QUARTZ - K-FELDSPAR INTERGROWTHS ENCLOSED IN ECLOGITIC GARNET AND OMPHACITE. ARE THEY PSEUDOMORPHS AFTER COESITE?

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Summary
According to literature and our observations on rock samples from the Western Alps, the Dabie Shan, the Shandong peninsula and the Erzgebirge containing relics of coesite, this mineral transforms only to quartz. Thus, it is confusing that inclusions in omphacite and garnet have been considered by other investigators as pseudomorphs after coesite even though they consist of discernible amounts of K-feldspar in addition to quartz. Only the impressive cracks in the host minerals around such inclusions are similar for both inclusion types.

We have investigated the questionable type of inclusion that appears in eclogites of the Gneiss-Eclogite Unit of the Erzgebirge where garnet peridotite and diamondiferous gneiss prove an ultrahigh-pressure (UHP) metamorphic nature at least of parts of this unit. The ideal shape of such inclusions that can be observed in both omphacite and garnet is a pseudohexagonal plate. Our SEM studies demonstrate that these inclusions are now symplectites that consist of quartz and significant amounts of K-feldspar. In contact with the garnet host, micas and chlorite have formed at the expense of K-feldspar. The inclusions can even consist of two or more generations of symplectites showing increasing grain size towards the center.

The shape and the textures of the inclusions point to a former solid phase rather than to a silicate melt, but we believe that neither a transformed pure SiO_2 phase nor exsolution from Si-rich UHP omphacite (Yang *et al.* 1998) is the right interpretation. Because HP experiments neither point to K-bearing coesite nor to a phase between SiO_2 and $KAlSi_3O_8$ composition, we assume that K-cymrite, $K[AlSi_3O_8]\cdot H_2O$, was transformed to the symplectites during exhumation. However, significant amounts of K and Al must have been removed by H_2O released during its breakdown.

Introduction
Since Chopin's (1984) discovery of coesite in metamorphic rocks, that occur in regional distribution within the Dora Maira Massif, Western Alps, this mineral was observed in several other areas, as well. Smith (1988) and Wain (1997) reported coesite from the Western Gneiss Region, Norway. Wang *et al.* (1989) and Hirajima *et al.* (1990) detected coesite in rocks from the Dabie-Sulu terrain in Eastern China. Caby (1994) and Parkinson and Katayama (1999) found coesite in Mali and on Sulawesi, respectively. In these areas, coesite was detected preferentially in eclogites but other coesite-bearing rock types are known, as well, such as marbles from the Dabie Shan (Schertl and Okay 1994) and metapelites from the Western Alps (Reinecke 1991). Typically, coesite was recognized as inclusion mainly in garnet by its relic nature. Especially larger inclusions can be considerably transformed to quartz that, additionally, shows a peculiar palisade texture around the coesite relic. Another indicative feature are the pronounced radial cracks around the inclusion in the host mineral.

Experimental results on the coesite-quartz transition obtained by various authors (e.g. Mirwald and Massonne 1980) show that coesite formation in nature requires pressures above 25 kbar. Thus, it is an important indicator mineral for a specific P-T regime that is related to the ultrahigh pressure metamorphism (UHPM).

According to the above references, although not always explicitly emphazised, the coesite inclusions can have transformed only to quartz. This is confirmed by our own observations on rock samples from the Dora Maira Massif, the Dabie Shan and the Shandong peninsula in China, and the Saxonian Erzgebirge (Fig. 1), Germany. Thus, it is a surprise that inclusions in omphacite and garnet have been considered by other investigators as pseudomorphs after coesite although they can consist of discernible amounts of K-feldspar in addition to quartz. However, impressive cracks in the host minerals around such inclusions were also observed suggesting the former presence of a mineral of higher density. Examples for this inclusion type without coesite but related to former coesite are from the Shandong peninsula (Enami et al. 1990), the Saxonian Erzgebirge (Schmädicke *et al.* 1992) and the Polish Sudetes (Bakun-Czubarow 1992). However, Yang *et al.* (1998) suggested that their quartz-rich inclusions with K-feldspar found in omphacites from the Shandong peninsula are the result of an exsolution from former K-bearing supersilicic clinopyroxene being typical for very high metamorphic pressures. Here, based on detailed investigations on very similar inclusions we present another explanation for them.

