TISSINTITE-II AND OTHER HIGH PRESSURE / HIGH TEMPERATURE MINERALS IN LUNAR METEORITE NORTHWEST AFRICA 13967.

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Introduction: Lunar meteorite Northwest Africa (NWA) 13967 is a 252 g shock-lithified, feldspathic breccia. The presence of spherule fragments indicates it was part of the lunar regolith. Abundant tissintite and corundum occur in its glassy groundmass [1]. Since tissintite [2] and its Fe, Mg, and Cr-enriched variant tissintite-II [3] were first identified in the Tissint and Zagami martian meteorites, these phases have been used to study temperature and pressure conditions of impacts. Recently, [4] studied nine lunar meteorites from this perspective. We investigated the mineral inventory of NWA 13967 to further constrain the conditions of its formation as a lunar regolith breccia.

Sample & Methods: Our sample of NWA 13967 is a 18 × 17 mm epoxy-encapsulated, polished mount. To explore its mineral inventory, we used a JEOL JXA-8530F electron microprobe (EMP) and a custom-built Raman spectrometer at Arizona State University. For quantitative analyses, the EMP was operated with 15 kV, 15 nA and a 5 µm electron beam diameter. Raman spectra were taken with exposure times between 10 and 30 seconds to a 532 nm, 6 mW laser power.

Results: *Tissintite-II.* In NWA 13967, tissintite-II commonly occurs in the glassy groundmass in tens of µm-wide regions in-between flow-textured, vitric melt and entrained clasts (Fig. 1A-B). All tissintite-II appears as angular <10 µm shards. Contrary to its occurrence as partially converted maskelynite in Tissint [2], NWA 13967 tissintite-II is enriched in FeO and MgO and grew from impact melt; this is similar to the occurrence of this mineral in Zagami [3] and nine impact-melt rich lunar meteorites [4] (Table 1). Raman spectroscopy indicates that tissintite-II coexists with anorthite in places (Fig. 2).

Corundum. Corundum occurs as up to 1 µm solitary crystals with skeletal shapes in glassy to cryptocrystalline, flow-textured impact melt (Fig. 1A,C). Semi-quantitative EDS analyses confirm high Al_2O_3 contents and their appearance is very similar to Si-rich corundum crystals in lunar meteorites NWA 2995 and NWA 10203 [3].

Olivine. Magnesian olivine clasts [Fo_{89-95}, n=19] entrained in impact melt show patchy, irregular textures in BSE images (Fig. 1B), yet Raman spectroscopy on 4 such clasts only indicates olivine.

Silica. We identified ~5 × 15 µm coesite regions associated with moganite and quartz in a SiO_2 clast entrained in impact melt by Raman spectroscopy.

