The preservation of high-pressure rocks during exhumation: metagranites and metapelites

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Abstract

Metagranites in the NKFMASH system require external hydration during prograde high-pressure metamorphism in order to equilibrate to ambient HP conditions by producing more siliceous muscovite. Any lack of external fluid or the disappearance of biotite stops re-equilibration and thus prevents recording of high-pressure conditions. The same hydration reactions cause dehydration during exhumation. Orthogneiss from shear zones or adjacent to metapelites and metabasites will take up external fluid during subduction and record the highest $P-T$ conditions, but will also be the first to dehydrate upon exhumation, now hydrating other lithologies and probably refuelling shearzones.

The (de)hydration behavior of Ca-bearing metagranitoids is similar to that in the Ca-free system. However, the anorthite component of plagioclase decomposes with increasing pressure to form either (clino)zoisite or a grossular-rich garnet. Both reactions are fluid-consuming. If H_2O is supplied from an external source, the garnet-bearing assemblage can record $P-T$ conditions up to very high pressures, but dehydrates again during heating and/or decompression to form a more Fe-rich garnet and Al-rich mica(s). The garnet compositions observed in natural HP-metagranites are mostly too Fe-rich to be formed in the presence of an H_2O-rich fluid.

N(C)KFMASH metapelites generally have a more complex mineralogy and succession of mineral assemblages along a $P-T$ path. The H_2O contained in hydrous silicates like chlorite and chloritoid is only partly released, but partly transferred to other minerals like paragonite, glaucophane or phengite during subduction and further dehydration during exhumation is common. The mineral assemblage preserved by the rock may then record $P-T$ conditions way below those of the actual pressure and temperature peak of the path. Contouring of the $P-T$ pseudosection of a specific metapelite composition with mode isopleths for H_2O shows which $P-T$ conditions along a given path are the ones most likely recorded by the rock.
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1. Introduction

High-pressure (HP) and ultrahigh-pressure (UHP) rocks are some of the most characteristic rock types of convergent plate boundaries and particularly of continental collision zones. However, the $P-T$ conditions derived from different rock types in a (U)HP area may differ considerably. In order to distinguish which rocks may have had a different $P-T$ history and which ones just have not been able to record and/or preserve the same (peak) metamorphic conditions as others, it is essential to consider the dehydration behavior of each rock along its $P-T$ path.

The preservation of high-pressure parageneses is possible if (a) H_2O is missing on the reactant side of

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retrograde reactions or (b) kinetic barriers inhibit re-equilibration of a mineral assemblage during exhumation. Reaction kinetics is promoted by deformation and, again, by the availability of fluid, either as a participant in the mineral reactions or merely as a catalyst and transport medium (Rubie, 1983). The evidence presented by Austrheim and Griffin (1985) or Wain et al. (2001) indicates that overstepping by at least 5 kbar and probably >13 kbar is possible for solid–solid reactions in the absence of a catalysing fluid.

Fluid can be derived either internally, by devolatilization (mostly dehydration) reactions or from an external reservoir by infiltration. Very often the external reservoir will be a dehydrating country rock. While internal dehydration will reset a rock pervasively, external hydration may only affect its marginal parts. The latter situation is typical for the most prominent and widely recognized high- and ultra-high-pressure rock types—eclogites, orogenic peridotites and marbles. Metabasites, for example, undergo continuous dehydration reactions during subduction, and even if hydrous phases (including phengite) are still present at the metamorphic peak, most retrograde paths require external fluid for re-equilibration to occur (Guiraud et al., 2001).

Marbles, eclogites and peridotites are generally present in subordinate quantities, embedded in voluminous host rocks, such as metapelites, paragneisses and acidic orthogneisses, which show little or no traces of a high-pressure stage. This situation has caused a prolonged discussion whether eclogites and other high-pressure rocks had been tectonically injected into their present country rocks or both lithologies had followed the same P–T paths, only with different chances of developing and preserving a HP mineralogy (e.g. Harley and Carswell, 1995; Cong and Wang, 1996). Heinrich (1982, 1986) was the first to demonstrate the importance of relating the dehydration behavior of eclogites and their pelitic and gneissic country rocks to the P–T conditions they are able to record. Only recently, an increasing number of studies has revealed that coesite is preserved as inclusions in zircons of orthogneisses which otherwise show no relics of an earlier high-pressure stage (Sobolev et al., 1995; Wain, 1997; Tabata et al., 1998; Ye et al., 2000,), thus rekindling the discussion of preservation conditions.

Taking dehydration reactions as the most important factor governing preservation of rapidly exhumed high-pressure assemblages, it is straightforward to describe the chances for preservation of different rock types by comparing dehydration reactions of adequate petrogenetic grids with probable or actually derived P–T paths. Assuming that fluid produced during prograde metamorphism escapes from the system almost instantly, a rock will preserve the most dehydrated mineral assemblage formed along its P–T path. This assemblage, the appertaining mineral compositions and modes, and the P–T conditions of formation can be determined for any given P–T path by contouring pseudosections with mode isopleths for H_2O. This method is less generally applicable than petrogenetic grids—it is strictly valid only for a particular bulk composition—but gives a very detailed insight that is also invaluable for making P–T estimates for specific samples. The method was outlined by Carson et al. (2000), and Guiraud et al. (2001) have discussed the preservation of eclogites and KFMASH metapelites in terms of such contoured pseudosections. The pseudosections in this paper have been calculated in a similar way with THERMOCALC 3.1 (available at http://www.earthsci.unimelb.edu.au/tpg/thermocalc/) using the dataset of Holland and Powell (1998) and mixing models of the same authors. Mineral abbreviations are according to Kretz (1983).

The present work discusses the two most problematic high-pressure country rocks of eclogites—metagranites and sodic metapelites—and their capacity to record and preserve the record of a high- or ultrahigh-pressure event.

2. Metagranites

Reports in the literature of leucocratic, acidic to intermediate orthogneisses that have recorded and preserved relics of a high-pressure history are scarce if compared to those of eclogites. Most examples are from the Western Alps, particularly from Dora Maira (Chopin et al., 1991; Biino and Compagnoni, 1992), the Sesia–Lanzo zone (Compagnoni and Maffeo, 1973; Oberhänsli et al., 1983; Koons et al., 1987) and the Gran Paradiso (Massonne and Chopin, 1989; Le Goff and Ballevre, 1990). Further studies are from Norway (e.g. Krogh, 1977; Griffin and Carswell, 1985), China (Wallis et al., 1997; Carswell et al., 2000), Northwest Spain (Gil Ibarguchi, 1995), Alaska

(Patrick, 1995) and other areas (see Mottana et al., 1990 for a summary).

This study is limited to orthogneisses that retain K-feldspar throughout their HP-metamorphic evolution, which holds for granitic and most granodioritic compositions. Those that loose K-feldspar (diorites, tonalites, etc.) develop parageneses similar to those of eclogites and can be described by phase diagrams for metabasites.

