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Relics of high-pressure metamorphism in different lithologies of the Central Alps, an updated inventory

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Abstract

In the Eastern and Western Alps, Cretaceous high-pressure mineral parageneses have been known for a long time. In the Central Alps s.l. between the Aosta and the Engadine Valley, the identification of more and more high-pressure relics in different lithologies suggests that large parts of the Pennine and Austroalpine nappe units of this region have also been involved in the Upper Cretaceous subduction event. Especially in the tectonically higher units, some of these high-P mineral parageneses survived the later Tertiary Barrovian type metamorphism in the cores of boudins or in the cores of coronas at thin-section scale. In *mafic rocks* such relics include the classical garnet-omphacite assemblage (± glaucophane, phengite, kyanite, talc, chloritoid) and lawsonite pseudomorphs consisting of zoisite and paragonite. Barroisitic cores in zoned amphibole crystals and albite / oligoclase / andesine-diopside-paragasite in symplectic microstructures are typical for the later decompression events. In ordinary *pelitic rocks* typical high-pressure relics are garnet-phengite-paragonite (± omphacite, glaucophane, chloritoid). In Al- and Mg-rich pelitic rocks kyanite-talc-Mg-chloritoid occur. Plagioclase-grossularite-rich garnet found in the Central Ticino area seem to indicate an unusual high pressure regime for the region. In *granitic* as well as in pelitic rocks, white mica with a 3T structure often coupled with unusual high Mg–Fe contents (RM > 0.12) indicate a former high-P history. Clinopyroxenes range from almost pure jadeites to aegirine-rich omphacites. In *carbonate rocks* a possible relic association is calcite-dolomite-diopside-zoisite. *Ultramafic lithologies* are not very sensitive to high-P conditions, the only sure relics involve garnet-forsterite-enstatite ± clinopyroxene with fresh garnet or pseudomorphs thereof. Different maps of the Central Alps s.l. have been compiled showing these relics as a function of lithology and tectonic unit, based on recent published and unpublished data.

Keywords: Metamorphism, high-pressure relics, blueschist, eclogite, Central Alps.

Introduction

It was during the period of 1965 to 1975 that omphacite- and glaucophane-bearing, mainly mafic rocks of the Western and Eastern Alps were recognized as indicators of a Cretaceous ("early-Alpine" or "Eoalpine") high-pressure metamorphism (Bearth, 1959; Plas, 1959; Niggli, 1973; Hunziker, 1974; Bocquet et al., 1974; Frey et al., 1974, and many articles in that volume). Since that time, more and more mafic rocks exhibiting eclogite-facies parageneses and relics of such have been discovered even in areas strongly overprinted by the Tertiary alpine orogeny (Ernst, 1977, 1981; Evans, Trommsdorff and Richter, 1979; Heinrich, 1982, 1986). During the last five years additional relics of early-Alpine high-pressure metamorphism have been identified, especially in pelitic and granitic lithologies. Only part of this information is published, and the following short *review* intends to summarize the present-day knowledge, albeit still limited, of an author team that has been involved in high-pressure research for several years. The area dealt with covers the Central Alps

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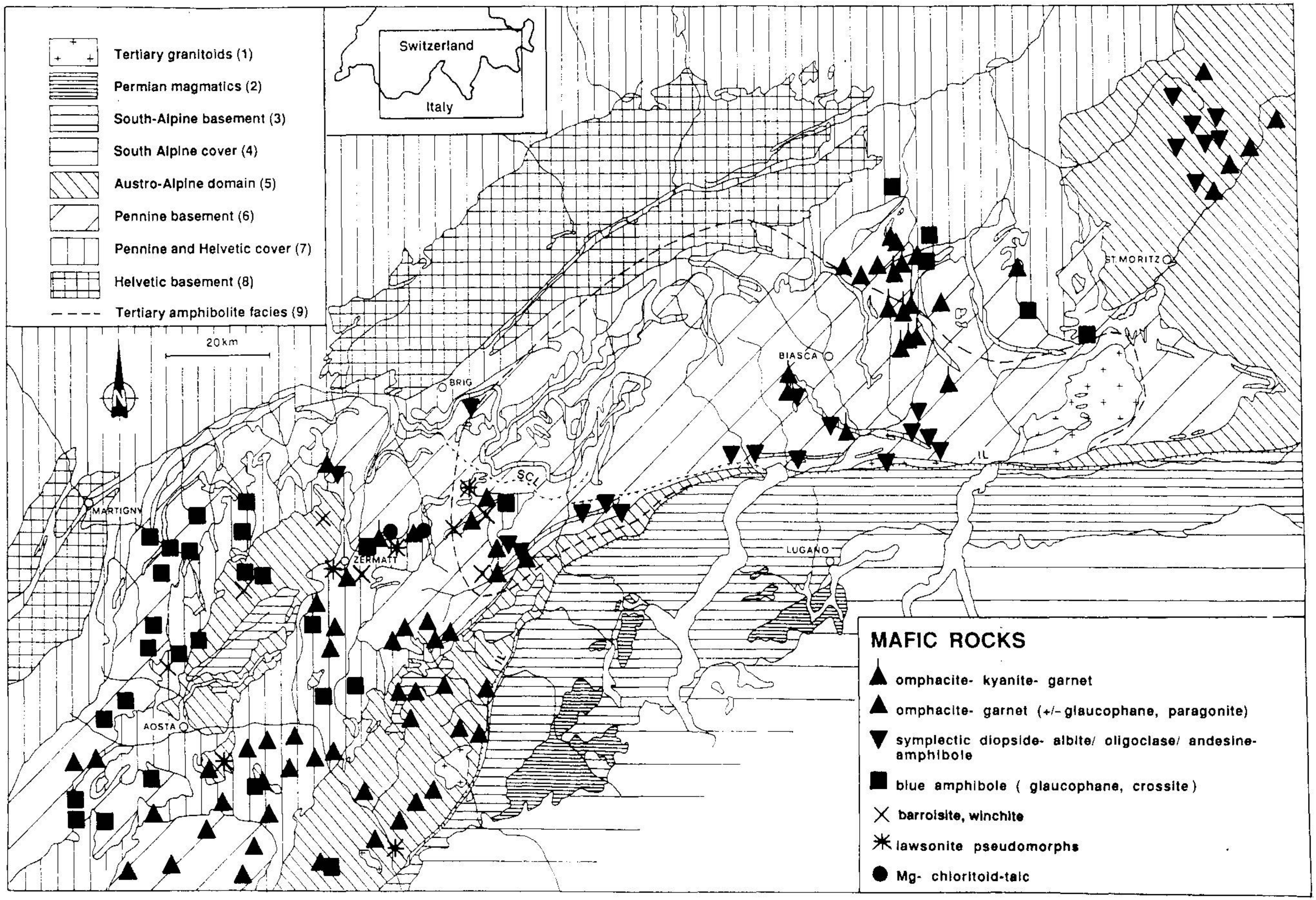

