"MATURATION" OF OXYGEN DEPTH PROFILES IN LUNAR METAL GRAINS. M. Maurette, CSNSM, Bat.108, 91405-Orsay, Campus, France (maurette cnsm@in2p3.fr).

Introduction: G.Hunt [1] gave a stimulating presentation of an intriguing dilemma dealing with the depth profiles of the elemental and isotopic compositions of oxygen measured at depths ≤ 1000 nm, with ion microprobes (SIMS), in individual lunar metal grains. They were reported by Hashizume and Chaussidon [2] and Ireland et al [3, 4]. The grains were collected in the magnetic fractions extracted with a hand magnet from several mature lunar soil samples, including the "consolidated" lunar soil from the very friable 79035 lunar breccias [2] and soil 10084 [3, 4]. Hunt pointed out rightly that the measurements are good. Therefore, the very different O isotopic compositions measured by the two groups, and attributed to the implantation of solar energetic oxygen ions, are surprising. They led to conflicting conclusions, as the Sun would be enriched in ^{16}O [2] or markedly depleted in ^{16}O [3, 4]. The O elemental depth profiles reported by the two groups are also very different. We next question how these "solar" depth profiles could have survived intact during both: – the reprocessing of regolith material by meteoritic and micrometeoritic impacts, which rule the degree of "maturation" of lunar soils (besides their role in the making of metal grains); – the pressing of the metal grains against indium or gold, as to get the flat surfaces that are required for SIMS analysis.

"Maturation" of oxygen elemental depth profiles. Both groups selected grains that did show a smooth decrease of the O elemental depth profile at depth ≤ 1000 nm, compatible with the implantation of energetic solar ions. This unavoidably led to a biased selection of grains in favor of such profiles that are rare. Indeed, Ireland et al selected 6 metal grains with sizes of about 20-80 µm that they recovered from a ~0.5 g aliquot of soil 10084 [3], and only the analyses of a sphere and a shard were reported. Hashizume and Chaussidon recovered 199 magnetic grains (with average sizes of ~34 µm) from about 0.15 g of soil 79035. They selected 5 favorable metal grains with unspecified texture.

As indicated by both the SW ^{36}Ar content and the density of tiny micrometeorite impact craters (Zap-Pits, or ZPs) of their constituent grains, these two soils have reached a similar degree of maturity. Most of their grains had a high-integrated residence time, Σo, on the top surface of the lunar regolith. For a given grain, Σo is ruled by a complex sequence of successive burial and excavation through ejecta blankets produced by meteoritic impacts, but also by the "mini-gardening" of the top layers of the regolith by micrometeoritic impacts. During Σo, the grains can be implanted with high fluences of energetic solar ions, such as O, C, N, ^{20}Ne and ^{36}Ar from the solar wind.

They also show other microscopic "scars" of maturity on their external surfaces. They were thoroughly investigated by Yves Langevin in our group, in the early 1970's [5]. They are visible on the high magnification SEM micrograph reported in figure 1 for a tiny area (~ 60 µm^2) of a feldspar grain from soil 10084. This mature surface shows in particular: – high density of tiny ZPs with typical rims and glassy linings that contain residues of the impacting micrometeorites; – an astonishing "zoo" of secondary glassy accretionary particles (SAPs). They are mainly produced by the rain of glassy splashes induced by meteoritic and micrometeoritic impacts in the regolith.

In Fig. 1, the SAPs include: – the largest "horny" splash (size ~3 µm) observed in the lower left-hand corner; – very long and narrow glass fibers, and; – a myriad of very tiny SAPs that look like globules on this JPEG compressed micrograph (their threshold of visibility on the original micrograph is about 30 nm). However, most of the SAPs show a "pancake" shape with a thickness, Δ , which is smaller than their average lateral dimension, D. The ratio, Δ/D, decreases with increasing D (see the horny splash with Δ/D ~ 0.1).

