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Paragonite: Why Is It So Rare in Medium-Temperature High-Pressure Rocks?

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Abstract

The rare formation of paragonite in medium-temperature (MT) high-pressure (HP) metabasites (= eclogites) can be easily explained by common geotherms in subduction-zone environments. Paragonite would disappear at pressures close to 20 kbar by a reaction forming kyanite and omphacite. During prograde metamorphic evolution and a geotherm of 6–7°C/km this takes place at temperatures below 500°C. Paragonite in higher-temperature eclogites is typically a retrograde product.

According to calculated pseudosections for H_2O excess conditions, paragonite should be abundant in MT-HP metapelites (and meta-rhyolites). We have experimentally proven by bracketing the reaction paragonite = kyanite + jadeite + H_2O in the P-T range 23.5 to 25.5 kbar and 560 to 710°C that the thermodynamic data of paragonite used for the pseudosections are justified. The rare occurrence of paragonite in MT-HP metapelites, which are frequently indicated by phengites with Si contents > 3.25 p.f.u. (P > 10 kbar in garnet-biotite-bearing assemblages), is due to insufficient H_2O in the rock, as again demonstrated by calculated pseudosections. Crustal thickening due to continent-continent collision produces MT-HP metapelites mainly by pressure increase, for instance, starting at mid-crustal levels (~ 20 km depth, 500°C). Rocks at these levels had been dried out by the previous prograde metamorphic evolution. During subsequent pressure increase, no water is liberated by mineral reactions to produce H_2O-excess conditions, and thus no paragonite can form. In turn, lacking paragonite and low paragonite contents of phengite in ordinary MT-HP metapelites are indicators of water-deficient conditions.

Introduction

THE SODIC white mica paragonite, as end member $NaAl_2[AlSi_3O_{10}](OH)_2$, is a rock-forming mineral that typically occurs in low- to medium-grade metamorphic rocks (Deer et al., 1966). It can appear in both metapelitic and metabasic lithologies, but less commonly also in other rock types such as metabauxites (Feenstra, 1996).

Paragonite can be abundant in blueschists and low-temperature eclogites, as many petrographic descriptions of such rocks demonstrate (e.g., Maresch and Abraham, 1981; Brown and Ghent, 1983; Schliestedt, 1986; Barnicoat and Fry, 1989; Sisson et al., 1997; Ballevre et al., 2003). However, these subduction-related metamorphic rocks rarely show paragonite in the medium-temperature (MT) environment, inasmuch as metamorphic pressures typically exceed 20 kbar. At pressures somewhat above 20 kbar, paragonite breaks down to form kyanite + omphacite (jadeite) + H_2O, as experimentally proven by Holland (1979) for the (Ca,Fe,Mg)O absent system NASH and calculated for the system NCFMASH (e.g., Wei et al., 2003). Nevertheless, paragonite can be a relict phase in eclogites with peak pressure conditions above 20 kbar, surviving as inclusions, for instance, in garnet, but it can also form again in such eclogites during exhumation along a cooling path. A corresponding eclogite (T_{max} ~ 600°C, P_{max} ~ 24 kbar) showing paragonite both as inclusions and as a late matrix phase was described by Vignaroli et al. (2005). Retrograde paragonite formation in MT eclogites was also reported by Hoschek (2001) and Massonne and Kopp (2005).

Paragonite in metapelitic rocks was reported, for instance, by Zen and Albee (1964), Höck (1974), Baltatzis and Wood (1977), Hoffer (1978), Klaper (1986), Jamieson and O'Beirne-Ryan (1991), and Nagel et al. (2002). The rocks studied by these authors can be assigned to medium temperatures and low-medium pressures ($P \leq 10$ kbar). However, paragonite in metapelites was reported by Theye and Seidel (1991) and Faryad (1995) also from low-grade, high-pressure (HP) areas (blueschist facies) and by Hirajima et al. (1988), Vuichard and

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TABLE 1. Rock Compositions Used for the Calculation of Pseudosections

	Wat AWBZ	Wat High-Al	Mix1	GR02-8c A	GR02-8c B
			wt%		
SiO_2	60.78	60.14	58.78	78.11	77.45
TiO_2			1.13	0.26	0.25
Al_2O_3	16.88	23.04	20.28	12.15	12.05
FeO	6.87	6.79	6.46	1.90	1.88
Fe_2O_3			1.16	0.23	0.23
CaO	1.21	1.20	0.49	0.83	0.83
MgO	3.44	3.41	3.96	0.63	0.62
MnO	0.13	0.13	0.09	0.03	0.03
K_2O	3.70	3.66	3.75	2.55	2.53
Na_2O	1.65	1.63	1.85	2.49	2.47
H_2O			2.05	0.82	1.65
Sum	94.66	100.00	100.00	100.00	100.00

[1]The Waterville compositions were taken from Tinkham et al. (2001). The corresponding water contents used by these authors were sufficiently high to saturate the system for the P-T range of the calculations. Mix 1 was used by Massonne et al. (2006). GR02-8c A and B are from Massonne (2006).

Ballevre (1988), and El-Shazly and Liou (1991) from medium-grade HP regions (eclogite facies). The corresponding rocks investigated by all these researchers contain chloritoid, pointing to relatively Al-rich pelitic protoliths. In fact, paragonite seems to occur also in MT-HP metapelites with ordinary compositions (see, e.g., Matsumoto and Hirajima, 2000) who described paragonite coexisting with garnet, chlorite, and albite), but such occurrences must be uncommon because of rare literature reports.

