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Mineralogy of Basaltic Material on the Minor Bodies of Our Solar System

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1. Introduction

The main idea of this chapter is to study the presence of basaltic material in the minor bodies of our Solar System. Basaltic material in the solar system is found not only in the surface of the terrestrial planets, but also on the surface of the Moon and asteroids. This material is reckoned as the result of an extensive geochemical differentiation.

Our modern understanding of the formation of the solar system is that it began in a cold cloud of gas and dust under conditions similar to other nebulae. After the dissipation of the gas and dust, the nebula continues to evolve as the planetesimals form larger bodies. In the process, these larger bodies are heated by collisions and radioactive decay. Asteroids are the remnants of these planetesimals that could not form a bigger planet. The materials currently present in the asteroids are the most primitive, less evolved one, and that's why is important to understand.

From this material, the less evolved is called chondritic and is composed with the same material (without the volatiles) as our star, the Sun. After accretion, the parent body consists of primitive material and is heated internally by decay energy of short-lived nuclides such as ^{26}Al (with a half-life of 0.72 Myr) and ^{60}Fe (with a half-life of 2.6 Myr). Some planetesimals accreted to form bigger objects but no thermal evolution was present and today the original chondritic material can be observed. Some other planetesimals, have a most complicated thermal evolution. Partial fusion of the initial chondritic material makes, first, the heavier liquid (Fe-Ni-S) migrate to the centre and second, the lighter silicated liquid (SiO_2) migrates to the surface. The final result of such a process is a body with a dense metallic core, a mantle of lighter olivine-rich material and an even lighter basaltic surface. This structure is seen in the Earth, the Moon, and terrestrial planets (Figure 1).

There is one particular case in which the original planetesimal formation of a differentiated small body can be observed. Initially, remote observations using ground-based telescope showed that the surface of the asteroid (4) Vesta is composed of basaltic material. Vesta with a mean diameter of 530 Km and a basaltic surface was an excellent candidate to be a small terrestrial planet. After the discovery of the basaltic crust on Vesta, the idea of a proto-planet, that could not grow to a bigger planet but was differentiated start to be accepted in the community.

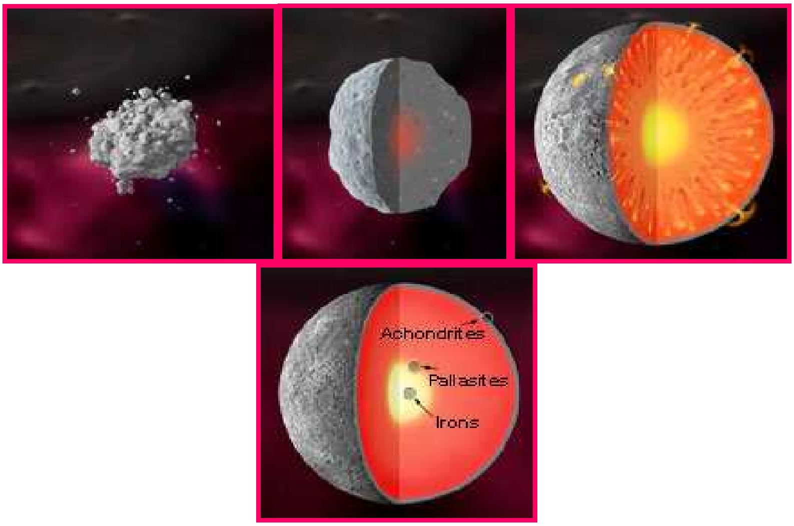

Fig. 1. Chronological step of the formation of a differentiated planetesimal. From left to right, the agglutination, heating, differentiation in a Fe-Ni nucleus, silicate mantle and basaltic crust and finally the identification with different kinds of meteorites.

Then, more asteroids' surfaces showed the same composition. These smaller asteroids (kilometre sized) were detected in the same region of Vesta and later were proved that they come from a craterization event on Vesta's surface. Then, asteroids with near Earth orbits (NEAs) were also identified to have basaltic surfaces. Later, the relation between a rare classes of meteorites (Howardites-Eucrites-Diogenites, HED) and these asteroids were linked together and the problem seems to be solved (meteorites are pieces of asteroids found on the surface of the Earth).

The proposed scenario was that great impacts excavated the surface of Vesta, producing a swarm of small fragments. Part of them, were injected into dynamical resonances which pumped up their orbital eccentricities, and were thus ejected due to close encounters with terrestrial planets. Most of these fragments fell directly into the Sun or escaped from the Solar System, but part of them remained in near-Earth orbits. Further collisions ejected fragments into Earth-colliding orbits, becoming the HED meteorites recovered on Earth (Drake 2001). Several observational facts corroborate this scenario: the identification of a Vesta dynamical family (Williams, 1989; Zappalá et al., 1990) called Vestoids, the confirmation that small asteroids in the region near (4) Vesta do have a basaltic surface composition (Binzel and Xu, 1993; Burbine et al., 2001) called V-type asteroids, the identification of a large impact basin on (4) Vesta (Thomas et al., 1997), the discovery of several NEAs with basaltic mineralogical surface composition (McFadden et al., 1985; Cruikshank et al., 1991; Binzel et al., 2004; Duffard et al., 2006) and, last but not least, the identification that most of the HED have similar isotopic composition, indicative of a common origin (Clayton and Mayeda, 1983, 1996; Mittlefehldt et al., 1998). The problem seems to be solved, and all the basaltic material was coming from the surface of Vesta, the only large enough asteroid to be differentiated.

But, there are few very important observations, however, that do not readily fit into an all-encompassing Vesta-HED story. A small (~30km diameter) basaltic asteroid, (1459) Magnya, was identified in the outer asteroid belt (Lazzaro et al. 2000). Magnya was proved not to come from Vesta. It was the first one, and then followed by the discovery of several others basaltic asteroids, all of them not related to Vesta (Duffard and Roig, 2009; Moskovitz et al. 2008).

On the other hand, in the field of meteorites, more precise laboratory techniques allows to identify that some HEDs are different from the main group. Meanwhile, more basaltic meteorite findings showed that some of them are completely different from the HEDs in the oxygen isotopic plot (Yamaguchi et al. 2002, Bland 2009.).

In Figure 2 is plotted all the basaltic material identified in the minor bodies, principally on the Main Asteroid Belt. On this plot of semi-major axis versus eccentricity of the orbits, Vesta is in the middle of the family cloud (black dots). The Vesta family is identified as fragments that can be dynamically linked with the big asteroid. Then Vestoids (blue squares) are kilometre sized asteroid, identified to have a basaltic surface and out of the family limits. The identification is done taken a reflectance spectrum of the surface (Florckzak et al. 2002). The origin of these objects should be Vesta but they suffer a dynamical process, which change the orbit and took it out from the limits of the family (Carruba et al. 2005). Magnya (at 3.18 AU) and several other small basaltic asteroids in the outer main belt (semi-major axis bigger than 2.5 UA) are all not related to Vesta. Finally, the basaltic SLOAN candidates are marked as green squares. The Sloan Digital Sky Survey Moving Objects Catalogue (SDSS-MOC; Ivezic et al., 2001; Juric et al., 2002) was used to identify candidate V-type asteroids. The SLOAN photometric survey obtained the photometry in 5 different wavelengths of several thousands asteroids. From that, the identification of the V-type candidates is done and at the end, confirmed spectroscopically (Duffard and Roig, 2009).

In summary, the asteroid Vesta remains the only big intact basaltic asteroid. Vesta has a swarm of near 4000 objects that are fragments from collisions on its surface. These small asteroids are fragments of the crust of Vesta and can give us information on different depths of the crust. Studying these vestoids give us clues on the different depths and is the only way to study the interior of a body of that size.

Although, both the smaller Vestoids and Magnya are clearly basaltic in nature, the Vestoids are related to Vesta, but Magnya and other in the outer main belt are not. Meteorites HEDs, NWA011, and Ibitira have very similar basaltic mineralogy, but appear to have distinct parent bodies, as it will be shown in next section. As shown in Figure 2, basaltic material is not only present in the Vesta region, but also in different parts of the Main Asteroid Belt. All the small asteroids found that are not related to Vesta are small (less than 20 km) and should be pieces of the crust of a larger differentiated object. Still not answered questions are: if the pieces of the crust are observed today, why the pieces of the mantle or nucleus of that body are not observed? If the body that generated that fragments was not completely destroyed, why it is not found? More searches looking for basaltic material not related to Vesta is in a urgent need.

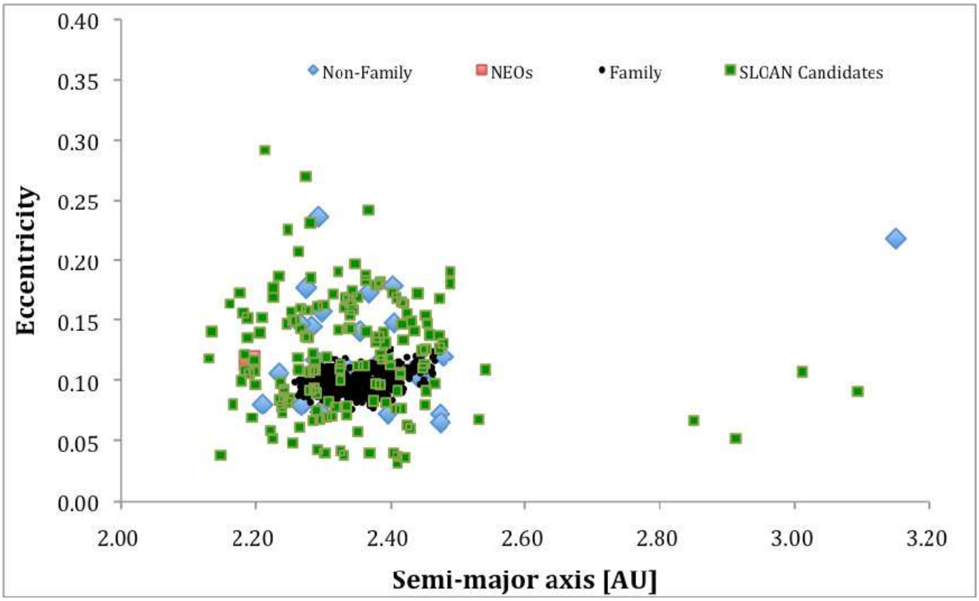

Fig. 2. Semi-major axis vs. eccentricity for the entire sample of basaltic asteroids identified until now.

