MRD-120a

MRD-120a: Generate and follow a project sample allocation and analysis plan to address the science objectives including those in the PLRA37 - a. Sample Anlaysis

Summary of Requirement

The Project is to prepare a Sample Analysis plan, which is a deliverable in 2019. As a precursor to this plan, listed below is the Sample Analysis Science Report, which is the basis of the Sample Analysis Plan.

Data Products Required

Report to the Project.

Ability/Availability of the System to Generate Sufficient Observations

Does not apply.

Minimum Success Criteria

A report that outlines the analytical strategies.

Dependencies per Mission Phase

Requires a successful launch of the spacecraft.

Adequacy of the DRM

Does not apply other than to state we will create a Sample Analysis Plan.

Data Products per Mission Phase

A report due in 2019.

Overview of Processing

Does not apply.

Provenance of Algorithms, Software and Techniques

Does not apply. The SPOC is not involved in meeting this requirement.

Expected/Simulated Data

We will conduct a Sample Analysis Readiness Test that will be used to test rigor of the Sample Analysis Plan.

Analysis & Verification Methods

The Sample Analysis Plan will be sent for external review. We will also conduct a pre-Earth return test of the analytical process defined in the plan by the Sample Analysis Team through the Sample Analysis Readiness Test.

Existing or Potential Liens

None

SPOC Requirements

None and does not apply.

External Interfaces

Does not apply.

Sample Analysis Science Report: Hypotheses for the Geological History of Asteroid Bennu Testable by Returned Sample Analyses

Introduction

Laboratory studies of astromaterials have yielded detailed constraints on the, properties, origins, and evolutionary histories of a wide range of Solar System bodies, including the Moon, Mars, comets, and asteroids. Yet, the parent bodies of meteorites and cosmic dust are generally unknown, genetic and evolutionary relationships among asteroids and comets are unsettled, and links between laboratory and remote observations remain tenuous. The OSIRIS-REx mission will offer the opportunity to coordinate detailed laboratory analyses of asteroidal material with known and well characterized geological context from which the samples originated on asteroid 101955 Bennu.

A L1 requirement of the mission is to bring back a minimum of 60 g of pristine bulk asteroid regolith (MRD-14) and a minimum of 26 cm2 of contact pad (MRD-15) in support of mission objectives to study the nature, history, and distribution of its constituent minerals and organic material. From the returned sample, the Science Team will receive 15 g of bulk material (MRD-105) and 6.5 cm2 of surface contact pad material for analysis. From the analysis of these materials we will reconstruct the history of Bennu and the processes that produced and evolved the asteroid from its pre-accretion environment to how it became a NEO.

To achieve this L1 requirement we have developed hypotheses relating to the origin and history of asteroid Bennu and its source materials that will be tested through the analyses of returned samples. As with the mission we have classified our developed hypotheses into three levels, each with a specific goal in mind.

Level 1 hypotheses are those which are fundamental to the mission science and are (1) Derived from or are founded in investigations of chondrites and their formation history as related to potential parent bodies and/or (2) Relate to established observational data from ground-based and orbital-based instruments for the surface of Bennu as related to hypothesized analog materials such as chondrites.

Level 2 hypotheses are those that derive from level 1 and are posed to test and place additional constraints on level 1 hypotheses or the interpretations of the data generated from the testing of level 1 hypotheses.

Level 3 hypotheses are those that derive from level 2 hypotheses or the interpretations of the data generated from the testing of level 2 hypotheses.

Here we summarize hypotheses relating to the potential origin and history of asteroid Bennu and its source materials that will be tested through the analyses of returned samples. These hypotheses reflect our best understanding of the properties of Bennu derived from remote astronomical observations viewed in the context of remote observations of asteroids, and laboratory studies of meteorites, cosmic dust, and Stardust cometary dust samples.

We have identified 2 level 1 hypotheses and several level 2 hypotheses that are derived from these level 1 that we will test by analysis of the returned samples, both the bulk sample and the material from the contact pads. The hypotheses are as follows:

Hypothesis L1-1: The surface of Bennu is analogous to carbonaceous chondrites (Fig. 1).