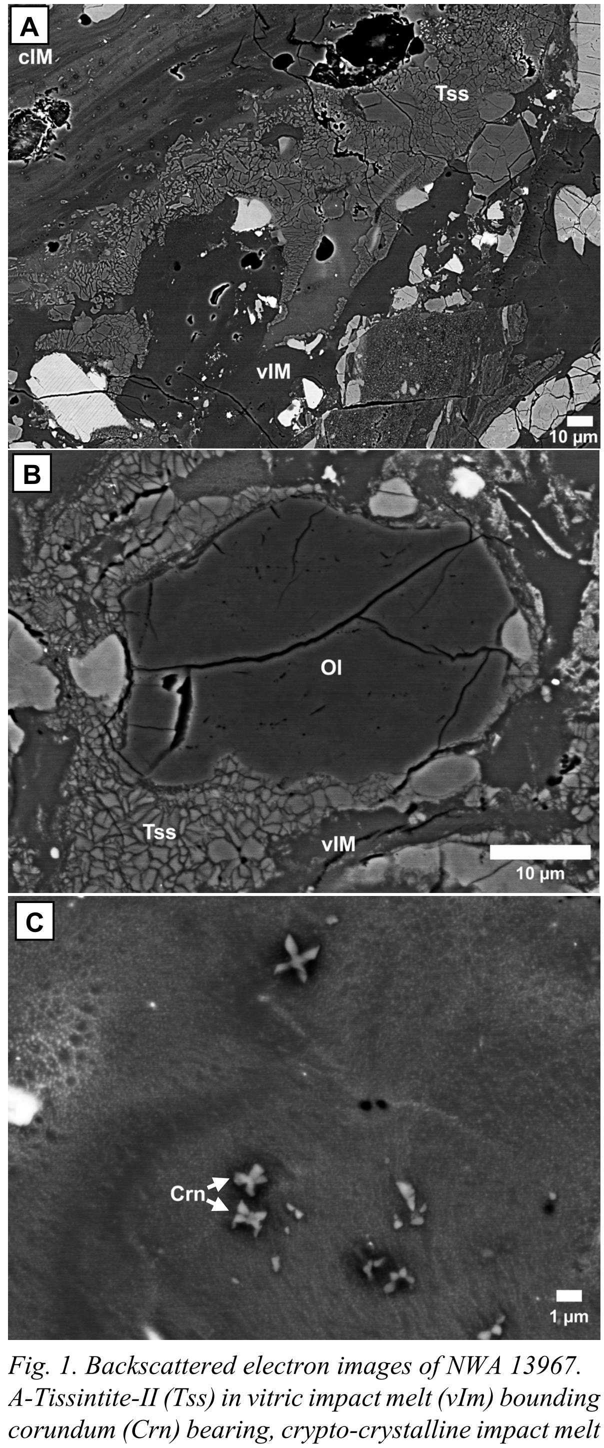

Fig. 1. Backscattered electron images of NWA 13967. A-Tissintite-II (Tss) in vitric impact melt (vIm) bounding corundum (Crn) bearing, crypto-crystalline impact melt (cIM); B-magnesian olivine (Ol) clast entrained in vitric impact melt, from which Tss grew; C- Crn in cIM.

Table 1. Tissintite-II electron microprobe data.

Sample (no. analyses)		NWA 13967 (n=16)	NWA 2995† (n=12)	Tissint‡ (n=9)	Zagami◆ (n=13)
SiO_2	[wt%]	45.09 ± 0.43	44.83 ± 0.40	53.0 ± 0.3	53.64 ± 0.30
TiO_2	[wt%]	0.15 ± 0.02	0.16 ± 0.03	0.08 ± 0.03	14.52 ± 0.86
Al_2O_3	[wt%]	29.28 ± 1.02	30.73 ± 0.65	29.2 ± 0.3	10.42 ± 0.24
Cr_2O_3	[wt%]	0.07 ± 0.02	0.07 ± 0.02	<0.05	0.12 ± 0.04
FeO	[wt%]	3.36 ± 0.53	3.52 ± 0.20	0.96 ± 0.02	12.31 ± 0.79
MnO	[wt%]	0.04 ± 0.04	0.05 ± 0.02	<0.06	0.32 ± 0.05
MgO	[wt%]	4.80 ± 0.78	3.52 ± 0.20	0.18 ± 0.02	5.68 ± 0.42
CaO	[wt%]	17.01 ± 0.51	17.61 ± 0.42	12.5 ± 0.2	10.42 ± 0.24
Na_2O	[wt%]	0.37 ± 0.03	0.37 ± 0.04	4.7 ± 0.2	2.97 ± 0.23
K_2O	[wt%]	0.03 ± 0.01	0.03 ± 0.01	0.06 ± 0.01	0.23 ± 0.02
Sum	[wt%]	100.21 ± 0.55	100.89	100.68	100.57
Si	[afu]	1.583	1.566	1.798	1.929
Ti	[afu]	0.004	0.004	0.002	0.010
Al	[afu]	1.212	1.265	1.168	0.616
Cr	[afu]	0.002	0.002	b.d.	0.003
Fe	[afu]	0.099	0.183	0.027	0.370
Mn	[afu]	0.001	0.001	b.d.	0.010
Mg	[afu]	0.251	0.103	0.009	0.304
Ca	[afu]	0.640	0.659	0.454	0.401
Na	[afu]	0.025	0.025	0.309	0.207
K	[afu]	0.001	0.001	0.003	0.011
Sum	[afu]	3.819	3.810	3.771	3.861

†Mg,Fe-bearing type [4]; ‡wormy type [2]; ◆[3].

