Impact craters mineralogy from OMEGA data: implications on alteration history, ejecta emplacement, and subsurface composition. D. Baratoux[1] , P. Pinet[1], A. Gendrin[2], L.Kanner[2], J. Mustard[2], Y. Daydou[1], J.-P. Bibring[3], [1]Observatory Midi-Pyrénées, Laboratory Dynamique Terrestre et Planétaire, UMR 5562, CNRS and University Paul Sabatier Toulouse III, Toulouse, France (Baratoux@dtp.obs-mip.fr) [2]Department of Geological Science, Brown University, Providence, Rhode Island, USA, [3]Institut d'Astrophysique Spatiale, UMR 8617, Orsay, France.

Introduction. Impact cratering is a common geologic process affecting all the regions of Mars. Ejecta of impact craters result from an excavation flow through heated and shocked materials and ejecta sedimentation, followed by an erosion and modification history of the deposit. The excavation flow depends on the first order on the crater size, even if second order changes are expected for different combinations of projectile velocity/projectile mass and target strength resulting in the same final crater diameter [1]. Ejecta emplacement is dependent on the target properties (presence of volatiles) and on the atmospheric properties at the time of impact as reviewed in [2] or [3]. The resulting geometry and composition of the deposit could differ substantially from those resulting from ballistic sedimentation. Then, the ejecta deposit is affected by mechanical and chemical erosion. Ejecta can be transported by winds, water flow or covered by ice deposit. Circulation of fluids, due to the development of a hydrothermal system after the impact event, or resulting for global scale surface fluid flow or subsurface aquifer can potentially affect the mineralogical composition of the ejecta layers. The study of the mineralogy of ejecta is thus a particularly challenging topic but represents a promising tool to investigate the local alteration history of Mars geological units, the emplacement mechanism and the sub-surface composition[4].

Our observations focus essentially on the volcanic shield of Syrtis Major, known for his prominent mafic composition. We show first that the alteration history of this region can be investigated from the correlations of ejecta mineralogy with age. Then, first-order ballistic modeling is used to discuss the main features of the subsurface mineralogy. Further implications are suggested concerning the ejecta emplacement mechanism itself from our observations.

Ejecta mineralogical changes through time

Before analyzing Mars observations, we would like to recall important lessons from the analysis of ejecta on the Earth. Fresh ejecta are generally difficult to find and the following conclusions result mainly from Meteor Crater (USA), Lonar Crater (India), Ries crater (Germany). (1) The ejecta have a diamictite nature, meaning that the deposit is well mixed [5] . (2) The volume of shocked or melted material is negligible in the ejecta deposit. (3) An axisymmetric pattern can be found in composition and physical properties (grain size). (4) The ejecta layer is strongly mixed with very superficial material eroded during ejecta emplacement. (5) Grain sizes usually decrease outward, but ejecta are never well sorted. On Earth, erosion affects rapidly the ejecta pattern, and even at Meteor crater, the spectral signature of ejecta appeared to be modified by wind erosion [6]. The presence of fresh ejecta at Syrtis Major is demonstrated from three criteria: thermal signature, the axisymmetry of the spectral signature, and the ferric indices more indicative of rocks rather than soil.

Thermal properties. Numerous ejecta at Syrtis show a distinct thermal signature from the background, characterized in particular by a warm thermal edge[3]. The thermal feature has been interpreted as resulting from the accumulation of larger particles at the front during the ground-hugging flow. The fact that this signature inherited from the impact even is still preserved today suggests that ejecta have been affected by minor amount of erosion.

Axisymmetry of the spectral signature. In order to quantify the degree of axisymmetry of ejecta, we have extracted spectra inside a sliding annulus for about 15 craters at Syrtis Major. The Fig. 1 represents an example of I/F values for a given wavelength as a function of the azimuth. The averaged values of I/F inside the annulus as a function of wavelength are represented on the Fig. 2, with standard deviation.

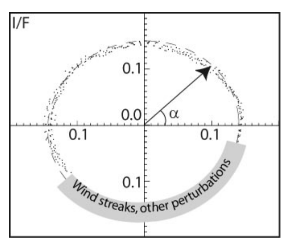

Figure 1. I/F as a function of the azimuthal direction (for a given wavelength) are fitted to an ellipse to characterize the degree of axisymmetry of the spectral signature of ejecta.

The spectral variations observed with distance are always larger than the spectral variations inside the sliding annulus demonstrating the axisymmetric pattern of the spectral ejecta signature. If an ellipse is fitted to the I/F values, the standard deviation is even decreased by one order of magnitude, suggesting that spectral variations inside the sliding annulus result mainly from the slightly non-circular pattern of excavation and ejecta emplacement, rather than from variations in erosional processes.

