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# High-pressure mineral assemblages and their breakdown-products in metasediments South of the Grossvenediger, Tauern Window, Austria

by *E. Dachs*<sup>1</sup>

## Abstract

Permomesozoic metasediments of Penninic series south of the Grossvenediger, Austria, have been studied along a cross-section.

Textures, mineral chemistry and metamorphic evolution of high-pressure relics and their breakdown-products in polymetamorphic metasediments closely associated with eclogitic rocks in the northern part of this cross-section ("Eclogite Zone") document a common metamorphic history of this area.

High-pressure mineral assemblages and their breakdown-products are:

in marbles: omphacite (jadeite<sub>31–33</sub>) → diopside → tremolite

omphacite → barrosite → actinolite + albite,

in garnet mica schists: omphacite (jadeite<sub>42–54</sub>) → symplectite

omphacite + kyanite → paragonite + zoisite/margarite ± symplectite

talc + phengite-I → biotite + chlorite + quartz

garnet + phengite-I → biotite + plagioclase

→ biotite + phengite-II + chlorite + calcite

kyanite + zoisite → margarite + quartz.

Lawsonite pseudomorphs (consisting of paragonite + zoisite + quartz), included in garnets of metasediments, were presumably formed at a metamorphic stage prior to the eclogite-facies metamorphism.

A minimum-pressure of  $12.5 \pm 0.5$  kb can be inferred from the coexistence of omphacite + quartz (temperature range 550–600°C). For the assemblage omphacite + kyanite + paragonite + zoisite/margarite ± symplectite and assuming a  $H_2O \sim 1$ , the pressure estimate is 20 kb, a similar value as derived for intercalated eclogites, by applying the equilibrium paragonite = jadeite + kyanite +  $H_2O$ .

This high-pressure event was followed by a strong uplift and reequilibration at 550°C/6–7 kb (Tertiary metamorphism). A compilation of all available PT-estimates documents the present knowledge of the PT-path of the high-pressure zone.

**Keywords:** Penninic metasediments, eclogites, metamorphic evolution, high-pressure metamorphism, Tauern window.

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### Zusammenfassung

Permomesozoische Metasedimente Penninischer Serien südlich des Grossvenediger, Österreich, wurden entlang eines Querschnittes untersucht.

Texturen, Mineralchemismus und die metamorphe Evolution von Hochdruck-Relikten und ihren Abbauprodukten aus polymetamorphen Metasedimenten, die eng assoziiert mit eklogitischen Gesteinen im Nordteil dieses Profils auftreten («Eklogit-Zone»), belegen eine gemeinsame metamorphe Geschichte dieses Gebietes.

Hochdruck-Paragenesen und ihre Abbauprodukte sind folgende:

in Marmoren: Omphacit (Jadeit<sub>31-33</sub>) → Diopsid → Tremolit

Omphacit → Barroisit → Aktinolith + Albit,

in Granatglimmerschiefern: Omphacit (Jadeit<sub>42-54</sub>) → Symplektit

Omphacit + Disthen → Paragonit + Zoisit/Margarit ± Symplektit

Talk + Phengit-I → Biotit + Chlorit + Quarz

Granat + Phengit-I → Biotit + Plagioklas

→ Biotit + Phengit-II + Chlorit + Calcit

Disthen + Zoisit → Margarit + Quarz.

Lawsonitpseudomorphosen in Granaten von Metasedimenten (bestehend aus Paragonit + Zoisit + Quarz) wurden wahrscheinlich vor der Eklogitfazies-Metamorphose gebildet.

Ein Minimaldruck von  $12.5 \pm 0.5$  kb lässt sich aus der Koexistenz von Omphacit + Quarz für dieses Ereignis ableiten (Temperaturbereich 550–600°C). Für die Paragenese Omphacit + Disthen + Paragonit + Zoisit/Margarit ± Symplektit und unter der Annahme  $a_{H_2O} \sim 1$ , ergibt sich bei der Anwendung des Gleichgewichts Paragonit = Jadeit + Disthen +  $H_2O$  eine Druckabschätzung von 20 kb und damit ein ähnlicher Wert, wie er aus benachbarten Eklogiten abgeleitet wurde.

Diesem Hochdruckereignis folgte eine starke Heraushebung und eine weitgehende, neuerliche Gleichgewichtseinstellung bei 550°C/6–7 kb (Tertiäre Metamorphose). Eine Zusammenstellung aller verfügbaren PT-Abschätzungen dokumentiert den gegenwärtigen Kenntnisstand über den PT-Pfad der Hochdruckzone.

### Introduction

Permomesozoic metasediments of the Tauern Window (TW) were involved in Alpine regional metamorphism. In the Penninic terrain exposed south of the Grossvenediger, a Cretaceous high-pressure event is well documented by the occurrence of eclogites, blueschists and high-pressure assemblages in metasediments of the "Eclogite Zone" (EZ, see MILLER, 1977, HOLLAND, 1979a, FRANZ & SPEAR, 1983, SPEAR et al., 1985, DACHS, 1985, FRANK et al., 1986). Estimates of peak-metamorphic conditions are about 20 kb, 550–600°C,  $a_{H_2O} \sim 1$  (eclogites).

After the overthrusting of the Austroalpine nappe pile, all units of the TW were affected by a Tertiary metamorphism, which largely obliterated the evidence of the earlier eclogite/blueschist-events. Various geothermometers and -barometers, as well as phase equilibria in Penninic rock suites along a cross-section south of the Grossvenediger, indicate an increasing grade for this younger metamorphic overprint, from 450–480°C at the TW-margin in the

south to 550°C / 6–7 kb in the central part near the base of the “Upper Schieferhülle” (USH, see HOERNES & FRIEDRICHSEN, 1974, HOSCHEK, 1982, DACHS, 1985).

The present paper concentrates on the high-pressure assemblages in meta-sediments, which occur in the EZ in the northern part of this cross-section (Dorfertal, Timmeltal).