Hypothesis L2-1: Bennu is similar to carbonaceous chondrite materials that are represented within our collections (Figure 1).

Hypotheses L2-2: Bennu is not similar to carbonaceous chondrite materials that are represented within our collections but still carbonaceous chondrite-like in nature (Figure 1).

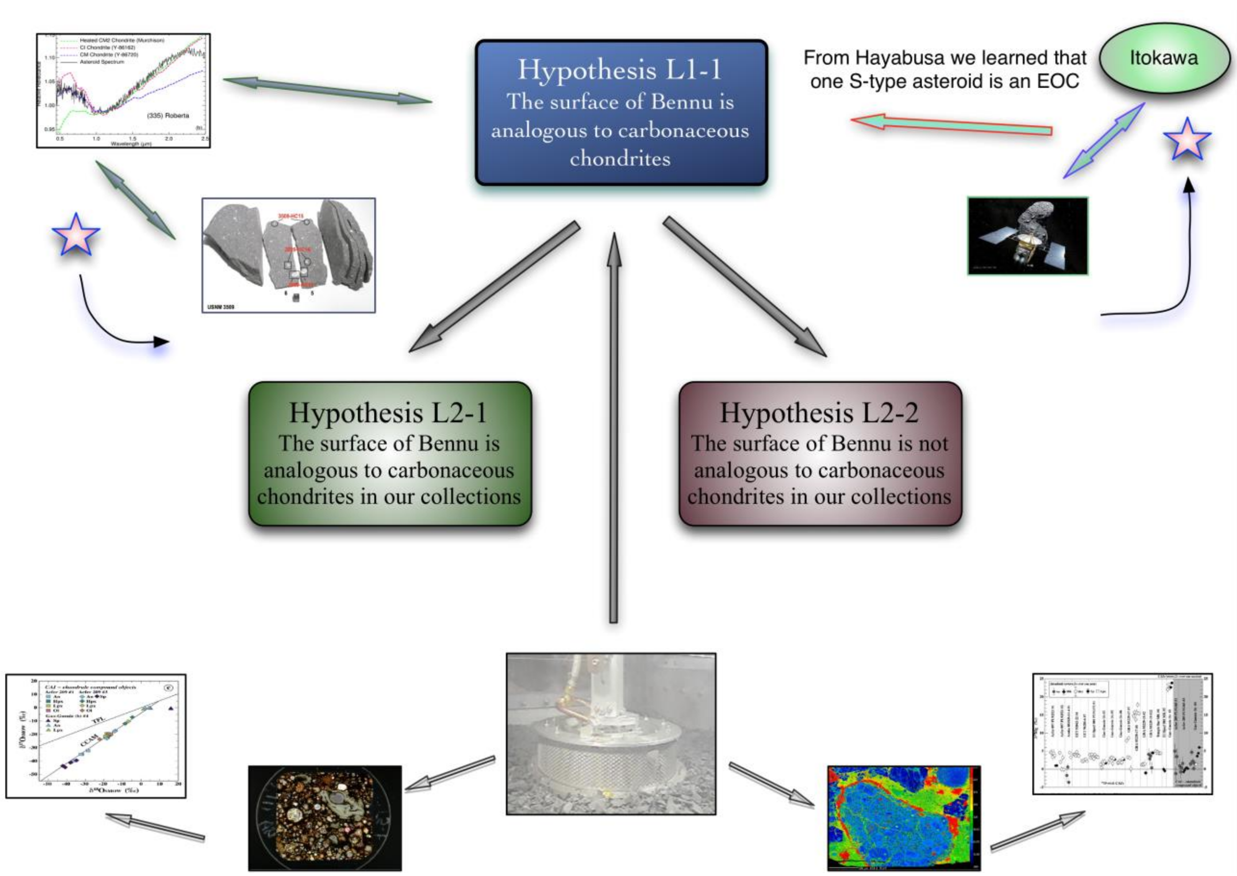

Figure 1. A schematic diagram of Level 1-1 hypothesis and two level 2 hypotheses derived from the level 1. The L1-1 hypothesis can be considered as a working assumption to have merit.