2. Basaltic meteorites

One criterion to classify the meteorites is in two big groups: **chondritic** and **achondritic**. The chondritic meteorites are samples of the most primitive material, the less altered (thermal, aqueous, radiated, etc). They present chondrules that are millimetre-sized spheres formed in the initial stage of the Solar System.

Achondritie meteorites are those that suffered extreme metamorphosis from the original chondritic material. Achondrite meteorites are divided in **Primitive Achondrites** (Acapulcoites, Lodranites, Brachinites, Winonaites, Urellites and the ungrouped Primitive Achondrites), **the HED group** (Howardites, Eucrites, and Diogenites), the other **evolved asteroidal achondrites** (Angrites and Aubrites), **the Lunar group** and finally the Martian meteorites called **SNC group** (Shergottites, Nakhlites and Chassignites). All these objects are Stony meteorites. On the other hand, there are the Stony-iron and Iron meteorites that represent the transition between mantle-nucleus and nucleus, respectively.

The Eucrites are named for a Greek word meaning "easily distinguished". Representing the most common class of achondrites, more than 100 Eucrites are known, excluding all probable pairings. Although they are easily distinguished from chondrites, they closely resemble terrestrial basalts. Actually, Eucrites are extraterrestrial basalts; volcanic rocks of magmatic origin, representing the crust of their parent body, thought to be Vesta. They are primarily composed of calcium-poor pyroxene, pigeonite, and calcium-rich plagioclase, anorthite. Additionally, Eucrites often contain accessory minerals such as silica, chromite, troilite, and nickel-iron metal. Based on mineralogical and chemical differences, the Eucrites have been further divided into three distinct subgroups: the non-cumulate group, the cumulate group, and the polymict group. In the microscope, they resemble terrestrial lava flows, and for a long time cosmochemists figured that Eucrites formed in the same way terrestrial basalts form, by partial melting of the interior of the parent body. However, assorted geochemical arguments, especially the concentration of siderophile elements (they concentrate in metallic iron), suggest that the parent body was totally melted (or nearly so) when it formed. As it crystallized, the last 10-20% of magma would have a composition like the Eucrites. Of course, somehow that magma has to be squirted onto the surface to make lava flows. Nevertheless, it is clear that Eucrites formed as lava flows. Their ages indicate that it happened 4.5 billion years ago.

The Diogenites are rare and this group consists only of about 40 members if all probable pairings are excluded, especially those that have been found in the ice fields of Antarctica. They are named for a Greek philosopher of the fifth century B.C., Diogenes of Apollonia. Mineralogically, the Diogenites are composed primarily of magnesium-rich orthopyroxene, with only minor amounts of olivine and plagioclase. The pyroxenes are usually coarse-grained, suggesting a cumulate origin for the Diogenites in magma chambers within the deeper regions of parent body's crust. They are intrusive igneous rocks similar to plutonic rocks found on Earth, and they experienced much lower cooling rates than did the Eucrites, which allowed the pyroxene to form sizeable crystals.

Howardites are named for Edward Howard, a renowned British chemist of the 18th century and one of the pioneers of meteoritics. They are nearly as rare as Diogenites, and there are only about 50 members to this group if all probable pairings are excluded. Consisting primarily of eucritic and diogenitic clasts and fragments, Howardites are polymict breccias. However, they also contain dark clasts of carbonaceous chondritic matter and impact melt clasts, indicating a regolith origin for the members of this group. The Howardites represent the surface of the parent body, a regolith breccia, consisting of eucritic and diogenitic debris that was excavated by a large impact. A schematic model of four hypothetical impacts into the layered crust producing different types of Eucrites is shown in Figure 3.

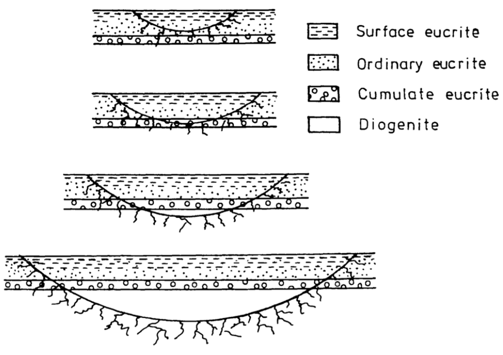

Fig. 3. A model of the layered crust of the HED parent body. (Figure from Takeda, 1997).

An important tool to identify the parent body of a group of meteorites like the HEDs is the oxygen isotopic plot. Oxygen has three stable isotopes with mean terrestrial abundance ratios: $^{17}O/^{16}O$ = 1/2700 and $^{18}O/^{16}O$ = 1/490. These ratios are variable in natural materials due to a variety of physical and chemical processes, ranging from stellar nucleosynthesis to ordinary mass-dependent chemical fractionation. As a natural isotopic tracer, oxygen has an advantage over other light elements, such as hydrogen, carbon, and nitrogen, in that the combined variation of two isotope ratios ($\Delta^{17}O = {}^{17}O/{}^{16}O$ and $\Delta^{18}O = {}^{18}O/{}^{16}O$) helps to identify the underlying process (Clayton 2002).

Chemical and physical processes within an isolated planetary body, such as the Earth, Moon, and Mars, almost always obey a simple mass-dependent relationship between variations in $\Delta^{17}O$ and $\Delta^{18}O$ ratios which is nearly 0.52. All rocks from the Earth should plot in a line of slope 0.52 and this line is called the Terrestrial Fractional Line (TFL). All meteorites from the same parent body should plot in a line with the same slope but parallel to the TFL. This oxygen isotopic plot helps us to identify if a meteorite can came from the same parent body as other one.

This is what it can be seen in Figure 4 where the slope of 0.52 is taken out and several HED meteorites plotted out of the horizontal line. Most of the Eucrites and Diogenites plot on the same line (the Eucrite Fractional Line – EFL) but there are several other Eucrites that plots outside the line, indicating the different origin.

From the basaltic meteorites, there are at least pieces from seven different crusts. On the basis of its unusual oxygen isotope composition, NWA 011 (out of the plot) is presumed to derive from a basaltic parent asteroid other than (4) Vesta. Six anomalous Eucrite-like basaltic meteorites were identified on the basis of their oxygen isotope compositions (and, in some cases, unusual mineralogy): Ibitira (a meteorite that fell in Minas Gerais, Brazil, in 1957), Asuka-881394 (found in the Queen Maud Land region of Antarctica, 1988), PCA 91007 (found in the Pescora Escarpment region of Antarctica, 1991), Pasamonte (fell in New Mexico, USA, 1933), NWA 1240 (found in the Sahara, 2001) and Bunburra Rockhole, some of them closer to the Angrite Fractional Line - AFL.

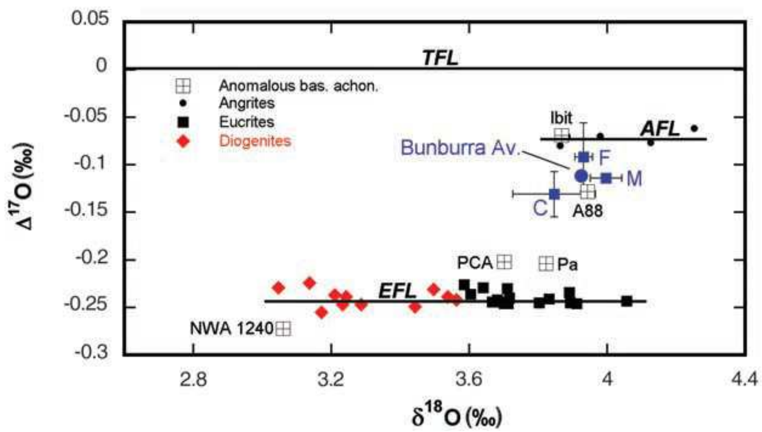

Fig. 4. Oxygen Isotopic plot showing the TFL and most of the Eucrites. Figure taken from Bland et al. (2009).

As was mentioned in the previous section, if a body suffered a differentiation, its internal structure is divided in a Fe-Ni nucleus, then a silicate (mostly olivine) mantle and a fine crust. If this kind of body is completely destroyed you can have samples of the nucleus (iron meteorites), the mantle (stony-iron meteorites) and the crust (basaltic meteorites).

From the iron meteorite collection it's proved the existence of at least 60 different nucleus (Bottke et al. 2006). This mean that at least 60 different differentiated asteroids were completely destroyed and some material were found in the surface of the Earth.

In summary, differentiation seems to be normal in the early solar system. The principal heater to produce the differentiation is the decay of ^{26}Al that has a half-life of 0.7 My. In that case, all the differentiated planetesimals formed in the first 5 My of formation of the Solar System. There are several works modelling Vesta type formation reaching that conclusion (Gupta and Sahijpal 2010 and references therein). After the formation of this small (400 Km or less in diameter) differentiated planetesimals, bigger differentiated planets start to be formed and Mars (after 12 My) or the Earth (after 32) were formed (Kleine et al. 2002). From the meteorite suite (iron meteorites) it can be inferred that at least several dozens of differentiated asteroids were formed.

3. Vesta, vestoids and V-type asteroids: Mineralogy

In the previous sections the basaltic material coming from Vesta was introduced. Until 10 years ago, it was a general thought that all the basaltic meteorites and all the basaltic asteroids are coming from this asteroid. Starting with the discovery that the surface of Magnya is composed of basalt, and then discovering several others basaltic asteroids not related to Vesta, those facts showed that Vesta is not unique. More precise laboratory techniques and meteorite founds showed the same evidence, there were more differentiated parent bodies in the beginning of the Solar System.

