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The metagabbros of the Kastelhorn area (Gotthard massif, Switzerland): their metamorphic history inferred from mineralogy and texture

by *Jürgen Abrecht*[1], *Giuseppe G. Biino*[2]

Abstract

Mineral assemblages from a large gabbro body in the Kastelhorn area (Gotthard massif, central Switzerland) are described. Numerous relic textures and occasional relic compositions are found. The textures are compared to textures from mafic rocks in the Gotthard massif where relic mineral compositions allow the derivation of the P-T-t path. Typical textures are symplectites and coronites. They show the replacement of primary magmatic assemblages by high-P minerals and subsequent assemblages of granulite and amphibolite facies. Retrograde overprint at greenschist facies conditions is generally weak. Relic minerals indicating an eclogite facies event are symplectites with sodic clinopyroxene + plagioclase and kyanite inclusions in garnet and plagioclase. The dominant amphibolite facies mineral assemblage is hornblende + plagioclase + garnet ± quartz ± biotite.

Keywords: metagabbro, relic texture, symplectite, coronite, metamorphic evolution, Gotthard massif, Central Alps.

Introduction

In the Gotthard massif of the central Swiss Alps, mafic rocks with mineralogical and textural relics that unambiguously indicate former eclogite-, granulite-, and amphibolite facies conditions were reported from the pre-Alpine basement in the Furkapass area, the Val Nalps, the Val Maighels, the Unteralptal (Rossbodenstock, Gafallen), and the Val Sumvitg (ABRECHT et al., 1991 a, b; BIINO, 1992). These rocks still display relic mineral parageneses allowing the reconstruction of their P-T-t evolution due to their suitable chemical and mineralogical composition. In the Kastelhorn area to the west of the Unteralptal, gabbroic rocks with very similar textures, but less abundant paragenetic relics were found. Relic textures and even more pronounced relic mineral assemblages usually are very difficult to interpret unambiguously.

However, based on the evidence obtained from other localities, the Kastelhorn metagabbros despite their very complex textures are still very meaningful with respect to their multiphase early metamorphic history. Such rocks necessarily reflect chemical equilibrium only on a local scale. Nevertheless, by a thorough comparison of mafic rocks within the same tectonic and geologic unit but with variable degrees of retrogression even strongly recrystallized rocks can be used to trace their metamorphic evolution. Thus, the purpose of this paper is not to present the P-T-t path of the Gotthard massif basement but rather to demonstrate the usefulness of certain rocks with no or only rare relic minerals in deciphering their history based primarily on relic textures.

Geological setting and petrography

The gabbroic rocks of the Gotthard massif generally occur as small bodies or inclusions within abundant metasedimentary biotite-plagioclase gneisses and migmatitic quartzo-feldspathic gneisses that constitute the "Gurschen gneiss" series along the northern half of the massif. The

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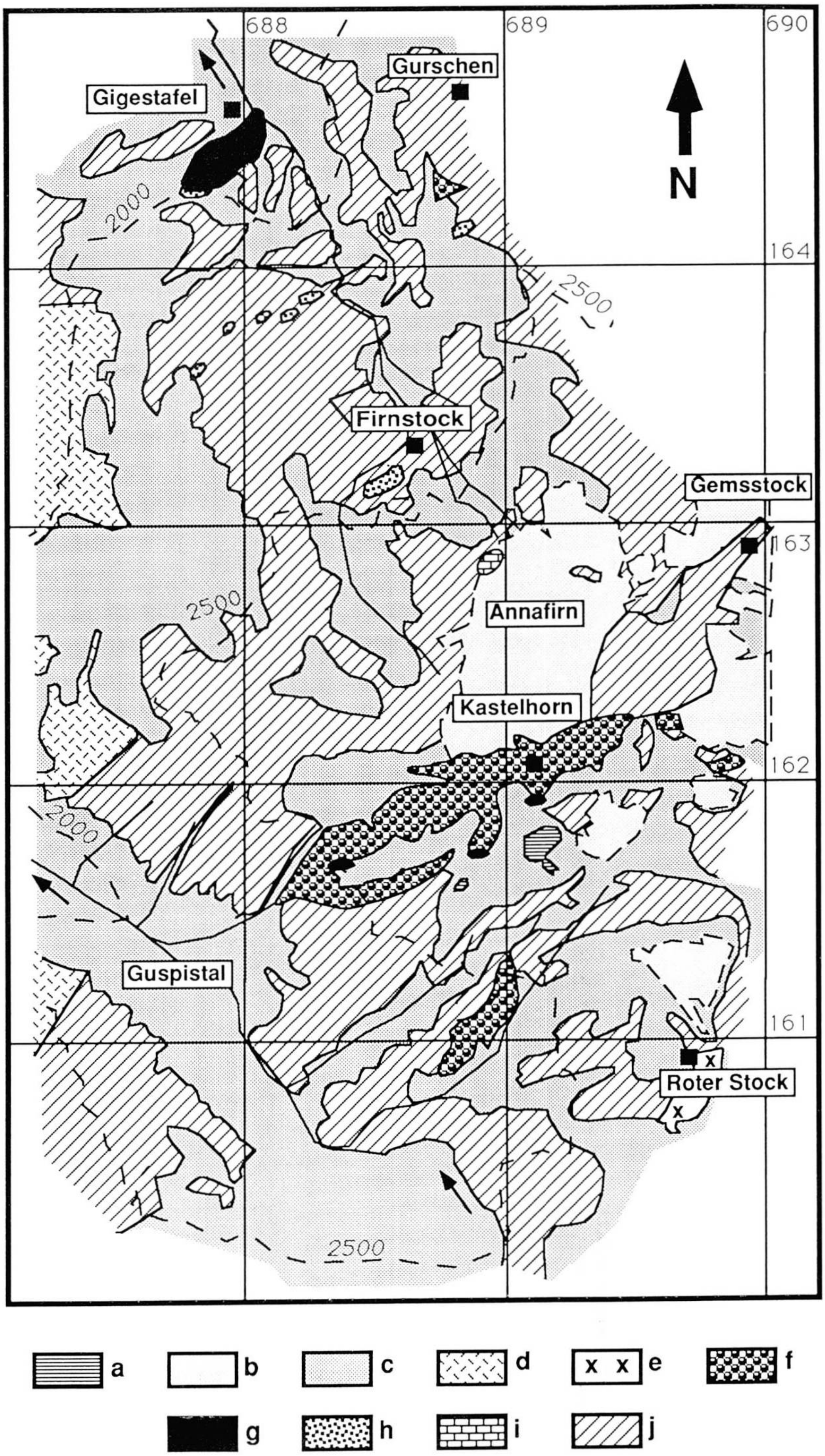


Fig. 1 Simplified geologic map of the Guspistal-Kastelhorn-Annafirn area.
a: Lakes; b: Glaciers; c: Quaternary; d: Gamsboden Granite (Late Variscan); e: Ordovician orthogneisses ("Streifengneis"); f: Gabbros; g: Ultramafic rocks; h: Amphibolites; i: Marbles; j: Paragneisses ("Gurschengneis").

Tab. 1 Mineral assemblages from gneisses.

Sample	Assemblage	Percent An in Plag	Remarks
Gi 38	Plg + bio + qtz + gt + musc + chl + ore + zirc + clz	≈ 40	Muscovite: X_{Mu} = 0.9
Gi 57	Plg + bio + qtz + gt + amph (tschermak. hbl) + musc + chl + clz + ore + zirc + ap	≈ 15 (and 25: 2 generations?)	Bio : hbl(bluish-green) ≈ 1 : 1
Gi 61	Plg + bio + qtz + gt + amph (Fe–Al hbl) + chl + ore + zirc + clz	25–38 (≈ 30)	Fine grained. Hbl: dirty green to bluish green
Gi 64	Plg + bio + qtz + gt + musc + chl + ore + zirc + clz	19–29 (≈ 22)	with calc-silicate lens strongly zoned gt
Gi 65	Plg + bio + qtz + musc + gt + chl + opaque + zirc + clz	≈ 22	Musc-rich Old garnet relics (gt1: $Alm_{75}Gr_{02}$) in idiomorphic garnet (gt2: $Alm_{57}Gr_{26}$)
AJ 1053	Plg + bio + qtz + gt + zirc + clz/ep	20–40	Slightly zoned gt

gneissic rocks have been described in detail by AMBÜHL (1929). AMBÜHL labeled the gabbroic rocks as amphibolites and did not refer to their conspicuous coronitic textures. Field evidence suggests the presence of at least two generations of gabbros. One of these (the older) is in tectonic contact with the country rock and is generally associated with deformed layered ultramafic rocks. No xenoliths of country rock have been observed in this unit. The other generation of gabbros consists of small intrusive bodies within basement rocks; such bodies do contain metasedimentary calc-silicate xenoliths. Based on textural and chemical features, associated ultramafics are believed to be cumulates (BIINO and MEISEL, 1993). The first generation was interpreted as representing a member of an ophiolite sequence and the second one as a basaltic melt of island-arc affinity.

