Mineralogical structure of the subsurface of Syrtis Major from OMEGA observations of lobate ejecta blankets

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[1] This paper focuses on the spectral characteristics of lobate ejecta across Syrtis Major volcano, a dark region of Mars presenting a mafic composition as revealed from the Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA) instrument. Two spectrally distinct crater types are identified. Type I is enriched in high-calcium pyroxene (HCP) relative to the volcanic rocks. Type II is similar to the lava flow mineralogy driven by HCP, compared to the Noachian crust dominated by low-calcium pyroxene (LCP). Type I craters are systematically younger than type II. The type II mineralogy has been likely affected by a long-term weathering in a cold environment for the last 2 Ga. The axisymmetric spectral signatures of type I ejecta appear dominated by rock-forming minerals rather than by soils and reflect the composition of excavated materials offering a window for exploring the subsurface. A progressive change in the slope of the spectra around 1.5–2 μm is observed across the ejecta layers, pointing at a change in the HCP/LCP ratio. The deconvolution of the spectra by the Modified Gaussian Model unravels a maximum of HCP/LCP band strength ratio located between 1.2 and 3 crater radii for all type I craters. Using Z-modeling, this observation translates into a maximum in the HCP/LCP abundances at a few hundreds of meters depth and suggests a homogeneous subsurface structure of the volcanic edifice. Below this horizon the HCP/LCP decrease may reveal a more ancient lava composition or the signature of the underlying Noachian crust.


1. Introduction

[2] The knowledge of the subsurface of Mars at all scales has been essential in the scientific goals of the instruments sent to this planet in the last few years. Investigations in this direction will probably develop even more as the structure, the mineral composition and the water content of the subsurface are key parameters for the future of Mars exploration. At a geographic resolution of hundreds of kilometers, the MOLA (Mars Orbiter Laser Altimeter) instrument onboard Mars Global Surveyor has established the variations of the crustal thickness and investigated the variations with time of the thickness of the elastic lithosphere through the measurement of the gravitational field and of the topography [Zuber et al., 2000; Neumann et al., 2004]. At a similar lateral resolution, the Mars Odyssey Mission and its Gamma Ray Spectrometer (GRS) have investigated the abundance of hydrogen in the first meter upper layer. More recently, at a few kilometers scale, the ongoing MARSIS radar experiment has released the first observations of reflectors beneath the south layered polar deposit [Plaut et al., 2006] and of reflectors corresponding to a large buried basin in the northern hemisphere [Watters et al., 2006]. In addition to these indirect views of the Martian subsurface, impact craters are natural probes of the Mars subsurface at all scale, everywhere on the planet, and throughout all the geologic history. Impact cratering is the most efficient process exposing deep-seated material on a planet in the absence of plate tectonics. Their morphologies have been used for the last three decades to discuss the subsurface material properties and the distribution of subsurface ice, water or brines [e.g., Barlow and Bradley, 1990; Baratoux et al., 2002; Barlow and Perez, 2003].

[3] Syrtis Major has been selected as one of the best regions of Mars to achieve a regional investigation of the subsurface mineralogy from impact craters using the OMEGA data (Observatoire pour la Minéralogie l’Eau, les Glaces,
et l’Activité, on board of the Mars Express spacecraft). Syrtis Major consists in a large shield volcano formed in the Hesperian epoch [Hiesinger and Head, 2004]. Its surface morphology is dominated by lava flows intersected by compressive ridges. Eastern and western parts of Syrtis have slightly different crater densities, respectively 133 ± 5.7 and 158 ± 6.3 craters larger than 5 km per 106 km², both crater densities corresponding to Hesperian ages [Hiesinger and Head, 2004]. The volcanic center consists of two calderas named Nili and Meroe. This region is characterized by an albedo among the darkest on Mars and by the presence of mafic materials identified from orbital [Mustard et al., 1993] and terrestrial spectral observations [Pinet and Chevel, 1990; Bell et al., 1997].

The Syrtis Major plateau belongs to the surface type 1 (ST1) as defined from the Thermal Emission Spectrometer observations. This surface type is basaltic in composition [Bandfield et al., 2000]. The deconvolution of TES spectra using a set of 36 end-members has led to the identification of several species: plagioclase (10–20%), high-calcium pyroxene (10–15%), isolated detections of olivine, and about 10% of sheet-silicates or high-Si glass [Bandfield, 2002]. This region is characterized by low values for the dust cover. More recently, OMEGA data has also observed at a higher resolution the strong spectral signature characteristic of mafic minerals (pyroxene, accompanied by detectable amount of olivine) [e.g., Mustard et al., 2005; Bibring et al., 2005; Pinet et al., 2006b; Poulet et al., 2007]. Impact craters on Syrtis Major have excavated through the volcanic layers and their ejecta contain subsurface material. This paper is motivated by these exposures of subsurface material which could potentially reveal for the first time the mineralogical composition at a depth down to a few hundreds of meters of a martian volcanic construct. Recent terrestrial remote sensing studies in the infrared domain have demonstrated the connection between the spectral signature of fresh ejecta morphologies with the spectral signature of the subsurface material [Ramsey, 2002]. Using the THEMIS spectral bands in the thermal infrared domain, the subsurface origin of the spectral signatures of ejecta on Mars has been searched [Tornabene et al., 2006]. A similar attempt is proposed on Syrtis Major craters using the OMEGA data in the visible and near-infrared domain from 0.7 μm to 2.6 μm. The high spatial resolution of OMEGA (up to 300 meters/pixel) combined with its the spectral resolution gives access to a detailed study of the ejecta layers and to the interpretation of their spectral variations in terms of relative pyroxene proportions, using the Modified Gaussian Model for the spectral deconvolution [Sunshine et al., 1990; Sunshine and Pieters, 1993]. However, spectral signatures of the ejecta unit do not necessarily represent the composition of subsurface material as ejecta can be covered by dust, transported, eroded, degraded and the initial mineralogy can be weathered with time. Consequently, the first part of the paper focuses on these aspects with the objective of characterizing and selecting which craters are pristine enough to be used as natural probes of the subsurface composition. Then, the variations of the spectral features within the ejecta layers are investigated. The different potential contributions to these variations are evaluated. In the last part, a first-order geometrical and kinematical model of the excavation flow inside a layered target is developed in association with the ballistic emplacement trajectories. This direct approach is aimed at proposing the first-order characteristics of the subsurface mineralogy explaining at best the variations in composition observed within the ejecta units.

2. Distinct Mineralogic Signature of Ejecta Blankets on Syrtis Major

2.1. Mineralogic Map of Syrtis Major: Two Spectrally Distinct Types of Ejecta

The Syrtis Major plateau belongs to the surface type 1 (ST1) as defined from the Thermal Emission Spectrometer observations. This surface type is basaltic in composition [Bandfield et al., 2000]. The deconvolution of TES spectra using a set of 36 end-members has led to the identification of several species: plagioclase (10–20%), high-calcium pyroxene (10–15%), isolated detections of olivine, and about 10% of sheet-silicates or high-Si glass [Bandfield, 2002]. This region is characterized by low values for the dust cover. More recently, OMEGA data has also observed at a higher resolution the strong spectral signature characteristic of mafic minerals (pyroxene, accompanied by detectable amount of olivine) [e.g., Mustard et al., 2005; Bibring et al., 2005; Pinet et al., 2006b; Poulet et al., 2007]. Impact craters on Syrtis Major have excavated through the volcanic layers and their ejecta contain subsurface material. This paper is motivated by these exposures of subsurface material which could potentially reveal for the first time the mineralogical composition at a depth down to a few hundreds of meters of a martian volcanic construct. Recent terrestrial remote sensing studies in the infrared domain have demonstrated the connection between the spectral signature of fresh ejecta morphologies with the spectral signature of the subsurface material [Ramsey, 2002]. Using the THEMIS spectral bands in the thermal infrared domain, the subsurface origin of the spectral signatures of ejecta on Mars has been searched [Tornabene et al., 2006]. A similar attempt is proposed on Syrtis Major craters using the OMEGA data in the visible and near-infrared domain from 0.7 μm to 2.6 μm. The high spatial resolution of OMEGA (up to 300 meters/pixel) combined with its the spectral resolution gives access to a detailed study of the ejecta layers and to the interpretation of their spectral variations in terms of relative pyroxene proportions, using the Modified Gaussian Model for the spectral deconvolution [Sunshine et al., 1990; Sunshine and Pieters, 1993]. However, spectral signatures of the ejecta unit do not necessarily represent the composition of subsurface material as ejecta can be covered by dust, transported, eroded, degraded and the initial mineralogy can be weathered with time. Consequently, the first part of the paper focuses on these aspects with the objective of characterizing and selecting which craters are pristine enough to be used as natural probes of the subsurface composition. Then, the variations of the spectral features within the ejecta layers are investigated. The different potential contributions to these variations are evaluated. In the last part, a first-order geometrical and kinematical model of the excavation flow inside a layered target is developed in association with the ballistic emplacement trajectories. This direct approach is aimed at proposing the first-order characteristics of the subsurface mineralogy explaining at best the variations in composition observed within the ejecta units.

2. Distinct Mineralogic Signature of Ejecta Blankets on Syrtis Major

2.1. Mineralogic Map of Syrtis Major: Two Spectrally Distinct Types of Ejecta

The details and discussion about the derivation of pyroxene maps from OMEGA data are given by Gendrin et al. [2006] and the main aspects are recalled here. The Modified Gaussian Model [Sunshine et al., 1990] is used to separate the high-calcium pyroxene (HCP) and the low-calcium pyroxene (LCP) contributions in the 1.0 to 2.5 μm domain using the SWIR wavelength range. This wavelength range is sensitive to the pyroxene features and influenced by hydrated minerals and olivine. The positions and widths of the pyroxene bands were fixed in order to process all the OMEGA data set in a reasonable amount of time. The continuum is defined as done by Hiroi et al. [2000]:

\[
\text{Continuum} = a \cdot \lambda + b + \frac{c}{\lambda} \tag{1}
\]

As presented in the work of Mustard et al. [2005] and Gendrin et al. [2006], LCP is prevalent in the Noachian crust surrounding the volcanic edifice while the Hesperian volcanic lava flows of Syrtis are enriched in HCP (Figures 1 and 2). Two spectrally distinct types of ejecta are recognized. The division into two spectral classes here is done for the purpose of this paper, from the spectral signature and without interfering with the efforts to standardize the nomenclature of impact crater ejecta morphologies [Barlow et al., 2000]. According to the standard nomenclature most of these ejecta morphologies correspond to Single Layer Ejecta or SLE. Some impact ejecta show a stronger HCP absorption band suggesting an enrichment in HCP relative to the volcanic lavas and are called here the HCP-rich ejecta or ejecta type I. However, some ejecta located within the volcanic region are not spectrally distinguishable from the lavas. These objects will be referred to the following as the ejecta type II. The geographic coordinates of the objects investigated in this paper are given in Table 1. The table includes a measurement of standard morphometric parameters, such as rim and cavity elevations from which the cavity depths are deduced.

