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Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **54 (1974)**

Heft 2-3: **Alpidische Metamorphosen in den Alpen**

PDF erstellt am: **06.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-42198

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Alpine Metamorphism of Peridotitic Rocks

By *Volkmar Trommsdorff* (Zürich)*) and *Bernard W. Evans* (Seattle)**)

With 9 figures and 2 tables in the text and 1 plate

Abstract

Maps are presented showing the distribution of critical mineral assemblages produced by alpine regional and contact metamorphism of peridotitic rocks in the pennine region between the Rhetic and Wallis Alps. In order of increasing grade are found: brucite + chrysotile + diopside, brucite + antigorite + diopside, olivine + antigorite + diopside, olivine + antigorite + tremolite, olivine + talc + tremolite, olivine + magnesiocummingtonite + tremolite, olivine + enstatite + tremolite, olivine + enstatite + tremolite + green spinel, olivine + enstatite + diopside + green spinel. All assemblages include chlorite, even at high grades where chlorite underwent a continuous reaction producing spinel. Spinel changes progressively from chrome-magnetite, through ferritchromite and chromite to green MgAl-spinel. Talc + enstatite instead of Ca-poor amphibole formed in rocks with low Fe^{2+}/Mg. Anthophyllite probably formed by inversion from magnesiocummingtonite during cooling. The antigorite-out isograd occurs midway between the staurolite and sillimanite isograds, suggesting much greater thermal stability for antigorite than determined for chrysotile by experiment. Ultramafic rock isograds are concordant with isograds drawn for other rock-types.

Overgrowth textures provide evidence for the progressive character of the isograd reactions up to the highest grades. Chemical and textural criteria for the metamorphic growth of olivine, orthopyroxene, clinopyroxene, and spinel are given. Overlap in the distribution of assemblages at the higher grades may be explained by the presence of CO_2 in the metamorphic pore fluid. Occurrence of Ca-poor amphibole + magnesite and enstatite + magnesite at medium and high grades respectively indicates that a CO_2-rich fluid was widespread.

The order of preference for major and minor elements in all the Mg-silicate minerals is given.

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INTRODUCTION

This account covers alpine-metamorphosed rocks rich in normative olivine, ranging in composition from dunite through harzburgite and lherzolite to olivine-pyroxenite. Some idea of their general compositional range is given in Fig. 1, which includes the majority of available analyses of penninic ultramafics between the Rhetic and the Wallis Alps (Plate I, Dietrich et al., 1974). Normative spinel ranges from zero to 11%, and $Fe^{2+}/(Fe^{2+}+Mg)$ ratios range from roughly 0.04 to 0.15. The cluster of points along the olivine-orthopyroxene edge involves both low and high-grade rocks and is probably due to loss of CaO during serpentinization.

The tectonic significance of the larger ultramafic masses and ultramafic-mafic complexes has been a subject of extended discussion for more than half

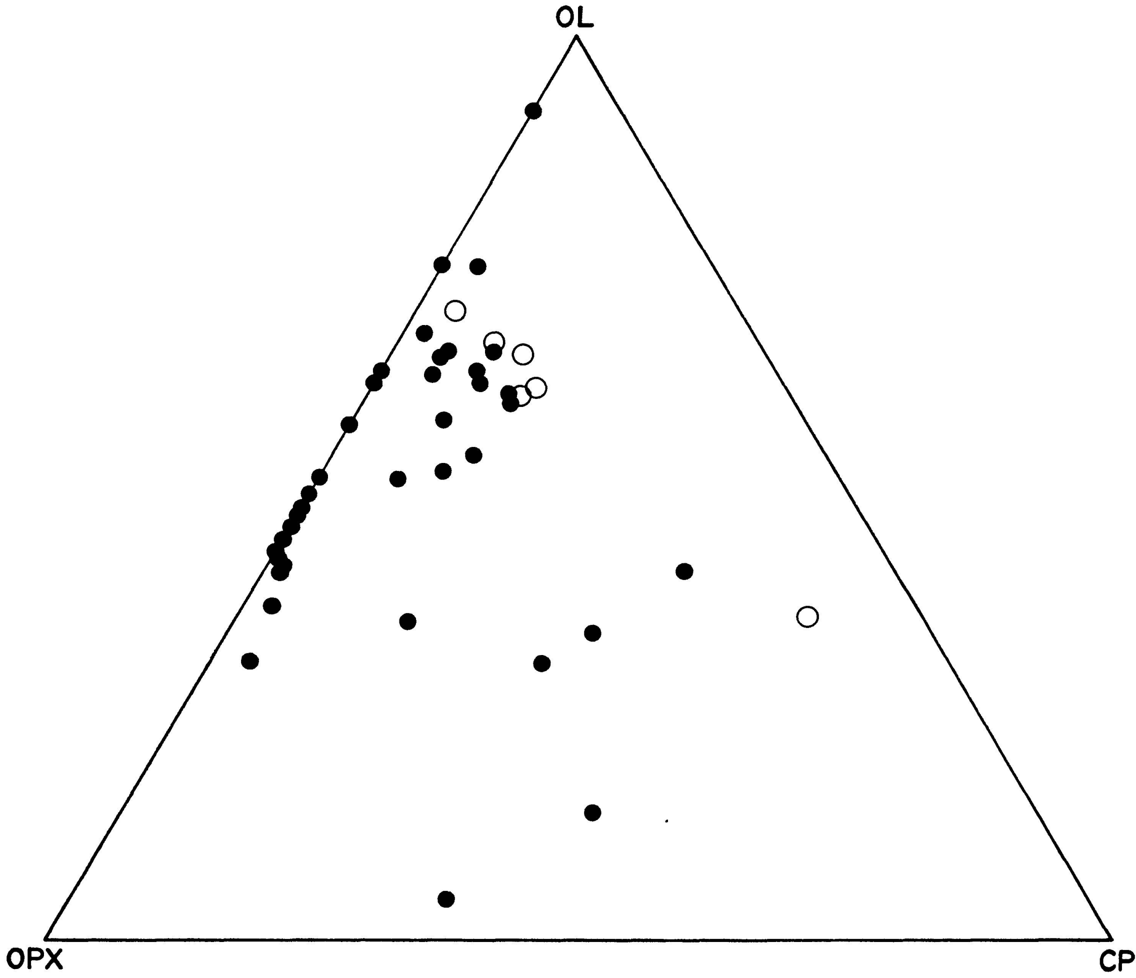

Fig. 1. Normative olivine, orthopyroxene, and diopside (molecular %) in alpine peridotitic rocks. Dots: analyses giving FeO and Fe_2O_3; circles: analyses giving total iron, redistributed as FeO. This is a "spinel peridotite" norm, i. e. corundum and anortite were converted to spinel, enstatite and diopside.

a century (for example, STAUB, 1922; CORNELIUS, 1935; BEARTH, 1967; TRUEMPY 1960, p. 887; DIETRICH, 1969; ERNST 1973; DIETRICH et al. 1974). Our study includes, in addition to some of these larger masses (Malenco, Platta, Zermatt/Antrona serpentinites), numerous smaller layers, lenses and boudins of metamorphic peridotitic rock widely distributed in the lower Pennine units of the Lepontine Alps.

Most of these rocks show evidence of polyphase deformation and crystallization (for example, BEARTH, 1967; DIETRICH and PETERS, 1971; KEUSEN, 1972; BUCHER and PFEIFER, 1973). Nevertheless, primary igneous layering, displayed by pyroxene, chlorite, and magnetite rich units, is not only preserved at low metamorphic grades, but is also frequently recognized in the high grade ultramafics of the Lepontine belt (e. g. MOECKEL, 1969). For a number of the medium and high grade bodies, it can be shown that they were serpentinites prior to the main alpine metamorphism.

The relatively simple chemistry of the metaperidotites is reflected in an equally simple mineralogy. Depending upon metamorphic grade, the following magnesium silicates and carbonates occur: magnesite, brucite, olivine, serpentine minerals, enstatite (clinoenstatite as a shearing product only), anthophyllite, magnesiocummingtonite, and talc. The additional components CaO and Al_2O_3 are responsible for diopside, tremolite, calcite, dolomite, chlorite, and green spinel. The alpine-metamorphic crystallization of pyropic garnet in peridotite (MOECKEL, 1969) is not yet proven. Widely occurring accessory metamorphic minerals are magnetite, ferrit-chromite, chromite, ilmenite, pyrrhotite, and pentlandite. Titanoclinohumite, perovskite, andradite, awaruite, and heazlewoodite occur in many of the serpentinites. Although considered as metamorphic as early as 1908 by GRUBENMANN, such an origin has only become firmly established in recent years for a number of these minerals, e. g. diopside (PETERS, 1963), olivine (BEARTH, 1967; PETERS, 1968) and enstatite (TROMMSDORFF, and EVANS, 1969).

The metamorphic peridotitic rocks in the Pennine region fall into three major groupings: 1. olivine-free, chrysotile/lizardite – or, at higher grade, antigorite-serpentinites (prehnite-pumpellyite and low greenschist/blueschist facies respectively), as displayed in the numerous ophiolites of the Platta nappe (Plate I, DIETRICH et al., 1974), 2. olivine + antigorite + diopside (or, at higher grades, tremolite) + magnetite schists (greenschist/blueschist and lower amphibolite facies), which form the serpentinites of Val Malenco, Geisspfad, and Antrona/Zermatt/Saas Fee (Plate I, DIETRICH et al., 1974), 3. serpentine-free olivine-rich ultramafic schists or rocks (amphibolite facies), as displayed by the majority of the bodies in the Lepontine region.

Closely associated with these ultramafics are rocks which do not correspond chemically to peridotite, namely contact metasomatic magnesian rocks and ophicarbonates.

ALPINE METAMORPHIC ASSEMBLAGES

Carbonate-free ultramafics

Assemblages in alpine metamorphosed ultramafic rocks (Fig. 2) are separated from each other in order of increasing grade by the following reactions:

chrysotile/lizardite = antigorite (+H_2O?) (1)
antigorite + brucite = olivine + 3 H_2O (2)
5 antigorite + 2 diopside = tremolite + 6 olivine + 9 H_2O (3)
5 antigorite = 6 olivine + talc + 9 H_2O (4)
9 talc + 4 olivine = 5 cummingtonite[1] + 4 H_2O (5)
cummingtonite[1] + olivine = 9 enstatite + H_2O (6)
chlorite[2] = olivine + 2 enstatite + spinel + 4 H_2O (7)
tremolite + olivine = 5 enstatite + 2 diopside + H_2O (8)

Despite evidence for alpine polymetamorphism, the sequence of assemblages follows a consistent regional pattern, permitting in places the construction of isograds. For most of the isograds, there is supporting textural evidence for the reactions, that is, the metamorphism was mainly progressive.

