	0.220	0.410		0.783
Mg	0.466	2.886	0.023	0.773	5.611	—	1.349
Ca	0.496	0.241	0.030	0.003	0.001	—	0.001
Mn	0.002	0.004	—	—	0.003	0.004	0.001
Na	0.495	1.540	1.812	0.140		0.008	
k		0.007	0.070	1.787			
Total	3.992	14.877	13.892	14.022	14.029	12.007	8.068

Green hornblende: With the approximate composition $K_{0.04} Na_{0.05} (Na_{0.8} Ca_{1.2})_{2.0} (Mg_{2.3} Fe^{3}_{0.8} Fe^{2}_{1.1} Mn_{0.03} Ti_{0.04} Al_{0.8})_{5.06} (Si_{6.9} Al_{1.1})_{8.00} O_{22} (OH)_2$ is forming from symplectite in eclogite amphibolites.

Phyllosilicates: Talc \pm paragonite \pm phengite occur in varying amounts in all eclogitic rocks. Their compositions are given in Table 1. *Talc* is especially common in type 3, but absent in type 4 rocks and in all eclogite amphibolites. The FeO content in the analysis corresponds to 6.6 mole % minnesotaite which is somewhat higher than the values (3–5) reported by CHINNER and DIXON (1973) for talc of the Allalin gabbro. *Paragonite* is frequently replacing kyanite in type 1–3 rocks, but it also occurs as cross-mica in the fine-grained matrix of type 2 and 3 rocks and it is commonly associated with glaucophane, clinozoisite and carbonate minerals in coarse-grained layers of type 3 and 4

rocks. The occurrence of *phengite* is apparently influenced by rock bulk chemistry, as it is restricted to rocks with K_2O in excess of 0.3 wt%. The analyses of three different samples indicate that this mica is containing Si in excess of three atoms per formula unit ($Si \cong 3.4$) as well as appreciable octahedral Fe and Mg. The greatest solid solution of paragonite is about 9 mole-%. *Chlorite* occurs only as inclusion in eclogite-garnets, but it is common in eclogite-amphibolites, where it retrogressed from garnet. The occurrence of tiny *biotite* flakes is also restricted to eclogite-amphibolites, where it appears to form from chlorite.

Epidote minerals: Zoisite with the composition of: $(Ca_{2.02}Mg_{0.01}Mn_{0.003})_{2.03}(Al_{2.9}Fe^{3+}_{0.07}Ti_{0.003})_{2.97}Si_{3.02}$ usually forms large and randomly oriented poikiloblastic crystals with euhedral outer margins in type 1-3 rocks, thus indicating late development.

Clinozoisite/epidote is present as inclusion in garnets and, containing about 16 mole-% pistacite, in nearly monomineralic layers up to 20 mm thick in type 4 rocks. In eclogite-amphibolites it either forms as breakdown product of garnet or it replaces zoisite. It is zoned, containing up to 23 mole-% pistacite.

DISCUSSION OF CONDITIONS OF METAMORPHISM

As the Pennine Mesozoic series has undergone metamorphism of Alpine age only and the majority of rocks are characterized by greenschist facies phase compatibilities, the eclogites probably represent an earlier high-pressure phase of Alpine metamorphism. The occurrence of pseudomorphs after lawsonite in nearby greenschists (FRY, 1973) also testifies to such an Alpine high-pressure event.

