The Al Haggounia "Fossil or Paleo" Meteorite Problem

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History and background

Several stones were purchased in December 2005 by Greg Hupé from a dealer in Tagounite, Morocco. Individual pieces of this meteorite were found both on the surface or excavated from 0.6 to 0.7 m depth beneath a saline playa or sabkha lake bed located 30 km east of El Haggounia and 60 km east of Laâyoune in southern Morocco (Western Sahara). At approximately the same time another group of stones from the same location was purchased by S. Turecki and B. Reed from A. Aaronson of *Sahara Overland*.

The Hupé stones were classified as an aubrite by A Irving and S. Kuehner (NWA 2828, *MAPS Bull.* **91**) and the Turecki/Reed stones were classified as an EL6/7 enstatite chondrite by T. Bunch and J. Wittke (NWA 2965, *MAPS Bull.* **91**). These meteorites were described as such in an abstract and poster presentation in August 2006 (Irving et al., 2006, *69th Met. Soc. Mtg.*, #5264), and comparisons were made with several other very similar stones (NWA 002, NWA 1067 and NWA 2736 – the last classified as an aubrite by Lowe et al., 2005, *Lunar Planet. Sci.* **XXXVI**, #1913). Upon further examination of much more material, both of our initial classifications were found to be in error. An abstract and poster presentation were given in December 2006 attesting to these errors, proposing that both stones were the same (an EL3 enstatite chondrite NOT an aubrite), and suggesting that they were part of a very large ancient strewnfield (Kuehner et al., 2006, EOS, *Trans. Amer. Geophys. Union* **87**, #P51E-1247).

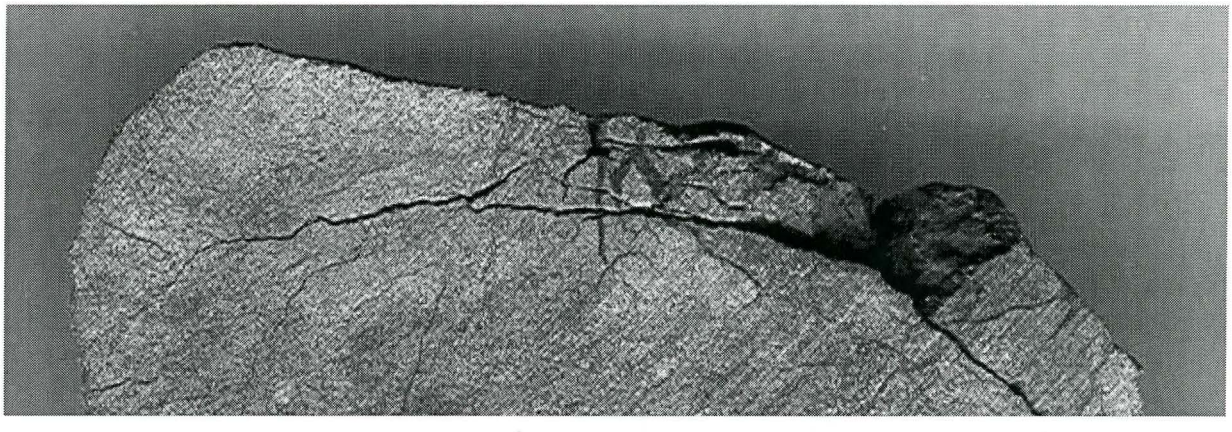
Since then, both groups have examined new material and have attempted to correct the misclassifications of NWA 2828 and NWA 2965 (see below). New information on the find site indicates that many of these stones were excavated from a subsurface deposit, and some were found to have terrestrial rhyolite and sedimentary rock pebbles with sandy matrix attached to the meteorite stones, indicating that, indeed, this meteorite is a component of an ancient localized conglomerate. Other samples collected from the strewn field and supplied by different Moroccan dealers were examined by A. Jambon (University of Paris), who classified his specimens (Al Haggounia 001) as an aubrite. In addition, a joint French and Moroccan team visited the find site in 2007 (see Aoudjehane et al.,

2007, *70th Met. Soc. Mtg.* #5329).

Physical characteristics

Observations given here are those from our own laboratory examinations, and from information supplied by A. Aaronson and other Moroccans who collected specimens from the surface and subsurface of the sabkha lakebed. Samples from the lakebed surface are very dark and fractured. Their highly oxidized surfaces resemble an earthy "iron shale," as can be found around oxidized iron meteorites. The weathered interior ranges in color from dark tan to a dark chocolate, and fractures are outlined by even darker hues (Figures 1 and 2).

