Melt Inclusions and Chromite in Lamproites from Smoky Butte, Montana.

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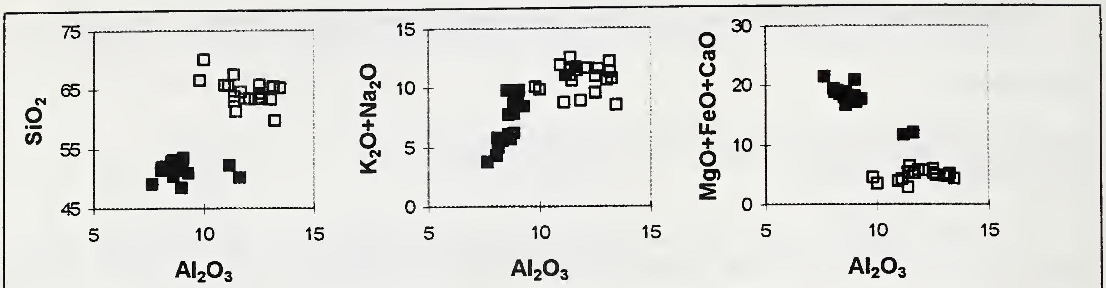
Smoky Butte is a series of thin dikes and plug-like bodies (K-Ar age - 27 Ma). All lamproites show evidence of rapid quenching and exhibit the extremely wide variation in modal abundances of phases (olivine, phlogopite, glass, leucite pseudomorphs, etc.) *(Mitchell et al., 1987).* However, two main rock varieties may be distinguished: olivine-bearing hyalolamproite and holocrystalline sanidine-bearing lamproite. Ca-Sr-Ba-carbonates, barite and davanite represent late-crystallizing phases, filling vugs in the rocks *(Velde, 1975; Wagner and Velde, 1986).* In general, all Smoky lamproites have similar chemical compositions. They are peralkaline, with high contents of K_2O (7-11 wt.%), MgO (7-9.5 wt.%), SiO_2 (48.5-53.5 wt.%), TiO_2 (5-6.5 wt.%), and P_2O_5 (up to 3 wt.%). Primary silicate-melt inclusions have been identified in minerals of both main rock varieties.

Silicate-melt inclusions in minerals

In glassy lamproites, melt inclusions (10-50 μm) were generally found in olivine-2 (Mg# - 0.82-0.86, 0.2-0.3 wt.% NiO, small grains) and in the outer zones of olivine-1 (Mg# - 0.87-0.92, 0.5-0.8 wt.% NiO, size -1-5 mm). The phase composition is glass + gas + daughter crystals (typically armalcolite and apatite, rarely diopside and priderite). In some silicate-melt inclusions hosted by olivine, the gas bubbles are partially or completely filled with carbonates (mainly, calcite). Single Cr-spinel crystals and sulfide globules (pentlandite + Ni-rich MSS ? + chalcopyrite) sometimes coexist with melt inclusions in olivine-1. Unfortunately, we were unable to homogenize the silicate-melt inclusions in both olivines due to darkening of the host at T>1250°C. The phase composition of inclusions at this temperature was liquid + armalcolite + fluid. Analcite in hyalolamproites also contain silicate-melt inclusions, but they are inherited from leucite (fresh leucite crystals was only preserved in pyroxene). Inclusions are commonly concentrically-aligned and similar to leucite-hosted inclusions in the Leucite Hills and Oscar Plug rocks *(Sobolev et al., 1975; Mitchell, 1991).*

In sanidine-bearing lamproites, silicate-melt inclusions (10-20 μm) are observed in zoned phlogopite phenocrysts and in groundmass diopside and apatite. Their phase composition is glass + gas + daughter phases. Gas bubbles sometimes contain salt phases. Single crystals of apatite, armalcolite and leucite occur in diopside and phlogopite. Homogenization of the inclusions in apatite occurred at 1220-1230°C, and of diopside-hosted inclusions - at 1160-1205°C. Melt inclusions in zoned phlogopite homogenized at temperatures ranging from 1085 to 1210°C.

