Highlights of Spanish Astrophysics VII, Proceedings of the X Scientific Meeting of the Spanish Astronomical Society held on July 9 - 13, 2012, in Valencia, Spain. J. C. Guirado, L.M. Lara, V. Quilis, and J. Gorgas (eds.)

Studying SNC achondrites: Looking for clues on Mars

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Abstract

We characterize here the main minerals forming four SNC achondrites (Zagami, Nakhla, Dar al Gani 735 and Tissint), studied with a petrographic microscope and a Raman spectrometer. Our goal is to obtain information on the physico-chemical processes that participated in their formation and delivery to Earth. We are also studying the ability of some minerals forming the different groups to retain Mars atmospheric gases during the post-shock stages [21, 2] in order to sample Mars' atmospheric evolution [15].

1 Introduction

A sample return mission from Mars has not been yet achieved, and this is why the study of meteorites naturally arrived from the red planet has become essential to obtain clues on Mars. These meteorites are classified in three types forming the so called SNC meteorites, acronym of shergottites (basaltic to lherzolitic igneous rocks), nakhlites (clinopyroxenites or wehrlites, formed as cumulate rocks) and chassignites (dunitic cumulate rocks). There is also a meteorite not included in any family: ALH 84001, an orthopyroxene-rich meteorite.

The age at which the SNC meteorites crystallized on Mars and also the age of ejection can be obtained using cross-correlated isotopic systems: shergottites would have crystallization ages from 165 to 475Myr, nakhlites 1.3Gyr, chassignites 1.35Gyr [22] and ALH 84001 would have a formation age around 4.1 Gyr [13]. The ejection ages can be measured adding the terrestrial age to the cosmic ray exposure ages (CREAs), and it seems that all Martian meteorites discovered so far come from seven different ejection events [22]. Therefore, they should come from a few launching sites: mostly the relatively young volcanic regions of Tharsis and Elysum Mons and Syrtis Major, except for ALH 84001, that would come from the ancient cratered terrain in the southern hemisphere [20].

Martian meteorites also contain small samples of Mars' atmosphere that give us some ideas about the evolution of the atmosphere of the red planet. Moreover, some aqueoisly-produced minerals in ALH 84001 seem to demonstrate that water was available in liquid state for at least a few hundred million years on Mars surface [7].

2 Experimental procedure

The meteorite samples studied here are 1 mm thick sections of Dar al Gani 735, Tissint, Zagami and Nakhla. To study them we decided to use a petrographic microscope together with a Raman spectrometer. By combining the results we can obtain information about the general composition and the origin of each meteorite.

We used a Zeiss Scope petrographic microscope to obtain several small images that we put together to create a high resolution mosaic of a whole thin section. The microscope allows us to obtain more detailed images, and to switch the illumination to bright field (provides high contrast and differentiation between densities) and dark field (allows more visibility of smooth features). Therefore, this technique is used to create a map of the sections where we can search the regions of interest for Raman spectroscopy.

We recorded micro-Raman spectra in backscattering geometry at room temperature with a Jobin-Yvon T-64000 Raman spectrometer attached to an Olympus microscope and equipped with a liquid nitrogen-cooled CCD detector. Raman spectroscopy is a technique used to study low-frequency modes in a system. Its operation is based on inelastic scattering of monochromatic light, usually from a laser. Light interacts with the excitations of the system and the result is a shift in the energy of the laser photons, which gives information about the material of the sample. Raman spectra can be collected from an area smaller than 1 μm in diameter, allowing us to get high resolution spectra. The Raman shifts are usually expressed in wavenumbers, with units of inverse length (cm^{-1} commonly).

2.1 DaG 735

Dar al Gani 735 is an olivine-phyric shergottite with a porphyritic texture, consisting of olivine megacrysts and a groundmass composed of olivine, pyroxene, maskelynite, chromite, ilmenite, phosphate and sulfide [12]. Most of the darker regions in the high resolution mosaic (Fig. 1) are zoned olivine megacrysts while the smaller ones all around the section are homogeneous olivine grains. The rest of the meteorite, lighter in color, is the groundmass. The white-to-orange layer at the bottom of the section is the outer layer of the meteorite, that shows terrestrial weathering, quite evident in that case compared to the other three meteorites. The results of Raman spectroscopy can be seen at Fig. 2. The two regions selected are a: a brighter area, and *b*: a darker area. The bright area is an orthopyroxene which spectrum is quite close to the one of enstatite, the magnesium endmember of orthopyroxene. The darker area is mainly olivine, but it also contains some calcium or iron carbonate.

