Introduction to MMC 2012

As of the end of 2012, we now know of about 65 different meteorites from Mars with a total weight about 120 kilograms. Some fell as showers (e.g. Nakhla, Tissint), and some can be paired by common lithology, age and fall location, but it is more instructive to consider how they are grouped by "launch pairs". If you add the terrestrial age to the cosmic exposure age (CRE) you get the time when the meteorite was launched off of Mars by impact. Since only rather large impacts would do this, there must be a finite number of such impacts – hence grouping of samples.

Now that we have such a large number of samples, it is time to understand what we have and infer what we can about Mars. It's like putting a puzzle together were someone keeps adding pieces as you go along (see my Introduction 2006). Most Martian meteorites are mafic basalts. That is, they have an abundance of Fe and Mg, are low in Si and Al and have a texture of intergrown minerals typical of terrestrial basalts (the tradition has been to call them "shergottites", after the first sample recognized as such). Some often have an abundance of large olivine crystals (so called olivine-phyric). Others have an abundance of both high- and low-Ca pyroxene, with poikilitic textures and were originally called "lherzolitic shergottites". But it has now been recognized that there is a more fundamental and better way to describe these rocks (Irving 2012).

Figure 1 shows a crude summary of CRE that have been determined for Martian meteorites. Note that there is a strong correlation with type. All the nakhlites have the same CRE (10 m.y.). The meteorites labeled