Remote sensing and laboratory studies of meteorites have posed the hypotheses within the VIS that the surface of Bennu may be similar to carbonaceous chondrites. In reference to one specific ground-truth data point for S-type asteroids, the Hayabusa mission returned samples from asteroid Itokawa that strongly support the hypothesis that S-type asteroids are analogous to ordinary chondrites.

Hypothesis L1-2: The surface of Bennu is not analogous to carbonaceous chondrites (Figure 2).

Hypothesis L2-3: Bennu is not a carbonaceous chondrite (or any other chondrite) (Figure 2).

Hypothesis L2-4: Bennu is a mixture of several different types of meteorites (potentially represented by samples within our collection and/or not in our collection or a combination of both-Figure 2).

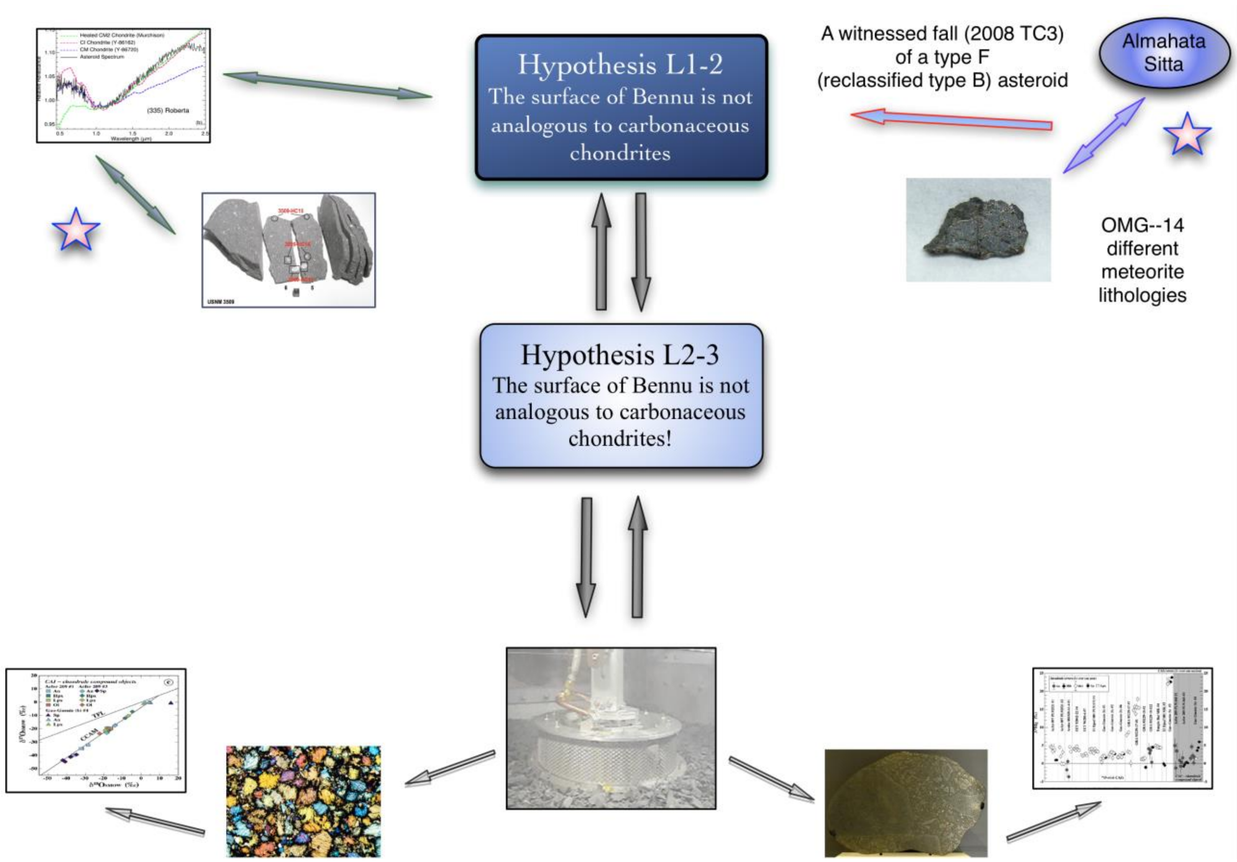

Figure 2: It is a viable hypothesis that Bennu is not a chondrite or that it is essentially composed of many different types of samples. It could be that Bennu is a type of primitive achondrite such as ureilite. The hypothesis that it is composed of more than one type of lithology (or equivalent meteorite class) has merit and is supported with a single data point in the form of the witnessed fall 2008 TC3. The tiny asteroid turned about to be composed of two different classes of meteorites (primitive achondrite and chondrites) of at least 14 different types of lithologies (Jenniskens et al. 2009).

Note: We may want to pose two additional hypotheses that (1) Bennu is a rubble pile and (2) that Bennu is not a rubble pile but a monolith.

Hypothesis L1-3: The surface of Bennu is comet-like (Figure 3).