Recently developed computer programs allow us to calculate so-called pseudosections (change of mineral assemblages for a fixed bulk-rock composition as a function of pressure and temperature), which help to elucidate the above observations on paragonite occurrences. Corresponding calculation results in the MnNCKFMASH system by Tinkham et al. (2001) confirm that paragonite can appear in metapelites of the low-pressure regime at low and medium (T > 500°C, then P > 3 kbar) temperatures when the pelitic bulk-rock compositions are rich in Al (see Waterville High-Al composition in Table 1 with Al_2O_3 ~23 wt%). Less Al-rich compositions are only suitable for paragonite occurrences at higher pressures (see AWBZ in Table 1, minimum P for paragonite ~8 kbar at 600°C) according to Tinkham et al. (2001).

Pseudosections (T = 600–1000°C, P = 10–40 kbar) calculated by Massonne et al. (2006) in the system TiNCKFMASH for several more or less ordinary pelitic compositions always resulted in a large P-T range for assemblages with paragonite. An example is given in Figure 1 for so-called Mix 1 (Table 1). At 600°C the pressures for stable appearance of paragonite range between at least 10 kbar to almost 25 kbar, although at these P-T conditions the water content of the bulk rock was even not quite sufficient to reach H_2O in excess. For other pelitic compositions, this range was between 10–12 kbar and close to 25 kbar. Maximum calculated temperatures for paragonite in metapelites were around 800°C, although at these temperatures the pseudosections may show metastable relationships due to ignoring the appearance of silicate melt. The above findings are widely confirmed by calculations of Proyer (2003). For all cited calculation results the thermodynamic data set by Holland and Powell (1998) was used.

In contrast to the results of the above pseudosections, paragonite seems to be very rare in ordinary metapelites formed at high pressures (P > 10 kbar)

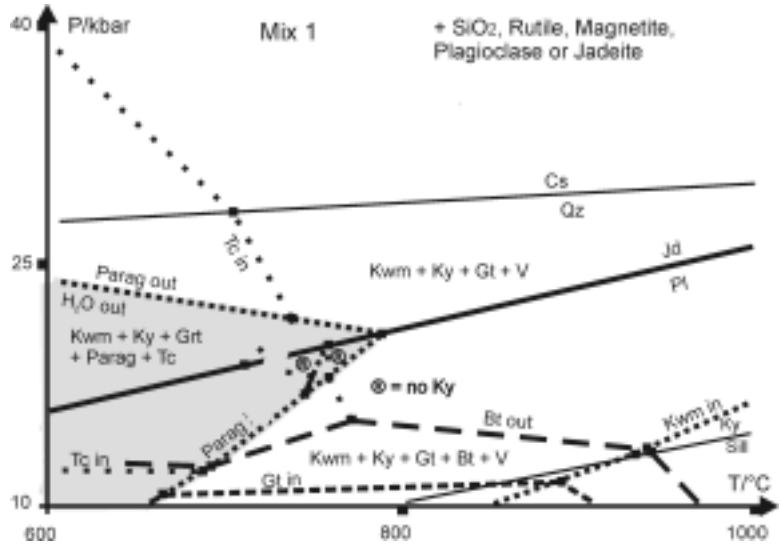


FIG. 1. Pseudosection calculated for an ordinary metapelitic composition (Mix 1, Table 1, from Massonne et al., 2006). The grey field marks the occurrence of paragonite. Abbreviations: Bt = biotite; Cs = coesite; Gt = garnet; Jd = jadeite; Kwm = potassic white mica; Ky = kyanite; Parag = paragonite; Pl = plagioclase; Qz = quartz; Sill = sillimanite; Tc = talc; V = vapor. Note that the contents of water in the bulk rock were almost sufficient in wide portions of the paragonite field to yield H_2O excess conditions.

and medium temperatures. Reasons include the following: (1) Paragonite (the Greek word paragon means misleading, inasmuch as it resembles talc [Deer et al., 1966], and thus also potassic white mica) in thin-sections could have been easily mistaken for phengite, which is an abundant phase in very many HP metapelites. (2) MT-HP metapelites could be very rare, and thus paragonite can only be rarely reported from such rocks. (3) The thermodynamic data for paragonite are incorrect, and hence the P-T range for stable occurrence of paragonite (in various assemblages) in the calculated pseudosections is significantly overestimated. (4) A chemical parameter such as H_2O activity is not sufficiently considered by the calculation of the pseudosection, so that in nature the stability is much more restricted compared to the computation. In subsequent sections, we present a solution to this problem, and argue for specific geodynamic scenarios explaining the rare occurrence in MT-HP rocks.

Experimental Study of Paragonite Breakdown

In order to check the quality of the thermodynamic data for end-member paragonite, we decided to re-investigate the upper pressure stability limit of paragonite decomposing to kyanite + jadeite + H_2O. The corresponding reaction was previously investigated by Holland (1979) to take place in the pressure range 23 to 27 kbar (T > 500°C).

All experiments were undertaken in a piston-cylinder apparatus using a WC pressure vessel. This vessel was loaded with two kinds of NaCl pressure cells (graphite or steel furnace) with a diameter of half an inch (12.7 mm; see Massonne and Schreyer, 1986). The starting material was sealed in gold capsules. Temperatures were determined with chromel-alumel thermocouples. Pressure and temperature corrections and uncertainties are given by Massonne and Schreyer (1989).

Synthesis runs, to produce either paragonite or the assemblage kyanite + jadeite, were performed using a glass prepared from pure chemicals (SiO_2 glass, γ-Al_2O_3, and sodium carbonate decahydrate [washing soda]), as starting material that was ground and filled with ~10 wt% pure H_2O in gold capsules. Diameter and length of these capsules were 4 mm and 10 mm, respectively. The synthesis experiment at 28 kbar and 700°C yielded a mixture of kyanite and jadeite. The product of the run at 20 kbar and 650°C consisted of $2M_1$ paragonite.