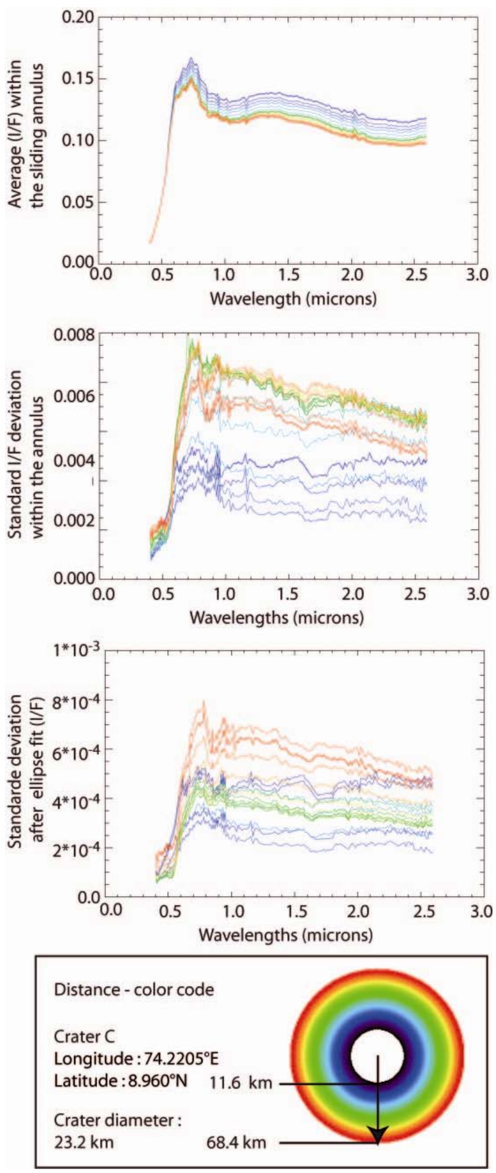

Fig 2. Top: Averaged spectra inside the sliding annulus (distance of the annulus is given by the color-color code at the bottom of the picture). Middle: Standard deviation of I/F values inside the sliding annulus. Bottom: Standard deviation of I/F values after the adjustment of I/F values to an ellipse.

Ferric/Ferrous state of ejecta. An additional evidence for the presence of fresh ejecta is given by the spectral indices relative to the ferric or ferrous state of the exposed material (Fig 3.). The two spectral indices developed by [7] suggest that ejecta material correspond to blocks or rocks rather than soil when compared to the Pathfinder case.

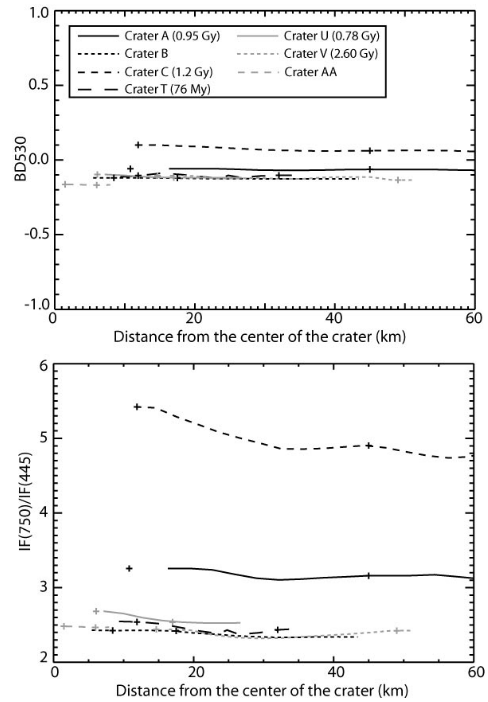

Figure 3. Spectral indices indicative of the state of oxidation and alteration of ejecta. The ejecta of these craters are closer to rocks than soils when compared with Pathfinder results.

Evidence for different alteration history: correlation between age and mineralogy. All the impact craters at Syrtis Major do not display a clear axisymmetrical spectral signature. Actually, two types of spectral signatures of ejecta have been identified at Syrtis and are named type I and II for convenience hereafter. The type I is characterized by enrichment in the High-Calcium Pyroxene signature relatively to the lava flow background, which is already enriched in HCP compared to the surrounding Noachian terrains. The type II ejecta do not display this signature (cf. Fig 4). These differences in ejecta mineralogy with time do not result from changes in the original composition of the excavated material. All the studied impact formed after the emplacement of Syrtis lava flow. Type I and type II impacts can be found at relatively small distances, and lateral variations in composition are unlikely to explain this situation while different ages and differences in ejecta alteration might be responsible for these variations.