Discussion: We describe tissintite-II from the fused particulate regolith groundmass of lunar meteorite NWA 13967 (Fig. 1A-B, Table 1). The average shock pressure for NWA 13967 likely was below 24 GPa, the transition pressure for the full transformation of anorthite to maskelynite at 20 °C [5]. Smooth clasts with anorthite composition associated with the impact melted groundmass of NWA 13967 likely represent maskelynite; in contrast, fractured feldspar crystals in mm-size clasts are likely to be anorthite. Comparison with shock experiments on lunar soil suggests the amount of intergranular melt and vesicles in NWA 13967 corresponds to moderate shock lithification at shock pressures of ~18–25 GPa [6]. Tissintite-II described from shock melt veins in the Zagami meteorite [3] formed during decompression from an average shock pressure of ~30 GPa [7].

The occurrence of tissintite-II in impact melt regions close to mm-size clasts indicates growth during rapid quenching from >2000 °C based on the presence of corundum [4]. While tissintite-II is ubiquitous in NWA 13967, we did not observe tissintite that grew from maskelynite. Nucleation kinetics are slower for tissintite that forms from sodic plagioclase compared to calcic plagioclase [2,8]. Moreover, the experimental formation of tissintite assemblages below 10 GPa and temperatures of 1000 °C is sensitive to quench times and heating durations [8]. While we cannot rule out that small fragments of anorthite clasts were retained in the impact melt and contributed a Raman signal, it seems more plausible that anorthite growth succeeded tissintite during decompression below 5 GPa [8]. The presence of coesite in SiO_2 clasts entrained in impact melt may indicate nucleation during decompression. Alternatively, only a small portion of coesite may have survived quenching from >2000 °C, while most coesite reverted to microcrystalline moganite/quartz. Likewise, wadsleyite, which would be expected to occur along Mg_{89} olivine in the P-T regime of 12–14 GPa and 1200–1600 °C [9] or stishovite, which would be expected to form at P-T of 9–12 GPa and ~1200–1600 °C [10], has not been found in NWA 13967 or other tissintite-II-bearing lunar regolith breccias [4]. This could mean that the impact-fused groundmass of NWA 13967 did not experience pressures >~9 GPa [4] or that during quenching, the metastable stishovite and wadsleyite reverted to quartz/moganite and olivine, respectively.

Conclusions: The high-pressure and high-temperature mineral assemblage in regolith breccia NWA 13967 likely records rapid quenching and decompression from moderate shock lithification during its launch from the Moon [6].

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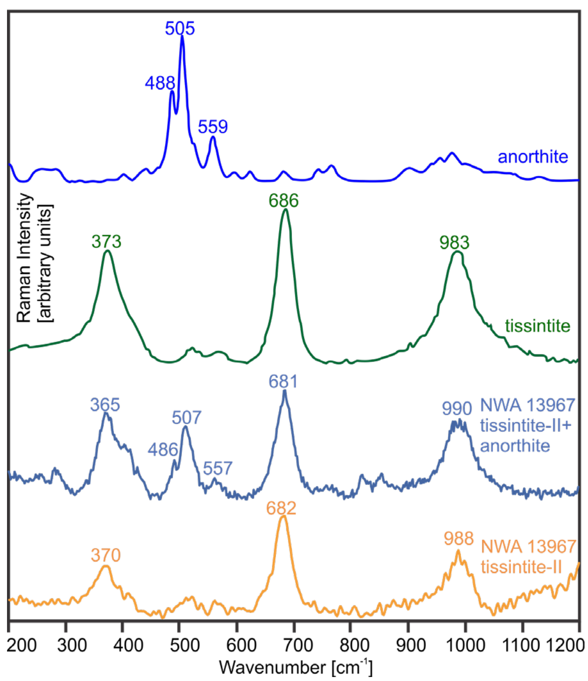

Fig. 2. Raman Data.
Representative Raman spectra for tissintite-II in lunar meteorite NWA 13967. Anorthite and tissintite reference spectra are from [4].