As textural evidence of equilibrium mineral associations in the Tauern eclogitic rocks is often inconclusive, the paragenetic relationships of the phases involved are difficult to assess. As the hydrous phases glaucophane, zoisite and paragonite often seem to postdate the formation of omphacite, garnet, kyanite and talc, at least some of the assemblages now present represent an eclogite mineralogy with superimposed blueschist and epidote-amphibolite assemblages and thus crystallization at different stages in the PTX_{H_2O} -evolution of Alpine metamorphism, similar to conditions known from the ophiolite complex of Zermatt-Saas Fee (BEARTH, 1967, 1973). Table 2 is a preliminary attempt at a summary of these postulated superimposed assemblages. Solid lines correlate pseudomorphic reactant phases, but they do not imply that these were the only ones involved. In fact, the mechanism for converting one assemblage to another must be very complex. It is considered to consist of a

Table 2. *Superimposed mineral assemblages in Tauern eclogites. See text for explanation*

pre-eclogite	eclogite	eclogite + blueschist	eclogite-amphibolite
	garnet	garnet	chlorite
plagioclase	omphacite 1	omphacite 2	amphibole
epidote		glaucophane	sodic plagioclase
hornblende	kyanite	kyanite	
chlorite	talc	talc	
white mica		paragonite	± paragonite
		phengite	phengite
		zoisite/clinozoisite	epidote
		carbonate	carbonate
quartz	quartz	quartz	quartz
rutile	rutile	rutile	sphene

series of interrelated coupled reactions involving concurrent solution and regeneration of most minerals in the rock with changing pressure, temperature and fluid compositions controlling their stabilities.

a) High-pressure event

In the absence of oxygen isotope data, an estimate of the approximate temperature of formation has been attempted by the comparison of the distribution coefficients between Fe/Mg of garnet and matrix clinopyroxene. Calculation of $K_{D_{Fe/Mg}}^{Px/Ga} = [X_{Fe}/(1 - X_{Fe})]^{Px} / [X_{Fe}/(1 - X_{Fe})]^{Ga}$ where $X_{Fe} = Fe^{2+}/(Fe^{2+} + Mg)$ in 14 samples gives 0.037 when the garnet cores are considered and 0.070 for garnet rims. K_D -values for eclogites from glaucophane-schist, amphibolite and kimberlite terranes have been reported e. g. by BANNO (1970) and MOTTANA (1970) as 0.044 and 0.043, 0.11 and 0.15, 0.28 and 0.50 respectively, thus clearly demonstrating an increase of K_D with increasing temperature.

K_D -values for California group-C eclogites with similar bulk compositions were calculated by SAXENA (1969), using the data in COLEMAN et al. (1963). They are in the range of 0.033–0.053, but, according to DUDLEY (1969), these data should also be differentiated for garnet-cores and -rims. DUDLEY also pointed out, that in the Franciscan K_D -values obtained from zoisite-eclogites are higher when compared to lawsonite-bearing type III (LEE et al., 1963) metabasalts, relating this trend with their higher temperature of formation. This is in good agreement with oxygen isotope temperatures reported by TAYLOR and COLEMAN (1968) which are in the range of 200–325° for type III and 400–550° for their type IV eclogites. Provided we are dealing with equilibrium partitioning, the K_D -values obtained for the Tauern eclogites would thus also indicate a temperature of formation of > 400°. Although there is no

simple interpretation of garnet-zonation with respect to grade of metamorphism (HOLLISTER, 1966, ATHERTON, 1968, BROWN, 1969), it seems reasonable to conclude that the initial Ca and Mn contents are determined by rock bulk composition and metamorphic grade and that Mg increases with increasing grade (GREEN and RINGWOOD, 1967). Growth and zonation of the garnets in the Tauern eclogites are therefore interpreted as reflecting an increasing grade of metamorphism and especially increasing pressure as supported by the low-pressure inclusion mineralogy.