Figure 1. Heavily fractured and weathered NWA 2965 surface samples used for the original classification. Field width = 6 cm.



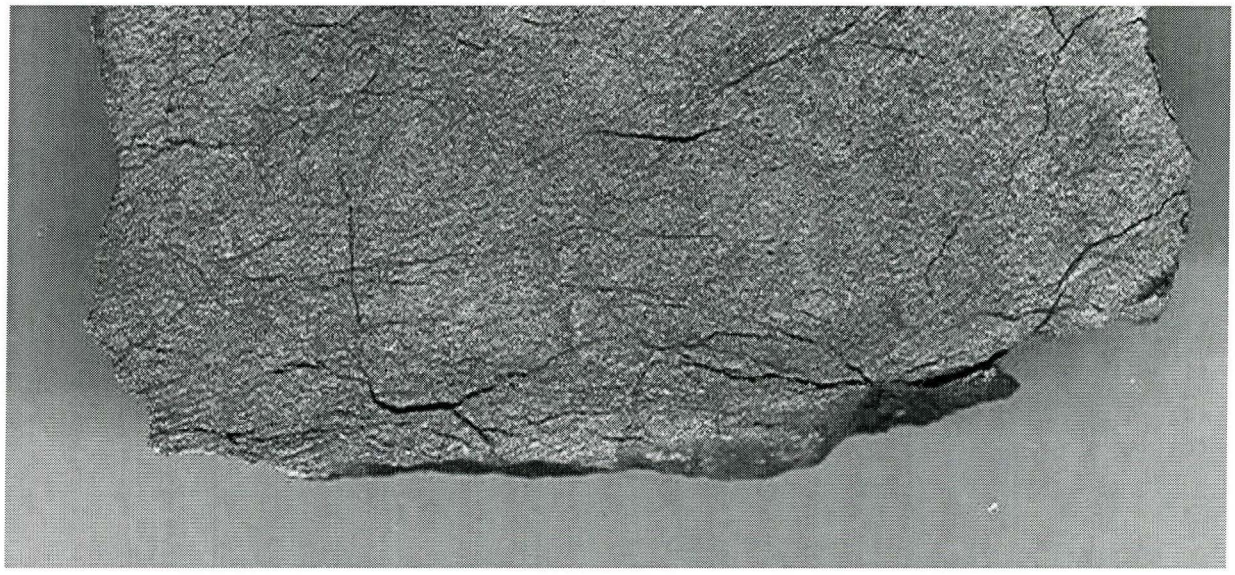


Figure 2. Heavily weathered NWA 2965 surface sample. Width = 7.4 cm.

Many of the samples collected from the surface and near surface have cores of less weathered material, are various shades of light tan to a bluish gray and are rarely fractured (Figures 3 and 4). Over time, these specimens evidently experienced heavy weathering from intermittent rainfall and intense solar radiation. Fractures acted as weathering channelways for aqueous alteration. The "porous" nature of all specimens is due to leaching out of formerly plentiful nickel - iron metal grains that are common in enstatite chondrites, but now are represented in these specimens by voids.

