# 11.5 Origin and Nature of Regolith on Minor Bodies

## A. Context and state of the art

Space missions (Veverka et al., 2001; Yano et al., 2006; Jaumann et al., 2012) and analysis of thermal infrared observations (Gundlach and Blum, 2013; Delbo et al., 2015) have shown that asteroids and comets (and many other small bodies, such as our Moon) have surfaces made by a layer of unconsolidated debris: the so-called regolith, which is also present on Earth (the soil), Mars and other rocky planets. Regolith is the material with which spacecraft and astronauts interact, as well as the portion of an object most readily observed from orbit or Earth. We only partly understand how regolith forms and the extent to which it is altered from its pristine condition by exposure to space. But, this information is critical for interpreting the data collected from these surfaces. For example, does all regolith form in the same way or does the primary mechanism change with time or location in the solar system? Understanding the regolith is also crucial to infer the nature of the underlying body.
The regolith properties vary dramatically across the population of minor bodies (Fig. 1): large (100 km-sized) asteroids have regolith grains in the size range of 10-100 μm, and small (km-sized) bodies have grains in the range of a few mm to a few cm (Gundlach and Blum, 2013). The km-sized near-Earth asteroids visited by space missions are characterized by abundant, but not uniformly distributed, ejecta blankets and conspicuously degraded craters, with the latter almost completely disappearing in the case of the 350 m-sized Itokawa. The smallest grains are mm-sized on Eros and cm-sized on Itokawa, with depths ranging from some 10s of cm to a few meters. In the case of very small asteroids, such as Itokawa, the low bulk density is evidence is that the entire body is made of regolith, with the largest blocks making some tens of meters in size. Hence, these types of asteroids are called ”rubble-piles”. On bigger asteroids (such as Lutetia and Vesta) regolith is finer and is estimated – based on the thickness of the ejecta blanket of the largest crater – to be 600 m and 800 m in depth, respectively. There is clear evidence of regolith motion and migration on asteroid surfaces, possibly due to seismic shaking induced by non-disruptive impacts and maybe close encounters to planets.

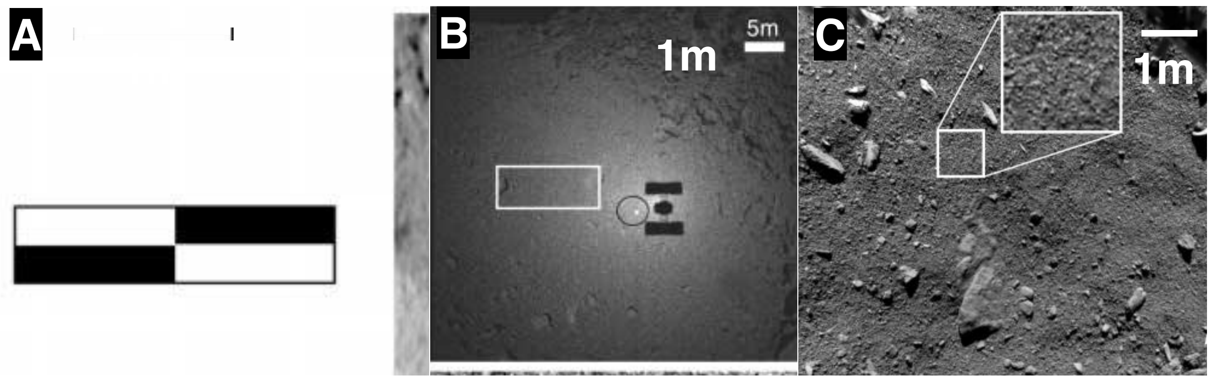


*Figure 1: (A) Close-up image of (433) Eros from the NASA NEAR Shoemaker mission (Veverka et al., 2001). (B) Image from the JAXA Hayabusa mission of the surface of (25143) Itokawa (Yano et al., 2006). (C) Last image acquired a few seconds before touchdown on the nucleus of 67P from an altitude of 9 m by Philae the Rosetta lander (Mottola et al., 2015)*