Perhaps a limit of the PT-conditions of formation of these eclogites can also be deduced from the absence of lawsonite and the occurrence of the high-pressure assemblage kyanite + zoisite \pm quartz. According to NEWTON and KENNEDY (1963) this and the absence of plagioclase would imply pressures above 5.4 kb and temperatures above 420°. Calculations by ESSENE and FYFE (1967), based on an ideal solid solution model for sodic pyroxenes, predict that the formation of omphacite with a jadeite content of about 40 mole-% and little acmite requires pressures of 8–9 kb in the 400–500° temperature range. The absence of aragonite and any pseudomorphs after aragonite could indicate that the pressure during the eclogite-event did not exceed 9–11 kb for temperatures between 400–480° (JOHANNES and PUHAN, 1971). Thus, considering anhydrous phases only, temperatures of > 400° C and lithostatic pressures between 8–11 kb are postulated for the formation of the Tauern eclogites. That P_{tot} was high is also shown by the following high-pressure mineral compatibilities: glaucophane + paragonite \pm zoisite-clinozoisite \pm carbonates and kyanite + talc, an assemblage investigated by SCHREYER and SEIFERT (1969). According to their preliminary data, kyanite + talc would require pressures in excess of 15–12 kb in the 300–550° temperature range to form instead of chlorite + quartz. This seems too high when compared with the pressure range deduced above, but, because of the volume relations of the phases involved, a low partial pressure of water would extend the kyanite + talc field of stability towards lower pressures. The lack of adequate thermodynamic data, however, does not permit calculations of the extent of this effect.

Low partial pressure of water has to be postulated in any case, as extrapolation of experimental data (FRY and FYFE, 1969, ESSENE et al., 1970) suggests that eclogite crystallizing within the crust cannot be in equilibrium with a fluid phase having the chemical potential of pure water (i. e. $P_{\text{S}} = P_{\text{F}} = P_{\text{H}_2\text{O}}$). That fluid was involved in the formation of these particular rocks is confirmed by the widespread development of hydrous phases and the common occurrence of cross-cutting veinlets which together with the compositional layering in some eclogites also suggest that some constituents were mobile at least on the scale of several cm during metamorphism. But the presence of hydrous phases need not be evidence of high $P_{\text{H}_2\text{O}}$ and the anhydrous and

hydrous phases present in the Tauern eclogites could have buffered $P_{\text{H}_2\text{O}}$ at a very low value. Calculations of phase equilibria by GHENT and COLEMAN (1973) indicate that for the P - T -range in question a mixture of omphacite + garnet + hydrates could be stable at very low $X_{\text{H}_2\text{O}}$ (in the order of 0.15 or even less).

In absence of any direct evidence of the composition of the fluid phase present during metamorphism of the Tauern eclogites, one could perhaps suggest the possibility of a fluid phase rich in CO_2 . A relatively rapid transport of the eugeosynclinal sediments and the interbedded ophiolites into a higher PT -environment would not only result in loss of free water due to compaction and hydration reactions, but also produce enough CO_2 by reactions occurring in impure calcareous rocks to effect a dilution of the fluid phase, thus sustaining a high P_f while $P_{\text{H}_2\text{O}} < P_s$. The ubiquitous occurrence of rutile \pm carbonate + quartz indicates that these rocks recrystallized at a higher X_{CO_2} than that defined by the reaction calcite + quartz + rutile = sphene + CO_2 (SCHUILING and VINK, 1967). The required minimum X_{CO_2} at 400–500°/8 kb would, however, be very small (≥ 0.05 –0.08). There is no reaction to provide an estimate on the possible upper limit of X_{CO_2} during eclogite formation and the question whether CO_2 did in fact dilute the fluid phase to the required extent remains open. The occurrence of magnesite in talc-rich layers of type 3 rocks, which is probably signifying a replacement reaction, and the late development of zoisite would limit X_{CO_2} to values between 0.05–0.10 at 400–460°/7 kb (JOHANNES, 1969, STORRE and NITSCH, 1972), at least for the time of their formation.

b) Main Alpine event

Many eclogites show incipient signs of “retrogressive” metamorphism, and more or less complete transformation into greenschist-facies assemblages is also very common. The major mineralogical process accompanying this retrogression was a successive breakdown of all major high-pressure eclogite phases with garnet and zoisite outlasting the others, and their replacement by the lower-pressure mineral associations indicated in Table 2. That a lowering of lithostatic pressure and not only increasing $P_{\text{H}_2\text{O}}$ was involved in this transformation is inferred from the fact that the first breakdown-product of omphacite is a fine-grained symplectite which was identified by X-ray diffractometry to consist of diopsidic pyroxene and sodic plagioclase.