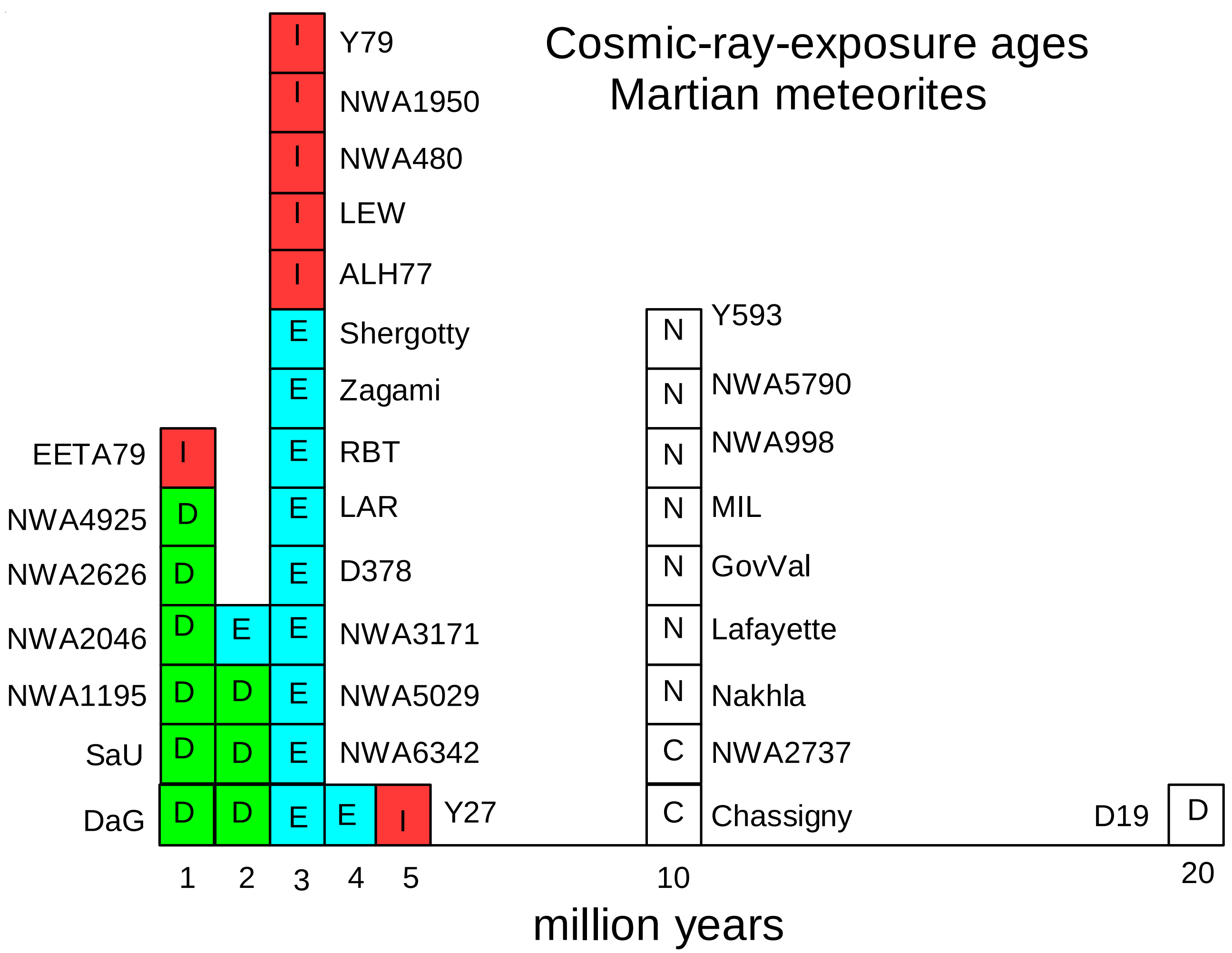

__Figure 1:__ Crude histogram summarizing what has been learned from cosmic ray exposure ages for Martian basalts. N = nakhlite, C = chassignite, D = depleted, E = "enriched" and I = intermediate.

"E" (enriched) all cluster around 3 m.y. The samples labeled "D" (depleted) are all about 0.6 – 1 m.y. The category labeled "I" (intermediate) are somewhat scattered. Dhofar019 is all by itself at 20 m.y. In addition, there are a few Martian meteorites that have unique lithologies, that may represent additional impact events (e.g. ALH84001, NWA7034). So, offhand, it looks like that there have been about 6 - 8 impacts on Mars large enough to launch meteorites to Earth (the debris created by older impacts has already impacted the Sun, or weathered away on Earth).

Next we need to consider what is are the basic parameters that distinguish one Martian basalt from another. Originally we used texture and mineral mode for this, but there is a better way. Geochemists love to use the patterns of rare-earth-elements (REE; La – Lu) to do this. Figure 2 a (from Irving *et al.* 2012) shows the REE for three main basalt types (E, D and I). D stands for depleted, meaning that the light REE are depleted compared with the heavy REE. Enriched is a bit of a misnomer, because the pattern is basically flat (*but enriched in comparison).* Intermediate is in between. In addition, now that we have precise isotopic data for radiometric ages (see internal mineral isochrons), we also have the initial isotopic composition of the source region for these basalts at the time of their formation. Figure 3 shows how the initial isotopes of Sr and Nd are tightly grouped (E, D, I and N). So, this then, is the basis of a new classification of Martian meteorites, and you will note the prefix to the title of each meteorite discussed herein.

There is also a strong correlation between crystallization age and cosmic ray exposure age (figure 4). Again, nakhlites and chassignities stand alone at ~1370 m.y. with CRE about 10 m.y. That's pretty convincing evidence that they are from one impact. Enriched shergottites also form a tight grouping on figure 4. They have a wider range of textures, from diabasic to subophitic (basaltic). Shergottites with intermediate depletion of REE are more scattered in this presentation and may represent more than one impact on Mars. Another interpretation is that some may have received cosmic ray exposure on Mars before they were launched into space, or that some were