TABLE 2. Experimental Run Conditions of Bracketing Experiments on the HP Stability of Paragonite (Parag), Jadeite (Jd), and Kyanite (Ky)

Run no.	Pressure/kbar	Temperature/°C	Duration/d	Growth
4	24.2	686	7	Parag
5	24.3	685	7	Parag
6	25.2	686	7	Jd + ky
7	25.4	588	7	Jd + ky
8	24.9	590	7	±
9	24.6	590	7	±
10	25.0	628	7	Jd + ky
11	24.4	614	12	±
12	25.2	704	7	Jd + ky
13	24.2	703	7	±
14	24.3	667	7	±
15	23.7	705	7	Parag
16	24.2	662	7	Parag
17	25.2	559	14	Jd + ky

For experimental runs to bracket the paragonite decomposition curve, a mixture of the products of both synthesis runs (weight proportions paragonite: kyanite + jadeite = 1:2) was used. This mixture + ~10 wt% H_2O was filled in a gold capsule with an outer diameter of 2 mm and a length of about 12 mm. This length refers to that after sealing the capsule and compacting it. The various run conditions are listed in Table 2. After the run, the persistence of water in the capsule was monitored by weighing. Growth or decomposition of paragonite was judged by comparing the powder X-ray diffractograms before and after the experiment. In five instances (runs 8, 9, 11, 13, and 14), no detectable change occurred between the starting material and the run product despite the run durations of at least a week. These durations were considerably longer than those of the experiments by Holland (1979).

Our newly derived decomposition curve of paragonite is compatible with all experimental run products of Table 2 (Fig. 2). This even includes all brackets given by Holland (1979). Nevertheless, our P-T curve shows a significantly lower dP/dT slope compared to that of Holland. At about 550°C, we determined the same pressure of 25.2 kbar for the decomposition of paragonite. However, at 700°C our decomposition pressure of 24.2 kbar is about 0.8 kbar higher than that given by Holland.

Because of the similarity of the newly derived paragonite decomposition curve with that by Holland (1979), a slight change of the thermodynamic properties of paragonite may be necessary. However, for any change, other bracketed reactions with participating paragonite have to be considered. These reactions concern the paragonite ± quartz breakdown at low pressures determined by Chatterjee (1970, 1972) as well as reaction of paragonite + zoisite + quartz + H_2O to form lawsonite + albite or jadeite (Heinrich and Althaus, 1988). In addition, the thermodynamic properties of the high-pressure decomposition products of paragonite—jadeite and kyanite—had to be checked. Kyanite has rather the function of an anchor phase whereas jadeite seems to be more critical in this respect. If we, for instance, consider the breakdown of pure albite to form jadeite + quartz/coesite at high temperatures, there is no consensus about the true decomposition pressures. Mirwald and Massonne (1980) reported a decomposition pressure between 31.0 and 31.7 kbar at 1090°C due to bracketing experiments. Calculations with the thermodynamic data set by Holland and Powell (1998) result in a high-pressure breakdown of paragonite almost compatible with the new results, but decomposition of albite occurs at a pressure of 29.55 kbar at 1090°C. Thus, a negligible change of the thermodynamic properties of paragonite in the Holland and Powell (1998) data set (thus still being compatible with the previously mentioned results of bracketing experiments, for instance, by Chatterjee) but a slight modification of

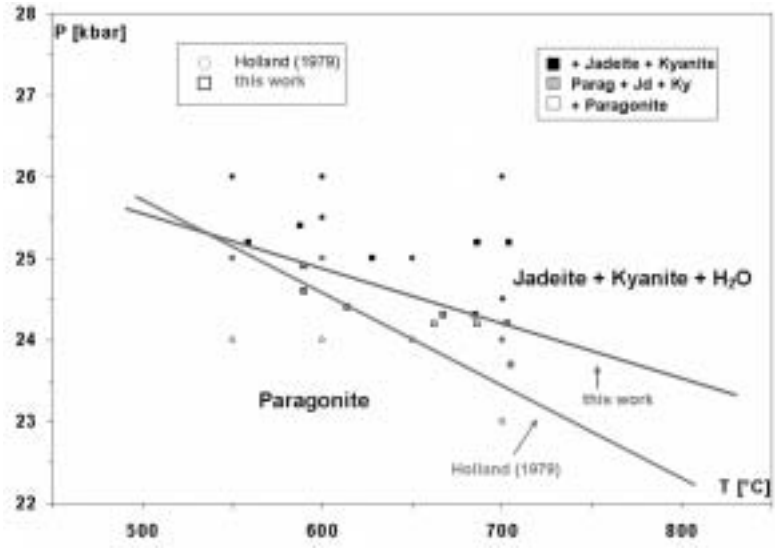


FIG. 2. P-T results of experimental bracketing of the reaction paragonite = jadeite + kyanite + H_2O in the system NASH. Our new curve (thick line) is compatible with all experimental runs, whereas the curve by Holland (1979, thin line) is incompatible with a few runs showing paragonite growth.