Sample provenance
The Variscan metamorphic area of the Erzgebirge that is part of the Bohemian Massif in Central Europe can be subdivided into several major units. One of them is the Gneiss-Eclogite Unit (GEU) that dominates the central portion of the Erzgebirge. Within the GEU abundant eclogite lenses occur in various types of para- and orthogneisses which had experienced high-pressure metamorphism with maximum temperatures of about 800°C (Willner *et al.* 1997) in Early Carboniferous times (Kröner and Willner 1998). Such eclogite occurrences and several garnet peridotite bodies, for which maximum P-T conditions were derived to be almost as high as 40 kbar and 1100°C (Massonne and Grosch, 1995) have been mapped in detail more than hundred years ago (e.g. Hazard 1886).

Fig. 1: Coesite relic enclosed in garnet of eclogite E99-24 from the Saidenbach reservoir, Saxonian Erzgebirge. Scale bar ~ 50 µm.

The samples that we have investigated with the electron beam are from two areas within the GEU. One locality is the easterly portion of the Saidenbach reservoir area about 1.5 km northwest of the village of Forchheim. In this area, Massonne (1999) detected microdiamonds as inclusions in garnet, kyanite and zircon of weakly foliated garnet-muscovite gneisses, for which maximum metamorphic temperatures around 1050°C were estimated. The true inclusion character of these microdiamonds was proven by micro-Raman spectroscopy (Nasdala and Massonne 2000). Several eclogite bodies occur in the easterly portion of the Saidenbach reservoir area, as well. In a fresh eclogite sample from this locality, Massonne (2000) recognized relics of coesite (Fig. 1). Our sample E42-1d, however, is from an altered eclogite occurring a few hundred meters away from a lens of diamondiferous gneiss. The other locality is about 5 km north of the Saidenbach reservoir. There, 3 km southeast of the village of Eppendorf, a large eclogite body about 2 km in length occurs that might consist, however, of two or more large separated lenses. Samples E103f and ECK2 are from the northeastern, E105b from the central, and E174c from the western portion of that large body. Coesite pseudomorphs but no coesite relics have been reported by Schmädicke (1991) and Schmädicke *et al.* (1992) from eclogites of our sample localities. In the latter work, maximum metamorphic temperatures were estimated to 800 to 900°C.

Electron microprobe and scanning electron microscope work

Several inclusions, looking like coesite pseudomorphs, were detected in each of the selected samples of the large eclogite body near Eppendorf. Typically around these inclusions, abundant cracks in the host mineral appear (Fig. 2). The shape of the inclusions is either oval (Fig. 2) or elongated (Fig. 3). Another typical feature is that many dust-like particles can be seen in plain light (Fig. 4).

Studies of such inclusions with a CAMEBAX electron microprobe led to the back-scattered electron (BSE) images shown in Figs. 3b and 4b. Typically, these inclusions consist of two phases intergrown like symplectites. These phases are quartz and K-feldspar that is poor in Na but always contains significant amounts of barium (see Table 1). Moreover, the grain size of the intergrowth can vary within one inclusion (Fig. 3b). The symplectite in

Fig. 2: Omphacite of eclogite E174c seen under crossed nicols. The inclusion is a quartz – K-feldspar symplectite. Image length is 0.7 mm.

the center is often coarser grained (Fig. 4b).

A scanning electron microscope was used for studying very fine-grained inclusions in garnet of eclogite E42-1d. We also observed

Fig. 3a: Inclusions in an omphacite of eclogite E174c under crossed nicols. Phe = phengite, Rt = rutile. The inclusion in the lower left corner is shown in Fig. 3b.

Fig. 3b: BSE image of a symplectite consisting of quartz (dark) and K-feldspar (lighter but somewhat darker than the surrounding omphacite). Image length is 120 µm.

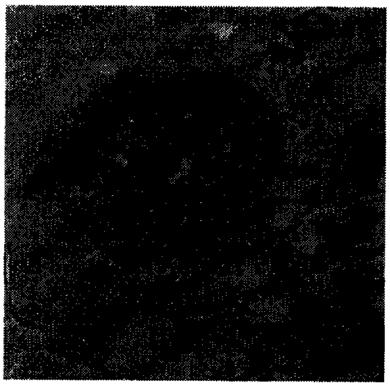

Fig. 4a: Inclusion in an omphacite of eclogite E105b in plain light. At the lower right side omphacite is replaced by a plagioclase-amphibole symplectite.