Regolith is also observed on comets, for example, on the nucleus of Comet 103P/Hartley 2 (Thomas et al., 2013) and of 67P/Churyumov-Gerasimenko (67P/C-G). In the case of the latter, images from ESA's Rosetta show a granular-like regolith, composed of debris and blocks ranging in size from centimeters to several meters, but no deposits of unresolved sand-sized particles (Mottola et al., 2015). This was totally unexpected, as comets are thought to have formed from the gentle coagulation of icy dust in the protoplanetary nebula. Regolith has always been assumed on a comet to be the product of its surface activity. But the presence of boulders and of a consolidated or an indurated substrate in the shallow subsurface, complicate the picture the formation of regolith on these bodies.

On the Moon, regolith generation has been extensively studied because of the Apollo and other space missions and has traditionally been attributed to the fall back of impact ejecta and by the break-up of boulders by micro-meteoroid bombardment (Housen et al., 1979). Likewise, it has been assumed that regolith forms on asteroids, with some differences, mainly due to the different escape velocities. However, a clear picture of how regolith is formed on asteroids is not yet available. Laboratory experiments and impact models (Housen et al., 1979), however, show that crater ejecta velocities are typically greater than several tens of centimeters per second, which corresponds to the gravitational escape velocity of kilometre-sized asteroids. Therefore, impact debris cannot be the main source of regolith on small asteroids. Indeed, in the era before space missions, many scientists believed that the small asteroids, e.g. near-Earth asteroids had bare rock surfaces. The regolith production process might change on asteroids of different composition and different size.

## B. Current activity

We are studying the process of collisional and gravitational re-accumulation by which small asteroids are formed. We showed that this process results in the creation of surfaces composed of boulders (Michel and Richardson, 2013). We investigate processes to make regolith on asteroids and comets from the fragmentation of said boulders, such as impact fragmentation and thermal cracking. The latter has been widely neglected, but we showed that as these small bodies spin around their rotation axes, their surfaces plunge in and out of shadow and that the oscillating thermal stress due to these diurnal cycles opens and extends cracks in surface rocks (Delbo et al., 2014). We studied this process by using meteorites as asteroid analogs, cycling their temperature every 2.2 hours in the laboratory. After 37 days, cracks were lengthened at an average rate of 0.5 mm/year, according to the measurements that we carried out using X-ray computer assisted tomography. This damage process is very well known in *material sciences* as thermal fatigue. By incorporating our measurements into a thermo-mechanical and fracture model, we extrapolated our experiments, carried out for durations of weeks to months, to the timescales typical of the lifetime of minor bodies i.e. thousands to millions of years. We showed that thermal cracking due to temperature cycling is more efficient than micrometeorite bombardment at fragmenting rocks on asteroids, in some cases by orders of magnitude (see Fig. 2; and Delbo et al. 2014).

The efficiency of thermal cracking is generally higher for carbonaceous chondrites than ordinary chondrites and increases for decreasing heliocentric distances (Delbo et al., 2014), leading us to make the prediction that thermal cracking below 0.3 au from the Sun becomes strong enough to grind away hundred-meter sized, low-albedo, carbonaceous asteroids. Very interestingly, the new near-Earth asteroid population model, developed by our team in collaboration with Finnish and Hawaiian scientists, finds evidence of catastrophic disruption of asteroids at small perihelion distances (Granvik et al., 2016).

Thermal cracking – in the form of immediate and fatigue cracking almost certainly aided by the presence of ice – is the mechanism that we and other colleagues invoke (Ali-Lagoa et al., 2015;

Vincent et al., 2016; Vincent et al., 2015) to form and propagate the fractures observed by the instruments on Rosetta on the nucleus of the comet 67P/C-G. We have already showed (Ali-Lagoa et al., 2015) that the areas of most rapid temperature variations on 67P/C-G, where thermal cracking is supposed to be more effective (Hall and André, 2001), are associated with the early activity of the comet. We are studying how crack opening can progressively expose ice, which subsequently can be available for sublimation driving the comet's activity.