Fig. 1 Distribution of high-pressure relics in mafic rocks of the Central Alps s.l. The exact location of the major tectonic units can be seen on figure 3. Additional informations concerning the legend: (1) Tertiary granitoids: Biella, Traversella, Bergell, Tonalite south of Bellinzona. (2) Permian magmatics in the Southern Alps: Baveno granite suite and South-Alpine Permian volcanics, predominantly rhyolites. (3) South-Alpine basement: Ivrea zone, Valpelline series of the Dent Blanche nappe, "Seconda Zona Dioritico-Kinzigitica" overlying the Sesia-Lanzo zone. (4) South-Alpine cover: Mesozoic and younger sediments. (5) Austroalpine domain: Silvretta and Ötztal nappe in the east, Arolla series of the Dent Blanche nappe in the west, Sesia-Lanzo zone in the southwest (6): Pennine basement: pre-Triassic magmatics and sediments. (7) Pennine and Helvetic cover: post-Permian sediments, including those of the Canavese zone in the south. (8) Helvetic basement: external massifs (Mont Blanc, Aiguilles Rouges, Aar, Gotthard). (9): Limits the area of the Tertiary amphibolite facies (Central Ticino area). IL: Insubric line (Canavese line in the west, Tonale line in the east). SCL: Simplon line and Centovalli fault zone.

s.l., i.e. between the Aosta Valley in the west and the Engadine valley in the east. Lithologies distinguished are mafic (basaltic and gabbroic), granitic, pelitic, carbonate and ultramafic rocks (Figs 1 to 3). Rather than to publish an interpretative synthesis, we present an updated inventory that contains more than thirty new localities exhibiting high-pressure relics.

Relics of high-pressure mineral assemblages occur in two typical situations: (1) in rock bodies that have survived the Tertiary penetrative deformation; these range in size from half a meter to several hundred meters, and either lie between megascopic shear zones or in the core of boudins and (2) as the core of corona structures at thin-section scale.

2. Mafic rocks (Fig. 1)

The typical high-pressure paragenesis in these rocks is omphacite-garnet. The additional presence of glaucophane, lawsonite (in the Central Alps found as yet only as pseudomorphs) and/ or paragonite indicates relatively low-temperature high-pressure metamorphism, i.e. low-temperature eclogite- or blueschist-facies, whereas the presence of kyanite indicates the presence of the high-pressure eclogite-facies (HEINRICH, 1986).

Except riebeckite and Mg-riebeckite, blue amphiboles indicate high-pressure-low-temperature-regimes. The newly defined epidote-blueschist facies (EVANS, 1990) is rarely evident from relics in the Central Ticino area, but is found at its periphery. This can be explained by the fact that the epidote-blueschist mineralogy is very susceptible to retrogression. In the Central Alps blue-green amphibole such as barroisite or winchite is often found in the core of green amphibole grains (actinolite, pargasite, common hornblende) and corresponds, according to most authors, to the retrograde part of the P-T path of high-pressure mafic rocks, i.e. to pressures between 5 and 10 kbar (ERNST, 1979; LAIRD and ALBEE, 1981; GANGUIN, 1988).

Assemblages of symplectic diopside + pargasitic amphibole or magnesio-hornblende + albite / oligoclase / andesine, which are typical for eclogitic amphibolites (or "meta-eclogites") also seem to correspond to an intermediate retrogressive stage of mafic eclogites (COLOMBI and PFEIFER, 1986; COLOMBI, 1989). In upper amphibolite-facies terrains, where diopside-amphibole-plagioclase is the stable paragenesis, the recognition of such rocks is somewhat critical, because the normal amphibolite-facies pyroxene-plagioclase assemblages only differ in their higher anorthite-content in plagioclase from retrogressive ones, formed after eclogite (COLOMBI, 1989).

Recent studies have shown that basaltic and gabbroic protoliths often exhibit quite different behavior during metamorphism, due to the different bulk rock composition, especially at medium P-T-conditions. Minerals of the relatively Ca- and Al-rich and Fe-poor metagabbros are often more Ca-rich than their counterparts in meta-basaltic rocks (e.g. plagioclase and amphiboles, COLOMBI, 1989; PFEIFER et al., 1989). In addition, Mg-rich minerals like chlorite and Mg-chloritoid and talc are often abundant in metagabbros. At high pressures the differences are less pronounced and for this reason we only present one single map. Mafic rocks rich in glaucophane often correspond to former basaltic rocks enriched in sodium (spilites).

In the following discussion, the different regions are presented from west to east. Emphasis will be placed on recently published and unpublished investigations. A rather complete overview of the high-pressure mineralogy of mafic rocks of the Central Alps is given by OBERHÄNSLI (1986, Tab. 2), although the paper as such is limited to the Pennine region and emphasizes blue amphiboles of Mesozoic rocks.

For the *Austroalpine basement nappes* (Sesia, Dent Blanche, Mt. Emilius etc.) MARTINOTTI and HUNZIKER (1984) discuss most recent publications. However, detailed investigations on a regional scale of the high-pressure mineral parageneses as a function of lithology are still missing and the maps presented here are mainly based on the few published petrographic maps of the *Sesia zone* (COMPAGNONI, 1977; PASSCHIER et al., 1981; KOONS, 1982, 1986; LARDEAUX et al., 1982; STÜNITZ, 1989). The controversy concerning the significance of blue amphiboles (barroisite, crossite) in the *Dent Blanche nappe* continues. Whereas for the Sesia zone and the isolated Austroalpine klippen, no one doubts the Alpine age of the high-pressure metamorphism, some authors reject the hypothesis of a high-pressure event in the Dent Blanche nappe (BALLÈVRE et al., 1986, 1987), and others postulate an early-Alpine high-pressure phase based on the occurrence of blue amphibole in mylonites along granite-gabbro contacts (BUCHER-NURMINEN, pers. commun. 1989). Age determinations of 45–47 Ma (AYRTON et al., 1982) could be interpreted as mixing ages (HUNZIKER et al., 1989).

For the *Southern (internal) Pennine basement nappes* of Gran Paradiso and Monte Rosa, DAL PIAZ and LOMBARDO (1986) summarized eclogitic parageneses found in basaltic, metapelitic and mylonitic granitic rocks. Additional information especially for the adjacent Piemonte ophiolites can be found in BENCIOLINI et al. (1984).

Concerning the *basement nappes of the northern (external) Pennine domain* of the Valais region, in the Mont Fort nappe (mainly former "Métailler" zone) and the Siviez-Mischabel nappe (part of the Bernhard super-nappe, west of the Dent Blanche nappe, ESCHER, 1988) more and more blue amphibole (mainly glaucophane) occurrences of undetermined age are being found in mafic and pelitic schists, extending farther to the south than previously thought (WUST and BAEHNI, 1986; SCHÜRCH et al., 1986; SCHÜRCH, 1987; GOUFFON, 1990). Recently, omphacite-bearing mafic eclogites, described by GILLIÉRON (1946), have been reexamined in the basement of the Siviez-Mischabel nappe in the Turtmann Valley, 25 km E of Sion/Valais (ZINGG, 1989; SARTORI, 1990; THÉLIN et al., 1990). Their age is still in debate, but many geological features indicate a Paleozoic age. In the Berisal zone of the Pontis nappe, E of Brig/Switzerland, STILLE and OBERHÄNSLI (1987) have found zoned Cr-diopside-rich cores of clinopyroxene in tremolite grains of garnet-bearing amphibolites, which they interpret as high-pressure relics.