Fig. 4b: BSE image of the objects of Fig. 4a. For gray code see Fig. 3b. Amphibole is lightest here. Image length is nearly 0.3 mm.

elongated and oval shapes of such inclusions as previously noted. Sometimes, hexagonal instead of oval shapes are discernible (Fig. 5). Cracks often accompany these inclusions. With the energy-dispersive system of the SEM we analyzed K-feldspar and quartz that can be intergrown similar to the symplectites observed in omphacite. Most of these inclusions contain, additionally, phengite, biotite, and chlorite. These phyllosilicates are products of reactions between garnet and enclosed K-feldspar, because we observed corresponding textures like the exclusive appearance of the phyllosilicates at the garnet wall formed at the expense of K-feldspar. Inclusions showing shapes and cracks around them as described above and being only composed of fine-grained micas and quartz are, thus, former K-feldspar – quartz inclusions, because sometimes K-feldspar relics are still present. According to electron microprobe analyses, this mineral contains again significant amounts of barium. After these findings, we were able to relate such inclusions in garnet of the eclogites near Eppendorf to former K-feldspar – quartz symplectites, as well. In addition, a minority of inclusions with shapes mentioned above either consist of intergrown K-feldspar, plagioclase and quartz showing similar proportions or of small rounded quartz crystals embedded in a feldspar matrix making up a few percent only. In the matrix, K-feldspar dominates over albite.

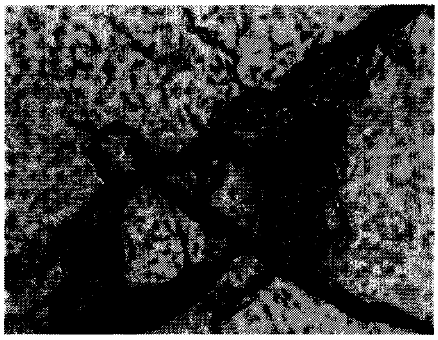

Fig. 5a: Inclusions in garnet of altered eclogite seen in plain light. Sample E42-1d. Image length is about 150 µm.

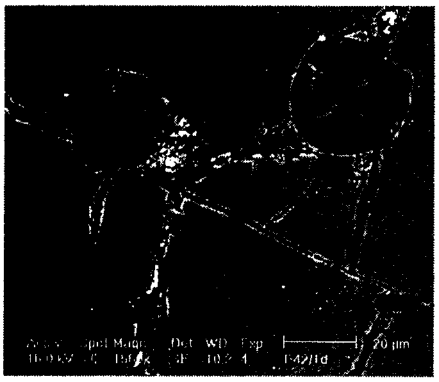

Fig. 5b: BSE image of the inclusions of Fig. 5a. They consist of quartz (dark) and K-feldspar as well as micas (light but darker than surrounding garnet.

Reconnaissance high-pressure experiments

Phase relations relevant for the system $KAlSi_3O_8$-SiO_2 at UHP conditions are known from experimental studies. Urukawa *et al.* (1994) as well as Yagi *et al.* (1994) determined the P-T curve of the reaction wadeite-type $K_2Si_4O_9$ + kyanite + coesite = sanidine to lie between 6 and 7 GPa at high T. At about 9 GPa, the hollandite-type $KAlSi_3O_8$ forms from $K_2Si_4O_9$ + kyanite + coesite according to Urukawa *et al.* (1994) and Yagi *et al.* (1994). The corresponding reaction curve lies very close to the stishovite-coesite transition as determined by Zhang *et al.* (1996). On the basis of thermodynamic calculations, Fasshauer *et al.* (1998) suggested that at P and T higher than 530°C and 5.2 GPa the reaction coesite + kalsilite = K-feldspar should be considered. $K_2Si_4O_9$ + kyanite + coesite should become stable at 7 GPa and 1100°C. In the presence of H_2O, a phase with cymrite structure called K-cymrite, $KAlSi_3O_8 \cdot xH_2O$ with $x \leq 1$, is stable at UHP conditions. The determination of the P-T location of the reaction K-cymrite = K-feldspar + H_2O resulted in a curve lying very close to the coesite-quartz transition curve (Massonne 1995; Fasshauer *et al.* 1997; Thompson *et al.* 1998).

In spite of the above experiments little knowledge exists on the precise composition of the SiO_2 and $KAlSi_3O_8$ phases as well as of K-cymrite when coexisting with each other. Therefore, we conducted a few reconnaissance experiments by crystallizing a mixture of a gel with $KAlSi_3O_8$ composition and a SiO_2 glass showing the weight proportions 3 to 1. Conditions were 4.5 GPa in a piston-cylinder apparatus (e.g. V1097) and 10 GPa in a Walker-type multi-anvil apparatus (MA104a). The dry experiment at about 10 GPa and 1000°C led to stishovite, kyanite, $K_2Si_4O_9$ and some melt. The wet experiments at 3.6 GPa yielded large amounts of a fluid phase above 730°C. At lower temperatures mainly coesite and K-cymrite appeared. Both SiO_2 phases formed idiomorphic crystals as large as several tens of micrometers. Thus, they were easily analyzed with the electron microprobe and showed only very small amounts of Al_2O_3 and K_2O (Table 1). The 1 µm large K-cymrite crystals were semiquantitatively analyzed with a SEM yielding after normalization to 100% a composition similar to ideally composed water-free K-cymrite (Table 1).

