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Petrology and Metamorphic Evolution of the Penninic Ophiolites in the Western Tauern Window (Austria)

By *M. Raith* *), *P. K. Hörmann* *) and *K. Abraham* **)

Abstract

The ophiolites of the Mesozoic Penninic rock sequence in the western Tauern window developed during the progressive stages of the Alpine metamorphic event (70–50 m.y.) into greenschists, amphibolites, eclogites and glaucophane schists.

The spatial succession of the mineral assemblages proves that the metamorphic grade increased from South to North: chlorite schists are followed by prasinites, garnet amphibolites and eclogitic rocks. From the specific mineral parageneses, mineral compositions, phase equilibrium data, and oxygen isotopic data it is concluded that the progressive metamorphism took place under conditions ranging from about 4 kbars/420°C to 6–10 kbars/550°C.

The general feature of the progressive reactions is dehydration, decarbonatization and reduction.

The metamorphic evolution with time can be traced by the compositional development of zoned minerals (epidote, amphibole, garnet, plagioclase) and by relics. The high grade assemblages have passed through the low grade stages.

In a late stage of the Alpine event (~30 m.y.) the whole sequence underwent "retrogressive" metamorphism which mainly affected the eclogites and glaucophane schists. By this process these rocks were gradually transformed into amphibolites and prasinites.

The major and trace element compositions indicate that the Mesozoic metaophiolites are derived from an olivine tholeiitic to alkalibasaltic source rock of marked high-alumina basalt character. Within the sequence massive types (lava flows) as well as banded types (tuffites) are encountered. The compositions of the massive metaophiolites have a strong similarity to fractionated ocean floor basalts. The tuffitic metaophiolites differ from the massive ones by their distinctly higher Ca, Li, and Ba contents which can be attributed to an admixture of sedimentary matter. Moreover, these types are highly oxidized.

As a result of their specific chemical composition the massive types during metamorphism develop into eclogites, the banded types into glaucophane schists.

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The metaophiolites do not necessarily represent parts of an oceanic crust which was generated along a spreading oceanic rift. The chemical composition of the metaophiolites as well as the lithology of the sequence is better conformable with the concept of basalts which generated under relatively low pressures (10–15 kbars) and extruded into an eugeosyncline trough underlain by a thin continental crust.

According to the structural and metamorphic development, the new geochemical data, and the available radiometric dates a geodynamic concept on the formation of the Penninic sequence comprises the following stages of evolution:

- a) Formation of the Penninic eugeosyncline during the Jurassic and Lower Cretaceous with sediments of the Bündner Schiefer facies and interlayered ophiolites.
- b) Overthrusting of the Austroalpine unit onto the Penninic sequence, and high pressure-low temperature progressive stage of metamorphism during the Upper Cretaceous and Eocene.
- c) Doming and uplift of the subducted rock complex, and Barrow-type “retrogressive” stage of metamorphism during the Oligocene and Lower Miocene.

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1. Introduction

During the last few years the Penninic rock series of the western Tauern Window has repeatedly been the focus of geological interest. The concept of plate tectonics and the application of the results of high pressure research work on natural rocks opened new perspectives on the possible tectonic and metamorphic development of the Penninic zone (ANGENHEISTER et al., 1972, 1974; HAWKESWORTH et al., 1975; DIETRICH, 1976; FRISCH, 1976).

The results of extensive geological field work yielded comprehensive information on the stratigraphy of the Penninic and provide an excellent basis for the tectonic and petrological interpretation (cf. KARL, 1953–1964; SCHMIDEGG, 1961; FRISCH, 1968; HÖCK, 1969; RAITH, 1971; MORTEANI, 1971; RAASE, 1972; THIELE, 1970, 1974).

Mineralogical and petrological investigations dealt with the development

of the Alpine metamorphism with respect to metamorphic grade and metamorphic zoning (KARL, 1959; RAITH, 1971; RAASE, 1971; MORTEANI and RAASE, 1974, 1976; HOERNES, 1973; HOERNES and FRIEDRICHSEN, 1974; ABRAHAM et al., 1974; MORTEANI, 1974).

Radiometric age determinations by the Rb-Sr and K-Ar methods furnished new information on the age and thermal history of the rock complex (KREUZER et al., 1973; RAITH et al., 1978; SATIR, 1975).

The Alpine metamorphism is characterized by mineral assemblages and mineral compositions which are typical for a medium-pressure metamorphism of the Barrow type. The metamorphic grade increases from greenschist facies in the peripheral zones to amphibolite facies in the centre of the Tauern Window. The data of K-Ar and Rb-Sr radiometric age determinations indicate that the Alpine metamorphism consisted of three distinct thermal episodes: 1. An early stage of crystallization at about 70 m.y. 2. The main crystallization which took place at 35–45 m.y. and corresponds to the main, Middle-Tertiary metamorphism of the Central Alps (cf. FREY et al., 1974), and 3. a post-kinematic crystallization stage at about 20 m.y. The Alpine metamorphic event ended with uplifting and erosion at 18–19 m.y. in the Venediger area and at 13–14 m.y. in the western Zillertaler Alps (RAITH et al., 1978).

Models applying the concept of plate tectonics on the evolution of the Eastern Alps were worked out on the basis of the structural and metamorphic development of the Penninic and Austroalpine rock series and by the use of radiometric data (OXBURGH and TURCOTTE, 1974; HAWKESWORTH et al., 1975; HAWKESWORTH, 1976; DIETRICH, 1976; FRISCH, 1976). In these models the intense Alpine deformation and early high-pressure metamorphism of the Penninic rocks is attributed to the overthrusting of the Austroalpine unit onto the Penninic complex. The overthrusting was completed at about 60 m.y. (OXBURGH and TURCOTTE, 1974) and followed by the post-kinematic stage of the Alpine metamorphism which was characterized by higher temperatures (MORTEANI and RAASE, 1974, 1976) or lower pressures (MILLER, 1974).

Although the main features of the Alpine metamorphic development are known from the above mentioned investigations, ABRAHAM et al. (1974) and MILLER (1974) have shown that the metamorphic evolution in the high-grade metabasites of the Southern Schieferhülle is more complex. This is illustrated by the occurrence of eclogitic, glaucophanitic, amphibolitic and prasinitic assemblages in close neighbourhood. A detailed investigation of the complex evolution of the mineral assemblages throughout the Penninic is, therefore, necessary. For that purpose the widely distributed metabasites are useful because their composition is highly sensitive to the changing physico-chemical conditions.

The present investigation of the metabasites was carried out under the following two aspects:

1. Chemical composition, major elements as well as trace elements, of the metavolcanic rocks of the southern Penninic Schieferhülle. This information is necessary for the discernment of the magma type of the source rocks and for the knowledge of the compositional variation throughout the rock series.

2. Investigation of the mineral assemblages and mineral compositions. The information on mineral parageneses and mineral compositions together with the data of experimental work on appropriate silicate systems can lead to a dynamic picture of the temporal and spatial evolution of the Alpidic metamorphism.

2. Geological setting

The southern Venediger area has been mapped geologically by WEIN-SCHENK (1894, 1903), ANGEL (1929), CORNELIUS (unpubl.), SCHARBERT (1954) and SCHMIDEGG (1961). During the last few years the region between the Frosnitz valley in the East and the Aurina valley in the West was mapped on a 1 : 10,000 scale by HÖRMANN (1969–1972), BRAUN and RAASE (1975), KLATT (1977), MEHRENS (1978) with emphasis on the lithostratigraphy and structure of the Penninic rock series. A detailed structural analysis by computer methods was carried out by BRAUN and HÖRMANN (1974).

A geological map of the region studied in this investigation is shown in Fig. 1. This map is based on the field work of the above mentioned investigators, except for the southernmost area, which is taken from the map of SÉNARCLENS-GRANCY (1972).

The Penninic unit consists in its northern (lower) part of the Paleozoic Lower Schieferhülle. This is built up of paragneisses and mica schists with subordinate graphite schists, quartzites, garnet amphibolites, and, to a lesser extent, of marbles. A dome of the Zentralgneiss massif consisting of orthogneisses and surrounded by migmatites is exposed in an area west of the Rostocker-Hütte.

The southern (upper) part of the Penninic unit is formed by a thin series of Permotriassic rocks and by the Mesozoic Upper Schieferhülle. This heterogeneous rock sequence consists of metasediments (phyllites, mica schists, calc-mica schists, quartzites, marbles) and metabasites (greenschists, garnet amphibolites, eclogitic to glaucophanitic rocks, serpentinites).

The Penninic complex is overthrust by the ortho- and paragneisses of the Upper Austroalpine Altkristallin. The thrust plane is shown by a line in Fig. 1. The border zone between the Penninic and the Altkristallin units consists of intensely folded and sheared phyllites, calc schists, marbles, quartzites, and serpentinites. According to SÉNARCLENS-GRANCY (1972) the rocks belong to the Matreier Schuppenzone (Lower Austroalpine), however, they could also be attributed to the Penninic zone in Fusch facies (c. f. FRANK, 1969).

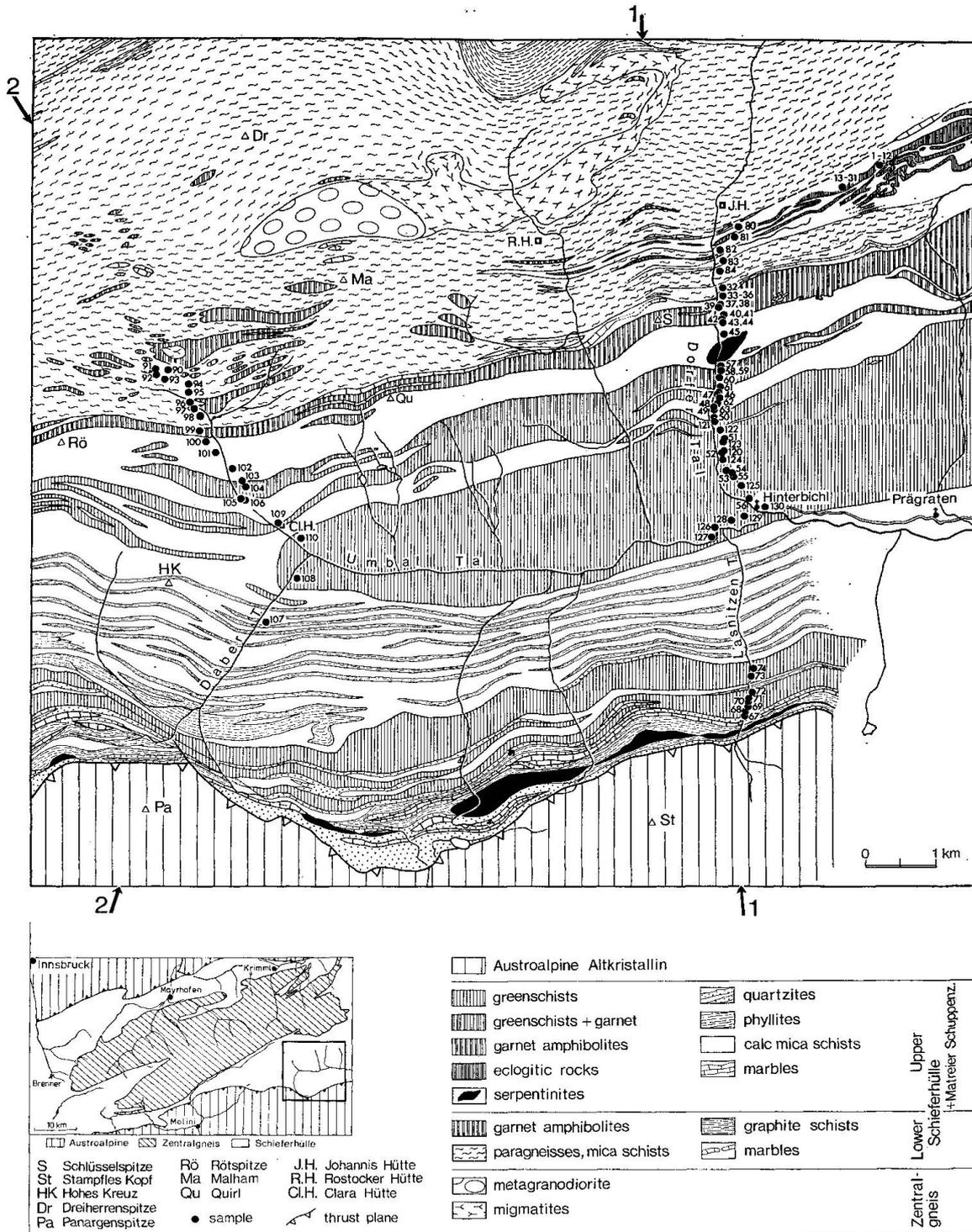


Fig. 1. Geological map of the southern Grossvenediger area, according to KARL (1953–1964), HÖRMANN (1969–1972), BRAUN and RAASE (1975), KLATT (1977), MEHRENS (1978), SENARCLENS-GRANCY (1972). Arrows 1 and 2 indicate the position of the Dorfer Valley and Umbal Valley profiles.

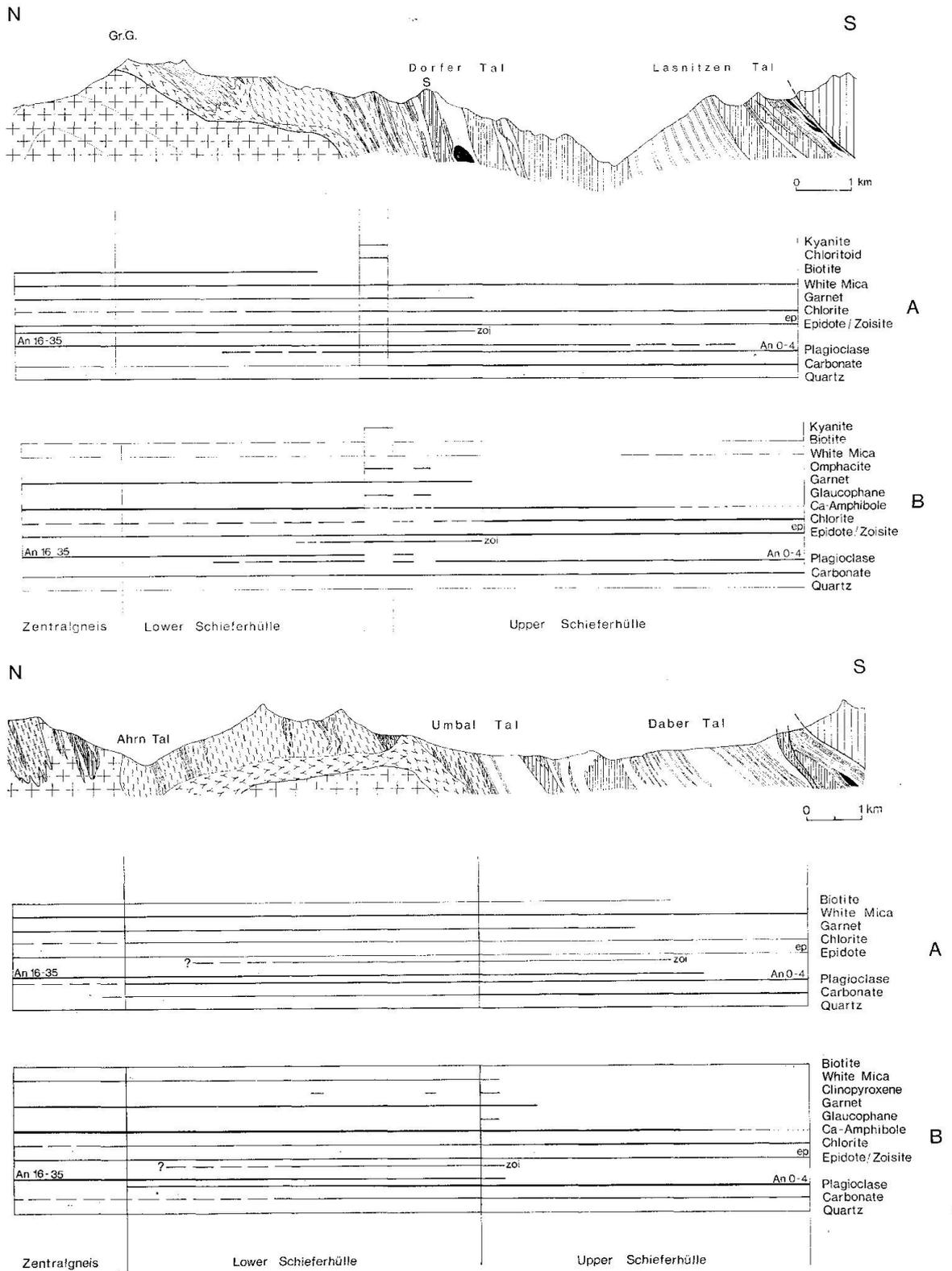


Fig. 2. Geological sections through the Penninic series of the southern Grossvenediger area (after BRAUN, pers. comm.). Mineralogical development of the metasediments (A) and metabasites (B) in the Dorfer and Umbal Valley profiles.