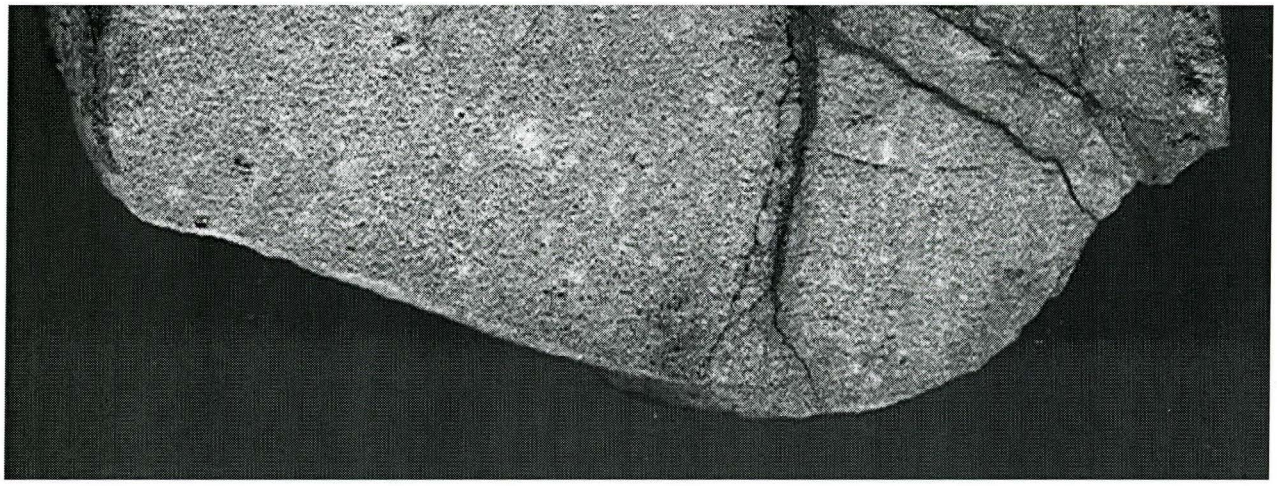


Figure 3. Highly fractured and weathered NWA 2965 sample that grades into the less weathered NWA 2828-like portion. Width = 7.8 cm.

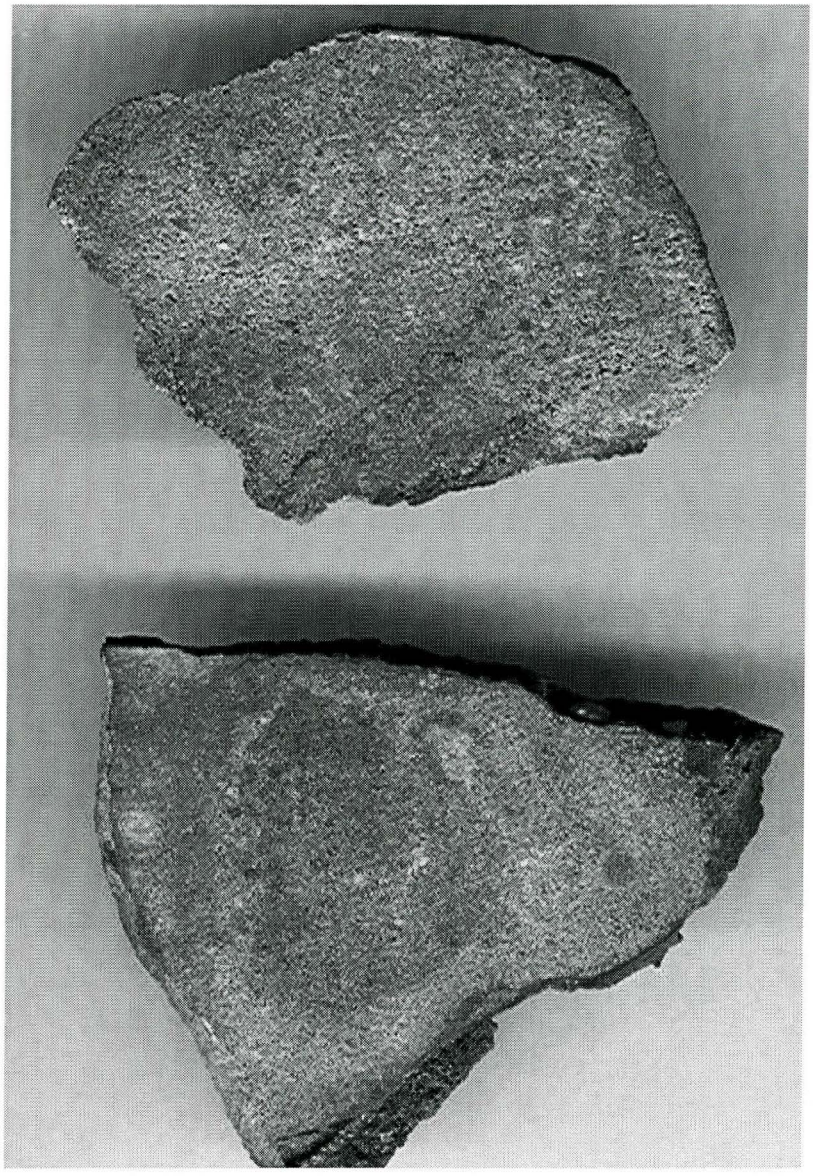


Figure 4. Fossil meteorite specimen with core of blue-gray NWA 2828-like material. Width = 6 cm.