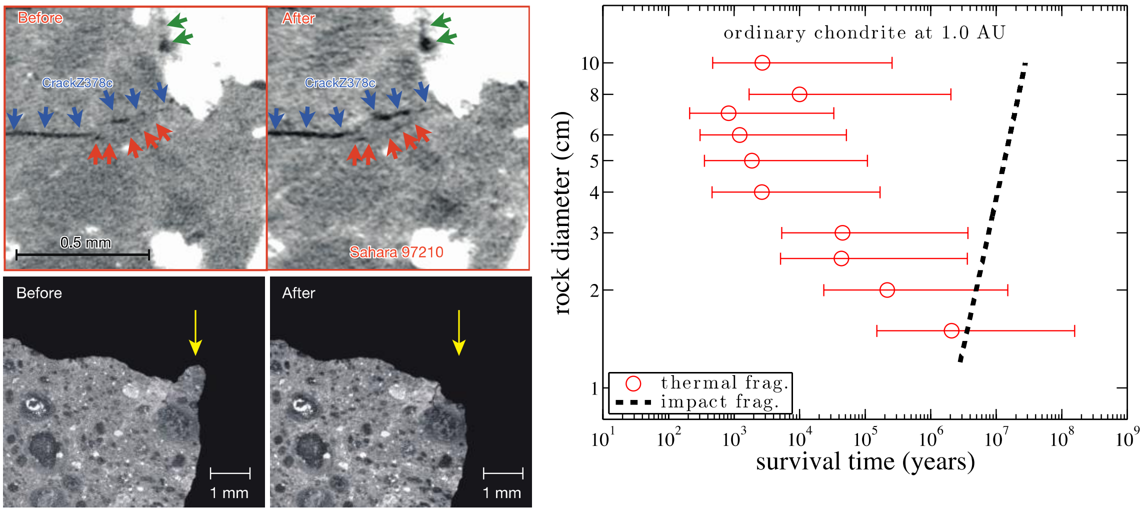


*Figure 2: **Left-top**: Crack growth in meteorites due to laboratory temperature cycling. Arrows of the same color mark growing cracks in the pictures before and after temperature cycling. **Left-bottom**: Regolith formation from Murchison in the laboratory. Tomographic slices of regions of the same sample of Murchison before and after temperature cycling. The arrows indicate fragments that broke off from Murchison. **Left**: Time required to break rocks on asteroids. Symbols show the time required to thermally fragment 90% of rocks for the nominal values of the model parameters. The thick dashed lines show the times at which 90% of these same rocks are broken by micrometeoroid impacts. Error bars show the change in the thermal fragmentation time when model parameters are varied within their uncertainties (Delbo et al. 2014).*

Concerning the production of the regolith by impacts, we are developing computer models to calculate the impact of rate and rock fracture by micrometeorites on different objects in the solar system. Next, we perform numerical simulations of high-speed impacts to check the rate of production of ejecta of all sizes, depending on the physical properties of the surface. We also use scaling laws, calibrated on bomb explosions, to estimate ejecta properties and velocities. We develop a procedure to calculate the evolution of fragments produced upon impact by taking into account the local gravity of the small body, the solar radiation pressure and the gravitational perturbation from other planetary bodies. Our preliminary results show that most of the fragments escape and do not fall back on km-sized or smaller asteroids at impact speeds typical in the asteroid belt (5 km/s). However, we have so far explored a very limited space in terms of the physical properties of the target and projectile, and impact conditions.

