

**PETROLOGY AND EJECTION HISTORY OF LUNAR PINK SPINEL-BEARING IMPACT MELT ROCK NORTHWEST AFRICA 10228.** Axel Wittmann<sup>1</sup>, Anthony J. Irving<sup>2</sup>, Kunihiro Nishiizumi<sup>3</sup>, Marc W. Caffee<sup>4</sup>, and A. J. Timothy Jull<sup>5</sup>, <sup>1</sup>EMC, Arizona State University, Tempe, AZ 85287, USA, [awittmal@asu.edu](mailto:awittmal@asu.edu); <sup>2</sup>Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA; <sup>3</sup>Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA, <sup>4</sup>Department of Physics, Purdue University, W. Lafayette, IN 47906, USA; <sup>5</sup>Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA.

**Introduction:** Northwest Africa 10228 is a 19.4 g lunar meteorite that was recovered in Morocco in 2015 and has been classified as a “lunar feldspathic melt-matrix breccia” [1]. Based on chemical and petrographic observations, [2] suggested NWA 10228 could be paired with the NWA 8455 group that also includes La’gad, NWA 8607, 8609, 8651, 8668, 8727, 8783, 10130, 10621, 10953, and three unnamed lunar stones [3].

Mg-rich, pink spinel occurs in our thin section of NWA 10228 (Fig. 1A-B) but such spinel has not been noted as a constituent in any of its purported paired stones. Mg-rich spinel assemblages can record P-T equilibration conditions [4-5], and the excavation and impact melting of lunar mantle rocks [6-7].

**Sample and Methods:** We analyzed a  $2.1 \times 1.5$  cm thin section of NWA 10228 with the optical microscope and a JEOL JXA-8530F electron microprobe at Arizona State University’s Eyring Materials Center. For the analysis of spinel assemblages, we used the approach of [6], and the analytical protocol of [8] for high resolution Ni, Ca, Co, and Mn analyses of olivine.

The cosmogenic radionuclides <sup>10</sup>Be (half-life 1.36 Myr), <sup>26</sup>Al (0.705 Myr), and <sup>36</sup>Cl (0.301 Myr) in NWA 10228 were measured by AMS at Purdue University’s PRIME Lab [9] along with proposed paired meteorites NWA 8668, NWA 10130, and La’gad. The major element compositions of those samples were measured by ICP-OES. Concentration of <sup>14</sup>C (half-life 5,730 yr) in NWA 8668 and NWA 10130 were measured by AMS at the University of Arizona [10].

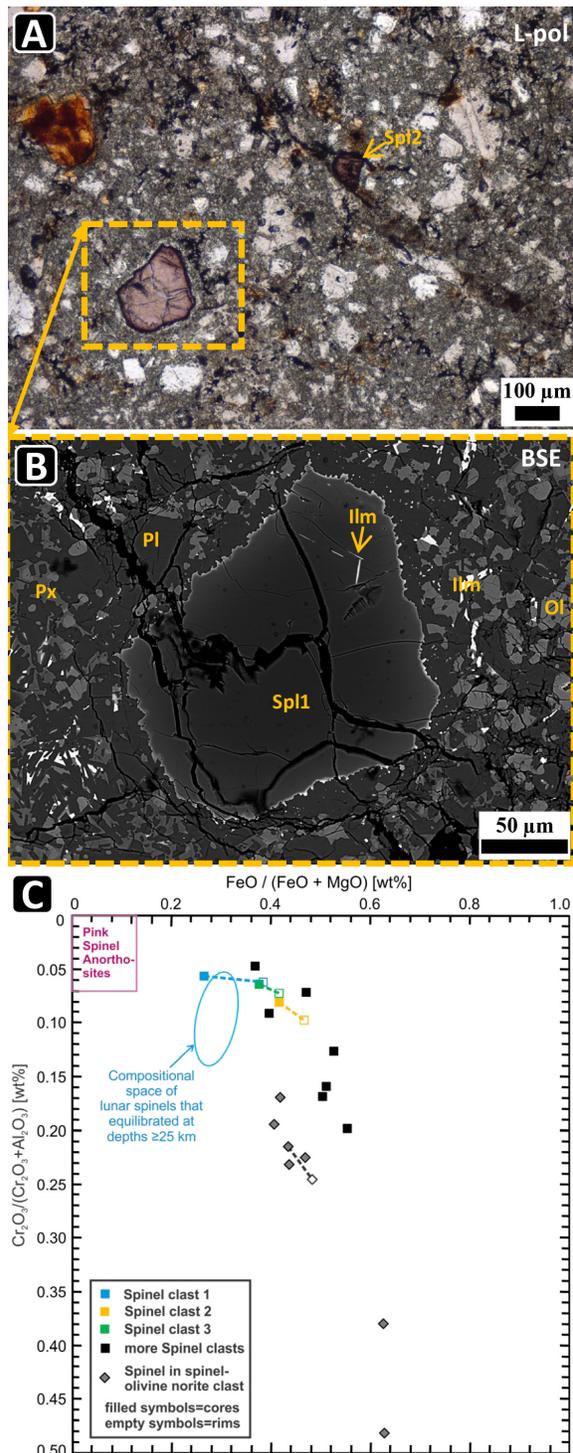
**Results: Petrography:** NWA 10228 is a very fine-grained, clast-rich impact melt rock composed of euhedral plagioclase and subhedral olivine phenocrysts that are poikilitically enclosed by late, interstitial pigeonite-augite. Accessory phases include up to 100  $\mu$ m troilite and Fe,Ni-metal intergrowths, e.g. a single 400  $\mu$ m kamacite inclusion; ilmenite that is in places intergrown with ZrO<sub>2</sub>, armalcolite, and rutile; SiO<sub>2</sub>; and Ce-rich merrillite intergrown with chlorapatite.