Large pieces of NWA 2828/2965 are found at depth, and after cutting them open the sliced surfaces show conglomeritic textures (Figures 5 and 6). These localized conglomerates consist of angular to subrounded carbonate clasts from the underling limestone (Aoudjehane et al., 2007), pebbles of other lithologies presumably emanating from the surrounding hills and alluvial fans, and fragments of NWA 2828/2965 all cemented together (ostensibly by leached solutions from included meteorite fragments).

Figure 5. Fossil meteorite specimen with fragments of the EL3 chondrite in the lower portion. Light colored clast in the upper left is limestone, which is surrounded by concentric Fe-Ni oxide bands. Width = 12 cm.

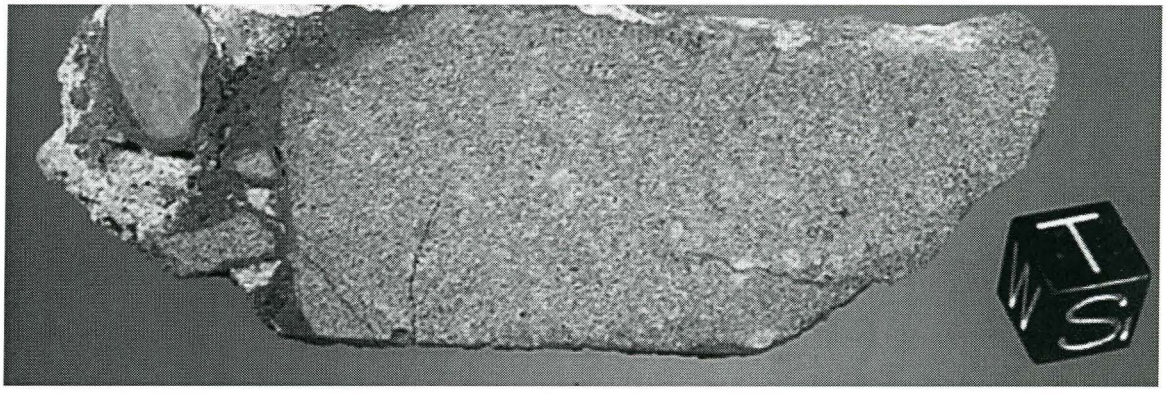
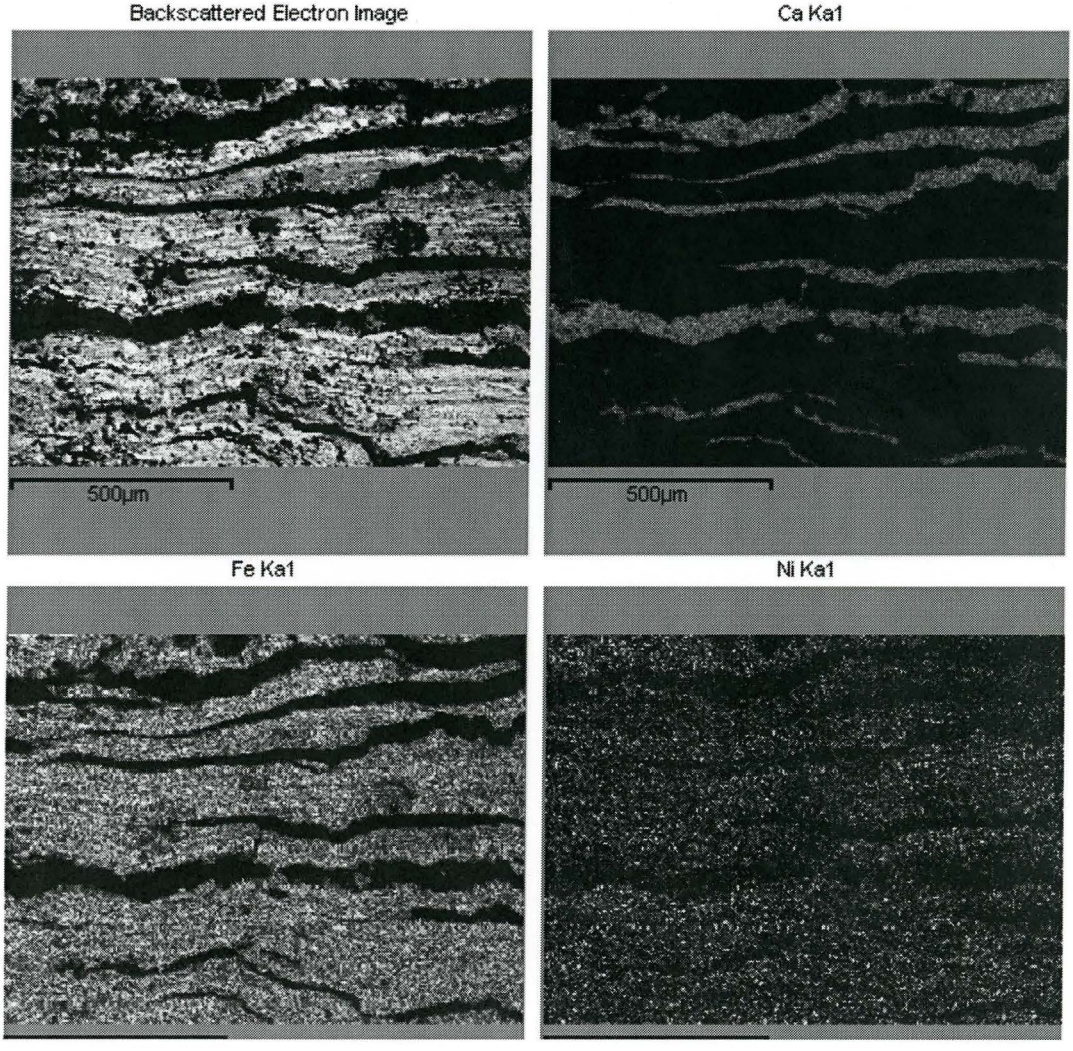


