A comparison of the evolution of diamondiferous quartz-rich rocks from the Saxonian Erzgebirge and the Kokchetav Massif: are so-called diamondiferous gneisses magmatic rocks?

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Abstract

The petrography and chemical composition of minerals of quartz-rich diamondiferous rocks from the Kokchetav Massif, especially the zonation of garnet, were studied and compared with diamondiferous quartzofeldspathic rocks from the Saxonian Erzgebirge. Many compositional and textural features were found to be similar. For instance, microdiamonds are enclosed systematically in a specific intermediate growth zone of garnet in these rocks. On the basis of experimental data, a magmatic scenario was constructed to check if the quartz-rich diamondiferous rocks are of magmatic origin. By this, the P–T paths, derived here for the Kokchetav rocks, and the textural observations it is concluded that the minerals of the diamondiferous rocks have crystallized from silicate melts. These melts originated by anatexis of deeply submerged metasediments (Erzgebirge: at T as high as 1200°C, Kokchetav Massif: at 50–100°C lower T) and ascended from at least 200 km depth. Relics of the pre-anatectic evolution are still present, for instance, as garnet cores. After ascent and emplacement of the magma in deep portions of thickened continental crust (Kokchetav Massif: 45–50 km close to 800°C, Erzgebirge: 55–60 km at 30–50°C lower T) considerable quantities of (white and/or dark) micas formed by peritectic reactions from melt. For instance, garnets could be resorbed at this stage and biotite grew instead. After the magmatic stage, retrogression took place much stronger in the Kokchetav Massif. This was accompanied by deformation transforming broadly the magmatic texture of quartz-rich diamondiferous rocks from the Kokchetav Massif to a gneissic texture.

1. Introduction

Microdiamonds in SiO_2-rich rocks, probably material from the continental crust, were unequivocally proven by 'in situ' studies from only two metamorphic complexes on Earth. The first de-

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tected location of this kind of rocks is in the Early Paleozoic Kokchetav Massif in northern Kazakhstan [1,2]. Recently, a second location was recognized in the Late Paleozoic Saxonian Erzgebirge [3,4] in the northwestern edge of the Bohemian Massif. A third occurrence of microdiamonds in felsic rocks, situated in the Norwegian Caledonides (island of Fjortoft), was reported some years ago [5]. However, so far, only some microdiamonds could be extracted from 50 kg Fjortoft gneiss. For the diamondiferous quartz-rich rocks from the Kokchetav Massif and the Saxonian Erzgebirge first peak pressure estimates of 4–4.5 GPa at temperatures close to 1000°C [2,3,6] were settled just above the graphite–diamond transition pressures. Later, because of observations such as SiO_2 exsolution and significant K contents in clinopyroxene, ultrahigh pressure (UHP) as high as 7 GPa was assumed for the diamondiferous rocks from the Kokchetav Massif [7]. The detection of TiO_2 with α-PbO_2 structure (UHP-TiO_2) [8] in the Erzgebirge even points to pressures in excess of 7 GPa according to the rutile–UHP-TiO_2 transition curve [9]. At such pressures, the temperatures of the Saxonian rocks with microdiamond might have been as high as 1200°C [10] because of the dT/dP slope (~ 6°C/kbar) of the applied Ti-in-garnet thermometer [11]. At such high temperatures, melting of SiO_2-rich rocks in the absence of a hydrous fluid phase is not unlikely at UHP conditions. Experiments at pressures of 3 GPa and higher with pelitic, andesitic, and granitic compositions (dry with small amounts of H_2O added) gave silicate melt coexisting with phases such as garnet at temperatures above 1000°C [12–14]. A further hint of, at least, partially molten rocks at the above UHP conditions are inclusions in garnet from the Erzgebirge consisting of microdiamond, quartz, feldspars and micas. These inclusions represent COH-bearing silicate-rich (supercritical?) fluids (or melts depending on the pressure for the second critical end point in a relevant fluid–melt system) trapped during exhumation but still at UHP conditions [15].

In spite of the many studies on the UHP rocks from the Kokchetav Massif, for instance, by Ota et al. [16] and Theunissen et al. [17], a well-constrained prograde and retrograde path of the P–T evolution could not so far be derived. For the Saxonian occurrence, the information is better, at least, with regard to a P–T date for an early, pre-diamondiferous stage (1.8 GPa and 650°C, see [18]). In addition, we know that exhumation was accompanied by significant cooling [3]. Thus, the aim of this study is: (1) to improve the knowledge of the P–T evolution of UHP quartz-rich rocks from the Kokchetav Massif, (2) to compare these rocks with the diamondiferous Erzgebirge's rocks, and (3) to answer the questions which degree of melting occurred and if it might have played a role in the exhumation of the diamondiferous rocks from both areas. The latter point also leads to a central problem, namely, are or were the so-called diamondiferous gneisses actually magmatic rocks?

2. Sample petrography

Diamondiferous quartzofeldspathic rocks in the central Erzgebirge occur as several lensoid bodies (see map in [19]) close to the Saidenbach reservoir. Although these rocks are surprisingly similar with regard to mode and fabric, in this paper only the diamondiferous, hardly foliated rock from the lens, extending several hundred meters in E–W direction north of the southern branch in the eastern portion of the reservoir, is addressed. Samples E97-1 to -4 (see [3,18]), St6100 (see [15]), and E99-2 contain about 15 vol% of garnet homogeneously distributed as 1–3 mm sized, misshapen grains (Fig. 1A). A very minor amount of garnet is due to clearly smaller, nearly idiomorphic grains. Relics of kyanite can be as large as several mm. They amount to about 1 vol%. However, the rocks might once have formed from several vol% of kyanite before its replacement by coarse-grained muscovite (Fig. 1B). A late alteration to fine-grained micaceous material has further diminished the amount of kyanite. In some fresh kyanite cores abundant small, idiomorphic garnets are enclosed (Fig. 1B). The rock contains 25–30 vol% of coarse-grained (mean ~ 0.5 mm), (almost) non-oriented muscovite. Along its grain boundaries some biotite has formed. The dominant phase is quartz. Feldspars, mainly plagio-
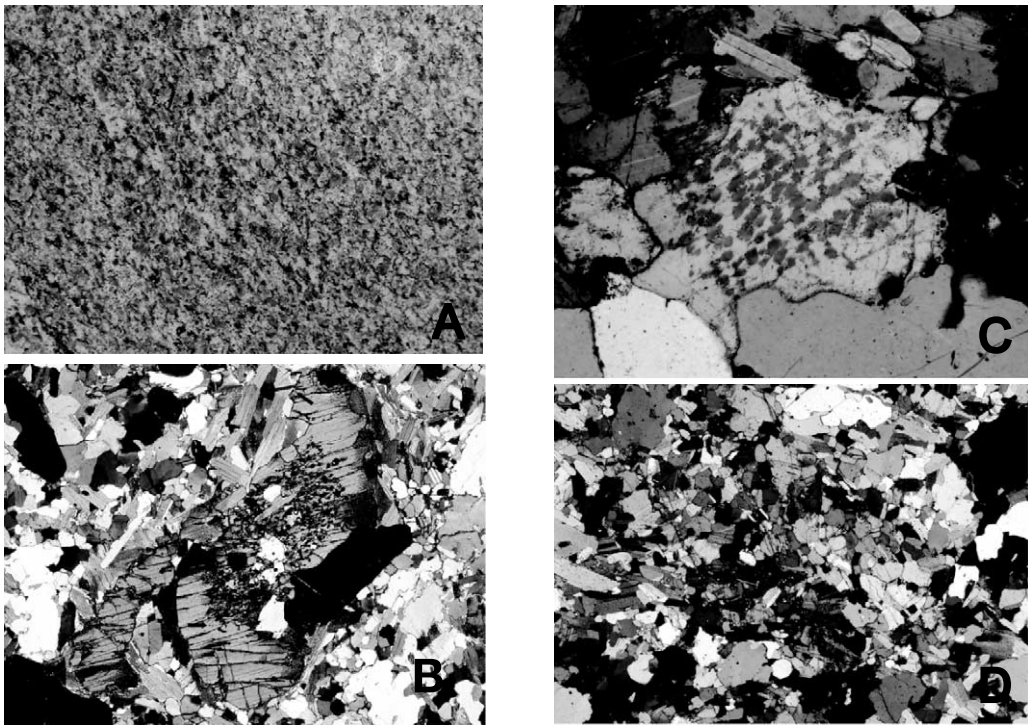
Fig. 1. Diamondiferous quartzofeldspathic rock from the central Erzgebirge, Germany. (A) Polished surface of sample E97-1. Image length is 6 cm. (B) Photomicrograph of kyanite partially replaced by coarse-grained muscovite in sample E97-3 as seen under crossed nicols. Image length is 4.0 mm. Enclosed microdiamonds are marked by arrows. In the center of the kyanite grain abundant small idiomorphic garnets are enclosed. (C) Photomicrograph of alkali-feldspar in E97-2 typically showing abundant antiperthitic exsolution bodies under crossed nicols. Image length is 1.3 mm. (D) Photomicrograph of a pseudomorphs after jadeitic pyroxene in E97-2 as seen under crossed nicols. Image length is 5.3 mm. The pseudomorph consists of equigranular plagioclase and some muscovite and biotite. Typically, these minerals are finer-grained than those of the surrounding matrix.

clase, amount to nearly 15 vol%, including about 1% of up to mm-sized alkali-feldspar grains characterized by abundant antiperthitic exsolution bodies (Fig. 1C). In addition, small K-feldspar grains were detected as rare interstitial fillings in the quartzofeldspathic matrix. Rutile (~ 0.3 vol%) occurs as inclusion in all other phases but also as up to 200 μm sized grains in the matrix. Further accessory phases are zircon, monazite and graphite, appearing as rare but, generally, relatively large grains (>100 μm) in the rock matrix. Up to 30 μm sized microdiamonds and (larger) graphite pseudomorphs after diamond are enclosed exclusively in garnet, kyanite, zircon, and (very rarely) rutile. Various pseudomorphs enclosed in garnet point to former coesite and a phase that might have been K-cymrite, $KAlSi_3O_8 \cdot H_2O$ [18]. Aggregates, up to several

mm in size, consist mainly of equigranular plagioclase, finer-grained than quartz and muscovite of the surrounding matrix, and some muscovite and biotite (Fig. 1D). These are interpreted as pseudomorphs after jadeitic pyroxene.