Table 5 contains the ratio of LCP/(HCP + LCP) for all the investigated craters. This ratio has been estimated for the ejecta layer, and the minimum, maximum, average and standard deviations are given. One can argue that the difference in the depth of the absorption at 2.5 μm attributed to the HCP might be induced by a difference between the grain sizes distribution for ejecta and for the lava flow surfaces. However, assuming that ejecta have similar grain sizes distribution, the fact that some ejecta do not display this enrichment is an evidence against a dominant grain size effect in the variations in the LCP/(LCP + HCP) band depths parameter. Moreover, the band strength ratio is mostly independent of grain size as defined by Sunshine...
and Pieters [1993]. Following Kanner et al. [2006], we found LCP/(HCP + LCP) ratios ranging from 0.4 to 0.5 within the lavas, a value only slightly higher than the values in type II craters, but twice higher than the average values in type I craters. In some ejecta layers, the ratio can be even as low as 0.06 suggesting that the high-calcium pyroxene end-member may represent up to 90% in the mixture [Kanner et al., 2006]. Then, the most probable interpretation is that the deep HCP band strength within the ejecta is associated with a change in the LCP/HCP ratio of weight abundances. The HCP-rich ejecta are distributed all over the volcanic edifice and do not display any ubiquitous clustering. A quantitative investigation of HCP-rich ejecta distribution is presented in the following sections. Ejecta types I and II are distributed in an apparent random manner relative to each other. One can find examples of pairs of close craters with similar diameters having a similar continuous ejecta blanket and displaying a different mineralogical signature. In such examples, the first crater is distinguishable from the lava background by a particular HCP-enrichment while the second one is not (e.g., craters 0705 + 058 and 0708 + 039, or craters 0694 + 138 and X2). Two alternative hypotheses could explain this observation: (1) the ejecta signature represents the signature of subsurface excavated material and these mineralogical differences represent lateral changes in the mineralogical composition at depth, or (2) the spectral differences result from post-impact modification processes of the ejecta layer. If so, the spectral

Figure 1. Shaded relief map of Syrtis Major from MOLA data with reference names for the type I (HCP-rich) and type II craters investigated in this paper.
differences would be associated with different states of degradation and alteration of the ejecta layer affecting the mineralogical composition. The age determination of HCP-rich craters relative to the other craters offers a test for the second hypothesis.

2.2. Ages and Spectral Types of Ejecta

Different approaches can be proposed to estimate and compare impact crater ages. The most direct one would consist in the observation of stratigraphic relationships between ejecta layers of close craters. This situation has been searched unsuccessfully for all the regions where ejecta types I and II were close to each other. Therefore, the three following methods have been followed. Some craters are clearly intersected by the compressive ridges while other craters formed after the ridge formation episode. Stratigraphic relationships between ejecta type I and II and the compressive ridges have been thus investigated. The state of degradation of the ejecta layer can be qualitatively estimated from morphologic criteria. Finally, for the largest craters for which high-resolution images were available, crater counts have been made on the ejecta units and on the crater floor to estimate absolute ages of impact events. We report in the following paragraph the independent results from the three approaches and the conclusion is drawn for a joint interpretation.

2.2.1. Stratigraphical Relationships With Compressive Ridges

Circular and radial compressive ridges have been identified and mapped by Hiesinger and Head [2004]. These ridges have formed after the main episode of volcanic activity of the Syrtis plateau. Numerous craters postdate the ridges suggesting that this tectonic activity has probably ceased during the Hesperian time. Some craters also predate the ridges, as evidenced by the continuity of faults through ejecta units and within crater cavities. Mangold et al. [2000] proposed from the analysis of the timing of compressive ridges in various places on Mars that they result from a single and global origin. For Syrtis Major, these authors conclude to a restricted period of

![Figure 2. RGB pyroxene map from OMEGA data. Blue, high-calcium pyroxene band strength; red and green, low-calcium pyroxene band strength. Labels correspond to the type I and type II craters investigated in this paper. For some of the largest craters, the ages have been derived from crater counts and are indicated (see section 2.2.3 for their derivation). Ages for type I ejecta (HCP-rich) appear in blue, while ages for type II ejecta appear in orange. The full-resolution OMEGA has been represented on a THEMIS-IR daytime image for the crater 0738 + 114 (RGB composition with a different stretch). The data are extracted from orbit number 444.](image-url)
tectonic activity occurring within the late Hesperian epoch. The relationships of these ridges with ejecta of type I and II are presented here. Three type II craters (X2, 0648 + 022 and 0685 + 028) have been analyzed in details. THEMIS-VIS images of the craters and the morphologic interpretation are shown in the Figure 3. For the crater AH, the observation of a compressive ridge inside the crater cavity is a clear evidence for the ridge being formed after the impact. Unfortunately, the trajectory of the ridge does not intersect the cavity for the craters X2 and 0648 + 022. However, the intersection of the ridge with the ejecta flow front offers also strong evidences for stratigraphic relationships. The ejecta flow front and its distal ridge are continuous and no topographical offset is observed at the location where the compressive ridge trajectory intersects the ejecta layer. The observation of the tectonic ridge within the ejecta layer is an argument for its presence resulting in a thickening of the deposit at the foot of the ridge on the downstream side of the flow. All these observations strongly suggest that type II craters have been formed before the tectonic episode, while HCP-rich or type I craters have been formed after it. All craters cannot be dated relatively to the tectonic episode by this approach but these observations strongly suggest that type II craters have postdated the formation of these three ridges. The situation for the crater 0738 + 114 is slightly more difficult to analyze. A THEMIS-IR image, 100 m/pixel in resolution, is used in addition to one THEMIS-VIS image covering only the southern edge for this crater. The compressive ridge is seen within the lobe but, given the thickness of the flow at this distance of the center of the crater, this observation cannot be taken as a strong point. However, the bulge at the lobe front is clearly continuous over the tectonic ridge and not affected or offset by the ridge. Conversely, the ridge is interrupted at the intersection with the flow front. A fourth more ambiguous case is reported at the crater 0661 + 096 for which the trajectory of the ridge intersects the ejecta unit. The THEMIS-IR daytime image I01171005 does not have a sufficient resolution to define the chronological sequence. The ridge is observed within the ejecta unit, but the flow appears to have been affected by its presence resulting in a thickening of the deposit at the foot of the ridge on the downstream side of the flow. All these observations strongly suggest that type II craters have been formed before the tectonic episode, while HCP-rich or type I craters have been formed after it. All craters cannot be dated relatively to the tectonic episode by this approach but the stratigraphic relationships for these samples suggest that type I ejecta are systematically younger than type II. This working hypothesis will be investigated further in the next section examining the surface state of degradation of ejecta.

Table 1. Geographic Coordinates of Investigated Craters With Their Spectral Type According to Their HCP Band Depth Relative to the Syrtis Plateau

<table>
<thead>
<tr>
<th>Crater ID</th>
<th>Latitude</th>
<th>Longitude (East)</th>
<th>Diameter, km</th>
<th>Type</th>
<th>Min. Elevation, m</th>
<th>Rim Elevation, m</th>
<th>Cavity Depth, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0708-014</td>
<td>-1.41</td>
<td>70.86</td>
<td>13.22</td>
<td>I</td>
<td>889</td>
<td>2339</td>
<td>1450</td>
</tr>
<tr>
<td>0705-058</td>
<td>5.89</td>
<td>70.55</td>
<td>23.00</td>
<td>I</td>
<td>461</td>
<td>1973</td>
<td>1512</td>
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<td>0743+089</td>
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<td>74.34</td>
<td>23.67</td>
<td>I</td>
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<td>1350</td>
<td>1858</td>
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<tr>
<td>0661+096</td>
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<td>1158</td>
<td>2620</td>
<td>1462</td>
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<td>10.32</td>
<td>64.14</td>
<td>12.61</td>
<td>I</td>
<td>1030</td>
<td>2254</td>
<td>1224</td>
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<td>11.08</td>
<td>67.65</td>
<td>13.96</td>
<td>I</td>
<td>1263</td>
<td>2388</td>
<td>1125</td>
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<td>73.04</td>
<td>17.66</td>
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<td>43.26</td>
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<td>1104</td>
<td>2445</td>
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</table>

The minimum elevation of the cavity, the maximum elevation of the rim, and the difference between these two values (cavity depth) have been measured for all the craters from MOLA data. The diameter corresponds to the rim-to-rim diameter. The top part of the table corresponds to the type I craters, and the bottom part corresponds to the type II craters. Inside each class, the craters are sorted by increasing values of latitudes.
2.2.2. State of Degradation of Type I and Type II Ejecta Layers

Qualitative indications of crater ages can be derived from ejecta and cavity morphology and morphometry [Barlow, 2005; Forsberg-Taylor et al., 2004]. The following observations are reported for 8 type I and 5 type II craters:

- Depth to diameter ratios
- Presence or absence of secondary craters
- Presence or absence of radial lineations
- State of degradation

Figure 3. Stratigraphic relationships between ejecta and compressive ridges for ejecta type II. (top) THEMIS-IR (daytime) or THEMIS-VIS images of the craters. (bottom) Morphological interpretation sketches.
degradation from ejecta surface texture at the THEMIS-VIS scale and presence or absence of a distinct thermal edge as defined by Baratoux et al. [2005]. These observations and the reference of each crater are reported in Tables 2 and 3.

2.2.2.1. Morphometric Characteristics

Depths and crater diameters are affected by erosion (crater infilling, mass wasting on the rim slope, etc.). Comparison of crater depths as a function of the crater diameters could help in the discrimination of fresh morphologies from morphologies affected by erosion associated with older ages. Crater depths and diameters have been measured from MOLA data for all the type I and type II craters (Figure 5). Crater depths are scattered around but mostly below the standard average law for Martian fresh craters [Garvin et al., 2003] suggesting erosional modifications. However, material properties can also explain the deviation from the average martian law [Boyce et al., 2006]. The important point is that ejecta type I and II are not distinguishable from their morphometric characteristics which consequently cannot be used to trace the erosional history of the lobate ejecta of Syrtis Major.

2.2.2.2. Secondary Craters and Radial Lineations

Secondary craters are features formed at the time of impact by fragment of ejecta and are easily erodible. Their

Figure 4. Stratigraphic relationships between ejecta and compressive ridges for ejecta type I (HCP-rich). (top) THEMIS-IR (daytime) or THEMIS-VIS images of the craters. (bottom) Morphological interpretation sketches.
presence suggests a young age for the primary crater. Radial chains or clusters of secondary craters have been unambiguously identified for two craters of the HCP-rich class (0743 + 089 and 0644 + 097). Secondaries are ubiquitous for the crater 0743 + 089 on THEMIS-IR daytime images I0932206 and I03143002 as shown in Figure 6 and they can also be noticed on nighttime images. Radial lineations are reported only for one crater which belongs to the HCP-rich class. The mechanism of formation of radial lineations is not known but it may develop during the radial surface flow of ejecta falling onto the crater rim producing scour marks [Mouginis-Mark and Boyce, 2004], or by impact-generated winds scouring the previously deposited ejecta layer [Suzuki et al., 2007]. These lineations are topographically small (few meters in height at maximum) and easily erodible. Their observation at the crater 0708–014 (Figure 7) in addition to the secondaries suggests a relatively younger age for the HCP-rich ejecta (Figure 7).