The Paleozoic Lower and the Mesozoic Upper Schieferhülle are characterized by the same tectonic structure: The rocks are intensely folded and sheared with fold axes and lineations predominantly striking N 60–70° E and dipping gently towards the West. Fold axes and lineations dipping eastwards are occasionally present as additional elements, particularly in the eastern part of the area. The style of deformation depends heavily on competence differences of the rocks and on layering (BRAUN and HÖRMANN, 1974). Bedding and foliation incline steeply towards the South. The observed strain pattern agrees well with the notion that the deformation was induced by the overthrust of the Altkristallin sheet onto the Penninic complex.

Within the area investigated the metamorphic development is characterized by a gradually increasing metamorphic grade from greenschist facies in the South to amphibolite facies in the North (ABRAHAM et al., 1974). This can best be shown by the mineralogical development of the metabasites in two South-North profiles along the Dorfer and Umbal valleys (Fig. 2). This aspect will be discussed in detail in chapter 4.

3. Chemical composition of the metabasites

MAJOR ELEMENTS

In a previous investigation of the metavolcanic rocks of the Dorfer Valley, ABRAHAM et al. (1974) found that the metabasites (greenschists, garnet amphibolites, and eclogitic rocks) had very similar chemical compositions which corresponded to tholeiitic and alkali basaltic rock types. These results were later confirmed for the eclogitic rocks by MILLER (1974).

The present study extends the Dorfer valley profile to the South into the Lasnitzen valley in order to get a complete section through the whole Mesozoic sequence. A second series of samples was taken along the Umbal valley because the metabasites there occur abundantly not only in the Upper, but also in the Lower Schieferhülle. Moreover, the metamorphic development in the Umbal valley profile differs to some extent from that of the Dorfer Valley profile (see p. 204). The chemical compositions of the various metavolcanic rock types of both profiles are shown in Table 1¹⁾.

The standard deviations, in Table 1, demonstrate that the chemical compositions of the individual rock types are quite variable. The same data, however, also demonstrate that all these rock types have similar average contents and similar standard deviations for a certain chemical component. This supports the conclusion that all rock types had the same source rock. Characteristic differences occur with respect to the oxidation ratio and the contents

¹⁾ Methods are reported in ABRAHAM et al. (1974).

Table 1. Major element compositions of the metabasites and their standard deviations from the Dorfer, Lasnitzen, and Umbal valleys

Rock series	Upper Schieferhülle						Lower Schieferh.	
	Eclogites (11)	Glaucofane schists (10)	Retrogressive eclogites (9)	Amphibolites (19)	Greenschists, Prasinites (42) + Lasnitzen V.	Amphibolites (16)	Umbal Valley	
Rock type Samples Locality			Dorfer Valley					
SiO ₂	49.84 ± 3.44	43.66 ± 2.04	43.31 ± 3.79	47.21 ± 2.03	46.80 ± 2.51	45.71 ± 1.98	46.71 ± 3.63	
Al ₂ O ₃	16.61 ± 2.14	15.99 ± 1.21	14.23 ± 3.18	17.35 ± 2.06	15.76 ± 1.21	16.34 ± 0.39	14.47 ± 1.29	
TiO ₂	1.19 ± 0.40	1.42 ± 0.20	1.29 ± 0.46	1.41 ± 0.36	1.43 ± 0.39	1.51 ± 0.28	2.00 ± 0.55	
Fe ₂ O ₃	3.74 ± 1.08	6.45 ± 1.24	4.36 ± 1.71	4.69 ± 1.61	5.20 ± 1.92	3.86 ± 0.66	3.10 ± 1.28	
FeO	6.60 ± 1.12	4.80 ± 1.16	6.28 ± 2.24	4.80 ± 2.11	4.54 ± 1.19	6.37 ± 1.32	8.28 ± 2.26	
FeO*	9.97 ± 1.05	10.61 ± 1.14	10.21 ± 1.89	9.03 ± 1.78	9.22 ± 1.46	9.85 ± 0.96	11.07 ± 1.71	
MnO	0.159 ± 0.018	0.186 ± 0.033	0.180 ± 0.051	0.157 ± 0.031	0.184 ± 0.025	0.182 ± 0.012	0.184 ± 0.075	
MgO	6.90 ± 1.89	7.65 ± 2.52	7.42 ± 2.02	6.37 ± 2.16	5.91 ± 1.68	7.88 ± 1.21	7.02 ± 1.52	
CaO	9.98 ± 2.30	12.67 ± 2.31	11.51 ± 3.74	10.36 ± 3.05	11.57 ± 2.43	10.10 ± 2.43	9.57 ± 3.61	
Na ₂ O	3.39 ± 0.88	2.76 ± 0.68	2.39 ± 0.93	3.31 ± 1.00	3.08 ± 0.61	2.75 ± 0.21	3.08 ± 0.90	
K ₂ O	0.33 ± 0.29	0.48 ± 0.42	0.29 ± 0.16	0.18 ± 0.20	0.27 ± 0.25	0.14 ± 0.12	0.75 ± 0.51	
H ₂ O	0.86 ± 0.44	0.90 ± 0.20	2.97 ± 0.44	2.53 ± 0.66	2.63 ± 0.59	3.39 ± 0.59	2.19 ± 0.70	
CO ₂	0.19 ± 0.11	4.15 ± 1.30	4.67 ± 2.12	0.55 ± 0.53	0.82 ± 0.69	0.63 ± 0.42	0.52 ± 0.35	
P ₂ O ₅	0.149 ± 0.094	0.153 ± 0.038	0.132 ± 0.037	0.166 ± 0.076	0.150 ± 0.050	0.117 ± 0.023	0.350 ± 0.217	
Ox	34 ± 6	55 ± 10 (***)	40 ± 17	45 ± 20	49 ± 14 (**)	32 ± 10	25 ± 12	

*) Total iron as FeO.

**) Samples 68-74: Ox 59 ± 7; samples 130-50: Ox 48 ± 13; samples 49-57: Ox 43 ± 15. Ox = 100 · Fe³⁺ / (Fe³⁺ + Fe²⁺).

***) See text.

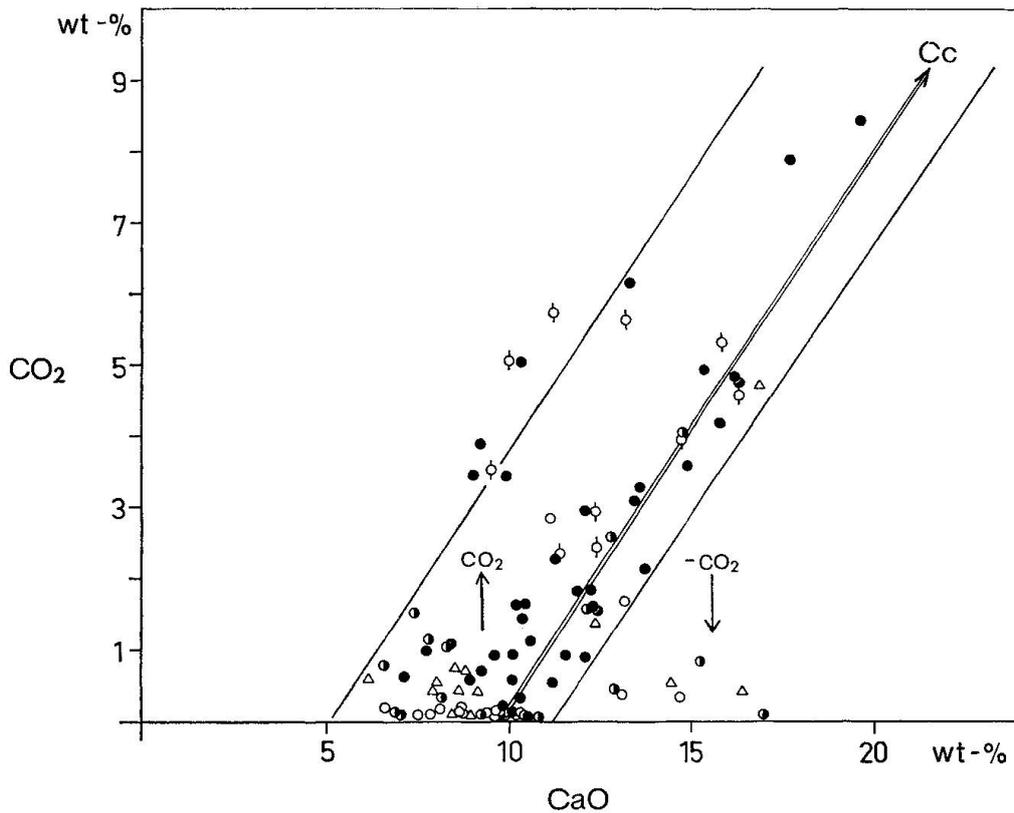


Fig. 3. CaO-CO₂ diagram of the metabasites. Solid circles represent prasinites, half filled circles garnet amphibolites of the Dorfer Valley, triangles garnet amphibolites of the Umbal Valley, open circles eclogites, open circles with vertical bars glaucophane schists. Arrow Cc indicates the chemical variation by an admixture of calcite to the original basalt matter.

of H₂O and CO₂. The oxidation ratio, though variable, decreases steadily with increasing metamorphic grade from South to North (Tab. 1, Fig. 1). The water content decreases considerably with rising metamorphic grade, mainly at the transition of garnet amphibolites to eclogites.

Glaucophanitic assemblages have higher oxidation ratios, higher calcium and higher CO₂ contents than the eclogites. This can be attributed to an admixture of sedimentary calcite to the volcanic matter (Fig. 3).

Other chemical differences can be observed with respect to the SiO₂, MgO, and Na₂O contents (Tab. 1) and the Cr, Ni, Co contents (Tab. 2) which indicate that the glaucophane schists possibly represent basalt types with higher normative olivine and clinopyroxene contents.

	ppm Cr	ppm Ni	ppm Co
10 Glaucophane schists	287 ± 108	148 ± 87	39 ± 8
11 Eclogites	155 ± 60	84 ± 52	26 ± 12

Chemical differences also exist between the homogeneous and banded green-schists which represent the low-grade equivalents to the eclogites and glaucophane schists.

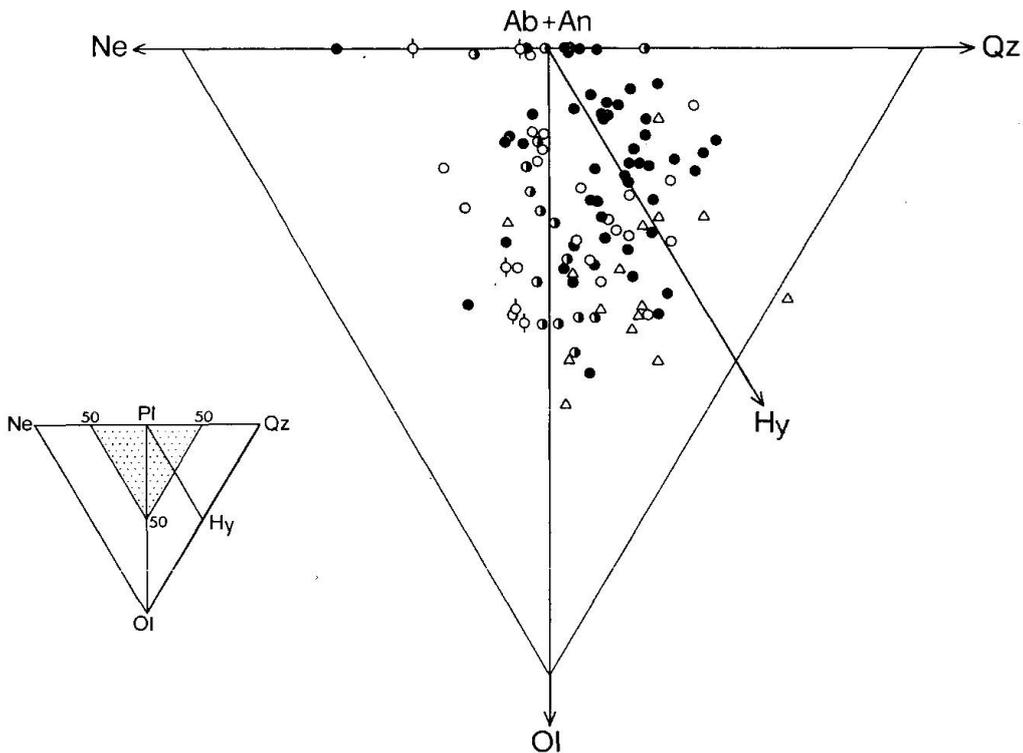


Fig. 4. Representation of the metabasite compositions in the basal plane of the basalt tetrahedron (YODER and TILLEY, 1962). Symbols as in Fig. 3.

phane schists, respectively. The major element composition of the glaucophane schists corresponds to that of the banded greenschists, that of the eclogites to the homogeneous types.

The diaphthoritic eclogites have characteristically higher H_2O and CO_2 contents.

The metabasites of the Lower Paleozoic Schieferhülle differ from those of the Upper by their higher TiO_2 , total iron, K_2O and P_2O_5 contents, and by their lower Al_2O_3 , contents. Their oxidation ratio is extremely low.

The data of Table 1, and their graphical representation in the basal plane of the basalt tetrahedron (YODER and TILLEY, 1962) (Fig. 4) indicate, that most of the metavolcanics have the typical composition of olivine tholeiites and alkali olivine basalts. The compositions extend into both the quartz tholeiitic and basanitic basalt fields respectively. The graphical representation of the analyses in the basal plane of the tetrahedron can form the basis of discussion because most of the samples have a fairly constant normative clinopyroxene content which is about 20 weight per cent.