At the Kastelhorn, gabbroic rocks consisting of plagioclase, hornblende, and garnet form a large elongate body covering an area of about 0.4 km^2 (Fig. 1). This lensoid body extends in a southwest-northeast direction. Smaller bodies with mylonitic contacts were also found in the Guspis Valley and small gabbroic and amphibolitic lenses are quite frequent on the northern side of the Kastelhorn (Firnstock). A strongly deformed contact with the surrounding gneisses is only exposed along the southeastern border in the main gabbro body. The northern contact is mostly hidden under the Annafirn Glacier, but abundant blocks do not show any evidence for a mylonitic contact. Single-crystal U–Pb ages from abraded zircons in retrograded eclogitized metagabbros yielded ages of 468 ± 2 Ma (OBERLI et al., 1993). The country rock consists of biotite-plagioclase gneiss, garnet micaschists, augen-gneiss and gneiss with variable amounts of hornblende and/or garnet. Gneiss of granitic composition ("Streifengneis": metagranite intrusions of Late Ordovician age; ARNOLD, 1970; BOSSART et al., 1986; SERGEEV and STEIGER, 1993) occurs farther to the south, but is never in contact with the gabbros. Within or along the gabbroic body, small lenses of metaperidotites occasionally occur. The gabbro itself is rather inhomogeneous with coarser grained portions irregularly alternating with finer grained ones. Locally, the presence of coarse-grained discordant leucocratic veins or pods makes the unit appear migmatitic. The leucocratic component mainly consists of plagioclase and quartz with variable proportions of amphibole and biotite. Minor dark lenses are interpreted as strongly deformed mafic dikes.

The gneisses

Gneisses of the area have been described in detail by AMBÜHL (1929). Some typical parageneses and mineralogical data are given in table 1.

Of some interest are the amphibole-bearing gneisses adjoining the gabbro body along its southern flank (Sample Gi 57). They are in part separated from the gabbro by a mylonitic zone consisting of a garnet-rich hornblende gneiss which most likely was derived from the gabbro. These amphibole-bearing gneisses might represent the external part of the gabbro which, unlike its internal part, was strongly recrystallized during retrograde metamorphism. This interpretation was drawn from field evidence and based on biotite compositions in the mylonitic zone interme-

Tab. 2 Mineral assemblages and main characteristics of the three gabbro types in the Kastelhorn area.

Gabbro type	Characteristics	Mineral assemblages
Type i: "Normal" gabbro Gi 13, 18, 42, 43, 46, 70	Undeformed, mesocratic. Sporadic or minor coronitic textures, rare coarse grained symplectites	Plag + amph + gt + qtz ± bio Ap, zirc, clz, chl, ilm, rut, preh
Type ii: Coronitic mesogabbro Gi 16, 45, 47, 55	Undeformed, locally leucocratic. Coronitic textures common -> troctolitic texture. Amph-qtz-symplectites in cores of coronas	Plag + amph + gt + qtz + bio Ap, zirc, mon, clz, zo, chl 2 generations of plag, 3 generations of amph, 3 generations of bio
Type iii: Coronitic melagabbro Gi 21, 27, 28, 48, 69, 93	Undeformed, melanocratic. Corona textures and symplectites common (plag-amph ± cpx)	Plag + amph + gt ± cpx Qtz, bio, zo, ky, ap, zirc, musc, marg, 3 generations of plag, 3 generations of amph

diate between typical biotite compositions in the gneiss and the gabbro (Fig. 2).

Mineralogical composition and texture of the metagabbro

Based on textural and mineralogical evidence, three major rock types can be distinguished: (i) "normal" non-coronitic gabbros, (ii) coronitic mesogabbros, and (iii) coronitic melagabbros. Mineral assemblages and the main chracteristics of the three types are summarized in table 2. Relic textures and mineral assemblages are abundant in the melagabbros and flaser gabbros (iii), somewhat less abundant in the coronitic gabbros (ii), and even less common in the "normal" gabbros (i) (Figs 3–6). This indicates a more advanced state of re-equilibration (both textural and mineralogical) for the "normal" gabbros. In the field the three types occur within short distances and may represent variable degrees of deformation/recrystallization, fluid availability, and primary differences in bulk composition.

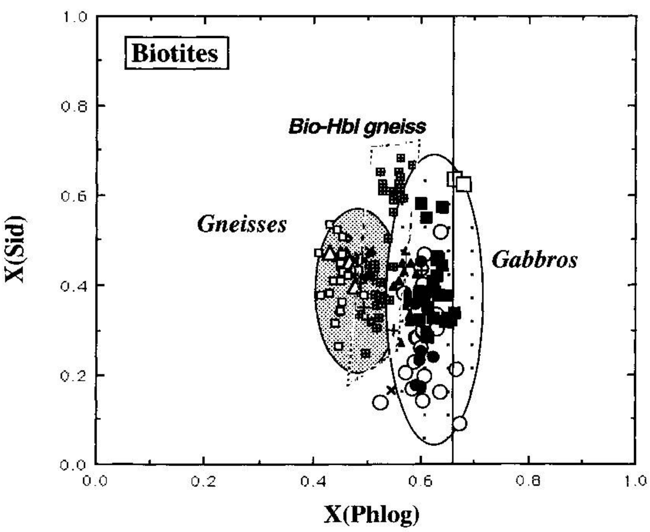


Fig. 2 Biotite compositions from gabbros and gneisses. Biotites from hornblende gneisses are intermediate between biotites from gabbros and bio-gt gneisses.

Relic textures and their interpretation

Because the most important relics are coronas and symplectic intergrowths found dominantly in the melagabbros (type iii) and to a lesser degree in the coronitic mesogabbros (type ii), only a few relic textures or minerals typical of the gabbro types (i) and (ii) are described. These are rutile inclusions in garnet (type i), corroded apatites (type ii), inclusion-rich biotite (type ii), amphibole and/or garnet coronas (type ii). The melagabbros, being least re-equilibrated and exhibiting different corona types and abundant symplectic intergrowths, are treated in more detail.

INCLUSIONS IN GARNET

Garnet is a major phase in the non-coronitic gabbros. It contains tiny rutile inclusions in clusters. Single clusters consist of well oriented grains clearly representing the outlines of a former mineral phase such as pyroxene or amphibole. No sagenite-type patterns characteristic for biotites were observed. Small relic plagioclase grains also occur in the core of strongly altered garnets. In contrast to matrix plagioclase with a range in anorthite content between 35 and 60 mole percent plagioclase inclusions typically have An-values