Table 1: Analytical results mentioned in the text. n = number of analyses. The analyzed coesite of E99-24 is shown in Fig. 1. The alkali deficit and the high SiO_2 content are due to a focussed electron beam used to analyze the fine-grained K-feldspar of a K-feldspar – quartz intergrowth in omphacite of eclogite E105b. The corresponding sum includes other oxides among them are 0.57 wt.% BaO, 0.15 wt.% Na_2O. The same refers to coesite of E99-24.

sample	V1097	V1097	MA104a	E99-24	E105b
n	14	13	15		
SiO_2	64.6	99.65	99.59	98.98	68.81
Al_2O_3	19.2	0.28	0.18	0.03	20.06
K_2O	16.2	0.20	0.08	0.02	13.58
sum		100.13	99.86	99.23	103.26

Conclusions

The shape and the symplectitic textures of the K-feldspar – quartz inclusions observed point to a former solid phase rather than to a silicate melt. However, the rare inclusion type with similar amounts of K-feldspar, plagioclase and quartz is interpreted as former melt by comparison with nearly identical but much larger inclusions observed in an eclogite from the Variscan Münchberg Massif, Germany (Massonne 1993). The interpretation of inclusions, that are similar to those described here, by Yang *et al.* (1998) as exsolution from Si-rich UHP omphacite is unlikely, especially when large inclusions in small omphacites as in Fig. 2 are considered. Moreover, the same K-feldspar – quartz inclusions, although later partially transformed, appear in garnet. This is another striking argument against the view of Yang *et al.* (1998).

However, the question of the precursor phase for the K-feldspar – quartz symplectites remains. According to the experimental data, there is no phase between SiO_2 and K-feldspar composition nor does coesite dissolve significant K and Al. Under these circumstances, we think that K-cymrite is the most likely candidate. This hexagonal phase might indeed form crystals with shapes of hexagonal plates as observed, albeit in the experimental products they occur rather as short columns. However, the composition of the symplectites is probably richer in Si than K-cymrite because there is no experimental evidence that K-cymrite compositionally deviates significantly from water-bearing K-feldspar. Thus, we assume that H_2O released during breakdown of K-cymrite removes considerable amounts of K and Al as dissolved components by escaping through the abundant cracks in the host minerals. Then, SiO_2 would remain in the inclusions in excess. The same explanations as given above could also be related to phengite. However, this mineral as we learn from Fig. 3, was obviously not decomposed. The former existance of K-cymrite, that has a P-T stability very similar to coesite, would be in accordance with the fact that such inclusions typically occur in rocks of UHPM areas.

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References

Bakun-Czubarow, N., 1992. Quartz pseudomorphs after coesite and quartz exsolutions in eclogitic omphacites of the Złote Mountains in the Sudetes (SW Poland). Arch. Mineral., 48: 3-25.

Caby, R., 1994. Precambrian coesite from northern Mali: First record and implications for plate tectonics in the trans-Saharan segment of the Pan-African belt. Eur. J. Mineral., 6: 235-244.

Chopin, C., 1984. Coesite and pure pyrope in high grade blueschists of the Western Alps: a first record and some consequences. Contrib. Mineral. Petrol., 86: 107-118.

Enami, M. and Zang, Q., 1990. Quartz pseudomorphs after coesite in eclogites from Shandong province, east China. American Mineralogist, 75: 381-386.

Fasshauer, D.W., Chatterjee, N.D., Marler, B., 1997. Synthesis, structure, thermodynamic properties and stability relations of K-cymrite, $K[AlSi_3O_8]\cdot H_2O$. Phys. Chem. Minerals, 24: 455-462.

Fasshauer, D.W., Wunder, B., Chatterjee, N.D., Höhne, G.W.H., 1998. Heat capacity of wadeite-type $K_2Si_4O_9$ and the pressure induced stable decomposition of K-feldspar. Contrib. Mineral. Petrol., 131: 210-218.

Hazard, J., 1886. Geologische Specialkarte des Königreichs Sachsen No. 116. Section Pockau-Lengefeld. Königliches Finanz-Ministerium (Ed.) under the supervision of Credner, H.