Diamondiferous quartz-rich rocks (sample numbers 22755 and 22756) from an area in the Kokchetav Massif close to the southeastern shore of Lake Kumdy-Kol (see map in [20]) were investigated. In contrast to the Erzgebirge, several rock types such as marble and garnet pyroxenite contain microdiamonds at this locality [2]. As best information on UHP metamorphism in the Kokchetav Massif results from investigations on marbles, a siliceous calcite marble (sample number 22761) was also studied to better consider previous findings of other authors in this study. The petrography of the three samples was previ-
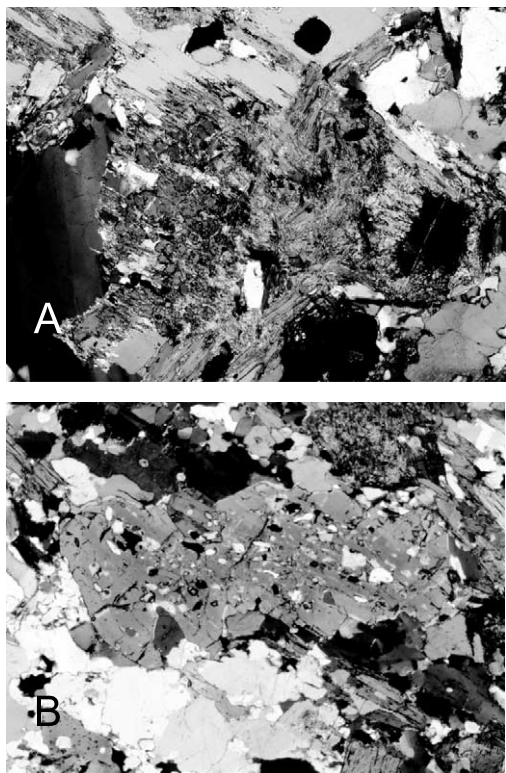
Fig. 2. Photomicrographs of sample 22755 from the Kokchetav Massif, northern Kazakhstan. Crossed nicols. (A) Relic of kyanite. Image length is 1.9 mm. On the right-hand side, a small relic of garnet is also discernable. (B) Zoned tourmaline with abundant quartz inclusions in a quartz-rich band. Plagioclase, K-feldspar, and muscovite grains are also present in the neighborhood of tourmaline. Image length is 4.0 mm.

ously described [21]. Among the many samples collected near Lake Kumdy-Kol, 22755 and 22756 are closest to the mineral mode and fabric of the Saxonian rock.

Sample 22755 is a moderately folded and banded rock with quartz- and mica-rich layers in the mm to cm range. It still contains some garnet which is significantly replaced by aggregates of fine-grained micas. Originally, the rock might have formed from almost 10 vol% of garnet with size and shape being similar to those of garnet in the Erzgebirge's diamondiferous rock. Kyanite (Fig. 2A) is an accessory phase, however, the amount of which might have exceeded 1 vol% before replacement by, among others, fine-grained micas. Probably an early alteration phase

was slightly reddish dumortierite. The main boron-bearing phase, however, is tourmaline, which can appear as mm sized grains in quartz-rich layers (Fig. 2B). Similar to the Erzgebirge's rock is the appearance of muscovite. Biotite has grown along the grains of this mineral but isolated large biotite flakes occur as well. Feldspars, mainly plagioclase, form somewhat more than 10 vol% of the rock. Rutile, appearing as inclusion in garnet and kyanite as well as in the matrix, zircon, (altered) Fe-phase, apatite, graphite, and allanite are accessories. The latter phase, originally forming idiomorphic grains up to 0.5 mm in size, is strongly altered to fine-grained mineral aggregates. Microdiamonds with virtually identical size and abundance to those in the Erzgebirge's rock were observed as inclusions in garnet and its replacement products as well as in zircon.

Sample 22756 is rich in garnet, biotite and quartz. Garnet is relatively homogeneously distributed in the rock (Fig. 3A) as mm sized grains. This mineral in thin-sections is typically slightly brownish-reddish colored in wide inner portions and colorless along rims. The colorless variety also forms atoll garnets surrounding biotite. Garnet amounts to somewhat more than 30 vol%; however, it could be that the original content was around 40 vol% considering (some) biotite as an early replacement product of garnet. A minor constituent of the rock is Ca-amphibole. Fig. 3B shows a rare example for a clinopyroxene relic not entirely replaced by amphibole. Zircon, titanite, and graphite are accessories. White mica is virtually absent. Chlorite, prehnite and carbonate are alteration products of biotite and amphibole. It might be that a few tiny rutile grains occur in garnet. However, microdiamonds and abundant graphite pseudomorphs as well as multiphase inclusions ($<$ 100 μm), consisting chiefly of biotite, minor microdiamond (or graphite) and other phases (Fig. 3C), are much more frequently enclosed in garnet. Aggregates formed only of quartz can rarely appear in garnet. Their fibrous texture and the cracks in garnet around these inclusions point to former coesite (Fig. 3D).

In the marble 22761, mm sized clinopyroxenes and garnets occur. Amphibole, biotite and talc are probably alteration products whereas magnetite
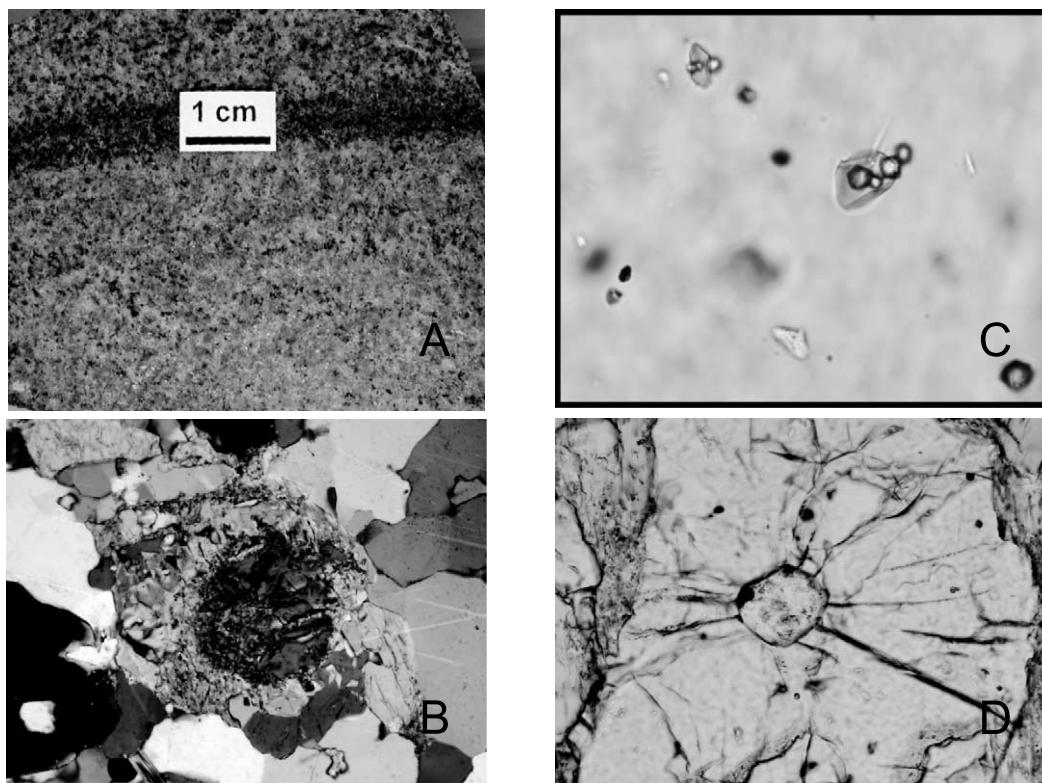
Fig. 3. Quartz-rich diamondiferous rock 22756 from the Kokchetav Massif, northern Kazakhstan. (A) Polished surface of a hand specimen. (B) Photomicrograph of a relic of clinopyroxene partially replaced by amphibole. Crossed nicols. Image length is 1.0 mm. (C) Photomicrograph of inclusions in garnet. Near the center, a multiphase inclusion consisting of micas and microdiamonds is located. Plain polarized light. Image length is 150 μm. (D) Photomicrograph of an inclusion, consisting of quartz, in garnet interpreted as coesite pseudomorph. Plain polarized light. Image length is 650 μm.

and rutile could be primary accessories. Microdiamonds, enclosed in clinopyroxene, were reported to be aligned tracing a growth zone of clinopyroxene [21].

3. Analytical results

Bulk rock analyses (main elements and a few trace elements) were obtained from rock powder, fused with Li-borate (1:10) to prepare a glass disk, using standard procedures of wavelength-dispersive X-ray fluorescence (XRF) spectrometry. The results for three diamondiferous SiO_2-rich rocks are given in Table 1.

Minerals in polished thin-sections were analyzed with a Cameca electron microprobe (EMP). In addition, element concentration maps were prepared for several objects with the EMP. The analytical procedures for spot analyses (beam diameter > 5 μm for micas and feldspars) and element mapping were virtually the same as applied previously [3]. In addition, measurements along several garnet profiles were undertaken with 20 kV, 50 nA, and longer counting times for the minor elements (e.g. 150 s for Ti).

Compositions of minerals from the Erzgebirge's rock were already reported [3]. However, for better comparison with the studied rocks from the Kokchetav Massif, a chemical profile through a garnet from sample E97-2 is displayed in Fig. 4. Previously not published mineral analyses such as those of feldspars (Table 2) are given here.

