

**AN ENIGMATIC SODIC FERROGABBROIC ACHONDRITE FROM MOROCCO CONTAINING ZIRCONOLITE, BADDELEYITE, FLUORAPATITE AND COPPER SULFIDES.** A. J. Irving<sup>1</sup>, S. M. Kuehner<sup>1</sup>, K. Ziegler<sup>2</sup>, R. M. Conrey<sup>3</sup>, R. L. Korotev<sup>4</sup>, L. Huber<sup>5</sup>, M. Riebe<sup>5</sup>, R. Wieler<sup>5</sup>, K. Nishiizumi<sup>6</sup>, M. W. Caffee<sup>7</sup>, D. E. Moser<sup>8</sup>, I. Barker<sup>8</sup> and R. Chaoui<sup>1</sup> Dept. of Earth & Space Sciences, University of Washington, Seattle, WA 98195 ([irving@ess.washington.edu](mailto:irving@ess.washington.edu)), <sup>2</sup>Institute of Meteoritics, University of New Mexico, Albuquerque, NM, <sup>3</sup>GeoAnalytical Laboratory, Washington State University, Pullman, WA, <sup>4</sup>Dept. of Earth & Planetary Sciences, Washington University, St. Louis, MO, <sup>5</sup>Institut für Geochemie und Petrologie, ETH Zürich, Switzerland, <sup>6</sup>Space Sciences Laboratory, University of California, Berkeley, CA, <sup>7</sup>Dept. of Physics, Purdue University, Lafayette, IN, <sup>8</sup>ZAP Lab, Dept. of Earth Sciences, Western University, London, Ontario, Canada.

**Introduction:** A dense, dark brown, ellipsoidal 304 gram stone was found by a nomad in February 2013 while searching in the strewnfield of the Tissint shergottite fall, 24 km south of Tanzrou, Morocco (altitude 382 meters). After testing, the same place was searched again resulting in the discovery of two smaller stones plus ~40 grams of slightly magnetic fragments within an area of several square meters. All stones lack any fusion crust but have a thin desert varnish patina, and the fresh interior of the largest stone revealed by wire-sawing is dark gray and exhibits some preferred orientation of elongated, subhedral to euhedral crystals.



**Figure 1.** The 304 g stone. Brown knobby features are large, irregularly-distributed Fe-Ti oxide grains with desert patina coatings. Photo © R. Chaoui.

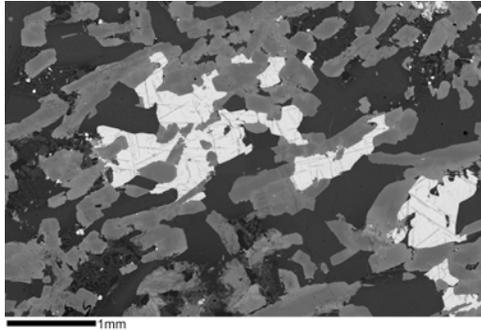
**Noble Gases and Cosmogenic <sup>10</sup>Be:** Two ~50 mg subsamples both show the presence of terrestrial atmospheric Ne and (presumably) atmospheric Ar, but no solar wind or other trapped Ne component. Both samples contain small but discernible excesses of <sup>21</sup>Ne (<sup>21</sup>Ne/<sup>20</sup>Ne being almost twice the atmospheric ratio in one), and small but measurable amounts of <sup>3</sup>He were found in one sample (the other <sup>3</sup>He analysis failed). Interpreting the <sup>3</sup>He and <sup>21</sup>Ne<sub>exc</sub> as cosmic-ray products acquired on Earth would yield minimum exposure ages (ignoring erosion) on the order of many million years for irradiation at the find site, and still on the order of a million years if irradiated at high altitudes in the Atlas Mountains. This seems implausible. Assuming the <sup>21</sup>Ne<sub>exc</sub> to be nucleogenic from the reaction <sup>18</sup>O(n,α)<sup>21</sup>Ne would result in a <sup>21</sup>Ne<sub>nuc</sub> retention age of

about 600 and 2000 Ma for the two subsamples – much higher than the K-Ar age (see below) – and would imply implausibly high <sup>21</sup>Ne<sub>nuc</sub>/<sup>4</sup>He<sub>rad</sub> ratios [1]. This strongly suggests that the <sup>3</sup>He and <sup>21</sup>Ne<sub>exc</sub> were produced by cosmic rays in space. Corresponding exposure ages (assuming a meteoroid size of 10-50 cm, cf. [2]) are on the order of 3,000-10,000 years for one sample and about 3 times less for the other; this difference could result from target elemental inhomogeneity.

The very low <sup>10</sup>Be concentration (0.0039±0.0001 dpm/kg) is consistent with an exposure age of 350±40 years (assuming no terrestrial contamination and 10-30 cm radius in space). <sup>26</sup>Al and <sup>36</sup>Cl measurements are in progress. The amounts of radiogenic <sup>4</sup>He and <sup>40</sup>Ar in concert with the measured abundances of U, Th and K document a relatively young event (~100 Ma ago).