In this section it will be shown different techniques to analyze the spectroscopic features in the reflectance spectra of basaltic asteroids and compare with the meteorites. To obtain information on the mineralogy of asteroids, remote sensing using telescopes is a powerful technique. The most common and expanded way to obtain mineralogical information on the surface of an asteroid is the reflectance spectroscopy in the visible and near-infrared (VNIR). In this spectral range (0.4 – 2.5 microns) there are several absorption bands that can be identified to characterize the mineral/s present in the surface of the asteroid. With a suitable spectrograph in a medium size telescope, the reflectance spectra of the asteroid can be obtained. As the asteroid only reflects the light from the Sun, the final spectra must be corrected extracting the Sun light component. This final result has only the information on the asteroid's surface.

One interesting technique is to compare meteorites spectra with asteroid's spectra. As the asteroids are only accessible by remote sensing, like the reflectance spectra, lets do the same with the meteorites. The Reflectance Laboratory (RELAB) is one of the large existing databases of reflectance spectra (Pieters 2004). One of the best characteristics is the homogeneity in the spectra acquisition. In RELAB database it can be found reflectance spectra of meteorites and minerals from 0.3 to 2.6 microns, in same cases taken with different grains sizes, temperatures, and other conditions.

The first step to identify the mineralogy of an asteroid is the comparison of the reflectance spectra of the asteroid with one taken from the reflectance spectra databases (Figure 5). All the basaltic reflectance spectra are characterized by the presence of prominent absorption bands, near 1 and 2 μm, indicative of a mixture of pyroxene and possibly olivine. The spectrum of pyroxene is dominated by its characteristic absorption features near 1.0 and 2.0 μm. Olivine spectrum is dominated by a complex absorption centred near 1.0 μm. In both cases, these absorptions are produced by spin-allowed electronic transition of Fe^{2+} in distorted octahedral (M1 and M2) crystal field sites (Burns, 1970).

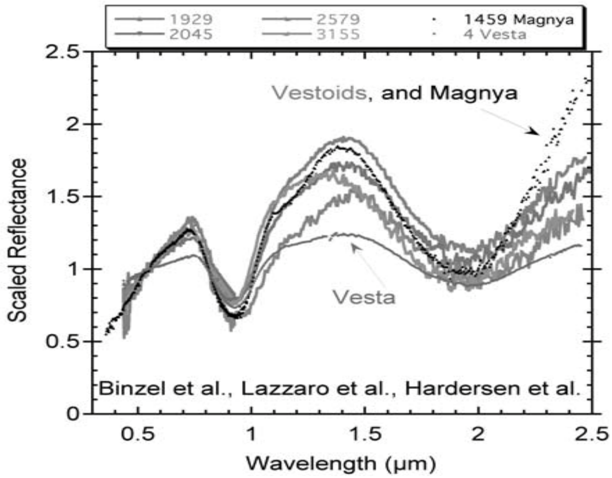

Fig. 5. Reflectance spectra of asteroid (4) Vesta, Magnya and some Vestoids. It can be seen the two characteristics absorption bands near 1 and 2 microns. Figure taken from Pieters et al. 2005.

3.1 Mineralogical analysis

One of the most important parameters in order to characterize the mineralogy associated with this kind of spectra is the position of the centre of the absorption bands near 1 and 2 μm. Two parameters can be used: the *band minimum* and the *band centre*. These are defined (Cloutis and Gaffey, 1991) as the wavelength position of the point of lowest reflectance before and after the removal of the continuum, respectively.

The spectra obtained after the removal of the continuum were used to compute the position of the *band centres*, using the same procedure adopted for computing the minima and maxima. These final spectra were used also to compute the *band areas* and the *band depths*. Following Cloutis (1985), *band area* is defined as the area enclosed by the spectral curve and a straight-line tangent to the respective maxima. By convention *band area I* is between the maxima at 0.7 and 1.4 μm, while *band area II* is between the maxima at 1.4 and 2.4 μm. The parameter *BAR* is then defined as the ratio between the *band area II* and the *band area I*. Finally, the *band depth I* and the *band depth II* are measured as the ratio of the reflectance maximum at the peak between *band I* and *band II* to the reflectance of the *band I centre* and to the reflectance of the *band II centre*, respectively.

Each of the above computed spectral parameters are diagnostic of the associated mineralogy present on the surface of the observed asteroids. The relationship between these parameters and the mineralogy for reflectance spectra, particularly pyroxene and olivine, has been studied in various papers over the last years (Adams, 1974, 1975; King and Ridley, 1987; Cloutis and Gaffey, 1991) and recently reviewed by Gaffey et al. (2002) and Duffard et al (2004, 2005).

As stated above, *band centres* are among the most important diagnostic parameters of the mineralogy in a spectrum. According to several authors (Adams, 1974; Cloutis and Gaffey, 1991) in most pyroxenes and in the basaltic achondrites there is a strong correlation between the position of *band I centre* and *band II centre* and the associated mineralogy. For example, orthopyroxene bands shift to longer wavelengths with increasing amounts of iron, whereas clinopyroxene bands shift to longer wavelength with increasing calcium content. The parameter BAR, which is the ratio between the *band areas* II and I, can give information about the abundance of olivine since for pure olivine this parameter is essentially zero for all the phases.

In figure 6 its shown the relationship between the BAR parameter and band I centre for a sample of achondrite meteorites. In this plot its marked the regions where the meteorites with high content of olivine (Ol), the ordinary chondrites (OC) and the basaltic asteroids (BA) should plot (right panel). In this plot, HED meteorites and some other achondrites are plotted. In the right panel it’s shown the same areas, but V-type asteroids and some other minerals are plotted. Due to the large error in the BAR parameter determination for Magnya, this asteroid plots in an extended region.

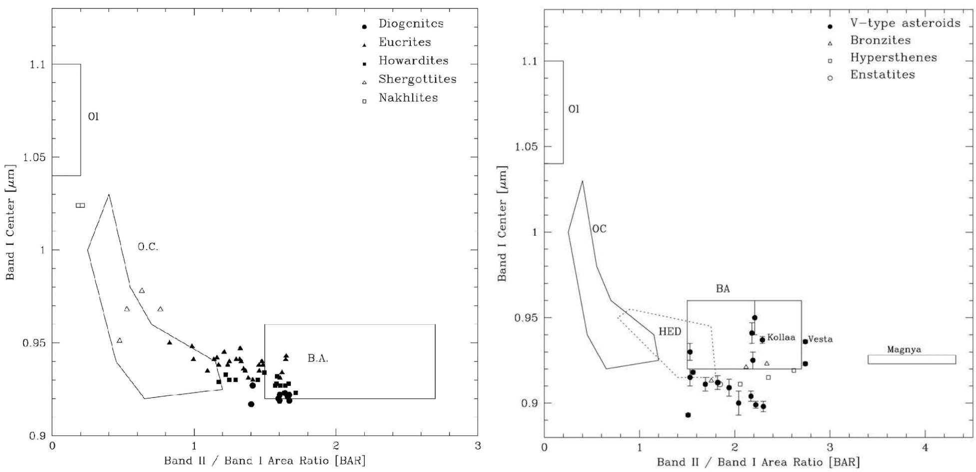

Fig. 6. BAR parameter versus band I centre for the achondrite meteorites: Howardites, Eucrites and Diogenites (left panel) and for some V-type asteroids. Figure from Duffard et al. 2005.

The pyroxene composition, i.e., the molar calcium, [Wo], and iron, [Fs], contents can be obtained from the values of the absorption band centres near 1 and 2 μm using equations derived by exhaustive laboratory calibrations performed by several authors (Adams, 1974, 1975; King and Ridley, 1987; Cloutis and Gaffey, 1991). These equations have recently been recompiled by Gaffey et al. (2002) and in order to derive the pyroxene composition they are used in an iterative mode.

This relation was, therefore, used to compute the relative abundance of the [Wo] and [Fs] contents, as shown in Figure 7. In this figure it can be seen the determination of [Wo] and [Fe] content for all the asteroids determined in this work and from literature (Duffard et al. 2004, deSanctis, et al. 2011). The measured ranges of the average [Fs] and [Wo] contents of pyroxene (Mittlefehldt et al. 1998, Takeda 1997) are for the Eucrites (in red): [Fs] ~ 30–55 and [Wo] ~ 6–15; Howardites (in blue): [Fs]~31–42 and [Wo]~4–8; Diogenites (in green): [Fs]~20–30 and [Wo] ~ 1–3. Asteroidal values using the mentioned equations are in the range of HED meteorites, considering the large errors (+/- 5) in the determination of [Fe] and [Wo].

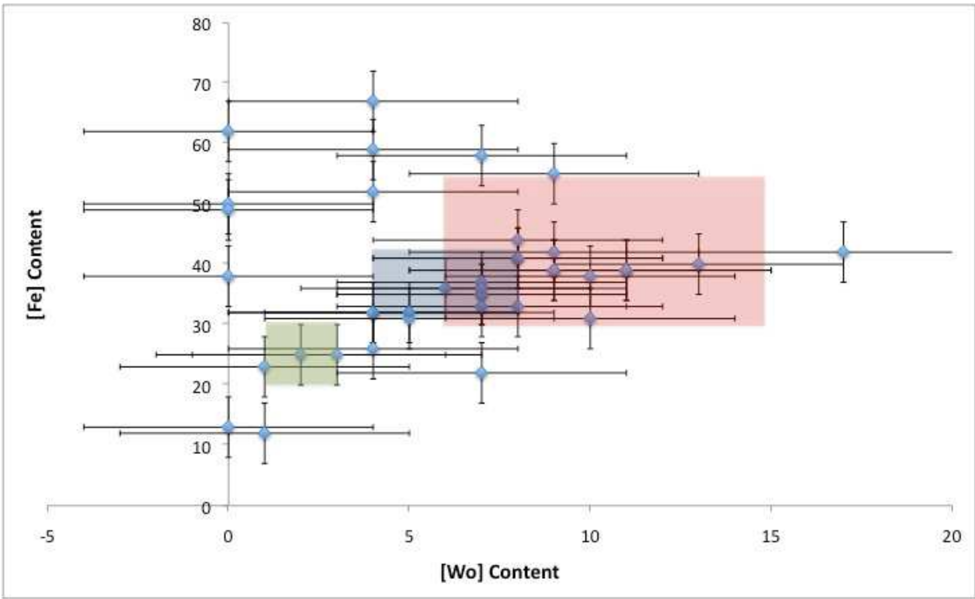

Fig. 7. Molar contents for the observed V-type asteroid obtained from Duffard et al. 2004 and DeSanctis et al. 2011.