The chemical zonations of garnets in the quartz-rich rocks 22755 and 22756 (Figs. 5 and 6, Table 3) are characterized by extended nearly

Table 1
XRF analyses of quartz-rich diamondiferous rocks from the Kokchetav Massif and the Saxonian Erzgebirge (E99-2a)

Sample no.	22755	22756	E99-2a
P_2O_5 in wt%	0.06	0.01	0.05
SiO_2	68.57	65.67	64.35
TiO_2	0.74	0.28	0.76
Al_2O_3	14.07	10.81	17.17
MgO	2.85	4.09	2.32
CaO	1.18	5.16	0.90
MnO	0.02	1.24	0.05
FeO	4.75	9.08	5.10
Na_2O	0.74	< 0.10	2.30
K_2O	4.30	1.07	3.23
Sum	97.30	97.39	96.23
Ba in ppm	355	28	415
Cr	90	57	77
Ni	37	28	28

Fig. 4. Chemical profile (~ 1.7 mm) through a garnet from diamondiferous sample E97-2 (Erzgebirge) obtained by spot analyses with the EMP.

homogeneous core regions. However, a slight zonation by increasing Fe and decreasing Ca (and Mg) contents towards the rim of the core zone is discernable. The narrow rim zone shows a significant chemical zonation with increasing Ca and decreasing Mg (and Fe) contents towards the grain margin. The minor elements Na and Ti tend to decrease from core to rim. Only in garnets of 22755 an increase of Ti in the rim zone towards the margin was detected. Enclosed microdiamond appears exclusively in the outermost core zone, as was proven by many garnet analyses close to microdiamonds. In addition, the garnet cores in 22756 are slightly colored so that the relative position of microdiamonds in garnet could also be microscopically identified. The above-described feature of the garnet zonation (+position of microdiamonds) resembles that observed for the diamondiferous rock from the Erzgebirge (see [3] and Fig. 4). This concerns the irregular shapes of extended core regions (zone I, chemically defined) as well. Garnets of the siliceous marble show a somewhat different zonation pattern (Fig. 6, Table 3). From core to rim a decrease of the Ca content is discernable. In the rim zone, Fe increases significantly. Highest Ti contents were observed in an intermediate zone where microdiamonds are enclosed. In the rim zone they are lowest.

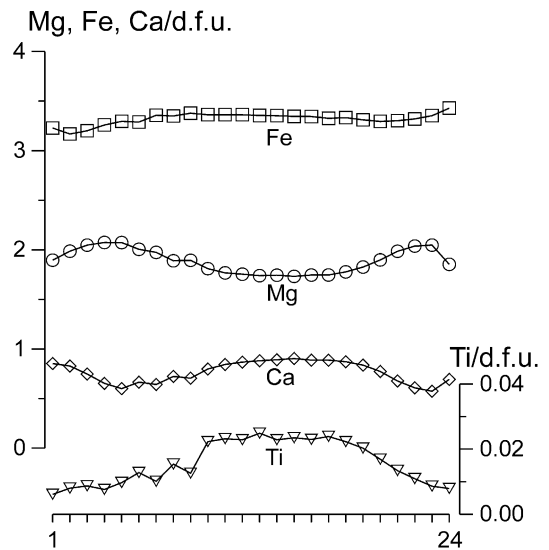Large muscovite flakes in 22755 are zoned as well. Extended core zones (again chemically de-

fined) are highest in Si (6.4–6.3 per double formula unit (p.d.f.u.), see Table 4). The chemical compositions and trends (e.g. decreasing Si contents from the inner to the outer core zone) resemble those of coarse-grained muscovite in the Erzgebirge's rock (Table 4). However, a narrow rim zone with significantly lower Si contents was detected only in muscovite flakes from 22755. The chemical zonation of large biotite flakes in 22755 is

Table 2
EMP analyses (in wt%) of feldspars in quartz-rich diamondiferous rocks from the Saxonian Erzgebirge (E97-2, left) and the Kokchetav Massif (22755, right)

Anal. no.	070121	070116	070110	161205	161213
SiO_2	67.70	66.69	65.00	61.21	64.66
TiO_2	0.02	0.03	0.01	0.02	0.04
Al_2O_3	20.54	20.91	18.41	24.79	18.70
Cr_2O_3	0.00	0.01	0.01	0.01	0.00
CaO	1.41	2.13	0.00	6.25	0.06
FeO	0.00	0.09	0.02	0.02	0.02
BaO	0.02	0.03	0.30	0.00	0.00
Na_2O	11.14	10.75	0.87	8.27	1.13
K_2O	0.42	0.27	15.47	0.48	15.06
Sum	101.27	100.93	100.08	101.05	99.67

070116 is plagioclase of an assumed pseudomorph after jadeitic clinopyroxene.
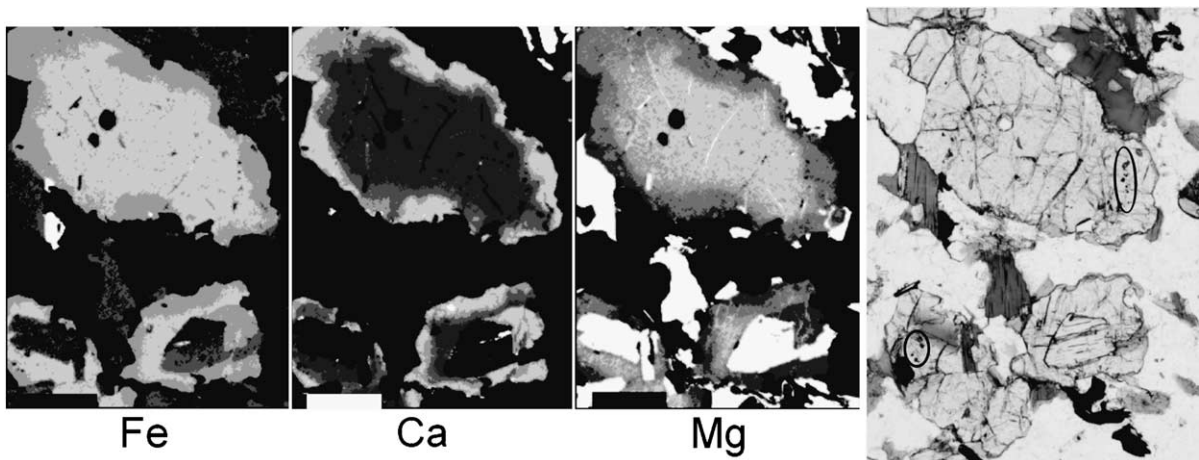
Fig. 5. Chemical zonation of garnets from garnet–quartz–biotite rock 22756 (Kokchetav Massif). Rising concentrations of Fe, Ca and Mg are shown by increasingly lighter tones of the gray code. Slightly zoned biotite (see Fe) is white in the Mg image. Ovals in the photomicrograph (right-hand side) mark areas with enclosed microdiamonds. Scale bar (black or white) represents 300 μm.

similar to those of muscovite. A core zone with Si contents (around 5.6 p.d.f.u., see Table 4) higher than in the rim zone (around 5.45 p.d.f.u.) could also be detected. Only a slight zonation, for instance, by rising Fe/Mg ratios from core to rim was observed for coarse-grained biotite in 22756. Biotite of multiphase inclusions in garnet is some-

what richer in Si and Ti than coarse-grained biotite. Phengite (see Table 4) can be part of the multiphase inclusions as reported previously [2]. This phase was also observed in similar (fluid) inclusions in the Erzgebirge's garnets (see [15]).

Kyanite in 22755 is characterized by low Fe contents and very small but significant concentra-
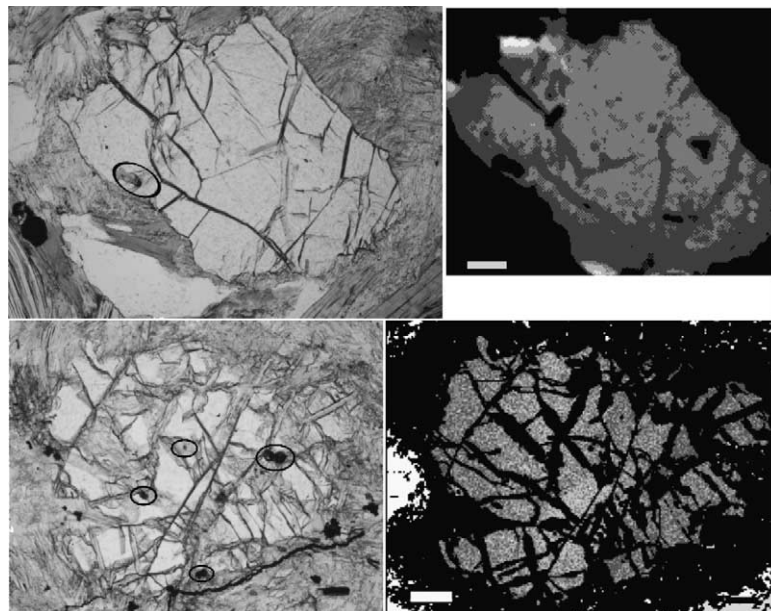

Fig. 6. Photomicrographs and Ca zonation patterns of garnet from quartzofeldspathic rock 22755 (at the top) and siliceous marble 22761 (at the bottom). For ovals and gray code see Fig. 5. Scale bars represent 100 μm.