Large-scale metasomatism does not appear to have been operating, as indicated by the limited range of whole rock compositions (Fig. 2) although e. g. pseudomorphs of chlorite after garnet or of sericite or paragonite + epidote after kyanite are evidence for a fluid phase and for chemical exchange on a small scale.

PT-conditions prevailing during the main Alpine metamorphic event in this area have been deduced from the greenschist-facies assemblages of the rocks which constitute the main part of the Peripheral Cover Sequence in this area. Pelitic and psammitic rocks are typified by the following phases: quartz + garnet + phengite \pm kyanite \pm chloritoid \pm chlorite \pm epidote \pm carbonate \pm graphite, apatite, tourmaline. Prasinite assemblages include: albite/oligoclase + chlorite + epidote \pm actinolite \pm garnet \pm phengite + minor quartz, carbonate, biotite and accessory sphene, apatite, magnetite. Observed assemblages in calcareous lithologies are: dolomite \pm calcite + quartz \pm garnet \pm clinozoisite + chlorite + white mica \pm biotite + accessory sphene, apatite, pyrite, tourmaline or calcite + quartz + tremolite \pm clinozoisite + sphene or dolomite + calcite + quartz + talc + sphene.

Accepting the PT-values from experimental studies by KERRICK (1968), HOSCHEK (1969), RICHARDSON et al. (1969), the pelitic assemblages and the absence of staurolite even in the rocks of appropriate bulk composition indicate temperatures in the range of $> 430 < 550^\circ$ and $P_S = P_{H_2O} \geq 3.6\text{--}4.8$ kb. These temperature limits could be lowered e. g. if P_{H_2O} was again reduced by development of high P_{CO_2} . This, however, is unlikely as indicated by the presence of sphene. The persistence of antigorite and the absence of forsterite in the serpentinite-bodies associated with the prasinites not only indicates high P_{H_2O} , but, according to SCARFE and WYLLIE (1967) also temperatures of $430\text{--}470^\circ$ C. The higher degree of oxidation of the prasinites ($Fe_2O_3/FeO > 1.0$) especially when compared type 1–3 eclogites ($Fe_2O_3/FeO < 0.5$), resulting in the formation of magnetite, could also have been induced by a higher partial pressure of water.

Therefore it is concluded that the main recrystallization of these rocks occurred in a PT-environment characterized by temperatures of $430\text{--}470^\circ$ and $P_S = P_{H_2O} \geq 3.6\text{--}4$ kb. This estimate would be consistent with the only oxygen isotope temperature of 457° available so far, obtained from quartz-phengite in a kyanite-chloritoid-garnet-micaschist (R. BECKINSALE, pers. comm.) and with the thickness of the overlying units during Alpine metamorphism, estimated by FRANK (1969) as 15 km.

As no radiometric ages on any eclogite minerals are yet available, correlation of the thermal history with time is highly speculative. But as the geochronological data discussed by CLIFF et al. (1971) are consistent with the possibility of a main phase of regional metamorphism within the Tauern window in the 55–36 my range, with biotite ages around 20 my indicating a period of cooling and uplift, it seems tempting to somehow correlate the earlier high-pressure parageneses with the Cretaceous ages (90–60 my) of the high-pressure assemblages reported from the ophiolite complex of Zermatt-Saas Fee by BEARTH (1973) – especially as the overthrusting of the Tauern must have occurred around 80 my ago (OBERHAUSER, 1968).