Figure 6. Slice of conglomerate showing showing a large EL3 cobble (note porosity and sparse whitish chondrules) and a terrestrial rhyolite pebble (pink, upper left) in a matrix of sand-sized detritus and iron hydroxides. Cube is 1 cm on a side.

SEM observations show concentric structures that surround all types of pebbles and clasts (Figure 7). These structures consist of alternating thin bands, tens to hundreds of micrometers thick, of Ni-Fe-rich oxides and hydroxides, very fine-grained carbonate, sulfate, and clay alteration products.



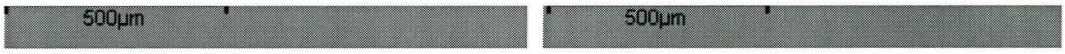


Figure 7. Alteration banding surrounding meteorite fragments. (upper left) Backscattered electron image in which brighter regions have higher average atomic number; (upper right) Ca-Kα x-ray map showing location of calcium carbonate alteration (caliche); (lower left and right) Fe-Kα and Ni-Kα x-ray maps showing distribution of alteration bands rich in ions derived from meteoritic metal.

Petrography and mineral composition summary

Some of the meteorite stones contain sparse (<5 vol. %) but very distinct round, radial pyroxene chondrules (up to 3 mm across), as well as rounded, fine-grained aggregates (up to 6 mm across) rich in either enstatite or sodic plagioclase (Figures 8 and 9). Remnant Na-Al-Si-rich glass is present within cavities in chondrules, both between enstatite blades and in annular zones.