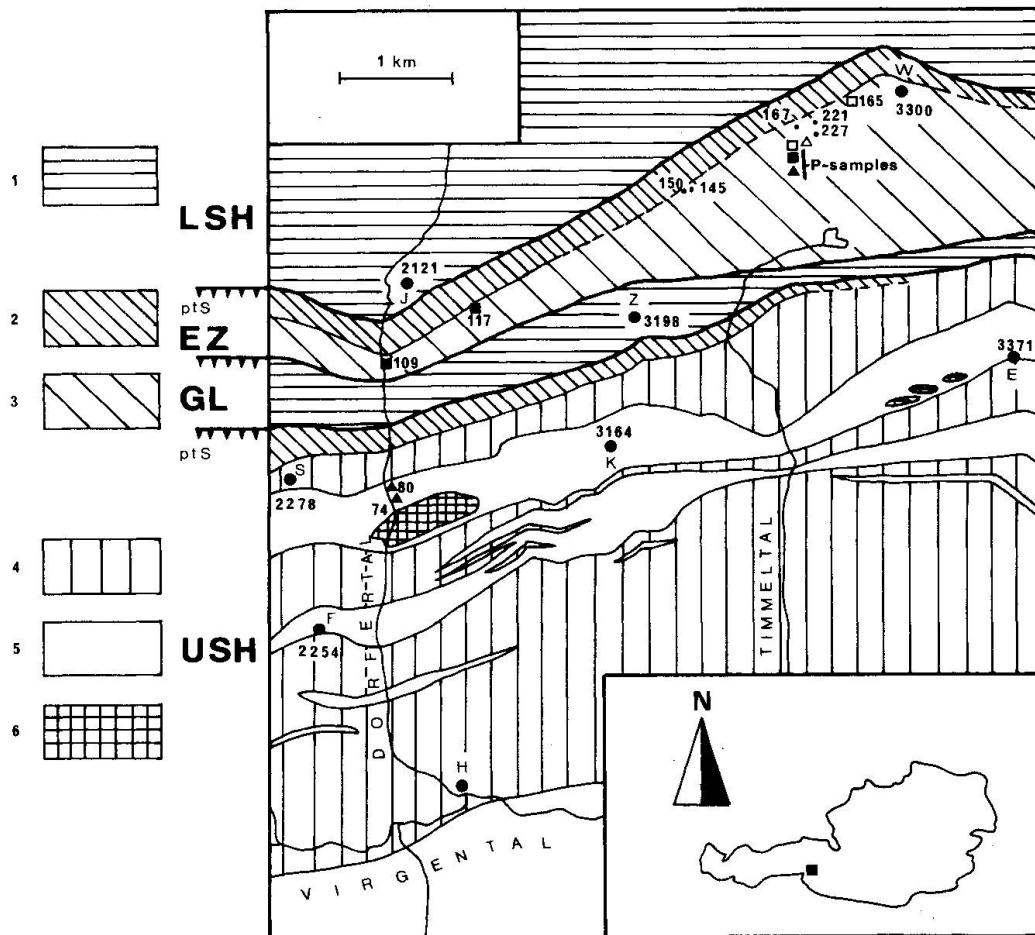


Fig. 1 Geological map of the southern Grossvenediger area (simplified after RAITH et al., 1980, and own results). Numbers give sample localities.

- 1: mainly paragneisses and mica schists of the LSH / paleozoic?
- 2: quartzites, garnet mica schists ( $\pm$  graphitic), marbles / permotriassic?
- 3: high pressure rocks of the EZ / jurassic-cretaceous?
- 4: greenschists (“prasinites”) of the USH;  $\pm$  garnet in the north / jurassic-cretaceous?
- 5: calc(carbonate-)mica schists ( $\pm$  garnet) of the USH (“Bündner schists”) / jurassic-cretaceous?
- 6: serpentinite of the USH / jurassic-cretaceous?
- ▼▼▼ thrust plane
- ▲ lawsonite pseudomorphs included in garnets of metasediments
- omphacite-relics in marbles
- omphacite relics in garnet mica schists
- △ talc-phengite in metasediments
- W = Weissspitze, Z = Zoppetspitze, J = Johannes-Hütte
- K = Kreuzspitze, E = Eichham, S = Schlüsselspitze, F = Finsterwitz, H = Hinterbichl.



### Geological setting

The area of study lies in the central part of the TW, south of the Gross-venediger. A geological map of the generally south dipping rocks, simplified after RAITH et al. (1980) and own results, is given in Fig. 1.

In the north rock series of the "Lower Schieferhülle" (LSH), or "Venediger nappe" (FRISCH, 1976), form the lowest tectonic unit. The Hercynian metamorphic rocks of the LSH are intruded by granodiorites and granites of Permian age ("Zentralgneis-cores"). A series of probably Permotriassic sediments (ptS) was deposited onto this basement complex. White marbles of this rocks unit are a striking feature beneath brown-coloured clastic metasediments in the north-ridge of the Weissspitze (3300 m).

Going further south we enter the EZ. It forms a narrow zone of high-pressure metamorphic rocks with its greatest thickness in the upper Timmeltal, then thinning out to the west and to the east. Metabasic eclogites and their retrograde derivatives (MILLER, 1977, HOLLAND, 1979a) occur in association with high-pressure metasediments, mainly calcareous rocks with gradations to garnet mica schists and quartzites (FRANZ & SPEAR, 1983, SPEAR et al., 1985, DACHS, 1985). Near the boundary of the underlying LSH, the eclogites outcrop as boudinaged, lenticular bodies of various extent, with sheared contacts to the enclosing metasediments (mainly calc mica schists). This basal horizon of the EZ could be a tectonic melange (MILLER, 1977, FRANZ & SPEAR, 1983).

Intact geological layering of eclogites and metasediments over considerable distances has on the other hand been preserved in the central EZ of the upper Timmeltal (RAITH et al., 1980, DACHS, 1985). The thickness of the eclogite-layers there (metabasalts and -tuffs) ranges from some 10 m down to a few cm and less. Small omphacite-symplectite layers and omphacite in marbles and garnet mica schists could represent tuffitic material transformed during the Eoalpine high-pressure event.

Due to lithological and geochemical affinities to the rocks of the USH (ABRAHAM et al., 1974, RAITH et al., 1977) or "Glockner-nappe" (FRISCH, 1976), the EZ is regarded as tectonically separated part of the USH.

To the south the EZ is in part overlain by a series of micaschists, metaarcoses, gneisses and subordinate garnet amphibolites. This "Glimmerschiefer-Lamelle" (GL), which separates the EZ in the north from the main body of the USH in the south, has been interpreted as a sheet of the LSH by RAITH et al. (1980). The GL is overlain by the clastic, Permotriassic, basal sequence of the USH, followed by a thick unit of Jurassic/Cretaceous age ("Bündner-schist series"), consisting of carbonate-rich schists, intercalated with prasinites, chlorite schists, amphibolitic metabasites and serpentinites.

**High-pressure assemblages and their breakdown-products in metasediments**

The observed high-pressure relics in metasediments and their breakdown-products are listed in Table 1. Sample localities are indicated in Figure 1. Selected mineral analyses of assemblages from Table 1 are compiled in Table 2.