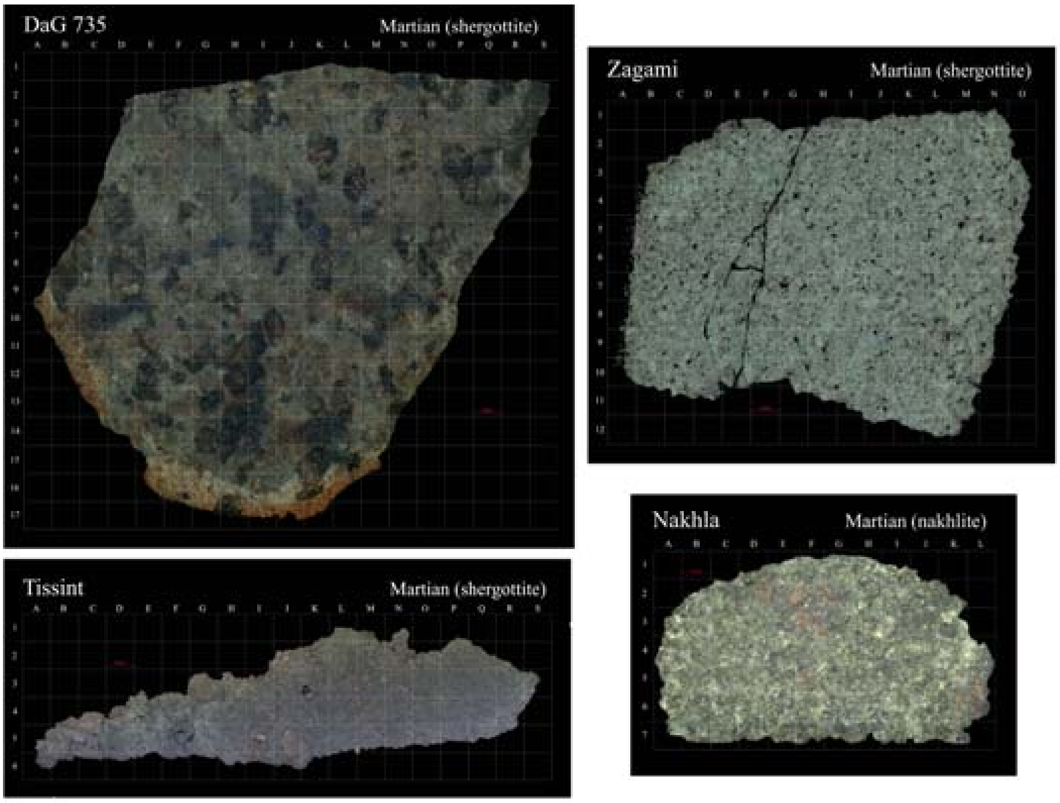

Figure 1: High resolution mosaics of a DaG 735 (left top), Zagami (right top), Tissint (left bottom) and Nakhla (right bottom) thin sections; the grid is 1 mm wide.

2.2 Tissint

Tissint is the most recent Martian meteorite to fall on Earth. It is an olivine-phyric shergottite composed of olivine macrocrysts (to 1.5 mm) and microphenocrysts (to 0.4 mm), set in a finer groundmass of patchily zoned pyroxene, plagioclase (maskelynite), Ti-poor chromite, ilmenite, pyrrhotite and minor merrillite. The Tissint high resolution mosaic (Fig. 1) shows a section mainly composed by a grey material with paler and darker areas. It also shows some fractures with black glass. The absence of weathering is remarkable. We found a different region with a brighter spot, and also several tiny veins. We applied Raman spectroscopy and the results can be seen in Fig. 2. The cracked region studied is *a*. The different region is in *b* and the veins in *c*. In *b* we selected three different points: the main different region mineral (B), the brighter area at the bottom of it (D) and the dark material next to it (A), which corresponds to the dark grey areas in *a*. In *c* we selected two points, the tiny veins (E) and