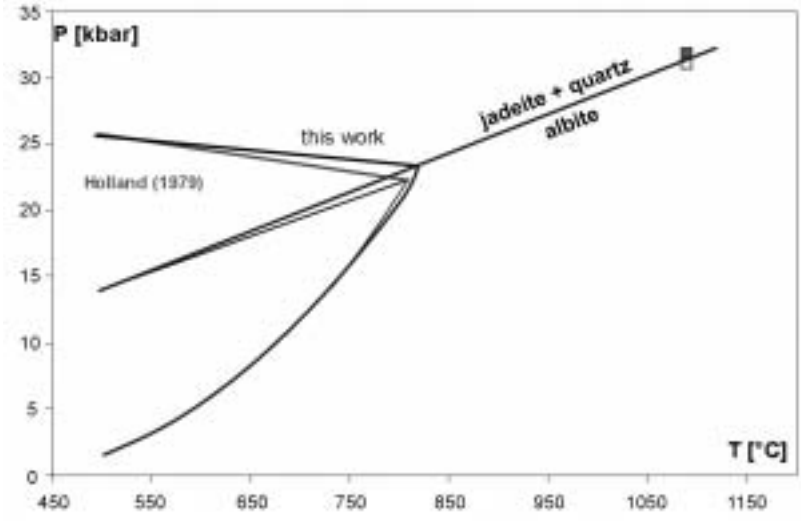


FIG. 3. P-T stability of paragonite (+ quartz), ignoring the occurrence of silicate melt, and the reaction curve jadeite + quartz = albite in the system NASH according to the new experimental results of this study and a bracket (see boxes) by Mirwald and Massonne (1980). The thin line shows the equivalent curves by Holland (1979).

the jadeite data are required in order to reproduce the newly derived breakdown curve for paragonite and the experimental bracket by Mirwald and Massonne (1980). Resulting curves as a possible consequence of our new experimental data are shown in Figure 3.

Theoretical Considerations Using Pseudosections

In previous attempts to calculate pseudosections for pelitic rocks in appropriate model systems such as CNKFMASH (see Introduction) the water con-

tents in the bulk rocks were so high that H_2O was in excess, or the system was almost saturated with H_2O. By calculations of pseudosections for a psammopelitic composition (GR02-8c, actually a felsic granulite, see Table 1) we have tested the influence of relatively low water contents on extent of the P-T stability of paragonite in HP mineral assemblages. In fact, the selected bulk-rock composition could just as well be that of a graywacke but, according to the discussion in Massonne (2006), it could be also that of a highly differentiated granite. The pseudosections, including mineral compositions and modal composition of the rock at fixed P-T conditions, were calculated for the P-T range 8 to 28 kbar and 550 to 950°C using the thermodynamic data set of Holland and Powell (1998), the DEKAP code by Gerya et al. (2001), and activity models for the solid solution phases from various authors (see Massonne et al., 2006).

In Figure 4 we present pseudosections for the GR02-8c composition with two different H_2O contents. H_2O-excess conditions resulted for the entire P-T range (the high-temperature, low-pressure range is metastable with regard to silicate melt) for GR02-8cB (Fig. 4A). Paragonite appears as in the previous examples over a considerable pressure range (although the bulk rock could be also a metagranite) of 13.5 to 24 kbar at 600°C. In contrast, in the pseudosection for composition GR02-8cA no paragonite occurs. In fact, the P-T ranges of other hydrous minerals, chlorite and biotite, are reduced (maximum pressure of biotite: ~14 kbar for GR02-8cA, ~16 kbar for GR02-8cB) as well, but the disappearance of paragonite is the most obvious result of less H_2O in the bulk-rock composition. Another interesting result of the above comparison of different H_2O contents in the bulk rock is the content of paragonite in potassic white mica. Table 3 shows this content for selected P-T conditions. For H_2O-excess conditions (GR02-8cB) at 600°C and in the pressure range 14.5 to 22.5 kbar, the modal content of paragonite is between 5 and 7 vol%. The paragonite content in potassic white mica can exceed 10 mol% especially at the lower pressures of this pressure range (see Table 3). In contrast to these data, the calculated paragonite contents in potassic white mica are below 3.6 mol% over the entire P-T range for the pseudosection of composition GR02-8cA. In the P-T range above 12 kbar and below 690°C, these contents are even below 2 mol%.

Discussion

At the end of the Introduction, we presented four possible reasons for the rarity of paragonite in MT-HP metapelites. According to our new investigations, we can exclude reason 3: incorrect thermodynamic data for paragonite. In addition, the thermodynamic solid solution model for potassic white mica by Powell and Holland (1999), used in the above calculations of pseudosections, seems to be appropriate to estimate a realistic mica composition, especially with regard to the paragonite-phengite solid solution. This is important because the appearance of paragonite at high pressures in the pseudosections might reflect only small amounts of paragonite component stable in the potassic white mica solid solution. We calculated contents of paragonite component in phengite (Si > 3.2 per formula unit = p.f.u.) coexisting with paragonite that even exceeded 10 mol%. Such high values are rarely observed in phengites of corresponding natural rocks. Not relevant for this problem is the solvus in the pure binary system paragonite-muscovite (e.g., Chatterjee and Flux, 1986). For instance, at P-T conditions of 15 kbar and 600°C somewhat more than 30 mol% of paragonite can be accommodated in muscovite, but celadonite component in muscovite (= phengitic micas) clearly diminishes the amount of paragonite component stable in the potassic white mica.

Reason 1 (paragonite mistaken for phengite or talc) might have been occasionally the case in the past, but modern analytical instruments, especially backscattered electron (BSE) detectors in electron microprobes, allow the routine discrimination of paragonite, potassic white mica, and talc in rock thin sections. An example is given in the BSE image of Figure 5. The corresponding rock, an eclogite from the Saxonian Erzgebirge (Massonne and Kopp, 2005), contains dominant phengite but also (Fe-bearing) talc and accessory paragonite. Nevertheless, paragonite was easily detected because of the high greytone contrast between phengite (+ talc) and paragonite in the BSE images.