A first simple view in NKFMASH gives an impression of the fundamental dehydration behavior of granitic orthogneisses. High-pressure indicator minerals are jadeite, coesite and, to a certain degree, a Si-rich muscovite. As the conversions of albite to jadeite and quartz to coesite are fluid-absent, the key to understanding fluid-driven re-equilibration and recording of ambient $P–T$ conditions in a K-feldspar-bearing orthogneiss is muscovite.

The paragenesis K-feldspar + plagioclase + quartz + muscovite + biotite (+ fluid) is trivariant in NKFMASH and stable over a wide range of pressures and temperatures. Muscovite and biotite are the only Fe–Mg- and OH-bearing phases, so the system can be legally reduced to NKMASH to show the possible net transfer reactions between end-members, which are all dehydration reactions:

3 celadonite + 2 paragonite

   = 2 muscovite + 1 phlogopite

     + 2 albite + 3 quartz + 2 H_2O (1)

3 celadonite = 2 K-feldspar + 1 phlogopite

       + 3 quartz + 2 H_2O (2)

1 muscovite + 2 paragonite + 2 phlogopite

   = 3 eastonite + 2 albite + 3 quartz + 2 H_2O. (3)

3 muscovite + 2 phlogopite

   = 2 K-feldspar + 3 eastonite
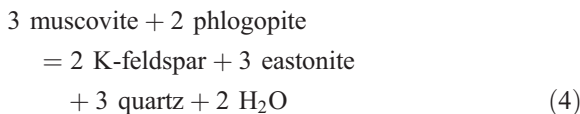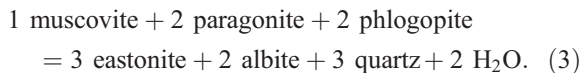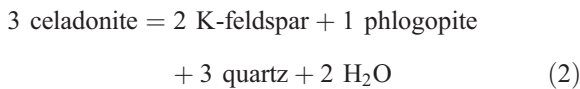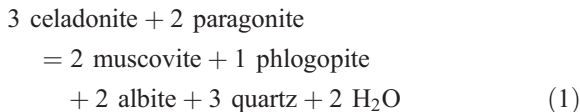
     + 3 quartz + 2 H_2O (4)

Fig. 1 shows that these reactions—calculated for a particular orthogneiss sample (SM-1) from the Dabie Shan UHP region—have a subparallel trend in $P–T$ space, with H_2O always on the high-temperature side. They indicate that feldspars and aluminous mica end-members combine to produce more siliceous micas
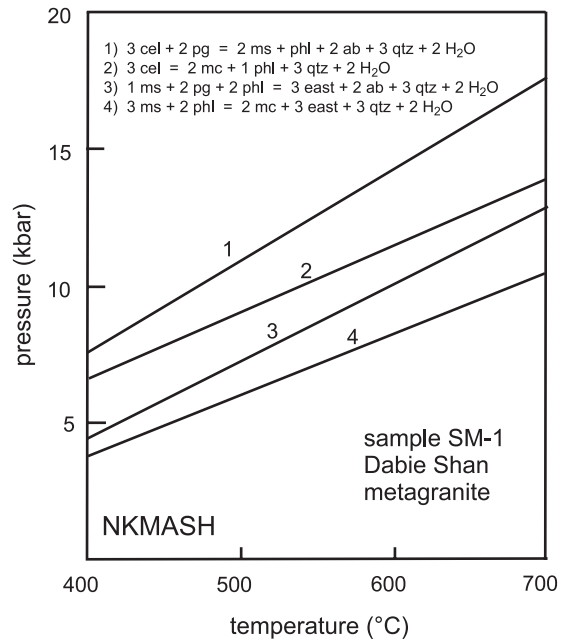

Fig. 1. Net transfer reactions between mineral end-members of a metagranite, calculated in NKMASH with THERMOCALC (mode 3) for the specific mineral compositions of sample SM-1, from Shima, Dabie Shan. The slopes of these dehydration reactions in $P–T$ space are similar to each other and point to a uniform type of dehydration.

along a pressure dominated subduction path, provided that H_2O is available as a reactant.

The changes in mineral modes and compositions as well as the dehydration behavior across the large stability field of this assemblage can be illustrated more clearly by a $P–T$ pseudosection (Fig. 2). Both the amount of muscovite and its Si-content increase from the muscovite-out boundary at low pressures towards higher pressures and lower temperatures until all biotite is consumed. The mineral modes are characterized by an increase in phengitic white mica and a decrease in biotite and K-feldspar with pressure, according to the generalized reaction formula:

biotite + K-feldspar + quartz + H_2O = phengite.

                                          (5)
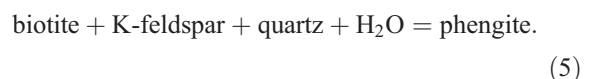
This reaction has been investigated experimentally in the KMASH by Massonne and Schreyer (1987), who found it to be strongly pressure-dependent. Changes in mineral composition and growth textures
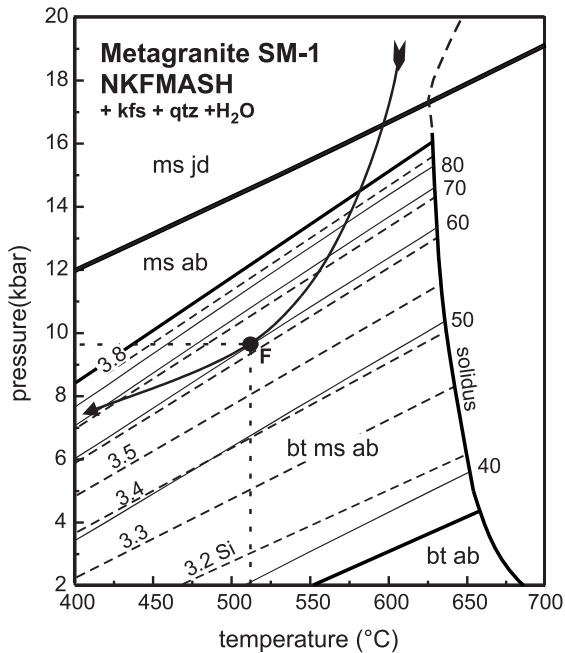
Fig. 2. *P–T* pseudosection for orthogneiss SM-1 in the NKFMASH system. Mineral stability fields are shown up to the wet melting curve. Dashed lines are H_2O-mode isopleths, full thin lines are isopleths for the Si-content in muscovite. The *P–T* conditions recorded by the rock are those around point F, where the *P–T* path becomes tangential to a specific H_2O-mode isopleth.

corresponding to this reaction have been observed, e.g. in metagranitoids from Dora Maira, Western Alps (Chopin et al., 1991; Biino and Compagnoni, 1992), in the Erzgebirge in Germany (Rötzler et al., 1998) or in the Brooks Range of Alaska (Patrick, 1995).