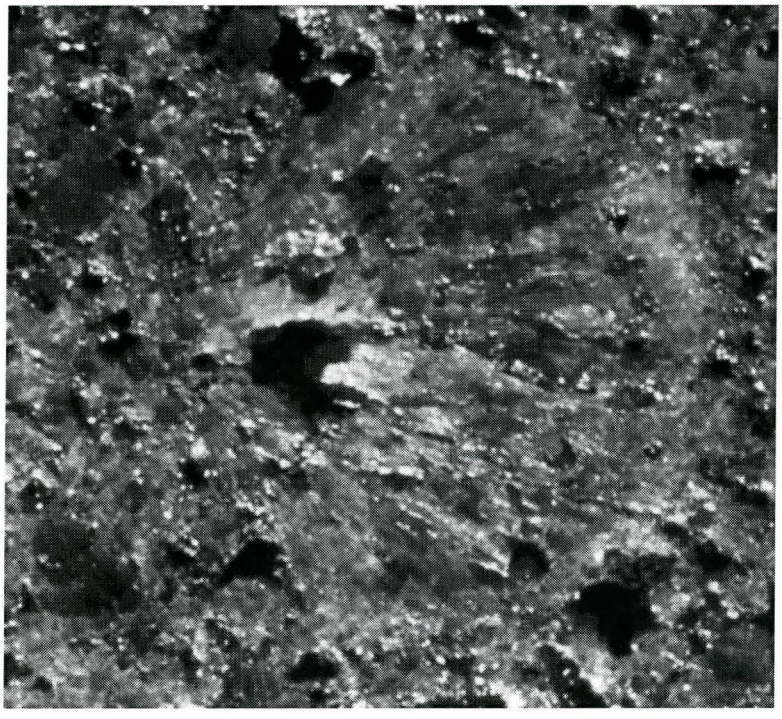
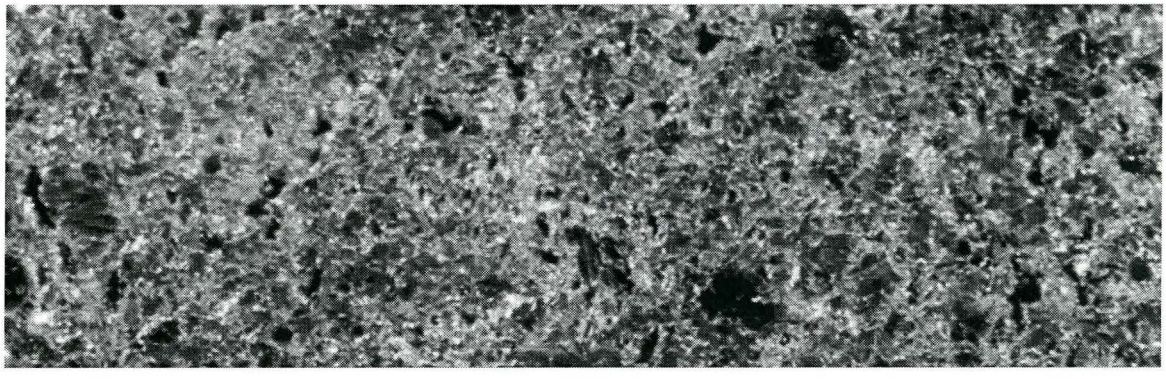


Figure 8. Radial chondrule in NWA 2828 with glassy mesostasis. For an example of another chondrule see http://www.rocksfromspace.org/November_30_2007.html



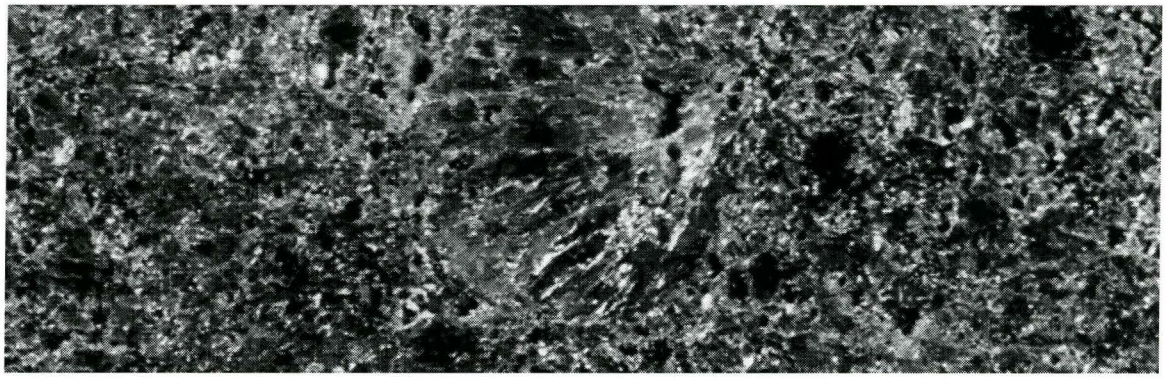


Figure 9. NWA 2828 showing radial enstatite chondrule in a primary matrix of enstatite, sodic plagioclase and cavities (after former metal).

The matrix contains pervasive 0.2-0.5 mm cavities with coatings of calcite and minor halite and gypsum. Iron sulfate (after troilite), jarosite, an inhomogeneous (possibly amorphous) phase rich in Fe, Cr, Si, Ca, Ti, P, S and Cl, minor native sulfur and silica also are present, and brown Fe-rich rinds on one stone contain up to 6.5 wt.% Ni. These secondary minerals signify terrestrial alteration of primary metal, sulfides, phosphides, nitrides and glass in an ancient fluvial and/or acidic lacustrine environment. The dominant primary phase in NWA 2828/2965 is enstatite ($En_{98.4}Wo_{1.4}$), which forms stubby untwinned, prismatic grains. Additional primary phases are sodic plagioclase ($An_{14-15}Or_{3-4}$), troilite, graphite, daubreelite, alabandite, oldhamite, schreibersite and very rare kamacite.