*Tab. 1* High-pressure assemblages and their breakdown-products in metasediments of the EZ. Numbers in parenthesis refer to analyses of these phases given in Table 2.

| rock type                             | sample                                                                | high pressure relics (assemblages)                                                                                                             | breakdown products                                                                                                                                                             |
|---------------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| marble                                | P12<br>109<br>117                                                     | omph(1) <sup>1)</sup><br>omph-inclusion in zoned act (4)                                                                                       | dio(2), tre(3), dol, qz<br>barr(5), act(6), ab(7), cal                                                                                                                         |
| garnet mica<br>schist<br>+ quartzitic | P7, P8<br><br>165, 167<br>217<br><br>P7<br>P7, P14<br>165, 167<br>145 | omph (zoned in P8)<br>rim(8) - core(9)<br>omph - ky(10)<br>omph - ky<br><br>tc(12) - phe-I(13)<br>ky - zoi(14)<br>ga - phe-I(16)<br>ga - phe-I | sy (diopsidic pyroxen + ab-rich<br>pl ± actinolitic amph)<br>pa(11), ma, ± sy<br>pa, zoi, sy<br><br>bio, chl<br>ma(15), qz<br>bio(17), pl(18)<br>phe-II(19), bio(20), chl, cal |

<sup>1</sup> Mineral abbreviations: act = actinolite, ab = albite, amph = amphibole, ap = apatite, barr = barrosite, bio = biotite, cal = calcite, chl = chlorite, dio = diopside, dol = dolomite, ep = epidote, fes = Fe-sulfide, ga = garnet, gr = graphite, il = ilmenite, jd = jadeite, ky = kyanite, law = lawsonite, ma = margarite, omph = omphacite, pa = paragonite, phe = phengite, pl = plagioclase, qz = quartz, ru = rutile, sy = symplectite, tc = talc, tit = sphene, tur = turmaline, zoi = zoisite.

**MARBLES**

The marbles are medium to coarse grained rocks, with calcite as the dominant carbonate mineral. Dolomite is often completely lacking. Phyllosilicates (phengite-I with Si-values ranging from 6.63–6.94 per formula unit (pfu), related to 22 oxygen, phengite-II, a texturally younger mica phase with Si = 6.20–6.22 pfu, chlorite and/or phlogopite), quartz, tremolite, talc, albite, paragonite and a Fe-sulfide may be additional phases. In phlogopite-bearing marbles phengite-I shows the highest Si-contents (Si = 6.84–6.94 pfu).

*Omphacite* (30.5–32.5 mol% jadeite-component, acmite component < 5.5 mol%) forms

a) isolated clusters within the carbonate-matrix together with diopside, tremolite, dolomite, quartz. In this case a breakdown

(1) omphacite → diopside → tremolite,

involving Na-loss from the marble seems to have been operative.

b) Omphacite also occurs in a special marble type ("albite-tremolite-marble") with the paragenesis

actinolite-albite (anorthite-component < 1.3 mol%) ± calcite.

**Tab. 2a** Selected microprobe analyses of phases listed in Table 1. Mineralchemical data were obtained on an ARL-SEMQ electron microprobe at the Department of Mineralogy and Petrography, University of Innsbruck. Analysed natural minerals were used as standards and the data were corrected with the empirical Bence-Albee method. An attached energy dispersive system (KeVex) was used only for fast qualitative analyses. Mineral formulae of the amphiboles were calculated with a program of MOGESSIE & TESSADRI (1982), formulae of pyroxenes with total cations = 4.000 according to DIETRICH & PETRAKAKIS (1984).

| Nb. <sup>a</sup>               | 1     | 2     | 3      | 4     | 5      | 6      | 7     | 8           | 9            | 10    |
|--------------------------------|-------|-------|--------|-------|--------|--------|-------|-------------|--------------|-------|
| mineral                        | omph  | dio   | tre    | omph  | barr   | act    | ab    | omph<br>rim | omph<br>core | ky    |
| SiO <sub>2</sub>               | 55.75 | 55.10 | 56.81  | 56.29 | 52.98  | 55.79  | 67.84 | 57.54       | 55.42        | 36.28 |
| TiO <sub>2</sub>               | 0.01  | 0.00  | 0.00   | 0.00  | 0.02   | 0.00   | 0.00  | 0.02        | 0.05         | 0.00  |
| Al <sub>2</sub> O <sub>3</sub> | 8.71  | 3.29  | 1.49   | 7.95  | 5.52   | 0.59   | 19.00 | 12.14       | 11.37        | 63.40 |
| FeO <sup>b</sup>               | 0.56  | 0.86  | 0.45   | 3.01  | 4.21   | 5.13   | 0.12  | 1.89        | 7.02         | 0.09  |
| MnO                            | 0.06  | 0.06  | 0.00   | 0.07  | 0.02   | 0.25   | 0.00  | 0.00        | 0.31         | 0.04  |
| MgO                            | 13.17 | 16.96 | 25.69  | 12.03 | 21.16  | 22.47  | 0.07  | 9.77        | 6.52         | 0.00  |
| CaO                            | 15.62 | 20.16 | 10.99  | 15.17 | 9.03   | 12.32  | 0.22  | 11.97       | 10.22        | 0.00  |
| Na <sub>2</sub> O              | 5.27  | 2.11  | 1.29   | 5.33  | 3.09   | 0.05   | 11.79 | 7.10        | 8.66         | 0.00  |
| K <sub>2</sub> O               | 0.00  | 0.00  | 0.12   | 0.02  | 0.02   | 0.02   | 0.05  | 0.01        | 0.00         | 0.00  |
| F                              |       |       | -      |       | 1.22   | 0.81   |       |             |              |       |
| total <sup>c</sup>             | 99.15 | 98.54 | 96.84  | 99.87 | 98.31  | 98.84  | 99.09 | 100.44      | 99.57        | 99.81 |
| Si                             | 1.980 | 1.990 | 7.777  | 1.996 | 7.452  | 7.830  | 2.995 | 2.003       | 1.971        | 0.982 |
| Al <sup>IV</sup>               | 0.020 | 0.009 | 0.223  | 0.004 | 0.548  | 0.098  | 0.989 | 0.000       | 0.029        | 0.018 |
| Al <sup>VI</sup>               | 0.345 | 0.131 | 0.017  | 0.329 | 0.368  | 0.000  | 0.000 | 0.501       | 0.448        | 2.003 |
| Ti                             | 0.003 | 0.000 | 0.000  | 0.000 | 0.002  | 0.000  | 0.000 | 0.001       | 0.001        | 0.000 |
| Fe <sup>2+</sup>               | 0.000 | 0.000 | 0.052  | 0.047 | 0.496  | 0.602  | 0.004 | 0.055       | 0.034        |       |
| Fe <sup>3+</sup>               | 0.038 | 0.027 |        | 0.042 |        |        |       |             | 0.175        | 0.002 |
| Mn                             | 0.002 | 0.002 | 0.000  | 0.002 | 0.002  | 0.030  | 0.000 | 0.000       | 0.009        | 0.001 |
| Mg                             | 0.697 | 0.913 | 5.241  | 0.636 | 4.437  | 4.701  | 0.005 | 0.507       | 0.346        | 0.000 |
| Ca                             | 0.594 | 0.780 | 1.662  | 0.576 | 1.361  | 1.853  | 0.010 | 0.445       | 0.390        | 0.000 |
| Na                             | 0.363 | 0.148 | 0.342  | 0.367 | 0.843  | 0.014  | 1.009 | 0.479       | 0.597        | 0.000 |
| K                              | 0.000 | 0.000 | 0.021  | 0.001 | 0.004  | 0.004  | 0.003 | 0.000       | 0.000        | 0.000 |
| F                              |       |       | -      |       | 0.543  | 0.360  |       |             |              |       |
| OH                             |       |       | -      |       | 1.457  | 1.640  |       |             |              |       |
| tot. cat.                      | 4.019 | 4.000 | 15.335 | 4.000 | 15.513 | 15.130 | 5.015 | 3.991       | 4.000        | 3.007 |
| jd/X <sub>F</sub> /an          | 30.00 | 12.10 |        | 32.50 | 0.271  | 0.180  | 1.000 | 50.70       | 42.20        |       |
| ac                             | 3.50  | 2.70  |        | 4.20  |        |        |       | 0.00        | 17.50        |       |