Table 3
Representative EMP analyses of garnet from diamondiferous rocks of the Lake Kumdy-Kol area, Kokchetav Massif

Anal. no.	210559 inner I	210574 outerm. I	210522 inner II	210571 outerm. II	190508 inner I	190504 outerm. I	190502 inner II	190530 outerm. II	180504 core	180505 intermed.	180509 rim
SiO_2	38.88	38.48	38.54	38.52	38.66	38.56	38.45	38.09	40.25	40.36	40.29
TiO_2	0.150	0.073	0.042	0.100	0.289	0.219	0.088	0.083	0.117	0.292	0.197
Al_2O_3	22.19	22.13	22.10	21.94	21.63	21.68	22.08	21.70	23.16	22.89	22.98
Cr_2O_3	0.012	0.018	0.018	0.016	0.020	0.022	0.006	0.018	0.025	0.029	0.029
FeO	23.12	26.70	26.31	24.14	20.09	20.54	19.48	17.68	5.38	5.33	6.66
MnO	0.230	0.217	0.261	0.256	3.07	3.19	3.26	3.79	0.768	0.723	0.859
MgO	7.64	7.10	6.66	5.64	6.96	6.75	5.44	3.84	10.57	11.29	11.18
CaO	8.23	5.84	6.84	9.96	9.41	9.05	11.33	14.22	19.26	18.51	17.39
Na_2O	0.090	0.046	0.050	0.031	0.044	0.040	0.027	0.018	0.016	0.023	0.011
Sum	100.56	100.61	100.81	100.61	100.17	100.05	100.16	99.44	99.55	99.45	99.60

Analyses from samples 22755 (left), 22756 (middle) and 22761 (right) are given in wt%. The selected data are also representative of the concentrations of the minor elements obtained by long counting times. Fe is given as FeO. I = core zone, II = rim zone, separated into inner and outer areas.

tions of Mg and Ti (Table 5) comparable with kyanite from the Erzgebirge's rock. Dumortierite, replacing kyanite, contains unusually high Mg (and Fe) contents (Table 5) which are, however, lower than those in the Mg-dumortierite reported from a UHP rock of the Dora Maira Massif, Western Alps [22]. Mg-dominant tourmaline is chemically (and optically) zoned showing decreasing Na, Ti, and Fe contents and rising Ca concentrations from core to rim (Table 5). Plagioclase and K-feldspar in 22755 contain about 70 and 10 mol%, respectively, of albite component (Table 2). This component in plagioclase grains from the Erzgebirge's rock amounts to 90 mol% and more. Grains in pseudomorphs after jadeite-rich

clinopyroxene contain somewhat less albite component than large ones of the matrix (Table 2).

Clinopyroxene relics in 22756 (Table 5) show low concentrations of jadeite component around 9 mol%. Ca-amphibole replacing clinopyroxene is chemically (and optically) inhomogeneous. It seems that early formed amphibole is relatively poor in Al (Si > 7 p.d.f.u.) and tends to become a hornblende at a late equilibration stage (rim composition in Table 5). Titanite contains moderate amounts of Al and F (Table 5).

Finally, it is noteworthy that diopside in 22761 shows up to 0.4 wt% of K_2O (Table 5). The molar fraction of the Ca-Tschermak's component, $CaAl_2SiO_6$, in diopside is about 0.015.

Table 4
Representative compositions of potassic micas from sample E97-2 (left), 22755 (middle), and 22756 (right)

Anal. no.	117755 I	117757 II	070108	1312B3 inner I	703109 outer I	703115 inner II	703114 outer II	703173 inner I	703095 outer I	703090 inner II	703088 outer II	152920 Incl.	152922 Incl.	152936 I	152908 II
Sum in wt%	93.25	93.41	94.69	95.47	93.95	93.16	93.42	94.97	94.86	94.59	94.26	94.95	95.63	94.15	94.71
H_2O calc.	4.41	4.43	4.17	4.52	4.49	4.45	4.46	4.04	3.96	3.91	3.92	4.46	4.01	3.91	3.92
Si	6.480	6.369	5.608	6.393	6.317	6.120	6.222	5.618	5.552	5.438	5.474	6.659	5.616	5.562	5.560
Ti	0.268	0.277	0.332	0.164	0.112	0.096	0.116	0.288	0.254	0.229	0.254	0.249	0.423	0.301	0.215
Al	4.518	4.669	3.012	4.760	5.059	5.484	5.317	3.120	3.101	3.255	3.226	4.271	2.715	2.645	2.728
Cr	0.005	0.002	0.006	0.004	0.000	0.003	0.005	0.005	0.002	0.001	0.000	0.000	0.009	0.008	0.003
Fe^{2+}	0.127	0.148	1.116	0.212	0.156	0.120	0.094	1.815	2.199	2.324	2.271	0.153	1.753	1.883	2.037
Mn	0.007	0.002	0.001	0.000	0.004	0.001	0.000	0.005	0.011	0.010	0.001	0.004	0.028	0.041	0.046
Mg	0.586	0.552	3.413	0.529	0.393	0.217	0.246	2.682	2.524	2.448	2.432	0.621	3.056	3.372	3.272
Ca+Ba	0.007	0.012	0.014	0.000	0.002	0.003	0.003	0.001	0.004	0.000	0.002	0.003	0.008	0.008	0.000
Na	0.065	0.072	0.031	0.068	0.045	0.064	0.065	0.048	0.085	0.073	0.082	0.046	0.055	0.068	0.059
K	1.679	1.688	1.779	1.835	1.677	1.677	1.683	1.819	1.827	1.882	1.844	1.832	1.836	1.759	1.836
F+Cl	0.034	0.000	0.000	0.000	0.000	0.000	0.010	0.003	0.003	0.012	0.006	0.025	0.036	0.053	0.038

Analyses were recalculated to double formula unit (42 val. for tetra-+octahedral cations). Incl. = inclusion in garnet, I = core zone, II = rim zone.
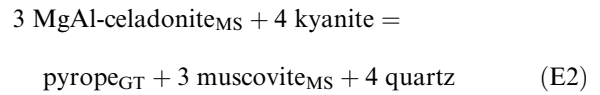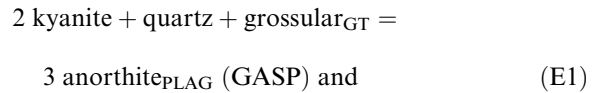
Table 5
Representative EMP analyses of various minerals from diamondiferous quartz-rich rocks from the Erzgebirge (E97-3) and the Lake Kumdy-Kol area, Kokchetav Massif, (22761 = silicate marble)

| Sample:	E97-3	22755	22755	22755	22755	22756	22756	22756	22756	22756	22761
Mineral:	Kyanite	Kyanite	Dumortierite	Tourmaline core	Tourmaline rim	Clinopyroxene (Cpx)	Amph rim to Cpx	Amph core	Amph rim to matrix	Titanite	Clinopyroxene
Anal. no.:	116542	1312A5	703172	161211	161212	181203	181212	152803	152810	152816	107027
SiO_2 in wt%	36.63	36.72	30.03	37.05	36.50	53.24	50.87	51.48	46.15	30.17	54.70
TiO_2	0.07	0.055	1.38	0.93	0.69	0.18	0.31	0.37	0.48	35.99	0.01
Al_2O_3	63.31	63.62	58.43	33.22	33.97	4.34	7.55	3.40	12.42	3.00	1.10
Cr_2O_3	0.03	0.03	0.06	0.04	0.01	0.01	0.02	0.03	0.06	0.01	0.03
FeO	0.11	0.15	1.07	5.05	4.37	5.68	9.13	14.07	9.77	0.34	1.12
MnO	0.00	0.00	0.02	0.00	0.00	0.25	0.29	1.05	0.33	0.09	0.05
MgO	0.04	0.040	1.44	8.46	9.03	13.35	16.55	13.97	13.86	0.02	17.22
CaO	0.00	0.00	0.03	0.56	1.73	21.59	12.04	12.06	12.63	28.82	24.79
Na_2O	–	0.02	0.02	2.88	1.99	1.37	0.60	0.24	0.78	0.03	0.28
K_2O	–	0.00	0.00	0.15	0.13	0.02	0.50	0.26	1.04	0.00	0.33
F+Cl	–	–	0.00	–	–	–	–	0.05	0.09	0.74	–
Sum	100.21	100.63	92.49	88.34	88.43	100.04	97.88	96.97	97.61	99.23	99.65
H_2O calc.	–			3.78	3.79		2.06	2.05	2.06	0.24	
B_2O_3 calc.	–		6.0	10.97	11.00						

Amph = amphibole. The calculated B_2O_3 content of dumortierite was confirmed by semiquantitative EMP measurements.
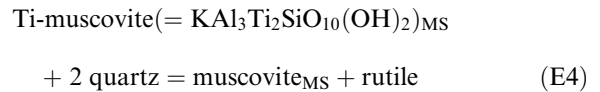
4. Thermobaric evaluation

Because of the identical mineral assemblage of 22755 and the Erzgebirge's rock the same geothermobarometric methods, as previously applied to the latter rock [3], can be used to determine the P–T conditions of equilibration of the matrix phases, i.e. after diamond formation. In case of the rock from the Kokchetav Massif, two stages should be distinguished according to the zonation (core and rim zones) of muscovite and biotite in the matrix. At least for the earlier of these stages, the coexistence of plagioclase (PLAG), garnet (GT), muscovite (MS), and quartz with kyanite can be assumed so that two equilibria:

$$2 \text{ kyanite} + \text{quartz} + \text{grossular}_{GT} =$$
$$3 \text{ anorthite}_{PLAG} \text{ (GASP) and} \qquad \text{(E1)}$$

$$3 \text{ MgAl-celadonite}_{MS} + 4 \text{ kyanite} =$$
$$\text{pyrope}_{GT} + 3 \text{ muscovite}_{MS} + 4 \text{ quartz} \qquad \text{(E2)}$$

could be thermodynamically calculated to derive pressure conditions. Because of the presence of biotite (BT) and K-feldspar (KF), the equilibrium:

$$\text{MgAl-celadonite}_{MS} =$$
$$\text{K-feldspar}_{KF} + \text{quartz} + \text{phlogopite}_{BT} + H_2O \quad \text{(E3)}$$
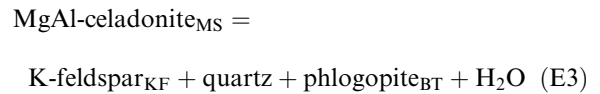
can, in fact, be used to derive P–T data for the equilibration during the late-matrix stage (and tentatively for the early-matrix stage as well) but it is dependent on the activity of H_2O (the lower this activity, the higher the calculated P), which is not directly deducible from the rock. However, the equilibrium:

$$\text{Ti-muscovite}(= \text{KAl}_3\text{Ti}_2\text{SiO}_{10}(\text{OH})_2)_{MS}$$
$$+ 2 \text{ quartz} = \text{muscovite}_{MS} + \text{rutile} \qquad \text{(E4)}$$

is independent of H_2O activity and can be applied to both stages because unaltered rutile is present in the rock matrix of 22755. For temperature estimates, the subsequent Fe–Mg exchange equilibria are applicable:

Table 6
Examples for calculated P–T conditions of diamondiferous rocks from the Lake Kumdy-Kol area, Kokchetav Massif, using representative analyses given in the previous tables

Analyses or activities	Method	Equilibrium	Rock	P (GPa)	T (°C)
(A) Early-matrix stage					
210522_{GT} $a_{An} = 0.4$	I	E1	22755	1.33	*700*
				1.53	*800*
210522_{GT} $1312B3_{MS}$	I	E2		1.40	*700*
				1.64	*800*
210522_{GT} 703109_{MS}				1.03	*700*
				1.245	*800*
$1312B3_{MS}$ $a_{Kf} = 0.9$ $a_{Phl} = 0.116(703173)$	I	E3		≥ 0.97	*700*
				≥ 1.18	*800*
703109_{MS} $a_{Kf} = 0.9$ $a_{Phl} = 0.097(703095)$				≥ 0.87	*700*
				≥ 1.07	*800*
$1312B3_{MS}$	I	E4		1.23	*700*
				1.38	*800*
703109_{MS}				0.92	*700*
				1.04	*800*
210522_{GT} 703173_{BT}	II	E5			802
210522_{GT} 703095_{BT}					(961)
210574_{GT} 703095_{BT}					(911)
210522_{GT} $1312B3_{MS}$	I	E6		*1.5*	836
210522_{GT} 703109_{MS}				*1.0*	764
				1.5	777
210574_{GT} 703109_{MS}				*1.0*	810
210522_{GT}	I	E10		*2.0*	688
				1.0	612
210574_{GT}				*1.0*	683
190502_{GT} 152936_{BT}	II	E5	22756		753
190504_{GT} 181203_{CPX}	II	E7		*3.0*	793
				1.5	750
190502_{GT} 181203_{CPX}				*1.5*	757
190504_{GT} 181203_{CPX}	I	E7 + E8		1.55	825
190502_{GT} 181203_{CPX}				1.71	806
		E8		2.58	*1000*
181203_{CPX}	I	E9		≥ 0.62	*700*
				≥ 0.73	*800*
190502_{GT}		E10		*1.5*	≤ 690
180509_{GT}	I	E10	22761	*3.0*	≥ 793
				1.5	≥ 674
(B) Late-matrix stage					
703115_{MS} $a_{Kf} = 0.9$ $a_{Phl} = 0.088(703090)$	I	E3	22755	≥ 0.31	*600*
				≥ 0.45	*700*
703114_{MS} $a_{Kf} = 0.9$ $a_{Phl} = 0.087(703088)$				≥ 0.51	*600*
				≥ 0.69	*700*
703115_{MS}	I	E4		0.56	*700*
				0.65	*800*
703114_{MS}				0.66	*700*
				0.76	*800*
210574_{GT} 703090_{BT}	II	E5			(971)
210571_{GT}	I	E10		*1.0*	683
190530_{GT} 152908_{BT}	II	E5	22756		691
190530_{GT} 181203_{CPX}	II	E7		*1.0*	745
190530_{GT}	I	E10		*1.0*	≤ 644

Table 6 (*Continued*).

Analyses or activities	Method	Equilibrium	Rock	P (GPa)	T (°C)
(C) UHP stage					
210559$_{GT}$	I	E10	22755	*7.0*	1115
				5.0	1003
210574$_{GT}$				*4.5*	903
190508$_{GT}$			22756	*7.0*	≥ 1210
				5.0	≥ 1090
190504$_{GT}$				*4.5*	≥ 1021
180505$_{GT}$ 107027$_{CPX}$		E8	22761	5.84	*1000*
				7.73	*1200*
180505$_{GT}$		E10		*7.0*	≤ 1058
				5.0	≤ 946

Methods I and II refer to those in [23] (+supplements) and classical Fe–Mg thermometers, respectively (see text). Equilibria are defined in the text. Fixed values for P or T are given in italics. Results in parentheses mean: not realistic as a result of used mineral compositions not being in equilibrium (in accordance with petrographic observations).
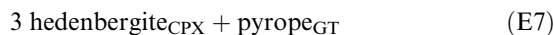
phlogopite$_{BT}$ + almandine$_{GT}$ =

annite$_{BT}$ + pyrope$_{GT}$ (E5)
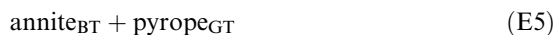
MgAl-celadonite$_{MS}$ + almandine$_{GT}$ =

FeAl-celadonite$_{MS}$ + pyrope$_{GT}$ (E6)
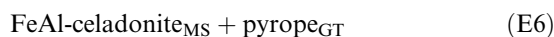
(E5) can be taken for T estimates on minerals from 22756 too as another Fe-Mg exchange equilibrium, namely:

diopside$_{CPX}$ + almandine$_{GT}$ =

3 hedenbergite$_{CPX}$ + pyrope$_{GT}$ (E7)

because of the presence of clinopyroxene (CPX) possibly during an early stage of equilibration of the matrix phases. The Ca-Tschermak's component in clinopyroxene was applied as a barometer according to the equilibrium:

2 grossular$_{GT}$ + pyrope$_{GT}$ =

3 (CaAl$_2$SiO$_6$)$_{CPX}$ + 3 diopside$_{CPX}$ (E8)
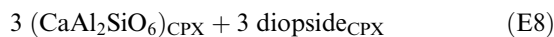
This barometer was also used for garnet–clinopyroxene pairs in sample 22761. Since plagioclase is absent in 22756, only minimum pressures can be derived considering the equilibrium:

jadeite$_{CPX}$ + quartz = albite$_{PLAG}$ (E9)

For the pre-matrix stages, we know that we have to deal with UHP conditions due to the presence of diamond. Unfortunately, only one

mineral with geothermobarometric potential, namely garnet, is present. Thus, the Ti-in-garnet thermometer [11], using the theoretical garnet component Mg$_3$Al$_2$Ti$_3$O$_{12}$, is of particular interest here. The corresponding equilibrium is:

pyrope$_{GT}$ + 3 rutile =

3 coesite (or quartz) + (Mg$_3$Al$_2$Ti$_3$O$_{12}$)$_{GT}$ (E10)
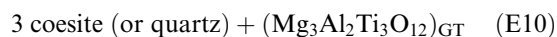
However, its application requires the presence of both coesite (or quartz) and rutile. In the absence of rutile (probably relevant to 22756) minimum T can be estimated. Maximum T (relevant to 22761 and possibly 22755) would result in the presence of rutile but absence of coesite, for which no indication was found in 22755, although this rock is now rich in quartz. In this case, E10 can be applied as a geothermometer, at least to the equilibration stages of the matrix.

The calculation procedure including the thermodynamic data sources is reported by Massonne [23]. Additional information on the components phlogopite, FeAl-celadonite, and Ti-muscovite are given elsewhere ([24–26], respectively). Moreover, classical Fe–Mg thermometers were used [27,28]. Obtained calculation results are shown in Table 6. The P–T data for the stage represented by garnet rim and mica core compositions (early-matrix stage) scatter around 1.45 GPa and 780°C, considering a relatively high uncertainty of T derived from E10 due to very low Ti concentrations in garnet. At the end of this stage (outermost

mica core compositions), P had decreased to about 1.1 GPa, probably accompanied by a slight temperature decrease (see Fig. 7). Pressure data for the stage characterized by mica rim compositions (late-matrix stage) are around 0.65 GPa at temperatures close to 700°C. Only at the final late-matrix stage the presence of a hydrous fluid ($a_{H_2O} \sim 1$) is likely because of (nearly) identical results (see Table 6) obtained from E3 and E4. The estimated P–T conditions for the entire matrix stage are compatible with the stability of muscovite+quartz (+H_2O only at $T < 700$°C of the final late-matrix stage) [13].

The application of E10 to garnet core compositions (UHP stage) results in temperatures above 900°C at 4.5 GPa (Fig. 7). Assuming pressures as high as 7 GPa, T could have been somewhat above 1100°C for the diamond-bearing garnet zone of 22755 (Table 6). Considering 22756 and 22761 as well as the minimum–maximum esti-

mates, the data rather suggest different peak temperature conditions in a range of, at least, 1050–1200°C. Different peak pressures cannot be excluded either, but the pressure estimate for a garnet–clinopyroxene pair, using compositions related to a zone with microdiamond inclusions in both minerals, confirms the previous assumption of 7 GPa (close to 1100°C, see Table 6) [7].