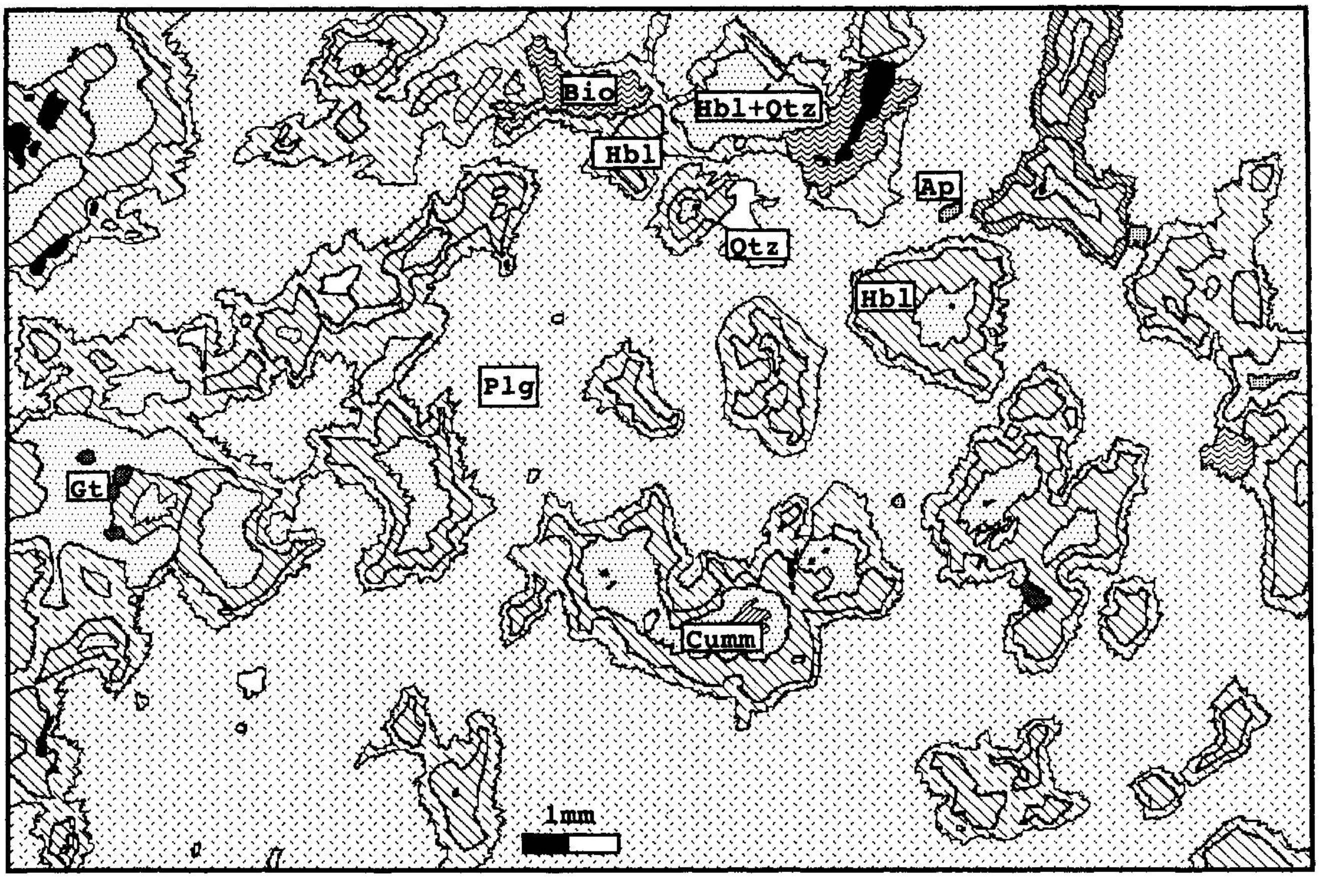


Fig. 3 Primary magmatic texture preserved in coronitic mesogabbro. Amph-qtz intergrowths (symplectites) form irregular patches (occasionally with cummingtonite relics) surrounded by two-amphibole coronas (amph 2 and amph 3). Matrix: plagioclase. Other phases: Qtz, bio, ap, ilm, gt.

around 90 mole percent. These high An values may, to a certain extent, still reflect equilibrium compositions attained during the first metamorphic event at the time of garnet growth. However it appears more likely that the same re-equilibration occurred during a subsequent high-T event.

OXIDE INCLUSIONS IN BIOTITE

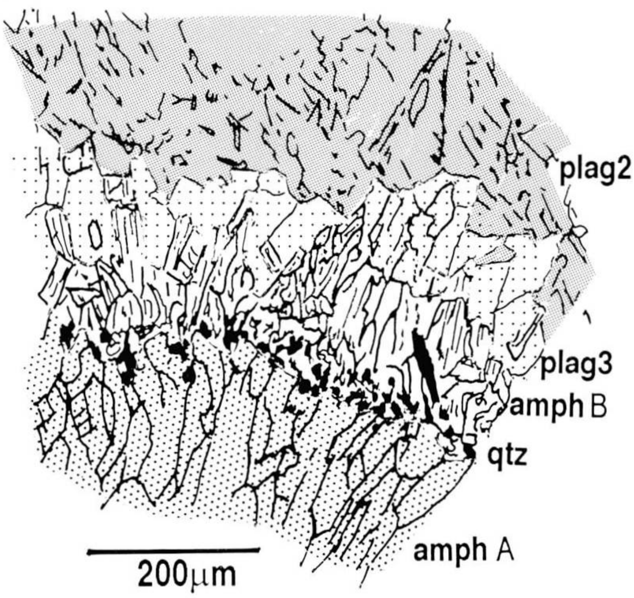
Non-coronitic gabbros often contain small amounts of reddish-brown biotite occurring in clusters up to 20 mm in size. Many of these biotites include skeletal grains of ilmenite oriented along crystallographic planes of the host mineral. Garnet overgrows both the biotite and the oxide inclusions. These Ti-rich biotites predate the garnet.

CORRODED APATITES

Large grains of apatite, often quite abundant in the coronitic gabbros are of special interest. In mela- and mesogabbros the phosphate mineral is a fluorapatite with fluorine contents between 0.6 and 1.0 F per formula unit.

Two features deserve to be mentioned here: First, the apatite grains often show indentations otherwise typical of corroded quartz grains in extrusive volcanic rocks. Secondly, the grains have a thin rim of epidote or garnet (Fig. 7). This rim is present only along the contact with plagioclase or amphibole, but never along apatite-quartz grain boundaries. We believe that these rims result from a reaction between apatite and surrounding plagioclase.

Inclusions in garnet, Ti-rich biotite and corroded apatites are interpreted as related to a very early stage in the evolution of the gabbros. The inclusions in the garnet (Ti-augite?) as well as the corroded apatites probably are phases or features of the magmatic stage. Biotite containing Ti-rich inclusions (ilmenite) and overgrown by garnet or amphibole, may be a relic primary magmatic biotite.

a


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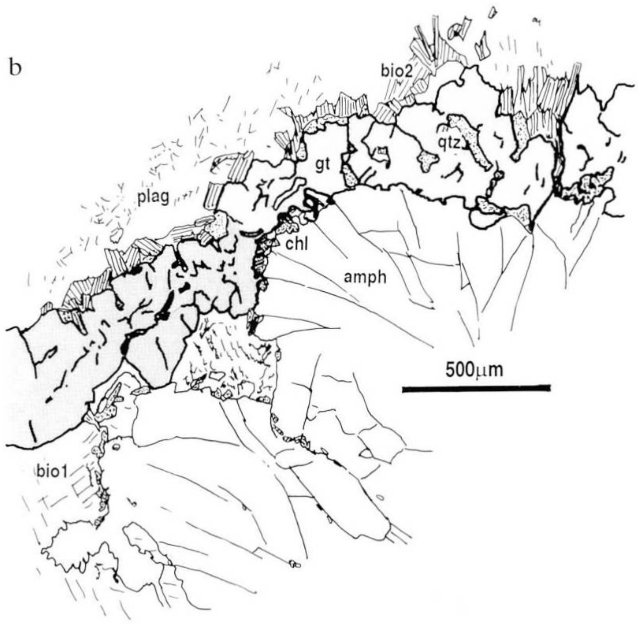

Fig. 4 Thin section drawings of amphibole coronas. (a) Detail from amphibole corona. Core: large grains of hornblende or cummingtonite (A) ± quartz. Inner rim: quartz. Outer rim: small grained hornblende (B; former orthopyroxene?) + plagioclase (3). Matrix: plagioclase (2) with clinozoisite/sericite inclusions.
(b) Detail from amphibole-garnet corona. Core: cummingtonite or hornblende + biotite. Rim: garnet (reacting to chlorite and green biotite).

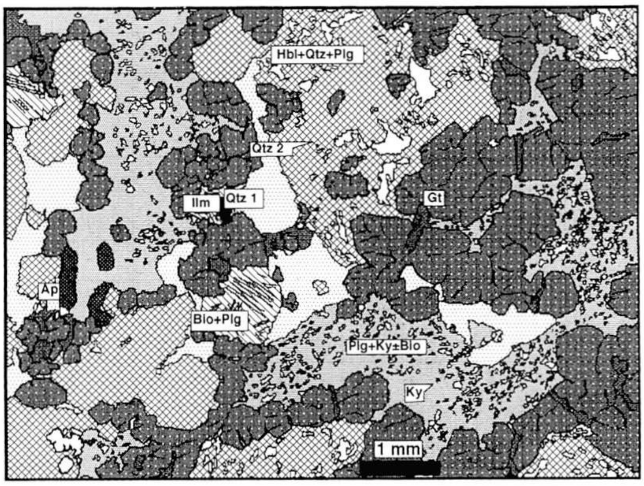

Fig. 5 Garnet-rich melagabbro with coronite-symplectite texture. Plagioclase with numerous kyanite and biotite inclusions. Garnets form reaction zone (corona) between former pyroxene (now: hornblende symplectite) and plagioclase.

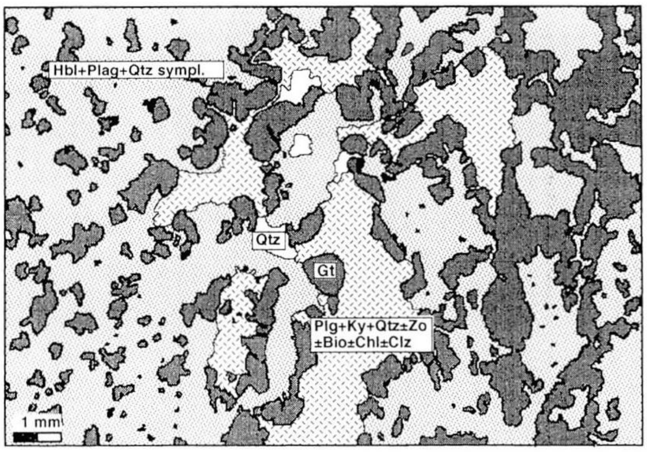

Fig. 6 Melagabbro with coronite-symplectite texture. Plagioclase with numerous kyanite and biotite (± chl ± clz) inclusions. Note the garnet corona between plagioclase and hornblende-plagioclase symplectite.