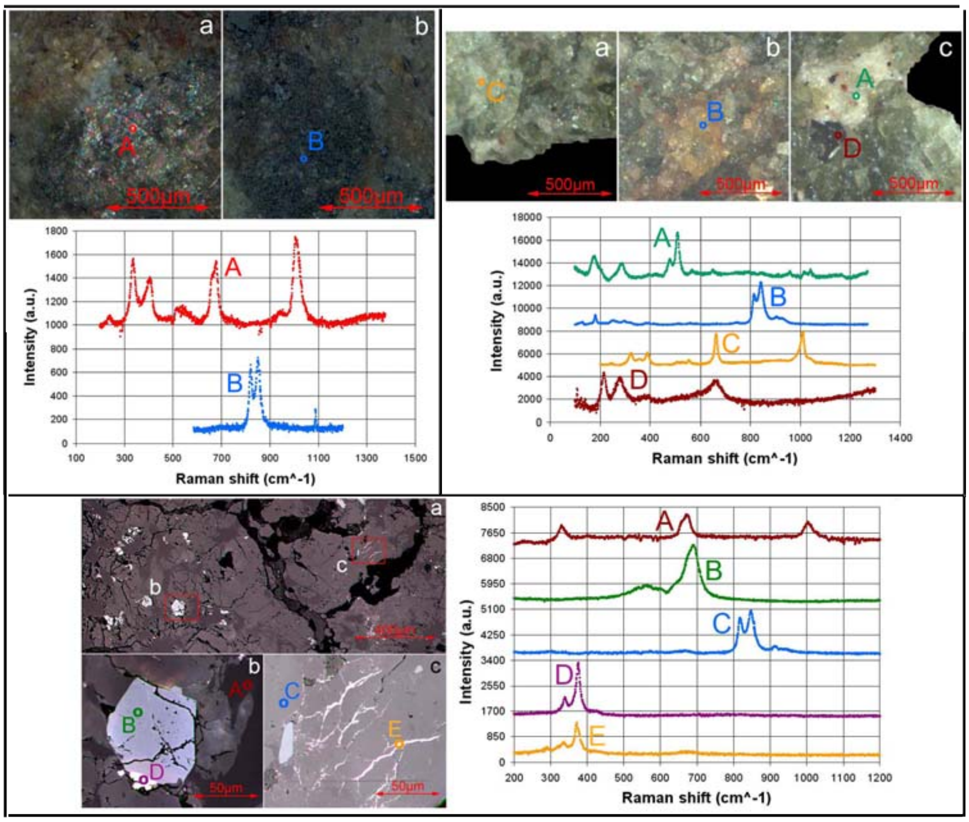

Figure 2: Optical images of DaG 735 (left top) and Nakhla (right top) and optical bright field images of Tissint (bottom), together with the Raman spectra obtained. The spectra are shifted vertically to avoid superposition. Intensity units are arbitrary as we are only interested in the shape. The beam is actually smaller than the circles shown.

the grey material surrounding them, which corresponds to the pale grey areas in *a*. A, is some poorly defined pyroxene, while C is olivine. B seems to be mainly made of chromite. However, D seems to be an iron sulfide that in E appears drifted probably as a consequence of shock.

2.3 Zagami

Zagami is a basaltic shergottite. It seems to be heterogeneous containing three lithologies, at least. One is a basalt similar to Shergotty, the type specimen of shergottites [17]; exhibits a foliated texture produced by preferential orientation of pyroxene prisms and maskelynite grains [17] and is cross-cut by glass veins of shock-melt [17]. A darkmottled-lithology is separated from the previous lithology along a sharp but sometimes irregular boundary, and contains pockets of shock-melt with Martian atmosphere within [14]. A Fe-rich lithology has been described as a residual melt [18]. Zoning of pyroxene found in Zagami is nearly identical to the one in Shergotty [19]. Plagioclase has been shocked to maskelynite in this meteorite. The high resolution mosaic of Zagami (Fig. 1) shows that this section belongs to the first lithology explained above: it exhibits a quite homogeneous green-grey groundmass mainly composed of pyroxene and black glass grains (maskelynite). There is a thin shock vein crossing the meteorite from top to bottom, also filled with black glass. The effects of weathering can not be seen so clearly as in DaG 735.

2.4 Nakhla

Nakhla gives name to the nakhlites, augite-rich igneous cumulate rocks [6], formed from basaltic magma around 1.3 Gyr ago, and containing excess crystals over what would form from pure magma. They consist in euhedral to subhedral crystals of augite and olivine (to 1 cm long) in fine-grained mesostasis [23]. These crystals contain multiphase inclusions representing trapped magma. Among these crystals is mesostasis, composed principally of plagioclase and/or glass, with euhedra of many minor minerals. Olivine and mesostasis glass are partially replaced by veinlets and patches of iddingsite. Compared to common basalts, they are rich in Ca, strongly depleted in Al, and they also contain little pre-terrestrial organic matter [9]. The high resolution mosaic of Nakhla (Fig.1) is green in color, going from a very pale color to a greenish one. The grain is well defined and fine, compared to the one in shergottites. In this section there are also some reddish areas that probably come from terrestrial weathering. We applied Raman spectroscopy on the four different mineral compositions that can be distinguished at naked eye on this meteorite due to their colors: green, orange, dark-grey and white (Fig.1). The selected specific points are shown in Fig.2, together with their spectra. A, the white mineral, is feldspar, probably plagioclase. B, the orange-red mineral, is olivine. The clinopyroxene augite, more common in nakhlites than in shergottites, is also found in this section in C, the green mineral. The black mineral, D, shows another distinctive feature of Martian meteorites, the presence of iron oxides, in the form of a mixture of hematite and magnetite.

