

Melt Inclusions in Minerals of Scapolite-Bearing Granulite (Lower Crustal Xenoliths from Diatremes of the Pamirs)

V. P. Chupin, D. V. Kuz'min, and I. A. Madyukov

Presented by Academician N.V. Sobolev August 1, 2005

Received August 5, 2005

DOI: 10.1134/S1028334X06030366

The study of scapolite-bearing eclogite-like rocks and granulites [1, 2], experimental data [3], and finds of scapolite in igneous rocks [4] showed that high-Ca scapolite can be of both metamorphic and magmatic origin under the high partial pressure of CO₂ and/or SO₃ in the fluid or melt. This communication presents the first direct data on scapolite crystallization in the lower crust with participation of CO₂-saturated melts.

Scapolite-bearing granulites are relatively rare among compositionally unique abyssal derived xenoliths from Neogene fergusonite diatremes in the South-eastern Pamirs [5, 6]. The studied xenolith of these granulites (Sample 1324 from the collection of E.A. Dmitriev) is fine- to medium-grained patchy rock with chaotic felsic patches among aggregates of mafic minerals. The distribution of leucocratic minerals varies from 20 to 70% in different parts of the xenolith. The rock consists of garnet (Mg#_{40–46} composition: almandine (41–44), pyrope (25–36), grossular (17–29), clinopyroxene (salite with jadeite content 6–8%), K-plagioclase (Ab_{38–49}, An_{41–52}, Or_{6–9}), titanite, scapolite, quartz, insignificant K-feldspar, graphite, biotite, accessory apatite, ore phases, rutile, zircon, and carbonate. The primary high-Ca scapolite (Me_{67–69} with Cl up to 0.92 wt %) (Table 1) and titanite (Al₂O₃ up to 5.2 wt %) are present as major components (approximately 15 and 5%, respectively). Garnet encloses primary small quartz grains of the first generation, carbonate (dolomite with FeO up to 7.0 wt %), rutile, zircon, apatite, and ore mineral, which suggests presence of these minerals in the rock during garnet crystallization. Small grains of

quartz and carbonate (calcite with FeO up to 10.5 wt %) are recognized in clinopyroxene as well. Pyroxene grains are missing in garnet, which implies that pyroxene formed after garnet or at later stages of its crystallization. Mafic minerals are intensely altered along edges of grains. The central parts of garnet grains are characterized by close compositions, while the composition of their rims is variable. Some garnet and clinopyroxene grains have a weak progressive metamorphic zoning (Table 1).

Primary melt inclusions occur in all the major and accessory minerals from Sample 1324 (Fig. 1). Such inclusions were first discovered in scapolite from the Pamir xenoliths. The inclusions are characterized by azonal distribution. The central parts of scapolite grains host groups of numerous inclusions. Inclusions are less common in other minerals. The inclusions are usually 5–15 μm across. They can be as large as 40–60 μm in quartz and titanite grains. Their phase composition at 20°C is glass + heterogeneous fluid bubble (gas and liquid) + one or two daughter microcrystals. Practically all the inclusions in garnet are partly decrepitated (Fig. 1a), while inclusions in quartz and scapolite are usually hermetic. Inclusions in quartz have the negative form of its high-temperature modification (Fig. 1c), which allows the minimal temperature of quartz crystallization to be estimated. At a pressure of 15 kbar, the high-temperature quartz modification is stable at temperatures above 940°C [7].