Coronitic and symplectic textures in the gabbros

Coronas are the most striking macroscopic features of the coronitic meso- and melagabbros. There are two distinct corona types: The first one consists of amphibole coronas surrounding a core of symplectic, locally quite coarse grained, amphibole + quartz.

The second type is characterized by garnet coronas surrounding symplectic amphibole-plagioclase (± quartz) cores. While the first one is typical of the type (ii) gabbros, the second one is found solely in type (iii) gabbros.

AMPHIBOLE CORONAS (IN TYPE ii GABBROS)

The coronitic gabbros of type (ii) have preserved a texture often found in troctolites. The typically concave shape of the coronas is probably a relic of primary magmatic texture. The coronas are characterized by generally two, occasionally up to

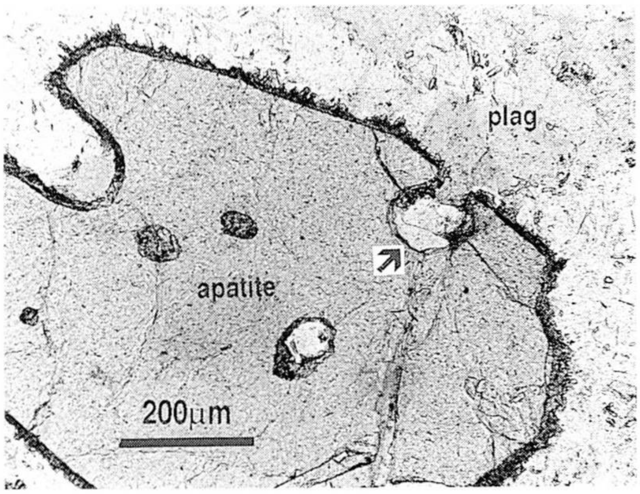

Fig. 7 Photograph of large apatite grains with reaction rims along apatite-plagioclase contact. No rim is present along apatite-quartz contact (arrow).

three, amphiboles in distinct microstructural sites and of different size, color and orientation (Fig. 3). The corona amphiboles usually show a distinctive radial orientation. Their color changes from very pale in the core to a bluish-green or green in the rim. The amphibole coronas are frequently rimmed by a corona of green biotite and/or chlorite. In the corona garnet may occur instead of amphibole.

The matrix consists of two generations of plagioclase distinguished by textural characteristics. An older generation consists of large xenomorphic grains, always filled with randomly oriented thin clinozoisite needles (the same feature is observed in bio-plag gneisses of the basement). The zoisites were probably formed during the high pressure phase and later overgrown by plagioclase which replaced high pressure clinopyroxenes as described by BIINO and COMPAGNONI (1992). According to RUBIE (1990), this texture typically indicates breakdown of high pressure plagioclases. These plagioclase grains have very irregular curved grain boundaries. They are frequently replaced by plagioclase with a typical granoblastic polygonal texture ("mosaic texture"). This younger generation of plagioclase contains few inclusions, but is generally twinned and displays smooth grain boundaries. Irregular patches of quartz (< 5 vol percent) are randomly distributed. Minor brown biotite and round apatite (see preceeding section) occur in the matrix or are overgrown by the coronas. Primary mineral phases and chemical differences have mainly been obliterated by later re-equilibration at lower metamorphic conditions. However, occasionally relic amphibole compositions remain.

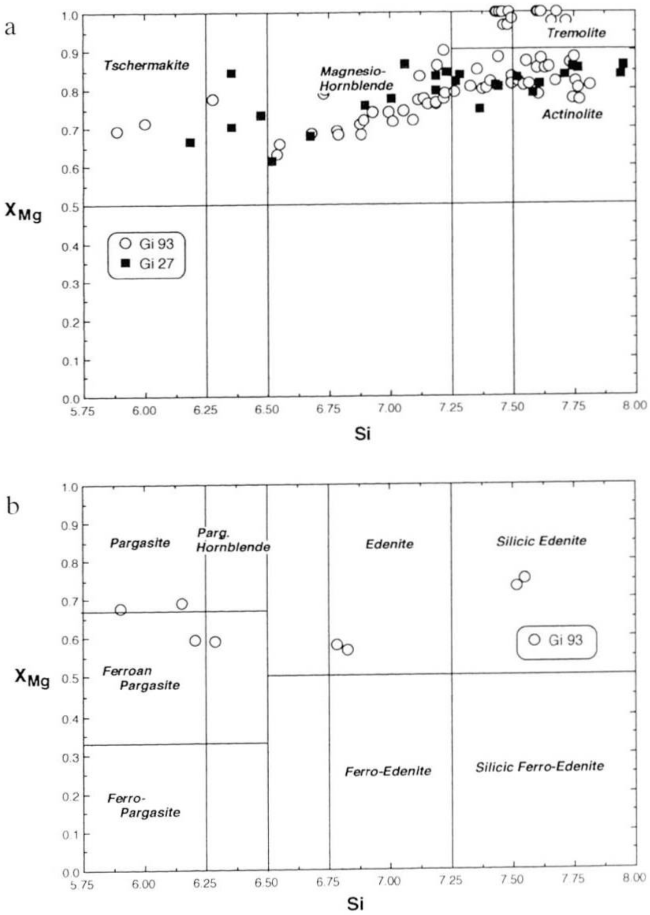

Fig. 8 Amphibole compositions from melagabbros. (a) for $(Na+K)_A < 0.5$, (b) for $(Na+K)_A > 0.5$. Amphibole nomenclature was calculated according to ROCK and LEAKE (1984).

SYMPLECTIC INTERGROWTHS (IN MESO- AND MELAGABBROS OF TYPE ii AND iii)

Meso- and melagabbros consist of plagioclase, garnet and amphiboles with minor quartz, biotite and accessory minerals. Amphiboles either occur as recrystallized idiomorphic to hypidiomorphic grains or in symplectic intergrowths with plagioclase, quartz and less abundant clinopyroxene or clinozoisite. Obviously, the symplectites represent the least recrystallized textural state. Amphiboles in symplectites typically display a complex compositional zoning that indicates that equilibrium was not reached even at grain size scale (Fig. 11).

MINERAL CHEMISTRY

Amphiboles: Amphiboles in symplectites and corona amphiboles always have compositions consistent with the tschermakite-magnesio-hornblende series, sometimes even ranging into the actinolite field (Fig. 8). Rarely, amphiboles of edenitic or pargasitic compositions or relic cummingtonite cores are observed. Mostly, there is a continuous series between tschermakitic and actinolitic compositions. This continuous series may be only apparent due to the fine intergrowth of the two phases. Occasionally, there is a distinct bimodal distribution indicating a miscibility gap between the two members.

Rarely, up to three amphibole compositions are observed in a single amphibole pseudomorph after magmatic amphibole or, more likely, pyroxene (Fig. 9). The oldest one, only preserved in the core, is an almost colorless cummingtonite coexisting with quartz. It is replaced by a green hornblende with different orientation which is itself rimmed by needles of pale green actinolite. These three compositions probably each represent one of the three latest metamorphic stages rather than a compositional gradient or local equilibrium.

Plagioclase: The two plagioclase generations distinguished texturally do not show significant differences in composition. The An-content roughly ranges from An_{42} to An_{52} with a mean An_{47} value.

Biotite: Minor reddish-brown biotite occurs in the matrix as large flakes. Their X_{Fe} ranges from 0.35 to 0.45. X_{Ti} is around 0.04. Light-green biotite with X_{Ti} equal to 0.025 occurs as a retrograde product of corona garnet. A slight correlation between Al and X_{Fe} indicates a Tschermak-type substitution.

Garnet: Garnet is rich in the almandine component (around 65 to 70 mol percent). Pyrope content varies between 15 and 20 mol percent. X_{Sp} is generally low (< 4 mol percent). There is a considerable range in grossular content from 7 to 20 mol percent. Though single grains are not homogeneous, a clear zonation is not usually observed. Rims are higher in pyrope and lower in grossular (Fig. 10).

Clinopyroxene: Clinopyroxenes are only preserved in hornblende-plagioclase symplectites. They are calcic pyroxenes with X_{Di} in the range 0.75 to 0.85, and jadeite component below 10 mol percent (samples Gi 93 and Gi 69, table 3).