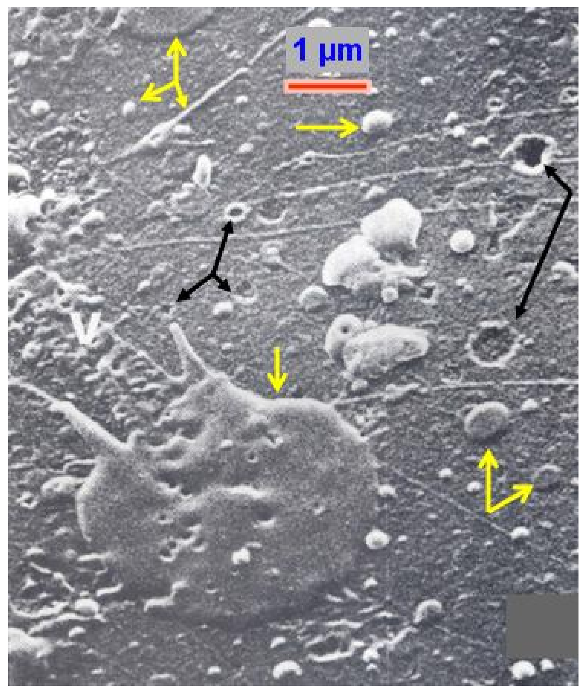

Fig. 1: *Identification of a few SAPs and ZPs, with yellow and dark arrows, respectively.*

The parent materials of the SAPs are O-rich rocks from both lunar and meteoritic and micrometeoritic origins. Consequently, as the small SAPs loaded with oxygen are much more abundant than the largest ones, their shorter lifetime against sputtering by the primary SIMS ion beam, which is ruled by Δ, will generate a decreasing O depth profile. The integral SAP size distribution imprinted in Fig.1 can mimic any "solar like" depth profile reported at depths ≥ 30 nm, in Ref. 2 and 3. One has just to adjust the Δ/D ratio, and the size of the largest SAP in the analyzed area.

"Maturation" of oxygen isotopic depth profiles. We mostly discuss the work of the Nancy group [2], which was generously responding to a request for additional information. Figure 2 show all the measurements of the O isotopic composition of their 5 metal grains (black dots). We also show the compositions of 11 olivines and 11 pyroxenes with sizes ≥ 20 µm (open red dots) measured by Engrand et al [6], and sampled in 20 Antarctic micrometeorites. They are displayed on the basic $\delta^{17}O_{SMOW}$ (‰) vs $\delta^{18}O_{SMOW}$ (‰) dispersion plot rigorously defined by Robert Clayton and collaborators [7].We also reported two fractionation lines: (i) the terrestrial fractionation line, TFL [7]; (ii) the Antarctic micrometeorite fractionation line, AMML, of slope ~ 1, which runs slightly upward (i.e., within ~3‰) of the classical CCAM line [7]. The AMML was defined from the set of anhydrous minerals (reported as red dots in Fig.2), and 5 refractory minerals (2 spinel and 3 melilite) that were extracted from two micrometeorites by Engrand (their 5 dots are out of scale on the left).

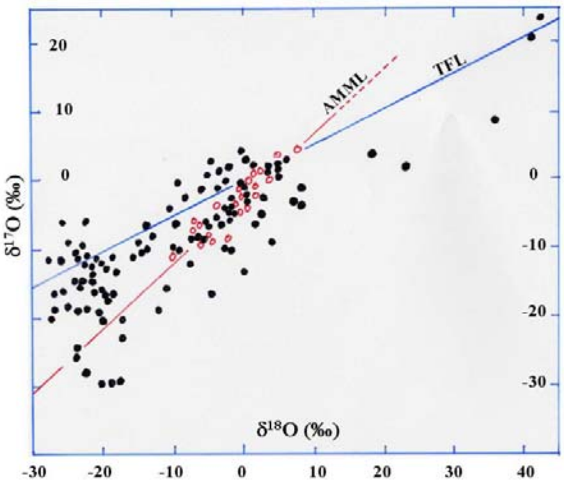

Fig. 2: *Oxygen isotopic composition of 5 lunar metal grains and 22 anhydrous silicates from Antarctic micrometeorites.*