Fig. 2 schematically summarizes the phase relationships recognized in the Alps in both regional and contact metamorphic environments. Stability fields depend on composition (i. e. the ratio $(MgO + FeO)/SiO_2$) as well as metamorphic grade. Figure 2 was drawn up for bulk Fe/Mg ratios typical of the alpine ultramafics. However, for lower $Fe^{2+}/(Fe^{2+} + Mg)$ ratios, reactions (5) and (6) become metastable and replaced by:

talc + olivine = 5 enstatite + H_2O (9)

thereby eliminating a field of stability for cummingtonite/anthophyllite + olivine (Evans and Trommsdorff, 1973) – as indicated by the dotted lines on Fig. 2.

The polymorphic relationships between cummingtonite and anthophyllite are not yet properly understood. These minerals are characteristically intergrown with each other as lamellae, and there is evidence for the inversion cummingtonite → anthophyllite, which is inferred to have taken place during cooling (Rice, Evans and Trommsdorff, 1974). Thus it is tentatively concluded that cummingtonite rather than anthophyllite was the stable Ca-poor amphibole in olivine + cummingtonite + tremolite assemblages (Fig. 2) during crystallization (when permitted by the bulk Fe/Mg ratio).

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[1] Or anthophyllite.

[2] Based on chlorite $Mg_5Al_2Si_3O_{10}(OH)_8$; according to Frost (1973), chlorite coexisting with olivine, enstatite, and spinel is $Mg_{4.8}Al_{2.4}Si_{2.8}O_{10}(OH)_8$.

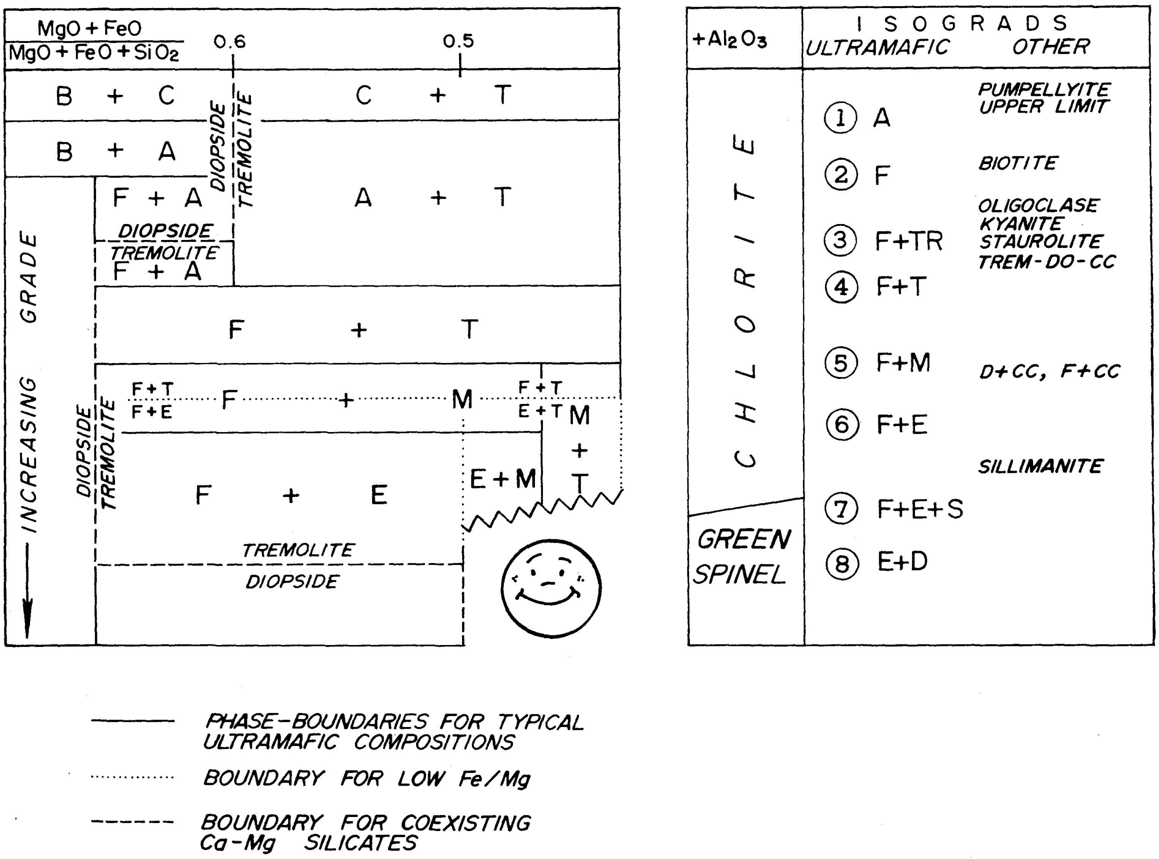


Fig. 2. Summary of mineral assemblages in metamorphic peridotitic rocks. Abbreviations: A = antigorite, B = brucite, C = chrysotile, lizardite, CC = calcite, D = diopside, DO = dolomite, E = enstatite, F = olivine, M = magnesiocummingtonite/anthophyllite, S = spinel, T = talc, TR = tremolite. Numbers correspond to reaction listed in the text.

The nature of the CaO-phase associated with the magnesian silicate assemblage is also indicated in Fig. 2. Diopside occurs at low grades with brucite + serpentine and with olivine + antigorite, and at high grades with olivine + enstatite. At all intermediate grades olivine assemblages are accompanied by tremolite (compositions more magnesian than olivine may carry diopside throughout, but such compositions are not realized in the ultramafics).

Chlorite is the principal Al-phase except at the higher grades, where it undergoes a continuous reaction, producing first ferrit-chromite, then red-brown chromite, and finally abundant green MgAl-spinel (together with enstatite, olivine, and H_2O). Only the transition to green spinel is indicated in Fig. 2. Garnet-peridotites have not been included in Fig. 2 because of their scarcity in the Pennine region and the uncertainty about their metamorphic age.

The principal textural observations which support the step-wise or progressive nature of the reactions are illustrated in Plate 2. They include post-kinematic growth of olivine and talc over a microfolded antigorite + magnetite fabric, overgrowth of metamorphic diopside on relic clinopyroxene, overgrowth of tremolite on metamorphic diopside, of cummingtonite on tremolite, of synkinematic enstatite over a schistose olivine + magnetite fabric, of green spinel on brown spinel (chromite), and formation of green spinel from chlorite.

Carbonate-bearing ultramafics

Ultramafic rocks totally lacking in carbonate, particularly near their margins, are unusual in the Pennine region. However, an understanding of the significance and origin of the abundant CO_2 must await further studies, particularly of stable isotopes.

At low metamorphic grades, serpentine is found to coexist with any of the three carbonates, calcite, dolomite, or magnesite (see for example Dietrich und Peters, 1971), although ophicalcite rocks are by far the most common. Progressive metamorphism of such ophicalcite can be observed along several profiles, e. g. Davos-Malenco, Zermatt-Antrona-Valle Loana, Bergell contact aureole, and across the Lepontine belt. Data are as yet very incomplete, however, and their significance is not yet understood. At low grades, serpentine + calcite rocks may contain tremolite or diopside or talc. At medium grades, close to the staurolite isograd, the pair antigorite + calcite becomes replaced by tremolite + dolomite or tremolite + olivine (Keusen, 1972; Mercolli, 1973; and unpublished observations in the Monte Rosa root-zone). At grades above the breakdown of antigorite, magnesite becomes the predominant carbonate in ultramafic rocks, in association with tremolite, Ca-poor amphibole, talc, enstatite or olivine.

Chlorite and magnesite are present in ophicarbonates up to the highest grades.

REGIONAL PATTERNS

Oberhalbstein - Malenco

A relatively good understanding of the progressive metamorphism of the peridotitic rocks occurring in the Davos-Oberhalbstein-Malenco profile (Fig. 3) has emerged from a number of recent studies (de Quervain, 1963; Peters, 1963, 1968; Dietrich, 1969; Evans and Trommsdorff, 1970; Dietrich und Peters, 1971; Trommsdorff and Evans, 1972; Bucher und Pfeifer, 1973). Despite evidence for polyphase alpine metamorphism (Dietrich et al. 1974), a continuous increase in grade is recognizable from north to south. In addition, within a contact aureole around the Bergell granitoids, a further