2.2.2.3. Surface State and Degradation of the Ejecta Layers

[14] The typical morphologies of ejecta observed at Syrtis suggest that all ejecta units have been preserved for erosion and it seems challenging to make a clear distinction between the ejecta morphologies. However, we tried to distinguish between fresh and degraded surface state from the comparison of visible images at the same scale. The ejecta is said “fresh” when the surface is homogeneous, smooth and when some features associated with the flow remains visible (concentric or radial textures). The ejecta is said “degraded” or “dissected” when the surface is rougher and displays evidence of erosion (e.g., presence of eroded small craters formed on the ejecta unit). Typical examples of surface states are given in Figure 8. The terms “degraded” and “dissected” correspond to a gradually rougher and less homogeneous surface (see Figure 8, right). Using images at similar resolution, we report that the surface texture is generally fresher for ejecta type I while ejecta type II display in most cases a more or less dissected or degraded surface texture. However, the ejecta layer and the flow front are always clearly identified for all analyzed type II ejecta. It is thus important to emphasize here that a similar but not extensive erosion has affected both type I and type II craters. This observation is consistent with the scatter of cavity depths around the standard Martian law. The continuous ejecta layer is present for both types of craters (at the exception of the 717 + 133 crater). Thus the absence of the HCP enrichment relative to the Syrtis lava does not correspond to a removal of the ejecta material. However, a slightly more advanced state of surface degradation suggests again an older age for the type II craters.

2.2.2.4. Thermal Properties

[15] The flow front of ejecta of a large majority of lobate craters at Syrtis Major shows a thermal anomaly at night [Baratoux et al., 2005]. The presence or absence of this thermal feature has been searched for the craters considered here. In some cases, the thermal anomaly outlines the flow front continuously following all the ejecta perimeter and is said complete. For other cases, the thermal anomaly can be only observed over a segment of the ejecta flow front and is said partial or sparse for the less developed cases. The warmer temperature at the flow front at night could result from grain sorting during the surface flow [Baratoux et al., 2005]. This hypothesis has been recently recalled from high-resolution images showing boulders at the edge of ejecta which could also correspond to remnants of massive material composing the edge of ejecta unit [Mouginis-Mark and Baloga, 2006]. This thermal feature is not clearly associated with one of the observed spectral types of ejecta (Tables 2 and 3). Whatever its exact origin, the observation of the warmer ejecta front appears thus not to be diagnostic of the age of the craters at Syrtis Major.

---

**Table 2. Synthesis of Morphological and Surface State Observations for HCP-Rich or Type I Craters**

<table>
<thead>
<tr>
<th>Crater ID</th>
<th>Secondary Craters</th>
<th>Radial Lineations</th>
<th>Surface Texture</th>
<th>Thermal Anomaly at the Front</th>
</tr>
</thead>
<tbody>
<tr>
<td>0708+014</td>
<td>no</td>
<td>yes</td>
<td>fresh</td>
<td>complete</td>
</tr>
<tr>
<td>0705+058</td>
<td>no</td>
<td>no</td>
<td>fresh</td>
<td>partial</td>
</tr>
<tr>
<td>0743+089</td>
<td>yes</td>
<td>yes</td>
<td>fresh</td>
<td>complete</td>
</tr>
<tr>
<td>0661+096</td>
<td>yes</td>
<td>no</td>
<td>fresh</td>
<td>partial</td>
</tr>
<tr>
<td>0644+097</td>
<td>no</td>
<td>no</td>
<td>fresh</td>
<td>partial</td>
</tr>
<tr>
<td>0676+110</td>
<td>no</td>
<td>no</td>
<td>degraded</td>
<td>complete</td>
</tr>
<tr>
<td>0738+114</td>
<td>no</td>
<td>no</td>
<td>fresh</td>
<td>complete</td>
</tr>
<tr>
<td>0694+138</td>
<td>no</td>
<td>no</td>
<td>fresh</td>
<td>complete</td>
</tr>
</tbody>
</table>

*Craters are sorted by increasing latitudes.

---

**Table 3. Synthesis of Morphological and Surface State Observations for Type II Craters**

<table>
<thead>
<tr>
<th>Crater ID</th>
<th>Secondary Craters</th>
<th>Radial Lineations</th>
<th>Surface Texture</th>
<th>Thermal Anomaly at the Front</th>
</tr>
</thead>
<tbody>
<tr>
<td>X2</td>
<td>no</td>
<td>no</td>
<td>degraded</td>
<td>complete</td>
</tr>
<tr>
<td>0660+147</td>
<td>ambiguous</td>
<td>no</td>
<td>dissected</td>
<td>complete</td>
</tr>
<tr>
<td>0776+184</td>
<td>few large ones</td>
<td>ambiguous</td>
<td>strongly dissected</td>
<td>absent</td>
</tr>
<tr>
<td>0676+055</td>
<td>no</td>
<td>no</td>
<td>degraded</td>
<td>complete</td>
</tr>
<tr>
<td>0685+028</td>
<td>no</td>
<td>no</td>
<td>dissected</td>
<td>sparse</td>
</tr>
<tr>
<td>708+039</td>
<td>no</td>
<td>no</td>
<td>dissected</td>
<td>sparse</td>
</tr>
<tr>
<td>0648+022</td>
<td>no</td>
<td>no</td>
<td>fresh</td>
<td>partial</td>
</tr>
</tbody>
</table>

*Craters are sorted by increasing latitudes.
Tables 2 and 3 synthesize the observations for ejecta type I and type II respectively. Some observations indicate that some HCP-rich ejecta correspond to youngest impact events. Other observations suggest that type I craters cannot be distinguished from type II craters on the basis of their erosional state. Indeed, the depth to diameter ratio and the presence of the continuous ejecta layer for all these craters suggest that minor amount of erosion has affected both types of craters. To conclude, one can state that the youngest craters are all among the HCP-rich class. However, a limited erosion has affected the crater cavities and the ejecta layers. Consequently, the erosional history cannot be used with confidence to compare crater ages. Instead, absolute dating when possible will provide in the next section a better and conclusive basis for age comparison.

2.2.3. Crater Counts: Absolute Dating of Type I and Type II Craters

Absolute dating of impact craters is challenging because the area of the cavity and ejecta units of one impact crater is small in comparison with the area of geologic units which are usually dated by this method. The unit associated with the impact crater has been divided in two zones, respectively the continuous ejecta blanket and the crater floor which have been counted separately for all the dated craters. The inner and outer walls of the rim are subject to severe modification (mass wasting, erosion) and have been systematically discarded. The objective is to date the impact event itself and not any subsequent episode of erosion or crater infilling. Both zones offer advantages and disadvantages for this purpose. The crater floor is identified without any ambiguity but has an area smaller than the continuous ejecta blanket and will induce lower accuracy of the counts. Moreover, the crater floor is easily filled by wind-transported sediments. Mass wasting from the rim inside the crater floor after the crater formation can also partially affect the floor surface. The continuous ejecta blanket has a larger area than the crater floor but its limits are less easy to define in particular for the thinnest part where underlying craters smoothed by the ejecta deposit could be accidentally added to the counts. The continuous ejecta blanket could be also affected by secondary craters. However, secondaries form ballistically and thus likely before the emplacement of the continuous ejecta unit. Secondaries are indeed mostly observed outside the continuous ejecta unit. Finally, we report that crater counts on the crater floor translate systematically into very young ages compared to the results from crater counts on the continuous ejecta blanket and are not considered here because we believe they only represent the last episodes of cavity infilling. Crater counts have been made essentially from THEMIS-VIS images and MOC images and 6 examples are shown in Figure 9. All the derived ages are presented in Figure 10 and reported on the pyroxene map (see Figure 2). Some of the ages show large error resulting from the small areas that were counted. It is emphasized here that similar crater classes have been used for all the crater counts, which justifies the comparison of the ages we derived. These results demonstrate once more that type I craters are systematically younger than the type II. The HCP-rich signature is thus strongly associated with younger ejecta.

Figure 5. Crater depth as a function of crater diameter for a set of large type I and type II craters whose topography can be measured with the MOLA data. The average depth-diameter relationship is taken from Garvin et al. [2003], the parameters being rigorously defined by Garvin et al. [2000]. Type I and type II craters are not distinguishable from their morphometric characteristics.
2.2.4. Age of Formation of Type I and II Craters, Erosion, and Alteration History During Hesperian and Amazonian

[18] Relative ages from stratigraphic relationships and absolute ages from crater counting demonstrate that HCP-rich craters are systematically younger than the other craters. The existence of these two surface compositions of ejecta is thus not necessarily connected with lateral variations of the subsurface mineralogy. Lateral variations in the subsurface mineralogy across Syrtis Major shield cannot be ruled out from these observations, but are considered as a second order contribution to the ejecta surface composition variability. The determination of the timing and duration of the tectonic episode is not the scope of the paper. According to Hiesinger and Head [2004], the following chronology in three stages can be proposed: (1) volcano construction, with most of the lava flows observed today being emplaced before the end of this stage, (2) compressive ridge formation (first radial, then circular), minor amount and decline of the volcanic activity, and (3) no tectonic or volcanic activity but continuation of impact cratering. HCP-rich craters would have formed after the compressive ridge episode. Type II ejecta result from impacts which would have occurred at the

Figure 6. An example of observation of secondary craters associated with HCP-rich ejecta. Areas with ubiquitous clusters of secondaries are outlined. The mosaic uses THEMIS-IR day images I09322006 and I03143002 and corresponds to the crater 0743 + 089 as referenced in the paper. The observation of secondaries suggests that erosion has been limited since the impact event and the presence of secondaries are thus consistent with the hypothesis that HCP-rich ejecta correspond generally to the younger craters.

Figure 7. Observations of radial lineations on the crater 0708-014 (THEMIS-VIS image V10908801). These lineations are easily erodible, and their presence suggests a young age for the impact event.
end of the first stage and possible during the second stage. Then, the type II craters likely had the HCP enriched signature at the time of their formation but this signature is now masked to the observation from orbit.