Large error bars on the $\delta^{17}O$ values are attached to the black dots. They have not been reported in Fig. 2, as to avoid facing an opaque forest of vertical bars. At least 4 different oxygen-bearing components would be entangled in the dark dots distribution. One of them is attributed to a layer of "FeO" (with thickness of 40 nm to 600 nm) due to an oxidation by terrestrial water. Then *"the large deviation of some data from the TFL would demonstrate the existence of a 4th component"*…identified as implanted fast solar ions.

Just for a try let us by-pass this wonderful complexity and incorporate the micrometeorite data in the discussion. With the exception of a few black dots (i.e., 5 dots at $\delta^{18}O \geq 15$, and the 3 lowest adjacent dots around $\delta^{18}O \approx -19$‰), the set of black and red dots is confined within a characteristic elongated cluster, which is intersected by the AMML. This cluster is grossly confined within the following boundaries: (i) the TFL, which is also the lunar fractionation line for silicates; (ii) a lower line with a slope of roughly 0.5; (iii) an approximate vertical boundary on the left (at $\delta^{18}O \approx -28$‰), beyond which the cluster is empty.

Microscopic blends of lunar igneous rocks and micrometeorites generated the SAPs and the ZPs glass linings.They could explain the main cluster of dots in Fig. 2, at the condition that micrometeorites contain phases still to be found (probably in their fine-grained matrix), which could fill the empty AMML range defined by $-25‰ \leq \delta^{18}O \leq -10‰$. We have no explanation, yet, for the ^{16}O depleted isotopic profiles reported in Ref. 4 for two metal grains of soil 10084, in part because additional information were missing.

Another intriguing dilemma is the role of the pressing procedure used to prepare flat areas on the lunar metals. In Nancy, the 5 metal grains were simultaneously pressed on indium with a glass plate, altogether with the bulk magnetic separate spread on a plastic film, which mostly contains glassy agglutinates, ilmenites and pyroxenes. Zap-pits with sizes larger than a few µm are observed on most SEM micrographs (at magnification ≥ x1000). Even though indium is a very soft metal, this gentle pressing was already sufficient to flatten and spread the ZP rim material onto the adjacent metal surface, which is clearly made of a soft metal. The pressing on gold used by Ireland et al was even more severe as the largest sphere *"was flattened slightly upon pressing"*. This "pressing" of a soft lunar metal and its load of SAPs and ZPs against another soft metal (In or Au) would likely blur any initial solar ions depth profile.

Conclusions. "Solar" oxygen can be best detected in grains with long exposures on the top surface of the regolith. However, in this position, they are simultaneously impacted by glassy splashes and micrometeorites that contaminate the metal surface with oxygen through the formation of a "zoo" of glassy SAPs and ZPs linings. There is a test of our "maturation" scenario. Indeed, if the Si- and O-depth profiles can be simultaneously measured, they should rather well match.

This discussion might be relevant to the depth profiles reported in metal, ilmenite and pyroxene, for other elements (such as N and C), also found in hydrous carbonaceous chondrites and micrometeorites. Therefore, they could be incorporated in SAPs and ZPs, like oxygen. The only elements that would be rather immune to "maturation" are the noble gases. Indeed, our early observations of micron-sized grains from soil 10084 with a high voltage TEM (see one of our best micrograph in Ref. 8, Fig. 4, available on Internet) showed that about 50% of the grain surface is still clean and free of SAPs. Furthermore, the noble gases were probably not well retained in the glassy material of the SAPs and ZPs. Consequently, the noble gases trapped in lunar dust grains are dominated by implanted solar noble gases [9]. However, the scale of depth (and consequently their depth profiles) inferred by stepped chemical etching of individual grains in HF, would unavoidably be distorted by the dissolution of their glassy SAPs (with regard to theoretical implantation depth profiles predicted by the TRIM code).

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