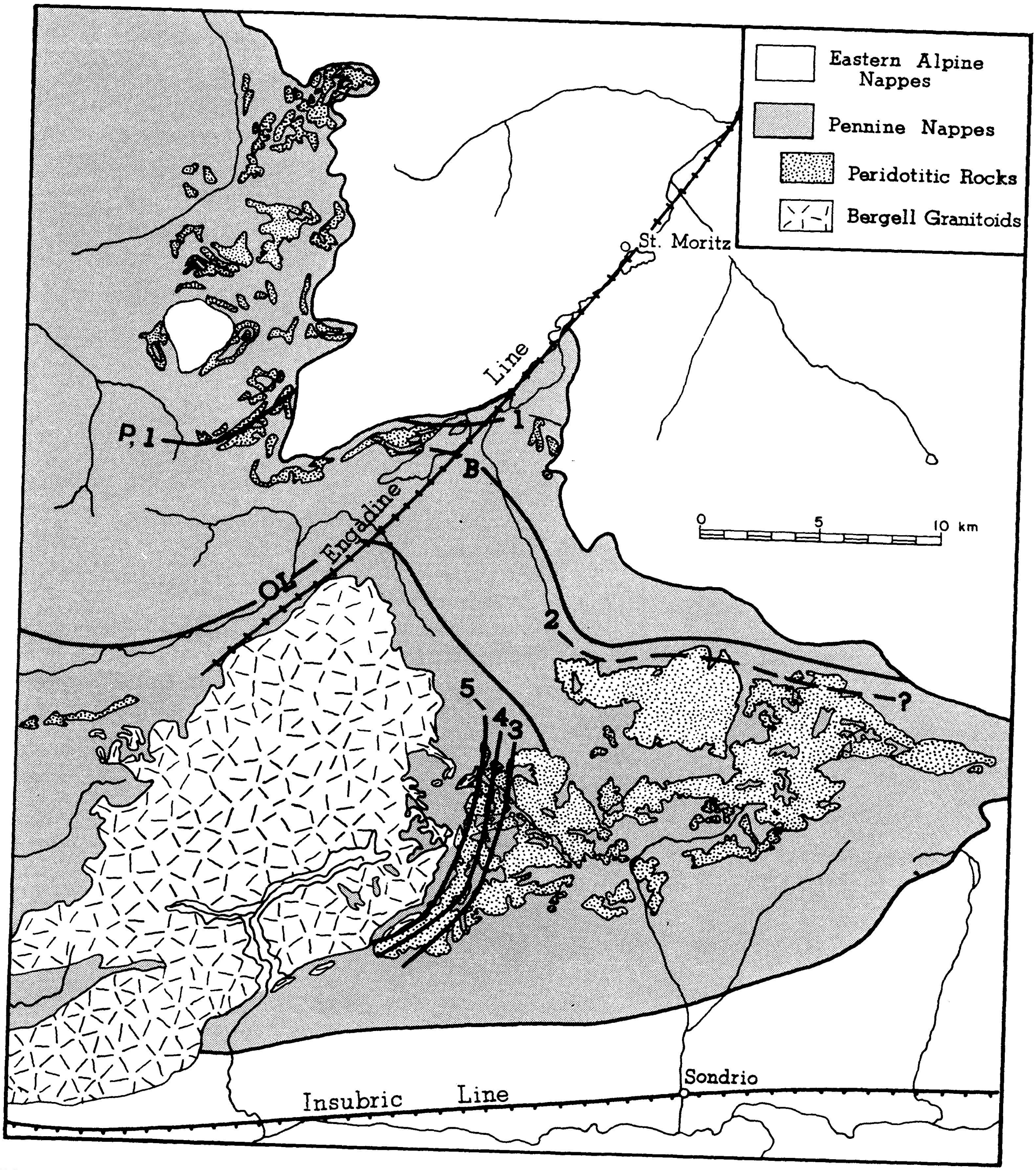


Fig. 3. Isograds in the Oberhalbstein-Malenco area. P = pumpellyite "out"; OL = oligoclase "in"; B = biotite "in". Numbers 1 to 5 refer to reactions in text.

increase in metamorphic grade is overprinted on the regional metamorphic Malenco antigorite schist.

At low grades, serpentine minerals coexist with brucite over a wide area free of metamorphic olivine. Between Davos and Oberhalbstein, the prehnite-pumpellyite facies gives way to greenschists (containing pumpellyite and actinolite). The transition from chrysotile/lizardite to antigorite in serpentinite rocks proceeds along a relatively well-defined boundary close to the upper limit of pumpellyite (Dietrich, 1969; Dietrich and Peters, 1971). Olivine, often in the form of porphyroblasts, enters a small distance above the biotite isograd, and thus is found in rocks of suitable composition throughout most of the Malenco mass. In compositions rich in normative olivine (Fig. 2) (or containing modal olivine), diopside is the stable Ca-phase everywhere and is typically found as clear needles and prisms overgrown on old, dusty clinopyroxene (Plate I A). Although at least two generations of antigorite are found in places, and retrogressive brucite + antigorite forms from olivine (Bucher and Pfeifer, 1973), the stable association of the main alpine regional metamorphic event in the Malenco area is diopside + olivine + antigorite + chlorite + magnetite. Progressive contact metamorphism of this assemblage up to reaction (6) takes place in the Bergell aureole.

The nature of the regional metamorphism within the Malenco area may be regarded as a model for the metamorphism of serpentinite in the Zermatt/Saas Fee/Aosta area (Bearth, 1967; Dal Piaz, 1967; Wetzel, 1972). Both areas share distinctive ultramafic rock and vein mineral assemblages and textures, including accessories such as titanoclinohumite (Carpanese, 1933; de Quervain, 1938), ilmenite, and perovskite. The blueschist facies metamorphism in the Western Alps is, however, not shared by the Malenco area.

Lepontine belt

Over most of the Alps, regional metamorphism of serpentinite went little beyond reaction (2), i. e. the diopside + antigorite + olivine zone. In the late alpine metamorphic events in the Lepontine belt, however, conditions up to the sillimanite + potash feldspar grade were reached.

Studies during the last 15 years have established isograds and mineral zone boundaries (Figs. 4 to 9) in pelitic (staurolite, sillimanite, Niggli, 1970, p. 18), metabasic and metacarbonate rocks (oligoclase, Wenk, 1970, p. 40; tremolite + dolomite + calcite and diopside + calcite + quartz, Trommsdorff, 1972), distributed about an elongate high grade core between Valle della Mera and Val Antigorio. A corresponding, continuous increase in grade is recorded (Figs. 4 to 9) for rocks of peridotitic composition, reaching in the inner belt at least reaction (7), i. e. a tremolite + spinel + enstatite + olivine zone.

The compilation of Figs. 4 to 9 incorporates, in addition to our own samples, material from a number of other collections (Gruetter, 1929; Knup, 1958; Blattner, 1965; Wieland, 1966; Reinhardt, 1966). Schistose antigorite-rich rocks continue to occur well inside the staurolite zone (Preiswerk, 1901; Gruetter, 1929; Keusen, 1972), almost as far as the diopside + calcite + (quartz or dolomite) isograd. The breakdown of antigorite is quite sharply

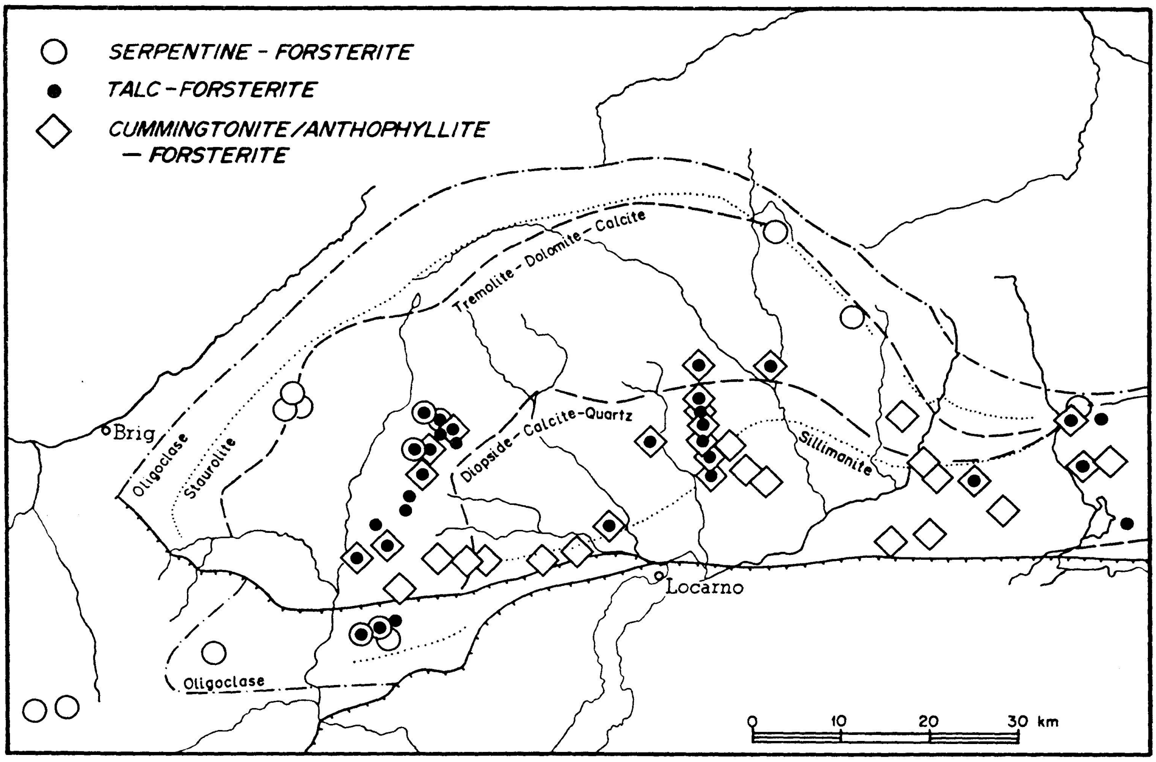


Fig. 4. Regional occurrence of the assemblages serpentine + olivine, talc + olivine and cummingtonite/anthophyllite + olivine in the Lepontine Alps.

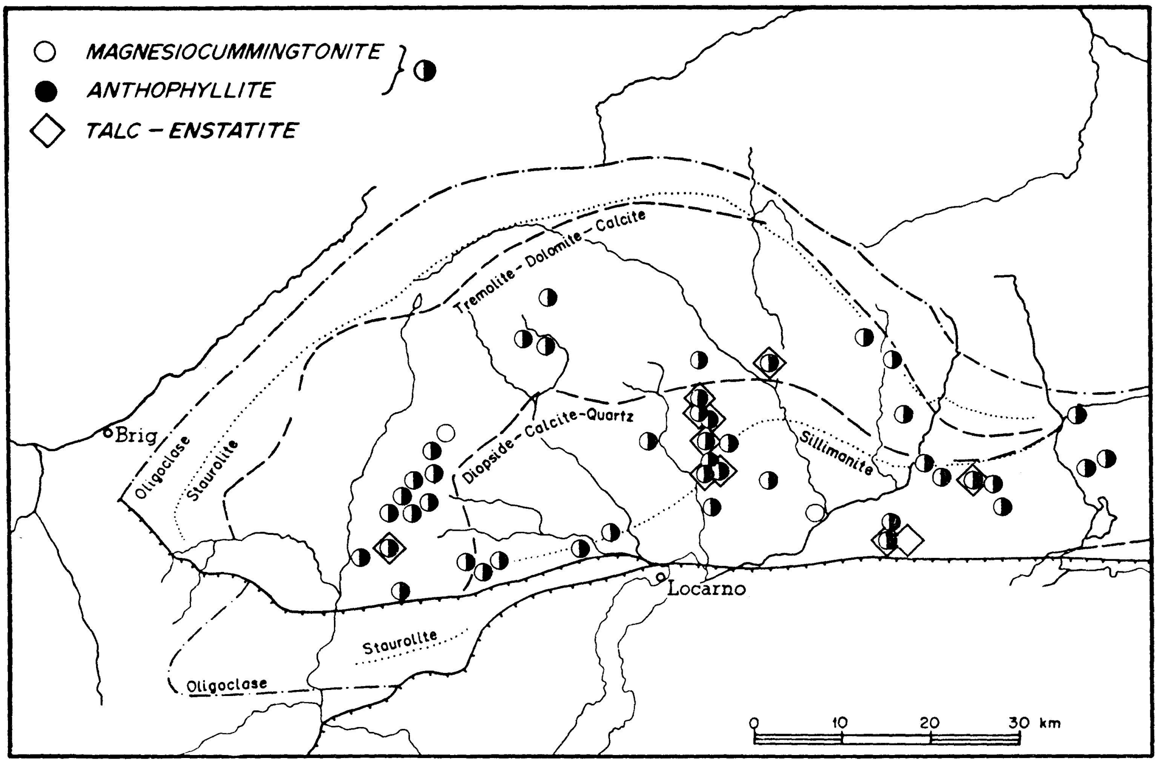


Fig. 5. Regional occurrence of magnesiocummingtonite, anthophyllite, and talc + enstatite in the Lepontine Alps.

