What are the main geological processes that determined the evolution and current state of small bodies and are they similar to those on larger bodies?

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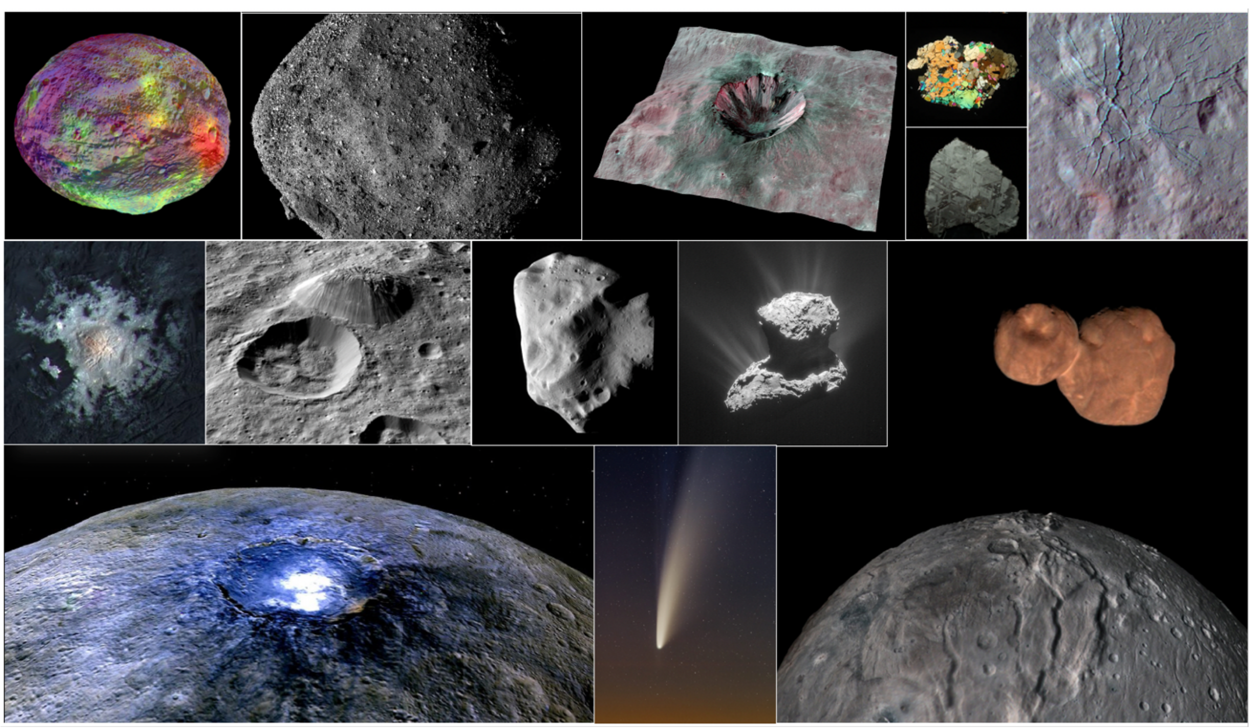

EXECUTIVE SUMMARY

The small bodies of the solar system, defined as objects that are not planets or moons, retain a record of conditions and processes that shaped our solar system during its early history. These bodies, whether, for example, asteroids, comets, or Trans-Neptunian Objects (TNOs), carry signatures of their formation and subsequent evolution on their surfaces and interiors. Moreover, their populations bear witness to the dynamical rearrangement of the solar system during planetary migration [e.g., WP1]. The geology of small bodies pertains to the morphology and composition of their surfaces; their physical structure and evolution including differentiation and thermal and chemical alteration; and changes resulting from impacts and exposure to solar energetic particles and micrometeoroids ("space weathering").