To be able to illustrate the dehydration behavior across the entire range of the diagram, the amount of H_2O in the bulk composition is not the one analysed, but the one calculated for the most hydrated assemblage possible within the *P–T* range. In this case, the amount of H_2O present in the solid phases has a maximum of 2.75 mol% in the muscovite + albite (or jadeite) field and decreases with the amount and Si-content of muscovite. For convenience, the H_2O-mode isopleths are scaled from 100 (at 2.75 mol%) to 0 (Carson et al., 2000).

The *P–T* conditions at which a *P–T* path becomes tangential to the driest H_2O-mode isopleth of any of the stability fields crossed—e.g. point F at 515 °C, 9.7 kbar in Fig. 2—are those most likely preserved by the rock, which from then on contains no more free fluid

phase. Net transfer reactions are kinetically blocked in the absence of a fluid and only exchange reactions may continue to operate to some degree. The corresponding H_2O-mode isopleth separates the hydration field from the dehydration field for that particular bulk composition and *P–T* path. It is a zero-mode isopleth for H_2O for the actual (analysed) H_2O content of the rock and a valuable petrological tool because it is a lower boundary for the *P–T* paths possible for that rock.

In this simple chemical system, metagranites require a significant amount of external hydration during prograde high-pressure metamorphism in order to equilibrate to the ambient HP conditions by producing more siliceous phengite and biotite. Any lack of external fluid or the disappearance of another reactant, like biotite, stops re-equilibration and thus prevents recording of HP conditions. The kinetic barriers in such a dry rock may be too large for the fluid-absent transformation from albite to jadeite to occur, so that plagioclase is preserved metastably within the jadeite stability field (e.g. Austrheim and Griffin, 1985; Wayte et al., 1989; Wain et al., 2001).

As long as the slope of the retrograde *P–T* path is steeper than that of the H_2O-mode isopleths, an orthogneiss will dehydrate during exhumation. Orthogneisses from shear zones or adjacent to metapelites and metabasites, which more or less continuously dehydrate during subduction (Guiraud et al., 2001), will take up external fluid on the prograde path and record the highest *P–T* conditions, but will also be the first to dehydrate upon exhumation, now hydrating other lithologies and probably refuelling shearzones.

As shown in Fig. 2, biotite is lost from the assemblage in most bulk compositions along a prograde subduction path before the jadeite stability field is reached. This conclusion may not hold in nature: Massonne and Szpurka (1979) replotted the experimental data for reaction (5) from Massonne and Schreyer (1987) against isopleths calculated from improved thermodynamic data for KMASH white micas (their Fig. 7). The discrepancy between isopleths and experimental values increases with pressure and led the authors to conclude that significant dissolution of silicates in H_2O-fluid reduces H_2O-activity at high pressures, which stabilizes the left-hand side of reaction G-5, including biotite, towards significantly higher pressures. If biotite was stable in the jadeite stability field, the transformation of albite into jadeite + quartz

would not change the slope of H_2O-mode isopleths significantly because these phases influence dehydration reactions only marginally via the paragonite end-member in phengite.
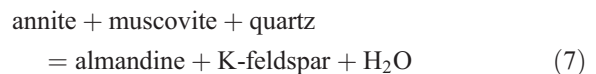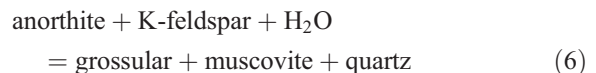
2.1. Additional components and phases

(Clino)Zoisite, grossular-rich garnet and clinopyroxene are relevant phases that could incorporate the Ca released during the high-pressure breakdown of plagioclase. If equilibration is attained on a whole-rock scale, clinozoisite has only a very small stability field at low temperatures (Fig. 3, inset). In nature, (clino)zoisite is the first Ca-phase to grow in plagioclase domains, together with albite/jadeite + quartz ± kyanite or phengite. In a fully equilibrated KF-bearing orthogneiss, it may be stabilized by significant amounts of Fe^{3+} and/or REE. In the meta-quartz diorite from the Sesia zone studied by Koons et al. (1987), K-feldspar is consumed during re-equilibration and zoisite becomes stable on the whole-rock scale.

Garnet is also very common in natural high-pressure metagranites. It nucleates at the outer margins of former biotite domains and develops a pronounced growth zonation with increasing Ca towards domains of former plagioclase (Koons et al., 1987; Biino and Compagnoni, 1992). Na-poor clinopyroxene is theoretically the most stable Ca-phase (Fig. 3, dashed line in the inset). In metagranites jadeite grows inside the pseudomorphs after plagioclase. A more Ca-rich or even omphacitic clinopyroxene develops only after a more thorough re-equilibration on a whole-rock scale at high pressures (e.g. Oberhänsli et al., 1983; Koons et al., 1987), indicating that clinopyroxene is less stable in nature than garnet. Mn would enlarge the garnet stability field, but most garnets described from high-pressure orthogneisses are rather low in Mn. As the $P–T$ positions of the low-pressure boundaries of the clinozoisite, garnet and clinopyroxene stability fields are very similar, the absence of a Na-poor clinopyroxene in natural rocks at moderate pressures may have thermodynamic reasons (mainly inaccuracies stemming from the mixing models), but kinetic reasons are also possible (almost none of the Al released during plagioclase breakdown can be incorporated in the clinopyroxene). Following natural evidence, the stability of a Na-poor clinopyroxene was disregarded and garnet considered to be the major stable phase. Lacking

a proper mixing model for Na-rich clinopyroxene, pure jadeite was used in calculating Figs. 3 and 4.

According to Fig. 3, garnet is not stable in a K-feldspar-bearing orthogneiss at $a_{H_2O} = 1$ except as a grossular-rich Ca-buffer phase. This is confirmed by natural samples: The majority of garnets in more thoroughly equilibrated HP-orthogneisses are Ca-rich (Oberhänsli et al., 1983; Koons et al., 1987; Le Goff and Ballevre, 1990; Chopin et al., 1991). However, Fe-rich garnet can be found at the rims of former biotite domains and even develops at biotite–K-feldspar grain boundaries (Biino and Compagnoni, 1992; Rubbo et al., 1999). Even though the actual garnet composition strongly depends on bulk rock composition (Gil Ibarguchi, 1995), it is difficult to explain the common range of $0.4–0.6$ X_{alm} in garnet in relatively well-equilibrated samples, and particularly the almost Ca-free garnet in a jadeite granite (Gil Ibarguchi, 1995) without assuming a strongly reduced H_2O-activity during formation. There is ample textural evidence for relatively low fluid activity in HP-metagranites, like strong, nonconcentric mineral zonations, corona textures, incompatible domain assemblages or growth of HP phases restricted to grain boundaries (e.g. Biino and Compagnoni, 1992; Gil Ibarguchi, 1995; Wallis et al., 1997). The effect of reduced H_2O-activity is illustrated in Fig. 4 for a fixed a_{H_2O} of 0.5. It stabilizes more Fe-rich garnet at lower temperatures (Fig. 4a) and also affects the slope of H_2O-mode isopleths (Fig. 4b). The marked change in slope of H_2O-mode isopleths in the grt + bt + ms + pl stability field in Fig. 4b is caused by the changing role of garnet: While the formation of grossular component requires hydration, almandine component forms by dehydration of biotite:

$$\text{anorthite} + \text{K-feldspar} + H_2O$$
$$= \text{grossular} + \text{muscovite} + \text{quartz} \qquad (6)$$

$$\text{annite} + \text{muscovite} + \text{quartz}$$
$$= \text{almandine} + \text{K-feldspar} + H_2O \qquad (7)$$

Reaction (7) is stabilized towards subsolidus temperatures if H_2O-activity is low and can induce minor dehydration, which is internally buffered and may thus result in the incomplete reaction textures typically observed in HP-metagranites.