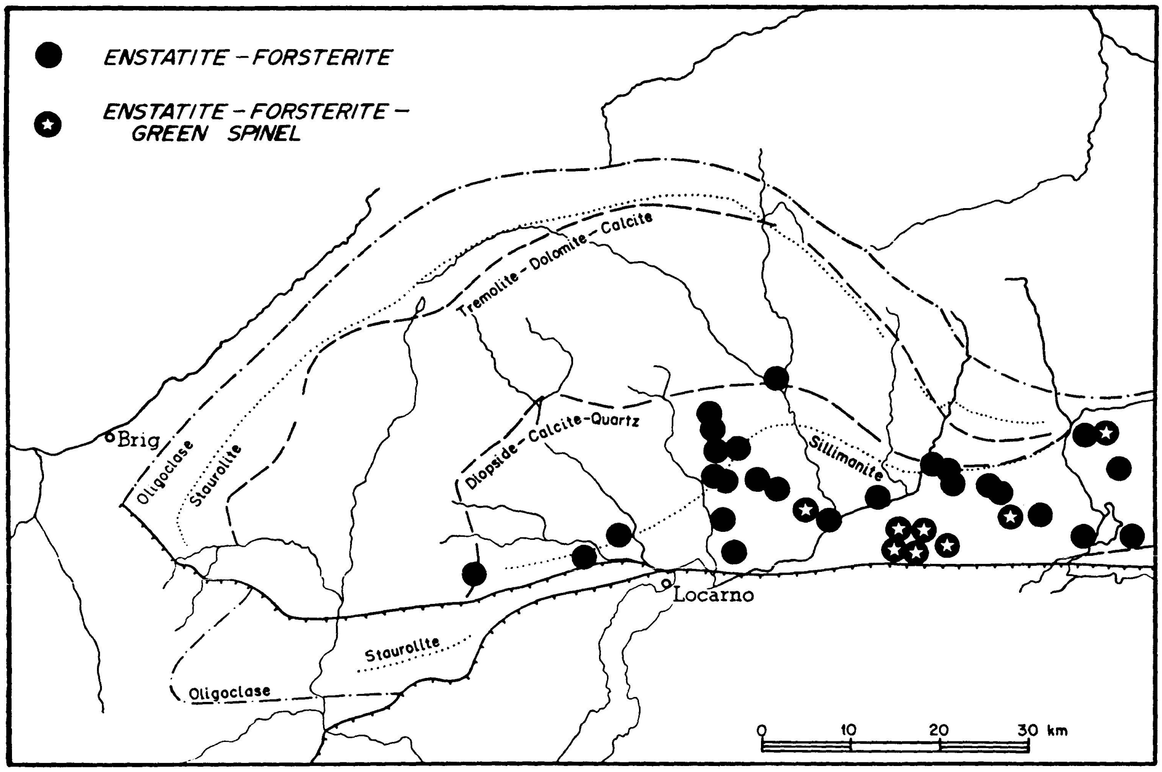


Fig. 6. Regional occurrence of enstatite + olivine and enstatite + olivine + green spinel in the Lepontine Alps.

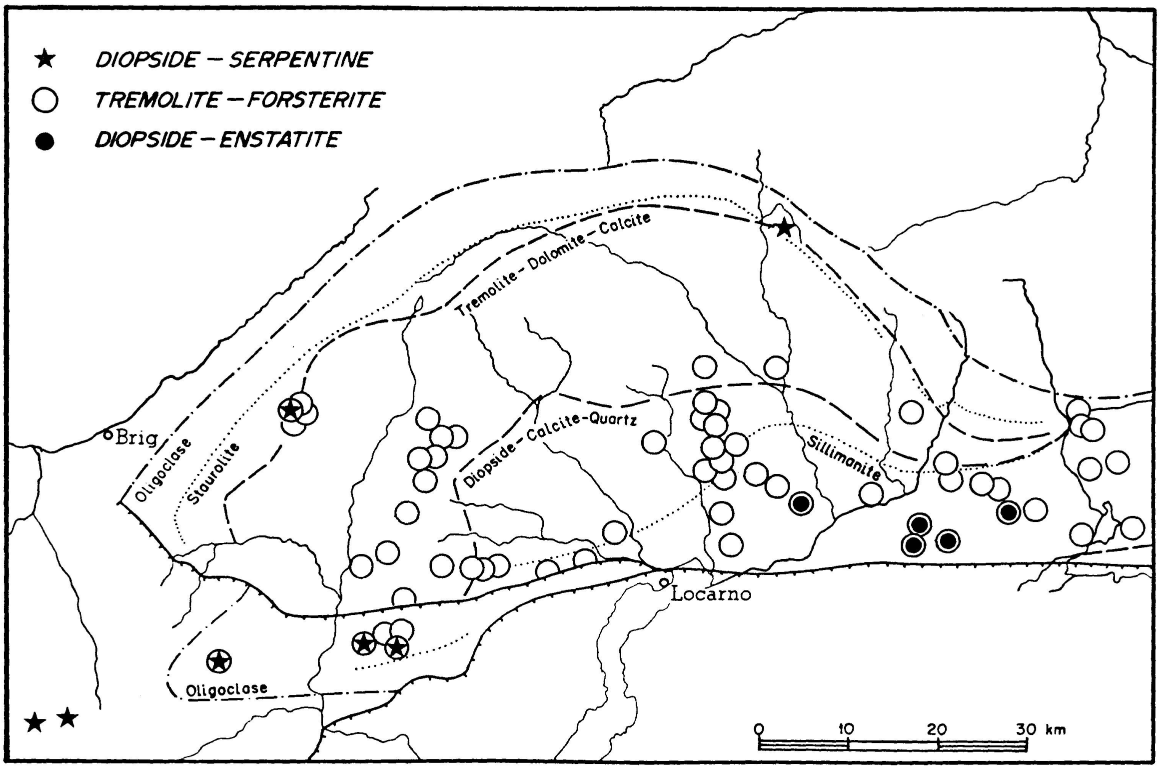


Fig. 7. Regional occurrence of diopside + serpentine, tremolite + olivine and diopside + enstatite in the Lepontine Alps.

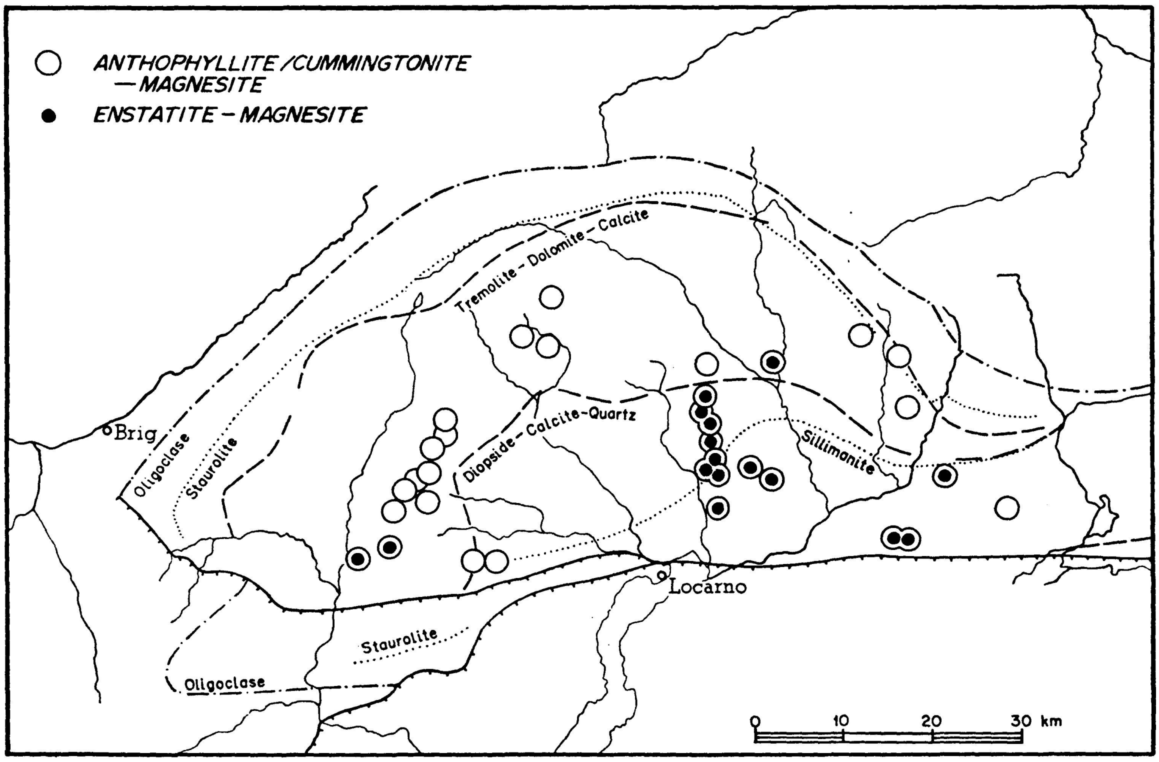


Fig. 8. Regional occurrence of anthophyllite/cummingtonite-magnesite and enstatite + magnesite in the Lepontine Alps.