In conclusion, a large and homogeneously obtained set of data redefines the regions where the different meteorite classes plot in spectral parameters spaces. Moreover, it is possible to study how these regions can be displaced by different physical properties, such as grain size, temperature, and mineralogy. However, when applying this kind of plot to the specific problem of relating classes of meteorites to types of asteroids, it can be observed that larger variations than expected do appear. This indicates either that it is indeed plotted different mineralogies or that this kind of plot is not appropriate for such a study. The second hypothesis is more favourable (Duffard et al. 2005). This kind of plot is only indicative on the mineralogy present on the surface of the asteroid. Another method is necessary to confirm or refute the minerals present on the asteroid. Of course, more data on meteorites and asteroids is needed before a secure conclusion is reached and the genetic link between specific members of these two populations is definitively established.

3.2 Modified Gaussian Model (MGM)

Another powerful technique to determine the mineralogy of a remote observed asteroid is the analysis using the Modified Gaussian Model (Sunshine et al. 1990). The Modified Gaussian Model (MGM) arose from the necessity of a more general fitting method of analysis that could resolve and distinguish individual spectral absorption features and representing them with discrete mathematical distributions. The use of this quantitative correlation is only dependent of the spectrum itself. MGM method supplies an objective and consistent tool to examine the individual absorption features of a spectrum (Sunshine at al. 1990).

This method uses deconvolution to represent absorption bands as discrete mathematical distributions (modified Gaussians) taking into account the physical processes that lead to the formation of the bands. Each individual absorption band is defined by three parameters: centre, width and strength. From previous analysis (Section 3.1) it's known that the surface of basaltic asteroids could be mainly composed of pyroxene (as they are classified as V-type asteroids). Following Sunshine and Pieters (1993), it can be computed the proportion of orthopyroxene or Low Calcium Pyroxene (OPX or LCP) and clinopyroxene or High Calcium Pyroxene (CPX or HCP) present in the surface of the observed asteroids. Eight individual absorption bands were used for each spectrum, corresponding to the individual absorption bands of both end-members. Sunshine and Pieters (1993) showed that the band centres of the primary absorptions remain essentially fixed; at 0.91 and 1.83 μm for OPX, and 1.02 and 2.29 μm for CPX, and that only the relative band strengths change as a function of CPX and OPX abundance. This effect can be quantified by computing the ''Component Band Strength Ratio'' (CBSR) defined as the ratio between the band strengths of OPX and CPX components at 1 and 2 μm. This CBSR should be the same in the 1 and 2 μm region if the fit is correctly done with both pyroxenes.

Given a set of different MGM input parameters (individual absorption band centres, widths and strength) and operating the first step of the fitting process, it must be met strict sequential steps in order to reach physically coherent results. The calibration procedures, applied to the whole sample can be summarized as follows. Given the input parameters the first step is to proceed to an initial fit. Once the fit-result is obtained then is necessary to proceed to check the bandwidth calibration and assure it is within the tabulated values (Sunshine and Pieters 1993). All the values of bandwidth to respect of band centres found may fall within a similar and expected region. Band centre calibration follows and again, comparing the results with the tabulated values, it should confirm if the LCP/HCP ratio band near 1 and 2 μm (the component band strength ratio,the CBSR) region is acceptable. All band centres obtained should fall within the expected area of the calibration data (Adams 1974). If all these conditions are met then the final result is achieved. The individual absorption bands all combined can describe the complex absorption bands, if not then a change in the band parameters (centres, widths, strength) is needed and the process should start again. An important addition to this procedure is to always keep in mind the fit of the residual and maintain its structures to a minimum (Canas et al. 2008).

In figure 8 (left) it's shown the spectra of Eucrite meteorite Juvinas, taken from RELAB, the individual absorption bands for LCP and HCP, the combined fitted spectra superimposed to the meteorite spectra, and the extracted continuum. In the upper part of the plot it's shown the residual that is the difference between the spectra and the fitted one. No structure or band is seen in the residual. Individual's bands of the HCP and LCP are marked in the plot. In the right panel, a similar fit is shown for the basaltic asteroid 2003 YG118. The visible part of the spectra (0.5 – 0.9 μm) is taken with one instrument and the near infrared part (0.8 – 2.5 μm) with another instrument. Both spectra are joined using the mutual region near 0.9 μm.

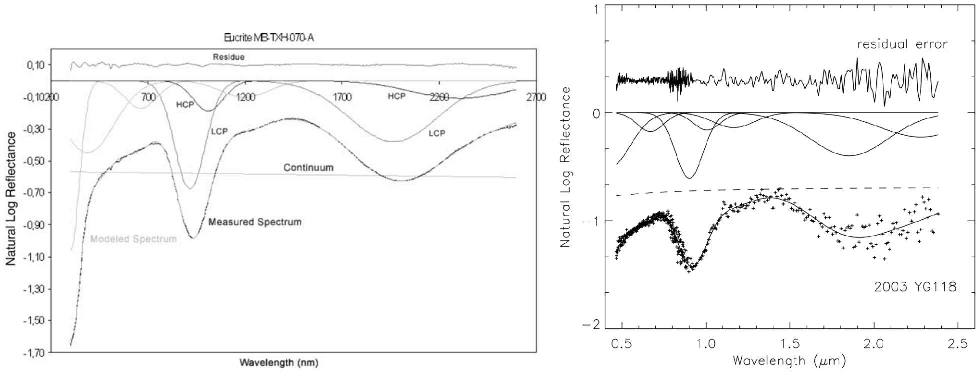

Fig. 8. An example of a MGM fit for the Eucrite Juvinas (MB-TXH-070-A) taken from the RELAB database) on the left panel and for the basaltic asteroid 2003 YG118.

After the acquisition of the spectra in the telescope, when the spectra are calibrated and ready to be analyzed, the MGM technique is applied. The first step is to verify the spectral analysis applying it to a sample of Eucrites/Diogenite meteorites. Then, the technique should be extended to a set of V-type asteroids.

Sunshine and Pieters (1993) derived a relationship from spectra of a set of powders of known proportions of high- and low-calcium pyroxenes and this relationship can be used to separate meteorite classes that have undergone various degrees of igneous processing (Sunshine et al. 2004).

3.2.1 MGM on meteorites

To build confidence in our results and to provide a basis for comparison to asteroid spectra, the first step is to examine the spectra of 25 Eucrites and 10 Diogenites (obtained from RELAB database) using MGM. These kinds of reference spectra were selected due to the spectral similarity and the higher signal to noise ratio in the meteorite spectra. On the other hand, the application of the MGM analysis in V-type spectra was recently used on the Eucrite Bouvante and V-type asteroid (4188) Kitezh (Sunshine et al. 2004), in asteroid (4) Vesta (Vernazza et al. 2005), in five Eucrites (Mayne et al. 2006), 2 V-type NEOs (deLeón et al., 2006) and 3 another V-type NEOs (Canas et al. 2008).

The MGM fit to the Eucrite meteorites indicates the presence of both low- and high-calcium pyroxene but does not require olivine to fit the overall spectrum. Similarly, the MGM fit to the Diogenite meteorites indicates the presence of only LCP pyroxene. The fitting procedure was done as described before and in all cases the restrictions were reached. In figure 9 it is shown the band centres and band widths in function of wavelength for the sample of selected Eucrite (open circles) and Diogenites (black circles) meteorites. As can be see in the figure 9, for all the fittings the individual's bands centre of the LCP and HCP end-members

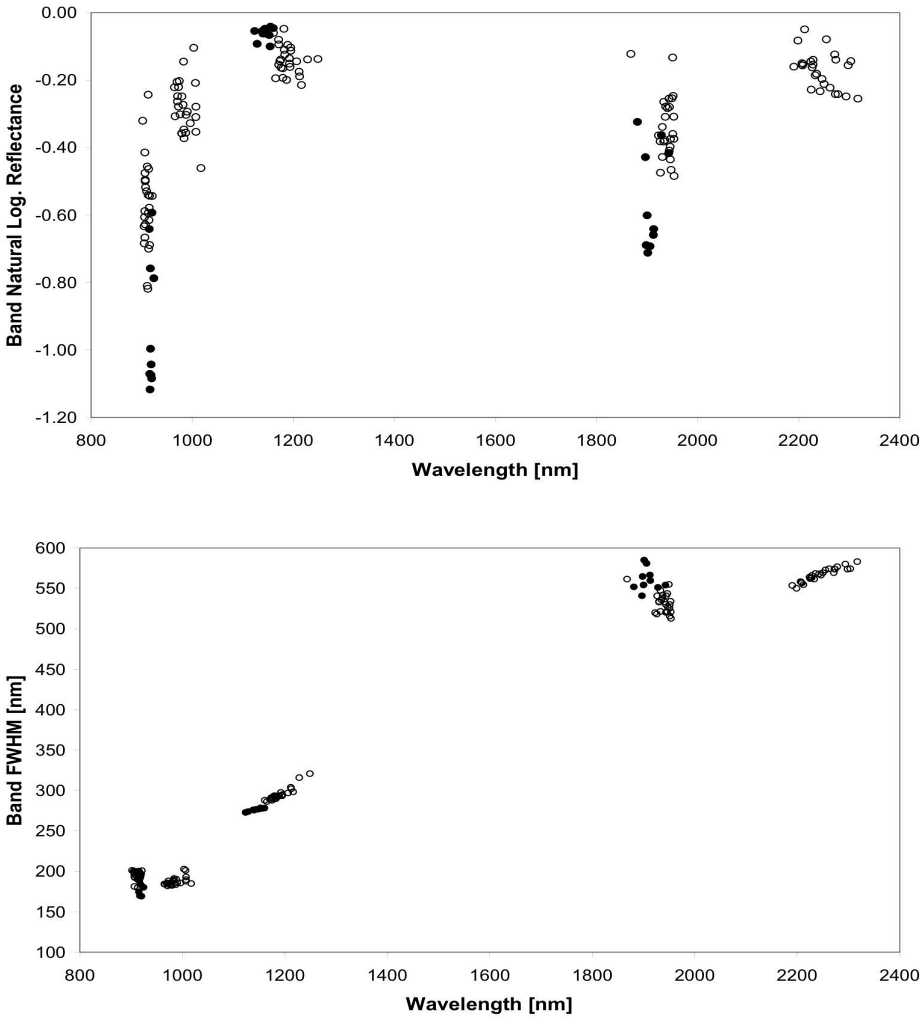

Fig. 9. Band strength for the five bands fitted to the Eucrite meteorites (white circles) and at 0.9, 1.2 and 1.9 microns for the Diogenite (black circles) meteorites (upper panel). Band widths for the same wavelengths for the Eucrites (white circles) and three bands for the Diogenite (black circles) meteorites.