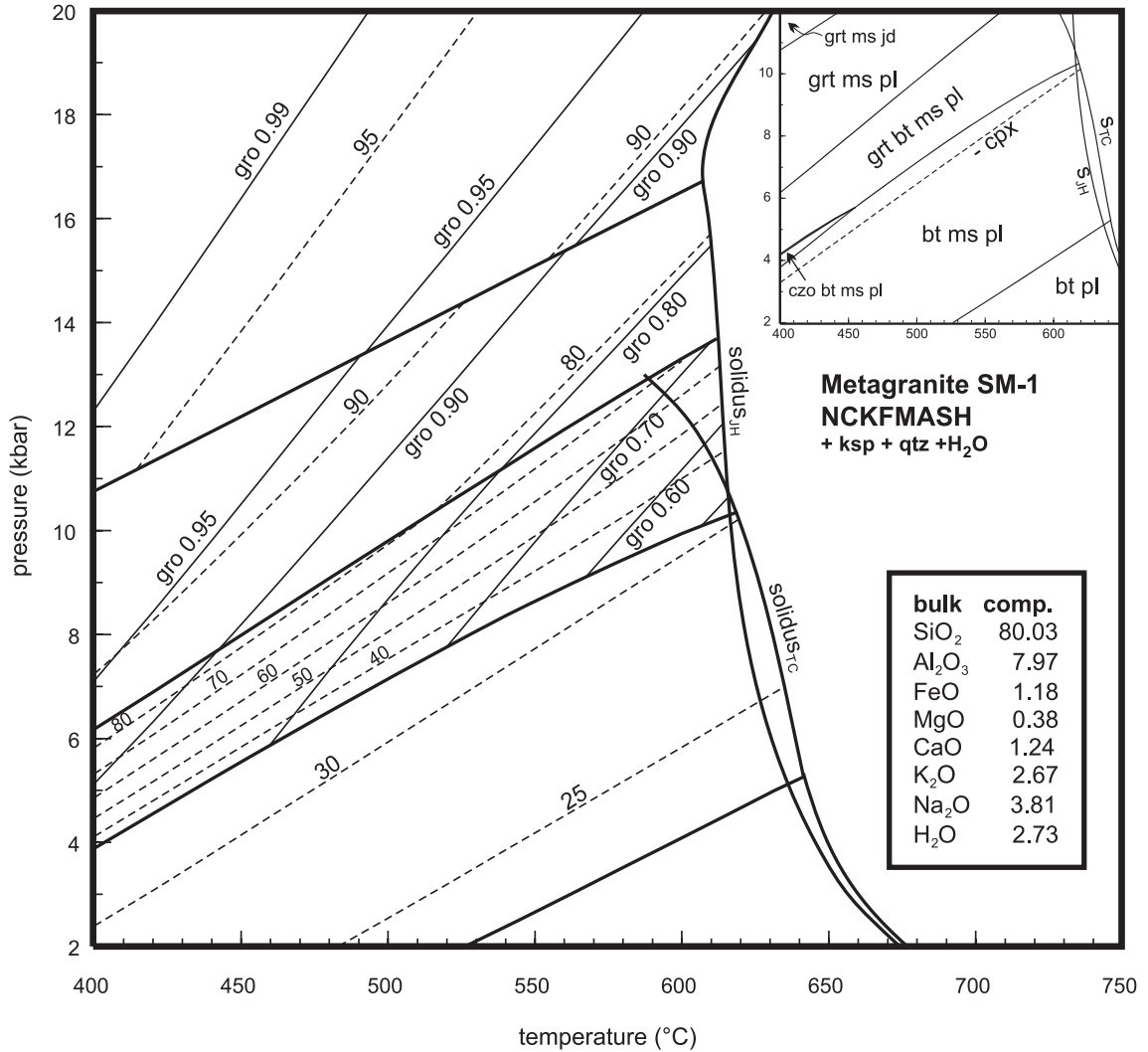The presence of calcium modifies the (de)hydration behavior of metagranites in several ways: Biotite

Fig. 3. $P-T$ pseudosection for SM-1 including calcium. Dashed lines are H_2O-mode isopleths, full thin lines are isopleths for the grossular content in garnet. Stability fields are labelled in the inset. The lower limit of a theoretical cpx + bt + ms + pl stability field is drawn with a dashed line. Relative stabilities of Ca-bearing phases are discussed in the text. S_{TC} is the wet solidus calculated with THERMOCALC, S_{JH} is an experimentally determined wet melting curve for a biotite–granite, taken from Johannes and Holtz (1996). S_{TC} runs to unrealistically low temperatures at high pressures and was cut off at 12 kbar.

stability is reduced, H_2O-mode isopleths are more condensed in the grt + bt + ms + pl stability field, and, most importantly, the rock is still reactive at higher pressures, provided that external fluid is supplied. No matter which Ca-phase is produced from plagioclase, anorthite is the most aluminous end-member involved. The reaction is always H_2O-consuming because the extra Al is buffered by muscovite, like in reaction (6). This holds for clinopyroxene of

any composition produced during the terminal breakdown of plagioclase. Due to the unfavourable slope of H_2O-mode isopleths, any orthogneiss sufficiently hydrated to record eclogite facies conditions should display at least a certain amount of muscovite breakdown and retrograde garnet zoning pattern during exhumation.