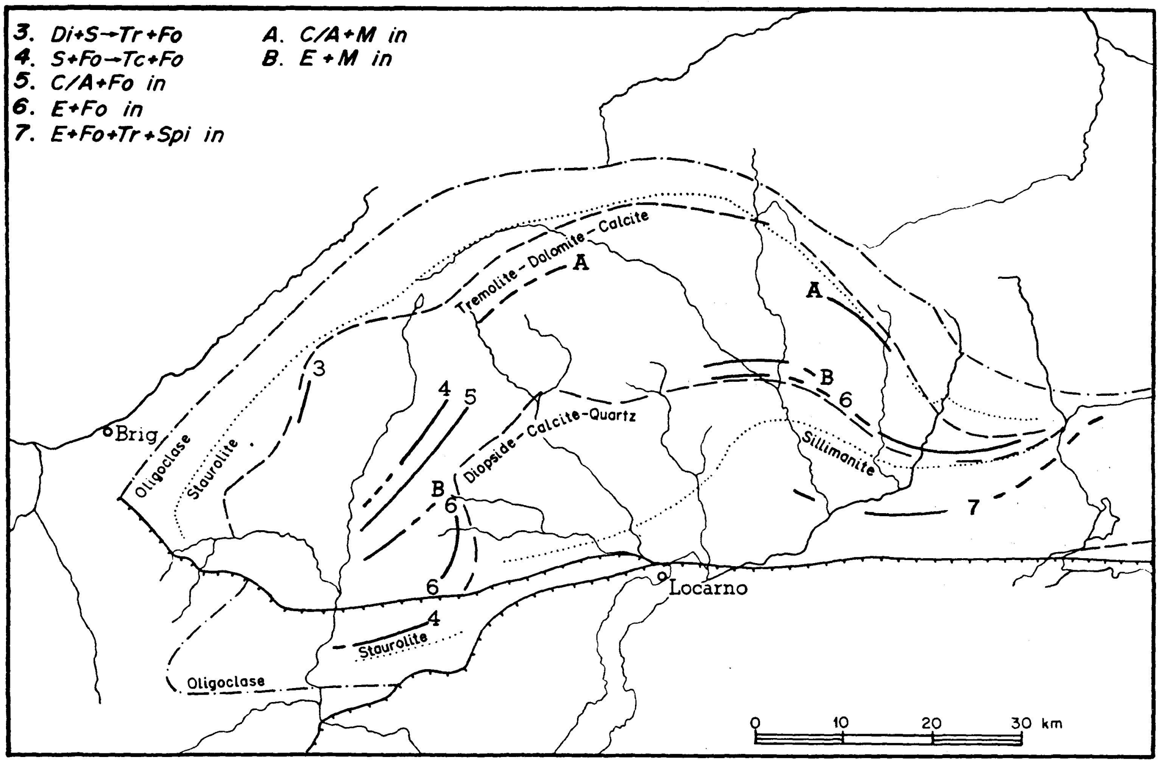


Fig. 9. Summary of isograds in ultramafic schists in the Lepontine Alps. Abbreviations for minerals: A, anthophyllite; C, cummingtonite; Di, diopside; E, enstatite; Fo, forsterite; M, magnesite; S, antigorite; Spi, green spinel; Tc, talc.

defined; in the Bosco Gurin area (Plate I, DIETRICH et al., 1974), olivine and talc overgrow a micro-folded schistosity formed by antigorite, magnetite, and chlorite (Plate IC). Thus, antigorite is stable to considerably higher temperatures than is generally assumed for serpentine (see also TROMMSDORFF and EVANS, 1972). Temperatures as high as 550–600° C may be inferred from the relationship between antigorite breakdown and the other isograds, including the outer limit of late alpine migmatites (WENK, 1970).

The pair talc + olivine is found up to the highest grades, although there it is reduced in amount and often demonstrably retrogressive (the latter have been omitted from Fig. 4). More significant, therefore, is the entry of the pair olivine + magnesiocummingtonite (5), only shortly above the talc + olivine isograd (4). In contrast, the pair talc + olivine possesses a wide ($\approx 200°$ C) stability range in the synthetic system MgO-SiO_2-H_2O (BOWEN and TUTTLE, 1949; GREENWOOD, 1963; SCARFE and WYLLIE, 1967). In addition to the effect that antigorite has on reaction (4), the closeness of isograds (4) and (5) and the overlap of talc and magnesio-cummingtonite in olivine-bearing rocks may be due to two additional factors. These are local differences in pore fluid composition (principally the proportions of H_2O and CO_2) and variation in Fe/Mg ratio. GREENWOOD (1967) and JOHANNES (1969) have shown experimentally that calcium-poor amphibole + olivine in a CO_2-rich fluid can occur at the same P and T as talc + olivine in the presence of H_2O-rich fluid. The influence of Fe on reaction (5) may be calculated from the relation $\frac{d \log K}{d(1/T)} = -\frac{\Delta H°}{2.303\,R}$ using standard reaction enthalpy and partitioning data in EVANS and TROMMSDORFF (1973). Relative to the synthetic system, reaction (5) for rocks with X_{Mg} (olivine) = 0.9, X_{Mg} (Mg-amphibole) = 0.888 ± 0.01 and X_{Mg} (talc) = 0.976 ± 0.003 is lower by $37 \pm 10°$ C (cf. TROMMSDORFF and EVANS; 1972, p. 433–434). Lowering will increase to approximately 60° C for the most iron-rich ultramafic rocks in the region. Thus, the Fe/Mg effect contributes to the early incoming of cummingtonite + olivine, but it does not obviate the need to infer the presence of generally more CO_2-rich fluids at these grades of metamorphism. That CO_2-rich-fluids were commonly present in the ultramafic rocks is witnessed by the frequent occurrence of cummingtonite/anthophyllite + magnesite and enstatite + magnesite (Fig. 8).

Magnesiocummingtonite is almost invariably intergrown with anthophyllite, its presumed inversion product. A comparison of Fig. 5 with Fig. 4 shows that cummingtonite without olivine extends to lower grades than with olivine. If anthophyllite is correctly interpreted as the lower temperature form, this observation severely restricts the stability field for natural anthophyllite + olivine parageneses in magnesian rocks.

The pair talc + enstatite, related to Ca-poor amphibole by:

$$\text{talc} + 4\ \text{enstatite} = \text{Ca-poor amphibole} \qquad (10)$$

is also widespread (Fig. 5), although not as common as magnesiocummingtonite/anthophyllite. Their relative distributions are believed not to reflect variations in P or T, but to be due to the stabilization of the left-hand side of (10) by higher $Mg/(Mg+Fe^{2+})$ ratios (EVANS and TROMMSDORFF, 1973).

At grades above the diopside + calcite + (quartz or dolomite) isograd, the pair enstatite + olivine becomes dominant and continues to occur up to the highest grades. Although the maps indicate a wide overlap with olivine + magnesiocummingtonite, rocks containing the latter assemblages in the enstatite + olivine zone are restricted in amount. Variable fluid compositions may again be the explanation for the overlap, but also alpine polymetamorphism is evident from crystallization – deformation relationships; despite widespread occurrence of postkinematic mosaic-textured enstatite + olivine + chlorite schist (TROMMSDORFF and EVANS, 1969), enstatite is found in places to be broken, kinked, and recrystallized along cracks. Such synkinematic crystallization of enstatite is particularly evident from rotated S-shaped inclusions of olivine and opaque oxide S-surfaces (Plate I E).

Relative to the pure Fe-free system, reaction (6) for X_{Mg} (olivine) $= 0.9$, X_{Mg} (Mg-amphibole) $= 0.888 \pm 0.01$ and X_{Mg} (enstatite) $= 0.907 \pm 0.005$ is *higher* by $11 \pm 10°C$ ($\Delta H°$ and partitioning data from EVANS and TROMMSDORFF, 1973). Thus, the overlap in this case cannot be ascribed to bulk composition variation.

Enstatite and olivine in ultramafic schists of the Lepontine Alps are frequently more magnesian and their modal ratio (enstatite/olivine) higher than in magmatic ultramafic rocks of equivalent bulk composition. This fact is probably due to oxidation during metamorphism (TROMMSDORFF and EVANS, 1969), related to the reaction:

$$\underset{\text{fayalite component}}{3\,Fe_2SiO_4} + 1/2O_2 = \underset{\text{ferrosilite component}}{3\,FeSiO_3} + \underset{\text{magnetite component}}{Fe_3O_4} \qquad (11)$$

The first readily detected reaction involving the Al_2O_3-component is the breakdown of chlorite to yield green spinel (Fig. 6), as shown by the idealized equation (7). This reaction is, in fact, a continuous one, with spinel (sensu lato) and chlorite of variable composition (p. 347) coexisting over the entire enstatite + olivine zone. Green spinel, as shown on Fig. 6, obviously indicates the highest grade zone. The alternative assemblage for ultramafic compositions, olivine + cordierite + enstatite (FAWCETT and YODER, 1966), was not found (see also WENK, H. R. et al., 1974, this volume).

Fig. 7 summarizes mineral parageneses in CaO-containing ultramafics. Reaction (3) is readily bracketed in the Geisspfad serpentinite (KEUSEN, 1972) and along the Zermatt/Antrona profile. In both regions, it occurs inside the staurolite isograd. Although searched for, the pair olivine + tremolite (right-hand side of (3)), was not found in the serpentinite of Val Carassina, which is in the narrow zone where chloritoid and staurolite coexist (Egli, 1966; Frey, 1969, p. 143).

Tremolite and olivine then coexist throughout the Lepontine belt into the highest grade zones. Their breakdown reaction may not be as simple as indicated by (8), because of solid solution of Al and other components in the amphibole at high temperatures. Although points for diopside-enstatite have been inserted on Fig. 7, there is not yet convincing textural proof for alpine crystallization of these diopsides. It may be noted, however, that diopside at Borgo, Val Darengo (Blattner, 1965) is undeformed and in mosaic equilibrium with enstatite + olivine. Furthermore, relics of earlier, higher Al-diopside do not survive much beyond the tremolite + olivine isograd.

Fig. 9 summarizes the information in Figs. 4 to 8, insofar as it can be incorporated into clearly defined isograds. The positions of the ultramafic isograds relative to those in rocks of other composition remain consistent throughout the region. In order of increasing grade, the sequence is: A, 4, 5, B, 6, 7, where numbers refer to reactions listed earlier and A and B delimit two significant ophicarbonate assemblages. Only 3 and 4 mark relatively narrow zones in which there is minimal overlap between reactant and product assemblages. All other lines represent the *entry* of a product assemblage.

MINERAL CHEMISTRY

In Table 1 are assembled typical analyses (microprobe) of metamorphic magnesium-rich silicates from pennine ultramafics. Up to and including the enstatite + olivine zone, chlorite is the only silicate mineral to show clear evidence of systematic compositional variation with metamorphic grade (see below). Although little data are available yet, enstatite, tremolite (and spinel) rapidly increase in Al-content within the spinel-olivine-enstatite zone. In addition, antigorite shows major variations in Al-content, but the reason for this is not yet fully known.