Dating a crater is a difficult task: the ejecta unit can be in some places discontinuous with the possible confusion between small impacts on the ejecta unit, and small impacts buried by the ejecta unit. The floor of the craters itself is often buried under eolian sediments, and cannot be used to estimate the age of the impact event.

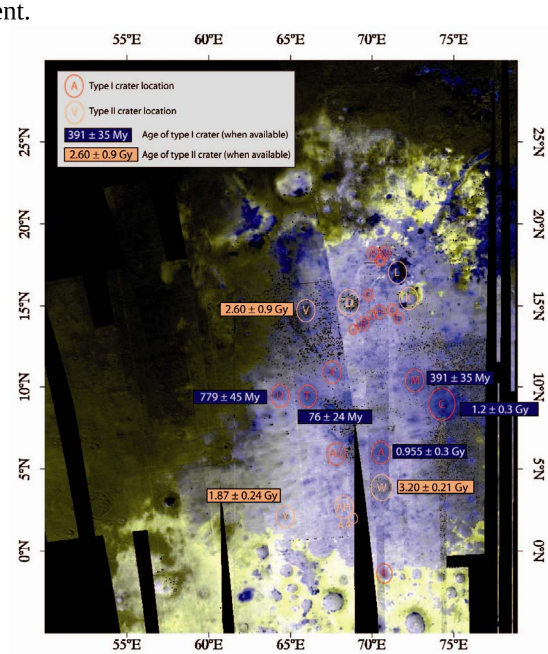

Figure 4. Pyroxene map of Syrtis Major from Modified Gaussian Model (HCP in blue, LCP in yellow) with the location of investigated craters.

Thus, only the largest type I and II craters have been counted from crater counts in the continuous part of the ejecta units. We conclude that HCP-rich ejecta are systematically younger that the type II (Fig. 5). In order to confirm this observation, relative chronology between type I and type II has been also searched. No direct overlapping of ejecta layers of type I and II have been found.

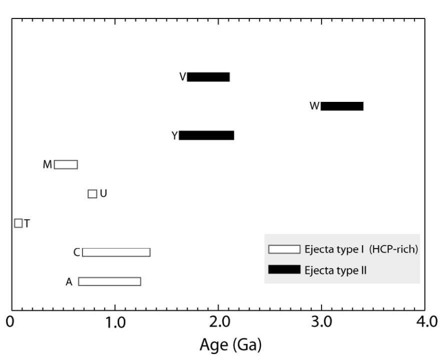

Fig. 5. Absolute dating of type I and type II craters at Syrtis Major.

However, the relative chronology of type I and type II demonstrates that type II craters are generally older than the ridge formation episode while type I craters are systematically younger (Fig. 6, 7). Other morphologic arguments, such as the presence of lineations and secondary craters for the type I are reported confirming the correlation between the presence of the HCP enrichment signature and the age of the crater.

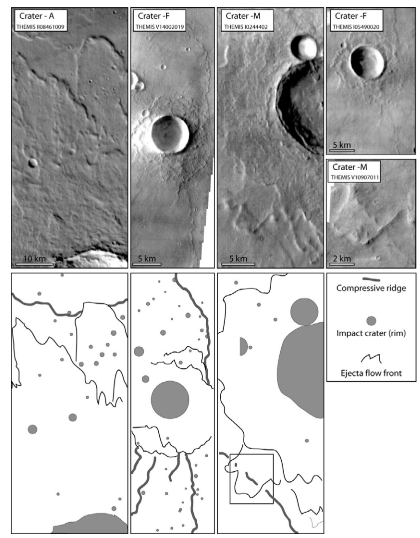

Fig. 6. Relationships between compressive ridges and type I ejecta.

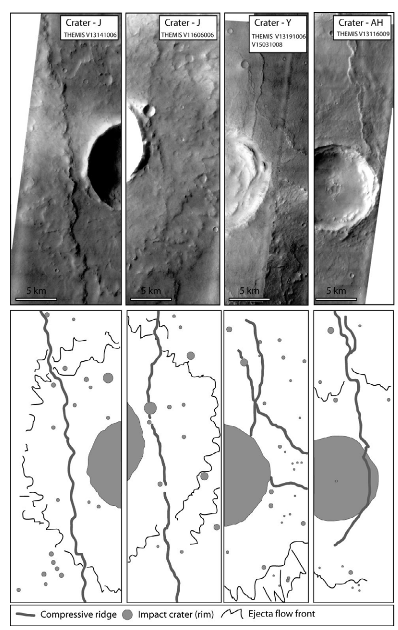

Fig. 7 Relationships between compressive ridges and ejecta type II.

