Evidence of Permafrost Processes in C-asteroid Regoliths

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Introduction: C-complex asteroids have suffered a wide variety of physical processing, some of which are not very obvious. Carbonaceous chondrites experienced and recorded a very wide range of chemical and physical processing in both nebular and asteroidal settings [1-7], resulting in the following textures: brecciation, flattened chondrules and foliation (CV and CM chondrites in particular), carbonate and phyllosilicate veins (CI, CM, CV3 dark inclusions), local alignment of matrix phyllosilicates (CR2, CI, CM), and shearing (mylonitization) around lithic fragments. Many of the extensively altered carbonaceous chondrites contain rounded to elliptical aggregates of phyllosilicates, carbonates, spinels (chromite and magnetite), Fe-Ni sulfides, and embayed olivines and pyroxenes, generally ascribed to impact shock or static burial pressures [6,7]. However, it is probable that even in the wettest regions of an asteroid dry periods were experienced during the periodic breaching of an icy surficial rind [8], which could have occurred during impacts or "volcanic" venting of gas and heat from the interior (this assumes internal heating). Thus, there should have been multiple wet-dry cycles experienced by these regolith or immediately subsurface materials. We have previously suggested that all the deformation features mentioned above would have arisen naturally from cycles of wet-dry and, more critically, freeze-thaw environmental conditions (permafrost) in asteroid regoliths [5]. Here we detail two related textures observed in CI chondrites, including asteroid Ryugu samples (essentially CI chondrite), consistent with permafrost processes.

Permafrost Processes in Regoliths: It is well-known to soil scientists that conditions of radically alternating humidity can have important morphologic and petrologic consequences [9]. Grains and lithic clasts can become rotated, crushed and drawn out into linear features (shearing). Porosity (including contraction and shearing cracks) and other bulk physical properties will vary in a dramatic manner. Easily altered materials will be dissolved while more resistant materials will be pulverized and mixed into matrix. These effects would be most pronounced for the C1-2 lithologies where the swelling clay saponite can be found in abundance, including the CI chondrite meteorites and asteroid Ryugu samples. Another important process to be considered is periodic growth and melting of ice crystals in the regolith [10-11]. The positive molal volume change during crystallization of water will induce oriented microfabrics to develop in the regolith, normal to the direction of ice crystal growth. Thus, masses of platy grains (in this case phyllosilicates, especially saponite flakes) will develop a pronounced compaction and preferred alignment. This process will recur for each freezing episode. Since the orientation of the growing ice mass will vary for each succeeding generation of growth, the eventual result will be to impart a particular, invasive, regolith fabric consisting of sheets of aligned clays for each generation, which will appear as anastomosing strings of phyllosilicates with roughly aligned basal directions in polished or thin sections (Figure 1). Our study has revealed that such textures are common in the CI chondrites.

Ice crystal growth could explain the preferred alignment of saponite observed in some Ryugu samples (see Figure 6b of [12]). However, a more likely explanation for this particular texture is mobilization of saponite flakes during wet, water saturated episodes, and deposition of these flakes onto the surface of underlying rock fragments under the force of gravity. These features are termed “silt caps”, and these are a common feature of permafrost soils [11,13]. Of course, a major difference between permafrost processes on earth as compared to asteroids is the greatly reduced gravity on the latter. However, mass wasting is usually observed on small bodies including asteroids (including Ryugu and Bennu) and comet nuclei [14,15], so gravity-driven processes operated on the Ryugu parent body. Growth and collapse of subsurface asteroidal icicles would also impart cyclical changes in bulk regolith porosity, induce rotation and movement of crystals and lithic fragments through frost heaving, and consequent shearing [11]. This process could also account, to some degree, for the flattened chondrules observed in some carbonaceous chondrites (especially CMs).

Conclusions: We therefore suggest that cyclical, indigenous environmental processes, rather than impact gardening, could be responsible for some of the late-stage petrologic characteristics of wet carbonaceous chondrites, and Ryugu samples. We note that this suggestion has also recently been proposed by another group [16]. Bulk petrographic features of additional Ryugu samples and carbonaceous chondrites should be investigated more systematically in order to test this idea, especially samples rich in clays such as saponite.

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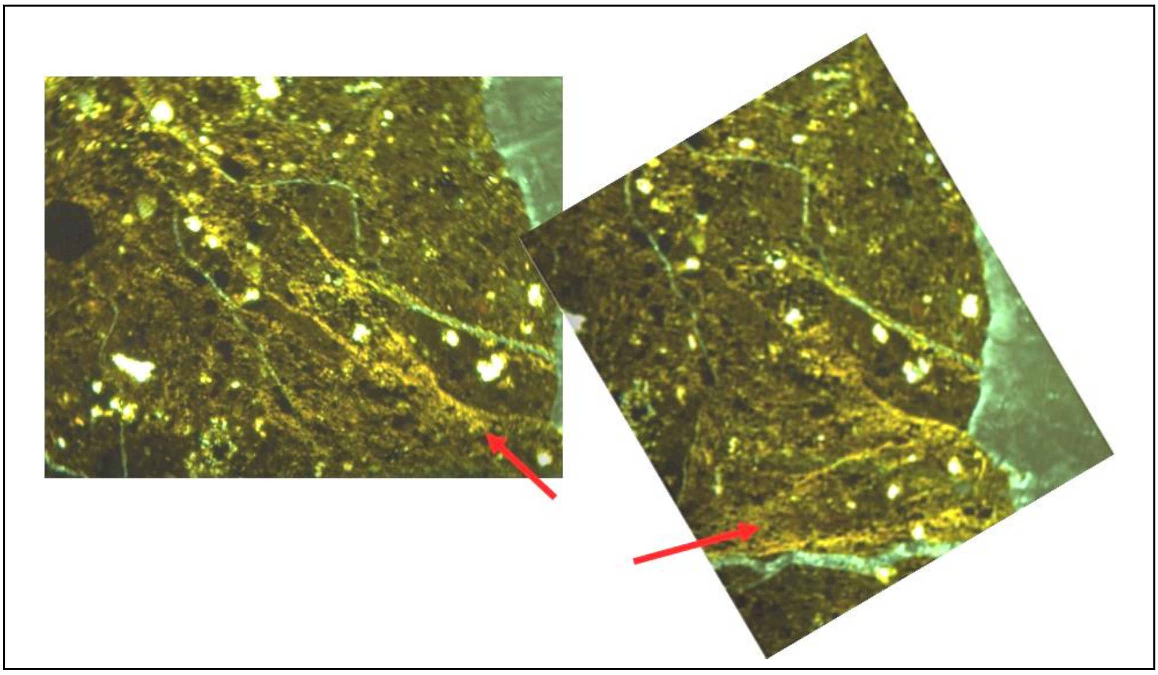

Figure 1. Ivuna CI chondrite, in cross polars. Two views of the same area in different rotation angles showing two distinct directions of phyllosilicate (yellow stringers) preferential orientations (arrows). Views measure 2 mm in longest dimension.