are almost in the same wavelength. The individual band widths are constant for all cases. The fulfilment of this two constrains is the first indication that the fit is correct, and then the similarity of the CBSR1 and CBSR2 is the next constraint to be fulfilled. As can be seen in Table 1 the CBSR1/CBSR2 are all similar to the unity, as it was demanded in the fit. In the case of Diogenite meteorites spectra, where there is no possible CBSR determination, only the individual band centres and widths were taken into account as indicators of a correct fit.

In the case of the Eucrites, with the CBSR value it is possible to obtain the HCP/(HCP+LCP) ratio using the calibrations presented as explained in the next section. Introducing these values in the melting model presented in Sunshine et al. (2004) it is possible to obtain the melting percentage. All the values are shown in Table 1 for all the Eucrite meteorite of the sample. The final values of HCP/(HCP+LCP) and the corresponding melting percentage can be compared with the literature (Sunshine et al. 2004, Vernazza et al. 2005, Mayne et al. 2006, deLeón et al., 2006, Canas et al. 2008). Due to the excellent quality and high signal to noise ratio of the spectra, the fitting procedure was straightforward. The next expected step is to do a similar process with the asteroid spectra.

Meteorite Name	RELAB file	CBSR1	CBSR2	CBSR1/CBSR2	HCP/(HCP+LCP)	% Melting
Ibitira	MP-TXH-054-A	2.315	2.174	1.065	0.41	26
Milbillillie	MB-TXH-069-A	2.185	2.130	1.026	0.43	25
Juvinas	MB-TXH-070-A	2.619	2.576	1.017	0.37	28
Y-74450	MB-TXH-071-A	5.206	5.078	1.025	0.21	39
Padvarninkai	MB-TXH-096-C	1.539	1.478	1.041	0.57	21
Stannern	MB-TXH-097-A	1.705	1.778	0.959	0.51	22
GRO 95533	MP-TXH-066-A	1.755	1.647	1.065	0.52	22
EET A79005	MP-TXH-072-A	2.994	3.073	0.974	0.31	31
EET 87542	MP-TXH-075-A	1.674	1.681	0.996	0.52	22
EET 90020	MP-TXH-076-A	1.917	1.904	1.007	0.47	23
LEW 85303	MP-TXH-078-A	1.647	1.647	1.000	0.53	22
PCA 82502	MP-TXH-080-A	1.694	1.656	1.023	0.52	22
Cachari	MP-TXH-084-A	1.909	1.898	1.006	0.48	23
Moore County	MP-TXH-086-A	2.471	2.551	0.969	0.37	28
Pasamonte	MP-TXH-087-A	2.507	2.456	1.021	0.38	27
Bereba	MP-TXH-089-A	1.895	1.863	1.017	0.48	23
Bouvante	MP-TXH-090-A	1.701	1.644	1.035	0.53	22
Jonzac	MP-TXH-091-A	2.242	2.204	1.017	0.40	26
Serra de Mage	MP-TXH-092-A	2.443	2.522	0.969	0.37	28
A-881819	MP-TXH-096-A	2.441	2.442	1.000	0.38	27
Y-792510	MT-TXH-041-A	1.698	1.682	1.010	0.52	22
Y-792769	MT-TXH-042-A	1.731	1.765	0.981	0.51	22
Y-793591	MT-TXH-043-A	1.871	1.839	1.018	0.49	23
Y-82082	MT-TXH-044-A	1.413	1.405	1.005	0.58	20
NWA 011	MT-TXH-059	1.447	1.455	0.994	0.58	20

Table 1. Results using the MGM and the Eucrite meteorites.

3.2.2 V-type asteroids

Considering the success in modelling laboratory spectra of differentiated meteorites, the same technique is applied to asteroid spectra. As was mentioned, the reflectance spectra of V-type asteroids considered in this work were taken from different works. Spectra were obtained with different telescopes and instruments and have lower signal to noise ratio than the reflectance spectra of meteorites. The procedure of the MGM fitting in the Eucrites, was used as a guide to the fitting procedure in asteroids.

The procedure started the fitting with the same input parameters as in the Eucrite corresponding to 25% of HCP and 75% of LCP. As in the meteorite cases the main idea is to fulfil the restrictions of band centres and band width at the same time to look for the CBSR1/CBSR2 ratio equal unity. In some MGM fitting the constraints were reached without problems and it was possible to obtain the HCP/(HCP+LCP) ratio and then the melting percentage.

In the specific cases of (809) Lundia, (2468) Repin, (2763) Jeans, (2851) Harbin, (3155) Lee, (4796) Lewis, (6331) 1992 FZ1, (10037) 1984 BQ, (10285) Renemichelsen, and (10349) 1992 LN it was not possibly to obtain a reliable fit using a combination of LCP and HCP individuals bands. The fulfilment of the constraints was impossible in those cases. It was found that it cannot be reached the mentioned restrictions specifically the CBSR1 equals CBSR2. In those cases it was tried another fitting only using the LCP bands reaching a better result. It has to be mentioned that in the cases of 6331, 10285 and 10349 it was used only the infrared part of the spectra from 0.8 to 2.5 μm.

From the point of view to know something on the possible origin and related mineralogy, the sample was separated in family and non-family members and NEOs. Family members have the certainty that were ejected from the Vesta's crust. Non-family members that are in the region of similar orbital parameters that Vesta should be ejecta from the crust but can be fragments of the crust of another differentiated parent body in the region, like Eunomia o Baptistina. Near Earth Objects, do not have a precise determined origin in the Main Belt. NEO's reach they actual position after a chaotic way to the interior solar system. Most probable came from Vesta but the probability to come from another part of the Main Belt is not zero.

In Figure 10 it's shown the obtained band strength and band FWHM versus individual band centres for the asteroids. Compared with the same plot for the Eucrites (Fig. 9) the dispersion in the parameters is higher but still maintain the tendency of having similar band centres and constant band width (similar to meteorites). For the asteroids that can be obtained the HCP/(HCP+LCP) ratio it was possible to calculate the melting percentage as was made with Eucrites. The results are shown in Table 2.

The ratios of LCP/HCP bands (which are a measurement of the ratio of the band strengths) from the fitted samples were used to perform a logarithmic transformation that allows us to determine HCP/(HCP + LCP) as can be seen in Figure 11.

Based on the pre-elaborated systematic variation in the relative strength of pyroxene absorption function of the HCP/(HCP + LCP) ratios the results are related to melting percentage. Using calculations of melting with the MELTS program (Ghiorso and Sack 1995;

Asimov and Ghiorso 1998) it was determined the correspondent values of degree of melting for the samples. H chondrite material is used as starting point because is the less altered and comparable with the material present in the solar nebula. In Figure 12 is presented the plot of the HCP/(HCP+LCP) ratios in the solid residual and crystallized partial melt from an H chondrite precursor as function of percent melting (adapted from Sunshine et al. 2004). The Eucrites shaded rectangular box is from the model. Individuals regions are shown as a Eucrite polygonic region on the curve for the entire determined Eucrite meteorite sample from this work and the V-type asteroids, distinguishing that belonging or not to the dynamical family and NEOs.

