MRD 137- Global Boulder Geology Map

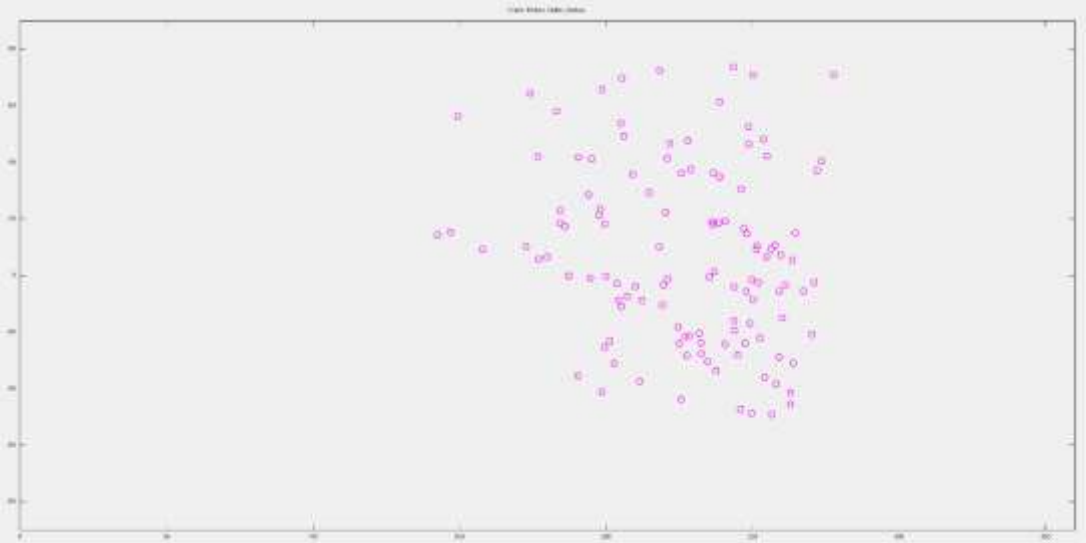
Boulder abundance and surface area maps

Data Product Mapping Results and Plots and Maps

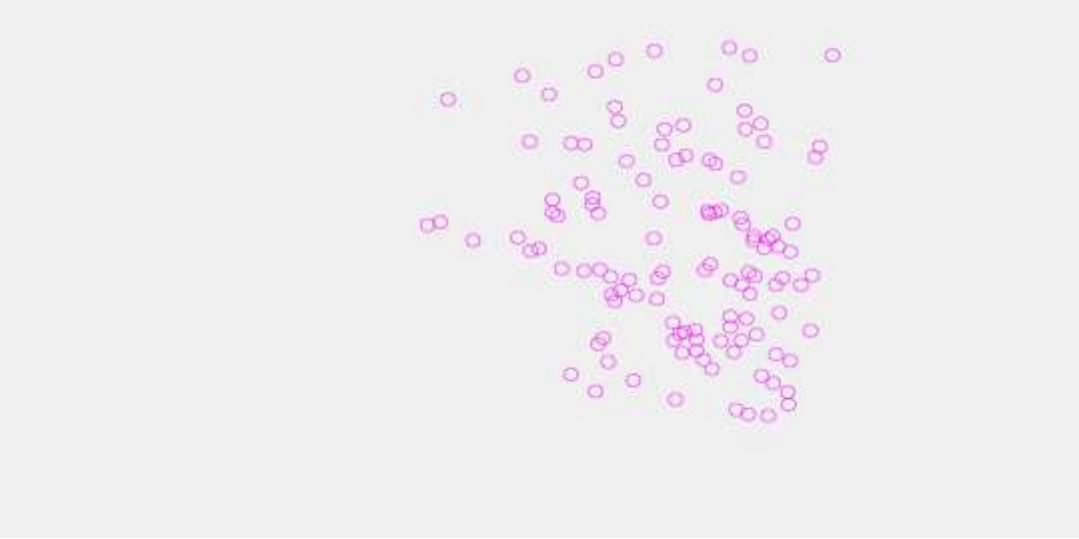
Mapping efforts are currently being led by Erica Jawin and Beau Bierhaus. The repository of SBMT files is maintained by Erica Jawin and stored on rdwg-drive in rdwg-1. Below are some files and plots to be used more widely. There are transparent PNGs meant to be used to simply overlay on plots in PPT, and also some with not labels meant to be imported into SBMT and wrapped on the shape model.