The high-temperature study of inclusions was carried out under atmospheric pressure in heat chambers with air and inert medium. Low-temperature studies have been performed using a cryometric device with a measurement accuracy of ±0.3°C. The chemical composition of minerals and glasses from inclusions were determined using a Camebax-micro electron microprobe under accelerating voltage of 20 kV and probe

*Institute of Mineralogy and Petrography, Siberian Division,
Russian Academy of Sciences, ul. akademika Koptyuga 3,
Novosibirsk, 630090 Russia; e-mail: chupin@uiggm.nsc.ru*

Table 1. Chemical compositions of minerals in Sample 1324, wt %

Component	Garnet		Garnet		Clinopyroxene		Plagioclase		Scapolite
	center	rim	center	rim	center	rim	center	rim	
SiO ₂	39.29	39.63	39.98	39.24	50.94	51.03	57.23	57.61	48.16
TiO ₂	0.08	0.15	0.12	0.16	0.47	0.54	0	0.02	0.03
Al ₂ O ₃	22.37	22.67	22.70	22.83	5.67	6.02	27.81	26.72	27.17
FeO	21.07	20.06	20.73	20.48	9.15	8.18	0.06	0.09	0.28
MgO	9.53	7.51	9.24	9.29	10.57	11.16	0.01	0.01	0.14
CaO	7.71	10.89	7.69	8.42	21.15	20.97	9.66	8.74	15.78
Na ₂ O	0.07	0.03	0.04	0.05	0.85	0.99	4.01	5.06	3.46
K ₂ O	0.00	0.02	0.01	0.00	0.01	0.03	1.53	1.29	1.28
Cl	N o t a n a l y z e d								0.91
Total	100.12	100.96	100.50	100.46	98.80	98.92	100.85	99.54	97.21
MgO/(MgO + FeO)	44.63	40.02	44.27	44.70	67.30	70.86			

current of 20 nA (L.N. Pospelova, analyst). To compensate for Na loss during the analysis of glass by the focused beam (diameter 3–4 μm), the Na₂O content was increased by 30%, in line with recommendations in [8] (Table 2). The contents of trace elements and H₂O in minerals and glasses of melt inclusions were determined by the SIMS method using an IMS-4f ion microanalyzer at the Institute of Microelectronics, Russian Academy of Sciences (Yaroslavl), following the Sobolev method [9].

Heating up to a temperature of approximately 800°C produces additional bubbles of dense CO₂ in hermetic melt inclusions, which indicates high pressures during the trapping of inclusions [10]. Heating to 1000–1020°C is accompanied by melting of daughter crystalline phases and insignificant increase in abundance of fluid vacuoles. However, no complete homogenization of inclusions is observed even under a temperature exceeding 1200°C. This temperature (1200°C) is substantially higher as compared with that of the inclusion trapping because of elastic expansion of vacuoles during the release of the high external pressure from the host mineral [10]. According to [11, 12], the melting temperatures of daughter liquidus crystalline phases (1000–1020°C) were taken for the trapping temperatures of examined melt inclusions. This is consistent with the average temperature (~1020°C) based on a garnet–clinopyroxene thermometer [13].

Garnet and scapolite host primary fluid inclusions that are syngenetic with melt ones (Fig. 1b). The fluid inclusions are 10–15 μm across. Most of these inclusions are partly decrepitated. The joint trapping of fluid and melt inclusions results in formation of combined inclusions with anomalously large fluid vacuoles (Fig. 1b). The cryometric study reveals that primary fluid inclusions

and fluid phases of melt inclusions are mainly represented by CO₂ with a density of ~0.75 g/cm³. With account for partial decrepitation of inclusions, the real density of CO₂ in inclusions was substantially higher.

Occurrence of syngenetic melt and fluid inclusions suggests that early garnet and scapolite were crystallized with participation of the CO₂-saturated melt and free CO₂-rich fluid. At temperatures of 1000–1020°C (probable temperatures of inclusion trapping), the fluid pressure for CO₂ inclusions with a density of approximately 0.75 g/cm³ was ~4 kbar. This is the minimal value of the pressure because of partial decrepitation of fluid inclusions in garnet or elastic expansion of inclusions in scapolite under the pressure release. The pressure estimated for the examined granulite using a garnet–clinopyroxene–plagioclase–quartz geobarometer [14] is 13–15 kbar.