Iron/magnesium ratios vary as a function of bulk rock composition, degree of oxidation, and the nature of the coexisting minerals. Olivine and orthopyroxene, for example, are found to range in $Fe^{2+}/(Fe^{2+}+Mg)$ ratio from 4.5% to 15%. The lower values of this ratio serve to discriminate metamorphic olivine and orthopyroxene from their igneous counterparts. In addition, in talc + olivine schists, the percentage NiO relative to % Fo in olivine is distinctly low, due to talc's equal preference for Ni with olivine. Otherwise the chemistry of olivine does not differ from that of plutonic igneous olivine. Orthopyroxene and low-grade diopside (see also Peters, 1968) exhibit a degree of purity which clearly sets them aside from pyroxenes of igneous

Table 1. *Some Typical Ultramafic Mineral Compositions*

	1	2	3	4	5	6	7	8	9	10
SiO_2	40.4	41.1	40.8	57.8	55.1	58.1	58.5	62.1	42.5	33.9
TiO_2	—	—	—	—	a)	0.05	0.01	a)	—	—
Al_2O_3	b)	b)	b)	0.02	c)	0.53	0.06	b)	2.1	12.2
Cr_2O_3	—	—	—	a)	0.02	0.05	0.01	0.01	0.25	3.07
FeO e)	9.09	9.67	8.85	6.18	0.91	2.25	8.5	1.29	3.21	2.80
MnO	0.33	0.11	0.18	0.23	0.02	0.08	0.19	0.01	0.04	0.02
MgO	49.8	49.2	49.5	35.5	18.2	23.9	29.6	31.5	39.9	35.3
NiO	0.43	0.23	0.40	0.07	0.05	0.10	0.18	0.27	0.22	0.23
CaO	b)	b)	0.01	0.08	25.7	12.6	0.49	0.02	b)	0.01
Na_2O	—	—	—	—	a)	0.20	a)	—	—	—
K_2O	—	—	—	—	b)	0.02	a)	—	a)	—
H_2O d)	—	—	—	—	—	2.20	2.20	4.70	—	12.7
	100.05	100.31	99.74	99.88	100.00	100.08	99.74	99.90	88.22	100.23

a) $< 0.01\%$ b) $< 0.02\%$ c) $< 0.03\%$ — not determined
d) stoichiometrie H_2O e) Total iron as FeO

1. Olivine in chlorite-diopside-antigorite schist, 123a, Trommsdorff and Evans 1972, Table 3.
2. Olivine in chlorite-talc-olivine schist, 30 B, Evans and Trommsdorff, 1973, Table 3.
3. Olivine in chlorite-cummingtonite-tremolite-enstatite-olivine schist, 31 A, Rice, Evans, and Trommsdorff, 1974, Table 3.
4. Orthopyroxene in chlorite-cummingtonite-tremolite-enstatite-olivine schist, 31 F, Rice, Evans, and Trommsdorff, 1974, Table 3.
5. Diopside in chlorite-diopside-antigorite-olivine schist, 123a, Trommsdorff and Evans, 1972, Table 7.
6. Tremolite in chlorite-cummingtonite-tremolite-olivine schist, 32, Rice, Evans and Trommsdorff, 1974, Table 2.
7. Magnesiocummingtonite in chlorite-enstatite-tremolite-cummingtonite schist, 31 B, Rice, Evans, and Trommsdorff, 1974, Table 2.
8. Talc in chlorite-talc-olivine schist, 30 A, Evans and Trommsdorff, 1972, Table 4, $F \leqq 0.02\%$, $Cl \leqq 0.01\%$.
9. Antigorite in chlorite-diopside-antigorite-olivine schist, 123a, Trommsdorff and Evans, 1972, Table 4. $F \geqq 0.02\%$, $Cl \geqq 0.01\%$.
10. Chlorite in chlorite-talc-olivine schist, 30 A, Evans and Trommsdorff, 1973, Table 5.

origin. Alumina, TiO_2, alkalis, and, in orthopyroxene, CaO, are quite distinctive in this respect. Work in progress suggests that % Al_2O_3 in orthopyroxene in olivine + chlorite + spinel parageneses may be a sensitive indicator of metamorphic temperature.

Unless coexisting with anthophyllite, magnesiocummingtonite is not chemically distinguishable from the former (Rice, Evans and Trommsdorff, 1974). The Ca-poor amphiboles have the distinction of being the most iron-rich of all the coexisting ultramafic silicate minerals.

Chlorite is the only Mg-silicate that accomodates appreciable amounts of Cr and Al. In a contact aureole in the Washington Cascades, a systematic increase in Al^{IV} in chlorite associated with olivine was found (Frost, 1973). At chlorite's breakdown, a maximum of 2.4 Al^{IV} per 8 tetrahedral sites is reached. Similar relationships can be expected for regional metamorphic chlorites in alpine ultramafics.

Over the metamorphic range encountered, elements are partitioned con-

Table 2. *Average Distribution Coefficients K_D*

	En	Cumm/ Anth	Antig	Talc	Chlor	Trem	Di
			Iron				
Ol	0.96	1.2	0.47	0.22	0.45	0.37	0.29
En		1.3	—	0.24	0.48	0.45	—
Cumm/Anth			—	0.18	0.38	0.33	—
Antig				—	—	0.68	0.62
Talc					1.9	1.8	—
Chlor						0.8	—
Trem							0.8
			Magnesium				
Ol	1.05	0.83	2.2	4.1	2.2	2.7	3.5
En		0.77	—	3.8	2.0	2.2	—
Cumm/Anth			—	5.1	2.6	2.9	—
Antig				—	—	1.4	1.6
Talc					0.6	0.6	—
Chlor						1.2	—
Trem							1.2
			Manganese				
Ol	1.8	3	0.18	0.1	0.2	0.7	0.4
En		1	—	0.1	0.1	0.4	—
Cumm/Anth			—	0.0x	0.0x	0.4	—
Antig				—	—	2.5	2
Talc					1.5	7	—
Chlor						10	—
Trem							0.7
			Nickel				
Ol	0.21	0.44	0.65	1.0	0.9	0.6	0.3
En		2	—	5.5	4.2	3	—
Cumm/Anth			—	2.5	1.7	1.2	—
Antig				—	—	0.9	0.5
Talc					0.8	0.7	—
Chlor						0.7	—
Trem							0.5

$$K_D(\text{Fe}) = \frac{X_{\text{Fe}}\,(\text{row})\,(1 - X_{\text{Fe}}\,(\text{column}))}{(1 - X_{\text{Fe}}\,(\text{row}))\,X_{\text{Fe}}\,(\text{column})}$$

and other K_Ds are similarly defined. Fe is total iron. Because different rocks have been used for different mineral pairs, each table is not entirely internally consistent. The other half of each table is the inverse of the half given. The metamorphic grade of different pairs is, of course, variable. Sources of data: TROMMSDORFF and EVANS (1969), TROMMSDORFF and EVANS (1972), EVANS and TROMMSDORFF (1973) and RICE, EVANS and TROMMSDORFF (1974).

sistently among the coexisting Mg-rich silicates. Table 2 lists average partition coefficients for Fe, Mg, Mn and Ni, four elements determined with good precision and accuracy. This table shows, for example, that the order of preference for Mg is: talc > diopside > tremolite > antigorite, chlorite > orthopyroxene > olivine > Ca-poor amphibole. Where there is no figure entered in the table, either that pair does not exist in equilibrium, e. g. diopside + talc, enstatite + antigorite, or the pair wasn't analyzed. For chromium relative to total octahedral cations, the order of preference is: chlorite > antigorite > tremolite >

Ca-poor amphibole > diopside > enstatite, talc > olivine. For aluminum, the sequence is chlorite > antigorite > tremolite > Ca-poor amphibole > enstatite > diopside, talc, olivine. For titanium and alkalis, it is tremolite > Ca-poor amphibole > all others. Table 2 can be used to show why a mineral, particularly if present in small amounts, may show unusual enrichment or impoverishment in any constituent, e. g. low Ni and high Mn in olivine coexisting with talc and antigorite respectively. Many of the K_Ds can be expected to be temperature sensitive (as well as composition sensitive), and, in a few pairs, this could reverse the order of preference. For example, a major change occures in partitioning of Fe and Mg between diopside and olivine when low temperature pairs are compared with high temperature ones (ONYEAGOCHA, 1973).

CONCLUSIONS

Metamorphism of peridotitic rocks in the pennine region between the Rhetic and Wallis Alps produced a consistent distribution of alpine mineral assemblages. In several places it has been possible to locate isograds with some degree of precision. These isograds are concordant with previously established isograds in rocks of different bulk chemistry. Textural observations indicate polyphase metamorphism, especially in the higher pennine nappes. However, in the Lepontine region, the main alpine crystallization mostly obliterated earlier assemblages. This main alpine metamorphism was largely progressive in character. Many of the higher grade bodies are believed to have originated from serpentinites.

The sequence of reactions found in experimental work in the system $MgO\text{-}SiO_2\text{-}H_2O$ for the most part corresponds to the *sequence* observed with increasing grade in the field. However, differences in sequence arise through two reactions that do not involve fluid:

(12) Magnesiocummingtonite = anthophyllite, an inversion which proceeds to the right-hand side with falling temperature, and

(13) talc + 4 enstatite = Ca-poor amphibole, an equilibrium which is strongly dependent on Fe/Mg ratios. The regional distribution of left-hand relative to right-hand assemblages is considered to be mainly a function of bulk rock chemistry.

The *spacing* of isograds poorly matches that of the corresponding equilibrium curves in $P = P_{H_2O}$ vs. T space for the system $MgO\text{-}SiO_2\text{-}H_2O$. In particular, a small distance separates the breakdown of antigorite to olivine + talc from the first appearance of Ca-poor amphibole + olivine, and from the first appearance of enstatite + olivine. This fact is ascribed in part to the higher thermal stability of antigorite relative to chrysotile (if true, this would also extend serpentine's stability to much higher CO_2-concentrations). Although Fe can advance the first appearance of amphibole + olivine, its effect on enstatite + olivine is, if anything, a slight retardation.

The overall pattern is believed to be due to regionally higher concentrations of CO_2 in the fluid phase attending metamorphism of the deeper seated ultramafics in the Lepontine region (EVANS and TROMMSDORFF, 1973). The alternate possibility that $P_{fluid} < P_{total}$ is unlikely by virtue of the ubiquitous fluid inclusions in the minerals of the ultramafics. Abundance of CO_2 in the fluid is indicated by the widespread occurrence of enstatite + magnesite and Ca-poor amphibole + magnesite up to the highest grades. These assemblages provide upper temperature limits (GREENWOOD, 1967; JOHANNES, 1969; EVANS and TROMMSDORFF, 1973), consistent with those previously inferred for the Lepontine region (e. g. JÄGER, NIGGLI und WENK, 1967) yet still lower than the breakdown of talc + forsterite in a pure H_2O fluid. The overlap of talc + olivine, cummingtonite + olivine, and enstatite + olivine, together with the extensive development of the latter assemblage, is thus readily explained.