[19] Different processes could have modified the HCP signature with time. The removal and transport of the ejecta layer affecting a thickness of a few meters or tens of meters of material could be invoked. The morphologic analysis suggests however that a minor amount of erosion occurred only consistent with partial removal of probably a minor fraction of the continuous ejecta layer. A more superficial process is thus more likely. For instance, a superficial coating or slow and long-term weathering during a cold and dry environment [Bibring et al., 2005] could affect the pyroxenes spectral signature without affecting the thermal features. Indeed, ejecta as rock fragments of all sizes are more easily weathered than massive lava layers. Alternatively, the accumulation of a dust cover which should be thicker on the older craters might also mask the HCP signature. A few microns of a homogeneous dust cover would be enough and such a thin deposit would not be detected by THEMIS-IR nighttime images. Poulet et al. [2003] have suggested that the south-west region of Syrtis may be covered by fines and oxide-rich particles. Very good examples of type II craters can be indeed found in the south-west region of Syrtis while type I craters are absent in the same area, but some type II craters can be also found north of the two pateras. Small and very recent craters impacting the ejecta deposit may expose material originating at depths of a few meters and representative of the mineralogy below the superficial layer made of dust or weathered basalt. The observations of the mineralogical signature of such small craters is beyond the capability of OMEGA given its resolution. However, CRISM observations might confirm or infirm this hypothesis. The mechanism modifying the HCP signature in older ejecta cannot be determined in this present study. However, given the rocks abundances at Syrtis and the lack of evidence for long-term dust accumulation at Syrtis, the slow and long-term weathering process more likely explains our observations. In any case, HCP-rich ejecta correspond to recent craters (roughly belonging to the Amazonian period) and the ejecta mineralogy of these craters reflects thus the mineralogical composition at depth giving access to the vertical variations.

2.3. Sizes and Distribution of HCP-Rich Craters

[20] HCP-rich ejecta reflect the enrichment of subsurface material in high-calcium pyroxene relative to the exposure of volcanic rocks between the craters. This structure and the mineralogical composition could be variable over the volcanic shield depending for instance on the variation of the thicknesses of volcanic deposits with the distance from the vent. Such lateral variations should be reflected into the geographic distribution of HCP-rich craters. In order to test this hypothesis, a catalogue of 143 HCP-rich ejecta objects has been realized. The excavation depth is related to the crater size. Thus the distribution of HCP-rich ejecta relative to the volcanic center has been explored as a function of the crater size (see Figure 11). Radial thickness or depth variations of a HCP-rich body should imply changes in the average distance of type I crater to Nil at as a function of crater diameters. For instance, let us consider a HCP-rich layer in the subsurface and assume that its depth increases will the radial distance. Then, the average distance of large
Figure 9. Crater counts and corresponding isochrons for craters 0705 + 058, 0743 + 089, 0738 + 114, 0661 + 096, 0644 + 097, 0660 + 147, 0708 + 039, and 0648 + 022. Isochrons are from the last update of Hartmann [2005].
HCP-rich craters would be larger than the average distance of small HCP-rich craters as a result of the decrease of small HCP-rich craters at large distance. Assuming that Nili Patera is the volcanic center, we find that the average distances of HCP-rich ejecta is independent of crater sizes which contradicts our hypothesis. Actually, this outcome is independent of the choice of the location of the volcanic center. This has been checked through different tests placing the center at Meroe Patera, north and south of Syrtis. This result strongly supports the idea that HCP-rich material is present at similar depths within all the Syrtis plateau.

[21] The depth of HCP-rich material can be discussed from the size distribution of HCP-rich craters. The HCP-rich signature of ejecta may result from a shallow material, typically at a few millimeters/centimeters depth, which would not be or only partially detected outside the ejecta. One possibility would be that the uppermost layer at Syrtis comprises a large proportion of dust or weathered basalt. However, the dust cover on Syrtis is not homogeneous as surface temperature variations at night demonstrate and the dust cover is not a satisfactory explanation. Alternatively, the HCP-rich ejecta signature may result from material present at larger depth which can be only excavated and deposited at the surface by large craters.

[22] Assuming that the HCP-rich material is homogeneously present within the volcanic construct as suggested by the geographic distribution of HCP-rich ejecta, the size distribution of craters associated with HCP-rich ejecta provides some information about the depth and thickness of the HCP-rich material. The size distribution has been normalized to the Martian isochrons according to the last update given by Hartmann [2005]. The crater count for the 16–32 km class has been used for the normalization. The normalized crater counts should be all equal to one if all craters excavated equally into the HCP-rich material. This

**Figure 10.** Comparison of the ages of ejecta types I and II. The rectangles account for formal uncertainties in age determination depending on the surface and the number of craters available. The ejecta type I (HCP-rich) surfaces appear systematically younger than the ejecta type II.

HCP-rich craters would be larger than the average distance of small HCP-rich craters as a result of the decrease of small HCP-rich craters at large distance. Assuming that Nili Patera is the volcanic center, we find that the average distances of HCP-rich ejecta is independent of crater sizes.

**Figure 11.** Average distance to Nili Patera and standard deviation for 143 impact craters within Syrtis Major and associated with HCP-rich ejecta blanket as a function of diameter. The numbers of craters in each class are in increasing order of diameter: 10, 39, 53, 27, 9, and 5.
would be the case if the HCP-rich material is found only at a few millimeters or centimeters depth. The typical excavation depth as a function of the crater diameter is given by (see details of this calculation in Appendix A)

$$H_{ex} = 0.109D^{0.872}$$  \[(2)\]

[23] A typical depth of excavated material is then considered and defined here as half of the maximum excavation depth. For the class of craters ranging from 4 to 8 km in diameter which goes across the simple-complex transition, an average value between the complex and simple case is chosen. The general increase of the normalized number of HCP-rich ejecta with diameter (Figure 12) indicates that small craters have less probability to excavate down the HCP-rich material. The depletion for the class of smallest craters is thought to be partially due to the resolution of the data. However, the 1–8 km craters would correspond to ejecta extended through more than a few pixels on OMEGA observations. Despite the fact that small craters can be eroded faster than larger ones explaining the increase of the proportion of HCP-rich ejecta with diameter, the lack of small craters associated with HCP-rich ejecta blanket more likely suggests that the HCP-rich material is buried at a few tens to few hundreds of meters depth. The hypothesis will be assessed further with the detailed analyses of OMEGA spectra within individual ejecta layers.

3. Spectral Variations Within the HCP-Rich Ejecta Deposit

3.1. Spectral Axisymmetry of Ejecta Deposit

3.1.1. Spectrum Integration Method Over Azimuthal Directions

[24] Impact craters are axisymmetric features as illustrated by the circular rim and the circular ejecta blanket except in the case of a very oblique impact. This property results from the deposition of momentum and energy in a quasi-ponctual source, the shock wave propagating as an expanding half-sphere [Holsapple and Schmidt, 1987; Melosh, 1989]. For this reason the spectral signature of ejecta which have not been perturbed by post-impact processes is expected to display an axisymmetric pattern reflecting the compositional distribution. In other words, the spectrum at a given distance of the center should be independent of the direction taken from to the center of the crater. The axisymmetric property of the spectra within ejecta deposits can be evaluated for the first time on Mars and may provide an additional evidence of the impact-related origin of the present spectral signature. If true, it will be then possible to take advantage of this situation to average all spectra at a given distance from the crater center to increase the signal to noise ratio in comparison with the analysis of an individual spectrum. The “noise”, or more precisely the spectral variability with azimuth, is defined in that case, in addition to the instrumental noise, by any local perturbations in the theoretical axisymmetric composition of the ejecta deposit due to instabilities in the surface flow or local post-impact modifications of the ejecta layer (e.g., erosion, wind streaks, dust patches, impact on the ejecta layer itself).

[25] The region of interest is defined for each crater with the objective to avoid the ubiquitous perturbations occurring on a restricted part of the ejecta unit. Among the possible post-impact modifications of the ejecta layer, two processes can be easily identified and discarded in the analysis: new impacts on the ejecta itself (craters larger than a few hundred of meters in diameter can be observed) and wind streaks which are the major modifications of the surface involving erosion or deposition of fine particles or soils. The definition of the set of selected spectra for one ejecta unit cannot be performed automatically and is thus done manually from the simultaneous inspection of OMEGA data and medium to high-resolution images (THEMIS-VIS and THEMIS-IR). The rim of the crater is also defined on the OMEGA data. The location of the crater center in the OMEGA data geometry is defined using the rim geometry fitted to an ellipse using a least-squares algorithm. The range relative to the crater center for each individual spectra of the region of interest is then estimated. An average spectrum at a given range is estimated from the average of all spectra inside a sliding annulus as a function of the radial distance and with a given width, the center of each annulus being the center of the crater (see Figure 13, right):

$$R(\lambda_i, d_j) = \frac{1}{n} \sum_{k=0}^{n} R(\lambda_i, d_k)$$  \[(3)\]
where \( R(\lambda_i, d_j) \) represents the average spectra as a function of the distance \( d_j \) of the crater center, \( \lambda_i \) represent the wavelength, \( R(\lambda_i, d_j) \) is a individual spectrum at the distance \( d_j \) from the crater center such as \(|d_j - d_i| < \delta\) where \( \delta \) is the chosen spatial resolution for the smoothing process (or the width of the annulus); \( n \) is the number of spectra within the previously defined region of interest and within the annulus of width \( \delta \). The number \( N \) of sliding annuli is defined by

\[
N = \frac{d_{\text{max}} - d_{\text{min}}}{\delta} + 2
\]

where \( d_{\text{max}} \) and \( d_{\text{min}} \) are respectively the minimum and the maximum distance of spectra from the center of the crater, so \( d_j \) varies from the \( d_{\text{min}} \) to \( d_{\text{max}} \) and is discretized along \( N \) points. Then using a \( \delta \) ranging from three to six OMEGA pixels, the average spectrum is generally estimated from a few tens to a few hundred individual spectra (Figure 13, left), with the exception of the most inner and most outer regions, the shape of the manually selected region of interest being not axisymmetric. In practice, the \( \delta \) parameter has been made variable for these regions such that a minimum of 100 spectra are used for each averaged spectrum.

**3.1.2. Assessment of the Spectral Axisymmetry of the Ejecta Layer**

[26] The different steps in order to evaluate the axisymmetry of spectral variations are presented with an example corresponding to the crater 0743 + 089 as seen by OMEGA from the orbit 422_3 (Figure 14). For each value of \( d_j \), the \( IF \) value for one wavelength of each individual spectra within the annulus can be seen in polar coordinates. In this representation \( IF \) values are function of the azimuth and an ellipse can be fitted for each wavelength and each distance \( d_j \) (Figure 14a). The selection of a region of interest, which tends to avoid wind streaks or other potential perturbations of the pristine ejecta composition as explained previously, results in a partial coverage of all azimuthal directions. The discarded sector never exceeds 50\%, so the ellipse parameters are always very well constrained. This process is repeated for all distances and wavelengths. The average spectrum and standard deviations within each annulus are represented in Figures 14b and 14c. The values of the standard deviation for each spectrum are systematically smaller than the range of spectral variations within the ejecta unit. This first analysis demonstrates that significant spectral variations can be detected within the ejecta unit. These variations appear to be organized and display an ubiquitous evolution from the inner part of the ejecta toward the edge of the continuous ejecta blanket. Figures 14d and 14e show the results of the ellipse fit. The ratio of the major axis to the minor axis of the ellipse obtained considering the \( IF \) values as a function of azimuth is also generally small, as seen in this example. This ratio is higher for the spectra corresponding to the distal region of the ejecta. This distal region corresponds to the thinnest part of the ejecta deposit which could be easily more degraded and modified than the inner parts. Also, the deposit is not expected to be perfectly symmetric. Initial heterogeneities in the cratering excavation flow and/or the development of surface flow instabilities leading to the sinuous pattern of the flow front are naturally more developed in the distal regions than in the proximal ones. The average spectra extracted from the ejecta flow front region should thus be considered with caution in the following analyzes. The ratios of major axis to minor axis are consistent with the values of the standard deviations suggesting that most of the scatter of the \( IF \) values at a given range from the center of the crater results from the slightly elongated shape of the \( IF \) values in polar coordinates, rather than from random scattering around a circle. The standard deviation of the residuals from the ellipse fit are one order of magnitude smaller than the total standard deviation within an annulus as seen in Figure 14 and confirming this assertion.