3 Discussion

3.1 Main mineralogy of Martian meteorites

Basaltic shergottites, most of Martian meteorites, contain the clinopyroxenes augite and pigeonite plus plagioclase (crystallized to maskelynite through shock), and also can contain olivine. These meteorites also contain Ti-magnetite and ilmenite, as the main oxide phase. Some shergottites contain large (1 to 3 mm) olivine grains, and this is why they are described as olivine-phyric shergottites. These meteorites also have low proportion of feldspar and higher bulk Mg-number and contain chromite as the main oxide phase. Pyroxenes in these shergottites are even more Mg-rich than in the basaltic shergottites. Nakhlites are cumulate olivine clinopyroxenites composed of augite, Fe-rich olivine, and mesostasis. Mesostasis is mainly composed of plagioclase and alkali feldspar grains, pyroxene, Ti-magnetite, ilmenite, silica and other minor minerals [5].

Studies on mineralogy can provide clues about the source regions of these meteorites on

Mars. The young crystallization ages of shergottites imply the existence of igneous activity on Mars' surface in relatively recent times, and there is evidence for young lava flows from the Mars Global Surveyor. Furthermore, it has been seen that 100 Myr lava flows are contained in Tharsis and Elysium-Amazonis Planitia, potential sources of SNC meteorites [10]. Material similar to the composition of nakhlites has been tentatively identified in the Valles Marineris. It seems quite probable that only ALH 84001 comes from the ancient southern highlands.

3.2 Impact features and shock modified minerals

All Martian meteorites have suffered moderate to strong effects induced by shock waves propagated through the mineral structure. It is generally accepted that these meteorites were ejected from Mars by large-scale impacts. These impact and ejection processes imply that Martian meteorites experienced extreme physical conditions that caused significant changes in some of their minerals, even an implantation of Martian atmospheric gases [2].

Shock effects can be seen through several known shock effects like shock-produced veins and melt pockets, the presence of of post-stishovite polymorphs of SiO_2 [8], and others, but the transformation of plagioclase into maskelynite is specially significative as the refractive index of this mineral is usually used to estimate the peak shock pressures of SNC meteorites. These peak shock pressures can provide information about the original meteoroids, as, according to the spallation model [16], the size of the displaced shocked rock fragments is inversely proportional to the shock intensity and the shock peak pressures increase in the downward direction from the surface and decrease in the radial direction from the impact point. Together with information about impact processes the sizes of the parent craters and launching conditions from Martian meteorites can be simulated [11].

3.3 Clues on Mars's atmospheric evolution

The composition of gas found in impact-produced melt glass in the shergottite EETA79001 was crucial to put the origin of SNC meteorites in Mars [2]. These gasses include volatiles with compositions that fit quite well the abundances measured by Viking on Mars, and are mostly trapped in maskelynite and silicate glass by high shock events [4].

Neon, argon, krypton and xenon in shock glass in several SNC meteorites have been studied thoroughly, and its abundances compared to the ones obtained from Mars [3]. The measures of Ar/Kr/Xe elemental ratios for the Martian atmosphere were obtained with higher precision in meteorites than with Viking [3], reason why the trapped gases in shergottite glass are considered more representative of the recent Martian atmosphere. Measures in shergottites and Chassigny apparently show a mix between Martian atmosphere and a second trapped component probably characteristic of the Martian interior [1], which is accepted to represent noble gases from the Martian mantle. A third component found in some SNC meteorites could represent trapped ancient Martian atmosphere. Therefore, SNC meteorites can be an important source of information about the actual and even ancient Martian atmosphere, giving us clues about the evolution of the atmosphere, or allowing us to corroborate the results obtained from models [15].

4 Conclusions

The study of four different SNC meteorites allow us to reach the following conclusions:

1 Raman spectroscopy is an excellent non-destructive technique that allows to characterize the main minerals forming SNC achondrites.

2 SNC meteorites are samples of Mars's surface mineralogy but biased towards high-strength materials capable to survive the shock pressures induced by impacts.

3 Some SNC achondrites exhibit minerals altered by shock. An example is the recently fallen Tissint shergottite, that shows shock veins in its inner structure.

4 Trapped gas in chassigny and shergottites can make these meteorites useful for obtaining new clues on Mars's atmospheric evolution.

Acknowledgments

Prof. Narcís Mestres who gave us access to the Raman spectrometer, Prof. Jordi Llorca that allowed us to use the UV spectrometer, Prof. José M. Madiedo who provided the section of DaG 735 and Prof. Hasnaa Chennaoui who provided us the section of Tissint.

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