The tholeiitic and alkalibasaltic character of the compositions is also shown by the McDonald-Katsura diagram in Figure 5. It must be stated, however, that the variation towards normative quartztholeiitic compositions (Fig. 4) does not necessarily represent a real magmatic differentiation trend. It is caused, at least in part, by an increase of the oxidation ratio during the metamorphic

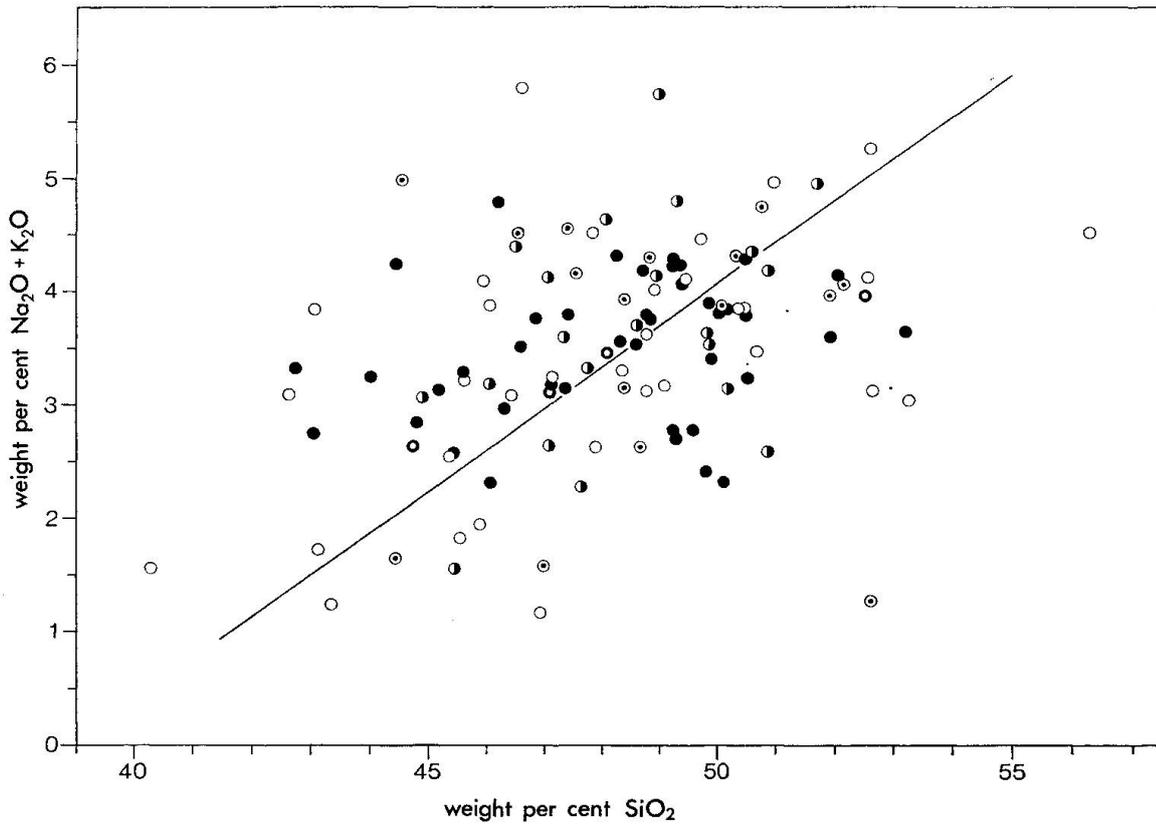


Fig. 5. Representation of the metabasites in a $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 diagram according to McDONALD and KATSURA (1964). Solid circles represent prasinites, half filled circles garnet amphibolites, and open circles eclogitic rocks of the Dorfer Valley, centered circles garnet amphibolites of the Umbal Valley.

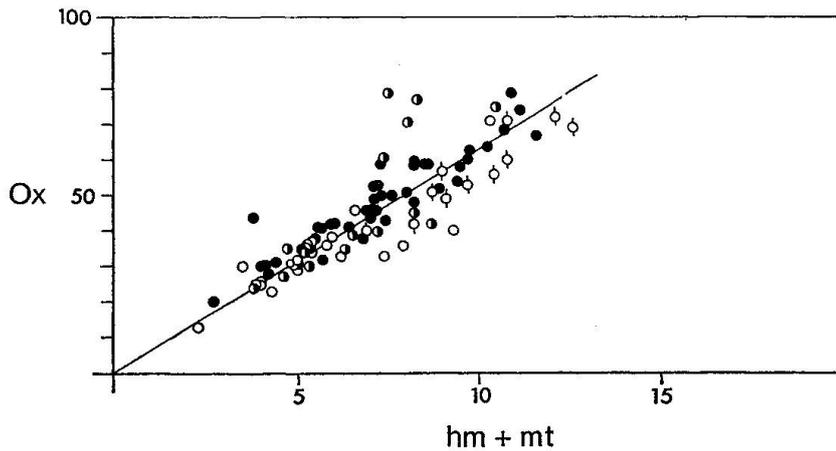


Fig. 6. Normative hematite + magnetite versus oxidation ratio $(\text{Fe}^{3+} \times 100) / (\text{Fe}^{3+} + \text{Fe}^{2+})$ of the metabasites. Symbols as in Fig. 3.

process from which increasing normative $mt + hm$ and SiO_2 contents result in the CIPW norms (Fig. 6). Similarly, a development into nepheline normative compositions results from the addition of sedimentary calcite to the original basaltic matter.

TRACE ELEMENTS

The occurrence of ocean floor basalts in the Penninic unit as discussed by MILLER (1974) and BICKLE and PEARCE (1975) are of fundamental importance for the geotectonic models on the formation of the Eastern Alps. These investigations recognized the ocean floor basalt character of these rocks by means of the relative abundances of Ti, Zr, Y, Nb and Sr (PEARCE and CANN, 1973).

However, the recognition of tholeiites and ocean floor basalts (abyssal oceanic tholeiites) mainly from the Ti, Zr and Y contents is in no way exclusive. In the light of the most recent data (WEDEPOHL, 1975), other elements would seem to be more or equally suitable: K, P, Rb, Ba, Sr and Cr, V, Ni. Compared to other basalt types, ocean floor basalts are highly depleted in Rb and Ba. Because of its importance for the geotectonic interpretation a more extensive chemical definition of the source rock of the metabasites is considered necessary. Consequently, we carried out trace element determinations of the elements Li, Rb, Sr, Ba, Ni, Co, Cu, Cr, V, Ti, Zr, P, on 114 samples of the various metabasite types (greenschists, garnet amphibolites, eclogites, glaucophane schists).

The results of these investigations are summarized in Figures 7, 8 and Table 2.

The data in Table 2 indicate the existence of a marked distinction in the trace element contents of the metabasites of the Upper and Lower Schieferhülle as mentioned above for the major elements. The metabasites of the Lower Schieferhülle have, on the average, higher K, Rb, Sr, Ba, Ni, Ti, Zr, and P contents than those of the Upper Schieferhülle.

The metabasites of the Lower Schieferhülle are closely related to "within-plate" tholeiites (PEARCE and CANN, 1973), whereas those of the Upper Schieferhülle have distinct affinities to ocean floor basalts (Tab. 2).

The ocean floor basalts are regarded as having K_2O contents of lower than 0.4 weight percent (ENGEL et al., 1965). Consequently, we have grouped the metabasites of the Upper Schieferhülle into a group with $K_2O < 0.4\%$ and another with $K_2O > 0.4\%$ (Tab. 2).

The group with $K_2O < 0.4\%$ now reveals an even closer correspondence in trace element composition to the ocean floor basalts. Nevertheless, the Ba and Li contents are distinctly higher and the Ni and V contents lower.

The differences will be discussed in chapter 6.

Table 2. Trace element composition of the metabasites

	Metabasites Upper Schieferhülle		Metabasites Lower Schieferhülle		Metabasites K ₂ O < 0.40% Upper Schieferhülle		Metabasites K ₂ O > 0.40% Upper Schieferhülle		Tholeiitic basalts*)	Abyssal oceanic*) tholeiites (ocean floor basalts)	Alkali olivine*) basalts
Li	26 ± 20 (18)	13 ± 5 (5)	22 ± 19 (13)	30 ± 20 (7)	7	8	12				
K	2814 ± 2950 (98)	6200 ± 4300 (16)	1238 ± 903 (68)	6820 ± 3049 (30)	6974	1740	13280				
Rb	8 ± 9 (18)	16 ± 17 (5)	5 ± 5 (13)	18 ± 9 (7)	22	2	32				
Sr	120 ± 63 (42)	331 ± 208 (18)	112 ± 59 (32)	193 ± 68 (10)	328	121	702				
Ba	61 ± 40 (20)	257 ± 124 (4)	52 ± 27 (14)	92 ± 57 (6)	246	14.5	528				
Ni	82 ± 52 (98)	133 ± 72 (18)	90 ± 67 (71)	89 ± 68 (30)	134	119	145				
Co	32 ± 11 (98)	37 ± 8 (17)	31 ± 13 (71)	34 ± 10 (30)	48	37	43				
Cu	69 ± 36 (98)	51 ± 27 (17)	65 ± 32 (71)	68 ± 32 (27)	90	66	85				
Cr	232 ± 127 (98)	226 ± 158 (18)	235 ± 142 (71)	218 ± 93 (27)	168	298	202				
Ti	7557 ± 3636 (98)	11988 ± 3199 (16)	8412 ± 2370 (71)	8751 ± 2530 (30)	9710	8570	14390				
Zr	97 ± 36 (42)	133 ± 74 (17)	95 ± 39 (30)	105 ± 27 (10)	137	98	189				
V	211 ± 65 (98)	213 ± 40 (18)	217 ± 60 (70)	209 ± 65 (29)	251	303	213				
P	678 ± 295 (98)	1540 ± 955 (16)	662 ± 320 (70)	711 ± 278 (30)	960	610	2094				

*) WEDEFOHL (1975, Tab. 2). Numbers of analyses are given in brackets.

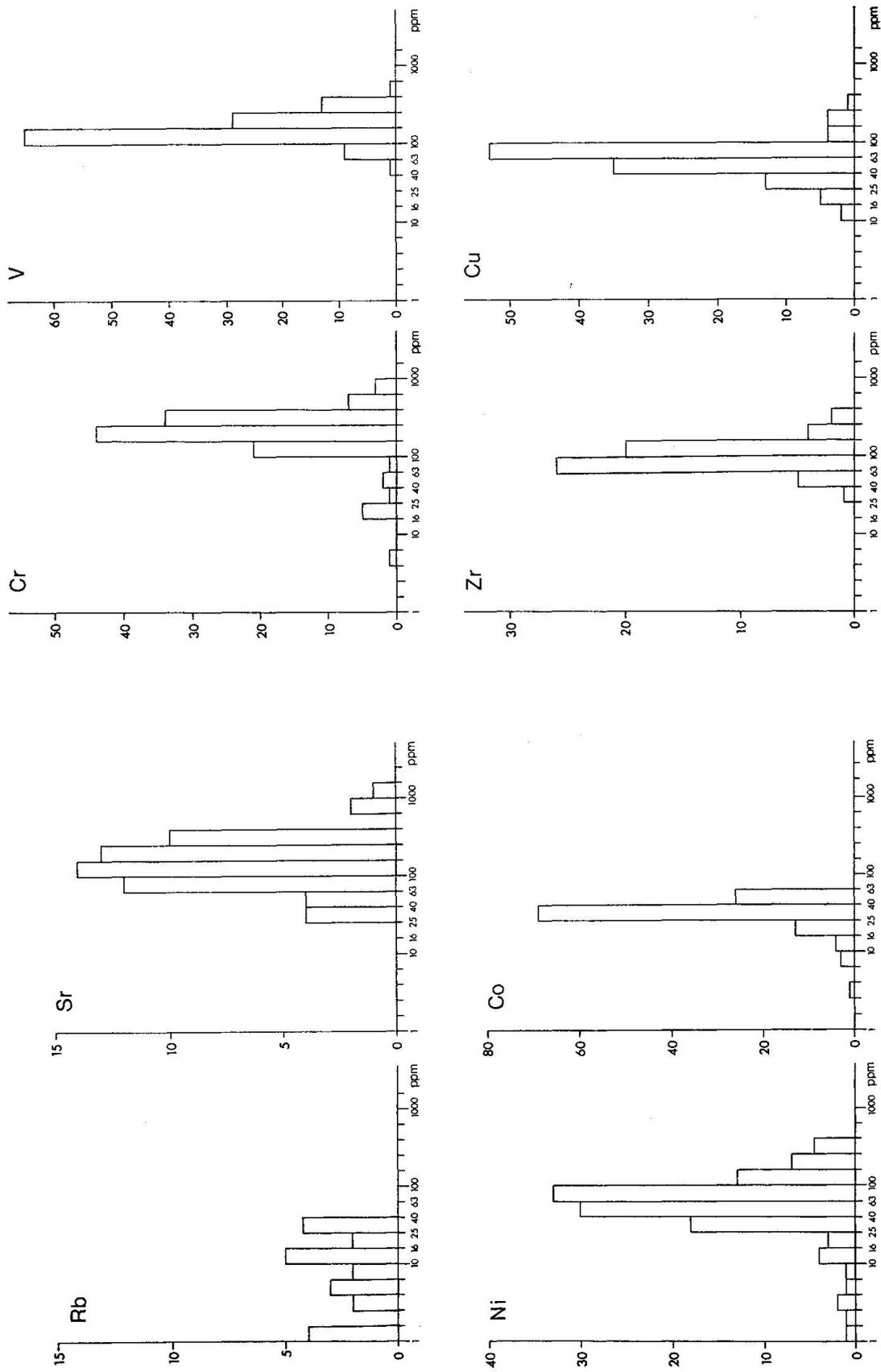


Fig. 7. Frequency distribution of trace elements of the metabasites.

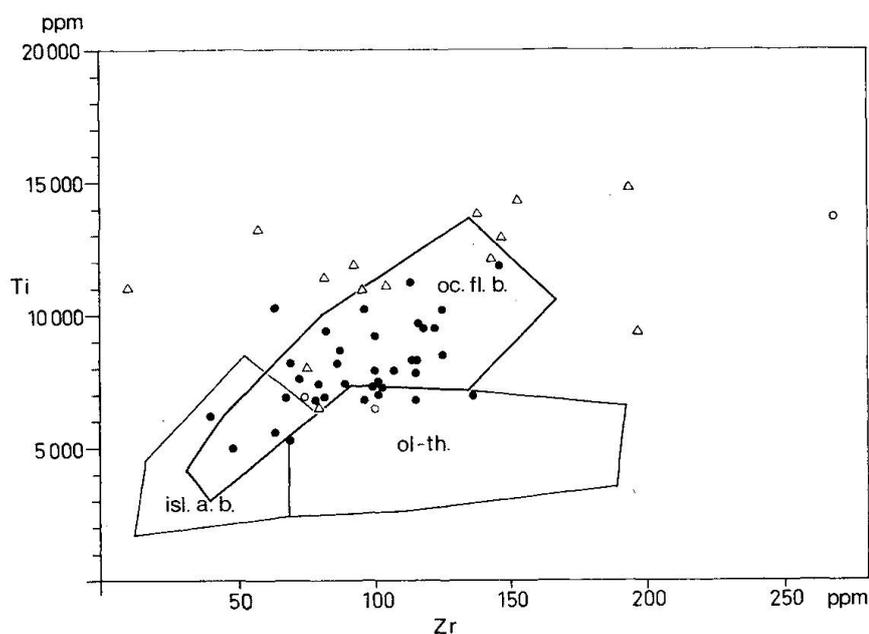


Fig. 8. Ti-Zr diagram (PEARCE and CANN, 1973) of the metabasites. Dots represent prasinites and garnet amphibolites of the Dorfer Valley, triangles garnet amphibolites of the Umbal Valley, circles eclogites.

4. Mineral assemblages of the metabasites

The mineralogical development of the metabasites along the two investigated profiles (Dorfer Valley, Umbal Valley) is represented in Figure 2.