Meta-tonalites and other plagioclase-rich and amphibole-bearing orthogneisses will lose their K-feld-
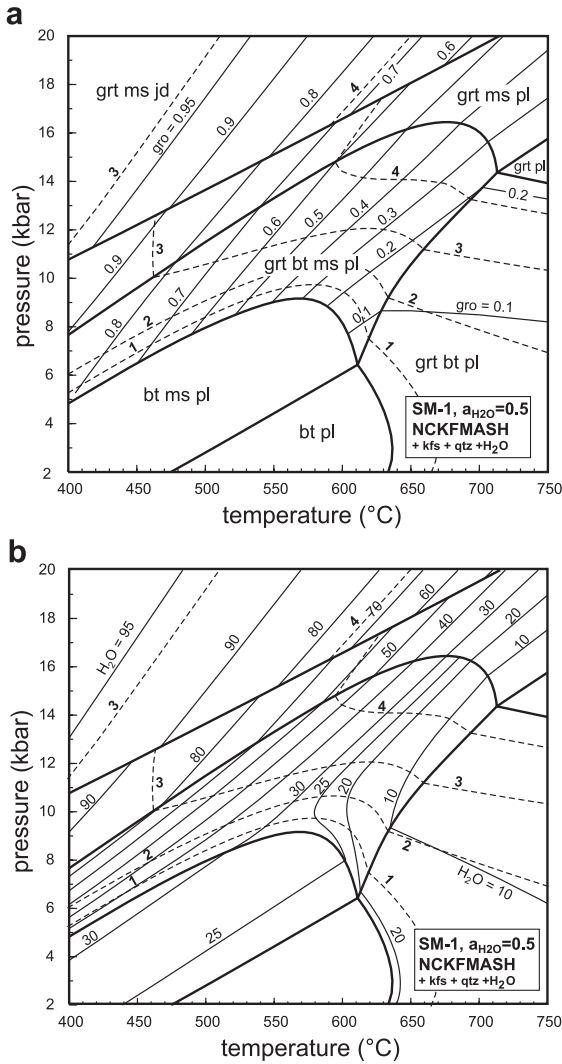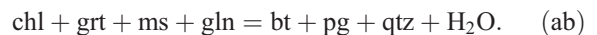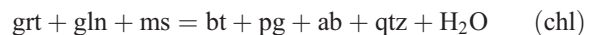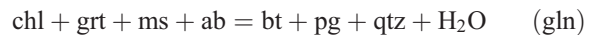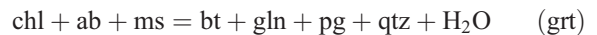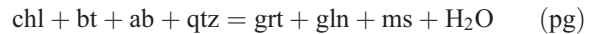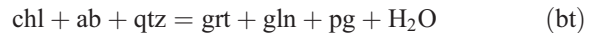
a

b

Fig. 4. Pseudosections for SM-1, calculated for a fixed activity of H_2O of 0.5 and comparing (a) the fluid budget (H_2O-mode isopleths) and (b) $X_{grossular}$ with the amount of garnet produced in the rock (up to >4 mol%). The solidus is outside the plot range.

spar rather early during re-equilibration along a high-pressure path. They are sufficiently high in Ca, Fe^{2+} and Mg to develop omphacite and garnet, thus evolving into leucocratic eclogites (Koons et al., 1987). The dehydration behavior in these rocks is controlled by amphiboles and clinozoisite/epidote, which generally dehydrate with increasing temperature and pressure (Guiraud et al., 2001, Fig. 2), so the peak parageneses are very likely to be preserved.

3. Metapelites

Metapelites have a more complex mineralogy and succession of mineral assemblages along a $P–T$ path than metagranites, so their dehydration behavior can be described not only by means of pseudosections but also with petrogenic grids. In the past, such grids have been devised mainly in KFMASH (mostly in the medium to low pressure range, except Mottana et al., 1990) or in NFMASH (high- and ultrahigh-pressure range, Guiraud et al., 1990; Massonne, 1995). A unified view, explaining the transition between the two systems and $P–T$ regions, has been developed recently. The petrogenetic grid for NKFMASH metapelites is presented elsewhere (Proyer, 2003), but the general principles of it and some aspects of the dehydration behavior of high-pressure metapelites shall be described here briefly.

The paragenetic evolution of metapelites strongly depends on bulk composition. Fig. 5 shows a NAFM-tetrahedral projection of the NKFMASH system. This tetrahedron consists of a classical AFM projection at the base and a sodic phase, either albite or jadeite, at the apex. The garnet−chlorite−albite and garnet−chlorite−paragonite composition planes in Fig. 5a separate the three main composition spaces of Al-rich, Na-rich and Al-poor metapelites. Fig. 5a is valid for the greenschist and lower amphibolite facies, until chlorite + albite becomes unstable with increasing metamorphic grade. The most important breakdown reactions are those stabilizing the joins biotite−paragonite and glaucophane−paragonite (Fig 5b and c). These reactions intersect at the NKFMASH-invariant point (NK 1) at 13.1 kbar/541 °C (Fig. 6). NK 1 is only relevant for Na-rich and Al-poor bulk compositions. The full set of reactions is:

$$chl + ab + qtz = grt + gln + pg + H_2O \qquad (bt)$$

$$chl + bt + ab + qtz = grt + gln + ms + H_2O \qquad (pg)$$

$$chl + ab + ms = bt + gln + pg + qtz + H_2O \qquad (grt)$$

$$chl + grt + ms + ab = bt + pg + qtz + H_2O \qquad (gln)$$

$$grt + gln + ms = bt + pg + ab + qtz + H_2O \qquad (chl)$$

$$chl + grt + ms + gln = bt + pg + qtz + H_2O. \qquad (ab)$$
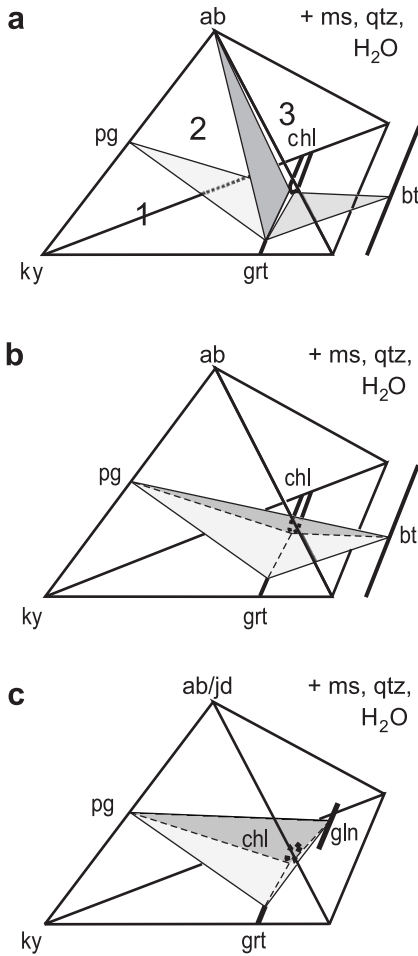
a

b

c

Fig. 5. NAFM-tetrahedral projections for sodic metapelites. (a) The three main compositional fields of (1) Al-rich, (2) Na-rich and (3) Al-poor metapelites. (b) Breakdown of chlorite + albite to biotite + paragonite with increasing temperature. (c) Breakdown of chlorite + albite to glaucophane + paragonite with increasing pressure.

The chlorite + albite stability field is terminated by reaction (gln) towards higher temperatures and by reaction (bt) towards higher pressures. The filled arrows in Fig. 6 stand for dry parts of exhumation paths, along which the high-pressure assemblages will be preserved. The open arrow indicates that glaucophane will disappear from the matrix of a chlorite-bearing high-pressure assemblage if the exhumation path passes at the high-temperatures side of NK 1.