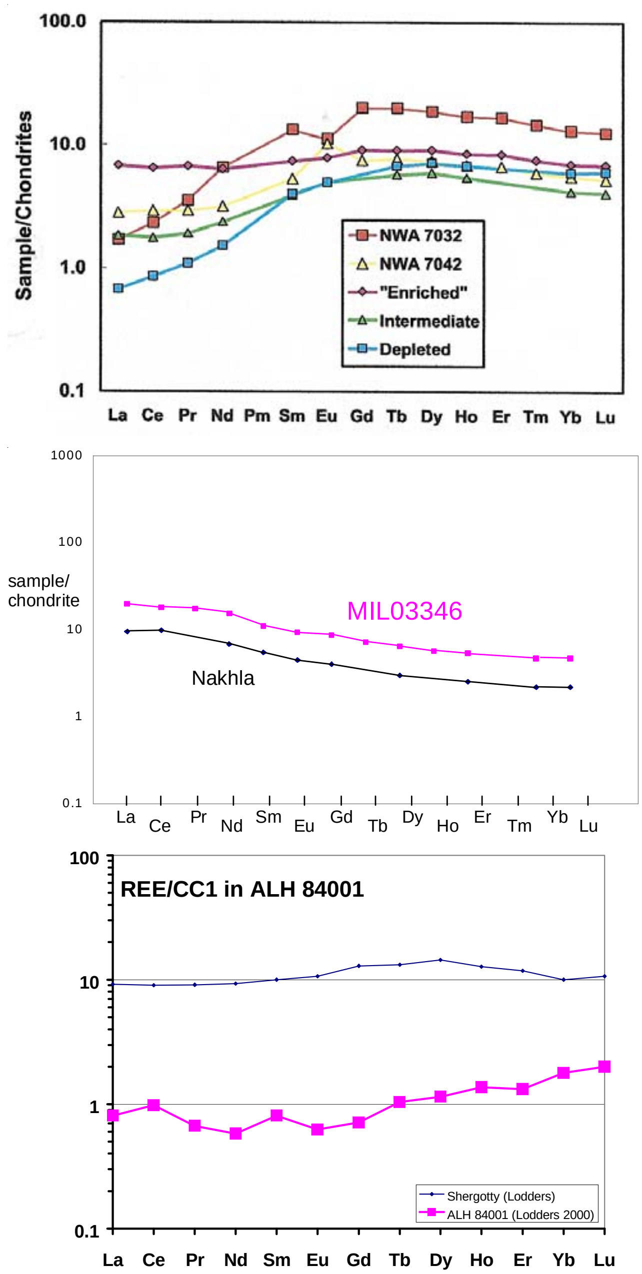

Figure 2: *Normalized rare-earth-element diagrams for:* ***a)*** *basalts (from Irving 2012) (E, D and I),* ***b)*** *Nakhlites and* ***c)*** *ALH84001.*

partially shielded inside a large body that broke-up in space. In any case they are still part of the puzzle.

At this point, there are three special cases. ALH84001 is the only plutonic sample and it is very old. Dhofar 019 has an old cosmic exposure age and it has a depleted highly siderophile element composition. NWA7034 is in a class all of its own, with a breccias texture and oxygen isotopes more extreme. In addition, there may be some rather mafic new shergottites.

The oxidation state during crystallization of lava on Mars has been the subject of further correlation. In some cases there is primary magnetite in the mineral assemblage (e.g. Shergotty). In other cases, mineral equilibria and element distributions indicate a highly reduced state. It is thought by some, that these oxidation conditions were established in the magma chamber of origin (e.g. Papike *et al.* 2009).

Since 2006 a lot has been learned about rocks on the surface of Mars from the two MER rovers. They have even spotted iron meteorites on the surface of Mars! This year has seen the successful landing and operation of the large Martian rover called Curiosity. Data from these missions should allow for comparison of Martian meteorites (6 -8 sites, this Compendium) with the data from rocks on the surface at these 3 landing sites, giving a more complete understanding of Mars (McSween 2012).

The successful landing of Curiosity has another significance. It is thought to be a giant leap towards a mission that could remotely collect samples and launch them back to Earth. But petrologists beware, such a mission would be driven by a different community of scientists – those in search for an understanding of the origin of primitive life on Mars (National Academy). Meanwhile, the emphasis is on finding more samples from desert regions of North Africa and/or the Arabian peninsula (figure 5).