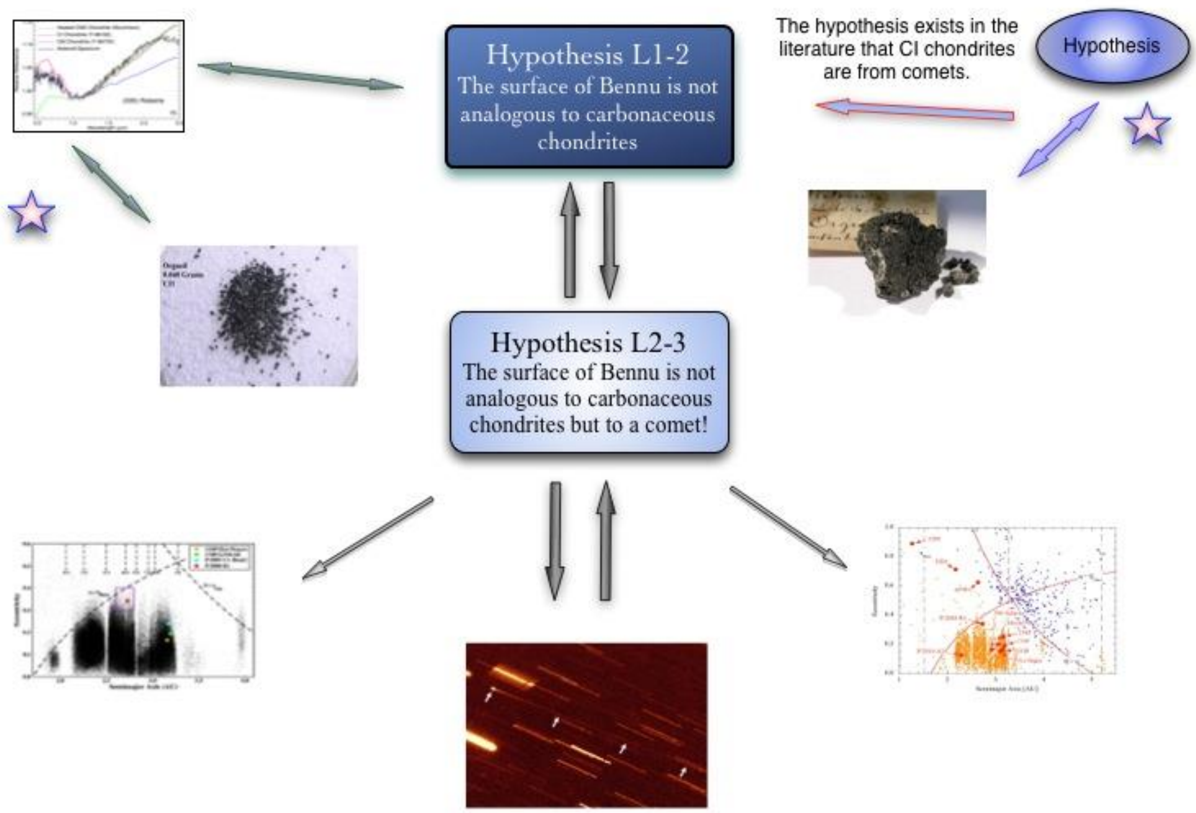

Figure 3: The hypothesis that Bennu is comet-like or, simply stated an extinct comet, is viable and cannot be discounted. Several outer belt asteroids (>3 AU) have been observed to have cometary-like activity near perihelion (Hsieh & Jewitt 2006). These 'main belt comets' are likely to be ice-bearing asteroids that formed beyond the snow line and have been rendered active by recent collisions. Their relationship to other comets or to asteroids is an emerging field. Although this hypothesis could fall under L1-2, the importance and implications of being a former main belt comet over a body that is simply not a carbonaceous chondrite or a mixture of different kinds of meteorites is considered too important to group it into L1-2

The testing of hypothesis L1-1 is essentially achievable to a nominal level by visual inspections of the sample during the first few hours that the SRC is opened at JSC. If it is chondritic, then we will determine the type of chondrite by petrographic and geochemical analyses. After evaluating the potential meteorite classification, we will organize our scientific investigations with reference to a timeline (Figure 4) following from the origins of the elements in evolved stars through the collapse of the protosolar nebula, formation of Bennu and its early geological history and subsequent dynamical and geological evolution.