<sup>a</sup> numbers refer to assemblages of Table 1 (numbers set there in parenthesis)

<sup>b</sup> total iron as FeO, except Fe<sub>2</sub>O<sub>3</sub> in zoisite and plagioclase

<sup>c</sup> total corrected for O = F

tot. cat. = total cations; - not determined

jd = mol% jadeite-component in pyroxenes

X<sub>F</sub> = F/(F + OH) in analyses with fluorine

an = mol% anorthite-component in plagioclase

ac = mol% aegirine-component in pyroxenes

The *actinolite* is discontinuously zoned in some cases with an amphibole of barroisitic composition in the core, which may contain omphacite as inclusion. In this case omphacite was decomposed according to a simplified reaction

Tab. 2b

| Nb. <sup>a</sup>               | 11    | 12    | 13    | 14    | 15    | 16    | 17    | 18    | 19     | 20    |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------|-------|
| mineral                        | pa    | tc    | phe-I | zoi   | ma    | phe-I | bio   | pl    | phe-II | bio   |
| SiO <sub>2</sub>               | 45.89 | 60.72 | 50.67 | 39.12 | 29.74 | 52.37 | 38.15 | 63.17 | 46.40  | 36.22 |
| TiO <sub>2</sub>               | 0.09  | 0.00  | 0.17  | 0.02  | 0.00  | 0.25  | 1.36  | 0.00  | 0.10   | 0.09  |
| Al <sub>2</sub> O <sub>3</sub> | 40.28 | 0.67  | 28.10 | 32.97 | 50.76 | 25.79 | 19.12 | 22.47 | 32.72  | 19.54 |
| FeO <sup>b</sup>               | 0.10  | 3.35  | 0.90  | 0.77  | 0.37  | 1.56  | 12.60 | 0.30  | 2.49   | 16.47 |
| MnO                            | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.07  | 0.00  | 0.00   | 0.11  |
| MgO                            | 0.23  | 30.87 | 4.13  | 0.13  | 0.70  | 4.77  | 14.43 | 0.48  | 1.78   | 12.81 |
| CaO                            | 0.41  | 0.05  | 0.01  | 25.16 | 10.66 | 0.00  | 0.18  | 3.00  | 0.01   | 0.03  |
| Na <sub>2</sub> O              | 7.33  | 0.13  | 0.65  | 0.02  | 1.56  | 0.30  | 0.15  | 9.31  | 0.55   | 0.12  |
| K <sub>2</sub> O               | 0.56  | 0.01  | 9.47  | 0.01  | 0.02  | 10.56 | 8.82  | 0.21  | 9.95   | 8.82  |
| F                              | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | -     | -     | -      | -     |
| total <sup>c</sup>             | 94.89 | 95.80 | 94.10 | 98.20 | 93.81 | 95.60 | 94.88 | 98.94 | 94.00  | 94.21 |
| Si                             | 5.887 | 7.784 | 6.762 | 2.969 | 4.002 | 6.934 | 5.587 | 2.817 | 6.285  | 5.462 |
| Al <sup>IV</sup>               | 2.113 | 0.101 | 1.238 | 0.031 | 3.998 | 1.066 | 2.413 | 1.181 | 1.715  | 2.538 |
| Al <sup>VI</sup>               | 3.976 |       | 3.181 | 2.918 | 4.050 | 2.959 | 0.887 |       | 3.506  | 0.935 |
| Ti                             | 0.009 | 0.000 | 0.017 | 0.001 | 0.000 | 0.025 | 0.151 | 0.000 | 0.010  | 0.010 |
| Fe <sup>2+</sup>               | 0.011 | 0.359 | 0.100 |       | 0.042 | 0.173 | 1.543 | 0.011 | 0.282  | 2.078 |
| Fe <sup>3+</sup>               |       |       |       | 0.049 |       |       |       |       |        |       |
| Mn                             | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.009 | 0.000 | 0.000  | 0.014 |
| Mg                             | 0.044 | 5.838 | 0.821 | 0.015 | 0.140 | 0.941 | 3.149 | 0.032 | 0.359  | 2.880 |
| Ca                             | 0.056 | 0.007 | 0.001 | 2.046 | 1.537 | 0.000 | 0.028 | 0.143 | 0.002  | 0.005 |
| Na                             | 1.823 | 0.032 | 0.168 | 0.003 | 0.407 | 0.077 | 0.043 | 0.805 | 0.144  | 0.035 |
| K                              | 0.096 | 0.002 | 1.612 | 0.001 | 0.003 | 1.784 | 1.648 | 0.012 | 1.719  | 1.697 |
| F                              | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -     | -     | -      | -     |
| OH                             | 4.000 | 4.000 | 4.000 | 1.000 | 4.000 | 4.000 | -     | -     | -      | -     |
| tot.cat.                       | 14.02 | 14.18 | 13.90 | 8.03  | 14.18 | 13.96 | 15.46 | 5.00  | 14.02  | 15.65 |
| an                             |       |       |       |       |       |       |       | 15.00 |        |       |

(2a) omphacite + H<sub>2</sub>O + CO<sub>2</sub> → barroisite + albite + calcite  
and in a second step

(2b) barroisite ± calcite → actinolite + albite,

with the paragenesis actinolite + albite as final product.

#### GARNET MICA SCHISTS

Common rock constituents are phengite-I (Si = 6.50–6.93 pfu), garnet and quartz. Varying amounts of paragonite, zoisite, kyanite, plagioclase and talc may be present as additional phases. Accessories are rutile, sphene, apatite, Fe-sulfide and graphite.

Textural evidence suggests that phengite-II (Si = 6.12–6.29 pfu), margarite, chlorite, biotite and plagioclase (anorthite component < 26 mol%) are break-down-products.

Dispersed grains of omphacite may occur in these rocks. Omphacite also forms clusters, or distinct mm- to cm-size layers, aligned with the foliation. In the garnet mica schists omphacite and kyanite are always mantled by symplectitic breakdown-products.

*Omphacite* is generally homogeneous. The jadeite-content varies between 42.2 and 54 mol%. The acmite-component is less than 2 mol% (in one sample a discontinuously zoned omphacite was detected, with 17.5 mol% acmite-component in the core).

In the fine grained *symplectites* sodic plagioclase forms intergrowths with diopsidic pyroxene and/or actinolitic amphibole.

Maximum  $\text{Fe}_2\text{O}_3$  in *kyanite* is 0.6 wt%.