According to microprobe data (Table 2), compositions of glasses in primary melt inclusions from all minerals of Sample 1324 correspond to high-K acid (from rhyodacites to rhyolites) melts of normal to elevated alkalinity. In pyroxene, titanite, and scapolite, unheated inclusions and varieties heated up to their trapping temperature (~1020°C) show close compositions, indicating the absence of crystallization of the host mineral on vacuole walls in inclusions. Compositions of heated melt inclusions were not determined in the earliest garnet. However, zircon- and apatite-hosted primary melt inclusions, which were trapped by early garnet, have high-K acid compositions (Table 2; analyses 2, 3). Hence, garnet also crystallized in the presence of compositionally similar acid melts. The composition of unheated melt inclusion in garnet (Table 2, analysis 1) confirms this assumption and characterizes the compo-

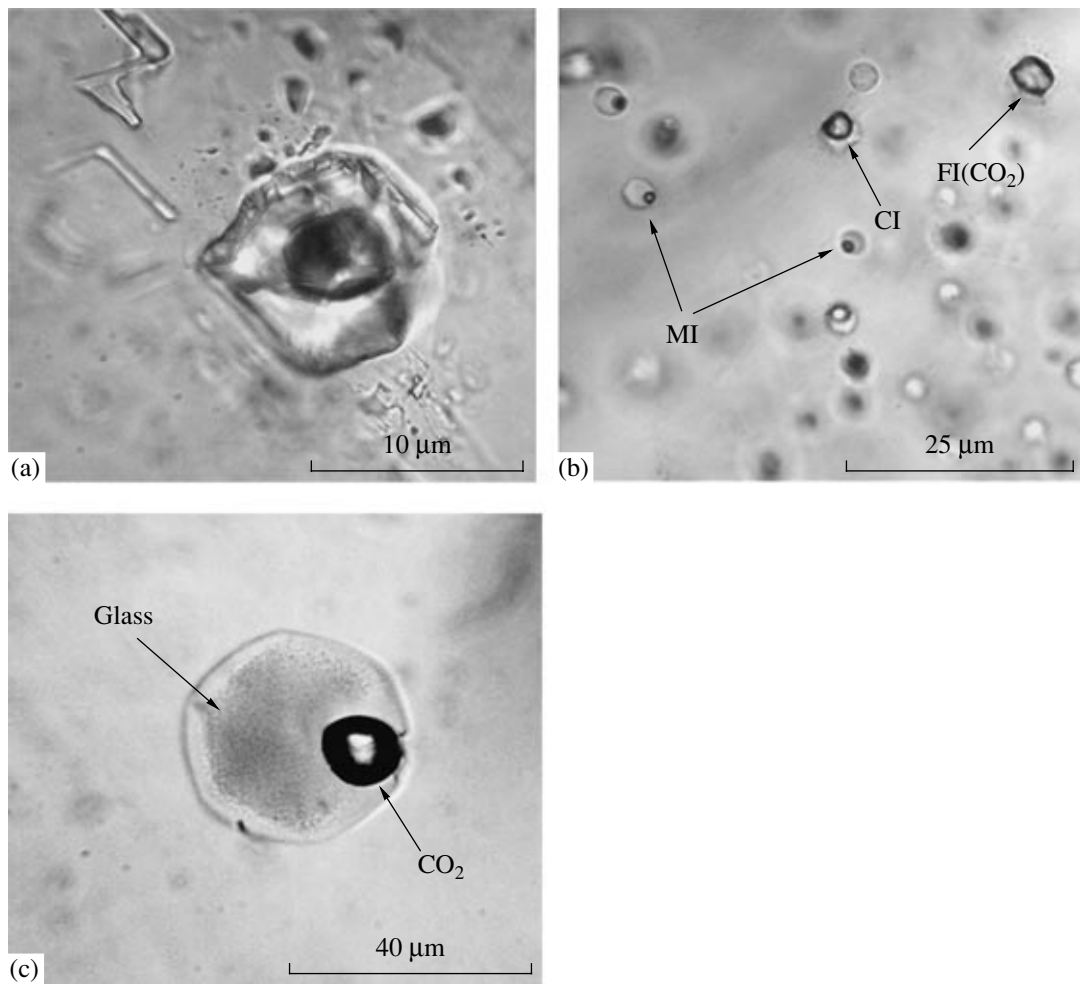


Fig. 1. Primary melt and fluid inclusions in minerals of scapolite-bearing granulite in: (a) garnet, (b) scapolite, (c) quartz. Inclusions: (MI) melt, (FI) fluid, (CI) combined.