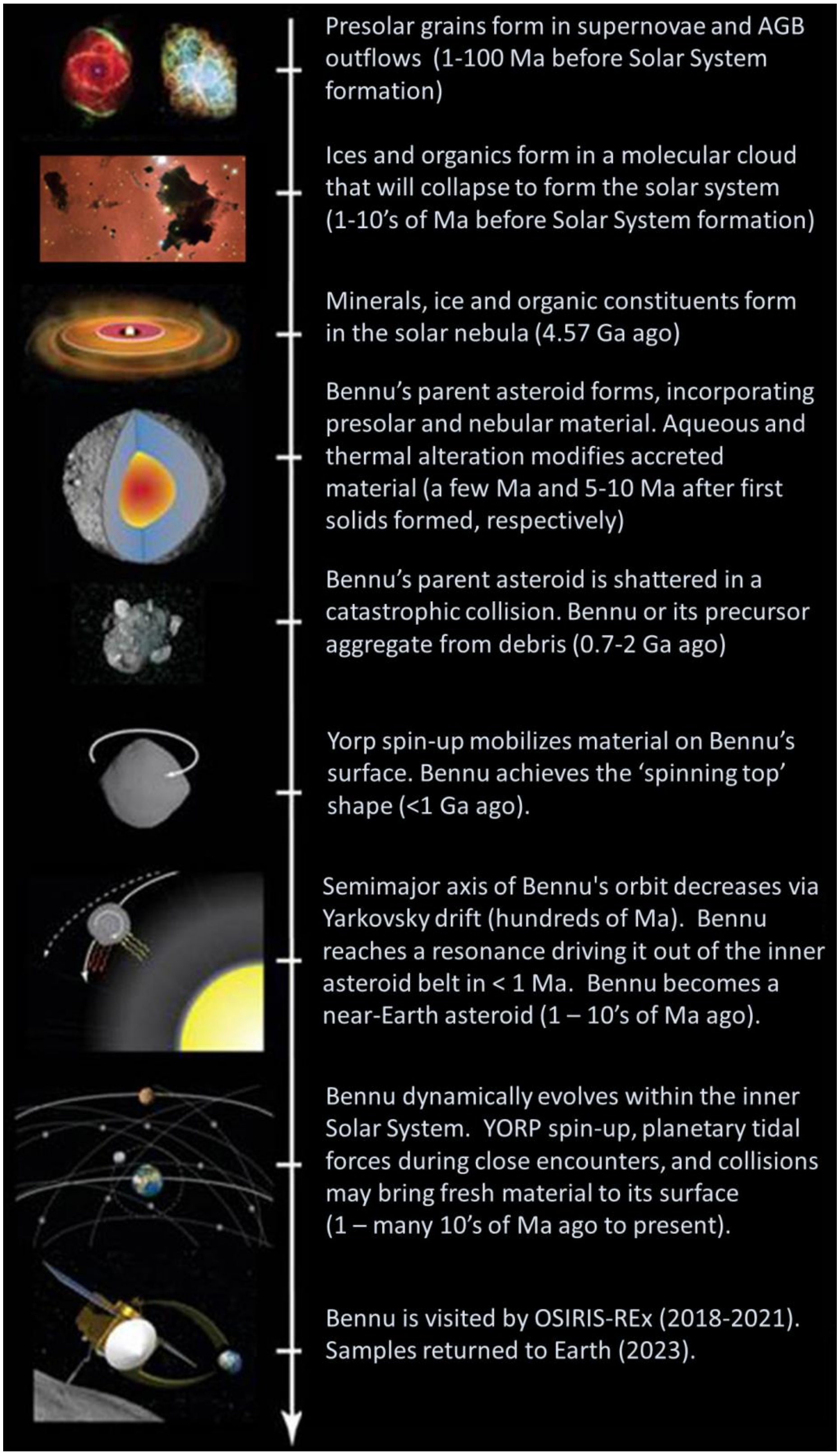

Figure 4. A schematic diagram of a notional time line for Bennu.

Pre-solar Epoch: Sampling materials before the collapse of the molecular cloud

Hypothesis L3-1: Asteroid Bennu contains abundant preserved pre-solar (stardust) grains derived from diverse stellar sources.

Make isotopic measurements of micrometer-sized matrix grains.

Analyze for noble gas abundance of the returned regolith.

Search for presolar silicates, which may preserve evidence of radiation, shock, material recycling and condensation processes in the interstellar medium.

Hypothesis L3-2: Organic matter in Bennu evolved from molecules and organic grains that formed in a cold molecular cloud.

Analyze the organic matter in Bennu to determine if it evolved from molecules and organic grains that formed in a cold molecular cloud or in another environment.

Hypothesis L3-3: The solar nebula was impacted by and may have been polluted with material from a supernova shockwave.

Use the analyses of premolar grains to compare abundance of supernova stardust with those found in meteorites and cometary materials.

Make measurement of daughter products of extinct short-lived nuclides 26Al and 60Fe.

Stable isotopic measurements of Ti, Cr, Ni, O, etc. .

Protoplanetary Disk Epoch: The pre-accretion environment of Bennu plus when and where did accretion of the primary parent body occur.

Hypothesis L3-4: Bennu was formed from materials whose origins spanned the entire spatial extent of the early solar nebula, from near the Sun to beyond the planets.

Search for common inner nebula components such as refractory inclusions and chondrules.

Search for evidence of isotopically anomalous organic materials that formed at low temperatures.

Oxygen isotope analysis, both bulk and in situ.

Determination of mineral compositions to constrain fO2 conditions during formation.

Hypothesis L3-5: Bennu was formed from materials whose origins were confined to a local or restricted area of the within the 'snow line' in the early solar nebula.

Search for common inner nebula components such as refractory inclusions and chondrules.

Search for evidence of isotopically anomalous organic materials that formed at low temperatures.

Oxygen isotope analysis, both bulk and in situ.

Determination of mineral compositions to constrain fO2 conditions during formation.

Determine the existence, abundance, and oxygen isotopic composition and D/H of aqueously-altered phases if they exist.

Investigate the paelomagnetic record of CAI, chondrules, and matrix to contain potential environments.

Hypothesis L3-6: Bennu formed beyond the ‘snow line’ in the outer portion of the asteroid belt or the vicinity of the giant planets.