The NASA Small Bodies Assessment Group (SBAG) Science Goals document lays out a set of overarching questions to guide future small body research and exploration. These questions relate to what the compositional diversity and distributions of the small bodies of our solar system reveal about the process by which material accreted to form planetesimals and eventually the planets [e.g., WP2], as well as the processes that modified those bodies after formation, with implications for retention of volatiles, production of organics and delivery of both to the planets as they formed. Also important are questions of how collisional processes have driven the interior evolution of small bodies via impact-driven volatile loss, surface modification, disruption and family formation, and delivery of exogenic material.

Important progress has been made during the past decade in understanding the current states and evolution of many small bodies. This has been accomplished by telescopic observations of small bodies in visible, ultraviolet and infrared wavelengths, including with new telescopes that have come on line. The European Southern Observatory's Very Large Telescope (VLT) SPHERE observations have determined the shapes and densities, and imaged the larger craters for several of the largest asteroids. NASA's planetary radar facilities have performed bi-static observations that improve spatial resolution by factors of 2-4 and provide access to fast-moving objects. NASA missions have explored main belt asteroids (MBAs) Vesta and Ceres (*Dawn)*, the Pluto system and Kuiper Belt Object (KBO) Arrokoth (*New Horizons),* and near-Earth asteroid (NEA) Bennu *(OSIRIS-Rex).* A sample of Bennu is due to return to Earth in 2023, and a sample of Ryugu, an NEA visited by the Japanese Space Exploration Agency (JAXA)'s *Hayabusa 2* mission will return to Earth late in 2020. The European Space Agency (ESA)'s *Rosetta* mission flew by MBAs Steins and Lutetia, before a rendezvous with comet 67P. This decadal period will end with the launches of two NASA Discovery missions - *Lucy* to the Trojans and *Psyche* to a presumed stripped iron core. The next decade will see JAXA's *MMX* mission to the martian moons Phobos and Deimos that will return a sample of Phobos. Other missions planned for this decade include DART (Double Asteroid Redirection Test–NASA planetary defense) and Hera (ESA) to the Didymos system, and NASA smallsat NEA missions *Janus* and *NEA Scout*. Each new data set provides a window into the evolutionary processes that shaped these diverse bodies.

Despite the tremendous advances achieved in the past decade, we are far from done. The astounding diversity of small bodies coupled with the importance of the constraints they provide towards fundamental questions of solar system formation, evolution and habitability, argue for continued and expanded investigations. New ground-based observations (VLT SPHERE) as well as the anticipated NEO Surveillance Mission) offer the promise of a many-fold increase in the number and variety of objects that are fully characterized. Focused *Discovery* class multi-object rendezvous and flyby missions to new classes of targets, as well as New Frontiers class sample return missions are needed to answer key questions regarding the small body processes discussed below. The emerging capabilities of smallsats (<180 kg) for small body exploration [WP4] offer the potential for cost-effective frequent missions to large numbers of small bodies, and opens the possibility that small body investigations can be carried out as augmentations to large (Flagship or New Frontiers) missions, including asteroid or Centaur flybys; flybys of outer planet moons prior to orbit insertion; and extended missions into the Kuiper Belt.

Summary of Recommendations:
Progress on these fundamental questions during the next decade will require:

- ❑ Ground-based radar [e.g., WP3], and ground- and space-based imaging and spectroscopic observations for populations studies and characterization of surface geology and composition
- ❑ In situ exploration of small bodies that are representative of the diversity of characteristics within and between the major small body populations, including both volatile-rich (e.g., 10 Hygiea, 24 Themis) and possibly volatile-poor (e.g., 221 Eos) large main belt asteroids, active asteroids (main belt comets [WP5]), Centaurs and KBOS, as well as sample return from Ceres [WP6].
- ❑ Healthy support for laboratory studies of meteorites and of returned samples [e.g., WPs 7, 8]
- ❑ Lab-based analog studies of behavior of materials on low-gravity airless bodies [WP9] including the role of electrostatic levitation, micrometeorite bombardment and thermal cracking in mass wasting and material loss; organosynthesis for a range of liquid environments; convective behavior of brine-organic-silicate mixtures; and rheology of icy materials
- ❑ Measurement of dielectric and optical constants for minerals and mixtures over a range of conditions relevant to small bodies.
- ❑ Experimental simulations of space weathering and impact on the spectral signatures of minerals and organics.
- ❑ Advanced analytical and numerical modeling of thermo- and geochemical evolution as a function of initial conditions.