[27] The same processing has been applied to all HCP-rich ejecta. Both standard deviations and ratios between the major and the minor axis confirm that spectral variations along the radial direction are larger than spectral variations within a given annulus. These values also demonstrate that the spectral signature of all HCP-rich ejecta is generally...
axisymmetric. The mean deviation from the ellipse confirms that most of the scatter within the annulus is due to the slightly elongated shape of the ellipse. The azimuth of the major axis is not constant and can vary abruptly with the range. The interpretations of eccentricities and variations of major axis azimuth are nontrivial and might be related to impact obliquity but are beyond the scope of this paper. Such a new investigation should be considered at the limit of the capabilities of OMEGA data given its resolution but is not out of reach for CRISM observations. We anticipate a possible correlation between these mineralogical variations and the instabilities of the surface flow outlined by the sinuous front of the ejecta deposit.

In conclusion, this analysis demonstrates the first-order axisymmetry of the spectral variations within the ejecta layers. The axisymmetrical property and the nonrandom evolution of the spectra within the ejecta layer is an additional evidence that the observed spectral variations on ejecta reflect the impact process and are not the result of post-impact modification processes. Consequently, it is founded to analyze these spectral variations in terms of subsurface mineralogical variations.

3.2. A First Analysis of Spectral Variations With Range

The averaged spectra for two of the largest type I (HCP-rich) craters are presented in Figure 15. For both...
craters, the first striking feature is a regular evolution of the average $I/F$ level with distance. The brighter region is always found in the vicinity of the rim. The presence of brighter regions suggests the presence of ferric phases which are found in the Martian dust. This can be investigated using spectral parameters which have been defined by Morris et al. [2000] or Bell et al. [2000] for the spectral and mineralogical analysis of rocks and soils at Mars Pathfinder landing site. The first criterion uses the absorption feature centered at 0.53 μm called BD530 in the work of Morris et al. [2000] and is defined as

$$1 - \frac{R(0.53)}{0.575 \times R(0.480) + 0.425 \times R(0.6)}$$

Increasing values of this parameter are interpreted as an increasing degree of alteration. As shown in the Figure 16, the negative or slightly positive value corresponds to the typical dark terrain with a lesser degree of alteration. No change in the degree of alteration can be noted within the ejecta layers from this spectral parameter. The second parameter is defined as the ratio of $I/F$ at 0.75 μm and 0.445 μm and is also a measure of the degree of alteration. This ratio has been evaluated for 7 type I craters as a function of the distance to the center of the crater (see Figure 16). This ratio for ejecta ranges from 2.5 to 3.5, except for the crater 0743 + 089 which has a value around 5. The comparison of this spectral parameter to the one obtained for Pathfinder rocks (2–5) and soils (4 to 7) indicates that ejecta material are dominated by ferrous rock-rich material rather than ferric dust-rich soil. This result confirms once more that the analyzed spectra are dominated by the composition of well exposed impact ejecta. A slight increase (5–15%) of the spectral parameter is observed in the brighter region close to

Figure 15. (top) Averaged spectra as a function of the distance to the center of the crater for (left) crater 0705 + 058 and (right) crater 0743 + 089. (middle) Averaged spectra scaled using reflectance at 0.7 microns. (bottom) Ratio of scaled spectra using a reference spectra defined by the most distal ejecta.
the rim. Ferric phases do also exhibit a broad absorption feature between 0.75 \( \mu m \) and 1.0 \( \mu m \). The ratio of \( I/F \) at 0.98 \( \mu m \) and \( I/F \) at 0.8 \( \mu m \) is a good index of the nature of the ferric oxides. This ratio ranges from 0.85 to 0.95 for the 7 craters presented in Figure 15, which is consistent with the presence of nanophase ferric oxides, with a size of about 10 \( \mu m \) [Morris et al., 1989, 1993]. For large craters, the ages have been determined as presented before, and are recalled here. The large value of the ferric index for the crater 0743 + 089 could be in favor of a possible relationship between age and abundance of the ferric nanophase, but this observation is isolated and no definitive trend between age and ferric indices can be established. In conclusion, the material observed within the ejecta layer is dominated by the ejecta fragments, with the possibility that the observed 10–15\% increase of albedo at small radial range results from the presence of a larger amount of a ferric nanophase soil component in the region close to the rim.

Besides the albedo variation, the spectral shape does also change with the range. This behavior can be investigated from scaled spectra. The \( I/F \) value at 0.7 \( \mu m \) is used to scale each averaged spectra for the craters 0705 + 058 and 0743 + 089 (see Figure 15, middle). Then, each scaled spectra has been also divided by the scaled spectra as the largest distance from the center of the crater (see Figure 15, middle). Small changes are found in the 1 \( \mu m \) domain but are difficult to interpret. Indeed, any change in this domain for the mafic materials found at Syrtis Major would likely result from the convolution of the 5 absorption features related to olivine, high-calcium pyroxene and low-calcium pyroxene. However, a trend is observed as a change in the slope around the 1.5 \( \mu m \)–2.0 \( \mu m \) domain which is both emphasized by the scaled spectra and the ratio of scaled spectra. Such an evolution could result from the variation of the band depth around 1.9 \( \mu m \) of the large absorption feature related to the low-calcium pyroxene. At longer wavelength, the change in band depth should be related to the high-calcium pyroxene absorption feature. These direct observations of the spectral shape suggests that a variation in the HCP/LCP ratio occurs across the ejecta, and is directly connected to the variation of those mineral abundances at depth. We will thus focus in the next sections of this paper on how the evolution of HCP and LCP abundances vary as a function of the distance to the crater.

### 3.3. Absorption Band Strength Variations on Ejecta

Spectral variations within the ejecta unit and as a function of the range have been established in the previous section. This section focuses on the corresponding variations in absorptions depth of high-calcium pyroxene and low-calcium pyroxene, suggested by the spectral shape evolution in the ejecta layer. Two approaches are presented, both relying on the Modified Gaussian model (MGM) [Sunshine et al., 1990; Sunshine and Pieters, 1993] which is suitable to deconvolve a spectra composed by a mixture of the two types of pyroxene and estimate their abundance [Kanner et al., 2006]. The first approach relies on the global mineral maps derived for Syrtis by Gendrin et al. [2006]
using the Modified Gaussian Model. The band strengths of pyroxene are averaged in a similar manner than individual spectra and all HCP-rich craters are studied by this fast approach. However, all individual spectra are not visualized, and our result relies on the accuracy of the general deconvolution process used for the derivation of this map. In the second approach, the averaged spectra are used as inputs to the MGM deconvolution. Each spectrum and each

Figure 17
fit achieved by the deconvolution can be visualized, so this approach can be considered more robust and applicable to local studies. However, this treatment cannot be applied for the hundreds of spectra obtained for all the HCP-rich craters. A few craters have been processed for comparison and used as a validation of the results of the first step.

### 3.3.1. Band Strengths From Modified Gaussian Model From Global Maps

[32] A few tens of spectral profiles are selected manually on the band strengths map. The manual selection has the same objective (see section 3.1.1) of avoiding wind streaks and other potential perturbations of pristine spectral signatures of the ejecta. The center of the craters is defined at the intersection of the selected profiles optimized by a least squares adjustment. The measurements are converted from cartesian coordinates to polar coordinates. Band strengths are then plotted as a function of the range from the center of the crater. A cubic spline interpolation method is applied in order to obtain smoothed variations of the band strengths at regularly spaced distances from the center of the crater. The interpolation is done over 100 points regularly spaced from the center to the maximum range for all profiles. As before, band strengths close to the crater center or at the edge of the continuous ejecta deposit should be handled with caution as they are derived from less points than the other parts. The regularly interpolated smooth band strength functions are then averaged and the standard deviation is estimated. This algorithm has been applied to the HCP and LCP bands in the 2 microns domain for 16 HCP-rich ejecta and 8 HCP-poor ejecta. A selection of the results on HCP-rich craters is presented in Figure 17. This selection shows that the HCP band strength presents a systematic maximum at a given range from the crater center for all HCP-rich ejecta observed. The positions of the rim of the crater and of the outer limit of the ejecta blanket have been indicated in order to visualize location of the maximum with respect to the ejecta morphology. The rims and ejecta boundaries locations have been obtained from MOLA data, THEMIS-IR daytime and THEMIS-VIS images when available. The light grey in Figure 17 corresponds to the extent of the ejecta layer (the gradation to white is used to represent the typical variations of the sinuous outer boundary). This maximum is reported for all the type I craters investigated in the paper and the maximum occurs generally between 1.1 and 3 crater radii. No trend can be reported between the band strength and the age of the craters.  

### 3.3.2. Band Strengths From Modified Gaussian Model on Averaged Spectra

[33] The Modified Gaussian Model is applied here to averaged spectra over azimuthal directions. One disadvantage of this approach is the possible loss of resolution. In the approach implemented in section 3.3.1, the MGM is applied to all spectra, and then HCP and LCP band strengths are interpolated and not averaged to produce a smooth curve of their variations. Here, the resolution is degraded before the application of the MGM taking into account the axisymmetry of the problem. Signal to noise ratio is increased at the expense of the resolution in the second approach. Ejecta blanket extending to large distances are the best targets for the computation of averaged spectra. The crater 0743 + 089 is one of the largest HCP-rich craters and it presents a HCP maximum as identified in the previous analysis. The initial parameters for the 3 bands and the continuum are similar to those of Gendrin et al. [2006] and are given in Table 4, except that the continuum is adapted to the level of $I/F$ as performed in the work of Pinet et al. [2006a, 2006b]. The set of averaged spectra along the azimuthal directions (see Figure 15) suggests an evolution with the range to the center of the crater. One example of fit is given in Figure 18 and the result of the MGM analysis for the crater 0743 + 089 is presented in the Figure 19. Results of the MGM fits presented in section 3.2.1 are displayed here for comparison. Similar band strengths for HCP and LCP are obtained using the two methods, and the HCP band strength maximum is detected at a similar distance from the crater center.