5. Discussion and conclusions

5.1. Comparison of the quartz-rich diamondiferous rocks from the Saxonian Erzgebirge and the Kokchetav Massif

The similarities of the quartz-rich UHP rocks from both areas, Erzgebirge and Kokchetav Massif, are obvious with regard to numerous facts. The most important ones can be summarized as follows:

1. Microdiamonds as well as multiphase inclusions, consisting of diamond, micas and additional phases, are enclosed in a specific growth zone of garnet surrounding a more or less extended garnet core zone. The enclosure of microdiamonds happened at decreasing (and for both areas similar) temperatures (and pressures, presumably) according to the Ti concentrations in specific garnet growth zones.
2. The highest Ti concentrations were observed in the garnet core zones representing the peak temperature (and pressure, presumably) conditions.
3. The shape and size of garnets are similar. This already concerns the irregular shape of the core zone (+diamondiferous zone) pointing to, at least, one stage of resorption of garnet at high temperatures.
4. The P–T conditions of the formation of the micas in the rock matrix are only slightly different. The micas in the Erzgebirge's rock equilibrated in the pressure range 1.8–1.5 GPa [3] at temperatures of 750°C or somewhat less, whereas (the extended cores of) those from the Kokchetav Massif formed between 1.45 and 1.1 GPa at about 30–50°C higher T. A major difference between the mineral compo-
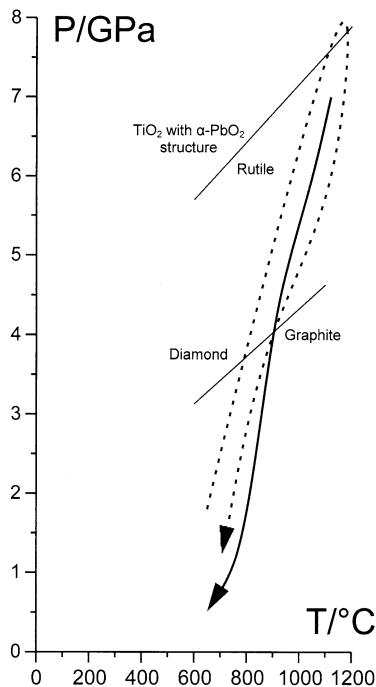

Fig. 7. P–T evolution of diamondiferous rocks from the Erzgebirge (broken line), according to [10], and from the Kokchetav Massif (this study). The paths include the 'matrix stages' (see Table 6): 1.8–1.5 GPa for the Erzgebirge, 1.45–0.65 GPa for the Kokchetav Massif. The upper pressure stability of rutile is that of Akaogi et al. [9].

sitions of the matrix of the various quartz-rich rocks can be observed. However, this is due to different bulk rock compositions (Table 1 and Fig. 8A), which could all be related to metasediments, as previously suggested [20,29]. Although containing nearly identical amounts of SiO_2, the Al_2O_3 and K_2O contents of sample 22756 are clearly lower than those of E99-2a, resulting in the lack of muscovite and much smaller amounts of micas in 22756 compared to the Erzgebirge's rock. A minor difference is the preservation of mineral relics of a pre-UHP stage in the Erzgebirge's rock [18] that was not observed in the investigated quartz-rich rocks from the Kokchetav Massif. Only on the basis of inclusions in zircon, such a stage was reported by Katayama et al. [30], which could, however, not be defined in terms of P–T conditions. Similar investigations by Hermann et al. [31] did not confirm this result. An important difference is the second equilibration stage (late-matrix stage) observed for the diamondiferous rocks of the Kokchetav Massif, which has no counterpart in the Erzgebirge. This (and subsequent) event(s), which was, according to other samples from the Lake Kumdy-Kol area, accompanied by deformation, is responsible for the worse preservation of the UHP–HP stages of the quartz-rich diamondiferous rocks compared to that of the diamondiferous Erzgebirge's rock. Most of these rocks from the Lake Kumdy-Kol area show a gneissic (or foliated) texture. The corresponding deformation event is related to a major shear-zone (megamelange) [14,17], whereas the entire UHP–HP unit after exhumation rather forms a flat-lying km-thick sheet, like a nappe, in both crystalline complexes, Erzgebirge [32] and Kokchetav Massif [33].

5.2. Magmatic and/or metamorphic evolution

Because of the above-discussed similarities between the quartz-rich diamondiferous rocks from both areas, we can treat them together asking for a possible magmatic evolution. The answer, however, cannot be derived exclusively from the mineral assemblage because metamorphic and magmatic rocks of the same bulk composition can display the same assemblage as we know from
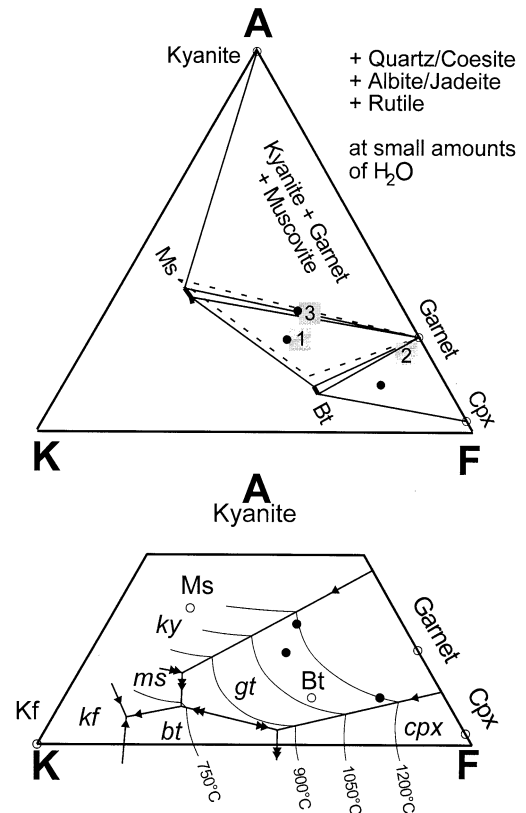

Fig. 8. Phase relations for diamondiferous quartz-rich rocks shown in modified A′KF diagrams (K = KAlO₂). Among several simplifications (see below), one is that CaO was added to FeO+MnO+MgO (= F). (A) The displayed tie-lines refer to the matrix stages (solid = early, broken = late). Excess phases for these stages are quartz as well as (although not present in 22756) albite (or jadeite) and rutile. Bulk rock compositions of Table 1 were plotted as 1 (22755), 2 (22756), and 3 (E99-2). The nearby dots mark compositions after subtraction of garnet related to about 10% of the total of mafic minerals (22756: 2/3 of the mafic minerals). Such amounts of garnet are considered as restite portions in the diamondiferous rocks so that the dots represent compositions of silicate melts addressed in Section 5 and in the liquidus diagram below. Small amounts of water (< 1.5 wt%) were considered for the silicate melt compositions. (B) Hypothetical liquidus diagram. P is not constant but decreases with falling T according to the P–T paths of Fig. 7. Liquidus fields are noted by small-case letters: bt, biotite; cpx, clinopyroxene; gt, garnet; kf, K-feldspar; ky, kyanite; ms, muscovite. Isothermal contour lines mark steps of 150°C. For mineral (open dot) and melt (closed dot) compositions see panel A. The solid excess phases, such as coesite, are not implicitly present at the highest T shown in this diagram.

ordinary granites and many medium- to high-grade orthogneisses even when garnet is a constituent. Thus, the difference between both rock types is rather a matter of (micro)fabrics. A typical feature of magmatic rocks are, for instance, melt inclusion. In fact, there is no doubt that microdiamonds in the quartzofeldspathic rocks from the Saxonian Erzgebirge and the Kokchetav Massif have formed from a 'fluid phase' [15,34–36] due to specific multiphase inclusions in garnet (Fig. 3C) but the question if the character of this (supercritical?) fluid was rather that of a silicate melt, although opened for the Erzgebirge's rock [37], remained unanswered for the Kokchetav Massif yet. Experiments on sedimentary compositions at UHP conditions [14] demonstrated that considerable melting can occur around 1000°C with some water in the system but this cannot be a sufficient evidence for a magmatic evolution because of the unknown amounts of H_2O in the deeply submerged rocks at the peak T conditions. However, here the attempt is made to draw a magmatic scenario in order to check if the textural and analytical observations on the diamondiferous quartz-rich rocks can be satisfactorily explained by it or not.

For this scenario it is assumed that considerable amounts of the diamondiferous quartz-rich rocks are molten at the peak temperatures of more than 1100°C, formerly thought to be only 1000°C. This is in accordance with the previously cited experimental works [12–14] even if the rocks contained only small amounts of water (< 1.5 wt%), that were stored in micas at pre-peak conditions. Such micas, phengites, were observed in the Erzgebirge's rock as relics preserved in garnet cores [3]. However, the garnets themselves in the quartz-rich rocks should be partially molten, resulting in irregular shapes of garnet with highest Ti concentrations attained at the highest temperatures. This was, indeed, observed for garnet cores in the Erzgebirge's rock and Kokchetav samples 22755 and 22756. Even zircons were considerably corroded (see cathodoluminescence images in [18]), as can be expected by the envisaged melting process. If the above scenario is correct, then garnet was the only major phase surviving the melting process at UHP as restite. This is in accordance with experiments with pelitic compositions and small amounts of water which resulted (above 30 kbar) in garnet and kyanite ± coesite coexisting with melt around 1100°C [12,14]. At lower T, phengite joined this assemblage. For andesitic compositions kyanite was lacking in this assemblage [12], whereas for granitic compositions (S-type) kyanite and coesite appeared first during cooling of the melt [13]. This information was used to tentatively draw a liquidus diagram (Fig. 8B) in order to elucidate possible magmatic phase relations for the investigated rocks. In addition, a similar attempt for 0.8, 1.7, and 2.4 GPa and a compositional range around the tie-line K-feldspar–dark-mica in the system K_2O–MgO–Al_2O_3–SiO_2–H_2O [38] was considered.

According to the liquidus diagram of Fig. 8B, garnet would first crystallize again (after the T climax) from all three melt compositions related to the investigated quartz-rich diamondiferous rocks after consideration of some garnet as restite, as pointed out above and in the legend of Fig. 8A. This phase is followed by kyanite for the Erzgebirge's rock and sample 22755 from the Kokchetav Massif during cooling and ascent (see P–T paths of Fig. 7) of the magma. However, kyanite would appear in the magma of 22755 at clearly lower temperatures (about 900°C according to Fig. 8B) and, thus, also at lower pressures compared to kyanite of the Erzgebirge's rock. This would explain why the Erzgebirge's kyanite could enclose microdiamonds (see Fig. 1B), which must have crystallized from the melt before trapping at $P > 4$ GPa and $T > 900$°C, but this phase from 22755 not. Moreover, only kyanite from the Erzgebirge's rock has enclosed, typically in core regions and, thus, before trapping microdiamonds, abundant small and equigranular garnets (Fig. 1B). Such garnets are preserved only there. This feature can be easily explained by a magmatic process but not by a metamorphic reaction. If we consider a fast ascent of the magma, an undercooling phenomenon is not unlikely to occur. This is characterized here by sudden crystallization of abundant little garnet grains in domains of the magma where no garnets were present, that means the relic garnets of the T climax, which also grew during cooling, were at a certain dis-

tance (mm to cm range) to this domain. Shortly after the garnet crystallization, kyanite started to grow, using perhaps the little garnets as seed, because P–T conditions given by the corresponding cotectic line of Fig. 8B were reached. Thus, the little garnets could be preserved before they grew to larger grains or even disappeared to feed larger garnet crystals.