sition of primary melt. Thus, one can outline the following trend in the variation of composition of melts in inclusions from early (garnet, pyroxene, titanite, and apatite) to late (scapolite, quartz, and K-feldspar) minerals: increase in the total content of alkali metals is accompanied by decrease in contents of CaO and Al₂O₃ in melts (the alumina index A/CNK records a transition from a peraluminous to a metaluminous composition). Low Cl contents in melts in the scapolite- and early apatite-hosted inclusions and elevated Cl contents (up to 0.8 wt %) in other minerals are also noteworthy.

The calculated CO₂ content in quartz-hosted melt inclusions amounts to 1.0 wt %. According to ion microprobe data, the water content in melt inclusions varies from 1.6 to 0.8 wt % in quartz (four analyses) and from 4.1 to 1.7 wt % in titanite (two analyses). Melt inclusions in quartz and scapolite are characterized by high contents of LREE, low contents of HREE (Fig. 2), and high contents of Th and Nb (up to 72 and 18 ppm, respectively).

The data on composition of melt and fluid inclusions in scapolite and other minerals from Sample 1324 offer an opportunity to elucidate specific features of chemistry in mineral-forming medium, which favored scapolite formation in the lower crust beneath the Pamirs at elevated *PT* parameters. Scapolite crystallization began probably at high CO₂ (~1 wt %) and Cl (up to 0.8 wt %) concentrations in melts and with participation of CO₂-rich fluid. The low Cl content in melt inclusions in this mineral can be explained by Cl redistribution from the melt into the scapolite structure. During crystallization of high-Ca scapolite instead of plagioclase, the melt became enriched in Na. This is confirmed by the higher Na content in melt inclusions from the later quartz as compared with inclusions in scapolite.

The data obtained suggest that the examined scapolite-bearing granulite crystallized from high-K acid melts with the high CO₂ and Cl contents and high Th/U values (7.7–9.4). The formation of such melts can be explained by incongruent melting of high-Ca substrate in the lower crustal settings (pressure >13 kbar, temper-

Table 2. Chemical compositions of glasses from melt inclusions in minerals of scapolite-bearing granulite, wt %

