LUNAR CORDIERITE-SPINEL TROCTOLITE: IGNEOUS HISTORY, AND VOLATILES.
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Marvin et al. [1] described a cordierite-bearing spinel troctolite in Apollo sample 15295,101. We are reinvestigating this sample because cordierite can contain significant volatiles (CO_2, H_2O), and because lunar spinel-rich rocks are more widespread than previously recognized [2-4]. The cordierite contains no volatile load detectable by EMP – more precise analyses are in progress. The bulk composition and textures of the troctolite are consistent with it being a partial melt of a spinel-rich cumulate, such as might have been generated in a significant impact event.

Analytical Methods. BSE imagery and chemical analyses were obtained using the SX-100 microprobes at the American Museum of Natural History and at Johnson Space Center (15 kV, 10 nA), using well-characterized natural and synthetic standards. At the AMNH, oxygen was analyzed directly (O Kα).

Petrography & Chemistry: The cordierite-bearing clast is as described [1], and we provide additional data. The clast contains (in order of abundance), plagioclase, olivine, cordierite, and Mg-Al spinel, with trace proportions of ilmenite, rutile, FeNi metal, and pyroxene. The major minerals are all in contact with each other. Spinel occurs as large euhedra (to 200 µm across; Fig. 1a), and as small euhedra (to 10 µm) scattered along a boundary among grains of plagioclase, olivine, and cordierite (Fig. 1b). Olivine and plagioclase are anhedral, and as large as 200 µm and 500 µm respectively. Cordierite occurs in two textural forms. In several fragments (Figs. 1a-c), it occurs as rounded and elongate masses within plagioclase and along grain boundaries. In one fragment cordierite appears to form euhedra embedded in plagioclase (to 100 µm; Fig. 1d).

The troctolite's minerals are chemically homogeneous [1] (Table 1): olivine, Mg*=91.5, 0.10% MnO; cordierite, Mg*=96, 0.01% MnO; ilmenite, Mg*=38, 0.00% MnO; spinel, Mg*=80, Al/(Al+Cr)=0.88, 0.08% MnO; and An_{95} plagioclase. The metal is nearly equimolar Fe-Ni, with ~1.5-3% molar Co [1], and Ni/Co ~20. By EMP, cordierite contains insignificant O beyond that required by stoichiometry with analyzed cations: 0.5±0.7% wt (1σ) [5]. However, plagioclase analyses give a similar oxygen excess, suggesting that the real excess O in cordierite is ~0.0±0.7% wt. EMP analyses for C were dominated by signal from the carbon coating. Thus, the cordierite cannot contain much H_2O, CO_2, or CO. FTIR analyses are in progress.

Metamorphism: The conditions of metamorphism for the crd-troct are important for understanding its history and origin [1,6]. T of equilibration can be estimated from Fe/Mg distribution thermometers between: olivine and spinel, ~720°C [7], 590°C [8], and 690±~20°C [9]; and olivine and ilmenite, ~540°C [10], and ~410°C [11]. We take the equilibrium T=700°C from the olivine-spinel formulae of [7,9], which are calibrated at relevant Al/(Al+Cr) from natural samples. The lower T for olivine-ilmenite may reflect re-equilibration [10].

Equilibration pressure is constrained imprecisely. The presence of cordierite (not orthopyroxene)

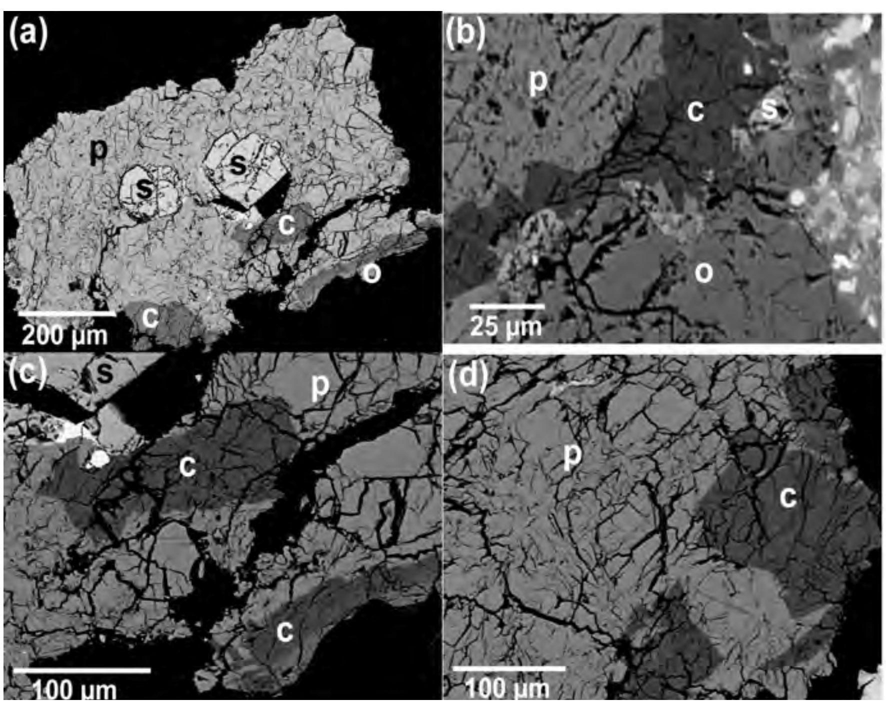

Fig. 1. BSE images of cordierite-troctolite in 15295,101. Minerals are: c, cordierite; p, plagioclase; s, spinel; o, olivine. (a) Largest fragment (Fig. 1a of [1]). Two spinel euhedra and many cordierite anhedra in plagioclase. Brightest-tone grains are ilmenite and rutile. (b) Cordierite and spinel on a grain boundary between plagioclase and olivine (Fig. 1d of [1]). (c) Detail of Fig. 1a, showing anhedral, rounded cordierite in plagioclase. (d) Cordierite grains with linear boundaries in plagioclase.