Major Scientific Questions
The major questions outlined in the SBAG Science Goals Document motivate a series of priority questions focused on the surface and interior geology of small bodies.

Q1: What does the geology of small bodies reveal regarding solar system accretion and formation of protoplanetary bodies, as modified by myriad processes?

- How was volatile material incorporated into, and processed within small bodies?
- Under what conditions did protoplanets (large planetesimals) melt internally, form metallic cores and sustain dynamo-generated magnetic fields?
- How have the surfaces of small bodies evolved (weathered) over geologic time, and what processes refresh those surfaces? Does space weathering differ for magnetized bodies?
- What processes dominated in different parts of the solar system over time?

***Q2*: How did initial compositions and distributions of small bodies evolve to the architecture we see today?**

- Can we reconstruct the distribution of early-forming planetesimals via understanding the effects of catastrophic disruption in creating diverse family members?
- What do cold classical KBOs (< 100 km diameter) thought to still be in their formation region tell us about planetesimal formation before collisional evolution?

Q3: How were elements that initiate and sustain life (volatiles and organics) delivered to the planets?

- Are organics synthesized within water-rich planetesimals, and what is their fate?

Q4: What geological processes, including impact-driven, modify composition and the physical state of bodies, including outgassing and resurfacing?

- What processes are responsible for activity on asteroids, e.g., main belt comets?
- How common are impact-driven hydrologic systems on large asteroids/dwarf planets?
- What drives "distant activity", e.g., that of centaurs, and how is it similar or different from cometary processes?

STATUS QUO AND KNOWLEDGE GAPS

Chemical Evolution and Physical Differentiation Processes in Rocky Bodies [Q1]

The earliest forming planetesimals (those formed < 2 M.y. after the first grains condensed) incorporated sufficient short-lived radionuclides (especially ^{26}Al) to drive internal melting. Vesta and iron meteorites provide solid evidence that some planetesimals differentiated, and certain metamorphosed chondrites (e.g., Allende) display a unidirectional magnetization attributed to a core dynamo [1]. Yet, Vesta is the only unambiguous differentiated body in the main belt. We know from recent work that iron meteorites come from both carbonaceous and non-carbonaceous chondrites [2], implying that melting took place in at least two very different regions of the solar system. Largely molten bodies are expected to produce large cores dominated by iron metal, rather than eutectic Fe-FeS mixtures (dominated by sulfur) that would form at lower temperatures, and evidence exists in the magnetism of meteorites for core dynamos in these early-forming bodies [1]. The *Psyche* mission to asteroid 16 Psyche, thought to be the stripped core of a Vesta-sized body, will test these hypotheses. These early-forming planetesimals were approximately chondritic in bulk composition, but significantly depleted in hypervolatile elements like sodium and potassium. Whether they formed in a hot nebula before most volatiles had condensed, or lost volatiles during magmatic differentiation is an open question, but volatile depletion is a ubiquitous characteristic of differentiated bodies, large and small.

In contrast to large planetary bodies, Dawn's data support the conclusion that Vesta's magmatic evolution was complex [3], with early equilibrium crystallization, collection of residual melts in magma chambers (crustal plutons) that underwent fractional crystallization, and periodic extraction and eruption of evolved melts, all occurring within a period of <100 M.y., before cooling halted magmatic evolution. The inferred internal structure of Vesta suggests that differentiation on small planetary bodies may have yielded compositionally-stratified mantles, with an olivine-rich lower mantle and an olivine-depleted upper mantle, perhaps accounting for the lack of olivine-rich asteroids [4]. The plutonic structure of Vesta's crust implies a more complex magmatic history than expected for rapidly heated and cooled protoplanets.