Despite the existence of a powerful barometer based on the composition of phengite, only few medium-temperature metapelites, commonly showing the ordinary mineral assemblage garnet–biotite–potassic white mica–quartz–plagioclase, were sufficiently geothermobarometrically evaluated. Nevertheless, coexisting white micas which are typically phengitic in composition, at least with regard to core

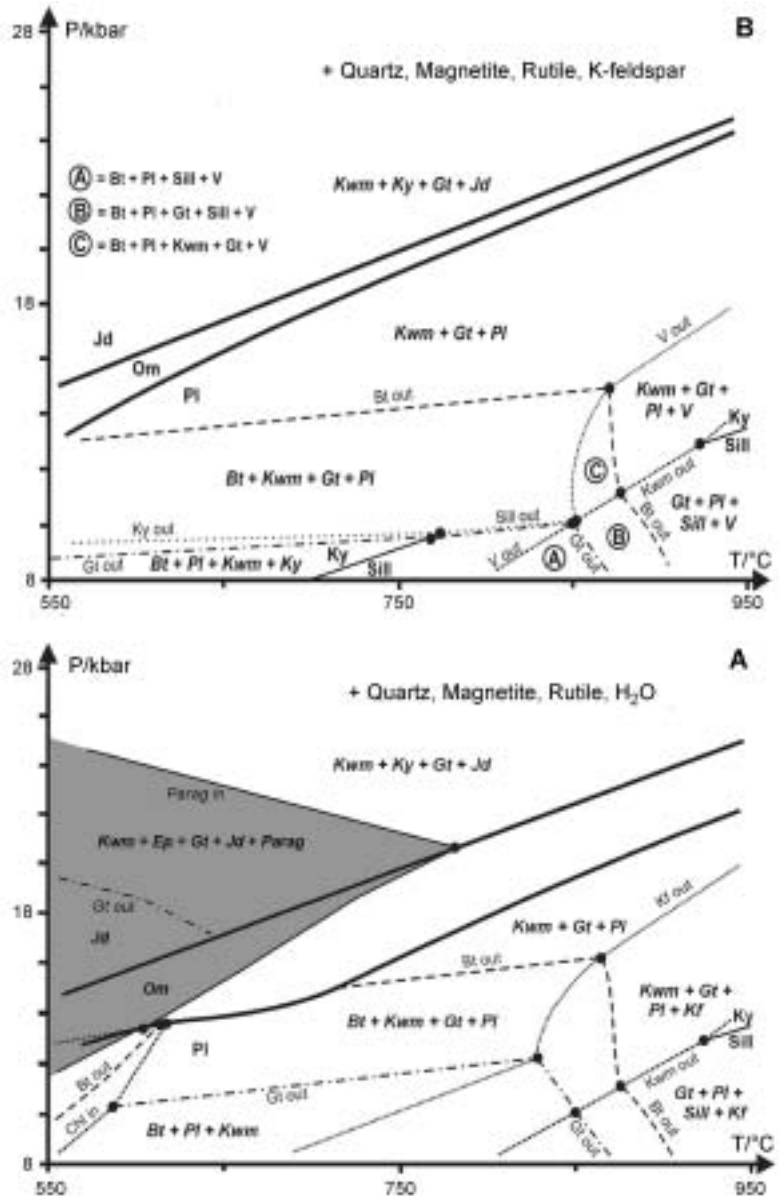


FIG. 4. Pseudosections calculated for metagraywacke (or metagranite) GR02-8c (Table 1). A. H_2O-excess conditions. B. Significantly less H_2O compared to (A). Abbreviations: Chl = chlorite; Kf = K-feldspar; Om = omphacite; and as in Figure 1.

compositions (rims of mica grains are often re-equilibrated during exhumation of the corresponding rocks) point to medium- to high-pressure conditions. This relationship is known from various experimentally calibrated phengite geobarometers (Massonne and Schreyer, 1987, 1989; Massonne and Szpurka, 1997), or from calculated phengite compositions in pseudosections (see Table 3) based on white mica solid solution models (Powell and Holland, 1999) derived from such experiments. For the pressure range 10 to 20 kbar (600°C), Si contents of phengite coexisting with kyanite and garnet are roughly

TABLE 3. Calculated Modal Content and Phengite Composition[1] by Applying the DEKAP Code to Rock Compositions of Table 1 and Various P-T Conditions

Composition	GR02-8c B			GR02-8c A			Mix 1	
P-T conditions	15 kbar, 600°C	20 kbar, 600°C	20 kbar, 700°C	15 kbar, 600°C	20 kbar, 600°C	20 kbar, 700°C	15 kbar, 600°C	20 kbar, 700°C
H2O in excess	Yes	Yes	yes	No	No	No	Almost	Saturated
Quartz	52.76	57.31	57.96	51.93	58.64	58.71	23.74	28.11
Rutile	0.16	0.17	0.17	0.17	0.18	0.18	0.80	0.82
Omphacite	4.03	12.6	13.83	0.25	16.07	16.10		6.24
K white mica	23.83	22.64	22.91	17.43	18.15	18.14	35.54	36.33
K-feldspar				2.72	2.71	2.78		
Garnet		0.51	1.11	1.11	2.05	2.14	10.65	13.9
Magnetite	0.18	0.14	0.18	0.18	0.18	0.18	1.96	2.02
Epidote		0.36						
Kyanite				0.05	2.01	1.76	2.97	1.3
Plagioclase	13.52			23.57			13.10	
Paragonite	5.53	6.28	3.84				4.51	9.51
Talc							6.72	1.78
Xmuscovite	0.4281	0.4997	0.5861	0.7143	0.6578	0.6893	0.6347	0.5778
XMgAl-celadonite	0.121	0.1292	0.1096	0.1433	0.1199	0.1077	0.1751	0.2411
XFeAl-celadonite	0.3239	0.3125	0.2375	0.1311	0.2193	0.1951	0.1237	0.1115
Xparagonite	0.127	0.0586	0.0669	0.0125	0.0029	0.0079	0.0666	0.0697
Si p.f.u.	3.445	3.442	3.347	3.274	3.339	3.303	3.299	3.353

[1]Molar fractions X and Si content per formula unit.