Problems and proposed solutions

1. **Erroneous classifications corrected**. The original NWA 2828 classification (aubrite) was based on a very small specimen of an apparently igneous-textured rock, but the misidentification of polysynthetic twinning features, discovery of chondrules and subsequent studies establish that it is instead an unequilibrated enstatite chondrite. Moreover, the original classification of NWA 2965 as an EL6/7 chondrite was based on two heavily altered samples, in which the true nature of constraining characteristics was obscured by oxidation. In addition, we took the presence of scarce and altered chondrules to mean that NWA 2965 was pre-terrestrially metamorphosed. The revised classification of ALL stones as an EL3 chondrite is based on careful study of 4 thin sections, several polished slices, and 5,885 g of hand sample material. The designation as Type 3 is appropriate, given the presence of glass in chondrules and the well-preserved chondrule shapes (note that abundance of chondrules is not a criterion).

2. **Failure of the Nom Com to publish corrections in the Bulletin**. We apologize for any confusion brought about by the erroneous classifications. In addition to the 2006 AGU abstract, we attempted to rectify the errors by submitting revised classifications (see below) to the Meteoritical Society Committee on Meteorite Nomenclature (a.k.a. the Nom Com) in the spring of 2007. To no avail. We

were never advised about any decision; apparently, the matter was ignored for whatever reason.

3. **Approval of Al Haggounia 001 as an aubrite**. The classification of and Nom Com approval of a pairing (Al Haggounia 001, Met. Bull. 92) to NWA 2828 and NWA 2965 as an aubrite are blatant errors. All parties had full knowledge that the meteorite in question contains chondrules and cannot be classified as an aubrite under present classifying elements.

4. **NWA 2828/2965 as a fossil or paleo meteorite**. Of course! However, there are few guidelines. The Meteoritical Society Guidelines for Meteorite Nomenclature say this about "relict meteorites":

> c) Special provisions are made in these Guidelines for highly altered materials that may have a meteoritic origin, designated relict meteorites, which are dominantly (>95%) composed of secondary minerals formed on the body on which the object was found. Examples of such material may include some types of "meteorite shale," "fossil meteorites," and fusion crust.

We find this rather confusing and ambiguous. Because rounded pieces of NWA 2828/2965 are clearly incorporated into a terrestrial rock (an indurated conglomerate) by natural geological processes, then they should be considered as fossil meteorites (albeit from a huge ancient fall).

Revised Classifications

Northwest Africa 2828 (revised classification)

Western Sahara
Find (purchased December 2005)
Enstatite chondrite (EL3)

History: Purchased in 2005 December by Greg Hupé from a Moroccan dealer in Tagounite. Individual pieces of this meteorite were excavated from 0.6 to 0.7 m beneath a saline playa or sabkha lakebed located 30 km east of El Hagounia and 60 km east of Laâyoune, Western Sahara.
Physical characteristics: 160 pale gray to whitish stones lacking fusion crust with a total weight of 34.19 kg. Most stones have exterior light orange staining, and some stones contain dark brown rinds or cross-cutting veins (1-2 mm wide) of magnetic, fine grained iron oxide and hydroxide minerals. Several stones have pink terrestrial rhyolite pebbles attached to them by a sandy matrix, indicating that the meteorite stones are cobbles in an ancient conglomerate bed.
Petrography: (A. Irving and S. Kuehner, *UWS*; T. Bunch and J. Wittke, *NAU*): Relatively fine but variable grain size (0.3 to 1.5 mm), and composed predominantly of prismatic grains of essentially pure enstatite (untwinned) with ~15 vol. %

oligoclase, accessory iron sulfate pseudomorphs after troilite (with fresh, subparallel exsolution blades of daubreelite) and sporadic rounded to ellipsoidal grains of graphite (up to 1.2 mm across). Several stones contain sparse, round RP chondrules (up to 2 mm across) and sporadic whitish, rounded, fine grained clasts (up to 6 mm across) rich in either enstatite or sodic plagioclase. Small (0.5 -1 mm) lobate cavities partly coated with fine grained calcite, halite, gypsum and iron sulfate are present in the interior of even the freshest stones. Small grains found as inclusions within enstatite are fresh Ti-free troilite, pure Mn-alabandite, daubreelite, fresh oldhamite (some Mn-bearing), schreibersite, and very rare specks of kamacite and taenite. Minor barite is present.