<u>Gaps and Emerging Concepts:</u> Given the plethora of iron meteorites, it is vexing that there seems to be a paucity of both differentiated asteroids and their fragments in the main belt. **Where did the different types of iron meteorites come from, and where are the asteroids that we expect to be associated with differentiated bodies? (**1) Relatively few non-Vesta family asteroids resemble basaltic crust. Objects cited as potential olivine-rich mantle fragments (A-type asteroids) are not abundant nor are they strongly associated with families. A-types have also been associated with R chondrites, rare olivine-rich meteorites that are not mantle products, and possibly ureilites, carbon-rich yet non-carbonaceous meteorites whose origins are mysterious; some even speculate ureilites are fragments of Mars. (2) Evidence from iron meteorites supports a population of early-formed differentiated planetesimals, but collisional families show little evidence for differentiation. This leads to questions of where the iron meteorites came from and what happened to their parent bodies? (3) Iron meteorites could also come from partially differentiated bodies. A possible example is the parent body of the large Eos family (K-type 221 Eos), whose members have spectral features similar to the Allende meteorite [5, 6]. Are disruption events needed to liberate core material and produce iron meteorite precursors, or is it sufficient to scramble the interior of parent bodies by collisions?

Recommendations to address the open questions discussed above: 1) conduct missions to large main belt asteroids, such as 221 Eos, to search for geologic, mineralogic and magnetic evidence of differentiation; 2) continue study of meteorites as recorders of processes within small bodies, in particular isotopic studies of iron meteorites; 3) secure access to large astronomical facilities (e.g., VLT, Keck, JWST) for visible and spectral imaging of surfaces of large planetesimals.

Chemical Evolution and Physical Differentiation Processes in Water-Rich Bodies [Q3, Q1]

Signatures of aqueous alteration are prevalent in carbonaceous chondrites and have also been found in drier material (i.e., eucrites [7]). Serpentinization is an efficient, exothermic process that progresses on timescales of a few thousand years for cm-scale particles. The extent of aqueous alteration is determined by the modalities of water circulation in a partially permeable medium [8], which may vary significantly depending on the object's size and the relative fraction of water to rock [9]. Both chemical and physical evolution determine the lifetime of liquid environments and the prospect for these bodies to exhibit geological activity. Dawn's visit to Ceres and New Horizons' visit to Pluto also showed those objects to have differentiated an icy shell and had complex, and likely ongoing, geological activity. Brine effusion from deep crustal reservoirs has been identified on Ceres [10, 11] and putative cryovolcanoes were identified on Pluto [13]. Other large, low-albedo main belt objects show spectral features similar to that of Ceres [14, 15] and evidence for differentiation of an icy crust (e.g., 10 Hygiea [16], 704 Interamnia), but it is not known whether their interiors and geological histories resemble those of the large dwarf planets. Similarly, other objects like 24 Themis that show evidence for surficial ice are associated with active asteroids, whose activity is thought to be sublimation-driven. However, it is unclear whether these objects are fragments of a differentiated parent body or maintain a primordial icy undifferentiated state. More generally, evidence for water of hydration varies significantly across the C-type complex (e.g., [16]), which may reflect a diversity of accretional environments.

Gaps and Emerging Concepts: A great deal is known about aqueous environments in carbonaceous chondrite parent bodies thanks to the meteoritic record. However, major gaps remain. In particular, **understanding the prospect for advanced prebiotic chemistry in large bodies like Ceres or 10 Hygiea with long-lived liquid environments is critical** if bodies in that class contributed the bulk of volatiles and organics to terrestrial planets [17, WP10]. (1) The role of aqueous alteration in creating new organic compounds is not well understood as the meteoritical record is hard to decipher and experimental research on the topic is in its infancy [18, 19]. (2) Emerging modeling of convection in mid-sized low-gravity bodies assume these objects behave as mudballs [20]. However, that modeling relies on poorly understood input parameters and assumptions. For example, colloidal systems where organic compounds and salts result in particle agglomeration can drive rapid settling of fines. (3) Fate of soluble and insoluble organic matter (SOM, IOM) during differentiation: meteorite analyses indicate SOM tends to stick with the rock [21], which implies that SOM could be removed from liquid environments and stored in the rock, with potential implications for prebiotic chemistry. (4) Comparison between large (100s km) asteroids can be used to probe accretional environments by comparing the degree of hydration and average density to constrain time of formation relative to calcium-aluminum inclusions (e.g., [22]).