**Fig. 1. Mg-rich spinel in lunar meteorite NWA 10228.**

**A** Clast-rich impact melt rock NWA 10228, linear-polarized light micrograph (L-pol);

**B** Spinel clast 1, back-scattered electron image (BSE);

**C** Fe# vs Cr# spinel plot, modified after [6].



Clasts include up to 2 mm anorthite, up to 0.5 mm olivine [F<sub>072-79</sub>; 140–310 ppm Ca, 30–100 ppm Cr, <34 ppm Ni, 120–190 ppm Co], and a 1.7 × 1.3 mm fine-grained spinel-olivine norite [Ab<sub>4-8</sub>An<sub>91-96</sub>Or<sub>0-1</sub>; F<sub>077-85</sub>, 140–200 ppm Ca, 40–140 ppm Cr, 40–100 ppm Ni, 90–210 ppm Co; En<sub>49</sub>Fs<sub>8-9</sub>Wo<sub>42-43</sub>, En<sub>75-83</sub>Fs<sub>13-18</sub>Wo<sub>4-10</sub>, 1.4–3.1 wt% Al<sub>2</sub>O<sub>3</sub>; Mg<sub>(0.68-0.78)</sub>Fe<sub>(0.24-0.36)</sub>Al<sub>(1.58-1.76)</sub>Cr<sub>(0.21-0.33)</sub>]. Glassy shock melt veins frequently cross-cut NWA 10228's melt rock fabric. Few fractures are filled with (terrestrial?) calcite.

**Spinel assemblages:** We characterized 22 spinel assemblages of up to 200 μm clasts (Fig. 1A–B) but more commonly small, ca. 20 μm, partly assimilated atoll or necklace assemblages surrounded by plagioclase in spinel-olivine norite or anorthositic spinel troctolite clasts. Most spinel is zoned with Mg-rich cores [Mg<sub>(0.74-0.86)</sub>Fe<sub>(0.17-0.28)</sub>Al<sub>(1.84-1.90)</sub>Cr<sub>(0.07-0.13)</sub>] and Fe- and Cr-rich rims. Only three of the grains show faint planar fractures suggesting a shock metamorphic overprint of <20 GPa [6]. The only enstatite we found is associated with the spinel-olivine norite clast, and its forsteritic olivine is notably enriched in Ni compared to other olivine clasts in NWA 10228. Some of the spinel analyses plot close to the field of deeply seated Mg-spinel assemblages (Fig. 1C). Applying the thermodynamic equilibrium calculations of [4] for the spinel-olivine norite clast assemblage, we find a minimum depth of equilibration of 16.5 km in the Moon; the core composition of the largest spinel clast in our thin section of NWA 10228 yields a minimum depth of equilibration of 24.7 km in the Moon.

**Cosmogenic radionuclides:** The concentrations of Mg, Al, Ca, Mn, and Fe in four lunar meteorites are shown in Table 1, and the concentrations of the cosmogenic radionuclides <sup>10</sup>Be, <sup>26</sup>Al, <sup>36</sup>Cl, and <sup>14</sup>C (dpm/kg) in these stones are shown in Table 2.