### 4. Interpretation of Band Strength Variations Within the HCP-Rich Ejecta Deposits

[34] The spectral variations within the HCP-rich ejecta have two striking properties: their axisymmetry and the evolution of the band strengths of the high-calcium pyroxene which is systematically characterized by a maximum occurring between 1.1 and 3 crater radius. The variations of the absorption depth could result from two contributions, a change in the modal composition and a variation of the grain size distribution. The shock effect is not discussed because the amount of shocked material in ejecta is very low (everywhere less than 1%) and is not likely to contribute to the spectral signal for the sizes of impact craters studied in this paper [Hörz et al., 1983]. The non-compositional effects are discussed first and we demonstrate that a real radial change in the pyroxene composition is observed on these ejecta. This conclusion justifies the

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**Table 4. Initial Parameters for the MGM Fits for the Ejecta of Crater 0743+089**

<table>
<thead>
<tr>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band positions, μm</td>
<td>0.950</td>
<td>1.900</td>
</tr>
<tr>
<td>Band widths, μm</td>
<td>0.400</td>
<td>0.500</td>
</tr>
<tr>
<td>Band depths</td>
<td>0.080</td>
<td>0.080</td>
</tr>
<tr>
<td>Error band depths</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Continuum coefficients</td>
<td>-1.75</td>
<td>-0.13</td>
</tr>
<tr>
<td>Error coefficients</td>
<td>1.00</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Figure 17.** HCP and LCP band strengths of selected HCP-rich type I craters as a function of the distance from the center of the crater. The two curves below and above the thick one indicate the uncertainties of band strength values estimated from the standard deviation of spline-interpolated functions. The absorption depths of pyroxene have been obtained from the interpolation of global maps derived from the Modified Gaussian Model as detailed in the work of Gendrin et al. [2006] and A. Gendrin et al. (Pyroxene diversity on Mars, submitted to Journal of Geophysical Research, 2006). On each crater the position of the crater rim is indicated. The extent of the ejecta layer is indicated by light grey, and the outer edge is symbolized by a gradation from grey to white.
attempt to derive the subsurface mineralogy from these observations and these aspects are presented in the last part.

4.1. Grain Size Variations

[35] Powders of the same material but with different particle sizes show pronounced distinctions in band strengths, even if the spectra are normalized or continuum removed [Adams and Filice, 1967; Shkuratov, 1987]. The spectral contrast and band depths at 0.95 μm and 2.0 μm have been demonstrated to be minimal for small (<50 μm) and large particle (>200 μm) on the lunar sample 24085 of Luna 24 [Shkuratov et al., 1999]. Then, one can argue that the maximum observed for the band strengths of pyroxenes can result from a monotonic increase or decrease in grain size as shown by Shkuratov et al. [1999]. However, this maximum of spectral contrast is expected to occur for particles of about 50–100 μm. As proposed by Putzig et al. [2005], the thermal inertia at Syrtis can be interpreted as indicative of effective particle sizes greater than 100 μm or indicative of rocky material. Monotonic particle size variations in this region are expected to produce monotonic changes in the band strengths. However, to be more demonstrative, we investigate below the expected grain size distribution in ejecta (1) from physical considerations of impact and ejecta emplacement processes, (2) from terrestrial observations, and (3) from the high-resolution thermal observations on the ejecta blanket using THEMIS images.

4.1.1. Grain Size Variations With Range Resulting From Ejecta Clasts Formation and Emplacement

[36] Distal ejecta experiment larger shock intensity and thus stronger fragmentation than proximal ones because their origin are close to the impact point. An increasing amount of small particles with range is thus expected. Ejecta emplacement departs from the ballistic case due to the atmosphere and to the possible fluidization resulting from the presence of a liquid or and gaseous phase filling the porosity between the solid particles [see Baratoux et al., 2005; Barlow, 2005]. Impact-generated wind vortices scour the ejecta blanket and entrain the fine particles at large distance [Barnouin-Jha et al., 1999]. The abundance of small particles is increased for distal ejecta by this process. Surface flow is also able to sort particles as proposed by Baratoux et al. [2005]. In this case, a dam of larger particles could form at the front of the flowing ejecta. This extent of this region as possibly identified on THEMIS-IR nighttime images is apparently limited to a few hundred meters and will not affect the band depths for the entire ejecta layer. Owing to the number of involved processes and unknown parameters, the characterization of the grain size distribution from physical considerations on ejecta fragments formation and emplacement processes is not yet feasible. However, the discussion above suggests that a regular increase of the effective or mean size of the particles with the distance of the crater is difficult to achieve from any combinations of these processes.

4.1.2. Terrestrial Observations

[37] Few craters have enough pristine ejecta in order to make observations concerning the grain sizes. At Elegante crater, and even more pronounced at Meteor crater, Peet et al. [2006] found a monotonic diminution of the abundance of blocks with the distance to the center of the crater. However, these two craters are small compared to the size of craters on Mars considered here. Ries crater in Germany (26 km in diameter) is the only known crater of this dimension which still has preserved and well exposed ejecta deposits. Fitting their observation, Hörz et al. [1983] found that the mean grain size of the Bunte breccia at Ries crater...
Table 5. LCP/(HCP + LCP) Ratio as Defined in the Experimental
Work of Kanner et al. [2006] for the Selection of Type I and Type II
Craters Investigated in This Paper

<table>
<thead>
<tr>
<th>Crater ID</th>
<th>Type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0708-014</td>
<td>I</td>
<td>0.237</td>
<td>0.442</td>
<td>0.327</td>
<td>0.040</td>
</tr>
<tr>
<td>0705+058</td>
<td>I</td>
<td>0.061</td>
<td>0.382</td>
<td>0.207</td>
<td>0.048</td>
</tr>
<tr>
<td>0743+089</td>
<td>I</td>
<td>0.128</td>
<td>0.335</td>
<td>0.211</td>
<td>0.030</td>
</tr>
<tr>
<td>0661+096</td>
<td>I</td>
<td>0.149</td>
<td>0.342</td>
<td>0.251</td>
<td>0.039</td>
</tr>
<tr>
<td>0644+097</td>
<td>I</td>
<td>0.216</td>
<td>0.408</td>
<td>0.281</td>
<td>0.035</td>
</tr>
<tr>
<td>0676+110</td>
<td>I</td>
<td>0.164</td>
<td>0.369</td>
<td>0.268</td>
<td>0.043</td>
</tr>
<tr>
<td>0738+114</td>
<td>I</td>
<td>0.097</td>
<td>0.348</td>
<td>0.231</td>
<td>0.041</td>
</tr>
<tr>
<td>0694+138</td>
<td>I</td>
<td>0.013</td>
<td>0.291</td>
<td>0.171</td>
<td>0.047</td>
</tr>
<tr>
<td>0717+142</td>
<td>I</td>
<td>0.092</td>
<td>0.333</td>
<td>0.213</td>
<td>0.056</td>
</tr>
<tr>
<td>0700+143</td>
<td>I</td>
<td>0.200</td>
<td>0.385</td>
<td>0.303</td>
<td>0.047</td>
</tr>
<tr>
<td>0703+144</td>
<td>I</td>
<td>0.074</td>
<td>0.352</td>
<td>0.217</td>
<td>0.050</td>
</tr>
<tr>
<td>0713+147</td>
<td>I</td>
<td>0.139</td>
<td>0.315</td>
<td>0.230</td>
<td>0.037</td>
</tr>
<tr>
<td>0677+159</td>
<td>I</td>
<td>0.081</td>
<td>0.365</td>
<td>0.210</td>
<td>0.064</td>
</tr>
<tr>
<td>X1</td>
<td>I</td>
<td>0.052</td>
<td>0.329</td>
<td>0.216</td>
<td>0.079</td>
</tr>
<tr>
<td>0701+181</td>
<td>I</td>
<td>0.159</td>
<td>0.337</td>
<td>0.240</td>
<td>0.045</td>
</tr>
<tr>
<td>0709+182</td>
<td>I</td>
<td>0.114</td>
<td>0.352</td>
<td>0.214</td>
<td>0.059</td>
</tr>
<tr>
<td>0648+022</td>
<td>I</td>
<td>0.338</td>
<td>0.490</td>
<td>0.400</td>
<td>0.027</td>
</tr>
<tr>
<td>0685+028</td>
<td>I</td>
<td>0.280</td>
<td>0.396</td>
<td>0.330</td>
<td>0.017</td>
</tr>
<tr>
<td>0708+039</td>
<td>I</td>
<td>0.197</td>
<td>0.491</td>
<td>0.361</td>
<td>0.049</td>
</tr>
<tr>
<td>0676+055</td>
<td>I</td>
<td>0.228</td>
<td>0.447</td>
<td>0.343</td>
<td>0.047</td>
</tr>
<tr>
<td>0717+133</td>
<td>I</td>
<td>0.197</td>
<td>0.839</td>
<td>0.448</td>
<td>0.132</td>
</tr>
<tr>
<td>X2</td>
<td>I</td>
<td>0.259</td>
<td>0.463</td>
<td>0.354</td>
<td>0.038</td>
</tr>
<tr>
<td>0660+147</td>
<td>I</td>
<td>0.262</td>
<td>0.620</td>
<td>0.343</td>
<td>0.042</td>
</tr>
<tr>
<td>0688+151</td>
<td>I</td>
<td>0.266</td>
<td>0.623</td>
<td>0.413</td>
<td>0.053</td>
</tr>
<tr>
<td>0776+184</td>
<td>I</td>
<td>0.154</td>
<td>0.999</td>
<td>0.380</td>
<td>0.162</td>
</tr>
</tbody>
</table>

*The top part of the table corresponds to the type I craters, and the bottom part corresponds to the type II craters. The ratios have been averaged over the entire ejecta units (fifth column); the maximum, minimum, and standard deviation values are also reported.

falls as the inverse ninth power of the distance from the center of the crater. It is essential to emphasize that in every drilling location, grain sizes vary by orders of magnitude and ejecta are never well sorted. This mean grain size evolution has been reported on the Figure 20 with the indication of the domain of sensitivity to particle size for the reflectance spectroscopy and surface temperature measurements from infrared images. At any given range, ejecta clasts are not well sorted and the grain size distribution is spread over few orders of magnitude, the physical meaning of the mean grain size should thus be considered with caution. Despite this remark, the graph suggests that grain size distribution in ejecta is not likely to explain alone the observed spectral variability on Martian ejecta. Some recent observations of the Ries ejecta layer [Schöning et al., 2005, 2006; Schöning and Kenkmann, 2006] have confirmed the diamicite nature of the superficial material. We would like to emphasize that these observations the fact that the surface observed from orbit on Mars corresponds really to a well-mixed layer of excavated material, the concept of inverted stratigraphy, as often illustrated from Meteor Crater in Arizona, being only valid in the inner part of the crater wall or in a region immediately in the vicinity of the rim.

4.1.3. Grain Size Distribution on the Ejecta Layer From THEMIS Images at Night

[38] The grain size distribution can be further examined from the thermal data. Examination of surface temperature at night from THEMIS images (Figure 21) reveals that the ejecta layer temperature is very homogeneous except for the few hundreds meters width front as mentioned earlier. Since thermal inertia is sensitive to a range of grain sizes which covers the range of sizes for which band depths could be also modified (few microns to few millimeters), the result above does not suggest systematic grain size variation with the distance to the center of the crater. Indeed, THEMIS images do not suggest any systematic grain size variation with the distance to the center of the crater.