Ophiolites of the Piemonte zone in general: In the Zermatt-Saas zone south of the Swiss-Italian border very little work has been done since the classical study of DAL PIAZ and coworkers, culminating in publications like ERNST and DAL PIAZ (1978 a, b), GOSSO et al. (1979). Local studies by DU BOIS and LOOSER (1987) in Val d'Ollomont, NE of Aosta, and by VANNAY and ALLEMANN (1990) at Valtournanche/Cervinia have confirmed the existence of barroisite in the former and omphacite-glaucophane in the latter region. For the Zermatt-Saas zone near Zermatt and Saas Fee, several detailed petrological and geochemical studies have confirmed the classical work of BEARTH (e.g. 1974), but include careful P-T estimates and detailed textural evidence (OBERHÄNSLI, 1980, 1983; MEYER, 1983; BARNICOAT and FRY, 1986; GANGUIN, 1986, 1988; BARNICOAT, 1988). Among other features, these authors have identified ferrogabbroic eclogites. They have found talc-kyanite veins and were able to show that the paragenesis Mg-chloritoid-talc-garnet is limited to magnesiogabbroic protoliths.

Ophiolites of the Antrona zone (NE Piemonte zone), including the complex Furgg zone W of Domodossola/Italy: Careful geological mapping and sampling has shown that only in rare cases true eclogites (containing omphacite) have survived the Tertiary amphibolite facies metamorphism in the cores of gabbroic or basaltic amphibolite boudins (WAHLI-WENGER, 1985; LOBRINUS and BÉGLÉ, 1985; VINARD, 1986; CORNAZ, 1988; COLOMBI, 1989). P-T estimates based on omphacite-garnet pairs have been made by COLOMBI and PFEIFER (1986) and by LADEUZE (1988).

Ophiolites of the Southern Steep Belt between Domodossola / Italy and Locarno / Switzerland: These zones in part accompany the eastern continuation of the Monte Rosa nappe as far as Locarno (eastern continuations of the Antrona and the Zermatt-Saas zones, Isorno-Orselina zone, Cardada zone etc.). No omphacite has been found, but diopside-rich pyroxene cores of amphibole grains and the aforementioned diopside-oligoclase symplectites are very likely the only relics of the Cretaceous high-pressure event (COLOMBI, 1989; COLOMBI and PFEIFER, 1986).

Basement of the Central and Eastern Ticino area: After the fundamental studies of ERNST (1977), EVANS et al. (1979) of the Cima Lunga nappe (western part of the Adula nappe), a few other authors studied dispersed eclogite relics of the same region, e.g. HEINRICH (1982, 1986), and BOCCHIO et al. (1985). Selected mafic eclogites of the eastern and southern Adula nappe have been decribed by HEINRICH (1982, 1986), AURISICCHIO et al. (1985) and OBERHÄNSLI (1986). HUNZIKER (1989) and SANTINI (1991) have studied the same area at a regional scale, including the Tambo and the Suretta nappe, emphasizing geochemical and age relations.

The blue amphibole occurrences of the *Southern Grisons/Switzerland* (Avers, Engadine), were studied by OBERHÄNSLI (1978). The sodic amphibole occurrences, which are only in part related to mafic rocks, were recently reviewed by OBERHÄNSLI (1986).

Detailed mineral and bulk rock data on yet undated mafic eclogite assemblages were recently published by MAGGETTI and GALETTI (1988) on the Paleozoic basement of the *Austroalpine Silvretta nappe* in Northern Grisons/Switzerland.

3. Pelitic rocks and granitic mylonites (Fig. 2)

Here we group all non-mafic rocks that contain abundant white mica. This mineral is more likely to preserve its high-pressure structure than other minerals, such as sodium-rich amphiboles or clinopyroxene (FREY et al., 1983). These authors use the presence of Alpine 3T-type white mica and their RM-content larger than 0.12 (RM = 2 Fe_2O_3 + FeO + MgO as mole %) to define regions of eo-Alpine high P/low T metamorphism on both sides of the Central Ticino area, where the Tertiary metamorphism is predominant. Their 3T-type distribution map served as the primary base of figure 2. Using the experimental white mica-K-feldspar data of MASSONNE and SCHREYER (1987), HAMMERSCHLAG (1985) estimated unusual high pressures of more than 8 kbar for white mica cores of the *Berisal zone E of Brig/Switzerland.* HAMMERSCHMIDT and FRANK