The dehydration behavior can be analysed in more detail by means of a pseudosection, contoured with H_2O-mode isopleths. This was done in Fig. 7 for a

Na-rich metapelite (composition see inset). Cordierite and melt stability fields were omitted. NK 1, now a very short univariant (open square), and four of the reactions emanating from it are "seen" by this bulk composition. The NKFMASH-univariant reactions have become narrow bivariant fields due to the small amount of Ca. Each of the larger paragenetic fields in the pseudosection is contoured with H_2O-mode isopleths (dashed lines). In this case, the most hydrated assemblage is chl + lws + gln + pg + ms + qtz (upper left corner), with 16 mol% H_2O contained in the solid phases.

Several clockwise $P–T$ paths are shown in Fig. 7 in order to illustrate both the paragenetic evolution and the relative position of the "metamorphic peak assemblage" (the one generally preserved by the rock because it is the least hydrated) compared to the true pressure and temperature peaks of the path.

Path A: Biotite is never formed along this cold subduction path, but paragonite grows as muscovite and chlorite continuously decrease in Al content. Glaucophane appears when reaction (bt) is crossed and garnet grows continuously from chlorite and lawsonite. The driest assemblage is formed at F_A near the true P and T peaks and only external hydration can cause a resetting along the exhumation path.

Path B: Chlorite is continuously consumed with rising temperature and disappears at b1. The glauco-
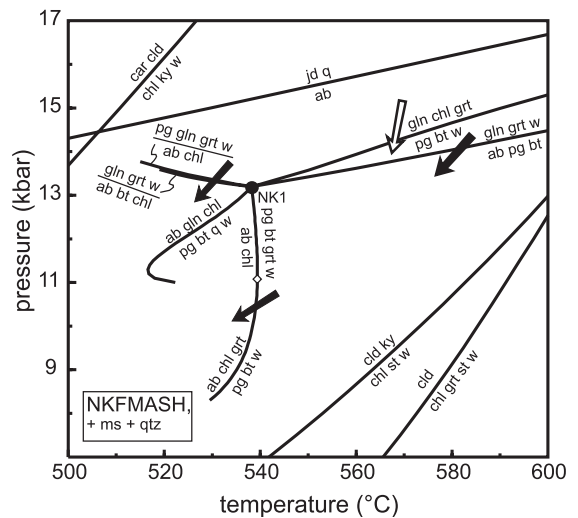

Fig. 6. NKFMASH-invariant point NK1 with pertinent reactions. Dark arrows indicate dry, light arrows wet parts of exhumation paths.
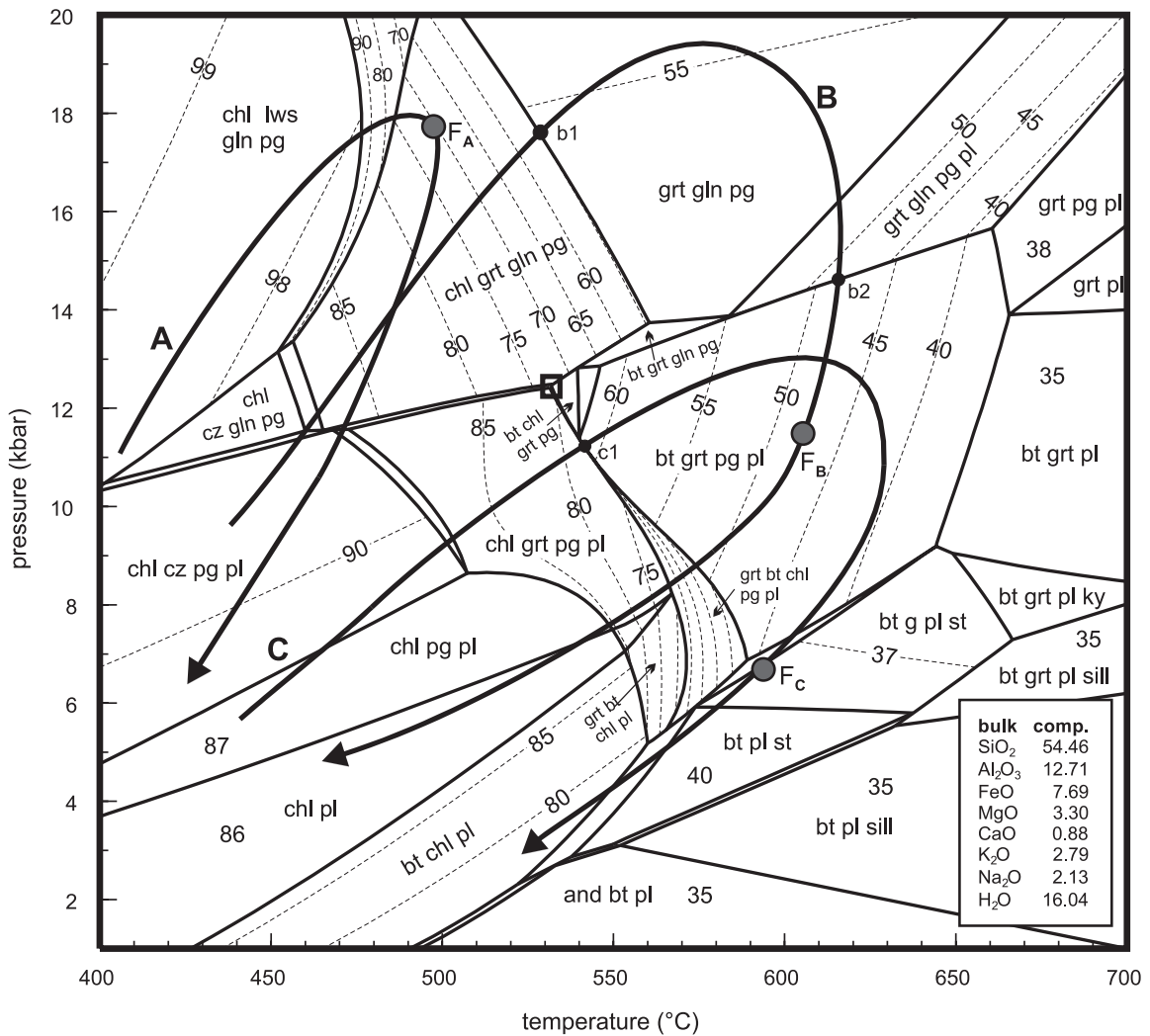
Fig. 7. NCKFMASH-pseudosection for a Na-rich metapelite. Invariant point NK 1 and four of its reactions are "seen" by the bulk composition. Arrows indicate different types of P–T paths, to illustrate the differences between preserved "peak" assemblages (F_A, F_B, F_C) and real pressure and temperature peaks of each metamorphic history.

phane formed up to this point starts to decompose in the grt + gln + pg + pl field and completely converts to biotite + plagioclase shortly after the flat-lying, almost fluid-absent reaction (chl) is crossed at b2. The rock preserved at F_B is a garnet–biotite–paragonite schist, which records 8 kbar less than the actual P peak.