Hirajima, T., Ishiwatari, A., Cong, B., Zhang, R., Banno, S., Nozaka, T., 1990. Coesite from Mengzhong eclogite at Dhonghai county, northeastern Jiangsu province, China. Min. Mag., 54: 579-583.

Kröner, A. and Willner, A.P., 1998. Time of formation and peak of Variscan HP-HT metamorphism of quartz-feldspar rocks in the central Erzgebirge, Saxony, Germany. Contrib. Mineral. Petrol., 132: 1-20.

Massonne, H.-J., 1993. High-pressure melting of eclogites from the Mid-European Variscides. Terra Abstr. 5, 4th Int. Eclogite Conf.: 16.

Massonne, H.-J., 1995. Experimental and petrogenetic study of UHPM. In: Coleman, R. and Wang, X. (Eds.) Ultrahigh Pressure Metamorphism. Cambridge Univ. Press, Cambridge Topics in Petrology: 33-95, Cambridge.

Massonne, H.-J., 1999. A new occurrence of microdiamonds in quartzofeldspathic rocks of the Saxonian Erzgebirge, Germany, and their metamorphic evolution. Proceed. 7th Int. Kimberlite Conf., Cape Town 1998, 2 (The P.H. Nixon Vol.): 533-539.

Massonne, H.-J., 2000. First find of coesite in the ultrahigh-pressure metamorphic region of the Central Erzgebirge, Germany. Eur. J. Petrol., submitted.

Massonne, H.-J. and Grosch, U., 1995. P-T evolution of palaeozoic garnet peridotites from the Saxonian Erzgebirge and the Aheim region, Norway. 6th Int. Kimberlite Conf., Novosibirsk, Abstr. Vol.: 341-344.

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. J. Geophys. Res., 85: 6983-6990.

Nasdala, L. and Massonne, H.-J., 2000. Microdiamonds from the Saxonian Erzgebirge, Germany: in situ micro-Raman characterisation. Eur. J. Mineral., in press.

Parkinson, C. and Katayma, I., 1999. Metamorphic microdiamond and coesite from Sulawesi, Indonesia: Evidence of deep subduction at the SE Sundaland margin. EOS, Transact. AGU, 80: 1999 / Suppl. Fall meet. 1999, F1181.

Reinecke, T., 1991. Very-high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. Eur. J. Mineral., 3: 7-17.

Schertl, H.-P. and Okay, A.I., 1994. A coesite inclusion in dolomite in Dabie Shan, China: petrological and rheological significance. Eur. J. Mineral., 6: 995-1000.

Schmädicke, E., 1991. Quartz pseudomorphs after coesite in eclogites from the Saxonian Erzgebirge. Eur. J. Mineral., 3: 231-238.

Schmädicke, E., Okrusch, M., Schmidt, W., 1992. Eclogite-facies rocks in the Saxonian Erzgebirge, Germany: high pressure metamorphism under contrasting P-T-conditions. Contrib. Mineral. Petrol., 110: 226-241.

Thompson, P., Parsons, I., Graham, C.M., Jackson B., 1998. The breakdown of potassium feldspar at high water pressure. Contrib. Mineral. Petrol., 130: 176-186.

Urakawa, S., Kondo, T., Igawa, N., Shimomura, O., Ohno, H., 1994. Synchrotron radiation study on the high-pressure and high-temperature phase relations of $KAlSi_3O_8$. Phys. Chem. Minerals, 21: 387-391.

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: 927-930.

Wang, X., Liou, J.G., Mao, H.K., 1989. Coesite-bearing eclogite from the Dabie Mountains in central China. Geology, 17: 1085-1088.

Willner, A.P., Rötzler, K., Maresch, W.V., 1997. Pressure-temperature and fluid evolution of quartzo-feldspathic metamorphic rocks with a relic high-pressure, granulite-facies history from the Central Erzgebirge (Saxony, Germany). J. Petrol., 38: 307-336.

Yagi, A., Suzuki, T., Akaogi, M., 1994. High pressure transitions in the system $KAlSi_3O_8$-$NaAlSi_3O_8$. Phys. Chem. Minerals, 21: 12-17.

Yang, J., Godard, G., Smith, D.C., 1998. K-feldspar-bearing coesite pseudomorphs in an eclogite from Lanshantou (Eastern China). Eur. J. Mineral., 10: 969-985.

Zhang, J., Li, B., Utsumi, W., and Liebermann, R.C., 1996. In situ X-ray observations of the coesite-stishovite transition: Reversed phase boundary and kinetics. Phys. Chem. Minerals, 23: 1-10.