In contrast to the kyanite-bearing rocks, the crystallization of garnet from a magma related to sample 22756 must be followed, after moderate cooling, by additional crystallization of clinopyroxene according to the liquidus diagram of Fig. 8B ($T > 1050°C$). Relics of this phase were observed in 22756 but no microdiamonds were found to be enclosed either in rare clinopyroxenes or in their decomposition products. The many microdiamonds enclosed in specific growth zones of clinopyroxene and garnet (Ti-richest zone = highest T) in the calcite marble 22761 could, in principle, be trapped during crystallization of clinopyroxene from a magma, but cannot referred to this problem (= liquidus diagram) which is related to SiO_2-rich rocks. It is also not intended to provoke that coesite was an early crystallization phase. This is possible but unlikely for the compositions (around 66 wt% SiO_2) discussed here and, thus, a matter of simplifications applied to the liquidus diagram of Fig. 8B. Rather, during further cooling ($T < 1050°C$), coesite could have started to crystallize in the quartz-rich rocks addressed here. Rare pseudomorphs of this mineral in the Erzgebirge's rock and in sample 22756 from the Kokchetav Massif, enclosed in the same growth zone of garnet which contains microdiamonds (see also [18]), witness this event. The occurrence of pseudomorphs, interpreted to be former K-cymrite [18], in the same zone of garnet from the Erzgebirge's rock is not understood in terms of the liquidus diagram of Fig. 8B. Thus, K-cymrite could be a misinterpretation of such pseudomorphs or it does not appear in the liquidus diagram due to the applied simplifications.

Further cooling close to 800°C and less should finally result, according to the liquidus diagram, in the formation of micas by peritectic reactions. In case of the kyanite-bearing rocks, muscovite should have formed from melt and kyanite as well as some garnet during further cooling. The replacement of kyanite by coarse-grained muscovite is, indeed, obvious in the Erzgebirge's rock (see Fig. 1B), whereas the boron-bearing phase dumortierite also played a role in sample 22755 from the Kokchetav Massif. The (slight) corrosion of garnet can also be deduced from petrographic observations combined with element concentration maps of this mineral (see Fig. 6) from both kyanite-bearing rocks. The estimated difference in T (30–50°C) between the onset of white mica production in both rocks could be due to higher x_{Fe} (= Fe/(Fe+Mg)) values of muscovite in 22755 compared to that of the Erzgebirge's rock (see Table 4, concerns garnet as well) and/or other chemical factors. According to the liquidus diagram of Fig. 8B (composition 2), biotite (and clinopyroxene) should form from garnet and melt. Analytical studies, such as, for instance, shown in Fig. 5, demonstrate a significant corrosion of garnet in 22756, as deep as into the core zone of this mineral, by biotite. This mineral in the kyanite-bearing rocks should also crystallize from melt (+garnet), at least, in significant quantities in sample 22755 as deduced from the liquidus diagram of Fig. 8B.

As demonstrated above, the petrographic and analytical observations on the quartz-rich rocks are compatible with crystallization from melts containing garnet as restite after melt formation. Several aspects, related to the formation of minerals other than garnet, kyanite, (diopside-rich) clinopyroxene, and mica, can be added to complete the magmatic scenario. For instance, it is likely that, at a relatively late stage of crystallization, jadeite-rich clinopyroxene, according to the observed pseudomorphs, formed from the remaining melt of the Erzgebirge's rock. It is not clear if jadeite-rich clinopyroxene formed in sample 22755 at all, but the estimated pressures for the formation of the micas (early-matrix stage) were too low to stabilize a jadeite-rich clinopyroxene between 750 and 800°C. The formation of K-feldspar, detected in both kyanite-bearing rocks, cannot be explained by the liquidus diagram of Fig. 8B unless the amounts of H_2O in the original melts were relatively low ($K > H_2O$ as a simple

approach). However, it ought to be considered that, in principle, a perfect equilibration of phases during natural crystallization processes rarely, if it all, occurs; otherwise there would be, for instance, no kyanite present in the studied rocks. It was armored by replacing muscovite, at least, in the Erzgebirge's rock, so that it was protected from further reaction. Thus, it is likely that a residual melt could further develop, reaching the eutectic point (granitic melt composition, see Fig. 8B) at which K-feldspar precipitated finally from melt, filling, for instance, interstices as observed in the Erzgebirge's rock. A formation by a metamorphic reaction cannot, in fact, be totally excluded, but features such as large tourmaline crystals, occurring in sample 22755 in a quartz–plagioclase–K-feldspar matrix (Fig. 2B), rather point to crystallization from a granitic melt.

Considering the above magmatic scenario, an answer to the mystery of the exhumation of the diamondiferous quartz-rich rocks from great depths can be given. It is due to a quick rise (see ages in [37]) of magmas accompanied by relatively fast cooling. Hints of this also come from the stable isotope signature (C and N) of microdiamonds from the Kokchetav Massif, although related to siliceous marbles, reported by Cartigny et al. [29]. These authors, in fact, preferred the interpretation that the growth of microdiamonds happened at temperatures below 700°C but presented the alternative idea of an extremely fast uplift of the rock (+cooling) starting at temperatures as high as 1000°C to explain the isotope signature of the microdiamonds. After formation of one mica phase (e.g. muscovite in 22755) due to a peritectic reaction, a considerable quantity of the melt had crystallized, so that a further ascent was hampered. Indeed, a further clear drop of the pressures during this stage could not be proven. At this stage, the melts (or crystal mashes) were already emplaced in the lowermost portion of continental crust that also contains ultrabasic slices of the mantle, such as garnet peridotites, in both areas. Perhaps the new (and lower) density contrast (crystal mash–crust (mantle before)) was another factor hampering further ascent. The subsequent lowering of the pressure (late early-matrix stage) by a few kbar only was possibly not the

result of further magma rise but concerned the (thickened) continental crust, in general, in which the magmas were emplaced. This process is then due to the denudation of the corresponding orogen.

Not addressed in the above discussion, so far, was the homogeneous distribution of garnet in the extended diamondiferous rock lenses in Saxony. This textural pattern would also be expected for a plutonic rock, normally relatively homogeneous, rather than for a metamorphic rock. The lack of homogeneous bodies in the hectometer range in the Kokchetav Massif is probably the result of deformation events leading to a megamelange [17]. Deformation was accompanied by 'metamorphic' retrogression. Among the true metamorphic reaction products in the diamondiferous quartz-rich rocks from the Kokchetav Massif seem to be garnet in sample 22756 which circumgrew biotite or formed narrow rims around previously resorbed garnet (Fig. 5). This could have led to the view of Shatsky et al. [2] that biotite of an early metamorphic stage was enclosed in diamond-bearing garnet from the Kokchetav Massif. No evidence for this assumption was, however, found in the investigated samples. As mentioned above, this is in contrast to the Erzgebirge's rock, where an early metamorphic stage, preceding the UHP evolution, could be characterized [18]. The varying P–T conditions and/or a reduction of the water activity could be the cause for the final garnet growth in 22756, whereas the outermost (incomplete) zone of garnet (increase of Ca, decrease of Mg; see Fig. 4 and Table 3) in the Erzgebirge's rock and in sample 22755 could also result from cation diffusion processes at a late stage. At a very late stage, garnets were altered (at estimated $T < 600°C$) but only in the studied Kokchetav rocks. Fine-grained biotite and other phases, forming symplectites, replaced garnet. In addition, kyanite was altered to micaceous material (Erzgebirge's rock and sample 22755) and amphibole replaced clinopyroxene in 22756 (also in the siliceous marble). The reason for these alteration processes, which hardly affected the Saxonian diamondiferous rocks, was a penetrative deformation event, mentioned above, that could have reduced larger magmatic bodies to much

smaller layers where magmatic textures are preserved. It is even possible that the majority of originally magmatic rocks in the Kokchetav Massif could have been so strongly deformed that these rocks have lost any memory of a magmatic event to appear now as ordinary folded gneisses.

The above view implies that diamondiferous rocks in the Kokchetav Massif, such as marbles, occurring in the vicinity of the quartz-rich rocks studied here were also subject to magmatic processes. Hints of this are, for instance, multiphase inclusions in marbles consisting of silicates, carbonate, and microdiamonds [39] and stable isotope data [29] as re-interpreted above.

Finally, it is noteworthy that the quartz-rich plutonic rocks of UHP–HP origin cannot be attributed to the series tonalite–granite because of the distinct contents of mafic minerals in the diamondiferous rocks compared to the rocks of this series. In addition, we even ignore that quartz and plagioclase in the UHP–HP magmatic rocks were originally coesite and jadeite-rich clinopyroxene, at least, to some extent. Thus, it is suggested to take this into account by the nomenclature of a new series. The kyanite-bearing rocks studied here (compositions 1 and 3 in Fig. 8), being rich in white mica and garnet, are proposed to be called saidenbachites [37]. The clinopyroxene-bearing rock (composition 2 in Fig. 8), being rich in garnet and biotite, is suggested to be named, also after the type locality, kumdykolite.

Acknowledgements

References

[1] N.V. Sobolev, V.S. Shatsky, Diamond inclusions in garnets from metamorphic rocks: an environment for diamond formation, Nature 343 (1990) 742–745.

[2] V.S. Shatsky, N.V. Sobolev, M.A Vavilow, Diamond-bearing metamorphic rocks of the Kokchetav Massif (Northern Kazakhstan), in: R. Coleman, X. Wang (Eds.), Ultrahigh Pressure Metamorphism, Cambridge Univ. Press, Cambridge, MA, 1995, pp. 427–455.

[3] H.-J. Massonne, A new occurrence of microdiamonds in quartzofeldspathic rocks of the Saxonian Erzgebirge, Germany, and their metamorphic evolution, in: Proc. 7th Int. Kimberlite Conf., 1999, pp. 533–539.