Path C: Along this path, a garnet–chlorite–white mica schist is stable up to 540 °C (c1), and only then the first biotite is formed by reaction (gln). Paragonite would be an indicator mineral for at least moderately high pressures in the bt + grt + pg + pl stability field, but

is resorbed during a staurolite-forming reaction which produces the typical Barrovian, final, peak assemblage bt + grt + pl + st at F_C. The actual P and T peaks differ by 6.5 kbar and 35 °C from the recorded value.

The angle of H_2O-mode isopleths is crucial for the proximity of preserved P–T conditions to the actual pressure and temperature peaks (Guiraud et al., 2001). A negative slope, as in the chl + grt + gln + pg field at the top left of Fig. 7, is beneficial; a positive slope like in the bt + grt + pg + pl field is adverse for the preservation of near-peak conditions.

4. Discussion

4.1. Method

The introduction of pseudosections as a geothermobarometric tool has improved the determination of $P-T$ paths because relatively small stability fields can be drawn for matrix and inclusion mineral assemblages and contoured with composition isopleths. In a similar way, the drawing of H_2O-mode isopleths advances our understanding of what section of a probable $P-T$ path is likely to be preserved and thus accessible for analysis by the various geoscience disciplines. These advances have pushed the door open to new questions such as that of recrystallization under fluid-absent conditions, as might be the case for garnet growth in metagranitoids. Fluid-absent equilibria in the subsolidus range have not yet been assessed by pseudosections, and neither so have been metastable reactions, which may also be responsible for a late-stage re-equilibration.

Although the quality of the thermodynamic database and the choice of the proper bulk composition (Stüwe, 1997) have an effect on the size and position of stability fields and their boundaries, the importance of these factors can be tested during modelling and, even more importantly, the general characteristics of a pseudosection, the arrangement of stability fields and the slopes of isopleths, are not likely to change significantly.

4.2. Geotectonic relevance

The preservation point F derived in pseudosections is relevant only if no external hydration occurs afterwards. This assumption may not hold in view of the complex fluid–rock interactions to be expected both within an exhuming rock pile and through contact with some still subducting and progressively dewatering crustal rocks during exhumation. However, external hydration affects a rock usually only from the margins and along discrete fluid pathways, and similar to amphibolite boudins with a well preserved eclogite core, other rock types are likely to preserve their "driest" state of internal dehydration in some part.

Although relatively simple in mineralogy, metagranites have turned out not to be straigtghtforward to assess thermodynamically because one of the primary simplifying assumptions of "fluid-present equilibria" may not be valid for this rock type over a wide range of $P-T$ conditions. Garnet-bearing parageneses often show indicators of strong disequilibrium on a thin section scale and thermobarometric tools need to be applied with even more caution than usual. Subduction in a relatively dry state and dewatering during exhumation will have a strong effect on the rheological behavior, very much in contrast to metabasic rocks, which behave just in the reverse way.

Contrary to metagranites, metapelites easily re-equilibrate along their prograde path and thus develop high-pressure parageneses. However, most of them will keep this record only if their exhumation paths do not pass through the stability field of biotite. Otherwise, only mineral inclusions in refractory phases like garnet or zircon may tell the high-pressure part of the story. High-pressure indicator minerals like lawsonite, glaucophane or jadeite should be searched for in suitable rocks.

5. Conclusions

Metagranites do not easily record or preserve high-pressure conditions, either because of metastable persistence throughout the high-pressure section of the $P-T$ path or because of significant dehydration during exhumation. The presence of calcium in these rocks has two important effects: (1) net transfer reactions changing the composition of muscovite are still possible outside the stability range of biotite, and (2) additional phases that indicate high pressures, mainly garnet, can be formed. Those metagranites which have been sufficiently hydrated during subduction to grow jadeite, omphacite or Ca-rich garnet at high pressures, and which re-enter the biotite stability field during exhumation at relatively low temperatures, may preserve a large amount of their high-pressure phases. Thermobarometry is difficult because in many cases equilibrium was not attained on a whole-rock scale, as indicated by corona textures or nonconcentric zoning patterns in muscovite and garnet. These kinds of textures and Fe-rich garnet compositions very likely developed in the absence of a free fluid phase, under internally buffered a_{H_2O} conditions.

The dehydration behavior of metapelites may vary considerably, depending on the actual $P-T$ path. They

are useful high-pressure indicators as long as chlorite is stable, and may still reveal some evidence of a high-pressure past at higher grades, if the inclusion assemblage is analysed carefully. The $P-T$ conditions derived from the matrix assemblage may differ significantly from those at the actual pressure and temperature peaks of the path and are no adequate criterion to rule out a former high-pressure history.

An investigation of the dehydration behavior of eclogites and their country rocks, like gneisses and metapelites, explains how these different lithologies may have interacted during their metamorphic evolution, both along the prograde and retrograde paths. With the principles already outlined in the seminal paper by Heinrich (1982), adequate methods for a quantitative treatment are available today. Such analyses will advance our general understanding of the sequential evolution of parageneses and microstructures, and on a broader scale that of the tectonic evolution of various parts of an orogen, particularly in high- and ultrahigh-pressure terrains.

References

Austrheim, H., Griffin, W.L., 1985. Shear deformation and eclogite formation within the granulite-facies anorthosites of the Bergen Arcs, Western Norway. Chem. Geol. 50, 267–281.

Biino, G.G., Compagnoni, R., 1992. Very-high pressure metamorphism of the Brossaco coronite metagranite, southern Dora Maira Massif, Western Alps. Schweiz. Mineral. Petrogr. Mitt. 72, 347–363.

Carson, C.J., Clarke, G.L., Powell, R., 2000. Hydration of eclogite from Pam Penisula, New Caledonia. J. Metamorph. Geol. 18, 79–90.

Carswell, D.A., Wilson, R.N., Zhai, M., 2000. Metamorphic evolution, mineral chemistry and thermobarometry of schists and orthogneisses hosting ultra-high pressure eclogites in the Dabieshan of central China. Lithos 52, 121–155.

Chopin, C., Henry, C., Michard, A., 1991. Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. Eur. J. Mineral. 3, 263–291.

Compagnoni, R., Maffeo, B., 1973. Jadeite-bearing mategranite l.s. and related rocks in the Monte Mucrone area (Sesia–Lanzo zone, Western Italian Alps). Schweiz. Mineral. Petrogr. Mitt. 53, 355–378.

Cong, B., Wang, X., 1996. A review of researches of UHPM rocks in the Dabieshan–Sulu region. In: Cong, B. (Ed.), Ultrahigh-pressure Metamorphic Rocks in the Dabieshan–Sulu Region of China. Kluwer Academic Publishing, London, pp. 1–7.