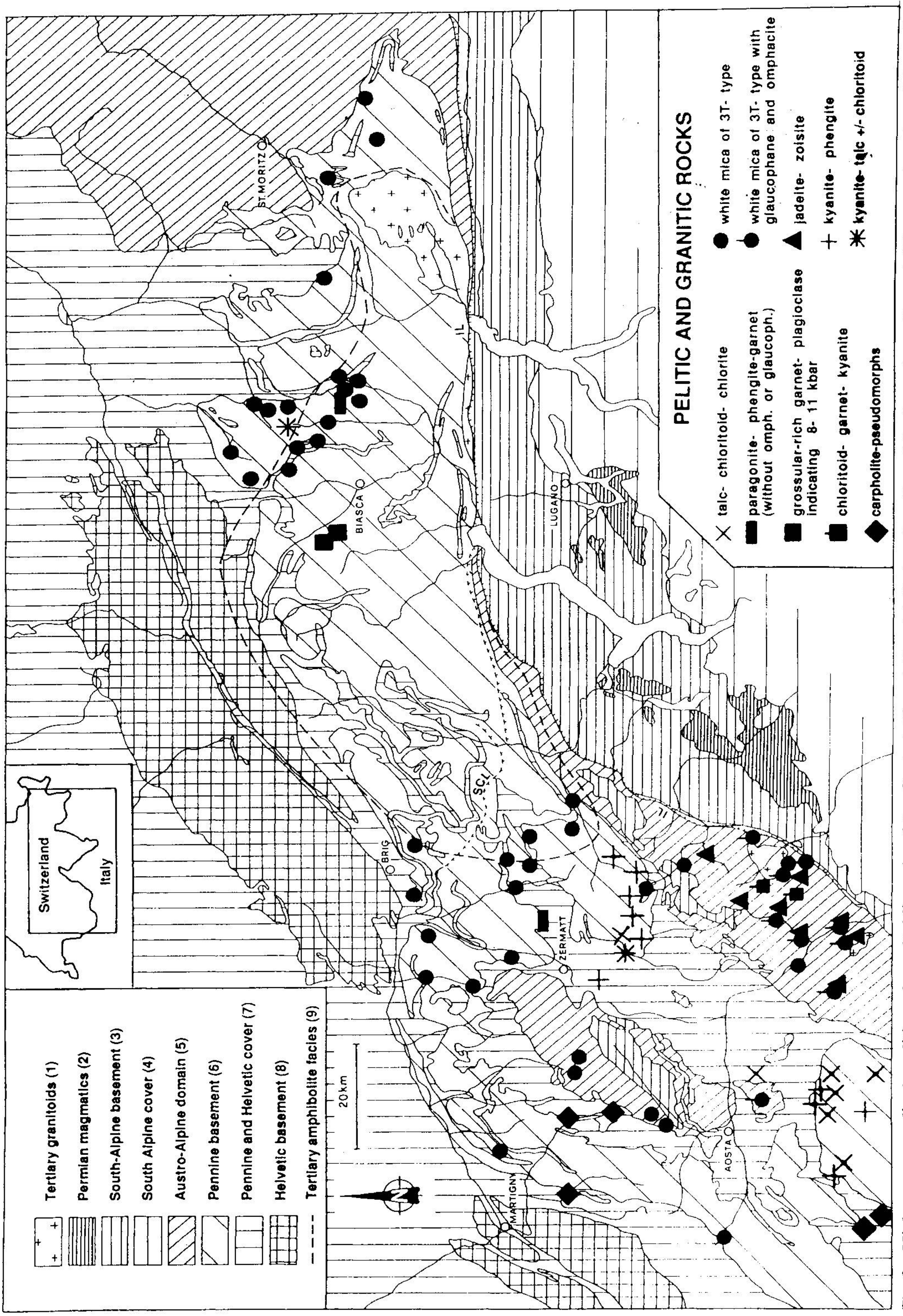

Fig. 2 High-pressure relics in pelitic and granitoidic rocks of the Central Alps s.l. For detailed explanation of the legend, see figure 1. The exact location of the major tectonic units can be seen on figure 3.

(1991) who worked in the same region obtained slightly higher pressures (13 kbar). However such relics are rare outside the region of eo-Alpine glaucophane or omphacite.

The most conspicuous mineral parageneses contained in high-pressure Al- and Mg-rich pelitic and granitic rocks are those involving talc and/or kyanite (details see Fig. 2). Such assemblages have mainly been found in the *Western Central Alps* (see review by DAL PIAZ and LOMBARDO, 1986), which is in part based on earlier publications by CHOPIN (1981) and CHOPIN and MONIE (1984). In a quartz-rich layer of the Combin unit at Breuil/Cervinia, RÖTHLISBERGER (1985) has found kyanite-celadonite-rich phengite. In the same area, but also in the Gran Paradiso, CHOPIN (pers. comm. 1990) has found more relics of high pressure, including talc-phengite and kyanite-phengite (cf. Fig. 2). Also the pure jadeite-bearing granitoid rocks of Mucrone and similar metagranitoid bodies of the SE Sesia zone seem to represent rather unique occurrences (OBERHÄNSLI et al., 1985; BIINO and COMPAGNONI, 1989), within the Central Alps s.l.

In ordinary metapelitic rocks (i.e. with moderate Al- and Mg-contents), a few authors have identified the omphacite- and/or glaucophane-free paragenesis of paragonite-phengite-garnet as a high-pressure equivalent of a later, lower-pressure paragenesis of biotite + less phengitic white mica (LADURON and MARTIN, 1969: *Monte Rosa nappe* in Valle Anzasca; GANGUIN, 1988: *Zermatt-Saas zone* in the Täsch Valley; HEINRICH, 1982: *Adula nappe*). Phengite-chloritoid-garnet ± kyanite or chlorite is another high-pressure mineral paragenesis of metapelites that has only recently been described (VUICHARD and BALLÈVRE, 1988: *Sesia zone*). For the *Dent Blanche nappe*, BALLÈVRE and KIENAST (1987) relate the presence of Mg-riebeckite and crossite, coexisting with garnet in impure quartzite, to the particular bulk rock composition and not to high pressure. However, OBERHÄNSLI and BUCHER-NURMINEN (1987) and JAQUEMIN (1990) have found celadonite-rich phengites in metagranitic rocks and attribute them to an unusually elevated pressure for the area.

Carpholite, which is a common mineral in the blueschist domain of the Western Alps (GOFFE and CHOPIN, 1986), has only been found as pseudomorphs in the metasediments of the Valais and the Piemonte zone (GOFFE, pers. commun. 1990).

In the *Central Ticino area*, IROUSCHEK (1983, 1985) found garnets in staurolite-alumosilicate-mica schists which are strongly enriched in grossular component. Using the garnet-biotite-plagioclase thermobarometer of ARANOVICH and PODLESSKIY (1980), these rocks correspond to pressures between 8 and 11 kbar with corresponding temperatures ranging from 550 to 630 °C. KOCH (1982) has obtained comparable results for the more easterly Adula nappe, whereas TEUTSCH (1982) has only found white mica somewhat enriched in phengite in the Misox zone. These unusual high pressures for the region are tentatively interpreted by these authors to correspond to the intermediate retrograde path beween the eo-Alpine and the Tertiary Barrovian type metamorphism. The only white schist paragenesis yet known from this part of the Alps has been decribed by SANTINI (1991) from a metasomatic metapelite layer within an eclogite boudin of the Adula nappe in the northern Calanca valley.

4. Carbonate rocks (Fig. 3)

Despite the fact that calcite-bearing rocks are poor pressure indicators, GANGUIN (1986) has identified the parageneses calcite-dolomite-diopside-zoisite as the high-pressure equivalent of the omphacite-bearing mafic rocks of the Zermatt-Saas area (cf. FRANZ and SPEAR, 1983, for the Tauern window). In the Central Ticino area also GRÜTTER (1929), KOBE (1956) and TROMMSDORFF (1966, from Someo, Valmaggia) describe the same paragenesis, however without attributing them to high-pressure metamorphism. In the Breuil/Cervinia area south of Zermatt, RÖTHLISBERGER (1985) described omphacite-marbles similar to the ones found in the Sesia zone (COMPAGNONI et al., 1977; COMPAGNONI, 1977). A systematic search would certainly identify similar rocks in other high-pressure areas.

5. Ultramafic rocks (Fig. 3)

Because the pressure-dependence of equilibria involving spinel is only poorly known (ENGI and EVANS, 1980; FABRIES, 1984), only Ca-Al-rich ultramafic rocks contain known pressure-sensitive parageneses (garnet-clinopyroxene, garnet-orthopyroxene). However this rock type (metalherzolite) is relatively rare. EVANS and TROMMSDORFF (1978) and ERNST (1978) identified the few occurrences of garnet-clinopyroxene-metaperidotites of the *Central Ticino area* as eclogite-facies rocks equivalent to the mafic eclogites known from the same zone (Cima Lunga-Adula nappe, see section 2). However, rocks containing typical chlorite ± tremolite aggregates (or small nodules) corresponding to garnet relics are quite abundant (KOBE, 1956; EVANS and TROMMSDORFF, 1970; ROST et al., 1979; HEINRICH, 1983) and are included here as high-pressure indicators (high temperature eclogite facies).