Bulk elemental abundances of the returned sample constrain whether Bennu was highly heated and/or differentiated

Measure the abundances of volatile elements in bulk returned sample

Precise measurement of the isotopic abundances of Hf, W, Ti, Cr, Ni, Mo, etc. in bulk material differentiate among meteorite groups and possible formation regions in the disk.

Determine the existence, abundance, and oxygen isotopic composition and D/H of aqueously-altered phases if they exist.

Model the dynamical history of Bennu placed in context of spectroscopically similar asteroids and meteorites and relate these finding to the hydrated nature of the minerals and abundance of chondrules and CAIs.

Hypothesis L3-7: If Bennu formed beyond the snow line there is or is not a relationship that can be constrained from sample analysis between Kuiper belt objects and active asteroids (e.g. main-belt comets).

Perform petrologic, mineralogical, geochemical and isotopic analysis of returned materials and comparison to Stardust samples.

Determine if evidence of hydration be used as a constraint?

Hypothesis L3-8: Bennu has a formation age of ~ 4.5 Ga

Make measurement of long-lived radionculides, including Pb-Pb and U-Pb

Hypothesis L3-9: Some organic matter in Bennu formed by low temperature processes in the outer solar system and/or by high temperature processes in the inner solar system.

Perform coordinated chemical and isotopic measurements of organic materials

Make compound-specific measurements.

Hypothesis L3-10: Distinguish between turbulent accretion versus streaming instability models for formation of km-sized planetesimals.

Analysis the size-scale of remanent magnetization in the returned samples.

Hypothesis L3-11: Constrain if mass and momentum transfer in the protoplanetary disk were mediated by nebular or T Tauri magnetic fields.

Search for an measure the intensity of per-accretional remanent magnetization in the returned samples (specifically CAIs, chondrules, and other components hypothesized to be pre-accretionary in nature).

Hypothesis L3-12: Determine if Bennu is part of a large, partially differentiated planetesimal.

Search for post-accretional remanent magnetization within the returned samples, a potential signature of an ancient core-dynamo effect.

The Geological Activity Epoch: Post-accretion geological activity within and on Bennu

Hypothesis L3-13: Aqueous processing did or did not occur early in the history of Bennu.

Perform petrographic and petrologic investigations of sample mineralogy searching for evidence of hydrated phases or other phases produced by aqueous processing (including their abundance).

Make measurement of ages of alteration products by short-lived nuclides such as Mn-Cr to constrain when the alteration process occurred.

Hypothesis L3-14: Some minerals and organic compounds in Bennu were formed and/or altered by the interaction of water.

Perform investigations of hydrated minerals or other phases that must or could have been formed by water/rock interactions (which feeds into L3-9 above).

Determine the presence or absence of soluble organic molecules thought to require formation in aqueous processes

Perform coordinated isotopic and chemical measurements of soluble organic molecules, particularly amino acids.

Hypothesis L3-15: Interior regions within Bennu were altered by thermal metamorphism

Perform a petrographic and petrologic investigation of phases that were produced by affected or produced by thermal metamorphism.

Thermally altered materials exhibit equilibrated mineralogy, dehydration, and maturation of organic matter.

Determine, if any, the movement of elements such as Cr within olivine and exsolution of high-Ni phase within FeNi-rich metal occur very early on in the metamorphic process.

Determine the cooling rates derived from opaque phases.

Regolith Evolution Epoch: The formation and evolution of regolith and related surface processes

Hypothesis L3-16: The surface materials have been exposed to the space radiation environment for ## years.

Make measurement of cosmic-ray exposure ages (exposure age at <meter-depths).

Make measurement of solar flare track densities in silicate minerals (exposure age at mm-depths).

Analysis of solar wind implanted noble gases and solar wind implantation effects (direct surface exposure age).

Hypothesis L3-17: Bennu has been subjected to shock and heating by impacts over its geological history.

Determine if varying Ar-Ar ages of regolith materials reflect impact resetting events as observed in ordinary chondrites and HED meteorites.

Search for evidence of impact history also given by presence of impact melts, such as shock veins, agglutinates, impact glassy spherules, melt splashes on rock chips.