The primary inclusion glasses hosted by the Smoky Butte minerals drastically differ in composition from the host rocks with respect to their SiO_2, TiO_2, MgO, Al_2O_3, CaO, and P_2O_5 contents. Residual glasses of olivine-hosted inclusions are characterized by high abundances of alkalis (9-10 wt.%), SiO_2 (63-66 wt.%), Al_2O_3 (11.5-13.5 wt.%), BaO (0.7-1.9 wt.%), ZrO_2 and F (up to 0.4 wt.%), moderate contents of TiO_2 (up to 3.6 wt.%) and femic components (MgO+FeO+CaO<6 wt.%) *(see Figure).* They are similar to groundmass glass of Smoky Butte rocks except that the contents of alkalies in the latter is typically low *(Mitchell et al., 1987).* The moderate TiO_2 contents may be explained by early crystallization of armalcolite and priderite. In sanidine lamproites, inclusion glasses in minerals slightly differ from those in hyalolamproite olivine, showing higher contents of SiO_2 (up to 70 wt.%) and TiO_2 (up to 6.5 wt.%). Raman spectroscopy of a bubble from melt inclusion in olivine-2 show that fluid is composed of CO_2 (26.6 mole %) and N_2 (73.4 mole %). Using these values and P-V-T-equations of FLINCOR program, the minimum trapping pressure for this inclusion can roughly be estimated as 1.7 kb at 1250°C.



■ rocks *(Velde, 1975; Mitchell et al, 1987)*; □ residual glasses of inclusions in minerals.

Chromite inclusions in olivine

As described above, the Cr-spinel inclusions form independent euhedra (up to 30 μm) in olivine-1 only. Single crystals have homogeneous composition and are characterized by high Cr_2O_3 (53-56 wt.%), TiO_2 (4.5-5.7 wt.%), NiO (0.1-0.5 wt.%), $Fe^{2+}/(Fe^{2+}+Fe^{3+})$=0.7-0.8, moderate $Mg/(Mg+Fe^{2+})$=0.4-0.6 and low Al_2O_3 (1.8-2.9 wt.%) *(see Table)*. Calculations based on *Fabries (1979)* and *Ballhaus et al. (1991)* show that equilibrium temperature ranges from 867 to 1106°C for the chromite-olivine pair and fO_2 values are above QFM buffer on 1-2 log. unit.

On the basis of petrological evidence, the Smoky Butte lamproites are interpreted to represent rocks formed from primitive relatively SiO_2-rich mantle-derived magma. This magma ascended rapidly and crystallized at high temperature *(Mitchell et al., 1987)*. The presence of armalcolite, and also sulfide globules and Cr-spinel with low Fe^{3+} content evidence the reduced state for initial magma at its early crystallization stages. According to experiments of *Friel et al. (1977)* and *Medvedev (1996)*, armalcolite is stable at low fO_2 ($<10^{-9.5}$ atm) and T>1200°C. Thus, the initial magma during the early crystallization of the Smoky Butte lamproites (before sanidine formation) was near peralkaline and evolved towards gradual depletion in P_2O_5, TiO_2, CaO, MgO, FeO with enrichment in SiO_2, alkalis, Al_2O_3, BaO, ZrO_2 *(see Figure)*. Probably, mass crystallization of sanidine led to the increase of alkalis, BaO, CaO, FeO, MgO, TiO_2 and the decrease of Al_2O_3 in residual melt. This evolutionary trend resulted in formation of K-Ti-richterite, magnesioarfvedsonite and davanite on the late stages. In the course of evolution, fluid acquired progressively higher contents of salt components that led to late-magmatic or post-magmatic crystallization of Ca-Ba-Sr-carbonates and barite. In general, evolution of initial magma for the Smoky Butte rocks is similar to that of melts parental for lamproites from W.Kimberley, Leucite Hills and other localities *(Sobolev et al., 1989; Solovova et al., 1989; Salvioli-Mariani and Venturelli, 1996; Sharygin, 1997)*.