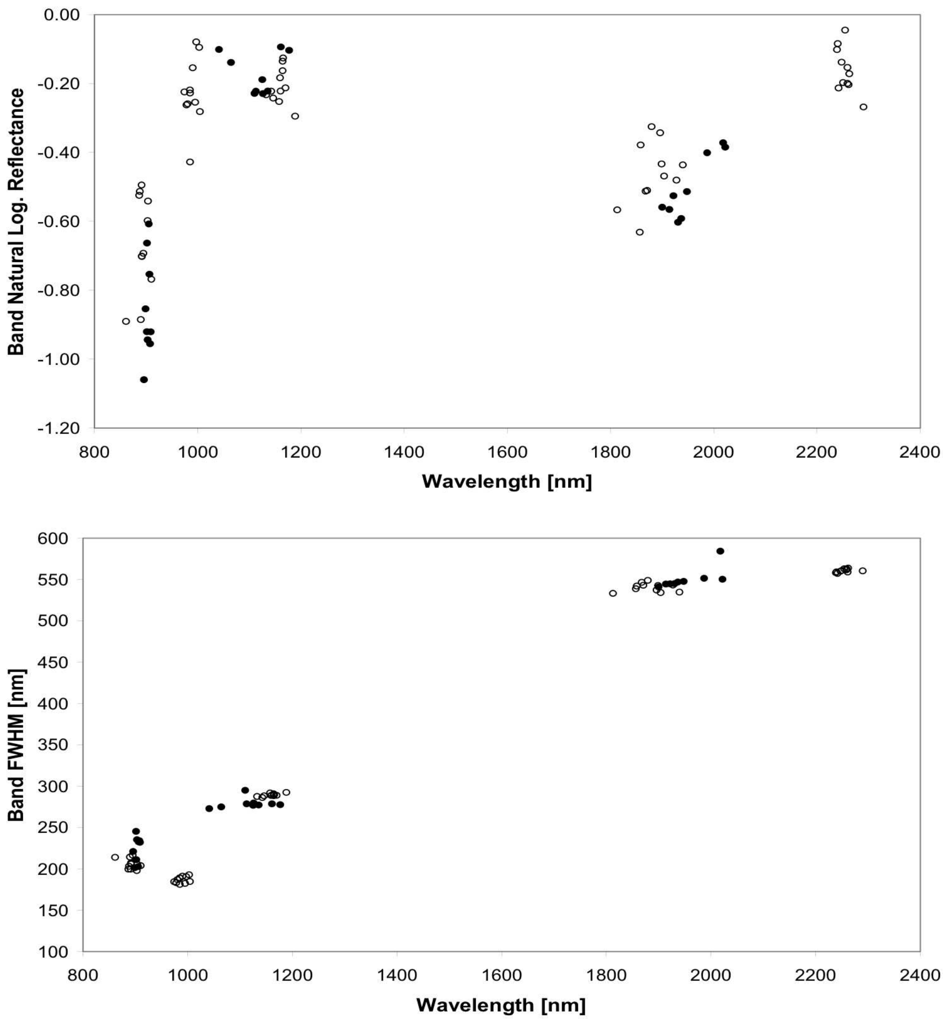

Fig. 10. Band strength (upper panel) and Band width (lower panel) for the five bands fitted to the asteroidal sample.

Asteroid Number	Family	CBSR1	CBSR2	CBSR1/CBSR2	HCP/(HCP+LCP)	% Melting
809	NO					
956	NO	3.38	3.11	1.088	0.30	32
2045	YES	3.16	3.13	1.009	0.30	32
2468	YES					
2763	NO					
2851	NO					
3155	YES					
3268	YES	2.28	2.23	1.023	0.41	26
3498	YES	3.20	3.19	1.004	0.31	31
4434	NO	2.49	2.40	1.036	0.38	27
4796	NO					
4815	YES	5.68	5.70	0.996	0.19	40
6159	YES	2.25	2.12	1.061	0.42	25
6331	YES					
6611	NEO	2.45	2.62	0.936	0.38	16
10037	YES					
10285	YES					
10349	YES					
88188	NEO	2.62	2.72	0.964	0.36	15
2003 YG118	NEO	2.02	1.89	1.069	0.46	17

Table 2. Results for the asteroidal sample.

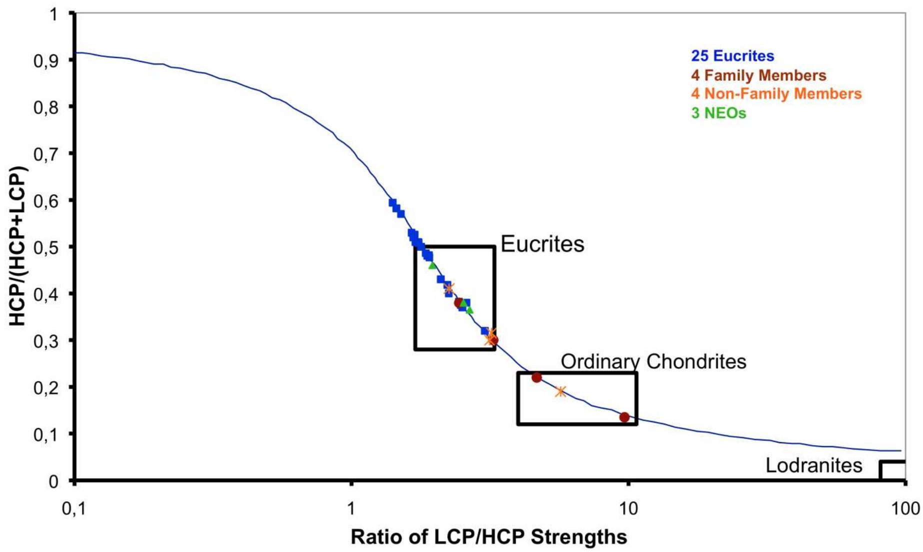

Fig. 11. Ratio of band strengths to obtain the relative proportion of LCP to HCP. Figure adapted from Sunshine et al. (2004)

To summarize, this section can be finished with some conclusions: the MGM fitting was applied to a set of 25 Eucrite and 10 Diogenites from the RELAB and this database was used for calibrating the method to be applied in the set of remotely obtained reflectance spectra of 20 V-type asteroids. This is the first time that a high number of MGM fit for Eucrite, Diogenite and V-type asteroids was calculated. In previous works, a direct comparison between spectra from meteorite and asteroids were applied.

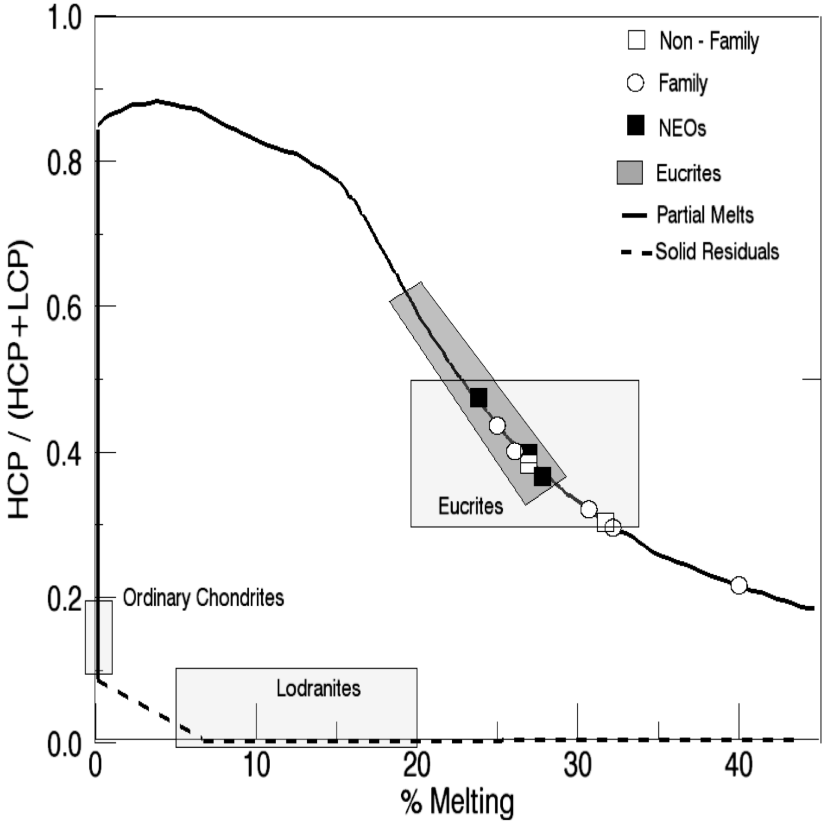

Fig. 12. High to Low calcium ratios in the solid residual and crystallized partial melt. Figure adapted from Sunshine et al. (2004)

In this work it was applied a spectral deconvolution technique that can separate end-members and determine the mineral composition present in the surface of an asteroid. As can be seen, the results are independent of the initial input. The starting point was a combination of 25/75 of HCP/LCP relation, and with a special mineralogical composition. From the sample of asteroids, it can be determined that 5 out of 11 (45%) from the Vesta family are Eucrite type, meanwhile 2 out of 6 (33%) non-family members are Eucrite type and also 100% of NEO. The small number of object in the sample needs to be taking into account here. Asteroid with presence of HCP (Eucrite type) are in all the three groups and HCP varies from 19 to 46%, which represent a melting between 15 to 35%.

The basaltic material outside the Vesta family is a nice and intriguing corundum. The Vesta family is defined as all the objects that can be ejected from collisions but allowed Vesta´s crust to survive. The limitation in collision energy or ejecta velocity is well restricted. Anyway, there are some basaltic objects outside the family, but in the region that can be explained by other alternative scenarios. They could be fragments from collisions on Vesta's crust and then transported to the current position (Carruba et al 2005). Or there are fragments from a different differentiated parent body, like Eunomia (Nathues et al. 2005) or Baptistina (Carvano and Lazzaro, 2010).

The only way to define without any doubt the mineralogy of the surface of an asteroid is going there. Several space mission visited many kind of asteroids, most of them doing only a fly-by. In the last decade, asteroids have become primary targets for space missions geared towards improving our understanding of SS formation. The Galileo mission, in 1991 (Russell, 1992), was the first to perform an asteroid flyby. On its way to Jupiter, it performed a flyby of the asteroids Gaspra and Ida, including its moon Dactyl. The NEAR-Shoemaker mission (Veverka et al., 2001) made a flyby of the asteroid Mathilde, and performed a rendezvous mission to Eros. Deep Space 1 (Nordholt et al., 2003) made a double fly-by of the asteroid Braille and comet Borelli. The Stardust mission (Brownlee et al., 2003) returned a sample of Comet Wild 2's coma material, and completed a flyby of asteroid Anne-Frank. In 2003, the Japanese Space Agency's (JAXA) Hayabusa mission was the first to focus on an asteroid with an aim to return a sample (Fujiwara et al., 2004). With only a basic scientific payload onboard Hayabusa, data gathered on the S-type asteroid Itokawa have nevertheless yielded incredible results (Nagao et al. 2011, Tsuchiyama et al. 2011) Ideas for visiting a V-type NEO in a sample return mission are presented in the work of Duffard et al. (2011).