TEXTURAL INTERPRETATION

Garnet is clearly a product of the reaction between a mafic phase (pyroxene or amphibole) and matrix plagioclase. Garnet growth may have occurred simultaneosly with growth of rim amphibole or pyroxene, respectively, and of brown biotite. Quartz occurs as a primary phase (1), as small inclusions in amphibole cores (2), as a minor phase in the corona rims (3a) or, more frequently, together with amphibole in symplectites (3b). It may have been formed during the decomposition of primary magmatic phases or high pressure phases. For example, quartz growth could result from a reaction such as

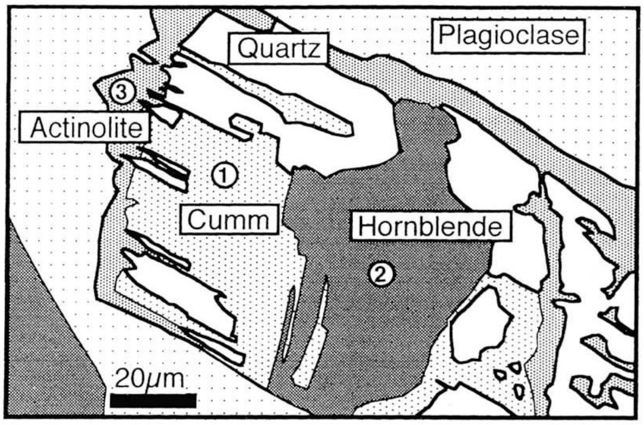

Fig. 9 Amphibole crystal from mesogabbro (after SEM micrograph). Three generations of amphiboles are observed. 1: Cummingtonite, 2: Hornblende, 3: Actinolite

$$\text{opx/cpx} + \text{Ca-plag}\ (1) + H_2O = \text{hbl} + \text{qtz}\ (2) \qquad [1]$$

Hornblende-quartz symplectites may have formed by replacement of the granulite facies plagioclase, brown hornblende, orthopyroxene/clinopyroxene and biotite assemblage:

$$\text{pyx/amph}\ (1) + \text{Ca-plag}\ (\pm\ \text{Fe–Ti oxides}) = \text{amph}\ (2) + \text{gt} + \text{bio}\ (2) + \text{qtz}\ (3) + \text{Na-plag} \qquad [2]$$

Such symplectites still containing relic orthopyroxene attributed to granulite metamorphism were observed in a fine-grained eclogite from the Val Nalps (ABRECHT et al., 1991a). In some samples, a transition from clinopyroxene-bearing symplectites to amphibole symplectites is observed. A model reaction similar to [2] was proposed by BARINK (1984) for the granulite-amphibolite transition in gabbroic rocks of the Labrador trough. BARINK advocated the simultaneous growth of coronitic garnet (between primary hornblende and plagioclase) and emphasized the "location-bound" occurrence of secondary hornblende and garnet. This model can be applied to the formation of coronitic garnets in gabbros of type (ii) as shown in figure 3.

Where large primary quartz grains are in contact with hornblende in the core of coronas, no rim has developed.

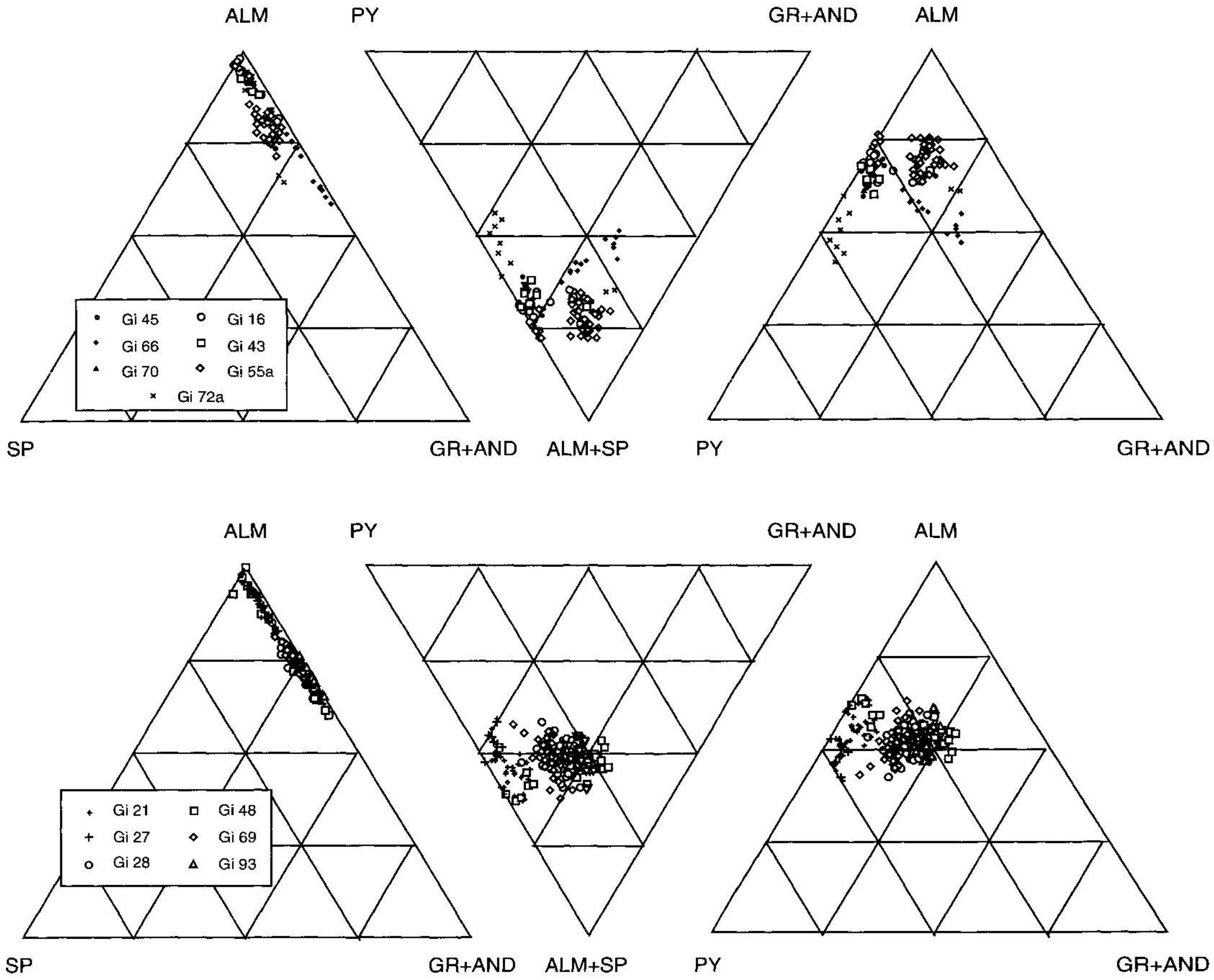

Fig. 10 Garnet compositions from different gabbro types.

Garnet coronas (in coronitic melagabbros of type iii)

Type (iii) gabbros display more complex textures than the other types. They have also preserved more relics of earlier metamorphic stages. While coronas in type (ii) gabbros generally are isolated patches completely surrounded by matrix plagioclase, coronas in the melagabbro have a highly irregular shape (Fig. 5). Together with symplectites they are the characteristic textural features of the melagabbros.

Because of preservation of disequilibrium assemblages relic minerals and mineral compositions are more frequently observed in this gabbro than in other gabbro types.

The melagabbro displays a particularly marked separation of mafic and leucocratic minerals. This may in part be due to primary processes but probably mostly results from metamorphic recrystallization. The leucocratic plagioclase-rich portions of the melagabbro are separated from the amphibole symplectites by a rim of garnet which appears to have formed by reaction between plagioclase and an earlier mafic phase, most likely a pyroxene. Garnet forms a peculiar texture, generally referred to as "honey comb" texture.

MAJOR MINERAL PHASES AND MINERAL CHEMISTRY

Up to three generations of plagioclase, amphibole and biotite occur in the melagabbro. It is not clear whether more than one generation of garnets is present. In plagioclase-rich areas, garnet occurs as idiomorphic grains with cores extremely rich in inclusions. Generally, however, garnet has irregular rims around the coronas and corroded, but originally idiomorphic faces against plagioclase and xenomorphic grain boundaries with the amphiboles.

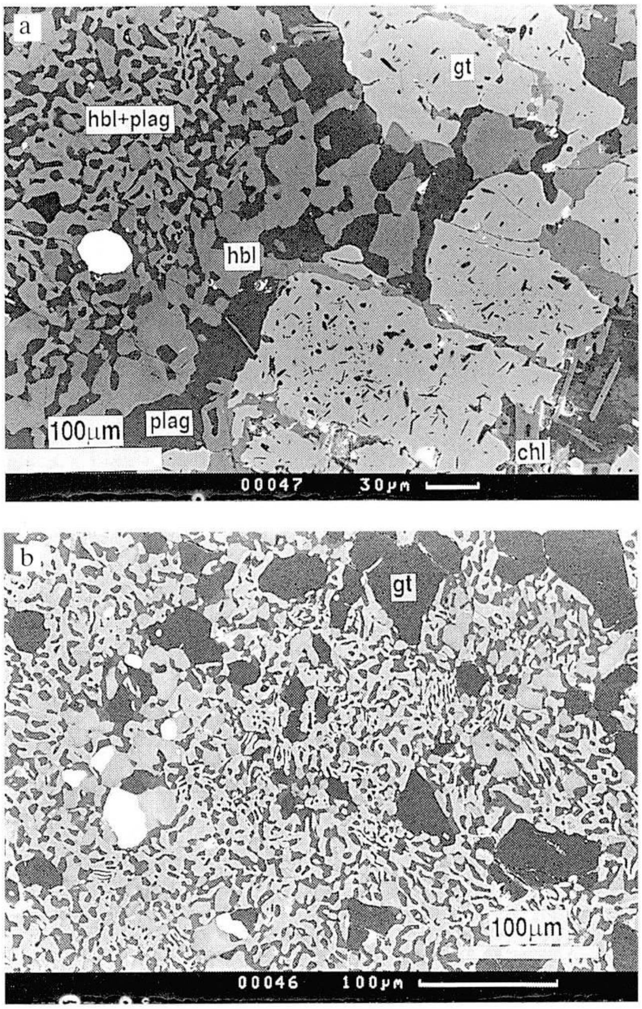

Fig. 11 a) SEM micrograph of amphibole-plagioclase symplectite with coarse-grained rim of amphibole (sligthly zoned). Grey: Garnet with kyanite inlusions (white: rutile). Between garnet and symplectite: plagioclase (sample Gi 69). b) SEM micrograph of amphibole-plagioclase-clinopyroxene symplectite (sample Gi 69). Dark grey: Garnet. White: ilmenite.