Different candidates can explain the fading of the HCP signature with time: progressive dust cover or slow weathering in a cold environment. The ejecta of impact craters can be weathered at a higher rate than the surrounding terrain due to the fragmentation related to the impact and presence of fines. Impact hydrothermalism may also contribute to the alteration in the period of time immediately following the impact event (few thousands of years). Building upon these first OMEGA results, CRISM observations at higher spatial resolution may help to discriminate between these different aspects.

From the ejecta to sub-surface composition

Observations. Averaged spectra inside sliding annulus for fresh ejecta suggest an evolution of ejecta composition with diameter (Fig 8). This trend is clearly seen from scaled I/F (at 0.7 microns) values or even ratio of scaled I/F values using the spectra at the largest distance from the center of the crater. Changes in the 2 microns domain should be related to relative variations in the proportion of high-Calcium to Low-Calcium pyroxenes. These variations are also indicated from spectral deconvolution using MGM. The spectral deconvolution suggests the presence of a maximum in the HCP/LCP ratio within the ejecta layer (Fig. 9).   .

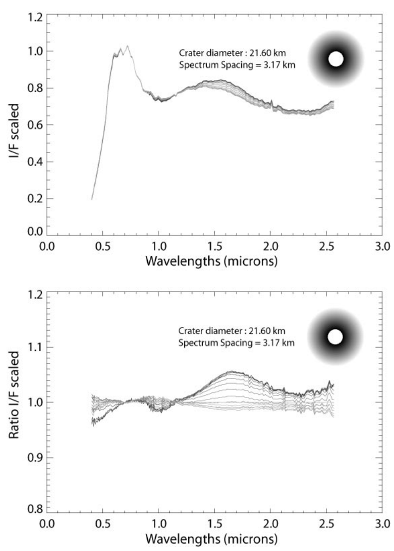

Figure 8. Example of scaled spectra (at 0.7 microns) and ratio of spectra (using the spectra at the largest distance from the crater center) emphasizing the variations in the 2 microns domain related to variations in the HCP/LCP proportions.

Z-model and Ballistic modeling. The derivation of subsurface composition from the composition of ejecta is a challenging inverse problem. A first approach consists in the forward modeling of the ejecta composition from a given sub-surface composition. The modeling is achieved first from Z-modeling of the excavation flow coupled to ballistic trajectories [8]. Ejecta surface flow after ballistic sedimentation, mixture of the substratum due to the erosive power of the ejecta flow, and atmospheric effect are progressively incorporated in the forward modeling. Various sub-surface models are compared with the mineralogical variations of ejecta. In the case of Syrtis Major, the presence of a maximum of the HCP/LCP ratio at few tens to few hundred meters is consistent with the observations.

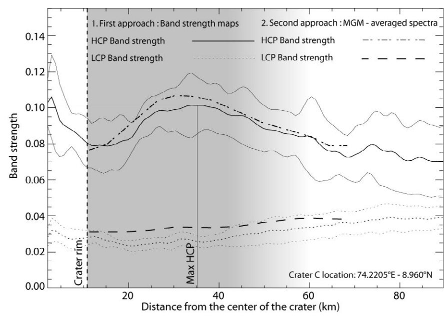

Figure 9. Example of spectral deconvolution using the MGM approach. The presence of a maximum in the HCP/LCP ratio is systematically observed within the ejecta layers for fresh craters.

Conclusion. This study emphasizes the importance of mineralogical studies of ejecta as an excellent and well-spread marker of the climate evolution and an excellent way to investigate the subsurface mineralogy of planetary surfaces. In the case of Syrtis Major, both alteration history and subsurface mineralogy have been discussed from spectral observations at impact craters. This approach should be extended to other areas of interest including clays and sulfates deposits. Second order variations of mineral compositions related to the impact event are suspected with azimuthal directions. From the CRISM resolution, it may be possible to correlate these features with the sinuous outline of the deposit, providing new hints for the emplacement mechanism and role of fluids.

References: [1] Melosh (1989), Impact cratering as a geological process. [2] Osinski, G.R. (2006), Meteoritics and Planetary Science, 41, 1571 – 1586. [3] Baratoux et. al (2005) , *J. Geophys. Res.*, *110*, E04011, doi:10.1029/2004JE002314. [4] Baratoux et. al, in revision for J. Geophys. Res. [5] Kenkmann T. and Schonian F. (2006), *Meteoritics and Planetary Science* 41: 1587 – 1603. [6] Ramsey, M. (2002), *J. Geophys. Res.*, *107* (E8), 5059, doi:10.1029/2001JE001827, 2002. [7] Morris, R. et al. (2000), *J. Geophys. Res.*, *105* (E1), 1757-1817. [8] Maxwell, D. (1977), in *Impact Explosion Cratering Pergamon*, edited by D. Roddy, R. Pepin, and R Merill, pp 1003-1008, New York, USA.