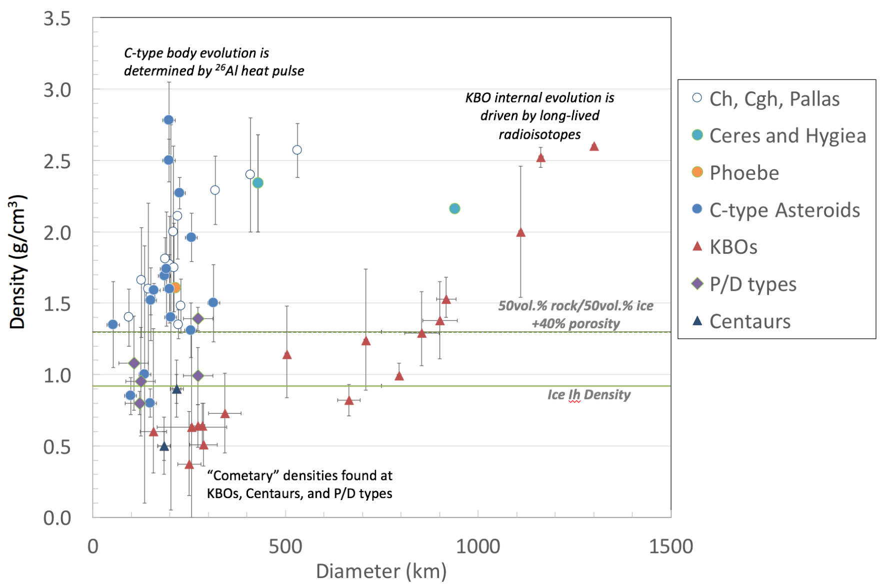

Figure 1. Density estimates available for small bodies across all reservoirs. Density varies by over a factor two between C-type asteroids and Kuiper Belt objects and P/D type asteroids, pointing to a difference in time of formation of >1 My between these different classes. Density variations are also found within the C-type complex, suggesting that the various C-type subclasses may have originated from different accretional environments (See [22] for references).

Recommendations to address the open questions discussed above: 1) pursue development of tools and experimental work to better understand the lifetime of mud convection in C-type bodies, to assess the extent of prebiotic chemistry and conditions that preserve brines. 2) continue meteoritical studies of organic matter; 3) continue astronomical observations across a broad range of icy bodies, including asteroids, Trojans and irregular satellites, to disentangle the effects of accretional environment (composition, formation time) and size on internal evolution; 4) follow-on exploration of Ceres and Pluto [WP10]; 5) exploration of the Themis family, to constrain the internal structure of large C-type [WP11]; 6) secure access to large astronomical facilities (e.g., VLT, Keck, JWST) for visible and spectral imaging of the surfaces of large planetesimals.

Chemical and Physical Surface Modification [Q1, Q4]

Linear features generally accepted as tectonic structures have been observed on several asteroids. Several different types of linear structural features have been observed—including grooves, troughs, pit crater chains and ridges. Determining how these features formed yields important information about geological history and thus internal evolution. Spacecraft observations of a wide range bodies covering a diversity of composition, size, and environments have led to the identification of different physical mechanisms by which linear fractures and faults can be formed [23]: impacts, down-slope scouring, thermal stresses, and even volcanism [24], or cryovolcanic activity [25] in the case of large bodies like Ceres and Vesta. Extensional faulting common to icy satellites is also seen across Pluto and Charon, and can be used help constrain modeling of many processes, e.g., true polar wander/reorientation of the icy crust due to loading of the giant Sputnik basin on Pluto [26], and interior thermal evolution and the lifetime of a subsurface ocean [27]. In addition, planetary encounters outside of the Roche limit may also result in seismic shaking and leave a record of mass wasting [WP12].

