NORTHWEST AFRICA 2191, AN EXTRAORDINARILY EVOLVED EUCRITE. Paul H. Warren[1] and Nicholas Gessler[2], [1]Earth, Planetary, and Space Sci., UCLA, Los Angeles, CA 90095, USA (pwarren@ucla.edu), [2]Information Sciences, Duke University, Durham, NC 27708, USA (nick.gessler@duke.edu).

Introduction: Don't let the low number fool you. NWA 2191 is a "new" large (440 g), essentially unbrecciated, noncumulate eucrite, and we present here initial petrologic observations, plus analyses from three separate chips using our standard combination of INAA and fused-bead EPMA (Table 1).

Petrology: The macroscopic appearance is distinctive. The fusion crust is uncrazed matte black, with a leathery luster; and the interior is mostly pale greenish grey, with an abundant, ~5 vol%, sprinkling of millimeter-sized rust spots (probably derived by weathering of Fe-metal). The texture shows very slight, localized brecciation. The rock consists dominantly of pyroxene and plagioclase, along with subequal proportions of silica, olivine and ilmenite, and lesser troilite, metal (and Fe-oxide products of metal weathering) and apatite. Grain sizes are diverse from place to place. Grain lengths are locally up to 1 mm but generally much smaller, and several enclaves consist mostly of equant grains of order 5-10 μm across. The original igneous texture was dominantly subophitic, but was uneven and is now somewhat obscured due to thermal metamorphism (and possibly metasomatism), which manifests as typical-eucritic style exsolution lamellae in pyroxene, abundant "cloudiness" (microinclusions) [1], and localized annealing textures.

Pyroxenes are equilibrated to near a single metamorphic tie-line, with low-Ca pyroxene clustering near Fs68Wo1.8 and augite near Fs31Wo43; very unusually ferroan for a eucrite. Pyroxene FeO/MnO averages (118 analyses) 32.6. Plagioclase (31 analyses) is An59-94, average An75±12; uncommonly sodic for a eucrite. Olivine (7 analyses) is uniformly Fa86-88. The aphanitic enclaves show phase compositions indistinguishable from the coarsest areas of the rock. X-ray maps document that within the larger pyroxenes strong Ca zoning survived through the thermal metamorphism. Surviving metal is extremely Ni-poor (undetectable by EDS analysis). In one area, several Fe-oxide clumps of presumed Fe-metal derivation (and sprinkled with surviving bits of Fe-metal) show highly elongate, vein-like shapes, reminiscent of NWA 5738 [2]. The bulk composition (below) also resembles NWA 5738. However, the far more ferroan pyroxenes of NWA 2191 militate against pairing with NWA 5738.

Bulk composition: Our three separate analyses show generally good agreement (Table 1). In various ways, NWA 2191 appears to be the single most evolved eucrite yet discovered. We compare it with a large database for eucrites, most notably the extremely ferroan MIL 090687 [3] and NWA 5721 [4] (which are not paired — NWA 5721 has ^{17}O-depleted oxygen for a eucrite, such that [4] argue it must be from a separate parent body), NWA 5738, NWA 8659 [5], Pomozdino and Yamato-82202 [6].

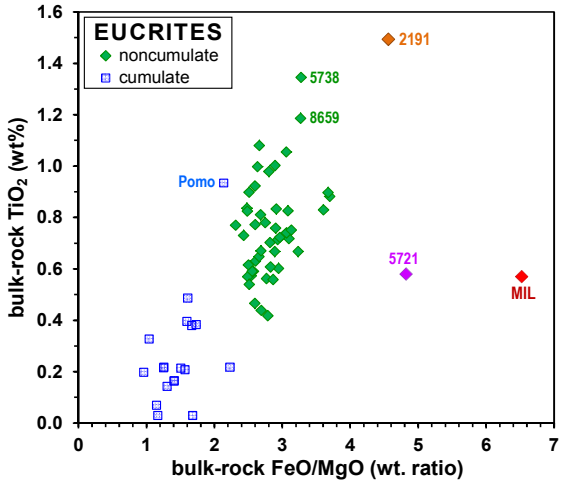
Table 1. Bulk composition of NWA 2191.

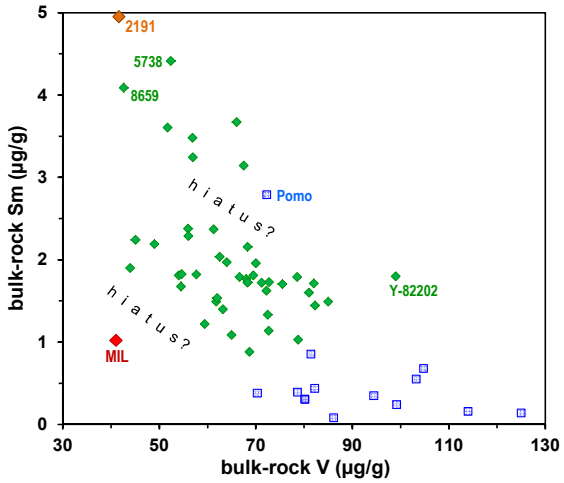
Sample mass (mg)		281	419	480
Na_2O	wt%	0.64	0.63	0.68
MgO		4.36	4.45	4.44
Al_2O_3		10.61	10.76	11.02
SiO_2		49.80	50.63	49.44
K_2O		0.25	0.23	0.25
CaO		10.84	10.99	10.72
TiO_2		1.46	1.46	1.56
Cr_2O_3		0.22	0.22	0.22
MnO		0.51	0.50	0.56
FeO_T		20.56	19.36	20.48
Sc	μg/g	35	34	28
V		43	44	38
Co		7.9	5.5	nd
Ga		<4	<3	nd
La		8.5	7.9	9.0
Ce		20.0	18.2	21
Sm		5.02	4.66	5.2
Eu		1.10	1.13	nd
Tb		1.21	1.13	nd
Ho		1.46	1.39	1.5
Yb		4.00	3.91	nd
Lu		0.63	0.59	0.58
Hf		3.35	3.17	3.14
Ta		0.50	0.47	nd
Th		0.80	0.64	nd
U		0.32	0.25	nd