4. DAWN mission at Vesta

It's really an exclusive opportunity to have a spacecraft orbiting the body that you are/were studying during years. This is the case for the Dawn mission and asteroid Vesta. Dawn was launched on 27 September 2007 and the mission's goal is to characterize the conditions and processes of the solar system's earliest eon by investigating in detail two of the largest proto-planets remaining intact since their formation. Ceres and Vesta have many contrasting characteristics that are thought to have resulted from them forming in two different regions of the early solar system. In a first stage of the journey, the spacecraft arrived at Vesta in August 2011 and will stay in two different orbits (low and high altitude) during one year after which will continue the journey to Ceres.

This spacecraft has an image-framing camera (FC), a visible and near infrared spectrometer (VIR) and a gamma ray and neutron detector (GRaND). The FC has a filter wheel with seven colour and one clear filter. An image consists of a frame of 1024 x 1024 pixels and one pixel has a field of view (FOV) of 93 μrad. The VIR mapping spectrometer is a compact spectrometer with both visible and infrared ranges: 0.25–1.0 and 0.95–5.0 μm. Its spatial resolution is 0.250 μrad with spectral resolution varying from 30 to 170. The GRaND instrument features neutron spectroscopy using Li-loaded glass and boron-loaded plastic phoswich. The gamma ray detection uses bismuth germanate and cadmium zinc telluride (Rusell, et al. 2006).

With all this instruments and after 1 year of orbiting Vesta the quantity and quality of information on this specific body will be incredible. As early as this chapter is written, first images on the surface of Vesta are arriving with unprecedented details [1].

During the early arrival to the asteroid the images could be compared with the one taken from the Hubble Space Telescope, showing that studies from ground are pretty close in details as studies from orbit. After entering the high altitude orbit, a mapping of the entire surface down to 260 meters per pixel was done. Unprecedented details on the surface can be observed. This is the first time a spacecraft is in orbit on an asteroid of this size and the feature characteristics are really unique. Thousands of new features are in the images, craters from several kilometres to some meters, grooves, faults, hills, etc. To name and characterize all these new features, a new reference system need to be taken. The zero-longitude, or prime meridian, of Vesta was defined by the science team using a tiny crater about 500 meters in diameter, which they named "Claudia," after a Roman woman during the second century B.C. Dawn's craters will be named after the vestal virgins—the priestesses of the goddess Vesta, and famous Roman women, while other features will be named for festivals and towns of that era.

One of the prominent details shown in the images are the equatorial ridges. Also there are grooves in the equatorial region of about 10 kilometres wide. Another distinct feature is a massive circular structure in the South Pole region. Scientists were particularly eager to see this area close-up. This feature is thought to be the origin of all the fragments forming the Vesta family and some V-type asteroids. Most of the HED meteorites would come from this impact region. The circular structure, or depression, is several hundreds of kilometres wide, with cliffs that are also several kilometres high. One impressive mountain in the centre of the depression rises approximately 15 kilometres above the base of this depression, making it one of the highest elevations on all known bodies with solid surfaces in the solar system.

As shown in Figure 13, the surface of Vesta is populated with craters in different sizes, showing a rather old surface. In some of the large craters it can be seen material movement to the centre due to gravity. Some small craters superimpose to the larger ones showing the intense bombardment that Vesta was affected in the past. Many of the smaller craters could also be part of the material ejected in the formation of the bigger craters. The grooves that are visible in the right part of the figure will give clues on the formation of the crust and discussion on the possible origin of this feature are open.

In next figure 14, it's shown that are some craters over the grooves which is indicative of the time of formation of the craters and grooves. Some worm-like features are also visible and there is still no explanation on the origin of this kind of feature. Dark and light material showing differences in compositions are also visible. Dark material can be organics, maybe rest of a cometary impact on Vesta. More detailed images on this region to try to explain the presence of this material will be taken in a lower orbit.

[1] All images in this section were taken with the Framing Camera. The framing cameras were developed and built under the leadership of the Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany, with significant contributions by the German Aerospace Center (DLR) Institute of Planetary Research, Berlin, and in coordination with the Institute of Computer and Communication Network Engineering, Braunschweig. The framing camera project is funded by NASA, the Max Planck Society and DLR. JPL is a division of the California Institute of Technology, in Pasadena.

The analysis, not only from the FC but also mainly from the VIR data will give us information on the different materials present in the craters. The South Pole region is the more interesting one because with this 15 km depth can show evidence of the upper mantle of Vesta. Several models were published discussing the probable depth of the crust, and the analysis of the images and spectra of this region will strongly constraint the models.

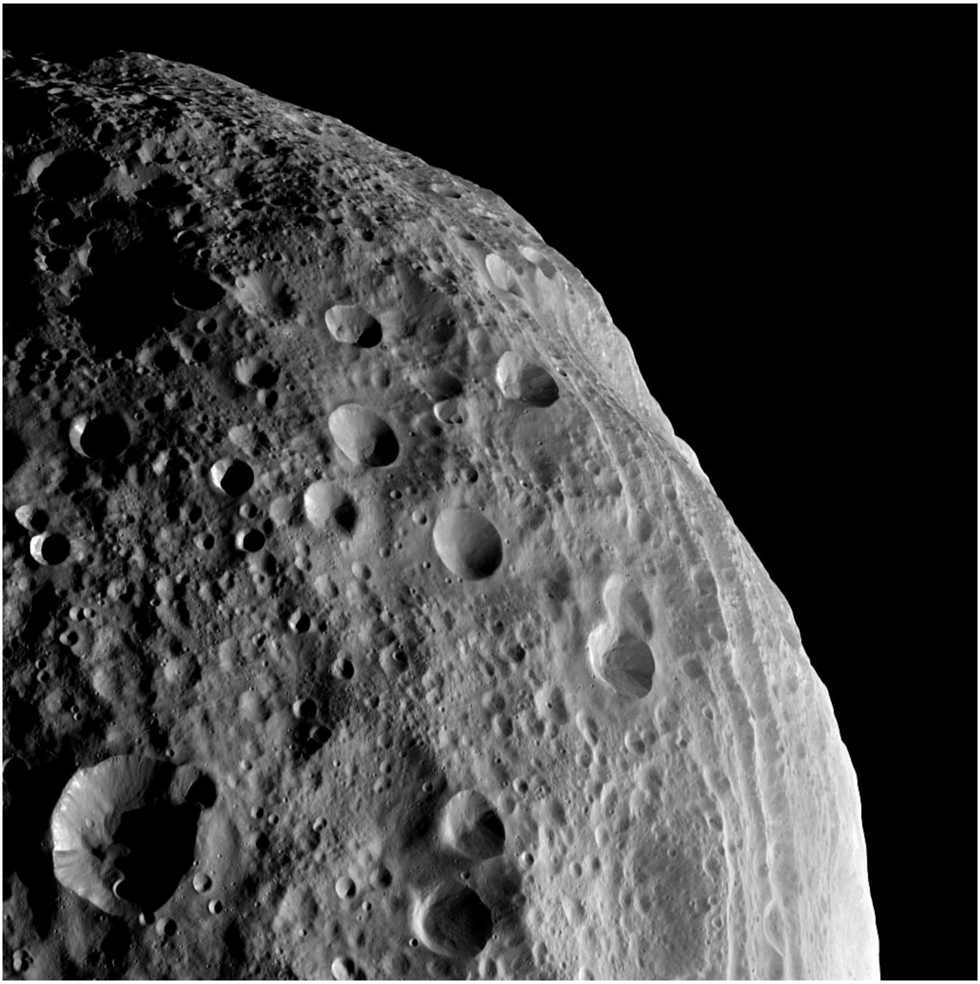

Fig. 13. This image was taken through the FC camera's clear filter and has a resolution of 260 meters per pixel. Image credits *NASA/ JPL-Caltech/ UCLA/ MPS/ DLR/ IDA*

In Figure 15 there is a comparison of the clear light picture and the false coloured one. Colours in the right picture are given to enhance differences in composition of the surface. In this false Red-Green-Blue (RGB) colour scheme, red is used for the ratio of the brightness at wavelengths of 750 nanometres to the brightness at 440 nanometres, green is used for the ratio to the brightness of 750 nanometres to 920 nanometres and blue is used for the ratio to the brightness at 440 nanometres to 750 nanometres. Red-blue tones capture the visible continuum and green tones capture the relative strength of the ferrous absorption band at 1 micron.

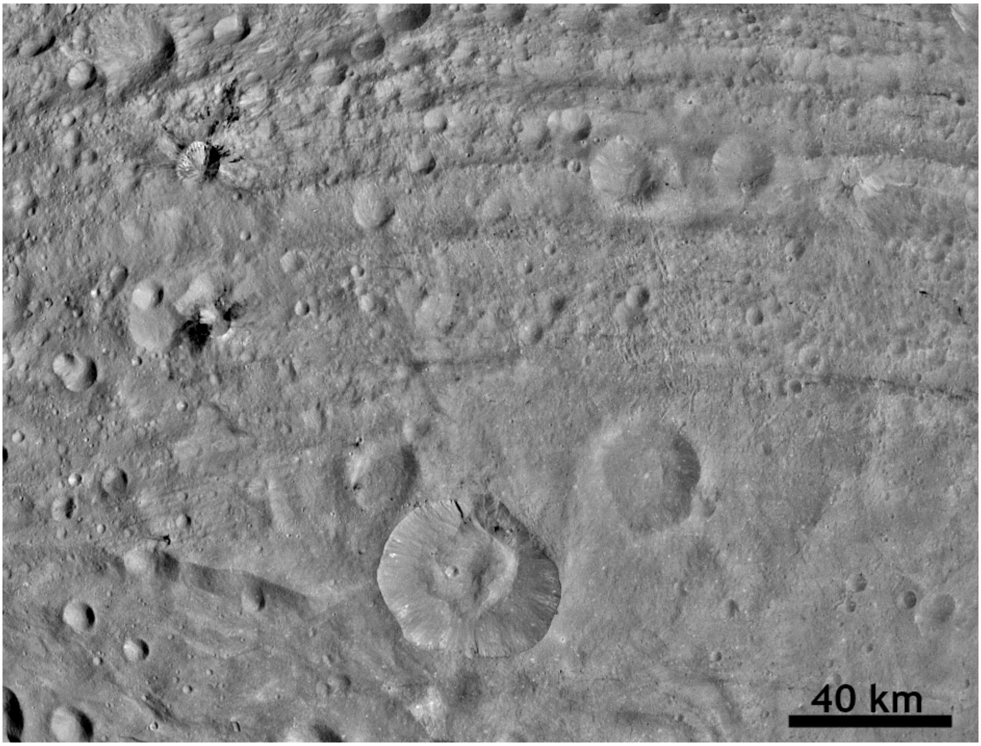

Fig. 14. This image, taken through the framing camera's clear filter, shows dark material at impact craters, up to 20 kilometre-wide and sets of worm-like tracks in the north-south direction. The image has a resolution of 254 meters per pixel. Image credits *NASA/ JPL-Caltech/ UCLA/ MPS/ DLR/ IDA*