The analysis of impact cratering on small bodies in our solar system is important to understand the geology, morphology, and evolution of planets, asteroids and small moons. Cratering processes on planetary bodies happen continuously and result in a large variety of crater morphologies. Impacts are a major transport and erosional process that redistributes materials laterally and vertically. Impact events result in brecciation and pulverization of surface rocks and boulders and can shatter subsurface bedrock. Moreover, impacts cause seismic shaking, which may trigger mass wasting processes (e.g., [28]). Excavated ejecta material and exposures in the crater walls provide a window into the composition of the subsurface. Furthermore, geological investigations of the crater itself and the post impact material provides important insights about the structure of the underlying material. For example, at Ceres, various crater morphologies (e.g., ring molds, pitted terrains) are driven by the presence of ice in the subsurface [e.g., 29, 30]. Large craters also display evidence for impact melt and cryovolcanic features probably triggered by shock-produced fractures reaching Ceres' deep brine [e.g., 4, 5]. Similar processes are expected to occur at other dwarf planets. The effect of impactor contamination on the reflectance spectrum of small body regolith, thought to be insignificant in previous decades, was demonstrated by Dawn at Vesta to be of measurable importance as its surface displays low-albedo spots of carbonaceous nature. Areas with lower crater density can reveal resurfacing mechanisms and can be calibrated to understand the ages of different geologic units.

On a more subtle but pervasive level, almost all small body surfaces are subject to micrometeorite and solar wind bombardment, exposure to galactic cosmic rays, some level of local mixing, and extensive thermal cycling, all of which can change the spectral properties of silicates, ices, and organic matter. Hence these weathering processes affect interpretation of remote sensing measurements of these surfaces. While our understanding of space weathering on silicate bodies like Eros, Itokawa, and the Moon is improving [WP13], space weathering on carbonaceous bodies is still poorly understood. However, observations of Ryugu by OSIRIS-REx provide evidence against dehydration of surfaces as a typical result of space weathering.

<u>Gaps and Emerging Concepts:</u> (1) Crater-based geochronology is still limited due to poor knowledge of the impactor populations in the outer solar system and conflicting theoretical frameworks (lunar- vs. asteroid-based) in the inner solar system [WPs 14,15]. (2) Impactor

material supplied by neighboring asteroids has no albedo contrast with Ceres' surface or other C-type asteroids, making identification of impactor contamination more difficult (although NIR spectroscopy has identified local 'foreign' rocks on Bennu). (3) More generally, recent studies indicate impactor material gets embedded in ice-rich crusts [31, 32] with implications for icy bodies across the solar system. This process may create a regolith dominated by contaminants [33]. (4) Space weathering tends to significantly alter both the spectral signatures of organic compounds and organic molecular structures until they are not recognizable [see WP16].

Recommendations to address the open questions discussed above are to: **Recommendations to address the open questions discussed above are to**: 1) secure access to large astronomical facilities (e.g., VLT, Keck, JWST) to characterize small body populations (both inner and outer solar system); 2) quantify space weathering on Bennu (and Ryugu) via analysis of returned samples; 3) future missions to small bodies should include the objectives to determine the fracture patterns in order to assess the mechanisms driving tectonic activity in heat-starved bodies, and to measure crater distributions in order to understand the impactor populations at a smaller scale than can be observed by telescopes; 4) continue theoretical and experimental research on the effects of micrometeorite and solar wind bombardment, as well as exposure to galactic cosmic rays on small body surfaces; 5) experimental research is needed to support past and future observations meant to understand the organic compound inventory of bodies across the solar system.

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