**Petrography:** The rock is a medium to coarse grained ferrogabbro (some grains up to 1.5 mm long by 0.6 mm wide) with an intersertal texture (see Figure 2), and is composed of ~41 vol.% prismatic grains of zoned clinopyroxene (subcalcic augite  $\text{Fs}_{27.6-48.4}\text{Wo}_{35.1-32.5}$ , FeO/MnO = 43-53 and ferropigeonite  $\text{Fs}_{63.7}\text{Wo}_{14.4}$ , FeO/MnO = 46), with broad rims of orthopyroxene ( $\text{Fs}_{71.3}\text{Wo}_{3.4}$ , FeO/MnO = 52) and ~56 vol.% lath-like grains of birefringent, twinned plagioclase ( $\text{An}_{55.6}\text{Or}_{1.8}$ ) plus ~3 vol.% large (to 1.2 mm) grains of iron-titanium oxides (ulvöspinel with ilmenite exsolution lamellae).

Accessory phases are fayalite ( $\text{Fa}_{86.6-89.7}$ , FeO/MnO = 75-86), silica polymorph, apatite, baddeleyite, zirconolite, zircon, monazite, Cu-Fe sulfide (chalcopyrite or cubanite), Cu monosulfide (possibly digenite), pyrrhotite, and interstitial K-feldspar+silica symplectitic intergrowths. Apatite contains 3.7 wt.% F, 0.2 wt.% Cl and no detectable S, but by difference could contain very minor hydroxyl in the X crystallographic site. Ulvöspinel contains 20 wt.% TiO<sub>2</sub>, 2.0 wt.% Al<sub>2</sub>O<sub>3</sub>, 3.0 wt.% V<sub>2</sub>O<sub>3</sub> and 70.7 wt.% total iron as FeO, with FeO/MnO = 220; the oxide sum deficiency implies the presence of some Fe<sub>2</sub>O<sub>3</sub> as magnetite component. Grain boundaries among all mineral phases are notably sharp and devoid of secondary minerals (in marked contrast to the presence of hydrous deuteric phases in typical terrestrial hypabyssal/plutonic gabbroic rocks).



**Figure 2.** BSE image of the specimen showing exsolved Fe-Ti oxides (bright with gray ilmenite lamellae), zoned pyroxenes (medium to lighter gray) and plagioclase (black). Tiny, very bright grains are mainly copper sulfides, baddeleyite and zirconolite.

A preliminary survey of Zr-rich and other accessory grains utilizing EBSD and CL techniques shows that all three Zr-rich phases have concentric igneous compositional zoning, and that the zirconolite is very Th-rich. No shock-related microstructures were detected.



**Figure 3.** CL image of igneous zoning in a 6 micron diameter zircon. Electron diffraction analysis suggests that CL-dark (U-rich) zones are metamict, consistent with protracted residence at temperatures <math><150^{\circ}\text{C}</math>.

**Oxygen Isotopes:** Three acid washed subsamples analyzed by laser fluorination gave, respectively  $\delta^{17}\text{O} = 3.221, 3.188, 3.318$ ;  $\delta^{18}\text{O} = 6.068, 6.075, 6.255$ ;  $\Delta^{17}\text{O} = 0.017, -0.020, 0.015$  per mil. These compositions plot on the Earth-Moon fractionation line, and they fall within the  $\delta^{18}\text{O}$  range measured for a variety of Apollo lunar samples by laser fluorination [3].

**Bulk Rock Composition:** Analyses of clean bulk cutting dust by XRF and of intact subsamples by INAA and ICP-OES gave the following mean abundances: (in wt.%)  $\text{TiO}_2$  2.8,  $\text{Al}_2\text{O}_3$  8.7, FeO 20.7, MnO 0.28, MgO 5.1, CaO 8.0,  $\text{Na}_2\text{O}$  1.3,  $\text{K}_2\text{O}$  0.67; (in ppm) Zn 290, Sc 60, Cr 55, Co 70, Ni 55, Zr 140, Hf 4.3, U 0.59, Th 1.5, La 7.4, Ce 16, Sm 3.6, Eu 1.04, Yb 4.3, Lu 0.65.

The chondrite-normalized REE pattern is relatively flat at 20-25 $\times$ chondrites with a small negative Eu anomaly.

**Discussion:** The Moroccan specimen is similar in primary texture, mineralogy and mineral compositions to the rare sodic ferrogabbro clasts described from Apollo 16 samples 67915, 62243 and 62283 [4]. The F-rich apatite is very similar in composition to that in some mare basalts [5], and, although zirconolite is a well known accessory phase in mare basalts, it is extremely rare in terrestrial mafic rocks (e.g., [6]).

The FeO/MnO ratios in mafic silicate minerals are near the lower ends of the ranges for lunar rocks (but greater than those for terrestrial rocks), and the bulk rock FeO/MnO ratio (74) is the same as in lunar mare basalts. Yet, the presence of ferric iron in ulvöspinel would be anomalous for a lunar rock. The relatively high Cu, Zn and S contents are further unusual features of this specimen, although copper sulfides have been identified in some lunar mare basalts [7].

Low space exposure ages in the range of hundreds to a few thousand years have been reported for some lunar meteorites [e.g., 8]. The Moroccan specimen is distinct from some lunar meteorites in lacking evidence for near-surface exposure, but many lunar meteorites show no such exposure and must be subsurface samples. The relatively young U-Th-He and K-Ar ages (if they record magmatic instead of gas-loss events) are also at odds with the known timing of igneous activity on the Moon, although there is evidence of lunar volcanism as recently as  $\sim 1000$  Ma ago [9]. The actual crystallization age could be much older, and is determinable from the U-Th-rich accessory mineral phases.

For now we exclude other potential sources, even though we note that the mineral compositions and potentially young age are not inconsistent with inferred attributes of magmatic rocks on Venus [10]. On verra.

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