These features are especially revealing with respect to the evolution of the gabbros:

(a) Plagioclase occurs in different microstructural environments indicating different modes of formations: in the core of corona garnets, as a decomposition product of garnet, in rims around garnets (Fig. 11 a), in symplectic intergrowths with amphibole (Fig. 11 a, b), and as a matrix phase displaying a cloudy appearance, or often, as chessboard plagioclase. Inclusions of quartz, kyanite, and zoisite are abundant. Plagioclase compositions display a strong scatter corresponding to their textural site and coexisting phases. Details are given below.

(b) Amphiboles are coloured from greenish-brown to light green or colourless. The colour variation indicates transformation from fine grained symplectic amphiboles to coarse grained symplectites and eventually to large grains exhibiting crystal faces. However, large amphibole crystals (50–100 μm) do not always recrystallize from symplectites, but rather coexist with fine-grained amph-plag-qtz symplectites. Such variations in composition also occur in the other gabbro types. Tschermakitic to magnesio hornblende compositions pass into actinolitic composition. SEM imaging revealed irregular intergrowths between amphibole phases; these represent either relic non-equilibrium compositions, or two-phase equilibrium assemblages. Generally, symplectic amphiboles are zoned (Fig. 11a).

(c) Garnet has preserved inclusions of several mineral phases (plagioclase, zoisite, kyanite, and quartz) which represent earlier metamorphic stages. Garnet is distinguished compositionally from garnet in non-coronitic gabbro and mesogabbro by its higher pyrope and slightly lower spessartine content.

(d) Biotite occurs either as large reddish-brown flakes containing ilmenite inclusions, as symplectic intergrowths with chessboard plagioclase, or as a retrograde alteration product of garnet. There exists no compositional difference to biotites from the other gabbro types. All biotites have X_{Mg} relatively constant, around 0.55 to 0.65.

LOCAL EQUILIBRIUM MINERAL ASSEMBLAGES AND THEIR MINERAL COMPOSITIONS

Plagioclase + kyanite + zoisite (± margarite-paragonite-muscovite$_{ss}$): Plagioclase in the melagabbro looks quite different from plagioclase in other gabbro types. The melagabbro plagioclases do not occur in mosaic texture or as large xenomorphic grains with abundant radiating aggregates of clinozoisite. They are cloudy with abundant inclusions of drop-like quartz and irregularly distributed xenomorphic kyanite. The range in plagioclase composition is quite wide (10 to 90 mol percent An component) but it is dominantly between 25 and 50 mol percent. The scatter is significantly larger than in coronitic gabbros with compositions between 42 and 53 mol percent. The cloudy appearance of the plagioclases is an effect of variations in anorthite content as revealed by SEM imaging. Areas low in anorthite component are included in a matrix slightly higher in An (by about 5 mol-percent). The texture indicates a replacement of the low-An by the high-An plagioclases.

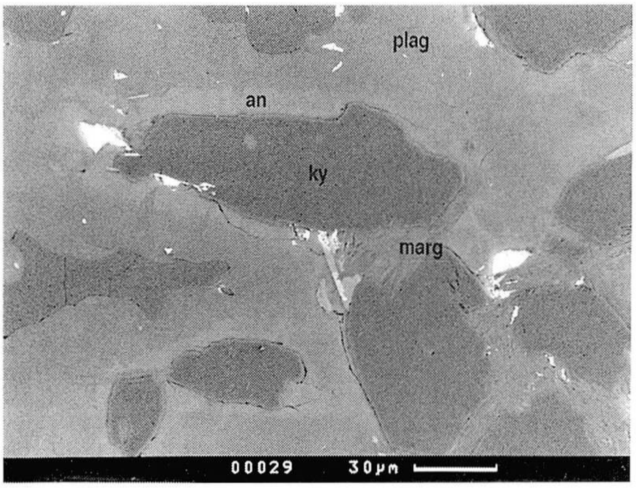

Fig. 12 SEM micrograph of relic kyanite (ky) with anorthite (an) + margarite (marg) decomposition products in Na plagioclase matrix.

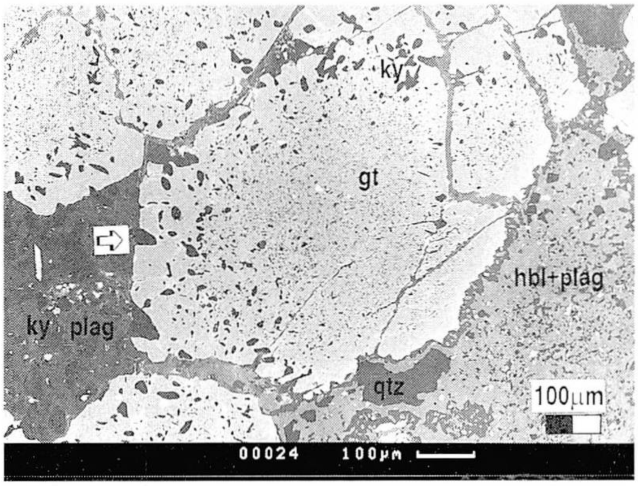

Fig. 14 SEM micrograph of kyanite inclusions (dark grey) in garnet. Note increasing size of crystals from core to rim. Largest grains in plagioclase matrix are only partially overgrown by garnet (arrow). No kyanite is formed along symplectite after former pyroxene (lower right).

Plagioclase with highest An-contents (up to 90 mol-percent) occurs in kyanite rims (Fig. 12). Such textures strongly indicate plagioclase formation at the expense of kyanite according to the reaction:

ky + zo = marg + an [3]

Micas grown by decomposition of kyanite and zoisite are margarite-paragonite-muscovite solid solutions (Fig. 13). They exhibit a miscibility gap between members rich in muscovite (15 to 25 mol-percent paragonite) and members rich in margarite (10 to 50 mol-percent paragonite).

Kyanite occurs either as inclusions in garnet and, more rarely, in zoisite or in plagioclase together with drop-like quartz and secondary phases. Kyanite inclusions in plagioclase are never needle-like, but rather short and rounded or have a corroded prismatic habit and abundant twinning (Fig. 14). Generally inclusions in garnet cores are needle-like, while along the edges of the garnet, they occur predominantly as larger crystals with columnar and rounded shapes. Kyanite inclusions are concentrated where garnet is in contact with plagioclase and decrease in abundance towards boundaries with amphibole (i.e. former pyroxene) grains. The shape of kyanite grains suggests that kyanite is not in equilibrium with the plagioclase. These textures strongly indicate a very early formation of kyanite and zoisite, simultaneous with or even preceding garnet growth in sites where sufficient alumina was available. Kyanite might represent an early prograde breakdown phase of calcic plagioclase, according to the reaction

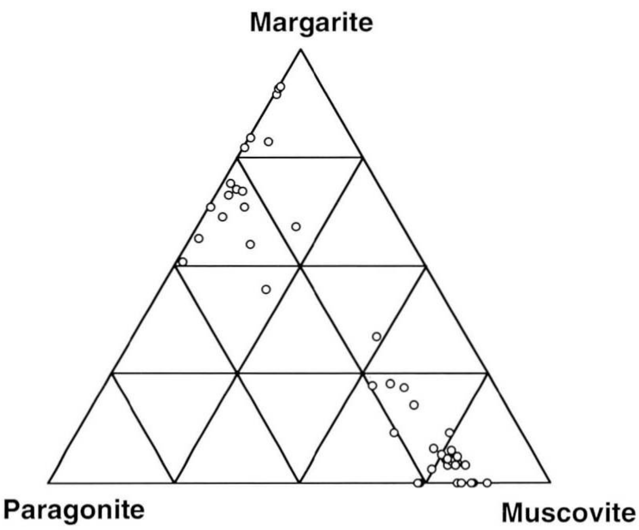

Fig. 13 Composition of white micas from melagabbros (sample Gi 28).