The following simplified breakdown-reactions can be deduced from the observed phase relations in the omphacite-bearing portions of the garnet mica schists:

- (3) omphacite +  $\text{H}_2\text{O}$  → symplectite (diopsidic pyroxene + albite-rich plagioclase ± actinolitic amphibole),
- (4) omphacite + kyanite +  $\text{H}_2\text{O}$  → paragonite + zoisite/margarite ± symplectite.

Other assemblages indicative for high-pressure metamorphism of the metapelites are (Table 1):

talc-phengite (Si = 6.76 pfu)

kyanite-zoisite (CHATTERJEE, 1976, CHATTERJEE et al., 1984, STORRE & NITSCH, 1974).

Coexisting talc + phengite are typical for high-pressure metapelites in the Gran Paradiso area (CHOPIN, 1981).

South of the Grossvenediger this assemblage has only been found in the phengite-paragonite-quartz matrix of sample P7, where rims of biotite + chlorite suggest the following breakdown-reaction:

- (5) talc + phengite-I → biotite + chlorite + quartz.

Kyanite and zoisite have been observed to break down according to

- (6) kyanite + zoisite → margarite + quartz.

*Margarite* contains little muscovite-component (< 0.43 mol%), but up to 29.9 mol% paragonite-component in solid solution and an average of 0.6 wt% MgO and 0.57 wt% FeO.

*Paragonite* contains 2.5–13.7 mol% muscovite-component and 0.5–3.8 mol% margarite component in solid solution. Only minor amounts of Fe and Mg (0.13–1.14 wt% FeO, 0.15–0.45 wt% MgO) were detected.

| sample | mineral constituents                                                                                             | zoning type |
|--------|------------------------------------------------------------------------------------------------------------------|-------------|
| 74 USH | phe-I, pa, qz, ga(ctd, ap, pa, zoi, qz), dol, cal, bio, zoi/ep, chl, pl                                          | 2           |
| 80 USH | qz, phe-I, cal, dol, ga(pa, zoi, qz, ru, chl, phe, ap, tit), pa, zoi, chl                                        | 3           |
| 145 EZ | phe-I, qz, ga(qz, phe, ru, chl), bio, chl, zoi, cal, tur, ru, fes                                                | 3           |
| 150 EZ | phe-I, qz, ga(qz, ctd, ru), bio, chl, pa, pl, il, ru, fes                                                        | 1           |
| 165 EZ | phe-I, qz, ga(qz, chl, ru), bio, zoi, pl, chl, omph, sy, ru, ap                                                  | 2           |
| 167 EZ | ga(qz, pl, chl), phe-I, qz, pl, pa, chl, bio, ab, act, tc, ru, ti                                                | 1           |
| 221 EZ | ga(ctd, pa, zoi, qz, chl, ru, ap), phe-I, qz, pa, ky, chl, ma, zoi, ru, il, fes                                  | 2           |
| 227 EZ | phe-I, qz, ga(qz, phe, bio, gr), bio, tit, zoi, ru, gr                                                           | 2           |
| P3 EZ  | ga(qz, phe, ru, il, chl), phe-I/II, qz, chl, pa, zoi, cal, dol, ap, ru, tit, gr                                  | 3           |
| P4 EZ  | ga(qz, phe, ru), phe-I, zoi, qz, bio, ru, tit, ap, gr                                                            | 3           |
| P7 EZ  | ga(zoi, pa, qz, ru, fes), phe-I/II, tc, pa, zoi, ky, qz, chl, pl, bio, omph, sy, ma, cal<br>fes, ru, tit, ap, gr | 3           |
| P8 EZ  | phe-I, ga(qz, ru, zoi, omph), zoi(omph), qz, bio, omph-I/II, sy, chl, pl, ru, fes                                | 2           |
| P14 EZ | ga(ctd, qz, phe, ru), phe-I, zoi, qz, ky, pa, ma, bio, ru, ap                                                    | 3           |
| P16 EZ | phe-I, ga(qz, ctd, pa, chl, gr, ru, fes), qz, pa, zoi, chl, bio, ru, gr, fes, cal, dol                           | 2           |

In the studied samples garnet + phengite-I very rarely show any signs of reaction. Narrow rims of biotite + plagioclase surrounding phengite-I and garnet indicate a similar type of reaction. A fine grained reaction-zone of phengite-II, biotite, chlorite and calcite between garnet and phengite-I points to another breakdown-reaction.

*Garnet* chemistry and zoning was analysed in 14 samples (various types of garnet mica schists) from the EZ and the USH (mineral constituents of these samples and the observed garnet zoning type, as discussed in the text, are listed in Table 3, whereas the variation of garnet core- and -rim-composition is given in Table 4).

All garnets are continuously zoned and three types of zoning may be distinguished (Figure 2a, b, c).

*Tab. 4* Variation of garnet composition expressed in terms of the almandine-, pyrope-, grossular- and spessartine component (mol%), analysed in carbonate-poor and in carbonate-rich garnet mica schists and in garnet mica schists containing omphacite-relics. r = rim; c = core.

| rock type              |   | garnet mica schist<br>carbonate-poor    | garnet mica schist<br>carbonate-rich | garnet mica schist<br>with omph-relics |
|------------------------|---|-----------------------------------------|--------------------------------------|----------------------------------------|
| almandine              | r | 48.8 - 75.7                             | 58.4 - 65.0                          | 47.7 - 56.1                            |
|                        | c | 51.2 - 74.7                             | 70.0 - 76.7                          | 51.2 - 66.9                            |
| pyrope                 | r | 6.4 - 34.7                              | 5.3 - 8.8                            | 20.5 - 35.2                            |
|                        | c | 3.0 - 18.0                              | 4.4 - 4.9                            | 4.7 - 19.4                             |
| grossular              | r | 8.9 - 27.2                              | 26.6 - 31.0                          | 14.3 - 22.1                            |
|                        | c | 8.7 - 22.2                              | 16.4 - 24.0                          | 14.5 - 19.5                            |
| spessartine            | r | 0.3 - 3.7                               | 0.9 - 2.2                            | 0.2 - 0.6                              |
|                        | c | 1.9 - 18.6                              | 1.4 - 5.9                            | 5.8 - 20.6                             |
| zoning type            |   | 1, 2, 3                                 | 2,3                                  | 2,3                                    |
| observed in<br>samples |   | 145, 150, 167, 221<br>227, P4, P14, P16 | 74, 80, P3                           | 165, P7, P8                            |

*Type 1* is restricted to samples without carbonate- or zoisite-minerals and is similar to the zoning of eclogite-garnets (MILLER, 1977). Examples of this type are shown in Figure 2a in the diagrams of sample P5 (retrograde altered eclogite) and sample 150 (garnet mica schist, EZ).

(Mn + Ca) are enriched in the core with simultaneous Mg-minimum. Towards the rim (Mn + Ca) decrease in a bell-shaped curve, whereas Mg increases continuously. Fe behaves antipathetic to Mn: an increase from core to rim, compensating the (Mn + Ca)-depletion is followed by two maxima, as soon as Mn has reached low concentrations. Near the rim Fe decreases.