Analysis no.	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	MnO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cl	Total	A/CNK	T, °C
In garnet														
1	71.75	0.09	14.17	1.35	0.22	0.05	1.53	1.34	5.34	0.00	0.38	96.22	1.32	Unheated
In zircon														
2***	67.41	0.36	15.02	4.53	1.05	0.05	3.07	1.94	4.98	H.†	0.24	98.65	1.06	Unheated
In apatite														
3**	69.71	0.21	14.85	2.69	0.82	0.03	2.02	0.82	5.33	0.18	0.04	96.71	1.38	Unheated
4	71.62	0.28	15.30	1.57	0.26	0.03	3.69	1.10	4.76	0.14	0.01	98.77	1.12	1020
5	70.38	0.28	14.63	1.75	0.28	0.02	3.51	1.24	4.64	0.14	0.00	96.88	1.09	1020
6	68.97	0.26	15.56	1.77	0.24	0.02	3.86	1.40	5.62	0.14	0.01	97.85	1.01	1020
7	70.40	0.21	14.65	1.73	0.27	0.01	3.17	1.94	4.89	0.13	0.53	97.92	1.03	Unheated
In clinopyroxene														
8*	70.44	0.25	14.62	2.00	0.95	0.03	3.66	1.30	3.73	0.05	0.46	97.48	1.14	1020
9	68.02	0.22	14.00	2.22	0.97	0.04	4.37	1.56	4.45	0.03	0.33	96.21	0.91	1020
10*	72.03	0.24	14.68	1.92	0.41	0.02	3.29	1.15	4.59	0.03	0.35	98.69	1.14	1020
11	71.10	0.15	15.18	1.39	0.96	0.03	2.62	1.30	5.13	0.02	0.29	98.18	1.22	1020
12*	69.12	0.18	14.67	1.92	0.62	0.03	3.47	1.15	3.85	0.02	0.40	95.42	1.19	1020
13	69.04	0.16	14.49	1.72	0.77	0.04	3.44	1.27	3.98	0.04	0.48	95.44	1.15	1020
14	68.96	0.16	14.05	2.11	0.73	0.04	3.79	1.59	4.26	n.a.	0.42	96.11	1.00	1020
15*	70.72	0.17	14.35	1.89	0.66	0.04	3.54	1.77	3.62	n.a.	0.44	97.19	1.08	1020
16*	72.55	0.10	14.75	0.59	0.22	0.04	2.64	1.21	4.19	n.a.	0.46	96.72	1.30	1120
17	71.58	0.14	14.13	0.81	0.45	0.03	3.66	1.19	4.28	0.03	0.43	96.73	1.07	1120
18	69.02	0.13	13.78	1.16	0.77	0.05	3.74	1.40	4.28	0.04	0.49	94.84	1.00	Unheated
In titanite														
19*	69.82	0.44	15.00	0.64	0.32	0.03	3.27	1.90	5.07	0.06	0.56	97.10	1.03	1020
20	69.79	0.32	15.46	1.42	0.32	0.01	2.97	1.37	5.03	0.07	0.43	97.18	1.18	1020
21 (<i>n</i> = 10)	68.51	0.28	15.26	0.64	0.04	0.05	2.93	2.33	5.25	0.06	0.51	95.81	1.04	Unheated
In plagioclase														
22*	71.17	0.41	16.05	1.74	0.40	0.02	1.61	1.34	3.91	0.07	0.57	97.27	1.72	1100
In scapolite														
23	70.42	0.25	14.14	0.80	0.11	0.01	1.56	2.15	7.24	0.02	0.11	96.81	1.00	1020
24	68.80	0.26	14.03	0.81	0.11	0.02	1.46	2.18	8.52	0.00	0.06	96.26	0.91	1020
25	73.20	0.80	14.50	0.30	0.50	0.0	0.10	1.00	8.65	0.06	0.07	99.61	1.17	1020
26	70.54	0.28	15.64	0.85	0.11	0.02	2.40	2.21	6.26	0.04	0.17	98.51	1.06	1020
27	72.39	0.28	14.47	1.14	0.18	0.03	1.46	2.55	7.03	0.02	0.09	99.63	1.00	1020
28 (<i>n</i> = 5)	70.15	0.29	14.15	1.10	0.11	n.a.	0.75	2.01	7.33	0.02	0.05	95.97	1.13	Unheated
In quartz														
29*	74.26	0.20	12.83	0.73	0.20	0.02	2.01	2.98	5.43	0.06	0.37	99.08	0.89	1020
30	73.13	0.31	12.39	0.73	0.24	0.03	1.92	2.70	5.03	0.02	0.32	96.82	0.93	1020
31*	72.06	0.35	12.97	0.71	0.23	0.04	2.02	2.96	5.09	0.05	0.34	96.82	0.92	1020
32	73.47	0.23	12.69	1.01	0.18	0.02	2.09	3.58	5.12	0.05	0.46	98.89	0.83	1080
33 (<i>n</i> = 4)	70.29	0.27	14.22	1.63	0.36	n.a.	1.87	2.09	6.65	0.04	0.50	97.90	1.02	Unheated
In K-feldspar														
34*	71.97	0.27	12.40	1.69	0.33	0.02	1.29	2.26	7.25	0.01	0.36	97.82	0.89	1080
35	77.63	0.37	7.79	1.37	0.30	0.01	1.26	1.34	5.18	0.04	0.43	95.72	0.77	1100

Note: (*) Average value of two analyses; (**) inclusion in the apatite grain trapped by garnet; (***) inclusion in the zircon grain from apatite trapped by garnet; (n.a.) not analyzed; (*n*) number of inclusions with calculated average values; A/CNK = mol Al₂O₃/(CaO + Na₂O + K₂O).