Investigate deformation microstructures in mineral grains to constrain shock pressures and processes.

Number-density of micrometeorite impacts pits.

Petrographic and petrologic investigations for meteorite material (xenoliths) other than what may be determined to be the host rock in the regolith samples.

Hypothesis L3-18: Surface regolith materials have been heated to moderate temperatures.

Abundance of volatile organics and thermally labile minerals in outermost surface materials (contact pads).

Identification of dehydration textures in phyllosilicates, annealing textures, and devitrification of glassy materials.

Hypothesis L3-19: Surface regolith has been gradually overturned and mixed by ‘gardening’ processes.

Evidence of space weathering and solar radiation exposure in subsurface mineral grains.

Abundance of micro-meteorite impact pits.

Hypothesis L3-20: Space weathering has modified the physical and chemical properties of Bennu regolith grains.

Observation of radiation effects including reduction and formation of nanophase metal and sulfide grains, and amorphous layers on mineral surfaces, and alteration of organic matter.

Evidence for impact processes: agglutinates, shock melts, patinas, and vapor-deposited grain coatings.

Are there differences in the extent of space weathering effects between contact pad samples and the bulk sample?

Reflectance spectra of the bulk returned sample compared to the orbital spectral data.

Determine how organics on the surface of Bennu may have been altered by cosmic rays etc.

Determine the relationship between the physical characteristics of the regolith assumed for engineering requirements during S/C construction and relate to the returned sample.

Dynamical History Epoch: The dynamical evolution of Bennu from main belt to near-Earth object

Hypothesis L3-21: Determine when Bennu was initially disrupted by a major impact or by planetary encounters.

Measurement of galactic cosmic-ray exposure ages.

Identification of shock features in minerals and matrix components indicative of major impact events.

The lack of any identifiable shock features favor planetary encounters over major impact event.

Quantify the orientation of opaque minerals within the samples if orientation exist (or plastic deformation).

Hypothesis L3-22: Determine when and how many times Bennu was disrupted after 'the initial' disruption event either by a major impact or by planetary encounters.

Measurement of galactic cosmic-ray exposure ages.

Identification of shock features in minerals and matrix components indicative of major impact events.

The lack of any identifiable shock features favor planetary encounters over major impact event.

Quantify the orientation of opaque minerals within the samples if orientation exist (or plastic deformation).

Hypothesis L3-23: Bennu is a member of an asteroid family formed ~800 Ma ago and has it been disrupted since that time?

Measurement of galactic cosmic-ray exposure ages.

Identification of shock features in minerals and matrix components indicative of major impact event.

Lack of any identifiable shock features favor planetary encounters over major impact event.

Orientation of opaque minerals within the samples.

Comparison of the orbital history of Bennu with the orbital properties of asteroid families.

Comparison of estimated dynamical age of putative asteroid family with shock and cosmic-ray exposure ages determined on the returned samples

OSIRIS-REx Epoch: Constraining the effects of OSIRIS-REx on Bennu

Hypothesis L3-24: OSIRIS-REx asteroid proximity operations and the TAG event(s) affected the surface of Bennu or Bennu itself.

Analyze in detail the data produced for TAG reconstruct to determine the extent that the entire TAG event(s) affected the surface of Bennu (or Bennu itself).

Analyze any data produced during rehearsal(s) to determined if the surface of Bennu (or Bennu itself) was affected by the rehearsal(s).

Measure the returned samples to determined if any contaminates from OSIRIS-REx were introduced to the sample during collection or any part of the post-TAG process.

References

Hsieh H.H. & Jewitt D. (2006) A population of comets in the main asteroid belt. Science 312, 561-563

Jenniskens P. et al. (2009) The impact and recovery of asteroid 2008 TC3. Nature 458, 485-488

From Dante's Nature Paper: History of Bennu

Pre-solar Epoch

Protoplanetary Disk Epoch

Nun-- Geological Activity Epoch

Nun-- Regolith Evolution Epoch

Bennu-- Main-Belt Epoch

Bennu-- Near-Earth Epoch