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Table.
Chemical composition (wt.%) of chromite inclusions and host olivines from glassy lamproites at Smoky Butte (Montana).

n	2	1	1	1	1	1	1	2	2	3	2
Cr-spinel											
TiO_2	4,84	5,18	4,78	4,70	4,80	5,70	4,65	4,75	4,87	4,66	4,63
Cr_2O_3	54,56	53,74	55,44	54,30	54,67	52,86	54,25	55,56	55,45	54,97	55,78
V_2O_3	0,12	0,18	0,13	0,15	0,16	0,22	0,14	0,12	0,15	0,13	
Al_2O_3	2,57	1,81	2,82	2,62	2,68	1,74	2,66	2,73	2,86	2,68	2,51
FeO_t	25,95	29,55	21,91	26,76	24,31	27,86	24,75	21,68	21,76	24,68	22,80
MnO	0,21	0,32	0,10	0,24	0,14	0,25	0,17	0,11	0,10	0,20	0,19
MgO	10,27	8,19	12,97	9,42	11,53	9,52	11,35	13,47	13,00	11,06	13,04
NiO	0,28	0,13	0,42	0,25	0,40	0,30	0,44	0,47	0,42	0,37	0,46
ZnO	0,18	0,19	0,10	0,22	0,15	0,22	0,19	0,10	0,16	0,15	
Total	98,96	99,28	98,67	98,66	98,84	98,68	98,59	98,98	98,75	98,90	99,41
FeOcal	20,26	23,77	16,07	21,30	18,26	21,86	18,22	15,31	16,07	18,83	15,99
Fe_2O_3cal	6,32	6,43	6,50	6,07	6,72	6,67	7,25	7,08	6,32	6,51	7,57
$Mg/(Mg+Fe^{2+})$	0,47	0,38	0,59	0,44	0,53	0,44	0,53	0,61	0,59	0,51	0,59
$Fe^{2+}/(Fe^{2+}+Fe^{3+})$	0,78	0,80	0,73	0,80	0,75	0,78	0,74	0,71	0,74	0,76	0,70
$Cr/(Al+Cr+V+Fe^{3+}+Ti)$	0,79	0,79	0,79	0,79	0,78	0,78	0,78	0,78	0,79	0,79	0,78
$Al/(Al+Cr+V+Fe^{3+}+Ti)$	0,06	0,04	0,06	0,06	0,06	0,04	0,06	0,06	0,06	0,06	0,05
$Fe^{3+}/(Al+Cr+V+Fe^{3+}+Ti)$	0,09	0,09	0,09	0,08	0,09	0,09	0,10	0,09	0,09	0,09	0,10
Host olivine											
Fo	89,52	88,29	88,58	88,22	90,16	87,55	87,74	90,98	88,84	89,24	90,84
Fa	9,43	10,96	10,44	10,91	8,82	11,57	11,45	8,05	10,29	9,77	8,22
Mn_2SiO_4	0,15	0,17	0,18	0,19	0,14	0,22	0,18	0,11	0,16	0,16	0,10
Ca_2SiO_4	0,17	0,21	0,22	0,22	0,18	0,22	0,19	0,16	0,17	0,17	0,13
Ni_2SiO_4	0,73	0,38	0,58	0,46	0,69	0,44	0,45	0,71	0,55	0,66	0,70
T, °C *	1145	867	1106	920	960	952	1055	1038	1097	971	1027
DlogfO_2 **	1,09	1,45	1,15	1,23	1,70	1,34	1,28	1,81	1,13	1,45	1,91

* - *Fabries, 1979;* ** - *Ballhaus et al., 1991* (values respect to QFM buffer).