Geochemistry: Pyroxene ($En_{98.4}Wo_{1.4}$, Al_2O_3 = 0.21 wt. %), plagioclase ($An_{13.5\text{-}15.3}Or_{3.0\text{-}4.4}$). Oxygen Isotopes (D. Rumble, *CIW*): Analyses of two acid-washed whole rock fragments by laser fluorination gave, respectively, $\delta^{18}O$ = 5.50, 5.56 ‰ ; $\delta^{17}O$ = 2.89, 2.90 ‰; $\Delta 17O$ = -0.001, -0.026 ‰.

Classification: The presence of sparse but well-formed enstatite-bearing chondrules containing glass (mostly dissolved) and the lack of recrystallization of the matrix make this an EL3 chondrite. Based upon the replacement of troilite by iron sulfate and complete dissolution of primary metal, the weathering/diagenetic grade is W4. This material is the less weathered equivalent of material classified as NWA 2965 (Kuehner et al., 2006).

Specimens: A total of 52.5 g of sample, two polished thin sections and one polished slice are on deposit at *UWS*, and 34.5 g are on deposit at *NAU*. G. Hupé holds the main mass.

Reference

Kuehner, S. M., Irving, A. J., Bunch, T. E., Wittke, J. H. and Hupé, G. M. (2006) EL3 chondrite (not aubrite) Northwest Africa 2828: An unusual paleo-meteorite occurring as cobbles in a terrestrial conglomerate. Eos, Trans. Amer. Geophys. Union, 87, Fall Meet. Suppl., Abstract P51E-1247.

Northwest Africa 2965 (revised classification)

Western Sahara
Find: 2004 to present
Enstatite chondrite (EL3)

History: Approximately 100 kg of various sized stones were purchased by S. Turecki from Saharaoverland, Morocco in 2005. These stones were collected from the surface of a saline playa, near El Hagounia, in Western Sahara. Many 100s of kg have been recovered from the surface (NWA 2965) and from depths to less than one m (NWA 2828). The recovery field has a length of at least 40 km (pers. comm., A. Aaronson, Saharaoverland). Specimens are continuously recovered from the site.

Physical characteristics: Small to medium sized stones (<300 g) are commonly

weathered to a dark brown with irregular networks of very dark weathering veins in contrast to those excavated from depth that tend to be less iron stained. Larger pieces may retain portions of weathered fusion crust.

Petrography: (T. Bunch and J. Wittke, *NAU*) Mostly composed of a fine-grained matrix (<0.5 mm) of sub-rounded to prismatic crystals of nearly pure enstatite. Clusters of coarser-grained (0.5 – 1.2 mm) enstatite, some with plagioclase, are scattered throughout. Rare RP chondrules and fragments are found in a few slices and sections (154 cm^2 visually analyzed). Tiny grains of troilite, daubreelite (as lamellae in FeS), and metal are found as inclusions in enstatite, vermicular graphite grains are found as inclusions and as larger grains in the matrix. Other minerals that are present in NWA 2828 (Kuehner et al., 2006) were not found. Severe weathering and chemical leaching have left cavities partially in-filled with a variety of secondary minerals that include carbonates, halite, gypsum, and Fe-oxides/sulfates. Shock level is low.

Geochemistry: Orthopyroxene, $Fs_{0.4\pm0.02}Wo_{0.8\text{-}1.3}$; plagioclase, $An_{14.8\text{-}17.6}Or_{4.1\text{-}4.9}$; FeS, Ti = 0.91 wt. %, Cr = 1.10 wt. %, Zn = 0.6 wt %.

Classification: Enstatite chondrite (EL3). The original, erroneous classification of EL6/7 (Bull. 91) was based on two heavily altered samples, in which, the true nature of constraining characteristics were obscured. The revised classification is based on 6 thin sections and 485 g of material. Weathering grade is 4/5.

Type specimen: A total of 2,245 g of samples (from several sources), 6 thin sections and 8 polished slices are on deposit at *NAU*. *S. Turecki* and *B. Reed* hold the main mass.

Reference

Kuehner, S. M., Irving, A. J., Bunch, T. E., Wittke, J. H. and Hupé, G. M. (2006) EL3 chondrite (not aubrite) Northwest Africa 2828: An unusual paleo-meteorite occurring as cobbles in a terrestrial conglomerate. Eos, Trans. Amer. Geophys. Union, 87, Fall Meet. Suppl., Abstract P51E-1247.

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