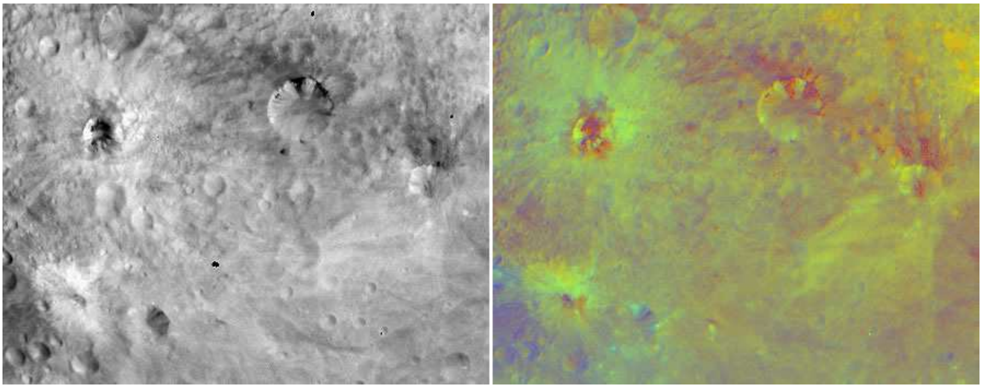

Fig. 15. Same region of Vesta taken in clear filter on false coloured images. The images have a resolution of about 490 meters per pixel. Image credits *NASA/ JPL-Caltech/ UCLA/ MPS/ DLR/ IDA*

5. Conclusions

The chapter started presenting the problem of the basaltic material on the minor bodies of our solar system. Then, two different techniques were presented to obtain clues in the mineralogy of these bodies. These methods showed that is possible to remotely obtain precise information on the surface of a body that can be visited by a spacecraft and confirm the findings. Data from those missions are powerful sources of information in details on the geology and mineralogy of the surfaces. After this entire journey the chapter can be ended with some conclusion and future work.

Vesta is NOT the only basaltic minor body in our solar system. Vesta is the only intact basaltic asteroid or basaltic proto-planet. Vesta has a “family” of objects that are related to them as to be the fragments of a collision or collisions. Some of these fragments are outside the boundary for some family determinations and these boundaries are related with the energy that a great impact would eject material from the crust but keeping the body as it can be observed today. One postulated option is that these fragments can be part of Vesta ejected material and then dynamically moved to their actual position outside the Vesta family. The other possibility is they are part of another differentiated parent body in the region. In the last years there are evidences that more differentiated bodies existed in the beginning of the solar system and now it can be observed fragments from the original ones. There is still no clear technique to remotely distinguish the mineralogy from one parent body to the other. Dynamics is needed to help in the solution of this problem. How is possible to remotely indentify a fragment from deep in the crust-mantle of a specific differentiated parent body with another from other different parent body? Here several professional interact from different areas: dynamics, astrophysics, geophysics and mineralogy to help find the answers.

A problem to be solved is the apparent homogeneity in the known asteroid's families. Mineralogical studies of the asteroids families, shows that there is no evidence of a differentiated family. This mean, there is no family with fragments similar to the crust, fragments similar to the mantle and fragments similar to the nucleus of the parent body. All families seem to be the catastrophic evidence of homogeneous parent bodies. A question that can be raised here is if the collision that broke-up that differentiated objects were in the beginning of the solar system, in the first megayears, can we identify those catastrophic families? Differentiated objects formed in the first 5 megayears and have nearly 600 My to be disrupted before the Late Heavy Bombardment. If the differentiated families formed before the LHB it will not be possible to identify those families because fragments will be dispersed or ejected from the solar system.

On the other hand, in the meteorite collection there are some clear example and proofs that there were more than one differentiated asteroid. This proof came not only from the basaltic meteorites (as shown in Sections 2), but also from the iron meteorites, fragments of the nucleus of those differentiated asteroids. All these differentiated objects were formed in the first 4-5 mega-years of evolution of the solar system, otherwise the ^{26}Al is not enough powerful to melt and differentiate the body. It's expected that several dozens of differentiated bodies formed from 40 to 500 km diameter. Some of these were destroyed by catastrophic impacts; some others formed bigger objects, some other, at least one, survived. Our Earth took 30 mega-years to be formed so its formation was with proto-planets that were differentiated and more primitive material. The same occurred with Mercury, Venus and Mars with different formation time depending on size.

Vesta is the only intact basaltic body. Here the word "intact" is intend to mention that Vesta has the basaltic crust and remains almost as it formed in the beginning of the solar system. As can be seen in the Dawn images of the preceding section, Vesta's crust is far to be "intact". An interesting part of the crust of this body is the South Pole region where a giant impact consequence can be seen. Most of the material ejected from this impact can be seen today as members of the Vesta dynamical family. Studying these fragments is a way to go deep in the crust and this is the main reason to study the mineralogy of family and non-family members and also V-type NEO's.

In this work I presented the results of a new analysis on the V-type asteroids. The mineralogy and LCP to HCP ratios of those V-type asteroids were analysed and compared to the HED meteorite using two different techniques. First, the two methods were applied to the HED sample to gain practise and be confidant and then applied to the asteroids where the quality of the data is lower. Combining all the data from this work and from literature a nice scenario of what happened in the crust of Vesta is revealed. Large impact/s excavated material from the crust and studying these fragments its possible to obtain information on different depths of the crust and maybe the mantle. From the current study (and others from the literature) its possible to infer the mineralogy of these fragments. Some of them are

Eucrite type showing a composition with LCP and HCP in different proportions. Other objects show a Diogenite composition testing deeper layers in the crust. Results on the calcium and iron content of the pyroxene were obtained here and in other works indicating that conclusion.

The studied V-type asteroids have a large range of mineralogy but with a prevalence of asteroids similar to Diogenites type material. This result goes in the same direction of Vernazza et al. (2005), suggesting that the spectral diversity observed in the Vestoids arises because these asteroids contain material present on the Vesta surface or coming from different layers of Vesta excavated by collisions and not because they originated from different parent bodies. After a big collision, fragment from the crust or re-accumulated fragments should show Howardite type spectra. This kind of spectra can be characteristics of asteroids where both Eucrite and Diogenite materials are present. A re-accumulated fragment after a collision should fulfil this requirement. As it can be seen in the previous section, the surface of Vesta is inhomogeneous, with lots of impacts that excavated material from deeper layers. A giant impact would extract material from different depth and then fragments would re-accumulate to form a Howardite type family member asteroid.

There are also some objects that can show evidence of olivine. If the collision that formed the South Polar Region excavate enough material to reach the mantle, it will be possible to identify olivine in the fragments. This assumption needs to be confirmed. Current magma ocean models do not predict heterogeneity at the small kilometre scale of the V-type asteroids, on the other hand modellers seems to support the idea that partial melting may have played a important role in the formation of Vesta.

Finally, the mineralogical composition and internal structure of the primitive Earth is unknown. Plate tectonic, mountain creation and erosion destroyed the geological information from that period. An innovative way to understand all this primitive process is to compare the Earth with bodies that did not suffer large alterations, like Mars, the Moon, Mercury or differentiated asteroids. Primitive Earth formed from the accumulations of planetary embryos, some of them already differentiated, with different sizes (Allegre et al. 1995). The most important of those bodies was a Mars sized differentiated proto-planet that collides with the still forming Earth. From this catastrophic event, the Moon formed (Zhang 2002). To understand the formation of the primitive Earth is important to know how those differentiated bodies formed. Bigger the body, larger was the time it took to accrete in a proto-planet (Kleine et al. 2002). At least, a large number of the bodies that accreted in the terrestrial planets were differentiated.

All this research is based in the interpretation of surface reflectance spectra obtained in ground-based telescope, space telescope and laboratories (known minerals or meteorites). Next step is to include the mineralogy of the exo-planets that are being discovered in the last years. The so called exo-Earths are starting to be discovered in the last 3 years and theories recall to be originated in at least two different ways: the formation of a big terrestrial planet with 3-5 times the mass of the Earth or they are the bared nucleus of a giant planet that migrated closer to the star and all the gas envelope were flown away.

Now the question to be answered is which is the mineralogy of these planets? In our case, the less altered meteorites have almost the same composition of our star, the Sun. They formed from the same primordial nebula, so with the exception of the hydrogen and helium that are mainly in the central star; all the mineral proportion should be the same. In the near future, when systems with several planets will be identified, and several Earth like planets be present on those system the possible composition of those planets can be inferred from the composition of the star. The chemistry of the central star will have a clue on the material that formed these planets.

It's curious, to know the mineralogy of a planet, some introspective looking, we also need to study the star that hosts this planet.

6. Acknowledgment

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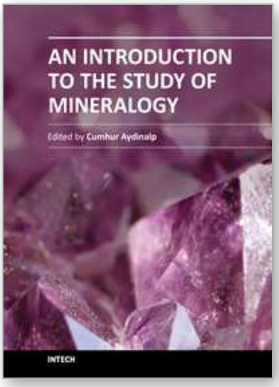

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