For ophicarbonate rocks, a buffering path leading to high CO_2-concentrations is provided by the CO_2-liberating reaction: 1 talc + 5 magnesite = 4 olivine + $H_2O + 5\,CO_2$ (14). For the carbonate-free ultramafics, e. g. chlorite + enstatite + olivine schists, such buffering paths are not obvious, and an alternate still unknown mechanism for producing a CO_2-rich fluid phase may have operated.

Further departure from the synthetic system MgO-SiO_2-H_2O may be found in all equilibria in which participating phases contain major amounts of Al_2O_3. For example antigorite breaks down to talc + olivine + chlorite. Also, chlorite and Ca-amphibole undergo continuous breakdown reactions due to progressive enrichment in Al at high grades.

Literature

SMPM = Schweiz. Mineral. Petrogr. Mitt.

BEARTH, P. (1967): Die Ophiolithe der Zone von Zermatt-Saas-Fee. Beitr. Geol. Karte Schweiz, N.F. 132.

BLATTNER, P. (1965): Ein anatektisches Gneissmassiv zwischen Valle Bodengo und Valle di Livo (Prov. Sondrio und Como). SMPM 45, 973–1071.

BOWEN, N. L. and O. F. TUTTLE (1949): The System MgO-SiO_2-H_2O. Bull. Geol. Soc. Amer. 80, 1947–1960.

BUCHER, K. and H. R. PFEIFER (1973): Über Metamorphose und Deformation der östlichen Malenco-Ultramafitite und deren Rahmengesteine (Prov. Sondrio, N-Italien). SMPM 53, 231–241.

CARPANESE, T. (1933): Contributo alla conoscenza della titanolivina. Period. Min. 4, 339–372.

CORNELIUS, H. P. (1935): Geologie der Err-Julier-Gruppe, I. Teil. Beitr. Geol. Karte Schweiz, N.F. 70.

DAL PIAZ, G. V. (1967): Le «granatite» (rodingiti l.s.) nelle serpentine delli Alpi occidentali italiane. Mem. Soc. Geol. Ital. VI. 267–313.

DAL VESCO, E. (1953): Genesi e metamorfosi delle rocce basiche e ultrabasiche nell'ambiante mesozonale dell'orogene Pennidico. SMPM 33, 173–480.

DIETRICH, V. (1969): Die Ophiolithe des Oberhalbsteins (Graubünden) und das Ophiolithmaterial der ostschweizerischen Molasseablagerungen, ein petrographischer Vergleich. Dissertation ETH Zürich, Verlag Lang & Cie. AG, Bern.

DIETRICH, V. und PETERS, T. (1971): Regionale Verteilung der Mg-Phyllosilikate in den Serpentiniten des Oberhalbsteins. SMPM 51, 329–348.

DIETRICH, V., M. VUAGNAT and J. BERTRAND (1974): Alpine Metamorphism of Mafic Rocks. SMPM 54, 291–332.

EGLI, W. (1966): Geologisch-petrographische Untersuchungen in der NW Aduladecke und in der Sojaschuppe (Bleniotal, Kanton Tessin). Dissertation ETH Zürich, 159.

ERNST, W. G. (1973): Interpretative Synthesis of Metamorphism in the Alps. Bull. Geol.-Soc. Amer. 84, 2073–2078.

EVANS, B. W. and V. TROMMSDORFF (1970): Regional metamorphism of ultramafic rocks in the Central Alps: Parageneses in the system CaO-MgO-SiO_2-H_2O. SMPM 50, 481–492.

EVANS, B. W. and V. TROMMSDORFF (1974): Stability of Enstatite + Talc and CO_2-meta somatism of Metaperidotite, Val d'Efra, Lepontine Alps. Amer. Jour. Sci. 274, 274–296

FAWCETT, J. J. and H. S. YODER (1966): Phase relations of Chlorites in the System MgO-Al_2O_3-SiO_2-H_2O. Amer. Mineral. 51, 353–380.

FREY, M. (1969): Die Metamorphose des Keupers vom Tafeljura bis zum Lukmanier-Gebiet. Beitr. Geol. Karte Schweiz 137; 160 p.

FROST, B. R. (1973): Contact Metamorphism of the Ingalls Complex at Paddy-Go-Easy-Pass, Central Cascades, Washington. Ph. D. Thesis. University of Washington, Seattle, USA.

GREENWOOD, H. J. (1963): The synthesis and stability of anthophyllite. J. Petrology 4, 317–351.

GREENWOOD, H. J. (1967): Mineral equilibria in the system MgO-SiO_2-H_2O-CO_2, in Researches in Geochemistry, Abelson, P. H., ed. New York, London, Sydney, J. Wiley and Sons, 542–567.

GRUBENMANN, U. (1908): Der Granatolivinfels des Gordunotales und seine Begleitgesteine. Vjschr. Natf. Ges. Zürich, 53, 129–156.

GRUETTER, O. (1929): Petrographische und geologische Untersuchungen in der Region von Bosco (Valle Maggia), Tessin. Verh. Natf. Ges. Basel 40, 78–152.

HAENNY, R. (1972): Das Migmatitgebiet der Valle Bodengo (östliches Lepontin). Beitr. Geol. Karte Schweiz, N.F. 145, 109.

JÄGER, E., NIGGLI, E. und WENK, E. (1967): Rb-Sr-Altersbestimmungen an Glimmern der Zentralalpen. Beitr. Geol. Karte Schweiz, N.F. 134, 67.

JOHANNES, W. (1969): An Experimental Investigation of the system MgO-SiO_2-H_2O-CO_2. Amer. J. Sci. 267, 1083–1104.

KEUSEN, A. R. (1972): Mineralogie und Petrographie des metamorphen Ultramafitit-Komplexes vom Geisspfad (Penninische Alpen). SMPM 52, 385–478.

KNUP, P. (1958): Geologie und Petrographie des Gebietes zwischen Centovalli, Valle Vigezzo und Onsernonetal. SMPM 38, 83–238.

MERCOLLI, I. (1973): Il margine sud-occidentale delle serpentini della Valle Malenco. Diplomarbeit ETH Zürich.

MÖCKEL, J. R. (1969): Structural petrology of the garnet-peridotite of Alpe Arami (Ticino), Switzerland. Leidse geol. Meded. 42, 61–130.

NIGGLI, E. (1970): Alpine Metamorphose und alpine Gebirgsbildung. Fortschr. Mineral. 47, 16–26.

ONYEAGOCHA, A. C. (1973): Petrology and Mineralogy of the Twin Sisters dunite, Washington. Ph. D. Thesis. Univ. of Washington, Seattle, USA.

PETERS, TJ. (1963): Mineralogie und Petrographie des Totalpserpentines bei Davos. SMPM 43, 529–685.

PETERS, TJ. (1968): Distribution of Mg, Fe, Al, Ca, and Na in coexisting olivine, orthopyroxene and clinopyroxene in the Totalp Serpentinite (Davos, Switzerland) and the alpine metamorphosed Malenco Serpentinite (N. Italy). Contr. Min. Petrogr. 18, 65–75.

PREISWERK, H. (1901): Über Dunitserpentin am Geisspfadpass im Oberwallis. Dissertation Universität Basel.

QUERVAIN, F. DE (1938): Zur Kenntnis des Titanklinohumites (Titanolivin). SMPM 44, 513–517. SMPM 18, 591–604.

QUERVAIN, F. DE (1963): Die Erzmineralien des Serpentins von Selva-Quadrada (Puschlav). SMPM 43, 295–312.

REINHARDT, B. (1966): Geologie und Petrographie der Monte-Rosa-Zone, der Sesia-Zone und des Canavese zwischen Valle d'Ossola und Valle Loana (Prov. di Novara, Italien). SMPM 46, 569–694.

RICE, J. M., EVANS, B. W. and V. TROMMSDORFF (1974): Widespread Occurence of Magnesiocummingtonite in ultramafic schists, Cima di Gagnone, Ticino, Switzerland. Contr. Min. Petrol. 43, 245–251.

SCARFE, C. M. and P. J. WYLLIE (1967): Serpentine dehydration curves and their bearing on serpentine deformation in orogenesis. Nature 215, 945–946.

STAUB, R. (1922): Über die Verteilung der Serpentine in den alpinen Ophiolithen. SMPM 2, 78–149.

TROMMSDORFF, V. (1972): Change in T-X During metamorphism of siliceous dolomite rocks of the Central Alps. SMPM 52, 567–571.

TROMMSDORFF, V. and EVANS, B. W. (1969): The stable association Enstatite-Forsterite-Chlorite in Amphibolite Facies Ultramafics of the Lepontine Alps. SMPM 49, 325–332.

TROMMSDORFF, V. and EVANS, B. W. (1972): Progressive Metamorphism of antigorite schist in the Bergell tonalite aureole (Italy): Amer. J. Sci. 272, 423–437.

TRUEMPY, R. (1960): Paleotectonic Evolution of the Central and Western Alps. Bull. Geol. Soc., Amer. 71, 843–908.

WANG, H. C. (1939): Petrographische Untersuchungen im Gebiet der Zone von Bellinzona. SMPM 19, 21–199.

WENK, E. (1970): Zur Regionalmetamorphose und Ultrametamorphose im Lepontin. Fortschr. Miner. 47, 34–51.

WENK, E. and KELLER, F. (1969): Isograde in Amphibolitserien der Zentralalpen. SMPM 49, 157–198.

WENK, H. R., WENK E. and WALLACE, J. H. (1974): Metamorphic mineral assemblages in pelitic rocks of the Bergell Alps. SMPM 54, 507–554.

WETZEL, R. (1972): Zur Petrographie und Mineralogie der Furgg-Zone (Monte-Rosa-Decke), SMPM 52, 161–236.

WIELAND, H. (1966): Zur Geologie und Petrographie der Valle Isorno (Novara, Italia). SMPM 46, 189–303.