Due to inclusions in garnets with a zoning similar to type 1 (chlorite, epidote, amphibole, albite in the core, omphacite, kyanite near the rim) increasing PT-



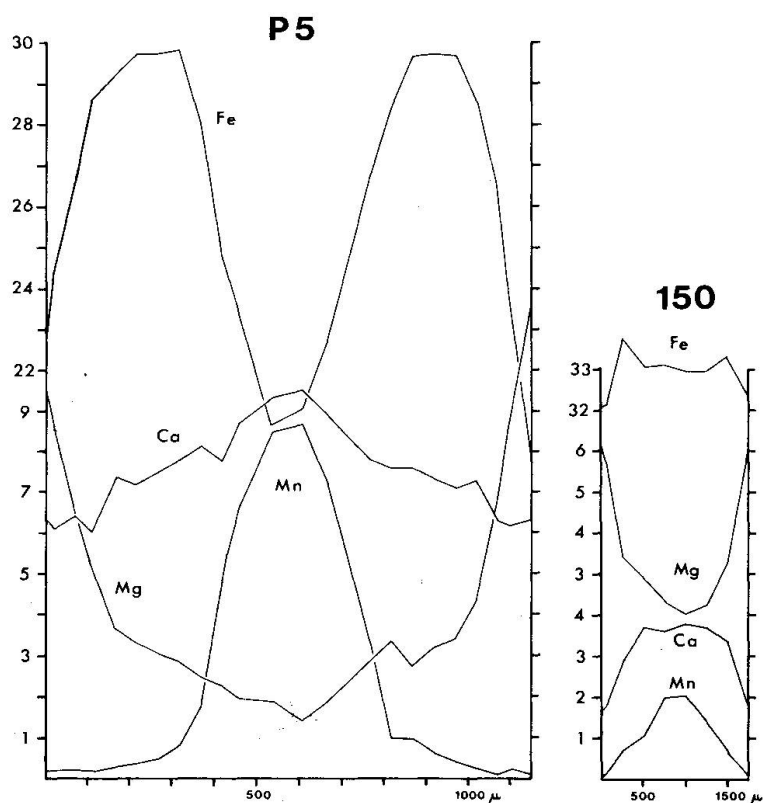
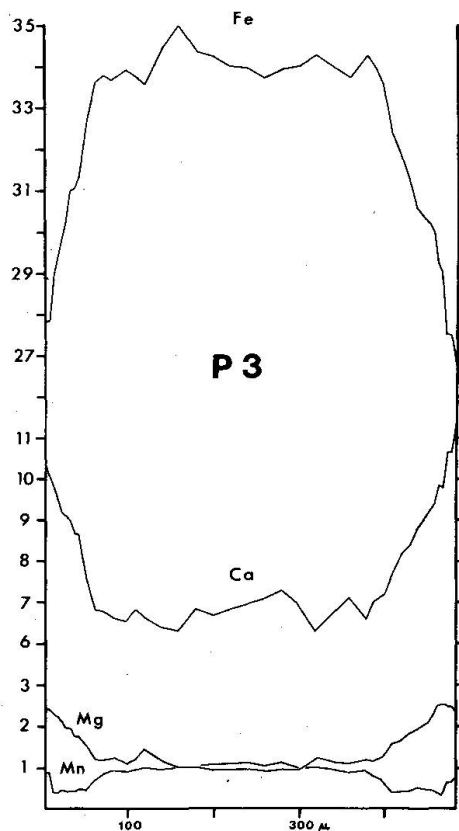
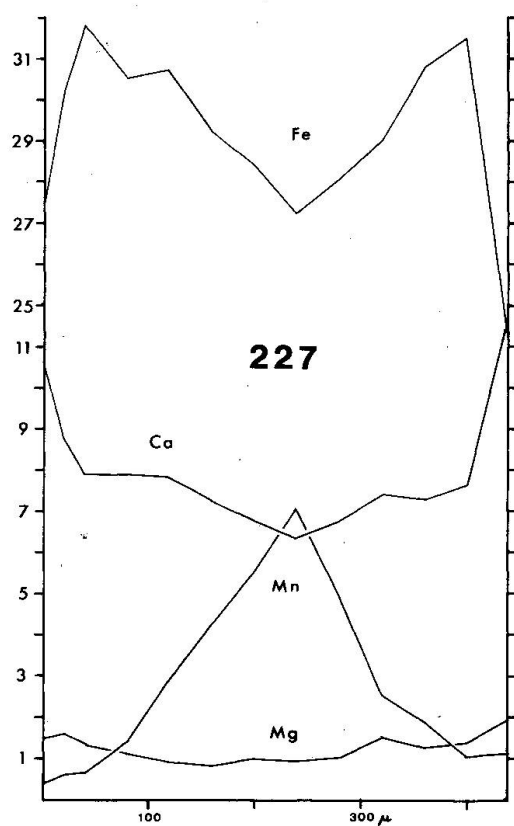


Fig. 2a, b, c Representative compositional profiles (wt%) of garnets from high-pressure rocks with a) zoning type 1 (retrograde eclogite, sample P5, EZ; garnet mica schist, sample 150, EZ), b) zoning type 2 (garnet mica schist, sample 227, EZ) and c) zoning type 3 (graphitic garnet mica schist, sample P3, EZ).





conditions during garnet growth have been documented by MILLER (1977). The same may be valid for garnets of high-pressure metasediments with zoning type 1.

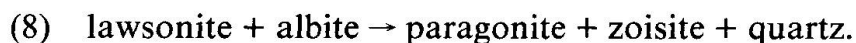
Other inclusions (listed in order of abundance) are: Fe-rich chlorite, chloritoid, zoisite, paragonite, quartz, phengite (Si = 6.21–6.42 pfu), rutile, graphite, ilmenite, apatite, Fe-sulfide, calcite, omphacite, kyanite, plagioclase.

Type 2 (Figure 2b) is characterized by the same development of Mn and Fe as in type 1, but (Mg + Ca) show a minimum in the core and an increase towards the rim.

Type 3 (Figure 2c) exhibits the similar concentration trend for Ca and Mg as in type 2, but there is only little Mn-enrichment in the core. This is compensated for Fe by a concentration-plateau in the core region with a sharp decrease of Fe towards the rim.

The same genetic interpretation, as suggested for garnets with zoning type 1, may also be valid for types 2 and 3, which probably are the result of different bulk rock composition. It is confirmed by the fact that omphacite may occur in these samples (as inclusion near the rim, or outside of garnet), indicating that they experienced a high-pressure event.

An additional indication for a high-pressure evolution of the metasediments are *lawsonite pseudomorphs*. They occur as rectangular or rhombic form-relics within garnet. The minerals now present are paragonite + zoisite + quartz, suggesting the reaction (FRANZ & ALTHAUS, 1977)



Lawsonite pseudomorphs also occur in metabasites and -sediments of the USH outside the EZ (FRY, 1973, MILLER, 1977, RAITH et al., 1977, 1980, DACHS, 1985).