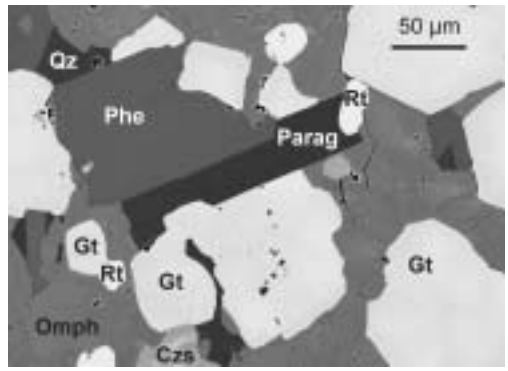


FIG. 5. Backscattered electron image showing the grey tone contrast between phengite (Phe) and paragonite (Parag) in a fine-grained eclogite (from Massonne and Kopp, 2005). Other phases are: Czs = clinozoisite; Gt = garnet; Omph = omphacite; Qz = quartz; Rt = rutile.

between 3.15 and 3.30 p.f.u. For phengites coexisting with biotite and garnet, the Si contents must be, for topological reasons, higher, ranging between 3.25 and 3.40 p.f.u. In K-feldspar–biotite bearing assemblages, phengite Si contents should be between 3.35 and 3.70 p.f.u. unless the H_2O activity is significantly less than unity (Massonne and Schreyer, 1987). In case of water deficiency, the phengite Si contents are lower compared to H_2O excess conditions. Inasmuch as the above-given Si contents are often observed in potassic white micas from metapelitic rocks, which lack paragonite, we abandon reason 2 (high-pressure, medium-temperature metapelites could be very rare) as well, although we could present only indirect evidence against this reason.

Finally, reason 4 (chemical parameter such as water activity) is left. Our calculations of pseudosections have, indeed, demonstrated that the P-T field of paragonite in various assemblages can be significantly reduced when the water content in the bulk rock falls below that resulting in H_2O excess conditions. This reason probably is the major cause for the absence of paragonite in ordinary MT-HP metapelites. In addition, we think that the lack of paragonite is indicative of the fact that water in the rock was insufficient to reach H_2O excess conditions.

Geodynamic Conclusions

As was pointed out earlier, paragonite is a normal constitutent in blueschists and low-temperature eclogites. These rocks chiefly form by subduction of oceanic crust. The involvement in a subdurction channel is a possible explanation for their return to the surface. Considering a typical subduction-related geotherm of 6–7°C/km (Massonne, 2004), paragonite would disappear (at 20 kbar = 70 km Earth's depth) during prograde metamorphic evolution in the temperature interval 420–490°C (Fig. 6). Because of the invoked breakdown of this hydrous phase (and other hydrous phases, such as lawsonite, as well) this evolution would happen at H_2O excess conditions. This scenario is very compatible with petrological information. Thus, paragonite would only rarely form in high-pressure metabasites in the medium-temperature environment (except by retrograde reactions).

Metapelitic rocks can, in principle, be deeply buried in a subduction environment as well; hence, paragonite would experience the same fate in these rocks as in the above eclogites during prograde evolution. However, the majority of HP metapelites, occurring widely in the continental crust even before HP metamorphism, might form by other processes. Crustal thickening to a possible maximum of 70 km (~ 20 kbar), due to continent-continent collision, is probably the most important process in this respect. This thickening can occur by thrusting one continental plate under the other, as assumed for the present orogenic situation in southern Asia (Himalaya, Tibetan Plateau) after long sustained collision of the Indian and Asian plates (Zhou and Murphy, 2005). As a result of this process metapelite (or metagranite as well), which was in an intermediate

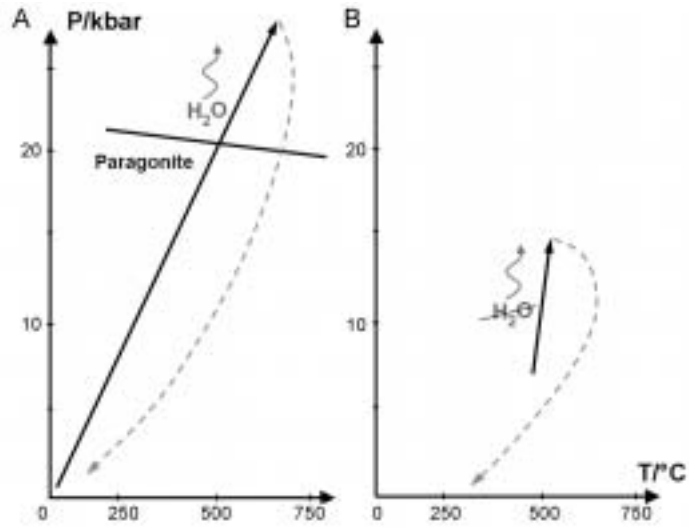


FIG. 6. Prograde P-T paths typical for the subduction of oceanic crust (A) and for continental crust of mid-crustal levels buried by an overriding continental plate (B) due to continent-continent collision. In case A, paragonite breaks down in metabasic rocks before reaching MT conditions. In case B, no paragonite is formed in HP-MT metapsammopelites and metagranites due to insufficient H_2O in the bulk rock. Possible retrograde paths are shown by broken curves.

level (~ 5 kbar) of the underthrust crust, is more or less isothermally compressed (e.g., to 15 kbar, Fig. 6) to reach the P-T field of paragonite in various mineral assemblages under H_2O excess conditions, as calculated in the pseudosections for ordinary metapelitic rocks (see Fig. 1). However, this metapelite from an intermediate crustal level had undergone a previous prograde metamorphism and dried out, conserving water only in the remaining hydrous minerals, mainly micas. During subsequent pressure increase (e.g., to 15 kbar) no further dehydration reactions occur to reach H_2O excess conditions. As a consequence, in such rocks, lacking water, paragonite would not form. Thus, the absence of paragonite in MT-HP metapelites would be indicative for the above outlined geodynamic process during continent-continent collision. In addition, relatively low paragonite contents in phengite of MT-HP metapelitic (and meta-acidic) rocks (Table 3) could also be indicative of the absence of hydrous fluid during HP metamorphism.