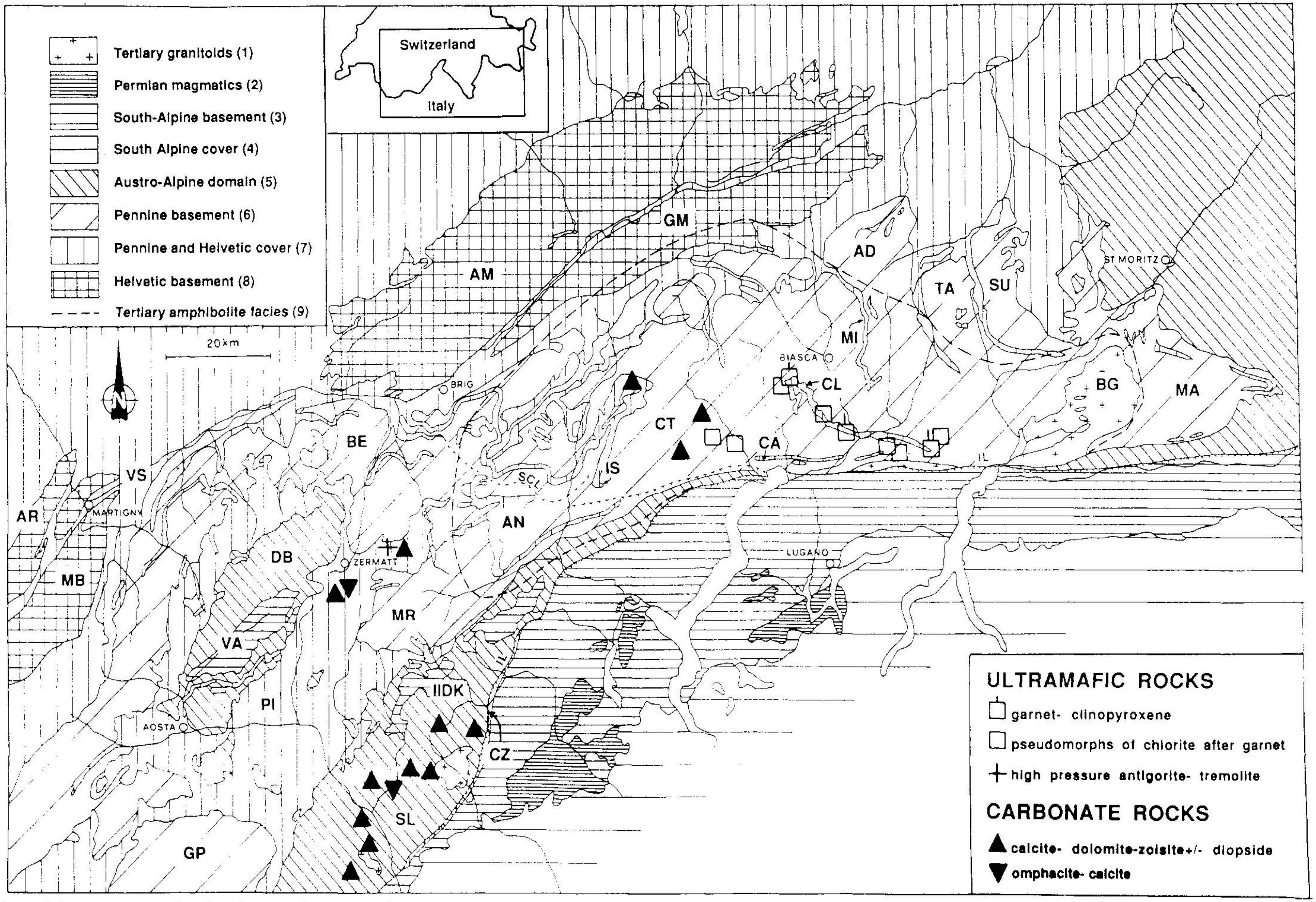

Fig. 3 High-pressure relics in ultramafic and carbonate rocks of the Central Alps s.l. For detailed explanation of the legend, see figure 1. Key to names of major tectonic units (from west to east): AR: Aiguilles Rouge, MB: Mont Blanc, VS: Valais, GP: Gran Paradiso, PI: Piemonte, DB: Dent Blanche (Arolla), VA: Valpelline, MR: Monte Rosa, BE: Bernhard. IIDK: Seconda Zona Dioritica-Kinzigitica, SL: Sesia-Lanzo, CZ: Canavese, AN: Antrona, IS: Isorno, CA: Cardada, GM: Gotthard, AM: Aar, CT: Central Ticino (Lepontic Alps, including Leventina, Simano, Maggia, Antigorio), CL: Cima Lunga, MI: Misox, AD: Adula, TA: Tambo, SU: Suretta, BG: Bergell, MA: Malenco.

Ca-poor (metaharzburgitic) rocks contain the uniform paragenesis enstatite-olivine-chlorite-FeCr-spinel from higher amphibolite facies to eclogite facies conditions (PFEIFER, 1981, 1987; HEINRICH, 1983). According to theoretical phase diagrams for pure end members, calculated with the thermodynamic data set of BERMAN (1988), the solid-solid equilibrium anthophyllite going to talc + enstatite at higher pressures is situated at pressures between 8 and 10 kbar for amphibolite facies temperatures. Consideration of the solid-solution in the minerals would shift it to even higher pressures. However, the presence of the pair enstatite-talc in late metasomatic veins of presumable Tertiary age seems to invalidate the pressure indication of the theoretical phase diagram (PFEIFER, 1987).

In serpentinites, antigorite-olivine ± Ca-silicate (diopside, tremolite)-magnetite-chlorite parageneses are only slightly sensitive to pressure (EVANS, 1977; PFEIFER, 1987). However, GANGUIN (1988) presents arguments that some of the antigorite-olivine-tremolite rocks of the *Zermatt area* have been formed at high-pressure. The presence of titanian clinohumite is considered as a high-pressure indicator by many authors. Experimental work by ENGI and LINDSLEY (1980) and its conspicious distribution at medium-grade metamorphic terraines (EVANS and TROMMSDORFF, 1983) showed that the stability of this mineral is not governed by pressure, but by temperature and the bulk rock chemistry (more abundant in lherzolitic ultramafics).

5. Conclusions

This inventory testifies the existence of many more relics of Paleozoic and Cretaceous high pressure events than have previously been known. Especially the area of the early Alpine (Cretaceous) high pressure metamorphism is considerably more extensive than thought some years ago (FREY et al., 1974, 1983). In particular in areas strongly deformed and metamorphosed during the later Tertiary events, new relics have been identified. As expected, tectonically higher units preserve high-pressure relics more readily than lower units (e.g. Adula nappe). Although we think that the data presented here do not allow yet a synthesis, the maps of figures 1 to 3 seem to indicate a poorly defined, but nevertheless visible, metamorphic zonation of the Cretaceous event, which is surprisingly parallel to southwest-northeast striking boundaries of the Alps. In the more external parts of the Central Alps s.l. blueschist facies parageneses seem to dominate, whereas in the more internal ones eclogite facies dominate.

In addition, the fact that the high pressure relics are not confined to particular tectonic units indicates that very probably almost all of the actual Central Alps was once subducted to depths corresponding to blueschist and eclogite facies. Thus, the piling-up of the basement nappes, as it is preserved today, very problably dates from this same high-pressure Cretaceous event. During the Tertiary then, the Central Alps seem to have just been folded and metamorphosed again, without major displacement of the different basement nappes relative to each other.

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References

ARANOVICH, L. and PODLESSKIY, K. (1980): The garnet-plagioclase barometer. Doklady ESS, 251, 101–103.

AURISICCHIO, C., BOCCHIO, R., LIBORIO, G. and MOTTANA, A. (1985): Petrogenesis of the eclogites from Soazza, Switzerland. Chem. Geol., 50, 47–63.

AYRTON, S., BUGNON, C., HAARPAINTNER, T., WEIDMANN, M. and FRANK, E. (1982): Géologie du front de la nappe de la Dent-Blanche dans la région des Monts-Dolin, Valais. Eclogae geol. Helv., 75, 367–390.