### Metamorphic evolution

Textures and phase relations clearly indicate that several metamorphic episodes are recorded in the eclogites and in the surrounding metasediments. Relevant phase equilibria and geothermo- und -barometers have been applied to provide constraints on the path of these rocks in PT-space (HOERNES & FRIEDRICHSEN, 1974, MILLER, 1977, HOLLAND, 1979a, RAITH et al., 1980, HOSCHECK, 1981, 1982, FRANZ & SPEAR, 1983, SPEAR et al., 1985, DACHS, 1985, FRANK et al., 1986). The results are summarized in Table 5. The common PT-path for metabasites and -sediments of the EZ is shown in Figure 3. It will perhaps be modified, if more reliable PT-estimates are available in future.

Lawsonite pseudomorphs preserved as form-relics in garnets of metasediments, as well as the inclusion mineral of garnet, probably represent fragmen-

Tab. 5 Compilation of all available PT-estimates from rocks of the EZ and the USH in the Grossvenediger area.

| nb. | rock type                                                   | geothermometer, -barometer/phase equilibrium applied                                                                                                                                                                                                                                                                                                                              | PT-estimate                                                                                                      | references                       |
|-----|-------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|----------------------------------|
| 1   | metasediment<br>EZ/USH                                      | $law + ab \rightarrow pa + zoi + qz$ ?<br>law-pseudomorphs in garnet                                                                                                                                                                                                                                                                                                              |                                                                                                                  | DACHS (1985)<br>this paper       |
| 2   | eclogite<br>EZ                                              | garnet-clinopyroxene-thermometry: $K_{Dga-omph}^{Fe-Mg}$ at 10 kb<br>omph coexisting with qz                                                                                                                                                                                                                                                                                      | 500 - 550°C<br>P > 10 kb                                                                                         | MILLER (1977)                    |
| 3   | eclogite<br>EZ                                              | garnet-clinopyroxene-thermometry: $K_{Dga-omph}^{Fe-Mg}$ at 20 kb<br>clinopyroxene + magnesite = dolomite + orthopyroxene<br>pa = omph(jd <sub>50</sub> ) + ky + H <sub>2</sub> O                                                                                                                                                                                                 | 620 ± 30°C<br>P = 19.5 ± 2.5 kb<br>a <sub>H2O</sub> ~ 1                                                          | HOLLAND (1979a)                  |
| 4   | eclogite<br>EZ                                              | garnet-clinopyroxene-thermometry: $K_{Dga-omph}^{Fe-Mg}$ at 10 kb<br>corrected for Ca-contents<br>oxygen isotope fractionation between qz/ru and qz/omph<br>ab = omph(jd <sub>50</sub> ) + qz<br>chl + ky = Mg-ctd + tc<br>pa = omph(jd <sub>50</sub> ) + ky + H <sub>2</sub> O<br>equilibria applied to coexisting omph, ky, pa, tc,<br>Mg-ctd of eclogite T-527 from Weißspitze | 550 - 570°C<br>540 - 580°C<br>P > 12.5 ± 0.5 kb<br>T ~ 570°C<br>P ~ 19.6 kb<br>a <sub>H2O</sub> ~ 1              | FRANK et al. (1986)              |
| 5   | marble<br>EZ                                                | coexisting dio-tre-dol-cal-qz + zoi<br>phase equilibria of the system CaO-MgO-SiO <sub>2</sub> -H <sub>2</sub> O-CO <sub>2</sub>                                                                                                                                                                                                                                                  | T = 600°C assumed<br>from 3, P = 18-25 kb<br>a <sub>H2O</sub> close to 1                                         | FRANZ & SPEAR (1983)             |
| 6   | omph-relics in<br>metasediments<br>EZ                       | omph coexisting with qz (inclusion in omph)<br>ab = omph(jd <sub>50</sub> ) + qz<br>pa = omph(jd <sub>50</sub> ) + ky + H <sub>2</sub> O, applied to<br>coexisting omph-ky-pa(-zoi/ma-sy) in metasediments                                                                                                                                                                        | T = 550 - 600°C<br>assumed from 3 and 4<br>P > 12.5 ± 0.5 kb<br>assuming a <sub>H2O</sub> = 1,<br>then P ~ 20 kb | DACHS (1985)<br>this paper       |
| 7   | metasediment                                                | phase equilibria not more elucidated in abstract                                                                                                                                                                                                                                                                                                                                  | T = 590°C, P = 19 kb                                                                                             | SPEAR et al. (1985)              |
| 8   | metabasites<br>and -sediments<br>EZ/USH                     | oxygen isotope - thermometry                                                                                                                                                                                                                                                                                                                                                      | T ~ 550°C in the EZ<br>decreasing to the<br>south                                                                | HOERNES & FRIEDRICHSEN<br>(1974) |
| 9   | metasediment                                                | garnet - biotite geothermometer<br>plagioclase-biotite-garnet-muscovite geothermobarometer                                                                                                                                                                                                                                                                                        | T = 500 - 550°C<br>P = 6-7 kb                                                                                    | HOSCHEK (1982)                   |
| 10  | metasediments<br>of th EZ, USH<br>and the<br>"Mätrier Zone" | calcite - dolomite geothermometer<br>garnet - biotite geothermometer<br>plagioclase-biotite-garnet-muscovite geothermobarometer<br>phase relations between tre-zoi-cal-dol-qz at 550°C                                                                                                                                                                                            | T max. 550°C in the<br>EZ, decreasing to<br>450-480°C at the TW-<br>margin in the south<br>P = 6-7 kb in the EZ  | DACHS (1985)                     |
| 11  | marble<br>USH                                               | fluid inclusion data                                                                                                                                                                                                                                                                                                                                                              | T = 460-525°C<br>P = 2.3-4.5 kb                                                                                  | HOSCHEK (1981)                   |
| 12  | metasediments<br>EZ                                         | data-source not explained in abstract                                                                                                                                                                                                                                                                                                                                             | T < 350°C<br>P < 2.5 kb                                                                                          | SPEAR et al. (1985)              |

tary assemblages of the earliest metamorphic stage recorded in the metasediments. A reaction that might be responsible for the breakdown of lawsonite is



which is traced in Figure 3 (labeled 1) according to FRANZ & ALTHAUS (1977), valid for  $a_{H_2O} = 1$ . Garnet growth probably started somewhere in this area.