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References

- ANGEL, F. (1954): Petrochemie der Hochalm-Ankogel-Gesteine. *Jb. Geol. BA.* 47, 1–16.
- (1957): Einige ausgewählte Probleme eklogitischer Gesteinsgruppen der österreichischen Ostalpen. *N. Jb. Miner. Abh.* 91, 151–192.
- ATHERTON, M. P. (1968): The variation in garnet, biotite and chlorite composition in medium grade pelitic rocks from the Dalradian, Scotland, with particular reference to the zonation in garnet. *Contr. Mineral. and Petrol.* 18, 347–371.
- BANNO, S. (1970): Classification of eclogites in terms of physical conditions of their origin. *Phys. Earth Planet. Interiors* 3, 405–421.
- BEARTH, P. (1967): Die Ophiolite der Zone von Zermatt-Saas Fee. *Beitr. geol. Karte Schweiz, N. F.* 132.
- (1971): Zum Chemismus der Eklogite und Glaukophanite von Zermatt. *SMPM* 51, 349–359.
- (1973): Gesteins- und Mineralparagenesen aus den Ophioliten von Zermatt. *SMPM* 53, 299–334.
- BROWN, E. H. (1969): Some zoned garnets from the greenschist facies. *Am. Mineral.* 54, 1662–1677.
- CHINNER, G. A. and DIXON, J. E. (1973): Some high-pressure parageneses of the Allalin Gabbro, Valais, Switzerland. *J. Petrol.* 14, 185–202.
- CLIFF, R. A., NORRIS, R. J., OXBURGH, E. R. and WRIGHT, R. C. (1971): Structural, metamorphic and geochronological studies in the Reisseck and southern Ankogel groups, the Eastern Alps. *Jb. Geol. BA.* 114, 121–272.
- COLEMAN, R. G., LEE, D. E., BEATTY, L. B. and BRANNOCK, W. W. (1965): Eclogites and eclogites: their differences and similarities. *Geol. Soc. Am. Bull.* 76, 483–508.
- CORNELIUS, H. P. und CLAR, E. (1939): Geologie des Grossglocknergebietes, Teil I. *Abh. Zweigst. Wien, Rst. f. Bodenforschung* 25, Wien.
- DUDLEY, P. P. (1969): Electron microprobe analyses of garnet in glaucophane schists and associated eclogites. *Am. Miner.* 54, 1139–1150.
- ERNST, W. G. (1968): Amphiboles. *Monograph Series of Theoretical and Experimental Studies I.* Springer-Verlag Berlin-Heidelberg-New York.
- ERNST, W. G., SEKI, Y., ONUKI, H. and GILBERT, M. C. (1970): Comparative study of low-grade metamorphism in the California coast ranges and the outer metamorphic belt of Japan. *Geol. Soc. Am. Mem.* 124.
- ESSENE, E. J. and FYFE, W. S. (1967): Omphacite in Californian metamorphic rocks. *Contr. Mineral. and Petrol.* 15, 1–23.
- ESSENE, E. J., HENSEN, B. J. and GREEN, D. H. (1970): Experimental study on amphibolite and eclogite stability. *Phys. Earth Planet. Interiors* 3, 378–384.
- FRANK, W. (1969): Geologie der Glocknergruppe. *Wiss. Alpenvereinshefte* 21, 95–111.
- FRASL, G. und FRANK, W. (1966): Zur Mineralogie und Geologie des Landes Salzburg und der Tauern. *Der Aufschluss* 15, 30–58.
- FRY, N. (1973): Lawsonite pseudomorphosed in Tauern greenschist. *Min. Mag.* 39, 121–122.
- FRY, N. and FYFE, W. S. (1969): Eclogites and water pressure. *Contr. Mineral. and Petrol.* 24, 1–6.