If you find any of the above discussion interesting or confusing, I highly recommend the excellent web site maintained by Tony Irving. Otherwise, I can find nothing wrong with my introduction in 2006 (*based on fewer samples). If you find nothing amusing about any of this, get a piece of NWA7034 from Carl Agee, and be happy.*

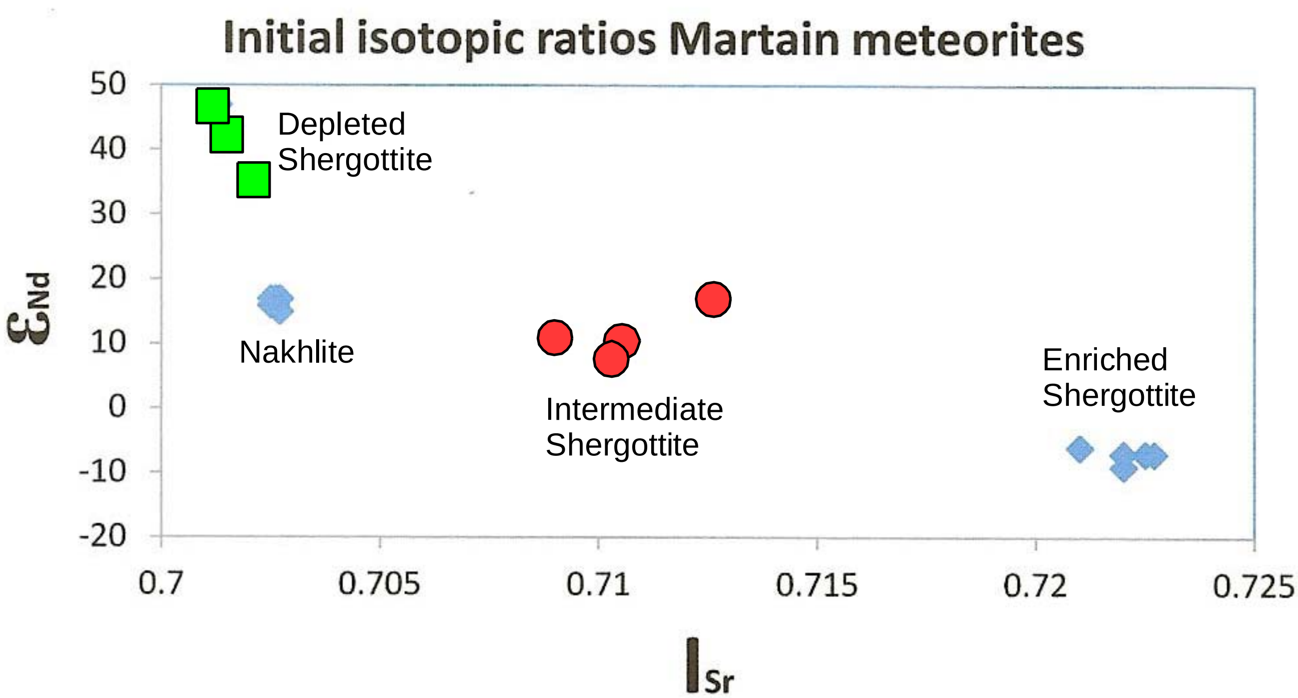

Figure 3: *The isotopic composition of the source region of Martian basalts can be used to identify the following grouping, which can be used as classification criteria. Enriched shergottites included Shergotty, Zagami, RBT, LAR, NWA856 and 1068. Depleted shergottites include QUE, Dohar019 and NWA5990. Intermediate shergottites include ALH77, EETA79, LEW and Y79. Nakhlites and Chassignites all plot together.*