BALLÈVRE, M, KIENAST, J.-R. et VUICHARD, J.-P. (1986): La "nappe de la Dent-Blanche" (Alpes occidentales): deux unités austroalpines indépendantes. Eclogae geol. Helv., 79, 57–74.

BALLÈVRE, M. and KIENAST, J.-P. (1987): Découverte et signification de paragenèse à grenat-amphibole bleue dans la couverture mésozoïque de la nappe de la Dent-Blanche (Alpes occidentales). C. R. Acad. Sci. (Paris), t. 305, série II, 43–47.

BARNICOAT, A. and FRY, N. (1986): High-pressure metamorphism of the Zermatt-Saas ophiolite zone. J. Geol. Soc. (London), 143, 607–618.

BARNICOAT, A. (1988): Zoned high-pressure assemblages in pillow lavas of the Zermatt-Saas ophiolite zone. Lithos, 21, 227–236.

BEARTH, P. (1959): Über Eclogite, Glaucophanschiefer und metamorphe Pillowlaven. Schweiz. Mineral. Petrogr. Mitt., 39, 267–286.

BEARTH, P. (1974): Zur Gliederung und Metamorphose der Ophiolite der Westalpen. Schweiz. Mineral. Petrogr. Mitt., 54, 385–397.

BENCIOLINI, L., MARTIN, S. and TARTAROTTI, P. (1984): Il metamorphismo eclogitico nel basamento del Gran Paradiso ed in unita Piemontesi della Valle di Campiglia. Mem. Soc. geol. it., 29, 127–171.

BERMAN, R. (1988): Internally consistent thermodynamic data for minerals in the system Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–CO_2. J. Petrol., 29, 445–522.

BIINO, G. and COMPAGNONI, R. (1989): Metagranitoids reequilibrated under HP conditions: two examples from the eclogitic belt of the Western Alps. Terra Abstracts 1, 3. 3rd Internat. Eclogite Conf., Würzburg, April, 1989.

BOCCHIO, R., LIBORIO, G. and MOTTANA, A. (1985): Petrology of the amphibolitized eclogites of Gorduno, Lepontine Alps, Switzerland. Chem. Geol., 50, 65–86.

BOCQUET, J., DELALOYE M., HUNZIKER, J. and KRUMMENACHER, D. (1974): K–Ar and Rb–Sr dating from blue amphiboles, micas and associated minerals from the Western Alps. Contr. Mineral. Petrol., 47, 7–26.

CHOPIN, C. (1981): Talc-phengite: a widespread assemblage in high grade pelitic blueschists of the Western Alps. J. Petrol., 22, 628–650.

CHOPIN, C. and MONIÉ, P. (1984): A unique magnesiochloritoid-bearing, high-pressure assemblage from the Monte Rosa, Western Alps: petrologic and ^{40}Ar–^{39}Ar radiometric study. Contr. Mineral. Petrol., 87, 388–398.

COLOMBI, A. (1989): Métamorphisme et géochimie des roches mafiques des Alpes ouest-centrales (Géoprofil Viège–Domodossola–Locarno). Mémoires de Géol. (Lausanne), 4, 216 p.

COLOMBI, A. and PFEIFER, H.-R. (1986): Ferrogabbroic and basaltic meta-eclogites from the Antrona mafic ultramafic complex and the Centovalli-Locarno region (Italy and Southern Switzerland) – First results. Schweiz. Mineral. Petrogr. Mitt., 66, 99–110.

COMPAGNONI, R. (1977): The Sesia-Lanzo zone: high pressure / low temperature metamorphism of the Austroalpine continental margin. Rend. Soc. ital. Mineral. Petrol., 33, 335–374.

COMPAGNONI, R., DAL PIAZ, V., HUNZIKER, J., GOSSO, G., LOMBARDO, B. and WILLIAMS, P. (1977): The Sesia-Lanzo zone, a slice of continental crust with alpine high pressure/low temperature assemblags in the Western Italian Alps. Rend. Soc. It. Miner. Petrol. 33, 281–334.

CORNAZ, S. (1988): Géologie et pétrographie du Zwischbergtal (Haut-Valais). Diploma thesis, Univ. of Lausanne, 144 p.

DAL PIAZ, G. and LOMBARDO, B. (1986): Early alpine eclogite metamorphism in the Penninic Monte Rosa-Gran Paradiso basement nappes of the northwestern Alps. Mem. geol. Soc. Amer., 164, 249–265.

DU BOIS, L. and LOOSER, M. (1987): Etudes géologiques, pétrographiques et géochimiques en Val d'Ollomont (région autonome de la Vallée d'Aoste, Italie). Diploma thesis, Univ. of Lausanne, 172 p.

ENGI, M. and EVANS, B.W. (1980): A re-evaluation of the olivine-spinel geothermometer: a discussion. Contr. Mineral. Petrol., 73, 201–203.

ENGI, M. and LINDSLEY, D. (1980): Stability of titanian clinohumite: experiments and thermodynamic analysis. Contr. Mineral. Petrol. 72, 415–424.

ERNST, W.G. (1977): Mineralogical study of eclogitic rocks from Alpe Arami, Lepontine Alps, Southern Switzerland. J. Petrol., 18, 371–398.

ERNST, W.G. (1978): Petrochemical studies of lherzolitic rocks from the Western Alps. J. Petrol., 19, 341–392.

ERNST, W.G. (1979): Coexisting sodic and calcic amphiboles from high-pressure metamorphic belts and the stability of barroisitic amphibole. Mineral. Mag. 43, 269–278.

ERNST, W.G. (1981): Petrogenesis of eclogites and peridotites from the Western and Ligurian Alps. Amer. Mineralogist, 66, 443–472.

ERNST, W.G. and DAL PIAZ, G. (1978a): Areal geology and petrology of eclogites and associated metabasites of the Piemonte ophiolite nappe. Breuil-St. Jaques area, Italian Western Alps. Tectonophysics, 51, 99–126.

ERNST, W.G. and DAL PIAZ, G. (1978b): Mineral parageneses of eclogitic rocks and related mafic schists of the Piemonte ophiolite nappe, Breuil-St. Jaques area, Western Italian Alps. Amer. Mineralogist, 63, 621–640.

ESCHER, A. (1988): Structure de la nappe du Grand-St-Bernard entre le Val de Bagnes et les Mischabels. Rapp. géol. Serv. hydrol. géol. nat. Suisse, 7, 26 p.

EVANS, B.W. (1977): Metamorphism of alpine peridotite and serpentinite. Ann. Rev. Earth Planet. Sci., 5, 397–447.

EVANS, B. (1990): Phase relations of epidote-blueschists. Lithos, 25, 3–23.

EVANS, B. and TROMMSDORFF, V. (1970): Regional metamorphism of ultramafic rocks in the Central Alps: parageneses in the system CaO–MgO–SiO_2–H_2O. Schweiz. Mineral. Petrogr. Mitt., 50, 481–492.

EVANS, B. and TROMMSDORFF, V. (1978): Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps. Earth Planet. Sci. Lett., 40, 333–348.