In both profiles the rock units of the Paleozoic Lower Schieferhülle and the Mesozoic Upper Schieferhülle can be easily distinguished by their different lithology: the former consisting mainly of gneisses and mica schists with intercalated lenses of garnet amphibolites and marbles, the latter being heterogeneously composed by interlayered calc-mica schists, marbles, mica schists, phyllites and metavolcanic rocks of basaltic composition.

Serpentinite bodies are encountered in a zone along the overthrust plane of the Altkristallin sheet and also in the lower part of the Upper Schieferhülle.

The development of the mineral assemblages of the metabasites is similar in both profiles:

The *southern part* of the profiles is characterized by typical greenschist mineral assemblages:

From South to North, chlorite schists with subordinate actinolitic amphiboles develop gradually into prasinites characterized by higher amounts of subcalcic amphibole.

These prasinite types are followed in the *medium part* of the profiles by garnet- and zoisite-bearing prasinites.

Proceeding *further to the North*, this zone is followed by an extended sequence of garnet amphibolites with only subordinate chlorite, plagioclase and calcite. The garnet amphibolite zone begins near the border of the Upper and Lower Schieferhülle and extends far into the Zentralgneis region.

The lowest part of the Upper Schieferhülle develops in the Dorfer Valley profile into a thick intensely folded sequence of eclogites and glaucophane schists. This sequence then thins out towards the Umbal Valley where it is reduced to a small zone of diaphthoritic eclogites.

The succession of the mineral assemblages of the metabasites proves that the complete Penninic rock suite has suffered a progressive Alpine metamorphism, with its grade increasing gradually from South to North.

The most abundant mineral parageneses of the metabasites are presented in order of increasing metamorphic grade in the following list:

Southern part of the profiles (Lasnitzen Valley, samples 67–74)

Chlorite schists, greenschists:

Ab + Ep + Chl ± Cc ± Phg ± Bio + Qz + Acc (Sph, He, Mag, Ap)
Ab + Ep + Chl + Act. Amph + Cc ± Bio ± Phg + Qz + Acc (Sph, Pyr, Ap)

Medium part of the profiles (Dorfer Valley, samples 47–56, 121–130; Umbal Valley, samples 107–110)

Prasinites:

Ab + Ep + Chl + Barr. Amph + Bio + Qz ± Cc + Acc (Sph, He, Mag, Pyr, Ap)
relic mineral: Law?

Northern Part of the profiles

Dorfer Valley, samples 57–60, 45–32; Umbal Valley, samples 104–99

Garnet-bearing prasinites, garnet amphibolites:

Ab + Ep + Chl + Phg/Par ± Qz + Acc (Sph, Ilm, He, Ap, Tur, Rut)
Ab + Ep + Chl + Barr. Amph + Gar ± Phg/Par ± Qz ± Cc + Acc
(Sph, Ilm, Rut, Pyr, Mag, Ap)
Ep + Chl + Barr. Amph + Gar ± Phg/Par ± Qz ± Cc + Acc (Sph, Ilm, Ap)
relic minerals: Glauc. Amph, Cl'pyx?
retrograde alterations: Gar → Amph, Ep, Mag; Gar → Chl, Bio, Mag, Ep;
Glauc → Amph + Ab (symplectitic)

Dorfer Valley, samples 1–31, 80–84

Eclogitic and glaucophanitic metabasites:**Eclogitic assemblages:**

Gar + Omph + Rut
 Gar + Omph + Ky + Qz + Rut
 Gar + Omph + Zoi/Ep + Par/Phg + Qz + Rut
 Gar + Omph + Ep + Cc + Rut
 Gar + Omph + Ep + Cc + Par/Phg + Rut
 Gar + Zoi + Tc + Ky + Amph + Rut
 relic minerals: Tsch. Amph, Ep, Phg, Bio, Cc

Glaucophanitic assemblages:

Gar + Ep + Glauc + Omph + Qz + Rut
 Gar + Ep + Glauc + Omph ± Ky + Qz + Cc + Rut
 Gar + Ep + Glauc + Omph + Par/Phg ± Ky + Qz + Cc + Rut
 Gar + Ep + Glauc + Par/Ms + Cc + Rut
 relic minerals: Ep, Phg, Tsch. Amph, Cc, Rut
 retrograde alterations: Omph → Amph + Ab (symplectitic);
 Glauc → Amph + Ab (symplectitic); Gar → Amph, Ep, Mag;
 Gar → Chl, Bio, Ep, Mag; Par → Ep, Ab; Ky → Par; Rut → Sph

Umbal Valley (Lower Schieferhülle), samples 98–90

Garnet amphibolites:

Plag + Barr. Amph + Gar + Bio + Ep + Qz ± Chl ± Phg ± Cc + Acc (Sph, Sulfides, Ap)
 Plag + Barr. Amph + Bio + Ep + Qz + Acc (Sph, Sulfides, Ap)
 Barr. Amph + Gar + Di + Cc + Ep ± Qz + Acc (Sph, Sulfides, Ap)
 relic minerals: Hbl
 retrograde minerals and alteration: Chl, Ep; Gar → Chl, Bio, Mag

The parageneses of the Dorfer Valley-profile have already been described by ABRAHAM et al. (1974), the eclogitic assemblages also by ANGEL (1929) and SCHARBERT (1954), and in a neighbouring area by MILLER (1974).

It must be emphasized, however, that the mineral assemblages of the prograde development as described by ABRAHAM et al. (1974) and in this investigation can be partly obliterated by later events that led to a recrystallization caused by changes in the intensive variables (e.g., pressure, temperature, and activities of H₂O, CO₂, O₂ etc.).

These processes, mainly affect the highest-grade zones of the profile. The eclogites become altered into assemblages ranging from the amphibolitic to prasinitic. To a lesser extent, the garnet amphibolites are transformed into prasinitic rocks. These retrogressive processes will be dealt with in more detail in a forth-coming investigation on the eclogitic and glaucophanitic rocks of the southern Grossvenediger area.

5. Minerals

The mineral compositions of the metabasites of the Dorfer Valley were the object of the investigation by ABRAHAM et al. (1974). The eclogitic and glaucophanitic assemblages were also investigated by SCHARBERT (1954), RICHTER (1973) and MILLER (1974). This paper extends the investigation of the Dorfer Valley profile to the South into the Lasnitzen Valley and presents new mineral data. Further mineral data on the metabasites of the Umbal Valley are presented with the aim of achieving additional information on the development of the minerals in the western part of the Schieferhülle.

This chapter compares the mineral compositions in both profiles, and shows that the mineral compositions develop differently in both profiles; the meaning of which will be discussed in chapter 6.

CHLORITES

The composition of the chlorites varies from Mg-rhipidolite to Fe-pycnochlorite ((TRÖGER, 1971).

Microprobe analyses of the Umbal and Lasnitzen Valleys are represented in Table 3.

The Al content of the chlorites is extremely constant, corresponding to 60–64 mole percent amesite component. On the other hand, the Fe-Mg-substitution is variable, ranging from 20–45 mole percent Fe. The Fe content in both profiles decreases within the northern part of the Upper Schieferhülle from South to North with increasing metamorphic grade (Fig. 9).

In the southernmost part near the overthrust plane of the Altkristallin, the Fe contents are definitely lower than expected from the general trend. Besides the effect of temperature the variation of the Fe content depends on the variability of the oxidation state of the assemblage. Chlorites with high Fe(II) content (assemblages with sulfides or magnetite) are formed at low oxygen fugacities, those with low Fe(II) contents (assemblages with hematite) at high oxygen fugacities. As the samples in the southernmost part of the profile are highly oxidized, indicated by the occurrence of hematite and iron-rich epidote, the low Fe contents are more probably due to the high oxygen fugacities than to a temperature rise.

AMPHIBOLES

The investigations of ABRAHAM et al. (1974) show that with increasing metamorphic grade the amphiboles develop continuously from actinolitic amphibole in the low-grade greenschists into subcalcic (barroisitic) hornblende in the high-grade prasinites and amphibolites. Glaucophane schists with glaucophane

Table 3. Chemical composition and atomic proportions of chlorites

Rock type Sample No. Analyses	Umbal valley						Lasnitzen valley					
	Greenschists (Upper Schieferhülle)			Garnet amphibolites (Lower Schieferhülle)			Greenschists LA 71		Greenschists LA 72			
	U 107	U 108	U 110	U 105	U 103		U 98	U 92e	U 92e	U 92f	LA 71	LA 72
	5	5	6	6	3		3	4	5	No. 2074	4	6
SiO ₂	25.5	26.1	26.1	26.6	25.8		26.5	25.7	26.0	26.2	26.7	26.3
TiO ₂	—	—	—	0.05	—		—	—	0.06	—	—	—
Al ₂ O ₃	19.5	19.7	19.8	19.6	20.8		20.0	19.7	20.8	19.6	19.3	19.3
Cr ₂ O ₃	—	—	0.04	0.13	—		0.1	—	—	—	—	—
FeO*)	21.5	18.7	19.4	17.1	19.1		16.4	23.9	19.1	19.1	18.9	18.6
MnO	0.23	0.18	0.27	0.19	0.25		0.15	0.13	—	0.09	0.25	0.27
MgO	17.8	19.7	19.5	21.3	19.1		21.4	16.4	19.5	19.4	19.8	19.6
Σ	84.5	84.4	85.1	85.0	85.1		84.6	85.8	85.5	84.4	85.0	84.1
	Number of cations (O = 28, anhydrous basis)											
Si	5.49	5.52	5.50	5.56	5.43		5.53	5.49	5.44	5.55	5.62	5.59
Al	2.51	2.48	2.50	2.44	2.57		2.47	2.51	2.56	2.45	2.38	2.41
Σ Z	8.00	8.00	8.00	8.00	8.00		8.00	8.00	8.00	8.00	8.00	8.00
Ti	—	—	—	0.01	—		—	—	0.01	—	—	—
Al	2.43	2.45	2.43	2.37	2.59		2.45	2.47	2.57	2.45	2.40	2.43
Cr	—	—	0.01	0.02	—		0.02	—	—	—	—	—
Fe*)	3.86	3.31	3.42	2.97	3.37		2.86	4.29	3.34	3.40	3.34	3.30
Mn	0.04	0.03	0.05	0.03	0.04		0.03	0.02	—	0.02	0.04	0.05
Mg	5.70	6.23	6.12	6.61	5.98		6.66	5.24	6.08	6.13	6.21	6.22
Σ Y	12.03	12.02	12.03	12.01	11.98		12.02	12.02	12.00	12.00	11.99	12.00
Fe/(Fe+Mg)	0.40	0.35	0.36	0.31	0.36		0.30	0.45	0.36	0.36	0.35	0.35
Mole% [Al] ^{IV}	63	62	63	61	64		62	63	64	61	60	60

*) Total iron as FeO.

Table 4. *Chemical composition and atomic proportions of amphiboles*

Rock type Sample No.	U 107	U 108	Greenschists (Upper Schieferhülle)					
			U 110		U 105		U 103	
			core	rim	relic core	rim	core	rim
SiO ₂	54.2	53.4	55.0	54.0	47.2	55.3	55.3	53.1
TiO ₂	—	—	—	0.6	2.1	—	0.04	0.09
Al ₂ O ₃	1.9	2.6	2.4	4.5	7.2	1.4	3.1	3.7
FeO*)	12.6	11.4	9.2	10.0	11.1	9.1	8.5	11.1
MnO	0.26	0.22	0.16	0.32	0.16	0.20	0.12	0.27
MgO	15.5	16.04	17.4	15.9	15.5	17.9	17.6	15.9
CaO	11.9	10.8	11.6	10.6	10.8	12.5	11.0	12.6
Na ₂ O	0.59	1.1	0.78	1.3	1.6	0.4	0.99	0.37
K ₂ O	0.08	—	0.06	0.08	0.29	0.04	0.07	0.08
Σ	97.0	95.5	96.6	97.3	96.0	96.8	96.7	97.2
							Number of cations	
Si	7.84	7.80	7.86	7.71	6.99	7.88	7.85	7.64
Al	0.16	0.20	0.14	0.29	1.01	0.12	0.15	0.36
ΣZ	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.16	0.25	0.25	0.47	0.25	0.12	0.36	0.27
Ti	—	—	—	0.05	0.25	—	—	0.01
Fe*)	1.52	1.39	1.10	1.19	1.37	1.08	1.01	1.33
Mn	0.03	0.03	0.02	0.04	0.02	0.02	0.01	0.03
Mg	3.34	3.48	3.69	3.39	3.32	3.81	3.71	3.40
ΣY	5.05	5.15	5.06	5.14	5.19	5.13	5.09	5.04
Ca	1.85	1.69	1.78	1.62	1.71	1.91	1.67	1.94
Na	0.17	0.31	0.22	0.37	0.45	0.10	0.27	0.10
K	0.02	—	0.01	0.02	0.05	0.01	0.01	0.02
ΣX	2.04	2.00	2.01	2.01	2.21	2.02	1.95	2.06

*) Total iron as FeO.

phanitic hornblende (gastaldite) and glaucophane occur as layers in the highest-grade eclogite zone.

Microprobe analyses of the amphiboles of the Umbal Valley are given in Table 4.

The amphibole compositions of the profiles are represented in the [Al]⁴ versus [Al + Ti]⁶ and [Al]⁴ versus [Na]⁸ diagrams of Figures 10–12 for the purpose of comparison and discussion. The variation of the Al and Na contents along the profiles is shown in Figure 9. The maximum Al and Na contents increase with increasing metamorphic grade. In zoned amphiboles, the Na, Al, and Fe contents increase from core to rim.