**Table 1.** Chemical composition of four lunar meteorites.

	Mg (%)	Al (%)	Ca (%)	Mn (ppm)	Fe (%)
NWA 8668	5.13	12.57	10.11	512	4.59
NWA 10130	5.07	12.04	9.74	538	4.94
NWA 10228	5.15	11.92	9.45	530	4.72
La'gad	5.42	10.50	9.10	927	7.37

**Discussion:** Recently, we explored upper mantle and impact-melt origins for some pink spinel-bearing lunar lithologies [6]. Ni, Mn, and Cr concentrations in NWA 10228 olivine clasts fall in the range of SIMS analyses of Apollo troctolite olivine [11]. NWA 10228 spinel-olivine norite clast spinel compositions are most similar to Luna 20 spinel troctolite [12]. The largest spinel clast's core composition falls just outside the compositional range for deep-seated lunar spinel and is most close in composition to a Dho 1528 spinel that indicates equilibration at a depth of 34 km in the Moon

**Table 2.** Cosmogenic radionuclide concentrations (dpm/kg) of four lunar meteorites.

	<sup>10</sup> Be	<sup>26</sup> Al	<sup>36</sup> Cl	<sup>36</sup> Cl*	<sup>14</sup> C
NWA 8668	0.302 ± 0.004	1.72 ± 0.09	0.441 ± 0.019	0.51 ± 0.02	2.0 ± 0.1
NWA 10130	0.294 ± 0.004	1.95 ± 0.08	0.443 ± 0.019	0.52 ± 0.02	3.6 ± 0.2
NWA 10228	0.224 ± 0.004	1.99 ± 0.06	0.67 ± 0.03	0.82 ± 0.03	
La'gad	0.261 ± 0.004	1.90 ± 0.06	0.599 ± 0.015	0.74 ± 0.02	

\* dpm <sup>36</sup>Cl/kg(16K+8Ca+Fe)

(Dho 1528 Sp14 in [6]; Fig. 1C). Our tentative depth of equilibration constraints for the NWA 10228 spinel assemblages likely relate to an impact-melted lithology that retains a partial record of a deep-seated origin. The poikilitic texture of the fine-grained impact melt rock suggests crystallization in a melt body on the order of 100 m thick [13]. Launch from the lunar surface likely produced the glassy shock melt veins in NWA 10228 but did not impart an equilibrium shock pressure larger than ~20 GPa because plagioclase is not completely transformed to diaplectic glass.

Nearly identical chemical compositions and cosmogenic nuclide concentrations of NWA 8668 and 10130 indicate they are paired. Based on <sup>10</sup>Be, <sup>26</sup>Al, and <sup>36</sup>Cl concentrations, NWA 8668 and 10130 were ejected from ~740 g/cm<sup>2</sup> depth on the Moon and their transition time from the Moon to Earth was >300 yr but shorter than 10<sup>4</sup> yr. The ejection depth of NWA 10228 was deeper than 1,000 g/cm<sup>2</sup> and the transition time was ~(20±2) × 10<sup>4</sup> yr, indicating NWA 10228 was not paired with NWA 8668 and 10130. Chemical compositions and <sup>36</sup>Cl concentrations also suggest La'gad is not paired with the other three lunar meteorites (Table 2).

**References:** [1] Irving A. J. & Kuehner S. M. 2017. *In*: Bouvier A. et al. (eds.), Meteoritic Bulletin #104, MAPS 52, 2284. [2] Korotev R. L. & Irving A. J. 2016. LPSC 47, abstract # 1358. [3] <http://meteorites.wustl.edu/lunar/stones/nwa8455.htm>. [4] Herzberg C. T. & Baker M. B. 1980. *In*: Proceedings of the Conference on the Lunar Highlands Crust, Papike J. J. & Merrill R. B. (eds.), Pergamon, 113–132. [5] Nazarov M. A. et al. 2011. *Petrology* 19, 13–25. [6] Wittmann A. et al. 2019. MAPS 54, 379–394. [7] Treiman A. H. et al. 2019. *Am. Min.* 104, 370–384. [8] Sobolev A. V. et al. 2007. *Science* 316, 412–417. [9] Sharma P. et al. 2000. *NIM Phys. B* 172, 112–123. [10] Jull A. J. T. et al. 1998. *GCA* 62, 3025–3036. [11] Shearer C. K. & Papike J. J. 2005. *GCA* 69, 3445–3461. [12] Brett R. et al. 1973. *GCA* 37, 761–773. [13] Wittmann A. et al. 2019. MAPS 54, 2167–2188.