EVANS, B. and TROMMSDORFF, V. (1983): Fluorine hydroxyl titanian clinohumite in alpine recrystallized garnet peridotite: compositional controls and petrologic significance. Amer. J. Sci., 283A, 355–369.

EVANS, B.W., TROMMSDORFF, V. and RICHTER. W. (1979): Petrology of an eclogite-metarodingite suite at Cima di Gagnone, Ticino, Switzerland. Amer. Mineralogist, 64, 15–31.

FABRIÈS, J. (1984): Utilisation des échanges Fe–Mg en géothermométrie. Application au roches mafiques et ultramafiques. In: LAGACHE, M., ed., Thermométrie et barométrie géologiques. Vol. I, chap. 7, 203–233. Soc. Franç. Min. Crist.

FRANZ, G. and SPEAR, F.S. (1983): High-pressure metamorphism of siliceous dolomites from the central Tauern Window, Austria. Amer. J. Sci., 283A, 396–413.

FREY, M., HUNZIKER, J., FRANK, W., BOCQUET, J., DAL PIAZ, G., JÄGER, E. and NIGGLI, E. (1974): Alpine metamorphism of the Alps, a review. Schweiz. Mineral. Petrogr. Mitt., 54, 248–290.

FREY, M., HUNZIKER, J.C., JÄGER, E. and STERN, W.B. (1983): Regional distribution of white K-mica polymorphs and their phengite content in the Central Alps. Contr. Mineral. Petrol., 83, 185–197.

GANGUIN, J. (1986): Reliques de faciès éclogitique dans les métasédiments polymétamorphiques: le cas d'un marbre de la couverture des ophiolites de la région de Zermatt, Alpes penniques, Suisse. C. R. Acad. Sci. (Paris), t. 303, série II, 575–580.

GANGUIN, J. (1988): Contribution à la caractérisation du métamorphisme polyphase de la zone de Zermatt-Saas Fee (Alpes Valaisannes). Ph. D. Diss. 8731, ETH-Zürich, 312 p.

GILLIÉRON, F. (1946): Geologisch–petrographische Untersuchungen in der Ni-Co-Lagerstätte Kaltenberg (Turtmanntal, Wallis). Beitr. Geol. Schweiz., geotechn. Ser. 25.

GOFFE, B. and CHOPIN, C. (1986): High pressure metamorphism in the Western Alps: zoneography of metapelites, chronology and consequences. Schweiz. Mineral. Petrogr. Mitt. 66, 41–52.

GOSSO, G., DAL PIAZ, G., PIOVANO, V. and POLINO, R. (1979): High-pressure emplacement of early-alpine nappes, postnappe deformations and structural levels (internal northwestern Alps). Mem. Ist. geol. Mineral., Univ. Padova, 32, 3–15.

GOUFFON, Y. (1990): Unités penniques moyennes au Val d'Aoste. Ph. D. Diss., Univ. of Lausanne.
GRÜTTER, O. (1929): Petrographische und geologische Untersuchungen in der Region von Bosco (Valle Maggia), Tessin. Verh. natw. Ges. Basel, 40, 78–152.
HAMMERSCHLAG, J.-G. (1985): Métamorphisme progressif dans la séquence quartzofeldspatique. Profil Aar-Bergell (Alpes Centrales). Ph. D. Diss., Univ. of Lausanne, 419 p.
HAMMERSCHMIDT, K. and FRANK, E. (1991): Relics of high pressure metamorphism in the Lepontine Alps (Switzerland) – $^{40}Ar/^{39}Ar$ and microprobe analyses of white mica. Schweiz. Mineral. Petrogr. Mitt., 71, 261–274.
HEINRICH, C. (1982): Kyanite-eclogite to amphibolite facies evolution of hydrous mafic and pelitic rocks, Adula nappe, Central Alps. Contrib. Mineral. Petrol., 81, 30–38.
HEINRICH, C. (1983): Die regionale Hochdruckmetamorphose der Aduladecke, Zentralalpen. Schweiz. Ph. D. diss. 7282. ETH-Zürich, 193 p.
HEINRICH, C. (1986): Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Alpine Adula nappe. J. Petrol., 27, 123–154.
HUNZIKER, J. (1974): Rb–Sr and K–Ar age determinations and the Alpine tectonic history of the Western Alps. Mem. Ist. geol. Mineral., Univ. Padova, 31, 1–55.
HUNZIKER, J. (1989): Eo-Alpine mylonitization in the Tambo-nappe. Abstract. Colloque Suisse métamorphisme, Neuchâtel, Febr. 1989.
HUNZIKER, J., DESMONDS, J. and MARTINOTTI, G. (1989): Alpine thermal evolution in the central and western Alps. In: COWARD, M.P., DIETRICH, D. and PARK, R.G. (editors), Alpine tectonics. Geol. Soc. Spec. Publ., 45, 353–367.
IROUSCHEK, A. (1983): Mineralogie und Petrographie von Metapeliten de Simanodecke unter besonderer Berücksichtigung der Cordierit-führenden Gesteine zwischen Alpe Sponda und Biasca. Ph. D. Diss., Univ. Basel, 205 p.
IROUSCHEK, A. (1985): Anzeichen einer alpinen Hochdruck-Metamorphose in Metapeliten der Simanodecke. Schweiz. Mineral. Petrogr. Mitt. 65, 118–119.
JAQUEMIN, C. (1990): Histoire tectono-métamorphique de la nappe de Dent Blanche. Ph. D. diss. Univ. of Liège, Belgium.
KOBE, H. (1956): Geologische und petrographische Untersuchungen in der Tessiner Wurzelzone zwischen Vergeletto-Onsernone und Valle Maggia. Schweiz. Mineral. Petrogr. Mitt., 36, 244–348.
KOCH, E. (1982): Mineralogie und plurifazielle Metamorphose der Pelite in der Aduladecke (Zentralalpen). Ph. D. Diss., Univ. Basel, 201 p.
KOONS, P.O. (1982): An investigation of experimental and natural high-pressure assemblages from the Sesia Zone, Western Alps, Italy. Ph. D. Diss. 7169, ETH-Zürich, 260 p.
KOONS, P.O. (1986): Relative geobarometry from high-pressure rocks of quartzofeldspathic composition from the Sesia Zone, Western Alps, Italy. Contr. Mineral. Petrol., 93, 322–334.
LADEUZE, F. (1988): Etude pétrologique et géothermobarométrique des éclogites de la zone d'Antrona, Alpes penniques. Diploma thesis, Univ. Louvain-la-Neuve, 87 p.
LADURON, D. and MARTIN, H. (1969): Coexistence de paragonite, muscovite et phengite dans un micaschiste à grenat de la zone du Mont-Rose (Valle Anzasca, Prov. di Novara, Italie). Ann. Soc. géol. Belg., 92, 159–172.
LAIRD. J. and ALBEE (1981): High-pressure metamorphism in mafic schists from Northern Vermont. Amer. J. Sci., 281, 97–126.
LARDEAUX, J.M., GOSSO, G., KIENAST, J.R. and LOMBARDO, B. (1982): Relations entre le métamorphisme et la déformation dans la zone de Sesia-Lanzo (Alpes occidentales) et le problème de l'éclogitisation de la croûte continentale. Bull. Soc. géol. France, 24, 793–800.
LOBRINUS, S. and BÉGLÉ, P. (1985): Géologie et pétrographie du Val Loranco (Antrona, Italie). Diploma thesis, Univ. of Lausanne.
MAGGETTI, M. and GALETTI, G. (1988): Evolution of the the Silvretta eclogites: metamorphic and magmatic events. Schweiz. Mineral. Petrogr. Mitt., 68, 467–484.
MARTINOTTI, G. and HUNZIKER, J. (1984): The Austroalpine system in the Western Alps: a review. Mem. Soc. geol. ital., 29, 233–250.
MASSONNE, H.J. and SCHREYER, W. (1987): Phengite geobarometry based on the limiting assemblage with K-spar, phlogopite, and quartz. Contr. Mineral. Petrol., 96, 212–224.
MEYER, J. (1983): Mineralogie und Petrographie des Allalingabbros. Ph. D. diss. Univ. of Basel, 303 p.
NIGGLI, E. (1973): Metamorphic map of the Alps, 1:100000. Unesco, Paris.
OBERHÄNSLI, R. (1978): Chemische Untersuchungen an Glaukophan-führenden basischen Gesteinen aus den Bündnerschiefern Graubündens. Schweiz. Mineral. Petrogr. Mitt., 58, 139–156.
OBERHÄNSLI, R. (1980): P-T-Bestimmungen anhand von Mineralanalysen in Eklogiten und Glaukophaniten der Ophiolithe von Zermatt. Schweiz. Mineral. Petrogr. Mitt., 60, 215–235.
OBERHÄNSLI, R. (1983): The P-T history of some pillow lavas from Zermatt. Ofioliti, 7, 431–436.
OBERHÄNSLI, R. (1986): Blue amphiboles in metamorphosed Mesozoic mafic rocks from the Central Alps. Mem. geol. Soc. Amer., 164, 239–247.
OBERHÄNSLI, R., HUNZIKER, J.C., MARTINOTTI, G. and STERN, W.B. (1985): Geochemistry, geochronology and petrology of Monte Mucrone: an example of eo-Alpine eclogitization of Permian granitoids in the Sesia Lanzo zone, Western Alps. Chem. Geol., 52, 165–184.
OBERHÄNSLI, R. and BUCHER-NURMINEN, K. (1987): Tectonometamorphic evolution of the Dent Blanche nappe. Terra cognita 7/2–3, 95. Abstract S01.41, EUG IV meeting Strasbourg.
PASSCHIER, C.W., URAI, J.L., VAN LOON, J. and WILLIAMS, P.F. (1981): Structural geology of the central Sesia-Lanzo zone. Geol. en Mijnbouw, 60, 497–507.
PFEIFER, H.R. (1981): A model for fluids in metamorphosed ultramafic rocks: III. Mass transfer under amphibolite facies conditions in olivine-enstatite rocks of the central Alps, Switzerland. Bull. (Franç.) Mineral., 104, 834–847.
PFEIFER, H.R. (1987): A model for fluids in metamorphosed ultramafic rocks: IV. Metasomatic veins in metaharzburgites of Cima di Gagnone, Valle Verzasca, Switzerland. In: HELGESON, H.C. (editor), Chemical transport in metasomatic processes, 591–632. Reidel Amsterdam.
PFEIFER, H.R., COLOMBI, A. and GANGUIN, J. (1989): Zermatt-Saas and Antrona zone: a petrographic and geochemical comparison of polymetamorphic ophiolites of the West-Central Alps. Schweiz. Mineral. Petrogr. Mitt., 69, 217–236.
PLAS, L. VAN (1959): Petrology of the northern Adula region, Switzerland. Leidse geol. Meded., 24, 415–602.