Ca-plag (1) + H_2O = zo + ky + qtz + Na-plag [4]

However, its frequent occurrence in garnet may also indicate a formation at the expense of calcic plagioclase under dry conditions:

Ca-plag = gross + ky + qtz + Na-plag [5]

Amphibole + plagioclase + quartz ± pyroxene: There are two types of amphiboles: large single grains and symplectites. Both types have irregular Mg, Fe and Al zoning (Fig. 11b).

Relic pyroxenes were observed in a few samples, only in the most fine grained portions of the symplectites (Fig. 6). Textures very much resemble those found in the less retrograded eclogites of the Val Nalps where they indicate the break-

Tab. 3 Representative microprobe analyses of clinopyroxenes from symplectite in melagabbro.

Sample Analysis	Gi 93 a2/7	Gi 93 a2/9	Gi 93 a2/21	Gi 93 a2/22	Gi 93 a2/24
SiO_2	54.32	54.75	54.86	54.81	54.70
TiO_2	0.21	0.08	0.12	0.13	0.12
Al_2O_3	3.34	2.32	2.09	3.32	1.57
Cr_2O_3	0.38	0.25	0.30	0.29	0.33
FeO	5.28	5.01	5.17	4.05	5.32
MnO	0.13	0.08	0.01	0.04	0.07
MgO	13.82	14.44	14.44	14.31	14.81
V_2O_5	0.45	0.31	0.28	0.46	0.29
CaO	21.43	22.29	22.41	21.67	22.83
Na_2O	1.50	1.26	1.10	1.78	0.77
K_2O	0.00	0.00	0.00	0.00	0.00
Total	100.86	100.79	100.78	100.86	100.81
Mineral formulas: atoms per 4.00 cations					
Si	1.975	1.990	1.998	1.979	1.996
Ti	0.006	0.002	0.003	0.004	0.003
Al	0.143	0.099	0.090	0.141	0.068
Cr	0.011	0.007	0.009	0.008	0.010
Fe^{+2}	0.161	0.152	0.157	0.122	0.162
Mn	0.004	0.002	0.000	0.001	0.002
Mg	0.749	0.782	0.784	0.770	0.805
V^{+5}	0.011	0.007	0.007	0.011	0.007
Ca	0.835	0.868	0.874	0.838	0.892
Na	0.106	0.089	0.078	0.125	0.054
K	0.000	0.000	0.000	0.000	0.000
Oxygens	5.997	5.991	6.004	5.983	6.001
JADEITE[a]	9.2	8.6	7.0	11.8	4.8
DIOPSIDE	72.9	75.9	76.8	75.4	78.5
HD	6.4	7.6	8.7	5.9	8.1

[a] Endmembers were calculated according the scheme of MORIMOTO (1988).
[b] Electron microprobe analyses were performed on an ARL-instrument at the Mineralogical Institute of the University of Bern. A method combining wavelength dispersive and energy dispersive systems was applied. Data correction was done by a theoretical ZAF correction procedure. Natural and synthetic minerals were used as standards.

down of omphacitic clinopyroxene (BIINO, 1994, this volume p. 89). Pyroxene composition varies from diopside-hedenbergite solid solutions to members with increased Na-contents. Usually they have aegirine components up to 5 mole-percent, but occasionally jadeite-contents up to 7 mole-percent were found (Tab. 3). Coexisting plagioclase has anorthite-contents ranging from 24 to 34 mole-percent (oligoclase-andesine).

Biotite + plagioclase + quartz intergrowths: Fine grained biotite-plagioclase intergrowths are often observed in kyanite-bearing rocks. Biotite is light-brown and contains small opaque inclusions. The flake-like shape of the biotite-plagioclase intergrowths strongly indicates pseudomorphic replacement of an earlier mica phase (Fig. 15). HEINRICH (1982) described very similar textures in eclogitic metapelites of the Penninic domain. He interpreted such textures as resulting from pseudomorphic replacement of phengitic mica by biotite in a plagioclase matrix:

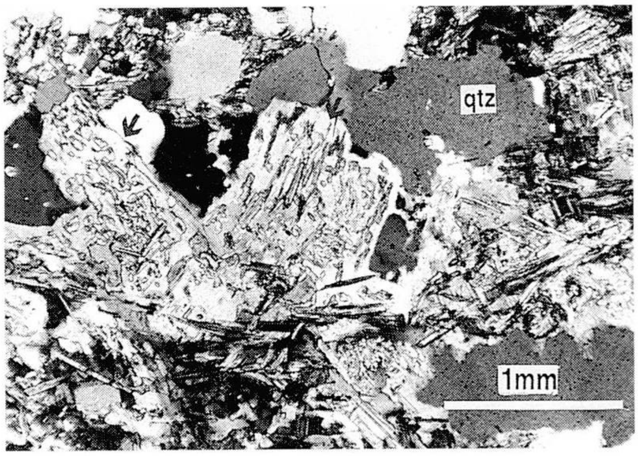

Fig. 15 Photograph of thin section: Arrow: biotite-plagioclase symplectites (replacing former phengite?) in quartz. Retrograde chlorite and clinozoisite in plagioclase.

$$\text{phe} + \text{gt} = \text{bio} + \text{plag} \ (\pm \text{qtz}, H_2O) \qquad [6]$$

Garnet-bearing assemblages: Garnet is a typical corona phase and occurs as continuous rims between mafic phases (originally pyroxene) and leucocratic phases (plagioclase). It is either hypidiomorphic or occurs as irregular relics in a symplectic amphibole-plagioclase matrix (Fig. 5). Often the grains have idiomorphic crystal faces against the external side of the coronas but are xenomorphic on their internal side (Fig. 5). Even though garnet coexists with all the other phases, it is difficult to define assemblages in chemical equilibrium with garnet. Textures unequivocally indicate an early metamorphic formation of garnet, most likely by a reaction of the magmatic mafic phases (pyroxene, amphibole?) with plagioclase. Garnets in the melagabbros are generally rich in inclusions (quartz, plagioclase, kyanite, rutile).

Zoisite-Ca plagioclase-quartz assemblages: A very peculiar texture is observed in quartz-bearing gabbroic rocks found near the Gurschen cable car station where they occur as lenses in schistose plagioclase gneiss. Deformation increases in intensity towards the margin of these lenses, where the gabbro is a typical flaser gabbro with relic

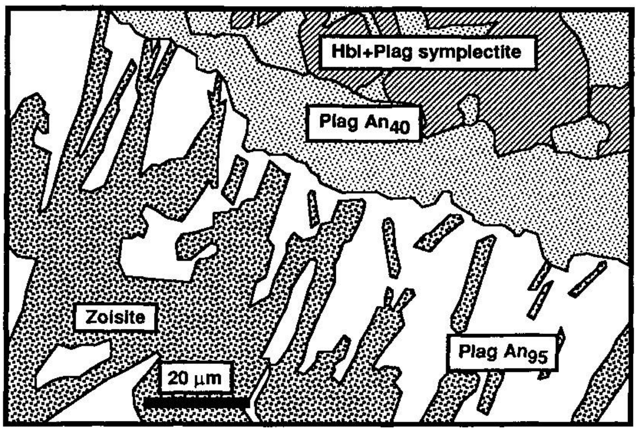

Fig. 16 Zoisite-anorthite pseudomorph after lawsonite in a symplectite matrix. Rim around pseudomorph is Na plagioclase.

porphyroblasts and pseudomorphic mineral aggregates of lenticular shape. The mineral aggregate consists of zoisite-anorthite ± clinozoisite ± mica ± opaque and is separated from the amphibole-plagioclase-quartz matrix by a rim of Ab-rich plagioclase (Fig. 16). Other evidence of increased deformation includes elongate and often folded quartz aggregates. In the cores of the aggregates fine mica (margarite?, paragonite?) may predominate. Zoisite composition is close to end-member composition (X_{Ps}= 0.02–0.05).

Plagioclase shows a strong variation in composition that reflects the highly unequilibrated relic texture. It shows highest An contents when in textural equilibrium with zoisite (An_{90-95}) and lowest An contents in symplectites and coronitic rims around garnets (An_{20-60}). The symplectites consist of plagioclase and coexisting magnesiohornblende and actinolite. Garnet shows a strong retrograde alteration with the formation of biotite, clinozoisite, biotite, and plagioclase.