4.1.4. Concluding Assessment About the Contribution of Grain Size

[39] THEM observations indicate that the surface temperature is homogeneous and not controlled by local dust deposits within the ejecta layer or by significant variations of thermal properties related to grain size. From the ferric spectral indices, we report a slight increase of a soil component only in the region close to the rim where the soil component may potentially affect the pyroxene band depths observed for pixels composed by a mixture of rocks and soils. However, the increase in the ferric index is restricted to the region immediately close to the rim (Figure 16), while the maximum in HCP occurs generally at larger range. Finally, the LCP band depth gently increases systematically outward, or sometimes even presents a minimum. A simultaneous increase or decrease of the HCP and LCP band strengths would have been consistent with a grain size change or a mixture with a soil component. However, the variation of HCP and LCP are not correlated. In addition, the maximum of the HCP band depth corresponds to a pronounced extremum in the normalized ratios of band depth. These observations taken together demonstrate the spectral evolution within the ejecta layer is controlled at the first order by mineralogical variations; the possible grain size changes across the ejecta layer cannot explain the observed spectral trends.

4.2. Compositional Variations Within the Ejecta Layer

[40] Noncompositional interpretations of the interesting spectral features on ejecta are thus ruled out and it is believed that the spectral variations, and in particular the HCP band strength maximum, results from a variation of the modal composition within the ejecta layer. It is possible to estimate with a reasonable uncertainty the proportion of the two pyroxenes in a melange from normalized ratio of LCP and HCP band strengths as recently demonstrated by Kanner et al. [2006]. The band strengths ratio LCP/(HCP + LCP) can be estimated to compare the modal abundances for the maxima and for the regions outside the ejecta. This ratio is independent of grain size and any variations of this ratio strengthening the demonstration that band strengths variations are not primarily related to grain size variations within the ejecta. Using typical values taken from the Figure 17 and reported in Table 6, the normalized band strength ratio is 0.136 ± 0.03 at the location of the HCP band strength maximum, and reaches 0.33 ± 0.07 outside the ejecta layer. This change in the ratio indicates a difference in the modal composition of about 20%. High-calcium pyroxene proportion is typically about 66% ± 12% at Syrtis Major, except within the ejecta unit where the proportion of HCP reaches 87.5% ± 10.5%, arguing for a quasi monopyroxene composition for the ejecta, nevertheless not
excluding the presence of olivine or feldspar. Uncertainties given in Table 6 are derived from
\[ \delta_{\text{HCP}} = \sqrt{\left(\frac{\delta_{\text{LCP}}}{\text{HCP} + \text{LCP}}\right)^2 + 0.12} \] (6)

where \( \delta_{\text{LCP}/(\text{HCP} + \text{LCP})} \) corresponds to the uncertainty on the measured ratio and 0.1 corresponds to the uncertainty of the MGM method of 10% estimated in Kanner et al. [2006]. The values only slightly overlap given the error bars, so we believe that the difference interpreted in modal composition is meaningful.

[41] Both methods have demonstrated the enrichment of the ejecta layer in HCP. The maximum of enrichment occurs within the ejecta layer, but not necessarily at the rim where the deepest material of the ejecta unit is exposed. An attempt is made in the next section to relate this variation of the HCP band-depth to the variations with depth of the mineralogical composition.

4.3. Modeling the Excavation and Ejecta Emplacement

[42] A model of excavation flow and ejecta emplacement is required to obtain insights into the subsurface mineralogy from the variation of the mineralogical composition inside the ejecta layer. Deriving the subsurface mineralogical structure from the variations of composition within the ejecta is a challenging inverse problem. As a first step, the methodology developed here proposes a direct approach and different plausible mineralogical models for the subsurface mineralogy are explored and tested. Modeling the excavation flow and ejecta emplacement is aimed at deriving the composition of the ejecta layer as a function of the range, given a subsurface structure and composition. Then, the features of the ejecta layer are compared to OMEGA observations. Absolute mineralogical concentration cannot be derived yet for the ejecta, owing to the uncertainty concerning other components (olivine, feldspar). However, we show that the relative trends (e.g., increase, decrease, minima or maxima) in mineralogical proportions within ejecta can provide with a quantitative information about the subsurface mineralogy of Syrtis Major.

4.3.1. Definition of the Subsurface Mineralogy

[43] The subsurface mineralogy used in this direct modeling of the excavation flow is described using a finite number of layers defined by their thicknesses and compositions (Figure 22). The composition of each layer is described with a number of minerals and their abundances. Minerals such as feldspars though certainly present [Bandfield, 2002] cannot be detected and mapped by OMEGA. The Modified Gaussian Model focuses on the deconvolution of spectra assuming mafic minerals, namely high-calcium and low-calcium pyroxenes. Olivine is also present [Mustard et al., 2005; McSween et al., 2006; Pinet et al., 2006b; Poulet et al., 2007], but most of the craters analyzed here do not contain a significant amount of olivine. Consequently, the presence of other spectrally neutral components has been incorporated into the

![Figure 20. Mean grain size variations with range according to the power-law fit of the observations made at Ries crater by Hörz et al. [1983]. At any given range, ejecta clasts are not well sorted, and the grain size distribution is spread over a few orders of magnitude; the physical meaning of the mean grain size should thus be considered with caution. The corresponding domain of the HCP maximum has been also reported on the graph, as the sensitivity domain of surface temperature and spectral contrast to grain size [Shkuratov et al., 1999; Pelkey et al., 2001]. This graph suggests that grain size variations within the ejecta layer are not likely to explain the maximum in the HCP absorption.](image-url)
excavation model, and the total abundance inside a layer is not necessarily 100%.

4.3.2. Z-Model Excavation Flow and Ballistic Trajectories

[44] The physical modeling of excavation flow is possible using hydrocodes such as SALE-B [see Amsden et al., 1980; Ivanov, 2003]. However, the SALE-B cannot handle easily a stratified target. An increasing number of difficulties arises when physical modeling of ejecta emplacement on Mars is attempted. These difficulties arise if one takes in account the fragmentation and grain size distribution of the ejecta, the interaction of these particles of different sizes with the atmosphere, and the possible surface flow of ejecta hitting the surface, possibly modified by the presence of volatiles. The coupling of excavation flow into numerical models of ejecta emplacement incorporating the interaction with the atmosphere and surface flow has not been really attempted yet [e.g., Barnouin-Jha et al., 1999]. Even if such a model existed, it would probably be highly time consuming to investigate a wide range of subsurface structures. Instead, we choose here to develop a simple first order analytical approach. In this approach, the excavation flow is described by the Z-model developed and validated for explosion experiments [Maxwell, 1973, 1977; Austin et al., 1981] followed by ballistic trajectories. The excavation flow field is qualitatively illustrated in Figure 23. Velocity vectors in the material surrounding the growing cavity can be connected by streamlines representing the paths along which target material moves during the excavation flow. The excavation flow is axisymmetric about a vertical line passing through the impact point and the streamlines correspond to the projection of stream surfaces which should be seen in three dimensions. The central equation of the Z-model [Croft, 1980] approximating the excavation flow relates the radial component of the excavation flow velocity to the inverse power of the radial distance to the impact point:

\[ u_r = \alpha(\theta, t) \frac{1}{r^2} \]  

[45] In this equation, the strength of the flow is controlled by \( \alpha(\theta, t) \), a function of time \( t \) and angular distance from the

**Table 6.** Examples of Typical Values for the HCP and LCP Band Strengths Within the Ejecta Layer and Outside With Their Associated Uncertainties

<table>
<thead>
<tr>
<th>Crater</th>
<th>HCP Maximum</th>
<th>Outside the Ejecta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0743+089</td>
<td>0.10 ± 0.01</td>
<td>0.07 ± 0.01</td>
</tr>
<tr>
<td>HCP band strength</td>
<td>0.03 ± 0.005</td>
<td>0.04 ± 0.005</td>
</tr>
<tr>
<td>LCP band strength</td>
<td>0.2 ± 0.06</td>
<td>0.36 ± 0.09</td>
</tr>
<tr>
<td>HCP/(HCP + LCP)</td>
<td>80% ± 12%</td>
<td>64% ± 13%</td>
</tr>
<tr>
<td>0713+147</td>
<td>0.19 ± 0.01</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>HCP band strength</td>
<td>0.03 ± 0.005</td>
<td>0.050 ± 0.005</td>
</tr>
<tr>
<td>LCP band strength</td>
<td>0.136 ± 0.03</td>
<td>0.33 ± 0.07</td>
</tr>
<tr>
<td>HCP abundance (weight %)</td>
<td>87% ± 10.5%</td>
<td>67% ± 12%</td>
</tr>
</tbody>
</table>
vertical \( \theta \). Z is the dimensionless parameter from which the model gets its name. The characteristic velocities of the excavation flow are generally subsonic; thus the flow can be assumed to be incompressible. The condition of incompressibility writes

\[
\nabla \cdot \mathbf{u} = 0
\]

and constrains naturally the angular component of the velocity to be

\[
u_\theta = u_r \frac{Z - 2}{1 + \cos \theta}
\]

The integration of (9) gives the parameterized equation of the stream surfaces:

\[
r = r_0 (1 - \cos \theta)^{1/(Z-2)}
\]

When the center of the excavation flow is assumed to be at the surface, \( r_0 \) represents the distance from the center of the crater at which the material along the streamline is ejected. The streamline that defines the divide between material ejected from the transient cavity and material which is merely displaced downward is called the hinge streamline. Roughly equal volumes of material are either ejected from the crater or displaced downward into the crater. The Z-model is used to define the origin of the material excavated at a given range from the center of the crater. The fate of this material depends on the ejection position and velocity angle. Ejection angle is assumed to be generally close to 45°. The dimensional analysis of the impact process has been applied to the ejecta deposits [Housen et al., 1983] and the following relationship

- **Figure 22.** The \((n, m)\) matrix defining the mineralogical structure of Syrtis for the direct modeling of excavation flow and ejecta emplacement. The mineralogical composition at depth is defined with a finite number of \(n\) layers. The proportions of the \(m\) different mineral species is given for each layer. The total of proportions for each layer could be less than 100%, allowing the presence in the rocks of mineralogical compounds which are spectrally neutral.

- **Figure 23.** Schematic representation of the excavation flow and ejecta emplacement according to the Z-model followed by ballistic trajectories. The area represented in light grey represents the transient cavity. The area in darker grey between the stream surfaces outlines the material that is eventually deposited in the region defined by the continuation of stream surfaces into the ballistic trajectories.
where $R$ is the radius of the transient crater, $g$ is the gravity at the surface of the planet and $r$ is the position of ejection.

The direct problem is solved numerically. The ejecta layer is gridded into a number of points at given ranges depending on the resolution desired. The material which falls within two nodes of the grid has traveled along the volume defined by two neighboring ballistic trajectories in the air intersecting the surface at two ejection points. Then, these two neighboring trajectories prolongate into two streamlines of the excavation flow. The ejecta deposit is thus assumed to be a perfect mixture of the material bounded by the two streamlines of the excavation flow.