At the same stratigraphical position in the profiles, the amphiboles of the Dorfer Valley are characterized by higher Na and Al contents than those of the Umbal Valley. This tendency is also substantiated in Figures 10–12. The variation of the compositions in the amphiboles is shown in the following Table:

Garnet amphibolites				(Lower Schieferhülle)								
U 98		U 94a		U 94c	U 92c			U 92e			U 92f	
core	rim	core	rim		relic core	core	rim	relic core	core	rim	core	rim
54.7	49.7	49.8	48.5	53.0	44.2	50.8	48.9	50.0	55.1	54.9	47.6	47.0
—	0.15	0.13	0.14	0.01	0.23	0.13	0.18	0.09	—	—	—	—
2.8	9.0	7.0	8.4	2.6	10.5	11.6	10.8	7.8	2.7	2.0	7.8	10.0
9.3	11.6	13.9	15.0	13.7	18.5	15.8	19.6	13.5	9.4	12.0	15.0	16.6
0.20	0.15	0.17	0.15	0.25	0.12	0.15	0.22	—	—	—	0.12	0.12
17.6	13.6	12.8	11.2	14.6	9.0	11.6	10.8	13.2	17.7	16.1	12.3	11.8
11.2	9.8	9.8	8.4	11.4	10.6	7.6	8.6	9.9	11.0	11.2	10.4	9.5
0.81	2.1	2.1	2.9	0.63	2.0	2.2	1.1	1.4	0.75	0.63	1.1	1.4
0.14	0.18	0.25	0.23	0.11	0.26	0.18	0.19	0.18	0.11	0.09	0.14	0.20
96.8	96.3	96.0	95.0	96.3	95.4	95.9	96.0	96.1	96.8	96.9	94.5	96.6
(O = 23, anhydrous basis)												
7.80	7.23	7.35	7.27	7.77	6.78	7.50	7.38	7.33	7.84	7.90	7.19	6.98
0.20	0.77	0.65	0.73	0.23	1.22	0.50	0.62	0.67	0.16	0.10	0.81	1.02
8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
0.27	0.77	0.57	0.76	0.21	0.69	0.79	0.51	0.68	0.28	0.23	0.58	0.73
—	0.02	0.01	0.02	—	0.03	0.01	0.02	0.01	—	—	—	—
1.11	1.41	1.72	1.87	1.68	2.37	1.95	2.47	1.65	1.11	1.43	1.89	2.02
0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	—	—	—	0.02	0.02
3.73	2.94	2.82	2.51	3.20	2.07	2.54	2.43	2.88	3.76	3.46	2.76	2.61
5.13	5.16	5.15	5.19	5.12	5.18	5.31	5.46	5.22	5.15	5.12	5.25	5.42
1.71	1.53	1.55	1.34	1.80	1.75	1.20	1.40	1.56	1.67	1.73	1.69	1.51
0.22	0.58	0.61	0.85	0.18	0.59	0.62	0.31	0.39	0.21	0.18	0.33	0.41
0.03	0.03	0.05	0.04	0.02	0.05	0.03	0.04	0.03	0.02	0.02	0.03	0.04
1.96	2.14	2.21	2.23	2.00	2.39	1.85	1.75	1.98	1.90	1.93	2.05	1.96

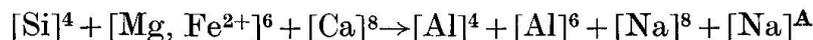
Greenschists and prasinites

	Dorfer Valley core → rim	Umbal Valley core → rim
[Al] ⁴ / [Al + Ti] ⁸	0.10/0.10 → 0.70/0.60	0.03/0.05 → 0.40/0.60
[Al] ⁴ / [Na] ⁸	0.10/0.10 → 0.70/0.60	0.03/0.05 → 0.40/0.40

Garnet amphibolites

	Dorfer Valley core → rim	Umbal Valley core → rim
[Al] ⁴ / [Al + Ti] ⁶	0.20/1.50 → 1.10/1.05	0.08/0.17 → 1.20/0.7
[Al] ⁴ / [Na] ⁸	0.20/0.35 → 1.10/0.70	0.08/0.05 → 1.20/0.8

The chemical variation of the amphibole compositions may be described by the following simplified substitution:



This substitution can be interpreted in terms of amphibole end members as an actinolite-tschermakite-glaucophane solid solution (Fig. 13).

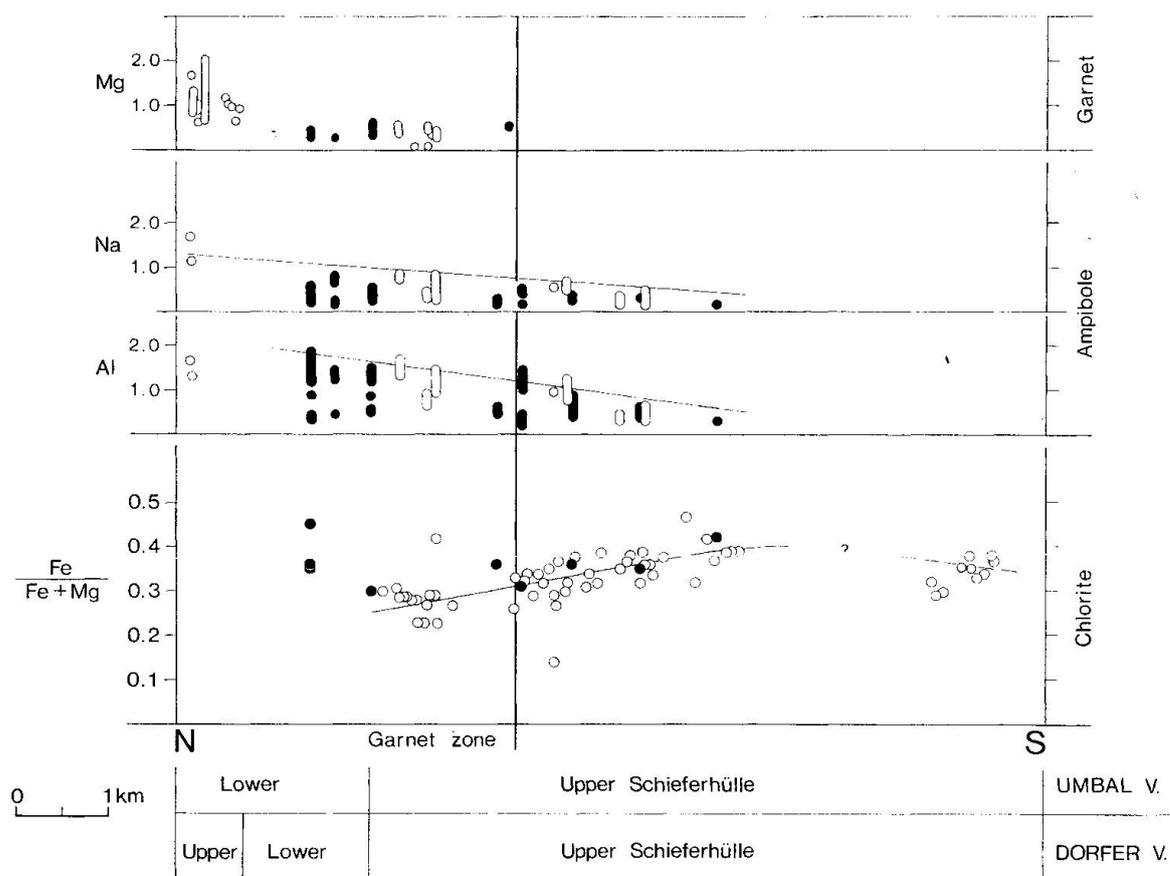


Fig. 9. Variation of the chlorite, amphibole, and garnet compositions along the profiles. Open circles and bars represent samples of the Dorfer Valley, filled symbols samples of the Umbal Valley. Chemical variation is expressed in terms of Mg, Na and Al atoms per formula unit and by the $\text{Fe}/(\text{Fe} + \text{Mg})$ atomic ratio.

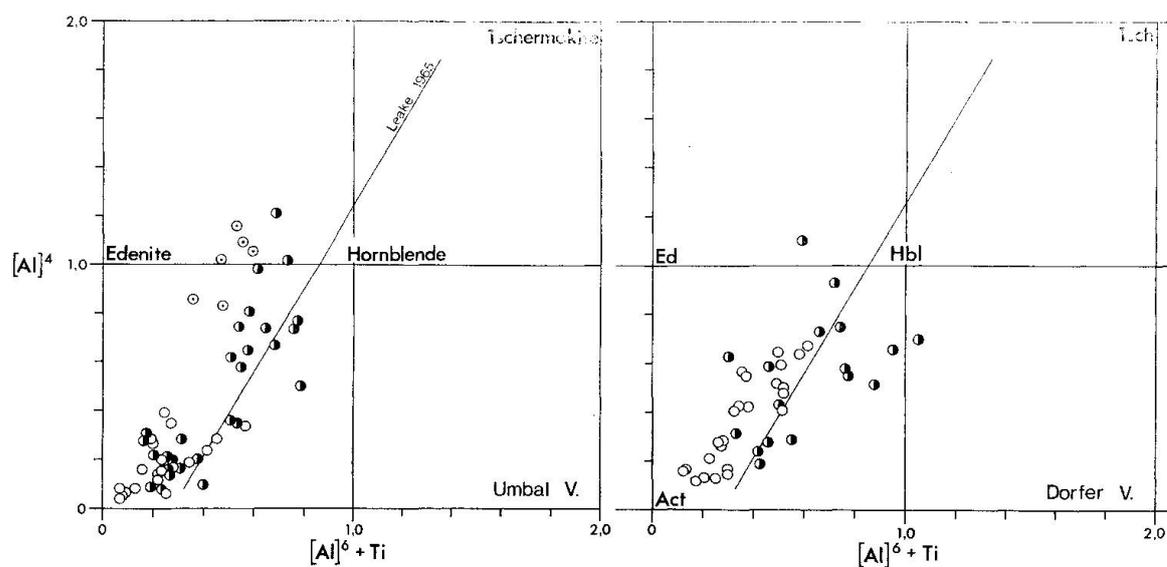


Fig. 10. Compositions of the amphiboles in $[\text{Al}]^4$ versus $[\text{Al}]^6 + \text{Ti}$ diagrams. Open circles represent amphiboles of the prasinites, half filled circles amphiboles of the garnet amphibolites, centered circles relic amphibole in prasinite.

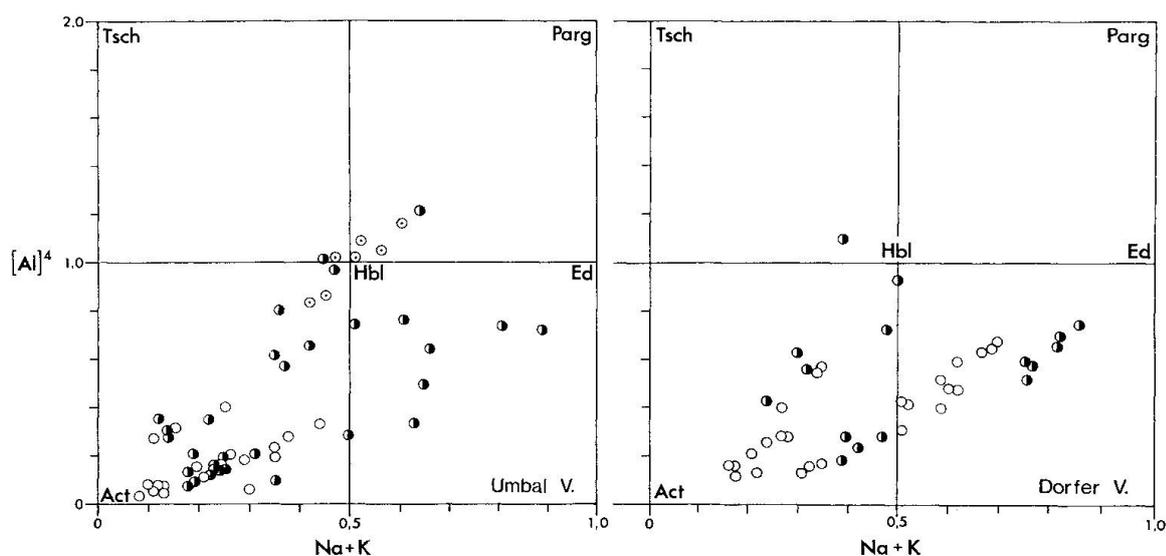


Fig. 11. Compositions of the amphiboles in $[Al]^4$ versus $Na+K$ diagrams. Symbols as described in Fig. 4.

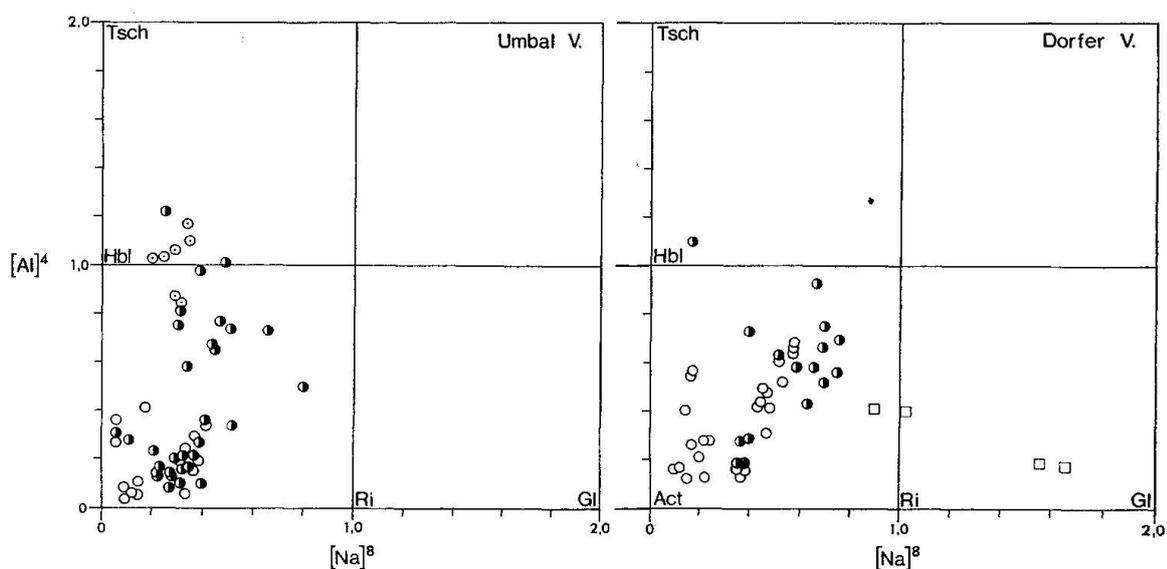


Fig. 12. Compositions of the amphiboles in $[Al]^4$ versus $[Na]^8$ diagrams. Symbols as described in Fig. 4; open squares represent alkali amphiboles of the glaucophane schists.

The compositional development described above is restricted to amphiboles formed during the Alpine metamorphism: amphiboles of the Upper Mesozoic Schieferhülle and the recrystallized and newly formed amphiboles of the Lower Paleozoic Schieferhülle. Relic hornblendes characterized by higher $[Al]^4$, $[Al]^6$, Ti and lower $[Na]^8$ are encountered in the garnet amphibolites of the Lower Schieferhülle of the Umbal Valley. These hornblendes exhibit lamellar exsolution structures parallel $(\bar{1}01)$. We suggest that these hornblendes are relics of an Variscian metamorphism (RAITH et al., 1978).

The amphiboles during the Alpine recrystallization tend to develop into a

Fig. 13. Compositions of the amphiboles in a Na versus Ca diagram. Symbols are described in Figs. 4 and 6.

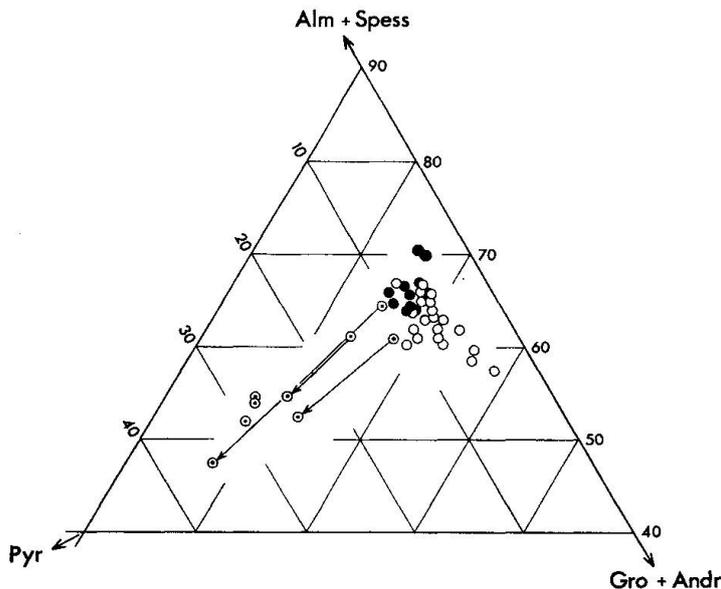
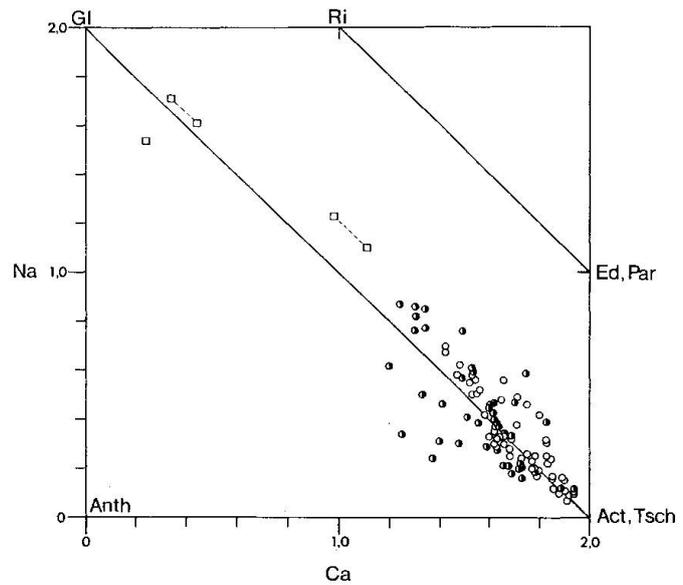


Fig. 14. Composition of garnets in terms of pyrope, almandite + spessartite and grossularite + andradite components. Solid circles represent garnets of the amphibolites of the Dorfer Valley, open circles garnets of the amphibolites of the Umbal Valley. Garnets of the eclogites are represented by centered circles. Arrows show the compositional development from core to rim.