Furthermore, in order to better understand the origin of regolith, we need to better understand its physical properties. Our team works on the determination of the thermal inertia of the surfaces of asteroids (Delbo et al., 2015; Hanus et al., 2015). We are developing a sophisticated thermophysical model (TPM) that allows one to calculate infrared fluxes of small bodies as a function of model parameters such as size, shape, albedo and thermal inertia (Delbo et al., 2015); the latter is adjusted until best-fit with thermal infrared observations is achieved. The TPM uses are inputs the shape and the spin state of the asteroid. These parameters were obtained from optical photometry using our own astronomical observational program (e.g. the 1m C2PU and the UH88-inch telescopes, at the Calern and Mauna Kea observatories respectively).

The thermal inertia measurements provide estimates of the regolith thermal conductivity that, when compared to the corresponding theoretical values for different volume-filling factors of the regolith grains, allows one to calculate the typical grain sizes of the regolith using e.g. the method of Gundlach and Blum (2013). Clearly, these models are very simplified at the moment, as they are based on limited amount of physical data of meteorites and simplified treatment of heat transfer in asteroids and meteorites.

## C. Future steps

C4PO offers to the origin of regolith project an innovative multi-disciplinary approach, characterized by the combination of expertise in astronomical observations, laboratory experiments, material properties, theoretical tools, cosmochemistery, geomechanics and numerical modeling.

Although our preliminary investigations have demonstrated the importance of thermal fragmentation for the origin of regolith, quantitative predictions of the contributions of the process on specific bodies require substantial additional experimental and theoretical efforts that we will undertake through this program. Specifically, we seek to understand the variation in thermal fragmentation as a function of temperature range and rate, petrology, grain size, and size-frequency distribution of the produced fragments. We need to perform sets of experiments of thermal cracking of meteorites and other asteroid analogs. So far, we have investigated the thermal fatigue behavior of one carbonaceous meteorite (CM Murchison) and one ordinary chondrite (LL3 Sahara 97201). However, some preliminary results show that, surprisingly, some meteorites (CR chondrites) might be more resistant, if not immune, to thermal cracking. To achieve this, we need to develop novel laboratory experiences of thermal cycling and analysis of X-ray tomographies of meteorite and other small bodies analog materials. One important issue is to observe the behavior of rocks of several tens of cm, while we are currently limited to 1 or 2 cm – as our results show that rock size matters (see Fig. 2, right panel). In addition, the thermal and mechanical behavior of cometary material is totally unexplored. The challenge here it is not only to understand the composition, but also, and maybe even more importantly, the *mise-en-forme* i.e. the microstructure and the thermal forming of the cometary (and asteroidal) material.

Quantifying the effect of thermal fragmentation on lunar rocks is another important future goal. This is because we have large samples of the lunar regolith, from meteorites and samples returned by the Apollo missions. But, the lunar thermal environment is very different to those of asteroids, mainly due to the much slower temperature cycles occurring on our natural satellite and the larger temperature excursions. To study the thermal breakdown of analog lunar rocks we need to perform ad-hoc laboratory temperature cycles on lunar rock analogs, such as anorthosites and basalts, and then extrapolate laboratory results to the much slower lunar cycles using our thermo-mechanical and fracture propagation models.

All the above, requires an experimental thrust focused on the characterization of the thermal fragmentation mechanism through experiments involving measurement of the associated mechanical and physical properties and processes. More specifically, although significant data exist on the fatigue properties of metals, the behavior of geologic materials has received little attention so far. However the complexity of geologic materials allows for fatigue response. Very little fatigue data exists for materials applicable to asteroids and the Moon. We need to perform mechanical fatigue experiments on the relevant materials (basalt, lunar samples/simulants and meteoritic materials) to provide the necessary input parameters for the fatigue mechanisms in the regolith evolution model. The core objective of these experiments is to determine whether such materials obey the classical fatigue behavior known as Paris' Law, a power-law relation between crack growth and change in stress intensity. Experiments are also needed to deter- mine the fundamental mechanical and physical properties of materials. Coefficients of thermal expansion (CTE) and the elastic properties are fundamental parameters that must be known.