The composition of this material is computed from the intersection between the equation of the streamlines and the matrix defining the composition of the subsurface material. The resolution used to describe the subsurface material is such that the volume inside streamlines contains enough cells (generally more than one hundred). Streamlines are approximated to follow the boundaries between the cells and no attempt has been made to consider fraction of cells along the streamlines. The perfect mixture assumption is justified by the observation of Chicxulub ejecta blanket which is a highly chaotic breccia or diamicrite with indications of turbulent mixing with the absence of bedding or stratification [Schönian et al., 2006]. The upper surface of the ejecta is thus expected to give a good representation of the ejecta layer content.

### 4.3.3. Main Limitations of the Ejecta Emplacement Model

A number of processes have not been yet taken into account in this approach. A single, stationary point-source for the Z-model is known to be inadequate to explain the details of the excavation flow for oblique impacts, even for angle as high as 45°. A new analytical model could be implemented in the future with a migrating point-source [Anderson et al., 2004] to address this issue. However the strong approximation arises when neglecting both possible atmospheric interaction and surface-flow after ballistic deposition for the Martian case. Atmospheric transport has the potential to mix material initially on different ballistic trajectories by aerodynamic drag [Schultz and Gault, 1979] or after deposition by vortex winds scouring superficial particles as suggested or reproduced by different experiments and models [Schultz, 1992; Barnoin-Jha and Schultz, 1996; Barnoin-Jha et al., 1999; Suzuki et al., 2007]. Ejecta analyses on terrestrial craters have demonstrated that distal ejecta which move faster incorporate a large fraction of surface material when they hit the surface [Schönian et al., 2006; Kenkmann and Schönian, 2006]. The fraction of superficial material in the ejecta, which is naturally higher at large range given the excavation flow, would be ever increased by this effect. The lack of correlation between the volume inside the rampart and the volume within the main part of the ejecta blanket emphasized the importance of the radial low in the final morphology as reported by Mouginis-Mark and Baloga [2006].

Stewart and Valiant [2006] have also indicated that the original Z-model does not provide a good fit to fresh Martian impact crater and discrepancies arise for the volume ejecta or rim height modeling. Besides this unsatisfying model for the excavation flow, other authors concentrated on the surface flow assuming rough approximation of the initial ejecta flow pattern. This is the case for instance in the work of Baloga et al. [2005] where the source is approximated by time-dependent flow depth at the rim with a constant velocity. This mathematical expression of the source is useful to provide a reasonable initial condition to study the surface flow. However, it is totally inappropriate for the investigation of the relationships between the ejecta final range and their original depth. However, this model illustrates probably well the flow pattern corresponding to the spreading of ejecta after their ballistic trajectories. Their solution makes obvious that a bijective function exists between the range of the final deposit and the range of the deposit approximated by the ballistic emplacement. The main effect of the radial flow would be to spread, with a radial differential effect, the ranges deduced from the ballistic sedimentation. In summary, it should be noted that (1) there is not yet a satisfactory model to reproduce analytically the excavation flow, (2) the interaction of ejecta with the atmosphere may scour superficial materials and result in a strong mixing of material initially on different ballistic trajectories, (3) the radial flow substantially modifies the prediction of a purely ballistic model of emplacement, and (4) the incorporation of surface material during the flow should consider an increasing amount of superficial material with ejecta range. These processes will be incorporated progressively as progresses are realized in each of these three aspects. Spectral studies of terrestrial craters should be a key point to further progress. Given these aforementioned limitations, the following results should thus be considered as first-order estimates.

### 4.3.4. Results

Different models of the mineralogical structure have been elaborated with the objective to reproduce the two main properties which have been observed for the youngest impact craters at Syrtis Major: (1) the enrichment in HCP in ejecta compared to the surrounding lava flows covering and being part of the structure of the volcanic shield and (2) the maximum of this enrichment occurs between 1.1 and 3 crater radii. In order to reproduce the global enrichment of HCP inside the ejecta, the subsurface should be HCP-enriched at some depth. A simple two layers model with an increase in the HCP/LCP ratio in the deeper layer would reproduce this ejecta property. The distal ejecta have a similar HCP and LCP proportion to the Syrtis lava flows; thus the superficial layer, used here as a reference to define the other layers, has an HCP proportion comparable to the average Syrtis Major rocks. However, whatever the depth and thickness of the second layer, it is not possible to explain the decrease of HCP inward. Indeed, the ejecta material which contains the largest proportion of a deep material is found in the immediate vicinity of the rim. The presence of a maximum at some distance from the rim can be only reproduced if one invokes a three layers model, or a model in which the HCP abundance has maximum at some depth and thus decreases at larger depths. The solution is
probably far from being unique and no attempt is made here to derive the exact depths and abundances within each layer. The model presented in Figure 24 is simply a reasonable model in which the trends of the normalized band depth ratio translate into a maximum of HCP proportion at a few hundreds of meters depth.

We have varied the parameters of this model to investigate the limit of the thicknesses that would reproduce correctly the ejecta mineralogy for craters ranging from 5 to 20 km in diameters. We find that the first layer has a thickness of a few hundred of meters. HCP proportion on the surface is thus representative of the HCP proportions in the first tens to hundreds of meters depth. This constraint is given by the distal ejecta which are less rich in HCP compared to the proximal ones. Recalling the fact that distal ejecta incorporate large proportions of surface material, a process which is not incorporated in the model, it is likely that the first layer has a shallower thickness than the estimate given from Z-modeling. Interestingly, an intermediate layer is enriched in HCP material compared to the exposed Syrtis lava. The thickness of this layer is difficult to determine. However, it should be thin enough such as craters of a few kilometers in diameters excavate through a third layer depleted in HCP with respect to the second layer. Then, the thickness of the intermediate layer, or the depth from which the HCP content starts to decrease should be less than one kilometer.

The following properties of the Syrtis major subsurface are consistent with all the observations. First, the surface mineralogy of the lava flows seems to represent also the first tens to possibly hundreds of meters of the Syrtis plateau. Then a change of the HCP/LCP ratio is observed which is characterized by an increase followed by a decrease at a depth of about 1 km. The main difficulty for the geologic interpretation arises with the possible evolution with depth for the other likely components of the rocks (feldspars, olivine and volcanic and/or impact glasses). The knowledge of the evolution of these minerals would be essential to characterize the petrology of the volcano at depth. However, the inferred change in the HCP/LCP ratio at a depth on the order of one kilometer opens the possibility that impact craters at Syrtis have excavated through the lava pile excavating through the underlying crust. A similar thickness of the lava pile has been independently estimated by Hiesinger and Head [2004].

5. Conclusion

This study has been undertaken to demonstrate that craters on Mars can serve as a natural probe of the
subsurface mineralogy of the planet. The axisymmetric spectral signature of ejecta was demonstrated for the first time using the OMEGA data, and is considered as the best evidence for the present relationships between the spectral signature of ejecta and subsurface material. A second important result concerns the new insights into the weathering history of Syrtis Major volcano. Two classes of craters have been identified according to their mineralogy. The type I craters shows an enrichment in HCP compared to the Syrtis lavas. The HCP type II craters have a spectral signature close to the Syrtis lava flows spectra. These two classes can be distinguished according to their ages. The type II craters are old and formed generally before the formation of the compressive radial and concentric ridges. The type I craters are younger and formed after the ridges. However, the two classes of craters have experienced a minor amount of erosion, as seen from the state of the ejecta layer. Then, the difference in the mineralogy could result from a superficial and long-term weathering occurring under the present environmental conditions. Fresh craters are selected for an investigation of the subsurface mineralogy. The distribution and sizes of these craters suggest at the first order a homogeneous subsurface structure of the volcanic edifice with an enrichment of HCP at depth.

[53] Then, fresh craters are selected to constrain the subsurface mineralogy. The spectral variations within the ejecta units are organized and axisymmetric. The maximum of the HCP band strength translates into a maximum of the HCP content at few hundreds of meters depth. The mineralogical sequence in the ejecta suggests a change in the HCP/LCP ratio with depth. The exposed outside the ejecta extends down to probably to a tens to a few hundreds of meters depths and is enriched in HCP compared to the Noachian crust. Then, an additional increase in the HCP/LCP ratio is observed below this layer. It could correspond to the presence of basalts which are less weathered than the superficial ones if LCP and HCP are weathered at a different rate. Alternatively, it could correspond to different history of crystallization and magma cooling at depth. The question is still open and difficult to solve without the knowledge of the other mineralogical components proportions. The third and deepest layer of our model seems to result from the excavation of the underlying Noachian terrain, the thickness of the decrease of the HCP/LCP being consistent with lava pile thickness estimated independently from morphology [Hiesinger and Head, 2004]. Alternatively, this layer could also represent a more ancient Syrtis lava composition which would have been closer in composition to the Noachian crust. CRISM should give even more spectacular results on fresh ejecta which should be targeted in volcanic regions. Fresh craters in nonvolcanic regions should be equally targeted to investigate the subsurface composition of sedimentary or hydrated layers (sulfates or phyllosilicates deposits) using similar or more sophisticated modeling of the excavation flow.

Appendix A: Excavation Depth of Complex Craters

[54] The typical excavation depth as a function of the crater diameter is estimated along the following lines. The widely accepted rule of thumb has been applied [Melosh, 1989]:

$$H_{ex} = \frac{D_t}{10}$$  \hspace{1cm} (A1)

where $H_{ex}$ is the maximum excavation depth and $D_t$ is the diameter of the transient crater. For simple craters (simple craters on Mars are smaller than 7 km in diameter), the diameter of the transient crater can be approximated with the apparent rim-to-rim diameter which has been measured in this study. For complex craters (diameters larger than 7 km), the transient diameter should be corrected from the apparent rim-to-rim diameter $D$. The equation relating the terrace width $W$, the apparent and transient diameters and the apparent and transient depths, respectively $H$ and $H_t$ given by Melosh [1989] has been used:

$$D_t H_t = \frac{5D^2 H}{1 + \frac{3}{6} \left( \frac{D}{W} \right)^2}$$  \hspace{1cm} (A2)

[55] The depth to diameter ratio for the transient crater can be assumed to be constant for simple and complex craters and is given by Melosh [1989]

$$\frac{H_t}{D_t} = \frac{1}{2.7}$$  \hspace{1cm} (A3)

[56] Then, the terrace width is assumed to be 1/10 of the apparent crater diameter (as measured for the moon) [Pearce and Melosh, 1986], so the diameter of the floor of the crater corresponds to 80% of the apparent diameter. Finally, the apparent depth of complex craters (the depth after crater collapse but before any subsequent infilling) is determined using the relationships established by Garvin et al. [2003]:

$$H = 0.36D^{0.49}$$  \hspace{1cm} (A4)

Equations (A2), (A3), and (A4) are finally combined into (A1) to provide an estimation of the maximum depth of excavation for complex craters:

$$H_{ex} = 0.109D^{0.872}$$  \hspace{1cm} (A5)

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References

Adams, J., and A. Filice (1967), Spectral reflectance 0.4 to 2.0 microns of silicate rock powders, J. Geophys. Res., 72, 5705–5715.


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