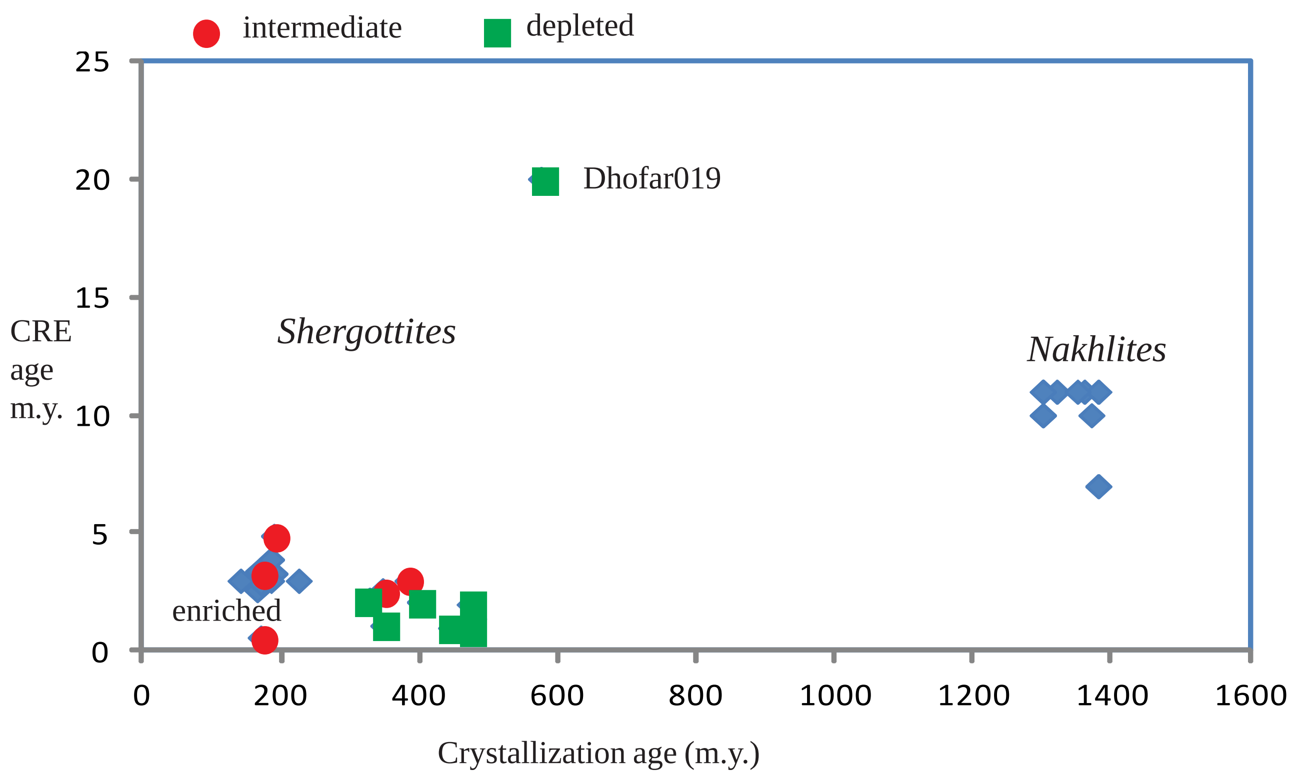

Figure 4: *Correlation of cosmic-ray-exposure ages (CRE) with crystallization ages for Martian basalts. Enriched shergottites all group around 180 m.y. with ~ 3 m.y. exposure to cosmic rays (blue diamonds). Depleted shergottites range in crystallization age from about 300 to 600 m.y. (green squares). Shergottites with intermediate depletion of light REE are shown in red circles. Nakhlites and dunites are all grouped about 1370 m.y. with about 11 m.y. CRE. (be sure to look up the details of each sample, herein)*