- GHENT, E. D. and COLEMAN, R. G. (1973): Eclogites from southwestern Oregon. *Geol. Soc. Am. Bull.* 84, 2471–2488.
- GREEN, D. H. and RINGWOOD, A. E. (1967): An experimental investigation of the gabbro to eclogite transformation and its petrological applications. *Geochim. Cosmochim. Acta* 31, 767–833.
- HOLLISTER, L. S. (1966): Garnet zoning: an interpretation based on the Rayleigh fractionation model. *Science* 154, 1647–1651.
- HOSCHEK, G. (1969): The stability of staurolite and chloritoid and their significance in metamorphism of pelitic rocks. *Contr. Mineral. and Petrol.* 22, 208–232.
- JOHANNES, W. (1969): An experimental investigation of the system $\text{MgO-SiO}_2\text{-H}_2\text{O-CO}_2$. *Am. J. Sci.* 267, 1083–1104.
- JOHANNES, W. and PUHAN, D. (1971): The calcite-aragonite transition, reinvestigated. *Contr. Mineral. and Petrol.* 31, 28–38.
- KERRICK, D. M. (1968): Experiments on the upper stability limit of pyrophyllite at 1.8 kb and 3.9 kb water pressure. *Am. J. Sci.* 266, 204–214.
- MOTTANA, A. (1970): Distribution of elements among co-existing phases in amphibole-bearing eclogites. *N. Jb. Miner. Abh.* 112, 161–187.
- MOTTANA, A. and EDGAR, A. D. (1969): The significance of amphibole compositions in the genesis of eclogites. *Lithos* 3, 37–49.
- NEWTON, R. C. and KENNEDY, G. C. (1963): Some equilibrium reactions in the join $\text{CaAl}_2\text{Si}_2\text{O}_8\text{-H}_2\text{O}$. *J. Geophys. Res.* 68, 2967–2983.
- NOCKOLDS, S. R. (1954): Average chemical compositions of some igneous rocks. *Geol. Soc. Am. Bull.* 65, 1007–1032.
- OBERHAUSER, R. (1968): Beiträge zur Kenntnis der Tektonik und der Paläogeographie während der Oberkreide und dem Paläogen im Ostalpenraum. *Jb. Geol. BA.* 111, 115–145.
- PEARCE, J. A. and CANN, J. R. (1973): Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Letters* 2, 290–300.
- RICHARDSON, S. W., GILBERT, S. W. and BELL, P. M. (1969): Experimental determination of kyanite-andalusite and andalusite-sillimanite equilibria; the aluminum silicate triple point. *Am. J. Sci.* 267, 259–272.
- RICHTER, W. (1973): Vergleichende Untersuchungen an ostalpinen Eklogiten. *TMPM* 19, 1–50.
- SAXENA, S. K. (1969): Silicate solid solutions and geothermometry 4. Statistical study of chemical data on garnets and clinopyroxene. *Contr. Mineral. and Petrol.* 23, 140–156.
- SCARFE, C. M. and WYLLIE, P. J. (1967): Serpentinite dehydration curves and their bearing on serpentinite deformation in orogenesis. *Nature* 215, 945–946.
- SCHARBERT, H. (1954): Die eklogitischen Gesteine des südlichen Grossvenedigergebietes (Osttirol). *Jb. Geol. BA.* 47, 39–63.
- SCHREYER, W. and SEIFERT, F. (1969): Compatibility relations of the aluminum silicates in the systems $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ and $\text{K}_2\text{O-MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ at high pressures. *Am. J. Sci.* 267, 371–388.
- SCHUILING, R. D. and VINK, B. W. (1967): Stability relations of some titanium-minerals (sphenes, perovskite, rutile, anatase). *Geochim. Cosmochim. Acta* 31, 2399–2411.
- STORRE, B. and NITSCH, K. H. (1972): Die Reaktion $2 \text{Zoisit} + 1 \text{CO}_2 = 3 \text{Anorthit} + 1 \text{Calcit} + 1 \text{H}_2\text{O}$. *Contr. Mineral. and Petrol.* 35, 1–10.
- TAYLOR, H. P. JR. and COLEMAN, R. G. (1968): $\text{O}^{18}/\text{O}^{16}$ ratios of coexisting minerals in glaucophane-bearing metamorphic rocks. *Geol. Soc. Am. Bull.* 79, 1727–1756.