Gil Ibarguchi, J.I., 1995. Petrology of jadeite metagranite and associated orthogneiss from the Malpica–Tuy allochthon (Northwest Spain). Eur. J. Mineral. 7, 403–415.

Griffin, W.L., Carswell, D.A., 1985. In situ metamorphism of Norwegian eclogites; an example. In: The Caledonide Orogen; Scandinavia and related areas, vol. 2. Wiley, Chichester, pp. 813–822.

Guiraud, M., Holland, T., Powell, R., 1990. Calculated mineral equilibria in the greenschist–blueschist–eclogite facies in $Na_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O$. Contrib. Mineral. Petrol. 104, 85–98.

Guiraud, M., Powell, R., Rebay, G., 2001. H_2O in metamorphism and unexpected behavior in the preservation of metamorphic mineral assemblages. J. Metamorph. Geol. 19, 445–454.

Harley, S.L., Carswell, D.A., 1995. Ultradeep crustal metamorphism: a prospective view. J. Geophys. Res. 100 (B5), 8367–8380.

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., 1986. Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Adula Nappe. J. Petrol. 27 (1), 123–154.

Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. J. Metamorph. Geol. 16, 309–343.

Johannes, W., Holtz, F., 1996. Petrogenesis and experimental petrology of granitic rocks. Minerals and Rocks, vol. 22. Springer, Berlin, Heidelberg, 348 pp.

Koons, P.O., Rubie, D.C., Frueh-Green, G., 1987. The effect of disequilibrium and deformation on the mineralogical evolution of quartz diorite during metamorphism in the eclogite facies. J. Petrol. 28 (4), 679–700.

Kretz, R., 1983. Symbols for rock-forming minerals. Am. Mineral. 68, 277–279.

Krogh, E.J., 1977. Evidence for Precambrian continent–continent collision in Western Norway. Nature 267, 17–19.

Le Goff, E., Ballevre, M., 1990. Geothermobarometry in albite–garnet orthogneisses: a case study from the Gran Paradiso nappe (Western Alps). Lithos 25, 261–280.

Massonne, H.J., 1995. Experimental and petrogenetic study of UHPM. In: Coleman, R.G., Wang, X. (Eds.), Ultrahigh Pressure Metamorphism. Cambridge Univ. Press, Cambridge, USA, pp. 33–95.

Massonne, H.J., Chopin, C., 1989. $P-T$ history of the Gran Paradiso (western Alps) metagranites based on phengite geobarometry. In: Daly, J.S., Cliff, R.A., Yardley, B.W.D. (Eds.), Evolution of Metamorphic Belts. Geol. Soc. (London) Spec. Publ., vol. 43, pp. 545–549.

Massonne, H.J., Schreyer, W., 1987. Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, quartz. Contrib. Mineral. Petrol. 96, 212–224.

Massonne, H.J., Szpurka, Z., 1979. Thermodynamic properties of white micas on the basis of high-pressure experiments in the systems $K_2O-MgO-Al_2O_3-SiO_2-H_2O$ and $K_2O-FeO-Al_2O_3-SiO_2-H_2O$. Lithos 41, 229–250.

Mottana, A., Carswell, D.A., Chopin, C., Oberhänsli, R., 1990. Eclogite facies mineral parageneses. In: Carswell, D.A. (Ed.), Eclogite Facies Rocks. Blackie, London, pp. 14–52.

Oberhänsli, R., Hunziker, J.C., Martinotti, G., Stern, W.B., 1983. Geochemistry, geochronology and petrology of Monte Mucrone: an example of eo-Alpine eclogitization of Permian granitoids in the Sesia–Lanzo zone, Western Alps, Italy. Chem. Geol. 52, 165–184.

Patrick, B., 1995. High-pressure–low-temperature metamorphism of granitic orthogneiss in the Brooks Range, northern Alaska. J. Metamorph. Geol. 13, 111–124.

Proyer, A., 2003. Metamorphism of pelites in NKFMASH – a new petrogenetic grid with implications for the preservation of high-pressure rocks during exhumation. J. Metamorph. Geol. 21, 493–509.

Rötzler, K., Schumacher, R., Maresch, W.V., Willner, A.P., 1998. Characterization and geodynamic implications of contrasting metamorphic evolution in juxtaposed high-pressure units of the Western Erzgebirge (Saxony, Germany). Eur. J. Mineral. 10, 261–280.

Rubbo, M., Borghi, A., Compagnoni, R., 1999. Thermodynamic analysis of garnet growth zoning in eclogite facies granodiorite from M. Mucrone, Sesia Zone, Western Italian Alps. Contrib. Mineral. Petrol. 137, 289–303.

Rubie, D.C., 1983. Reaction-enhanced ductility: the role of solid–solid invariant reactions in deformation of the crust and mantle. Tectonophysics 96, 331–352.

Sobolev, N.V., Shatskiy, V.S., Vavilov, M.A., Goryaynov, S.V., 1995. Zircon in high-pressure metamorphic rocks in folded regions as a unique container of inclusions of diamond, coesite, and coexisting minerals. Trans. (Dokl.) Russ. Acad. Sci. Earth Sci. Sect. 336, 79–85.

Stüwe, K., 1997. Effective bulk composition changes due to cooling: a model predicting complexities in retrograde reaction textures. Contrib. Mineral. Petrol. 129, 43–52.

Tabata, H., Yamauchi, K., Maruyama, S., 1998. Tracing the extent of a UHP metamorphic terrane: mineral-inclusion study of zircons in gneisses from the Dabie Shan. In: Hacker, B.R., Liou, J.G. (Eds.), When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-pressure Rocks. Kluwer, Dordrecht, pp. 261–273.

Wain, A., 1997. New evidence for coesite in eclogite and gneisses: defining an ultrahigh-pressure province in the Western Gneiss region of Norway. Geology 25 (10), 927–930.

Wain, A.L., Waters, D.J., Austrheim, H., 2001. Metastability of granulites and processes of eclogitisation in the UHP region of western Norway. J. Metamorph. Geol. 19, 609–625.

Wallis, S.R., Ishiwatari, A., Hirajima, T., Ye, K., Guo, J., Nakamura, D., Kato, T., Zhai, M., Enami, M., Cong, B., Banno, S., 1997. Occurrence and field relationship of ultrahigh-pressure metagranitoid and coesite eclogite in the Su-Lu terrane, eastern China. J. Geol. Soc. (Lond.) 154, 45–54.

Wayte, G.J., Worden, R.H., Rubie, D.C., Droop, G.T.R., 1989. A TEM study of disequilibrium plagioclase breakdown at high pressure: the role of infiltrating fluid. Contrib. Mineral. Petrol. 101, 426–437.

Ye, K., Cong, B., Ye, D., 2000. The possible subduction of continental material to depths greater than 200 km. Nature 407, 734–736.