The modeling thrust is focused on the development of scaling laws for thermal fragmentation and the development of equations for the evolution of regolith fragment size distributions as a result of multiple processes. We have already developed a preliminary thermal fatigue model that captures the observations noted above. However, at this point we have a thermal fatigue model rather than a thermal fragmentation model: the latter must account for multiple cracks and crack interactions.

We can address the thermal fragmentation problem using a combination of theoretical and computational analyses that examine crack spacing (derived from flaw densities), crack interactions and surface effects under cyclic loading.

We plan to use finite element method (XFEM) to extend our capabilities to the longer time-scales and length-scales associated with thermal diffusion and fatigue crack growth. The objective of this model is the definition of the fragment size distribution developed by thermal fragmentation, and the dependence of that size distribution on the initial material properties, the initial flaw distribution (arising, e.g. from other processes such as subcritical crack branching during impact fragmentation), and the cyclic thermal environment.

The evolution of a regolith is defined by the evolution equations for the key variables that define the regolith. We need to develop initial approximations for these equations, beginning with non-interacting and uncoupled mechanisms, and then incorporating coupled terms that link the mechanisms. For ex- ample, it is likely that impact fragmentation processes result in the development of substantial surface flaws on the individual fragments, arising from arrested crack branches off the main crack that created a surface. These surface flaws can be considered to be the seed-flaws from which cracks are propagated by thermal fatigue, so that the impact fragmentation process is now coupled to the thermal fragmentation process. Similarly, thermal fatigue will create a pre-damaged material that is now impacted, so that thermal fragmentation becomes coupled into the impact fragmentation problem. We will examine these coupling terms first by using linear coupling, and use available observational data and laboratory experiments to test the validity of the coupling approximations.

C4PO will forge collaboration between astronomers and experts of techniques of material formatting who will help to understand what is the definite micro-structural shape to the material the best fit the astronomical data. These materials will also be built (as long as it is possible) and tested in the laboratory experiments.

Studies are also necessary to further our understanding of the regolith properties on asteroids. We note that, due to the relative scarcity of both requisites for thermophysical modeling, namely high-quality IR data and asteroid shapes and rotation states, it is not surprising that only a meager set of 27 values of the thermal inertia have been determined to date for asteroids in the Main Belt (Delbo et al., 2015). New approach of lightcurve inversion led to a significant increase of derived shape models from ~100 to ~400 and Gaia data analysis in 2019 will provide shapes for ~10,000 asteroids, allowing us to obtain the same number of thermal inertias. This allows to build a new tool for the reconnaissance of the regolith nature of asteroid surfaces from remote sensing that, in addition to albedo and spectral data, will add a new dimension to the maps of the physical properties of asteroids throughout the Main Belt, with obvious benefits for various types of space missions.

In addition, we are establishing methods to treat the heat transfer by conduction and radiation in a multi-scale granular medium laid out on the complex, rough surfaces of asteroids (Fig. 3). These High-Performance Computing (HPC) methods should define a new approach to asteroid thermal modeling, instead of the classical TPMs used up to now. TPMs over-simplify the treatment of heat diffusion at the surface, assuming a solid medium and consider only a 1-D heat diffusion with depth. Instead, we use a finite element (FE) context, to virtually immerse or statistically generate complex multi-domain media as heterogeneous packing, multi-dispersed regolith grain distributions, assemblages of fine regolith and boulders and perform the heat diffusion calculation through these complex media. Of course, due to the numerical cost of precise thermal simulations in such kind of complex topology, representative surface elements of the considered asteroids will be used. Such numerical strategy will allow us to have a method that captures this type of soils and to infer the rock abundance, defined as the fraction of the surface covered with rocks of 10 cm or bigger compared to the surface covered with fine regolith6 . This parameter has been derived for the Moon by thermal infrared data from the DIVINER instrument, on board of NASA Lunar Reconnaissance Orbiter (LRO), but not yet for asteroids.