Mineral assemblages and shape suggest that lawsonite could be an early prograde precursor phase which became unstable at eclogite facies conditions and decomposed to zoisite, kyanite and quartz. Later, margarite grew at the expense of kyanite (HARLEY and CARSWELL, 1990):

lw = zo + ky + qtz + water [7]

Garnet-quartz-amphibole-plagioclase assemblages: In the quartz-bearing rocks containing lawsonite pseudomorphs, a second local equilibrium assemblage is interpreted in terms of earlier mafic minerals stable at higher P-T conditions. Our interpretation is based on observation of a reaction zone between garnet and quartz (Fig. 17). This reaction zone consists of plagioclase (An_{45}) becoming progressively more sodic (An_{25}) towards an hornblende rim, itself in contact with quartz. The present amphibolite facies assemblage shows partial greenschist re-equilibration (hornblende → actinolite, garnet → chlorite). The reaction zone may be due to the replacement of orthopyroxene having possibly formed at granulite facies conditions according to the reaction:

gt (1) + qtz = plag + opx [8]

Quartz and garnet are part of the high pressure assemblage and became unstable at granulite facies conditions with opx + cpx + plag + gt + hbl as stable phases. Accordingly the coarse-grained amphibole rim between plagioclase and amphibole-plagioclase symplectite (Fig. 11a) can be interpreted as the breakdown product of omphacitic cpx and high pressure garnet according to (HARLEY and CARSWELL, 1990)

gt (1) + omph + qtz = opx (2) + plag (2) [9]

Summary

Gabbroic rocks from the Kastelhorn area display small scale textures that indicate a complex multiphase metamorphic evolution. Today's mineral assemblages and compositions usually reflect amphibolite facies conditions. Only exceptionally are relic mineral compositions preserved. An unequivocal interpretation of the present mineral assemblages is very difficult.

ABRECHT et al. (1991a, 1991b) and BIINO (1992) have presented a P-T-t evolution path for gabbroic and basaltic rocks from the Val Nalps and Unteralptal area. In contrast to the Kastelhorn rocks, here relic mineral compositions have been preserved, allowing the derivation of P-T conditions pertinent to their origin.

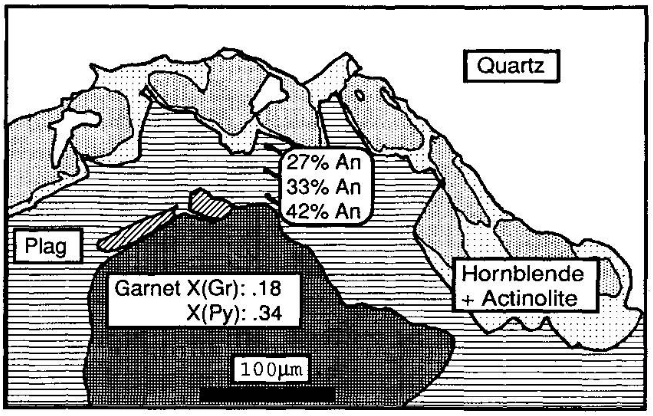

Fig. 17 Amphibole-plagioclase corona around garnet in quartz matrix. Note increasing An-content of plagioclase from garnet to amphibole

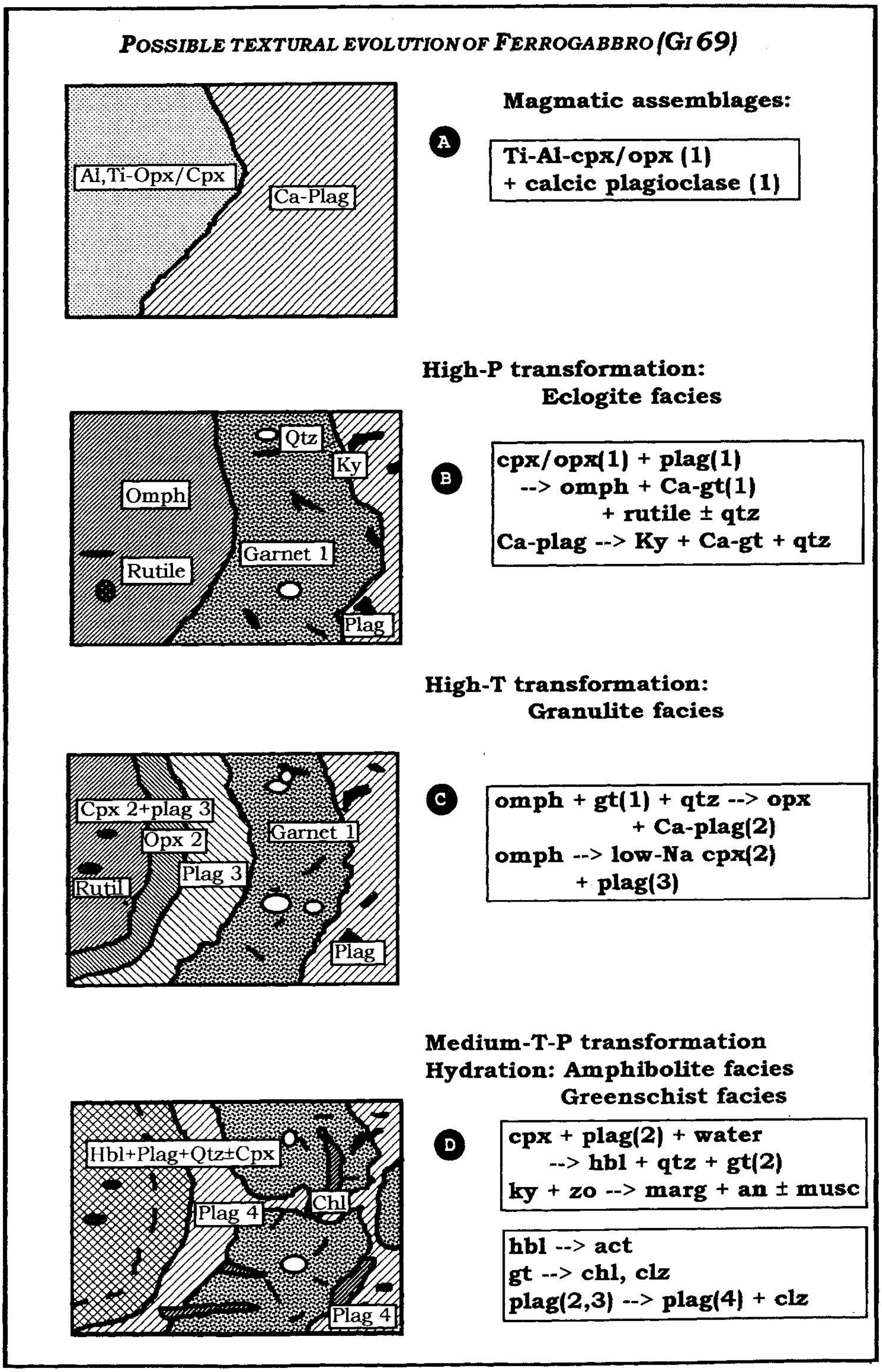

Fig. 18 Assumed sequence of the textural evolution of a melagabbro (simplified). For numbers see text.

Tab. 4 Sequence of metamorphic events with assumed stable mineral assemblages and derived mineral reactions. P-T estimates for stages 2 and 3 were obtained by thermobarometric calculations BIINO (1992, 1993). The estimates for stage 4 are based on observed mineral assemblages. Data for the greenschist metamorphism (stage 5) are from FREY et al. (1980).

Event and stable assemblage	Relics	Reactions	P-T estimates
1. Magmatic stage Ti-Al cpx + opx ± hbl (+ ol?) + plag + apatite + zircon + opaques	Zircon, apatite, biotite, monazite		high-T low-P
2. Eclogite facies metamorphism Na-cpx (omphacite) + gt + qtz + zo + ky + rutile + zircon + brown hbl ± phengite ± opaques (± lawsonite)	Garnet, kyanite, rutile	Breakdown of cpx, opx, calcic plag (1), bio, ol? breakdown of law (zo + ky?)	> 1.8 GPa ~ 700 °C
3. Granulite facies metamorphism calcic cpx + opx + gt + sodic plag + ky + qtz + brown bio + orthoamph? + cumm + zircon ± opaques	Cummingtonite, Ca pyroxene	Reactions: breakdown of omph (Ca cpx – sodic plag symplectites), breakdown of phe (bio-plag-qtz symplectites)	0.8 GPa 600–700 °C
4. Amphibolite facies metamorphism green hbl + plag (An_{40-60}) + gt + qtz + bio + clz/ep ± musc ± marg	Hbl, plag, gt?, bio, marg, musc	Reactions: breakdown of opx, cpx, cumm, ky	0.3–0.5 GPa 500–580 °C
5. Greenschist facies metamorphism Act + plag (An_{20}) + qtz + clz + green bio + chl		Breakdown of hbl, calcic plag, gt, brown bio	0.3–0.5 GPa 450–500 °C

Based on the similarities of primary rock compositions, and present small scale textures between Val Nalps, Unteralptal and Kastelhorn rocks a rather similar metamorphic evolution is assumed. Therefore, by comparison, the local equilibrium textures of the Kastelhorn gabbros can be tentatively interpreted in terms of mineral reactions characteristic for the polyphase evolution derived from the Val Nalps parageneses. Generally several mineral reactions can be envisaged for a given assemblage. Present mineral compositions are only of limited use and therefore constraints are mainly presented by the assumed P-T path. In table 4 an attempt is made to delineate a consistent mineralogical and textural evolution in agreement with the sequence of events presented by ABRECHT et al. (1991a, 1991b) and BIINO (1992). The suggested scheme given in figure 18 should be considered as one of several possibilities.

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