We conclude that the rarity of paragonite in MT-HP metapelitic rocks is the result of crustal thickening due to continent-continent collision where relatively dry continental crust is buried. Paragonite would be much more abundant if the corresponding rocks had experienced HP metamorphism under H_2O-excess conditions.

REFERENCES

Ballevre, M., Pitra, P., and Bohn, M., 2003, Lawsonite growth in the epidote blueschists from the Ile de Groix (Armorican Massif, France): A potential geobarometer: Journal of Metamorphic Geology, v. 21, p. 723–735.

Baltatziz, E., and Wood, B. J., 1977, The occurrence of paragonite in chloritoid schists from Stonehaven, Scotland: Mineralogical Magazine, v. 41, p. 211-216.

Barnicoat, A. C., and Fry, N., 1989, Eoalpine high-pressure metamorphism in the Piemonte zone of the Alps: South-west Switzerland and north-west Italy, *in* Daly, J. S., Cliff, R. A., and Yardley, B. W. D., eds., Evolution of metamorphic belts: Geological Society of London, Special Publications, v. 43, p. 539–544.

Brown, E. H., and Ghent, E. D., 1983, Mineralogy and phase relations in the blueschist facies of the Black Butte and Ball Rock areas, northern California Coast Ranges: American Mineralogist, v. 68, p. 365–372.

Chatterjee, N. D., 1970, Synthesis and upper stability of paragonite: Contributions to Mineralogy and Petrology, v. 27, p. 244–257.

Chatterjee, N. D., 1972, The upper stability limit of the assemblage paragonite + quartz and its natural occurrences: Contributions to Mineralogy and Petrology, v. 34, p. 288–303.

Chatterjee, N. D., and Flux, S., 1986, Thermodynamic mixing properties of muscovite-paragonite crystalline solutions at high temperatures and pressures, and their geological application: Journal of Petrology, v. 27, p. 677–693.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, An introduction to the rock forming minerals: London, UK, Longman, 528 p.

El-Shazly, A. K., and Liou, J. G., 1991, Glaucophane chloritoid-bearing assemblages from NE Oman: Petrologic significance and a petrogenetic grid for high-P metapelites: Contributions to Mineralogy and Petrology, v. 107, p. 180–201.

Faryad, S. W., 1995, Petrology and phase relations of low-grade high-pressure metasediments from the Meliata Unit (West Carpathians, Slovakia): European Journal of Mineralogy, v. 7, p. 71–87.

Feenstra, A., 1996, An EMP and TEM-AEM study of margarite, muscovite, and paragonite in polymetamorphic metabauxites of Naxos (Cyclades, Greece) and implications of fine-scale mica interlayering and multiple mica generations: Journal of Petrology, v. 37, p. 201–233.

Gerya, T. V., Maresch, W. V., Willner, A. P., Van Reenen, D. D., and Smit, C. A., 2001, Inherent gravitational instability of thickened continental crust with regionally developed low- to medium-pressure granulite-facies metamorphism: Earth and Planetary Science Letters, v. 190, p. 221–235.

Heinrich, W., and Althaus, E., 1988, Experimental determination of the reactions 4 lawsonite + 1 albite = 1 paragonite + 2 zoisite + 2 quartz + 6 H_2O and 4 lawsonite + 1 jadeite = 1 paragonite + 2 zoisite + 1 quartz + 6 H_2O: Neues Jahrbuch Mineralogie Monatshefte, v. 1988, p. 516–528.

Hirajima, T., Banno, S., Hiroi, Y., and Ohta, Y., 1988, Phase petrology of eclogites and related rocks from the Motalafjella high-pressure metamorphic complex in Spitsbergen (Arctic Ocean) and its significance: Lithos, v. 22, p. 75–97.

Höck, V., 1974, Coexisting phengite, paragonite, and margarite in metasediments of the Mittlere Hohe Tauern, Austria: Contributions to Mineralogy and Petrology, v. 43, p. 261–273.

Hoffer, E., 1978, On the "late" formation of paragonite and its breakdown in pelitic rocks of the Southern Damara Orogen (Namibia): Contributions to Mineralogy and Petrology, v. 67, p. 209–219.

Holland, T. J. B., 1979, Experimental determination of the reaction paragonite = jadeite + kyanite + H_2O, and internally consistent thermodynamic data for part of the system Na_2O–Al_2O_3–SiO_2–H_2O, with applications to eclogites and blueschists: Contributions to Mineralogy and Petrology, v. 68, p. 293–301.

Holland, T. J. B., and Powell, R., 1998, An internally consistent thermodynamic data set for phases of petrological interest: Journal of Metamorphic Geology, v. 16, p. 309–343.

Hoschek, G., 2001, Thermobarometry of metasediments and metabasites from the eclogite zone of the Hohe Tauern, Eastern Alps, Austria: Lithos, v. 59, 127–150.