$0.6 [Al]^4 / 0.6 [Al + Ti]^6 / 0.6 [Na]^8$ composition which is close to the most extreme point of the Alpine actinolite subcalcic amphibole trend (Figs. 10, 12). The variation of the glaucophanitic amphiboles covers a range from glaucophane to subcalcic hornblende (Fig. 13).

The amphibole types occurring as (1) reaction rims on garnet, as (2) symplectitic intergrowth with plagioclase replacing omphacite and as (3) diaphthoritic amphibole in glaucophane schists are not dealt with in this context.

GARNETS

Microprobe analyses of the garnets of the Umbal Valley are shown in Table 5, those of the Dorfer Valley were reported by ABRAHAM et al. (1974,

Tab. 8). The compositions are compared in terms of pyrope, grossularite + andradite, and almandite + spessartite components in Figure 14.

The garnets of the *garnet amphibolites and prasinites* are weakly zoned. The garnets of the Umbal Valley have higher grossularite and spessartite contents than those of the Dorfer Valley. The pyrope component of the garnets from both profiles is fairly constant with 5–10 mole percent. It does not vary along the profiles (Fig. 9).

The garnet composition of the *eclogitic and glaucophanitic rocks* contrasts considerably to that of the amphibolites. The garnets are strongly zoned with core compositions very similar to those of amphibolite garnets, but with rims of much higher pyrope content. The pyrope component increases up to a maximum of 36 mole percent.

Garnet is replaced during retrogressive alteration at most probably high temperatures by tschermakitic hornblende and iron-rich epidote, and at lower temperatures by chlorite and biotite \pm magnetite.

EPIDOTES

The composition of the epidotes of the Dorfer Valley metabasites was studied in detail by RAITH (1976). The epidotes in the metabasites of the Umbal Valley show the same compositional development. Epidote analyses from the Umbal Valley are given in Table 6.

The average iron content of the zoned epidotes decreases with increasing metamorphic grade. However, this is not only the effect of temperature and pressure but also depends on the oxidation state of the rocks.

In oxidized, hematite-bearing assemblages the Al_2Fe -epidote component decreases from 90 mole % in greenschists, to 70 percent in amphibolites, and 58 percent in the eclogitic rocks. In reduced, sulfide-bearing assemblages the corresponding development is 42 mole % Al_2Fe -epidote in greenschists, 24 percent in amphibolites, and 23 percent in eclogites. Zoisite together with garnet occurs first in the most reduced assemblages of the high-grade prasinites in the middle part of the profiles (Fig. 2).

The zoning of the epidotes shows the same compositional trend as described above for the development of the average epidote compositions along the profiles. It reflects the temporal changes of temperature, total pressure, and oxygen fugacity during crystallization. In the lower-grade metabasites the zoning of the epidotes is discontinuous due to a miscibility gap ranging from 54–70 mole percent $\text{Al}_2\text{Fe(III)}$ -epidote (RAITH, 1976).

The occasionally present iron-rich outer rims, which often corrode the zoned epidote crystals, were most probably formed during retrogressive metamorphism.

Table 6. *Chemical composition and atomic proportions of epidotes from the Umbal Valley*

Rock type Sample No.	Epidote Greenschist		Zoisite	Epidote Garnet amphibolites		Zoisite	Epidote
	U 110			U 94a			U 94c
	core	rim		core	rim		
SiO ₂	37.6	38.6	38.5	38.0	37.0	39.0	38.0
TiO ₂	0.11	0.09	0.17	0.19	0.11	0.08	0.07
Al ₂ O ₃	25.9	28.4	29.4	29.6	24.8	31.8	27.4
Fe ₂ O ₃ *)	9.1	6.6	5.1	5.2	10.6	2.0	7.6
Mn ₂ O ₃	0.10	0.14	—	—	0.14	—	—
MgO	—	—	0.10	—	—	—	—
SrO	—	—	0.16	0.20	0.27	—	—
CaO	23.5	24.0	24.1	24.1	23.2	24.4	23.9
Σ	96.3	97.8	97.5	97.3	96.1	97.6	97.1
Number of cations (O = 13, anhydrous basis)							
Si	3.00	3.00	2.99	2.96	2.98	2.99	2.99
Al	2.44	2.60	2.69	2.72	2.36	2.88	2.54
Ti	0.01	0.01	0.01	0.01	0.01	—	—
Cr	—	—	—	—	—	—	—
Fe*)	0.54	0.38	0.30	0.31	0.64	0.12	0.45
Mn	0.01	0.01	—	—	0.01	—	—
ΣY	3.00	3.00	3.00	3.04	3.02	3.00	2.99
Ca	2.00	2.00	2.00	2.01	2.00	2.00	2.02
Mg	—	—	0.01	—	—	—	—
Sr	—	—	0.01	0.01	0.01	0.02	—
ΣX	2.00	2.00	2.02	2.02	2.01	2.02	2.02

*) Total iron as Fe₂O₃.

CLINOPYROXENES

Clinopyroxenes which occur in the eclogitic rocks of the southern Venediger area, have already been described by ABRAHAM et al. (1974) and MILLER (1974): They are chloromelanitic omphacites. In zoned crystals the acmite component decreases from core to rim.

The jadeite component varies from 35–50 mole percent, acmite component from 0–15 percent and tschermaks molecule + diopside + hedenbergite from 40–60 mole percent.

The omphacites often undergo replacement by amphibole + plagioclase symplectite. The clinopyroxenes in the lowest metabasite layer of the Upper Schieferhülle of the Umbal Valley profile have also been altered usually into symplectite. Diopsidic clinopyroxenes are encountered in the serpentinite – mica marble contact of the serpentinite body of the Dorfer Valley and also in thin calc silicate bands in the southern part of the Lower Schieferhülle. A microprobe analysis from the latter occurrence is presented in Table 5.

MICAS AND TALC

Paragonite and phengite occur in the northern part of the profiles predominantly within the garnet amphibolite and glaucophane schist assemblages. They first appear together with garnet and zoisite in the higher-graded and more reduced prasinites.

In the southernmost part of the Penninic, near the overthrust plane of the Altkristallin, white micas are found in highly oxidized, hematite-bearing chlorite schists. The formation of white mica in the prasinites is most probably controlled by the oxidation state. Strongly oxidizing formation conditions favour the crystallization of phengite instead of biotite.

In addition to the analyses published by ABRAHAM et al. (1974) for the Dorfer Valley, new data of samples from the Umbal Valley are given in Table 7.

Table 7. *Chemical composition and atomic proportions of phengites and biotites*

Rock type Sample No. Analyses	Phengites Garnet amphibolites			Greenschist	Biotites Garnet amphibolites	
	U 98 6	U 94a 3	U 92e 3	U 107 5	U 98 5	U 94 3
SiO ₂	49.9	49.8	51.0	36.7	36.3	37.7
TiO ₂	0.24	0.21	0.19	1.30	1.50	0.63
Al ₂ O ₃	25.9	27.0	25.4	15.1	17.4	16.2
Cr ₂ O ₃	0.81	—	—	—	0.31	—
FeO*)	2.1	1.3	2.1	17.8	13.9	11.4
MnO	—	—	—	0.14	—	0.15
MgO	3.7	3.8	4.0	12.1	13.7	17.0
BaO	0.42	0.23	0.16	—	0.38	0.35
CaO	—	—	—	0.1	—	—
Na ₂ O	0.39	0.22	0.13	—	0.28	0.07
K ₂ O	10.4	10.3	10.7	9.0	9.2	9.9
Σ	93.9	92.9	93.7	92.2	93.0	93.4
Number of cations (O = 22, anhydrous basis)						
Si	6.81	6.78	6.93	5.72	5.54	5.66
Al	1.19	1.22	1.07	2.28	2.46	2.34
ΣZ	8.00	8.00	8.00	8.00	8.00	8.00
Al	2.97	3.13	3.00	0.51	0.66	0.53
Ti	0.02	0.02	0.02	0.15	0.17	0.07
Cr	0.09	—	—	—	0.04	—
Fe*)	0.24	0.15	0.24	2.32	1.77	1.43
Mn	—	—	—	0.02	—	0.02
Mg	0.75	0.77	0.81	2.82	3.11	3.80
ΣY	4.07	4.07	4.07	5.82	5.75	5.85
Ba	0.02	0.01	0.01	—	0.02	0.02
Ca	—	—	—	0.02	—	—
Na	0.10	0.06	0.04	—	0.09	0.02
K	1.81	1.80	1.86	1.79	1.79	1.90
ΣX	1.93	1.87	1.91	1.81	1.90	1.94

*) Total iron as FeO.

The phengites have a rather uniform composition with Si 3.40–3.45. The paragonite component varies from about 2 to 10 mole percent.

Paragonite is a typical phase of the garnet amphibolites, eclogites and glaucophane schists. The paragonites contain about 3 mole percent muscovite and margarite components (ABRAHAM *et al.*, 1974; MILLER, 1974).

Biotite occurs more frequently in the garnet amphibolites of the Umbal Valley than in those of the Dorfer Valley due to a higher potassium content of the rocks and a low oxidation state. However, complex relationships with rock composition and coexisting phases are evident but cannot be discussed because of the lack of necessary information. Microprobe analyses for biotites from the Umbal Valley are shown in Table 7.

Talc occurs as a stable phase in zoisite-kyanite-bearing eclogites (ABRAHAM *et al.*, 1974; MILLER, 1974).

PLAGIOCLASE

Albite is the characteristic feldspar of the chlorite schists and prasinites in the low-grade southern part of the profiles (Fig. 2). In the prasinite-garnet amphibolite transition zone oligoclase rims are formed around albite cores.

Zoisite and garnet appear together with oligoclase in the assemblages.

In addition to inversely zoned oligo-albites, quite homogeneously composed oligoclases are also abundant in the high-grade northern part of the profiles. In the eclogitic and glaucophanitic assemblages plagioclase is absent. In these rocks the Na component is incorporated in omphacite, glaucophane, and paragonite. Retrogressed rock types contain newly formed albite in a symplectitic intergrowth with amphibole, and less abundantly with diopside.

In contrast to the metabasites, oligoclase is formed at a lower metamorphic grade in the neighbouring calc mica schists, here in a more southerly part of the profiles (Fig. 2).

KYANITE

Kyanite is a characteristic mineral of some eclogite types. It occurs as late-kinematic prophyroblasts in the rocks as well as large crystals in fissures.

In a few occurrences kyanite was found in assemblage with talc and zoisite.

During retrogressive alteration kyanite is replaced by paragonite. In most of the glaucophane schists replacement of kyanite by paragonite is complete.

LAWSONITE PSEUDOMORPHS

Light euhedral pseudomorphs consisting of variable amounts of albite, epidote/zoisite, chlorite, and calcite have been found repeatedly in the prasinites of the southern Glockner and Venediger areas (ANGEL, 1929; CORNELIUS

and CLAR, 1939; FRY, 1973). They are now interpreted as pseudomorphs after lawsonite porphyroblasts (FRY, 1973). In the area investigated their occurrence is restricted to the thick prasinite layer in the middle part of the upper Schieferhülle (Fig. 1):

ACCESSORY MINERALS

Along the profiles the occurrence of accessory minerals is determined by the oxygen and sulfur fugacities and the metamorphic grade.

Greenschists and garnet amphibolites contain, depending on oxidation state of the rocks, either hematite, hematite + magnetite, or magnetite alone. Magnetite-bearing assemblages sometimes also contain pyrite. Parageneses without iron oxides commonly have pyrite and chalcopyrite.

Eclogites, which are highly reduced rocks, sometimes bear magnetite, pyrrhotite, pyrite, chalcopyrite and bornite. Glaucofane schists are highly oxidized and, consequently, are hematite and magnetite bearing.

The occurrence of accessory Ti-minerals depends characteristically on the metamorphic grade: sphene is typical for the chlorite schists and prasinites, ilmenite + minor rutile for the garnet-bearing prasinites and amphibolites, and rutile + minor ilmenite for the eclogites.

The most abundant sulfide mineral of the Upper Schieferhülle is pyrite, that of the Lower Schieferhülle pyrrhotite.

In diaphthoritic alteration of the metabasites, mainly in the eclogitic assemblages, secondary hematite and magnetite are formed by the decomposition of garnet. Sphene is formed as reaction rims around rutile crystals.

The highly reduced metabasites of the Lower Schieferhülle have an accessory mineral assemblage different from that of the Upper Schieferhülle. It is characterized by pyrrhotite, pyrite, chalcopyrite and minor ilmenite. Rutile, sphene and iron oxides have not been observed.

6. Discussion

SOURCE ROCKS

The chemical data, major elements as well as trace elements, treated in chapter 3 indicate that the metabasites of the Penninic have a basaltic source rock.

Primary volcanic rock structures are obliterated in the studied area because of the intense deformation and metamorphism of the rocks.

Massive and homogeneous layers were possibly lava flows. Banded rock types, consisting of alternating bands of basaltic and sedimentary matter

were most likely tuffs and tuffitic arenites similar to those described by HENNINGSEN and WEYL (1967) and by SCHMIDT-EFFING (1976) from the Nicoya-Complex in Costa Rica.

The basaltic rocks together with the intercalated serpentinite bodies are parts of an ophiolite series comparable to the Penninic ophiolite complexes of the Western Alps (BEARTH, 1967).

MILLER (1974) and BICKEL and PEARCE (1975) related the metabasites of the Upper Schieferhülle by means of Ti, Zr, Y, Sr and Nb contents to ocean floor basalts. The chemical data presented in this work substantiate this result to some extent (Tabs. 1, 2). In contrast to the metabasites of the Upper Schieferhülle, those of the Lower Schieferhülle, by their high Ti, Fe, K, P contents and low Al contents, resemble much more "continental" tholeiites (Tab. 1). This is also indicated by their trace element contents, which correspond quite closely to the average contents of within-plate basalts reported by WEDEPOHL (1975) (Tab. 2).

A comparison of the metabasites of the Upper Schieferhülle with ocean floor basalts by means of the chemical data is not so consistent. The major element data prove a distinct development into alkali olivine basalts (Tab. 1, Fig. 5). The occurrence of alkali olivine basalts in the present ocean floor areas is restricted to transform fault systems and the marginal zones of the rift valleys (cf. HEKINIAN and THOMPSON, 1976).

Moreover, an alteration of the original rock composition by metasomatic processes during diagenesis and metamorphism has to be considered. In addition to this, the occurrence of the tuffitic metabasite types makes it necessary to discuss the changes in chemical composition by the admixture of sedimentary matter, which is mainly calcareous.