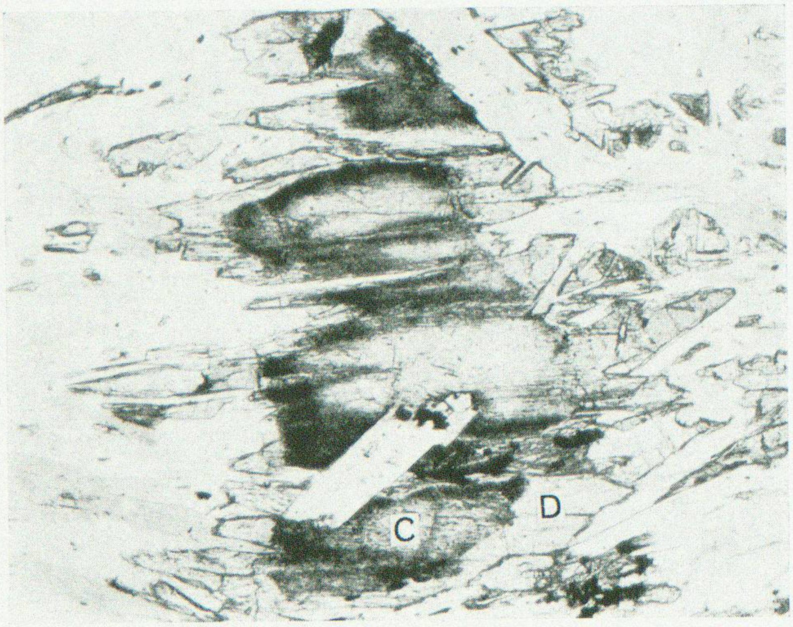
Manuscript received December 22, 1973.

Schweiz. Min. Petr. Mitt.
Volume 54, 2/3, 1974

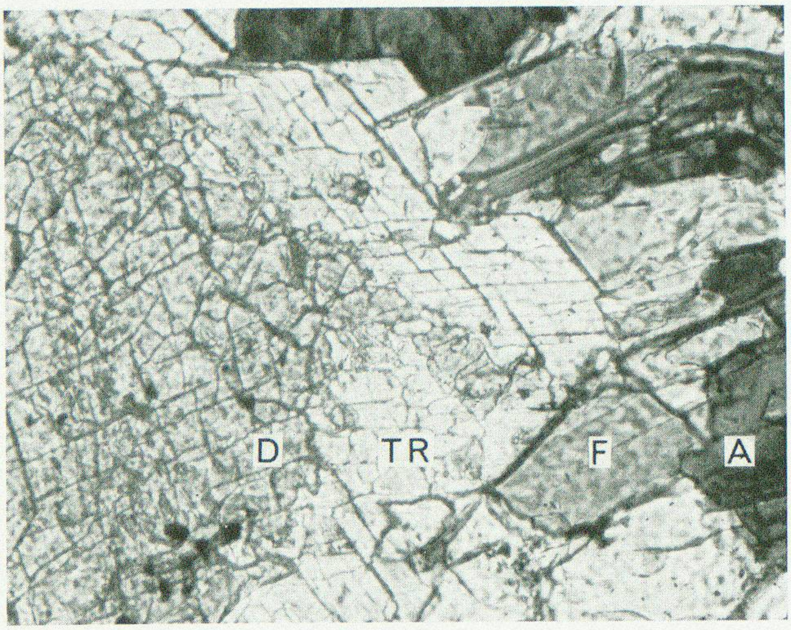
PLATE I

V. TROMMSDORFF and B. W. EVANS:
Alpine Metamorphism of Peridotitic Rocks

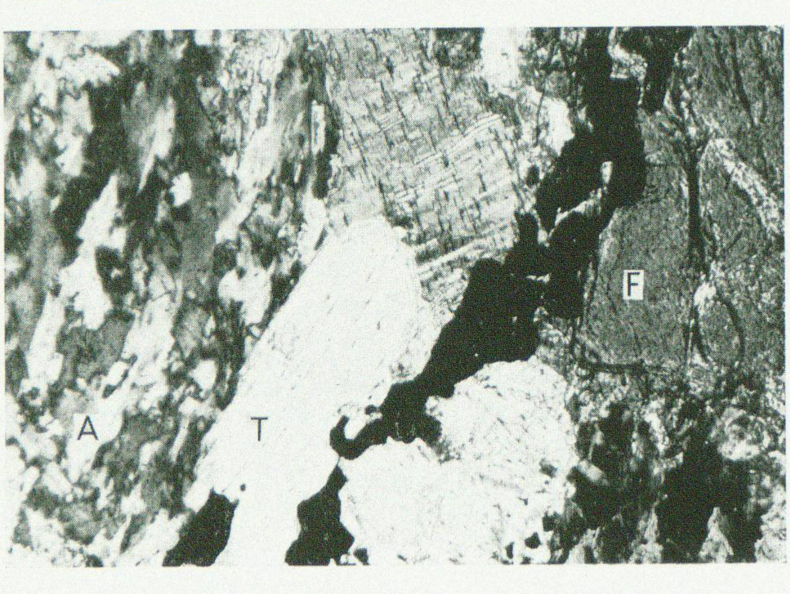
Photomicrographs of ultramafic mineral assemblages



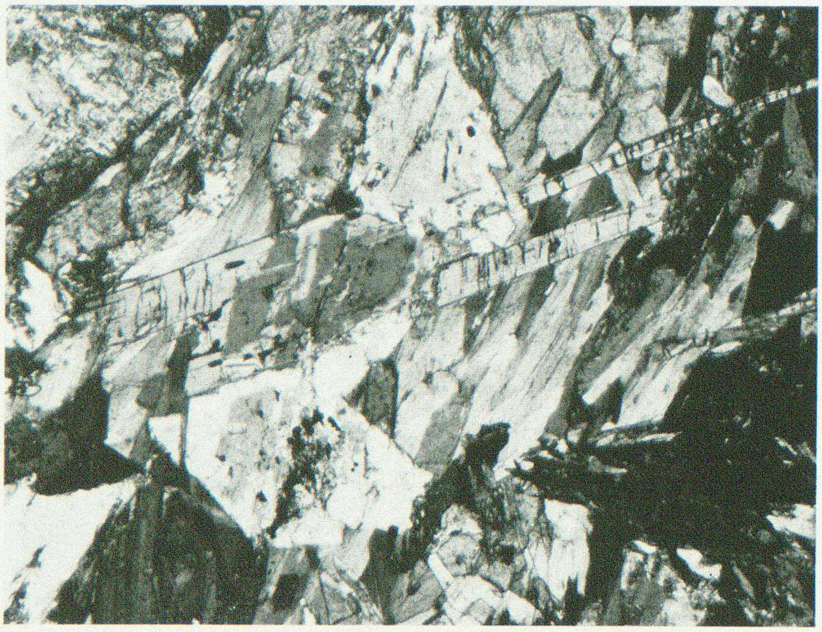
A Overgrowth of new metamorphic diopside (D) on old dusty clinopyroxene (C). Magnetite + chlorite + diopside + olivine + antigorite schist, Val Malenco, Italy. PPL, ×50.



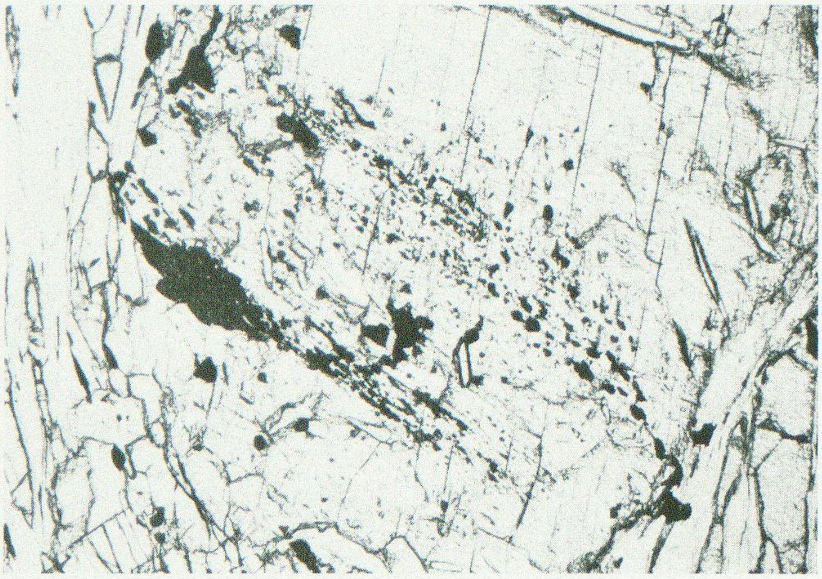
B Overgrowth of metamorphic tremolite (TR) on metamorphic diopside (D). Chlorite + magnetite + diopside + tremolite + olivine + antigorite schist, Val Malenco, Italy. PPL, ×60.



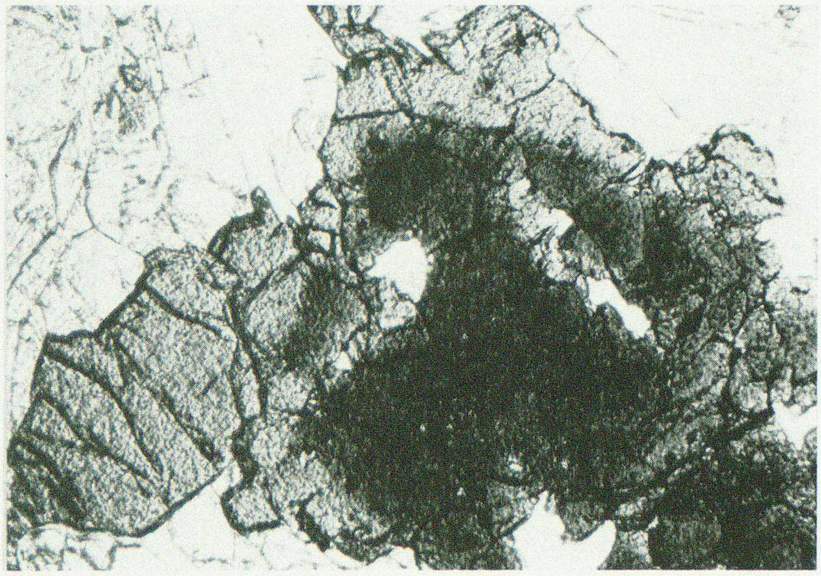
C Olivine and talc overgrowing schistose, microfolded antigorite magnetite fabric. Magnetite + antigorite (A) + talc (T) + forsterite (F) schist, Bosco Gurin, Ticino, Switzerland. Crossed Polarizers ×15.



D Magnesiocummingtonite with anthophyllite lamellae overgrown homoaxially on tremolite. Chlorite + tremolite + magnesite + talc schist, Val Verzasca, Ticino, Switzerland. Crossed Polarizers, × 30.



E Rolled enstatite enclosing pre-existing S-shaped S-surface of olivine and magnetite. Chlorite + magnetite + enstatite + olivine schist, Val Verzasca, Ticino, Switzerland. PPL, × 50.



F Zoned green spinel with tremolite and chlorite, chlorite + spinel + olivine + enstatite rock, Ganna Rossa, Ticino, Switzerland PPL, × 90.