The peak?-metamorphic conditions of the high-pressure event are best recorded by mineral parageneses of eclogitic rocks, with values of 550-600°C, pressures around 20 kb and  $a_{H_2O} \sim 1$  (estimates 2, 3 and 4). Estimate 5 is based

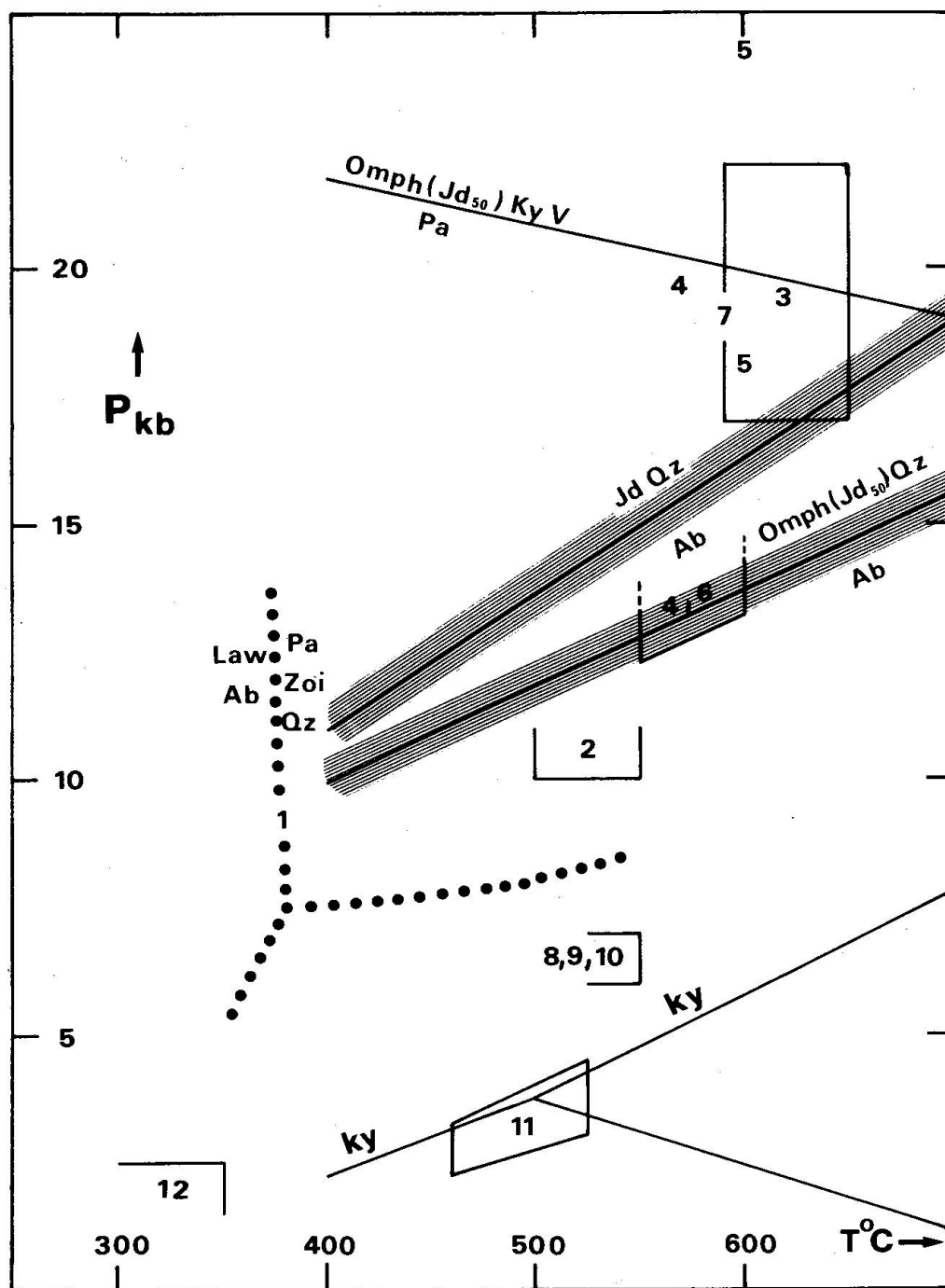


Fig. 3 Plot of PT-estimates (listed in Table 5), for high-pressure rocks of the EZ.

Data source of the traced equilibria:

paragonite = omphacite (jadeite<sub>50</sub>) + kyanite + vapor

albite = omphacite (jadeite<sub>50</sub>) + quartz

lawsonite + albite = paragonite + zoisite + quartz

phase-diagram of the Al<sub>2</sub>SiO<sub>5</sub>-modifications

HOLLAND (1979b)

HOLLAND (1980)

FRANZ & ALTHAUS (1977)

HOLDAWAY (1971)

on calculated phase relations of the marble-assemblage diopside-tremolite-dolomite-calcite-quartz  $\pm$  zoisite. It bears considerable uncertainties, as it is questionable, if the MRK-equation used in the calculations yields correct  $\text{H}_2\text{O}$ - $\text{CO}_2$ -activities at high pressures. Nevertheless relatively high pressures and a water-activity close to 1 are qualitatively indicated for this assemblage.

Assuming a temperature range of 550–600°C during eclogite-facies metamorphism (estimates 3 and 4), a minimum-pressure of  $12.5 \pm 0.5$  kb can be estimated from omphacite-relics in metasediments, based on the equilibrium

albite = omphacite (jadeite<sub>50</sub>) + quartz.

In Figure 3 a trace for the endmember-reaction and for omphacite (jadeite<sub>50</sub>) is given, calculated according to HOLLAND (1980), also showing experimental uncertainty. If also  $a_{\text{H}_2\text{O}} \sim 1$  as in eclogites (estimates 3 and 4), pressures of about 20 kb are indicated by the paragenesis

omphacite-kyanite-paragonite-zoisite/margarite  $\pm$  symplectite

and the equilibrium

paragonite = omphacite (jadeite<sub>50</sub>) + kyanite +  $\text{H}_2\text{O}$ ,

which is contoured in Figure 3 according to HOLLAND (1979b).

The subsequent metamorphic history is characterized by a strong uplift, which initiated the breakdown-reactions described. At 550°C/6–7 kb extensive reequilibration, post-dating the main tectonical displacements, took place, as indicated by consistent results of various geothermo- and -barometers (estimates 8, 9, 10). Deduced from calcite-dolomite geothermometry (DACHS, 1985), this Tertiary metamorphism shows an increasing grade from 450–480°C at the southern TW-margin to  $\sim 550^\circ\text{C}$  in the central part near the base of the USH.

Still later metamorphic stages are reflected by fluid inclusion data and by late mineral formations (estimates 11 and 12).

### Conclusions

The investigation of Penninic metasediments occurring together with eclogites in a narrow zone south of the Grossvenediger, clearly revealed that these experienced a common metamorphic history. The main arguments confirming this interpretation are as follows:

*Field evidence:* gradations from eclogites and their derivatives to metasediments without intervening shear zones suggest intact geological layering over considerable distances in the central EZ.

*Petrological evidence:* high-pressure assemblages as relics in metasediments. A minimum-pressure of  $12.5 \pm 0.5$  kb in the temperature range 550–600°C is

confirmed by omphacite (jadeit<sub>50</sub>)-relics coexisting with quartz. Assuming  $a_{\text{H}_2\text{O}} \sim 1$  a pressure near 20 kb results from the assemblage

omphacite–kyanite–paragonite–zoisite/margarite  $\pm$  symplectite.

Lawsonite pseudomorphs in garnets of EZ-metasediments, which probably were formed at a metamorphic stage prior to the eclogite-facies metamorphism, indicate a prograde metamorphic evolution.

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