HART (1970) and other investigators describe the changes of the chemical composition of the ocean floor basalts by sea water weathering. The main effects are an enrichment in K, Rb, Cs, Fe, Mn, Na, and P and a depletion of Si, Ca, and Mg. This might account for the rather large variation of these elements in the investigated metabasites.

The possibility of an alteration of the chemical composition during the regional metamorphic process, which was formerly discussed by CANN (1970) cannot be substantiated by our data. Although the major and trace element data of Tables 1 and 2 show a considerable variation of the contents, greenschists, amphibolites and eclogitic rocks have the same average chemical composition. There exists no correlation with increasing regional metamorphic grade, except in the case of H₂O content and oxidation ratio, which both steadily decrease.

However, it could well be possible, that during lowest-grade ocean floor metamorphism a migration of e.g. Na, K and Ca took place (MIYASHIRO, 1975).

As compared to the minor effects on the chemical composition by the above mentioned influences, a striking alteration should occur with the admixture of calcareous sediment to the basalt matter, mainly in the tuffitic metabasites.

These types have definitely higher Ca, Li and Ba contents than ocean floor basalts. The Li and Ba contents of marine sediments, shales and calcareous oozes are high. According to HEIER (1970) marine shales contain 4–400 ppm Li (aver. 76), pelagic sea clays 58–113 ppm (OHRDORF, 1968), globigerina oozes 21–120 ppm (aver. 59) (WELBY, 1958). The average Ba contents of pelagic clays are, according to WEDEPOHL (1960), 750 ppm Ba for the Atlantic and 4000 ppm Ba for the Pacific. Pelagic carbonates from the Atlantic contain on the average 689–1900 ppm Ba (TUREKIAN, 1968; EL WAKEEL and RILEY, 1961).

It can be easily shown by these data that a very limited admixture of marine sediments to the basalt matter could change the original Ba and Li contents to the observed values.

The notion of an admixture of calcareous sediments is in complete agreement with the field observation that the tuffitic metabasite types change gradually into calc mica schists, which are the most abundant metasediment type of the Upper Schieferhülle (Fig. 1).

The admixture of carbonate matter can be proven by a CaO-CO₂ diagram of the metabasites (Fig. 3). Most of the metabasite samples fall into a restricted area of low CO₂ contents. The change in the compositions resulting from the admixture of calcite is shown by the arrow Cc in Figure 3. Most of the tuffitic metabasite samples occur in a narrow field near this trend line. A few samples with high CaO but low CO₂ contents are tuffitic types which have undergone decarbonatization during metamorphism (ABRAHAM et al., 1974). Metasomatic addition of CO₂ to the basaltic source rock would shift its composition parallel to the CO₂-axis (arrow + CO₂ in Fig. 3).

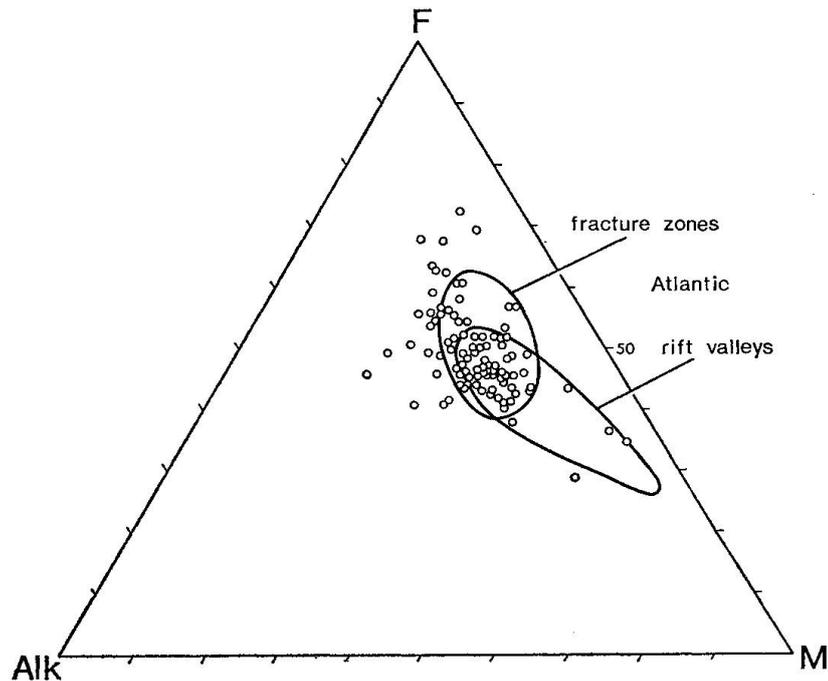
In contrast to the homogeneous greenschists and eclogites, the banded (tuffitic) metabasites, greenschists as well as glaucophane schists, are characterized by a distinctly higher oxidation ratio, possibly inherited from their different kind of volcanic formation.

It should be emphasized in this context that the most homogeneous metabasite types of the Upper Schieferhülle have a trace and major element composition that is closely related to that of ocean floor basalts (Tabs. 1, 2).

In chapter 3 the metabasites were grouped on the basis of the K₂O contents (ENGEL et al., 1965). The group with K₂O contents lower than 0.4 weight percent is regarded as representing the unaltered ocean floor basalt compositions (Tab. 2). About 70 percent of the samples fall into this group, in which characteristic differences from average ocean floor basalt as reported by WEDEPOHL (1975) are quite evident:

The Ni content is definitely lower (82 ± 42 ppm).

Fig. 15. AFM diagram of the metabasites. Fields of oceanic tholeiites according to HEKINIAN and THOMPSON (1976).



According to KAY et al. (1970), the Ni contents of the ocean floor basalts are positively correlated to the Mg contents. The representation of the samples in the AFM-diagram of Figure 15 indicates that the basalt compositions form a differentiation series along the FM-side of the diagram. This compositional trend may well result from a fractionation of olivine with its characteristically low Fe/Mg ratio.

This type of fractionation also generates high Al basalts, which are typical of abyssal oceanic tholeiites (KUNO, 1960) and also for the samples of this investigation. The fractionation of olivine is highly probable because olivine is a liquidus phase in the anhydrous olivine tholeiite system at pressures up to 12 bars and temperatures between 1250–1350°C (GREEN and RINGWOOD, 1967). The stability field of olivine extends to higher pressures by increasing water content of the melts (e.g. 15 kbars at 1250°C and 5 weight-% H₂O, NICHOLLS and RINGWOOD, 1973).

The distribution coefficient of Ni between olivine and basaltic melts is about 13.5 (SHAW, 1972). Thus, fractionation of a few percent of olivine can reduce the Ni contents to the observed low values. Such low Ni contents also occur abundantly in the olivine-tholeiites of the ocean ridges (KAY et al., 1970).

The Cr and V contents, although lower than the average values for ocean floor basalts reported by WEDEPOHL (1975), fall well into the known variation ranges (cf. MIYASHIRO, 1975; JAKEŠ and WHITE, 1972).

A reduction in the Cr contents may be due to a small amount of clino-

pyroxene or spinel fractionation. Both minerals are characterized by high Cr distribution coefficients (WAGER and MITCHELL, 1951). The V contents can be decreased by the fractionation of magnetite (DUNCAN and TAYLOR, 1968).

On the whole, the investigated metabasites of the Upper Schieferhülle show an affinity to ocean floor basalts. The formation of the basaltic melts took place under relatively low pressures (10–15 kbars) and at high heat flow. However, this must not necessarily imply that the basalts generated as true ocean-floor basalts along a spreading oceanic rift. The close interbedding of the metabasalts with thick sequences of metasedimentary rocks is not in good agreement with the lithological structure of the oceanic crust. The production of the basaltic melts can also have taken place within an eugeosynclinal trough characterized by a thin continental crust.

METAMORPHIC EVOLUTION

The Alpine metamorphic development of the metabasites of the Penninic rock series with respect to the changing mineral assemblages and mineral compositions has already been discussed by ABRAHAM et al. (1974). The new data presented here enable a discussion of the metamorphic development throughout the whole Mesozoic Upper Schieferhülle from the boundary zone of the Lower Schieferhülle to the overthrust plane of the Austroalpine Altkristallin in an area of 100 square kilometers (cf. Fig. 1). The investigation of the metamorphic evolution by means of the mineral assemblages of the metabasites also extends to the metasedimentary rocks, which occur abundantly within the Mesozoic Penninic sequence.

The metamorphic zoning along the profiles is the result of a *progressive metamorphism*, the grade of which increases from South to North. The basaltic source rocks reacted syn- to postkinematically into chlorite schists, prasinites, garnet amphibolites and finally into eclogitic rocks.

All mineral phases of the assemblages participate in the reactions. Moreover, the reactions linking the assemblages are of high variance because most of the minerals are mixed crystals and the fugacities of H₂O, CO₂, O₂ in the fluids are variable. Consequently, the decomposition and formation of minerals occurs within rather broad TP-bands. The general feature of the proceeding reactions is dehydration, decarbonatization, and reduction of the assemblages.

During progressive metamorphism the following mineralogical changes take place:

1. The amount of chlorite decreases continuously. The composition changes from Fe-hippidolite to Mg-hippidolite. The Mg-hippidolites break down completely at the transition of the prasinites into the garnet amphibolites and eclogitic rocks.

2. The amount of amphibole increases continuously. The amphiboles develop from actinolite into subcalcic (barroisitic) hornblende. Subcalcic amphibole breaks down at the transition from amphibolites into eclogites and glaucophane schists.

3. Modal albite and calcite decrease. In the garnet amphibolites (Lower Schieferhülle), oligoclase is formed instead of albite. Plagioclase breaks down in the eclogites and glaucophane schists.

4. The epidote composition depends strongly on oxygen fugacity. On the whole, the Fe(III)-contents decrease with increasing metamorphic grade. Eclogites contain zoisite, whereas the glaucophane schists bear epidote.

5. At the transition of amphibolites to eclogites and glaucophane schists, a decisive change takes place in the assemblages. Two different developments can be observed: The Ca-rich, highly oxidized assemblages, most probably of tuffitic origin, form glaucophane schists with calcite, garnet, glaucophane, epidote, paragonite, and minor omphacite; the reduced assemblages, originating from homogeneous basalts, form eclogites with garnet, omphacite, zoisite, and kyanite.

The sequence of the mineral assemblages along the profiles reflects the spatial distribution of the metamorphic grade within the Penninic rock pile at the final stage of progressive metamorphism.

The temporal development of the metamorphic event is substantiated by the compositional variation of the zoned minerals (epidote, amphibole, garnet, plagioclase) and by relics.

The zoning of the crystals exhibits the same development in the mineral compositions as can be observed along the profiles (Chapter 5). This supports the assumption that higher-graded assemblages (eclogites, glaucophane schists, amphibolites) have passed through the stages of lower metamorphic grade (chlorite schists, prasinites, amphibolites).

The occurrence of lawsonite pseudomorphs within the thick prasinite body in the middle part of the Upper Schieferhülle, as well as inclusions of relic glaucophane in the garnet amphibolites, indicate that the prasinitic and amphibolitic rocks have passed through an early stage of metamorphism characterized by low temperatures and relatively high pressures.

On the whole, the development of the metabasite assemblages conforms in the eastern part of the area (Dorfer and Lasnitzen Valleys) to that in the Western part (Umbal and Dorfer Valleys). Nevertheless, characteristic differences in the mineral compositions do exist: the amphiboles of the Umbal Valley have on average lower Na- and Al-contents. Inversely zoned oligo-albites first occur in the higher-grade prasinites. The garnets have a higher grossularite and spessartite component. Modal amounts of epidote are low.

The amphibole compositions indicate that the metamorphism in the Penninic rocks of the Umbal Valley has taken place under lower pressures than

in the Dorfer Valley. The same conclusion can be obtained from stratigraphic considerations: The thickness of the Mesozoic Penninic unit decreases from East to West. If the overlying Austroalpine nappe had a fairly constant thickness, then the lithostatic pressure would also decrease in the same direction. This could explain the absence of true eclogites in the western part of the area. However, the occurrence of symplectitic garnet amphibolites in the Lower Schieferhülle suggests that eclogites were present at an early stage of Alpine metamorphism.

The formation and persistence of eclogites and glaucophane schists in the eastern part of the area (Dorfer Valley) was probably favoured by a higher CO_2 fugacity of the fluid, possibly arising from the close interbedding with calc-mica schists and marbles. These calcareous metasediments are absent in the corresponding position of the Umbal Valley profile (Fig. 1 and 2).

The whole Penninic rock sequence underwent *retrogressive metamorphism*. Retrogressive alteration is more pronounced in the eclogites and glaucophane schists than in the garnet amphibolites and prasinites. The eclogites and glaucophane schists are gradually transformed into more hydrous assemblages: amphibolites and prasinites.

These transformations are described in some detail for the eclogites by MILLER (1974). Analogous alterations of eclogites were investigated in the Western Alps by BEARTH (1959, 1967, 1973, 1974) and in the Voltri group (W. Liguria, Italy) by ERNST (1976), CORTESOGNO et al. (1977).

In eclogites and glaucophane schists, omphacite is replaced by a symplectitic intergrowth of subcalcic amphibole + albite, kyanite by paragonite, garnet by barroisitic amphibole + epidote + magnetite or by chlorite + epidote + biotite \pm magnetite. Glaucophane is rimmed by barroisitic amphibole in a first stage, and gets replaced by an actinolite + albite intergrowth in a second stage. Epidotes exhibit rims of high Fe(III) content. Rutile is replaced by sphene.

In the amphibolites, garnet is first replaced by barroisitic amphibole + epidote + magnetite, and then by chlorite + biotite \pm magnetite.

In prasinites and chlorite schists, retrogressive alteration has possibly taken place but cannot be recognized as no paragenetic changes were induced. However, the reverse and discontinuous zoning of epidotes with Fe(III)-rich outer rims (RAITH, 1976) can be attributed to a late retrogressive stage of crystallization.