RÖTHLISBERGER, F. (1985): Etudes géologiques et pétrographiques du cirque de Breuil (Italie du Nord). Diploma thesis, Univ. of Berne.

ROST, F., WANNEMACHER, J. and ANTON, J. (1979): Garnet ultramafitites in the Ivrea zone and other crystalline zones along the periadriatic lineament. Mem. Ist. Geol. Mineral. Univ. Padova, 33, 183–191.

SANTINI, L. (1991): Geochemistry and geochronology of the high pressure parageneses from the Adula nappe, Central Alps, Switzerland. Ph. D. thesis, Univ. of Lausanne.

SARTORI, M. (1990): Géologie de la région du Barrhorn. Mémoires de Géol., 6, Lausanne, 156 p.

SCHÜRCH, M.-L. (1987): Les ophiolites de la zone du Versoyen. Ph. D. Diss. Univ. of Geneva, 159 p.

SCHÜRCH, M.-L., BERTRAND, J., CHESSEX et LOUBAT, H. (1986): Présence de l'omphacite dans la zone du Versoyen (Alpes franco-italiennes): implications structurales. Abstr. 4[e] réunion groupe tect. Suisse, Genève, déc. 1986.

STILLE, P. and OBERHÄNSLI, R. (1987): Petrology and alpine metamorphic evolution of the metabasic and ultrabasic rocks of the Berisal crystalline complex. Lithos, 20, 169–180.

STÜNITZ, H. (1989): Partitioning of metamorphism and deformation in the boundary region of the "Seconda Zona Dioritico-Kinzigitica", Sesia zone, Western Alps. Ph. D. Diss. 8817, ETH-Zürich, 244 p.

TEUTSCH, R. (1982): Alpine Metamorphose der Misoxer Zone (Bündnerschiefer, Metabasite, granitische Gneise). Ph. D. Diss. Univ. of Berne, 172 p.

THÉLIN, P., SARTORI, M., LENGELER, R. and SCHAERER, J.-P. (1990): Eclogites of Paleozoic or Early-Alpine age in the basement of the Penninic Siviez-Mischabel nappe, Wallis, Switzerland. Lithos, 25, 71–88.

TROMMSDORFF, V. (1966): Die Metamorphose kieseliger Karbonatgesteine in den Zentralalpen zwischen Bernina und Simplon. Schweiz. Mineral. Petrogr. Mitt., 46, 431–460.

VANNAY, J.-C. and ALLEMANN, R. (1990): La zone du Combin dans le haut Valtournanche. Eclogae geol. Helv., 83, 21–39.

VINARD, P. (1986): Géologie et pétrographie du Laggintal (Valais). Diploma thesis, Univ. of Lausanne, 236 p.

VUICHARD, J.-P. and BALLÈVRE, M. (1988): Garnet-chloritoid equilibria in eclogitic pelitic rocks from the Sesia zone (Western Alps): their bearing on phase relations in high-pressure metapelites. J. metamorphic. Geol., 6,135–157.

WAHLI-WENGER, J. (1985): Etudes pétrographiques et minéralogiques du versant entre Mittaghorn et Egginer (Val de Saas, Valais). Diploma thesis, Univ. of Lausanne, 199 p.

WUST, G. and BAEHNI, L. (1986): The distinctive tectonometamorphic evolution of the two basement complexes belonging to the Grand-Saint-Bernard nappe (Val de Bagnes, Valais). Schweiz. Mineral. Petrogr. Mitt., 66, 53–71.

ZINGG, M. A. (1989): Die Siviez-Mischabel-Decke: Entstehung und Entwicklung eines Altkristallins und seine Vererzungen. Ph. D. Diss. 8997, ETH-Zürich, 170 p.

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