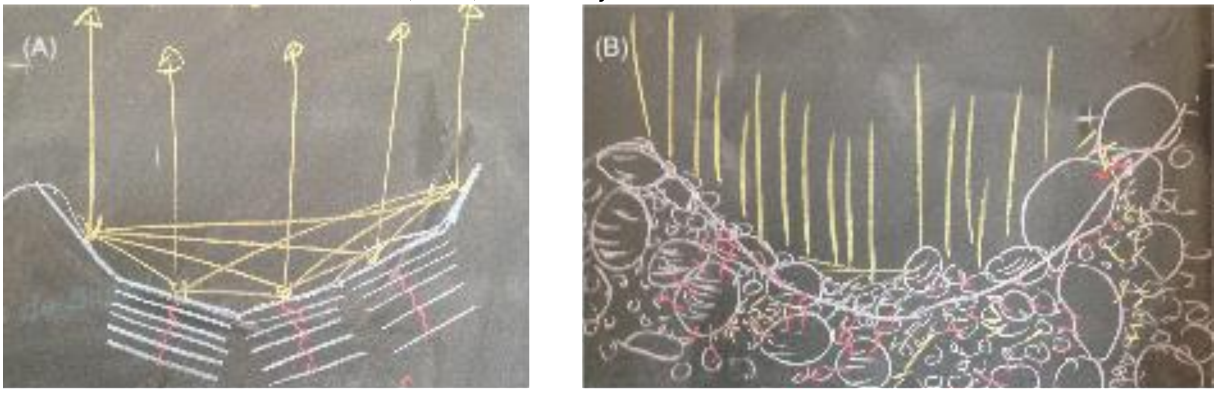


*Figure 3:* ***We want to pass from (A) the simple TPMs that treat 1D heat conduction in the subsurface of planar facets and radiative transfer to space and mutual facets heating, to (B) a physically based model of heat transfer into a multi-dispersed granular medium (regolith) with local 3D heat conduction and radiative transfer. Note that in the TPM there is no lateral conduction. Sketched here is e.g. a crater wall.***

***References (max. 10, more references in section "Most significant publications of the team")***

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## D. International collaborations

Hopkins Extreme Materials Institute (HEMI, Baltimore, MD, US): *Prof. KT Ramesh, K. Hazeli, C. El Mir*. From the University of Toronto (Canada): *R. Ghent*. From the University of Maryland Department of Astronomy (Baltimore, MD, US): *Prof. D. Richardson*. From the University of Texas at San Antonio (TX, US): *J. Wilkerson*. K.W. Walsh from the Southwest Research Institute (SwRI) Boulder (CO, US).

## E. List of people involved in the project

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## F. Most significant publications of the team


[11] Ali-Lagoa, V., Delbo, M., and Libourel, G. (2015). Rapid Temperature Changes and the Early Activity on Comet 67P/Churyumov–Gerasimenko. ApJL, 810 L22.
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### Short CV of participants

**M. Delbo**, CNRS research scientist, expert of the physical characterization of asteroids, ground- and space-based astronomical observations, modeling, and laboratory experiments on meteorites and other asteroid analogs. Co-I of space missions: ESA's Gaia (with responsibility of asteroid spectroscopy) and NASA's asteroid sample return OSIRIS-REx. 80 reviewed publications, H-index of 18 (source ADS). Asteroid (16250) named after "Delbo".

**P. Michel**, CNRS research director, leader of the team Theory and Observations in Planetology of the Lagrange Laboratory at OCA, expert in the impact process, granular material dynamics and asteroid physical properties, Co-I of Hayabusa-2 and OSIRIS-REx, science team leader of the space project AIDA (ESA-NASA collaboration), member of the Science Program Committee of CNES, Carl Sagan Medal of the Division of Planetary Science of the American Astronomical Society (2012), Prize Paolo Farinella in Planetary Science (2013), Prize Young Researcher of the French Society of Astronomy and Astrophysics (2006), more than 90 refereed publications.

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