$$5Mg_2SiO_4 + Mg_2Al_4Si_5O_{18} \Leftrightarrow 5Mg_2Si_2O_6 + 2MgAl_2O_4$$

forsterite + cordierite = (Al)orthopyroxene + spinel

with the observed mineral compositions requires P < 0.15 GPa (calculated with THERMOCALC 3.33 [12]), or <0.25 GPa for H_2O-saturated cordierite [see 13-16]. Another potential P constraint is [6]

$$2MgAl_2O_4+10TiO_2+5Mg_2SiO_4 \Leftrightarrow 10MgTiO_3+Mg_2Al_4Si_5O_{18};$$

spinel rutile olivine geikeilite cordierite;

its location was calculated as above [12]. The activity of geikeilite is ~0.5 [17], which suggests an equilibration P of 0.1±0.1 GPa for 700°C and 0.0±0.1 GPa at 540°C. However, uncertainty in the activity of geikeilite is so large [18] that this reaction is not yet a useful pressure constraint [6].

Origin of Cordierite: The cordierite-troctolite is lunar, with Fe/Mn = 80 in olivine [19], and probably is pristine (Fe-Ni-Co metal unlike those in asteroidal samples [1]). Although its mineral compositions reflect post-formation metamorphism (above), its bulk composition and textures provide clues to its origin [1].

The bulk composition of the cordierite troctolite [1], calculated from mineral proportions and compositions, is consistent with that of a melt saturated in spinel and plagioclase [1]. Liquidus relations in another projection (Fig. 2) show that the bulk composition is consistent with that of a melt cosaturated in spinel + anorthite + olivine (spinel saturation contours

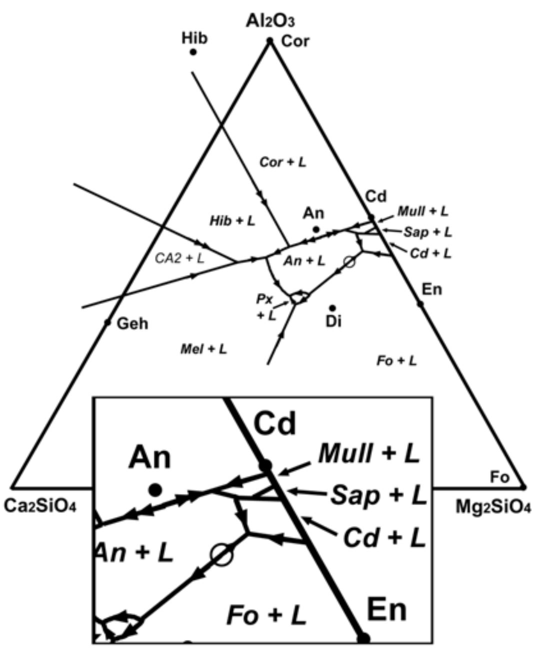

Fig. 2. Spinel-saturated liquidus surfaces in CMAS, projected from spinel ($MgAl_2O_4$) [20,21]. Phases are: L, liquid; Cor, corundum; Hib, hibonite; An, anorthite; Cd, cordierite; CA2, $CaAl_2O_4$; Mull, mullite; Sap, sapphirine; Px, pyroxene; Geh & Mel, melilites; Fo, forsterite. Inset shows region arround the spinel-Fo-An-Cd 'eutectic' (a piercing point). Circle is bulk composition of cordierite-troctolite.

[21] not shown). This special composition suggests that the cordierite-trocolite may have formed as a partial melt of a spinel troctolite cumulate. A melt from pure spinel + anorthite + forsterite would not produce cordierite, so the cumulate must have contained another component, perhaps aluminous enstatite.

Texures are consistent with the cordierite troctolite having crystallized from melt. The large spinels and massive plagioclase and olivine would have formed during crystallization along the sp-pl-ol cotectic, and the cordierite and small spinels would have grown (with pl and ol) at the sp-pl-ol-cd 'eutectic,' Fig. 2.

Geological Setting: New data on lunar spinel-rich rocks suggest a possible geological setting for the of the cordierite troctolite. Spinel-rich rocks may be widespread in the lunar crust where picritic magmas assimilated anorthositic rock [3], and spinel-rich rock has been located along the rims of major basins and in craters' central peaks [2,4]. If a spinel-rich mesocumulate rock were in the target of a significant impact, heat of the impact and pressure release (as from central peak uplift) could have partially melted the cumulate, and that partial melt could have been drawn off into an intrusion or into impact melt. This partial melt could then crystallize to rocks like the cordierite-spinel-troctolite.

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