[4] L. Nasdala, H.-J. Massonne, Microdiamonds from the Saxonian Erzgebirge, Germany: in situ micro-Raman characterisation, Eur. J. Mineral. 12 (2000) 495–498.

[5] L.F. Dobrzhinetskaya, E.A. Eide, R.B. Larsen, B.A. Sturt, R.G. Trønnes, D.C. Smith, W.R. Taylor, T.V. Posukhova, Diamond in metamorphic rocks of the Western Gneiss Region in Norway, Geology 23 (1995) 597–600.

[6] R.Y. Zhang, J.G. Liou, W.G. Ernst, R.G. Coleman, N.V. Sobolev, V.S. Shatsky, Metamorphic evolution of diamond-bearing and associated rocks from the Kokchetav Massif, northern Kazakhstan, J. Metam. Geol. 15 (1997) 479–496.

[7] K. Okamoto, J.G. Liou, Y. Ogasawara, S. Maruyama, Petrology of the diamond-grade eclogite in the Kokchetav Massif, northern Kazakhstan, Island Arc 9 (2000) 382–402.

[8] S.L. Hwang, P. Shen, H.T. Chu, T.F. Yui, Nanometer-size α-PbO$_2$-type TiO$_2$ in garnet: a thermobarometer for ultrahigh-pressure metamorphism, Science 288 (2000) 321–324.

[9] M. Akaogi, K. Kusaba, J. Susaki, T. Yagi, M. Matsui, T. Kikegawa, H. Yusa, E. Ito, High pressure high temperature stability of αPbO$_2$-type TiO$_2$ and MgSiO$_3$ majorite: calorimetric and in situ diffraction studies, in: Y. Syono, M.H. Manghnani (Eds.), High-Pressure Research: Application to Earth and Planetary Sciences, Am. Geophys. Union Monogr. 67, 1992, pp. 447–455.

[10] H.-J. Massonne, P.J. O'Brien, Reviews of representative UHPM terranes. 2.5. The Bohemian Massif and the NW Himalaya, in: D.A. Carswell, R. Compagnoni (Eds.), School on Ultra-High Pressure Metamorphism, EMU Notes Mineral. 5, 2003, Chapter 2, in press.

[11] A. Brandelik, H.-J. Massonne, New geothermobarometers on the basis of Ti incorporation into Al-garnet, in: 3rd EMU Workshop Solid Solutions in Silicate and Oxide Systems of Geological Importance, Lübeck, 2001, Abstr. Vol., p. 8.

[12] C.R. Stern, P.J. Wyllie, Melting relations of basalt-andesite-rhyolite-H$_2$O and a pelagic red clay at 30 kbars, Contrib. Mineral. Petrol. 42 (1973) 313–323.

[13] W.L. Huang, P.J. Wyllie, Phase relationships of S-type granite with H$_2$O to 35 kbar: Muscovite granite from Harney Peak, South Dakota, J. Geophys. Res. 86 (1981) 10515–10529.

[14] J. Hermann, D.H. Green, Experimental constraints on high pressure melting in subducted crust, Earth Planet. Sci. Lett. 188 (2001) 149–168.

[15] B. Stöckhert, J. Duyster, C. Trepmann, H.-J. Massonne,

Microdiamond daughter crystals precipitated from super-critical COH+silicate fluids included in garnet, Erzgebirge, Germany, Geology 29 (2001) 391–394.

[16] T. Ota, M. Terabayashi, C.D. Parkinson, H. Masago, Thermobaric structure of the Kokchetav ultrahigh-pressure - high-pressure massif deduced from a north-south transect in the Kulet and Saldat-Kol regions, northern Kazakhstan, Island Arc 9 (2000) 328–357.

[17] K. Theunissen, N.L. Dobretsov, A. Korsakov, A. Travin, V.S. Shatsky, L. Smirnova, A. Boven, Two contrasting petrotectonic domains in the Kokchetav megamelange (north Kazakhstan): Difference in exhumation mechanisms of ultrahigh-pressure crustal rocks, or a result of subsequent deformation?, Island Arc 9 (2000) 284–303.

[18] H.-J. Massonne, L. Nasdala, Characterization of an early metamorphic stage through inclusions in zircon of a diamondiferous quartzofeldspathic rock from the Erzgebirge, Germany, Am. Mineral. 88 (2003) 883–889.

[19] H.-J. Massonne, First find of coesite in the ultrahigh-pressure metamorphic region of the Central Erzgebirge, Germany, Eur. J. Mineral. 13 (2001) 565–570.

[20] N.L. Dobretsov, K. Theunissen, L.V. Smirnova, Structural and geodynamic evolution of the diamondiferous metamorphic rocks of the Kokchetav Massif (Kazakhstan), Russ. Geol. Geophys. 39 (1998) 1631–1652.

[21] H.-J. Massonne, H.J. Bernhardt, D. Dettmar, E. Kessler, O. Medenbach, T. Westphal, Simple identification and quantification of microdiamonds in rock thin-sections, Eur. J. Mineral. 10 (1998) 497–504.

[22] C. Chopin, G. Ferraris, G. Ivaldi, H.-P. Schertl, W. Schreyer, R. Compagnoni, C. Davidson, A.M. Davis, Magnesiodumortierite, a new mineral from very-high-pressure rocks (western Alps). Part II: Crystal chemistry and petrological significance, Eur. J. Mineral. 7 (1995) 525–535.

[23] H.-J. Massonne, Experimental and petrogenetic study of UHPM, in: R. Coleman, X. Wang (Eds.), Ultrahigh Pressure Metamorphism, Cambridge Univ. Press, Cambridge, MA, 1995, pp. 33–95.

[24] H.-J. Massonne, Is the concept of 'in situ' metamorphism applicable to deeply buried continental crust with lenses of eclogites and garnet peridotites?, Chin. Sci. Bull. 40 (1995) 145–147.

[25] H.-J. Massonne, An improved thermodynamic solid solution model for natural white micas and its application to the geothermobarometry of metamorphic rocks, in: Geol. Surv. Finland Guide 46, Mineral Equilibria and Databases, Abstracts, 1997, p. 49.

[26] H.-J. Massonne, U. Grosch, A.P. Willner, Geothermobarometrie mittels Ti-Gehalten in Kalihellglimmern, Ber. Dt. Mineral. Ges., Beih. Eur. J. Mineral. 5 (1) (1993) 85.

[27] J.M. Ferry, F.S. Spear, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet, Contrib. Mineral. Petrol. 66 (1978) 113–117.

[28] D.J. Ellis, D.H. Green, An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria, Contrib. Mineral. Petrol. 71 (1979) 13–22.

[29] P. Cartigny, K. de Corte, V.S. Shatsky, M. Ader, P. de Paepe, N.V. Sobolev, M. Javoy, The origin and formation of metamorphic microdiamonds from the Kokchetav massif, Kazakhstan: a nitrogen and carbon isotopic study, Chem. Geol. 176 (2001) 265–281.

[30] I. Katayama, A.A. Zayachkovsky, S. Maruyama, Prograde pressure-temperature records from inclusions in zircons from ultrahigh-pressure - high-pressure rocks of the Kokchetav Massif, northern Kazakhstan, Island Arc 9 (2000) 417–427.

[31] J. Hermann, D. Rubatto, A. Korsakov, V.S. Shatsky, Multiple zircon growth during fast exhumation of diamondiferous, deeply subducted continental crust (Kokchetav Massif, Kazakhstan), Contrib. Mineral. Petrol. 141 (2001) 66–82.

[32] A.P. Willner, A. Krohe, W.V. Maresch, Interrelated P-T-t-d paths in the Variscan Erzgebirge dome (Saxony, Germany): Constraints on the rapid exhumation of high-pressure rocks from the root zone of a collisional orogen, Int. Geol. Rev. 42 (2000) 64–85.

[33] Y. Kaneko, S. Maruyama, M. Terabayashi, H. Yamamoto, M. Ishikawa, R. Anma, C.D. Parkinson, T. Ota, Y. Nakajima, I. Katayama, J. Yamamoto, K. Yamauchi, Geology of the Kokchetav Massif, in: C.D. Parkinson, I. Katayama, J.G. Liou, S. Maruyama (Eds.), The Diamond-bearing Kokchetav Massif, Kazakhstan, Univ. Acad. Press, Tokyo, 2002, pp. 47–70.

[34] K. de Corte, P. Cartigny, V.S. Shatsky, N.V. Sobolev, M. Javoy, Evidence of fluid inclusions in metamorphic microdiamonds from the Kokchetav massif, northern Kazakhstan, Geochim. Cosmochim. Acta 62 (1998) 3765–3773.

[35] L.F. Dobrzhinetskaya, H.W. Green II, T.E. Mitchell, R.M. Dickerson, Metamorphic diamonds: Mechanism of growth and inclusion of oxides, Geology 29 (2001) 263–266.

[36] L.F. Dobrzhinetskaya, H.W. Green II, M. Weschler, M. Darus, Y.-C. Wang, H.-J. Massonne, B. Stöckhert, Focused ion beam technique and transmission electron microscope studies of microdiamonds from the Saxonian Erzgebirge, Germany, Earth Planet. Sci. Lett. 210 (2003) 399–410.

[37] H.-J. Massonne, Origin of microdiamond-bearing quartzofeldspathic rocks (saidenbachites) from the Erzgebirge, Germany: A progress report, in: UHPM Workshop 2001, Fluid/slab/mantle Interactions and Ultrahigh-P Minerals, Waseda Univ., Tokyo, 2001, pp. 11–15.

[38] H.-J. Massonne, Evidence for low-temperature ultrapotassic siliceous fluids in subduction zone environments from experiments in the system K_2O-MgO-Al_2O_3-SiO_2-H_2O (KMASH), Lithos 28 (1992) 421–434.

[39] N. Yoshioka, H. Ishida, Y. Zhu, Y. Ogasawara, Diamond-phengite and diamond-carbonate composite inclusions in UHP dolomite marble from the Kokchetav Massif - evidence for the formation of microdiamond from fluids, in: 6th Int. Eclogite Conf., Niihama, 2001, Abstr. Vol., pp. 182–183.