Unlike the cases of MIL 090687 and NWA 5721, the unusually high FeO/MgO of NWA 2191 is accompanied by exceptionally high concentration of TiO_2 (Fig. 1) (as well as more ideally incompatible but less often-determined elements, e.g. REE, Hf and Th). NWA 2191 appears to represent an extension of, and confirmation of, the dominant trend (the "Stannern trend") of the most evolved eucrites.

Vanadium-samarium systematics (Fig. 2) convey much the same message. V is mildly compatible with pyroxene [7], and thus anticorrelates with REE. (Sm is used in preference to lighter REE because the lightest REE, along with U [cf. the U/Th ratio], may have been significantly impacted by Saharan weathering.) These data also hint at a hiatus between the Stannern trend and the Main Group.

Figure 3 shows that NWA 2191 conforms to a general eucritic trend for Ca/Al to correlate with TiO_2 (et alia). Again, some eucrites including MIL 090687 and the cumulate EET 87548 [6, 8] depart from the general trend, but not NWA 2191.





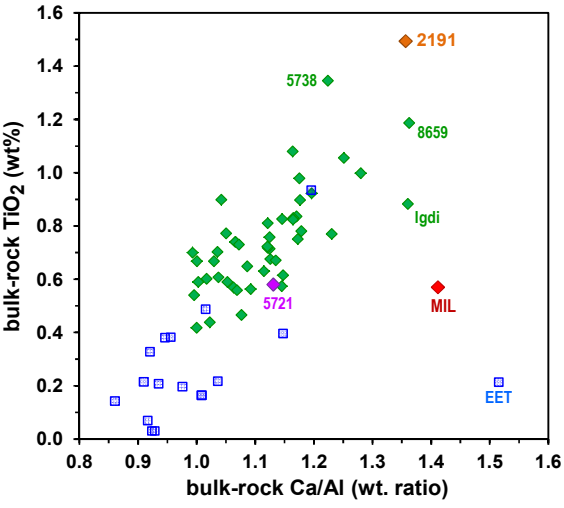


Fig. 1. FeO_T/MgO vs. TiO_2.

Fig. 2. Vanadium vs. samarium; symbols as in Fig. 1.

Fig. 3. Ca/Al vs. TiO_2; symbols as in Fig. 1.

Discussion: One way that an extraordinarily evolved eucrite like NWA 2191 can be useful is in constraining the process that thermally metamorphosed most of the noncumulate (NC) eucrites. These rocks are called basalts because they typically retain subophitic textures indicative of extrusive, or at least shallow and fast-cooling, origin. Yet in contrast to, e.g., lunar basalts, the NC eucrites in the vast majority of cases suffered thermal annealing that "equilibrated" (largely erased original compositional zoning within) their pyroxenes. Probably the most widely cited model to account for the pervasiveness of NC eucrite metamorphism is systematic burial deep within the parent-asteroidal crust [9]. A related hypothesis is that the evolved "Stannern trend" eucrites formed by extraction of partial melts formed in the deep crust [10]. By most accounts, the evolved Stannern trend eucrites formed later than the NC eucrite Main Group.

But if so, we should expect the late-formed extrusives (emplaced atop the Main Group others and after the initial intense phase of crustal genesis) to show a higher statistical frequency of avoidance of thermal metamorphism. A few years ago that indeed seemed a strong possibility. However, the discoveries of NWA 2191 and NWA 5738 [2] have altered the statistical picture (Fig. 4; NWA 8659 is not plotted as it is mildly yet not much metamorphosed [5]). Evidently, late-formed evolved eucrites were about equally as prone to thermal metamorphism as the Main Group. And thus, the origin/evolution of eucrites remains problematic.

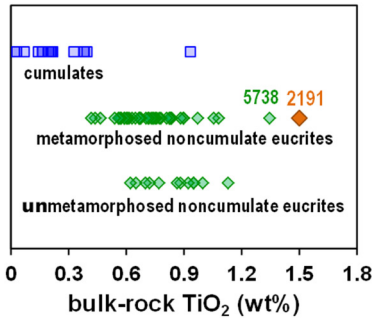


Fig. 4. NWA 2191 and NWA 5738 show that evolved, TiO_2-rich eucrites were far from immune to thermal metamorphism.

References: [1] Harlow G.E. and Klimentidis R. (1980) *Proc. LPSC* 11, 1131–1143. [2] Warren P.H. et al. (2014) *GCA* 141, 199-227. [3] Warren P.H. (2017) 80th Annual Met. Soc. Meeting, abstract 6162. [4] Bunch T.E. et al. (2011) LPSC, abstract 1615. [5] Warren P.H. et al. (2015) 78th Annual Met. Soc. Meeting, abstract 5374. [6] Warren P.H. et al. (2009) *GCA* 73, 5918-5943. [7] Kennedy A.K. et al. (1993) *EPSL* 115, 177-195. [8] Mittlefehldt D.W. and Lindstrom M.M. (2003) *GCA* 67, 1911-1935. [9] Yamaguchi A. et al. (1996) *Icarus* 124, 97-112. [10] Yamaguchi A. et al. (2009) *GCA* 73, 7162-7182.