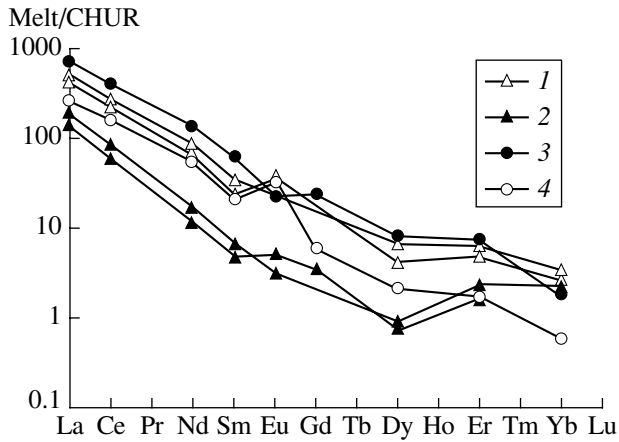


Fig. 2. REE spectra for glasses of melt inclusions in quartz and scapolite. (1) Unheated inclusions in quartz; (2) heated inclusions in quartz; (3) unheated inclusion in scapolite; (4) scapolite grain.

ature $\sim 1000^{\circ}\text{C}$). The incongruent melting was accompanied by crystallization under peritectic conditions of Si-poor and Ca-rich minerals (garnet, clinopyroxene, titanite, plagioclase, and scapolite), which trapped microportions of melts as inclusions. In the course of their evolution, melts acquired some features in common with A-type granitoids (elevated contents of alkali metals, high Fe# value, elevated Nb and LREE contents, and high generation temperatures). This is consis-

tent with the data in [15] on the probable origin of A-type acid magmas from the melting of granulites.

REFERENCES

1. V. S. Sobolev, *Geol. Geofiz.*, No. 1, 7 (1960).
2. O. Knorring and W. Q. Kennedy, *Miner. Mag.* **31**, 847 (1958).
3. G. L. Millhollen, *Am. Mineral.* **59**, 618 (1974).
4. F. Goff, B. H. Arney, and A. C. Eddy, *Earth Planet. Sci. Lett.* **60**, 86 (1982).
5. E. A. Dmitriev, *Cenozoic Potassic Alkaline Rocks of the Eastern Pamir* (Donish, Dushanbe 1976) [in Russian].
6. V. S. Lutkov, *Geokhimiya* **41**, 254 (2003) [*Geochem. Int.* **41**, 224 (2003)].
7. L. H. Cohen and W. Klement, Jr., *J. Gophys. Res.* **72** (16), 42 (1967).
8. S. V. Chupin, V. P. Chupin, J. M. Barton, et al., *Eur. J. Miner.* **10**, 1241 (1998).
9. A. V. Sobolev, *Petrologiya* **4**, 228 (1996) [*Petrology* **4**, 205 (1996)].
10. V. P. Chupin and A. A. Tomilenko, *Boul. Soc. Espan. Miner.* **18** (1), 39 (1995).
11. P. Schiano and R. Clocchiatti, *Nature* **368**, 621 (1994).
12. C. Szabo, R. Bodnar, and A. Sobolev, *Eur. J. Mineral.*, No. 8, 881 (1996).
13. R. Powell, *Metamorph. Geol.*, No. 3, 327 (1985).
14. D. Perkins and R. C. Newton, *Nature* **292**, 144 (1981).
15. J. B. Whalen, K. L. Currie, and B. W. Chappell, *Contrib. Mineral Petrol.* **95**, 407 (1987).