The *prograde development of the Penninic* is also substantiated by the paragenetical changes in the *metasediments* (Fig. 2, A). In the southernmost part of the profiles we encounter phyllites and calc phyllites with albite, minor chlorite and epidote. This low-grade zone is followed to the North by mica schists and calc-mica schists with inversely zoned plagioclase, biotite, zoisite and garnet. Some graphite-garnet-mica schists in the lower part of the Upper Schieferhülle bear chloritoid and kyanite. Proceeding further to the North, in

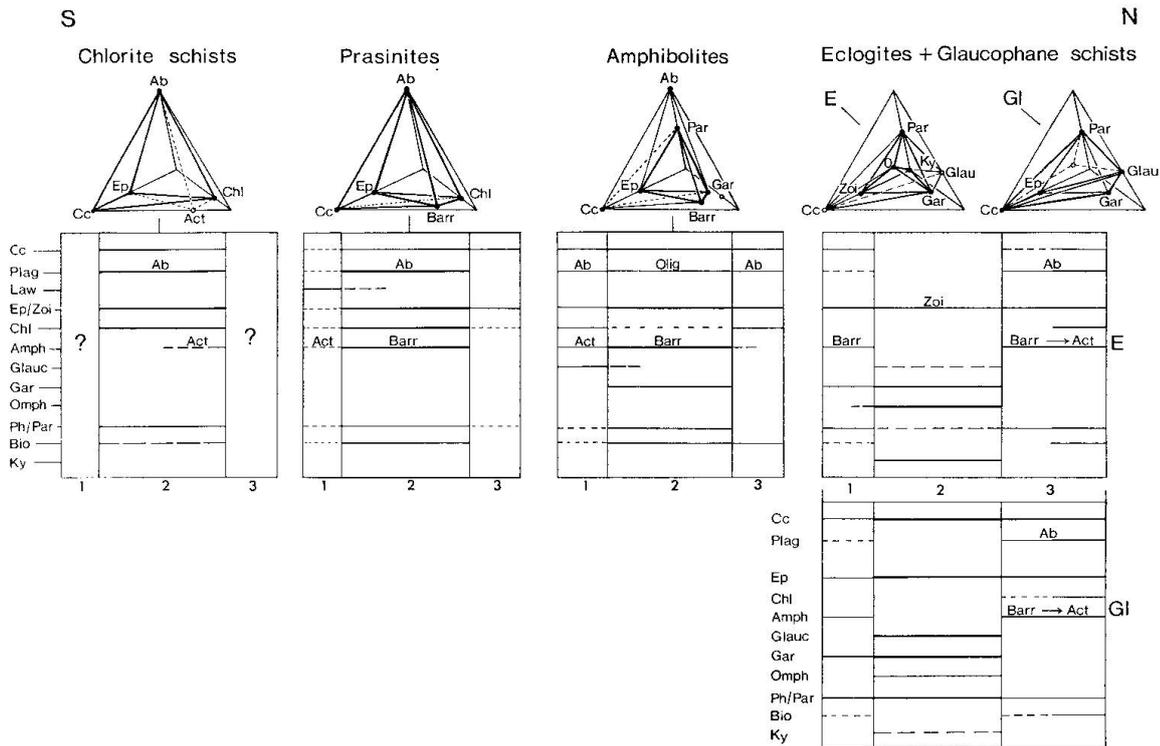


Fig. 16. Mineralogical development of the metabasites during the various stages of the Alpine metamorphism. Graphical representation of compatibility relations for the main crystallization stage in a $\text{CaO}-(\text{FeO} + \text{MgO})-\text{R}_2\text{O}_3-\text{Na}_2\text{O} \times \text{R}_2\text{O}_3$ tetrahedron. See text for discussion.

the highest-grade parts of the profiles, the carbonate-free metasediments of the Lower Schieferhülle have changed into garnet-mica schists and gneisses. No critical mineral assemblages have been formed because of the unfavourable composition of the rocks. A petrological investigation of the Mesozoic metasediments of the Penninic in a neighbouring area was published by Höck (1974).

On the basis of the microscopic analysis and chemical data, the metamorphic development of the metabasites of the Penninic complex is schematically illustrated by Figure 16. Three stages can be recognized in the Alpine metamorphic process.

An early stage of the metamorphic development (stage 1) which precedes the main progressive event (stage 2) can be identified by means of relic assemblages. Proceeding from South to North, the relic assemblages of stage 1 as well as those of the main stage 2 demonstrate a progressive development of the rocks.

A retrogressive event (stage 3) mainly affected the highest-grade rock types of the profiles, the eclogites and glaucophane schists, but can also be detected in the amphibolites and prasinites.

Simplified *reactions relating the assemblages* of the progressive evolution (stage 2) were formulated in ABRAHAM et al. (1974). The compatibility relations of these assemblages are represented in the $\text{Na}_2\text{O} \cdot \text{R}_2\text{O}_3 - \text{R}_2\text{O}_3 - \text{CaO} - (\text{Mg}, \text{Fe}) \text{O}$ tetrahedra of Figure 16. This representation entails a reduction of the 7 main components (SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MgO , CaO , Na_2O) of the rocks onto 4. The accessory components TiO_2 , MnO , and K_2O may form additional phases (sphene, ilmenite, rutile, micas) or are incorporated in the major constituent minerals. More than four mineral phases can occur in the four-phase assemblages of Figure 16 because of the different partitioning of Al-Fe(III) and

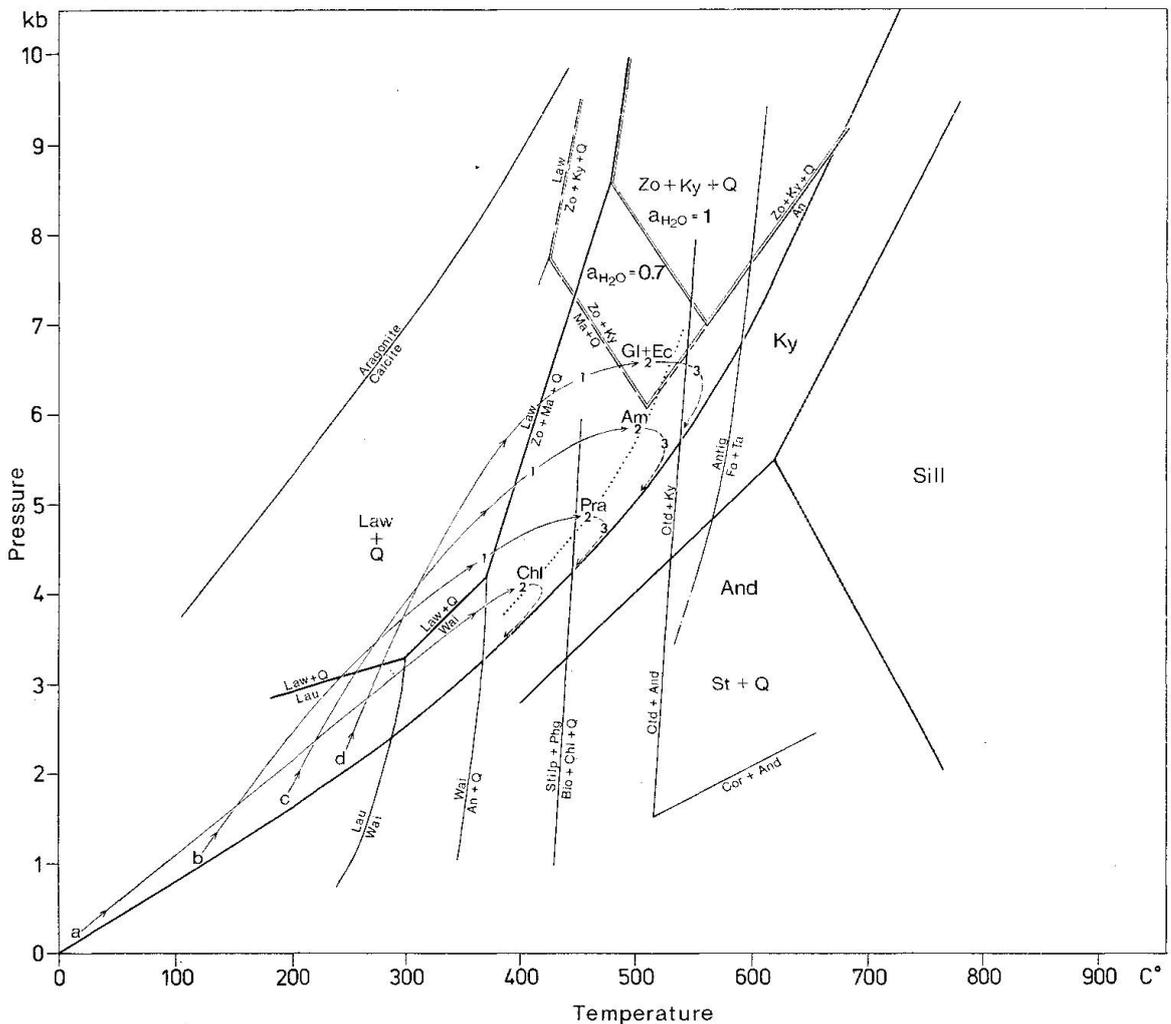


Fig. 17. P-T diagram of mineral reactions relevant for a discussion of the conditions of formation of the metabasites. References are given in the text. Arrows starting from a-d illustrate schematically the PT paths during the geodynamic evolution of the Penninic rock complex. a, b, c, d give the PT conditions within the Penninic rock series at the beginning of subduction, if a geothermal gradient of $25^\circ/\text{km}$ is assumed. 1 and 2 are the progressive stages of metamorphism, 3 the retrogressive stage. The PT paths are characterized by low geothermal gradients in the early stage of metamorphism. They develop towards a normal continental gradient in the late stage.

Fe(II)-Mg in coexisting minerals, by SiO₂-undersaturation, and by the varying fugacity ratios of O₂, CO₂ and H₂O in the fluids (ERNST, 1963; ABRAHAM et al., 1974; ERNST, 1976).

The *conditions of formation* of the prograde mineral assemblages (stage 2) can be derived from specific mineral parageneses, mineral compositions, mineral stability data, and oxygen isotope data.

The information on the relevant mineral reactions is summarized in Figure 17.

The *formation of the highest-grade rocks* of the sequence must have taken place at high pressures (P_{tot} in the range 6–10 kbars). This is indicated by: 1. The rather high Al-content of the amphiboles (LEAKE, 1965; BANNO, 1965; RAASE, 1974; BROWN, 1977); 2. the occurrence of omphacite (KUSHIRO, 1965; WIKSTRÖM, 1971) and glaucophanitic amphibole; 3. the presence of the parageneses zoisite + kyanite ± quartz (STORRE and NITSCH, 1974; CHATTERJEE, 1976) and kyanite + talc (SCHREYER and SEIFERT, 1969); and 4. the composition of garnets and coexisting clinopyroxenes (COLEMAN et al., 1965; SMULIKOWSKY, 1965; MOTTANA, 1970; RÅHEIM and GREEN, 1974). The occurrence of lawsonite pseudomorphs in some of the prasinites (ANGEL, 1929; CORNELIUS, 1942; FRY, 1973) also indicates high-pressure metamorphism.

The maximum temperature of formation did not exceed 550°C. This is concluded from the occurrence of the parageneses chloritoid + kyanite + quartz in the metapelites (GANGULY, 1969), zoisite + kyanite ± quartz in the eclogites (NEWTON and KENNEDY, 1963; CHATTERJEE, 1976), and the presence of antigorite in the serpentinite bodies (JOHANNES, 1975). The paragneisses of the Lower Schieferhülle were not affected by anatexis during the Alpine metamorphism.

The conditions of *formation of the lowest-grade rocks* are difficult to estimate. A pressure of about 5 kbars can be assumed from the thickness of the overlying, Austroalpine nappe, which is estimated as about 15 km (OXBURGH et al., 1971). Minimum temperature were lower than about 440°C. This is concluded from the occurrence of stilpnomelane (MEIXNER, 1958; CORNELIUS and CLAR, 1939). No data on the upper stability of stilpnomelane itself are available so far. However, the disappearance of stilpnomelane with increasing metamorphic grade could occur by the reaction stilpnomelane + phengite → biotite + chlorite + quartz which was investigated by NITSCH (1970) (Fig. 17).

The absence of prehnite, pumpellyite, and lawsonite in the lowest-grade metabasites indicates that the temperatures were not lower than about 400°C.

The oxygen isotope investigations of HOERNES and FRIEDRICHSEN (1974) gave a temperature range of 415–560°C for the prasinite-amphibolite-eclogite sequence.

In the following discussion the results of the petrological analysis are related to the recent concepts of the evolution of the Eastern Alps in the

light of plate tectonics (CLAR, 1965; OXBURGH and TURCOTTE, 1974; DIETRICH, 1976; FRISCH, 1974, 1976; HAWKESWORTH et al., 1975).

All investigators agree that the Alpine evolution of the Penninic is characterized by three events:

a) The formation of a subsiding eugeosyncline during the Jurassic and Lower Cretaceous characterized by sediments of the Bündner Schiefer facies (schistes lustrés) and interbedded ophiolites. Most investigators conclude that, in the expansion stage, an oceanic plate was generated along a rift zone of the trough. However, the complete series more probably represents a geosynclinal pile of conformable sediments and volcanic rocks deposited on a thin continental crust, as described by MIYASHIRO (1975) for the metaophiolite series of the Sanbagawa belt.

b) A compression phase during the Middle and Upper Cretaceous which resulted in the subduction of the Penninic rock series in a southerly direction under the Austroalpine basement. The subduction was completed in the Paleocene by the collision of the Penninic basement in the North with the Austroalpine Unit in the South.

c) Subsequent doming and uplift of the subducted rock complex in the Oligocene and Miocene.

The tectonic models are based on radiometric age determinations (CLIFF et al., 1971; KREUZER et al., 1973; SATIR, 1975; HAWKESWORTH et al., 1975). During the climax stage of subduction the Penninic rock series underwent a high-pressure type of metamorphism which corresponds to the progressive stages 1 and 2 of this investigation (Fig. 16). This process took place between 80 to 60 m.y. ago and was followed by a post-kinematic metamorphic episode during the uplift of the rock complex at about 50–20 m.y.

This latter event corresponds to the whole of stage 3 and possibly part of stage 2 of this investigation (Fig. 16).

The paths of the metamorphic crystallization of the Penninic during the processes of subduction, compression and uplift are now discussed schematically with the aid of Figure 17. At the beginning of the metamorphic crystallization (beginning of subduction) the Penninic rock suite is characterized by a specific, probably low geothermal gradient. Each level within the rock sequence has a specific starting temperature and pressure. Consequently, during the process of subduction each level in the sequence follows a different path in the PT-field (Fig. 17). The characteristics of the geothermal gradients and their temporal variation along the PT-paths are controlled by the heat flow in the Penninic on the one hand and by the thickness and temperature of the overthrust Altkristallin unit on the other (OXBURGH and TURCOTTE, 1974; BICKLE et al., 1975).

If it is accepted that the "cold" Penninic complex was subducted relatively quickly underneath the "hot" Altkristallin and that the thermal equi-

libration was slow, then during subduction PT-paths of low geothermal gradients were generated (Fig. 17). During subduction the rocks pass through different facies fields. For any particular level in the rock sequence the metamorphic crystallization proceeds along a specific PT-path (a-d in Fig. 17).

The basites of the highest part of the Mesozoic Penninic, near the overthrust plane of the Austroalpine (path a Fig. 17) develop gradually into chlorite schists by passing through the stability fields of laumontite, wairakite, and prehnite (stage 2 of Fig. 16).

The basites of the middle part of the Mesozoic Penninic, (path b Fig. 17), pass through the stability fields of laumontite, lawsonite, pumpellyite, and are thus transformed into prasinites (stage 2 of Fig. 16).

The basites of the lower part of the Mesozoic Penninic and those of the Lower Schieferhülle (path c Fig. 17), pass through the stability fields of laumontite, lawsonite, pumpellyite, and become garnet amphibolites (stage 2 of Fig. 16).

Near the base of the Mesozoic Penninic (Dorfer Tal) (path d Fig. 17) the basites develop into glaucophane schists and eclogites by passing through the fields of laumontite and lawsonite finally reaching at high pressures the stability fields of glaucophane, omphacite, and zoisite + kyanite \pm quartz (stage 2 of Fig. 16).

During doming and uplift the pressure in the Penninic decreases due to erosion and possibly to gravitational sliding of the Northern Calcareous Alps and their underlying Paleozoic rocks into their present positions (CLAR, 1965; FRISCH, 1976; HAWKESWORTH, 1975).

Temperature possibly increased further due to the slow thermal equilibration between the Penninic and the Austroalpine Units (OXBURGH and TURCOTTE, 1974; BICKLE et al., 1975) but then fell by the continuous uplift and erosion processes. At this stage of evolution the high-grade rocks of the Penninic underwent a pronounced retrogressive metamorphism of low-grade amphibolite to greenschist facies. This postkinematic crystallization corresponds to the stage 3 of this investigation (Fig. 16).

This model of the metamorphic evolution of the Penninic is in agreement with the previously stated concept of a prograde development of the investigated metabasites (ABRAHAM et al., 1974), but takes into account the complicated geodynamic process by which the Penninic rocks were formed.

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