Jamieson, R. A., and O'Beirne-Ryan, A. M., 1991, Decompression-induced growth of albite porphyroblasts, Fleur de Lys Supergroup, western Newfoundland: Journal of Metamorphic Geology, v. 9, p. 433–439.

Klaper, E. M., 1986, Deformation und Metamorphose im Gebiet des Nufenpasses, Lepontinische Alpen: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 66, p. 115–128.

Maresch, W. V., and Abraham, K., 1981, Petrography, mineralogy, and metamorphic evolution of an eclogite from the Island of Margarita, Venezuela: Journal of Petrology, v. 22, p. 337–362.

Massonne, H.-J., 2004, Ultra high pressure metamorphism, *in* Selley, R. C., Cocks, L. R. M., and Plimer, I. R., eds., Encyclopedia of Geology, v. 5, p. 533–540.

Massonne, H.-J., 2006, Early metamorphic evolution and exhumation of felsic high-pressure granulites from the north-western Bohemian Massif: Mineralogy and Petrology, in press.

Massonne, H.-J., and Kopp, J., 2005, A low-variance mineral assemblage with talc and phengite in an eclogite from the Saxonian Erzgebirge, Central Europe, and its P-T evolution: Journal of Petrology, v. 46, p. 355–375.

Massonne, H.-J., and Schreyer, W., 1986, High-pressure syntheses and X-ray properties of white micas in the system K_2O-MgO-Al_2O_3-SiO_2-H_2O: Neues Jahrbuch für Mineralogie Abhandlungen, v. 153, p. 177–215.

Massonne, H.-J., and Schreyer, W., 1987, Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz: Contributions to Mineralogy and Petrology, v. 96, p. 212–224.

Massonne, H.-J., and Schreyer, W., 1989, Stability field of the high-pressure assemblage talc + phengite and two new phengite barometers: European Journal of Mineralogy, v. 1, p. 391–410.

Massonne, H.-J., and Szpurka, Z., 1997, 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, v. 41, p. 229–250.

Massonne, H.-J., Willner, A. P., and Gerya, T. V., 2006, Densities of psammopelitic rocks at elevated temperatures and high to ultrahigh pressure conditions: what are the geodynamic consequences?: Earth and Planetary Science Letters, submitted.

Matsumoto, N., and Hirajima, T., 2000, Garnet in pelitic schists from a quartz-eclogite unit of the southern Dora-Maira massif, Western Alps: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 80, p. 53–62.

Mirwald, P. W., and Massonne, H.-J., 1980, The low-high quartz and quartz-coesite transition to 40 kbar between 600° and 1600°C and some reconnaissance data on the effect of $NaAlO_2$ component on the low quartz-coesite transition: Journal of Geophysical Research, v. 85, p. 6983–6990.

Nagel, T., de Capitani, C., and Frey, M., 2002, Isograds and P–T evolution in the eastern Lepontine Alps (Graubünden, Switzerland): Journal of Metamorphic Geology, v. 20, p. 309–324.

Powell, R, and Holland, T. J. B., 1999, Relating formulations of the thermodynamics of mineral solid solutions: activity modeling of pyroxenes, amphiboles and micas: American Mineralogist, v. 84, p. 1–14.

Proyer, A., 2003, Metamorphism of pelites in NKFMASH—a new petrogenetic grid with implications for the preservation of high-pressure mineral assemblages during exhumation: Journal of Metamorphic Geology, v. 21, p. 493–509.

Schliestedt, M., 1986, Eclogite-blueschist relationships as evidenced by mineral equilibria in the high-pressure metabasic rocks of Sifnos (Cycladic Islands), Greece: Journal of Petrology, v. 27, p. 1437–1459.

Sisson, V. B., Ertan, I. E., and Avé Lallemant, H. G., 1997, High-pressure (~2000 MPa) kyanite- and glaucophane-bearing pelitic schist and eclogite from Cordillera de la Costa Belt, Venezuela: Journal of Petrology, v. 38, p. 65–83.

Theye, T., and Seidel, E., 1991, Petrology of low-grade high-pressure metapelites from the External Hellenides (Crete, Peloponnese). A case study with attention to sodic minerals: European Journal of Mineralogy, v. 3, p. 343–366.

Tinkham, D. K., Zuluaga, C. A., and Stowell, H. H., 2001, Metapelite phase equilibria modeling in MnNCKFMASH: The effect of variable Al_2O_3 and MgO/(MgO+FeO) on mineral stability: Geological Materials Research, v. 3, p. 1–42.

Vignaroli, G., Rosetti, F., Bouybaouene, M., Massonne, H.-J., Theye, T., Faccenna, C., and Funiciello, R., 2005, A counter-clockwise P-T path for the Voltri Massif eclogites (Ligurian Alps, Italy): Journal of Metamorphic Geology, v. 23, p. 533–555.

Vuichard, J.-P., and Ballevre, M., 1988, Garnet-chloritoid equilibria in eclogitic pelitic rocks from the Sesia zone (Western Alps): Their bearing on phase relations in high pressure metapelites: Journal of Metamorphic Geology, v. 6, p. 135–157.

Wei, C. J., Powell, R., and Zhang, L. F., 2003, Eclogites from the south Tianshan, NW China: Petrological characteristics and calculated mineral equilibria in the Na_2O–CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O system: Journal of Metamorphic Geology, v. 21, p. 163–179.

Zen, E-an, and Albee, A. L., 1964, Coexistent muscovite and paragonite in pelitic schists: American Mineralogist, v. 49, p. 904–925.

Zhou, H.-W., and Murphy, M. A., 2005, Tomographic evidence for wholesale underthrusting of India beneath the entire Tibetan plateau: Journal of Asian Earth Sciences, v. 25, p. 445–457.