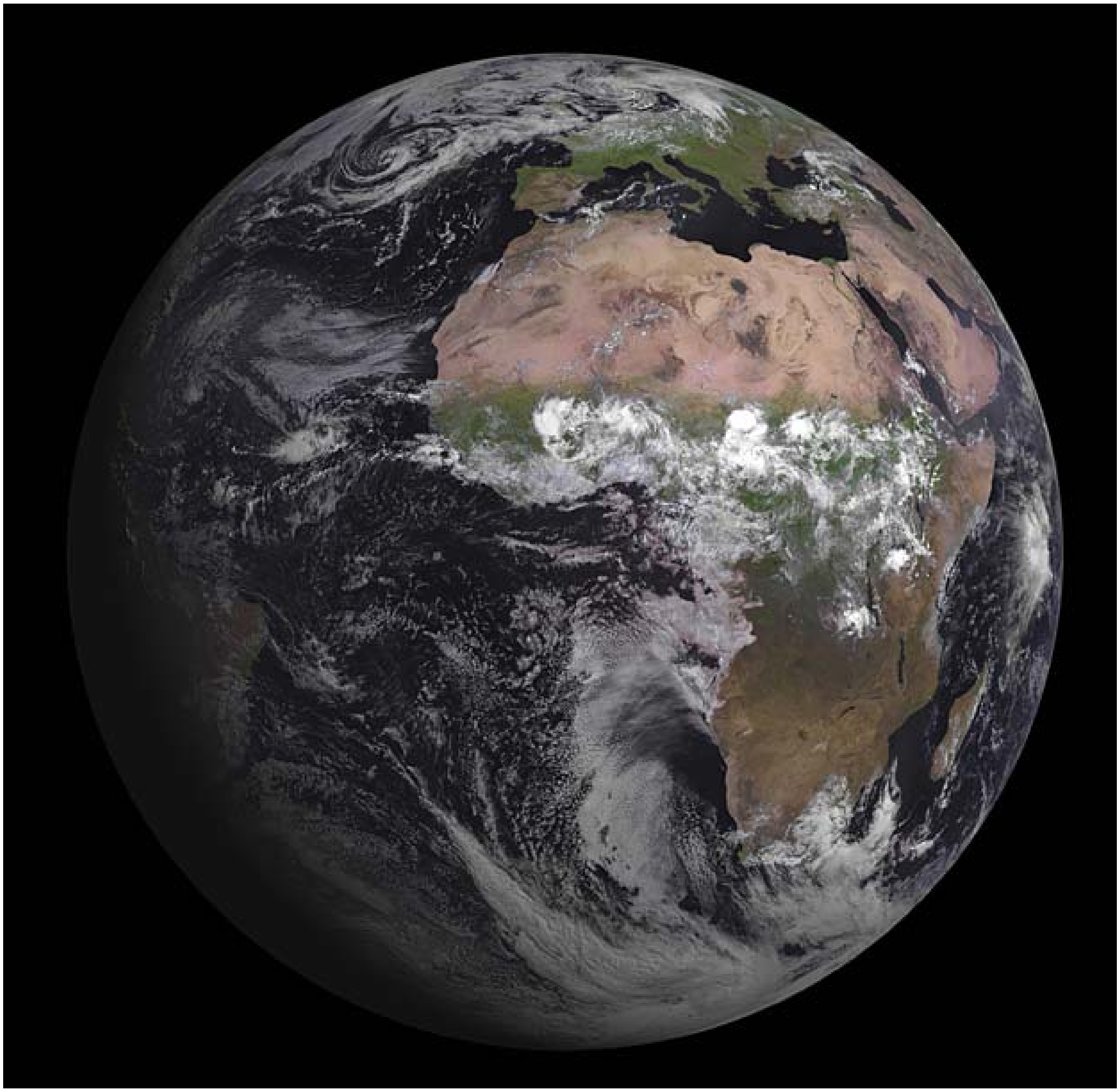

Figure 5: *Photo of Africa by European sattelite showing extensive desertification of North Africa and Arabian penisula.*