Locations of fractured boulders (Jamie Molaro, Marco Delbo, Ron Ballouz)

Ready for plot overlay.



Ready for SBMT wrap



Locations of possible Breccia Boulders (McCoy, Connolly Jr., Molaro, Delbo, Ballouz, Jawin):

Data Product Description

Data Product Overview

This is a map of the integrated geology of boulders located on the surface of Bennu. The boulder geology map presents the locations and sizes of boulders/rocks across Bennu, in conjunction with diagnostic spectral information and relationship to the geopotential of the body. This map will be done in two distinct stages, where by the end of Detailed Survey a map of the boulder "features" will be generated, and later a "geologic map" including analysis and interpretation that also incorporates compositional maps will be generated in the interest of long-term science.

Overview

In the general size scheme adopted by OSIRIS, a boulder is defined as a object >21 cm and derives its classification from anything that is larger than the TAGSAM mouth.

This map data product directly supports MRD-137 (boulder map), and will be a fundamental companion to MRD-136 (crater map), MRD-138 (regolith map), MRD-195a (geologic properties to constrain geologic history) and MRD-195b (geologic properties to constrain dynamical history). The input data for the boulder map will include elements of all the remote sensing data acquired at the asteroid. There will be a global version that utilizes the highest-resolution data that are uniformly available across the asteroid, and local higher-resolution versions that utilize data from the reconnaissance, TAG rehearsal, and TAG phases. Similarly there will be a rapidly produced version, the Crater Feature Map, that is used for sample site selection that will indicate the location and sizes of boulders. There will be a long-term science product that includes geologic interpretation gathered from other geomorphologic and compositional information.

- Image data comprise one of the two core data sets that enable the identification and characterization of the boulders: their size (long axis, short axis, and height when data resolution allows), angularity, location, and orientation
    - OCAMS color data will provide a means to assess spatially-resolved spectral variability of the rocks. Higher resolution image data of boulders on Itokawa revealed individual boulders with albedos distinctly different from the global average (Hirata et al. 2011).
- Topographic (OLA) data are the second core data set for identification and characterization of the boulders. The lidar data provide an independent assessment of boulder location, size, and shape.
    - Shape model: both OLA and OCAMS data contribute to the shape model, and given the shape of the asteroid, there is likely a fundamental correlation between the shape and gravity (brief description below), thus embedding the measured boulder/rock population in the shape model will be a key part of the analysis.

- OVIRS and OTES data: these data may be too coarse in resolution to resolve individual boulders, except perhaps from reconnaissance data. Nevertheless, there is a possibility that global trends of spectral behavior will correlate with the rock population. We already have preliminary evidence for this at Bennu; the ground-based spectra show measurable differences in slope depending on the orientation of the equatorial bulge relative to the viewing angle of the observations. It could be that the mean grain size changes from the equator to the mid- and higher latitudes.

- Gravity data: for such a small body to be so nearly spherical implies it is constructed of individual objects that are small (relative to the global scale), and that these objects are mobile even under the gentle forces of a microgravity environment. Analysis by one of the O-REx science team members (D. Scheeres) indicates the equatorial ridge may be the result of mobile material flowing "downhill". In which case the distribution of rocks/boulders on Bennu may be correlated with the gravitational potential or height relative to a reference geoid. On Itokawa, Eros, Leutitia there is significant evidence that fines flow down hill following potential or height contours (e.g., Mantz et al., 2002; Miyamoto et al., 2006; Thomas et al., 2012).

The final product, one of long-term science, will utilize data collected across all asteroid operations. The early, lower-resolution remote sensing data will be the basis for the initial, global-scale measurements, while the reconnaissance and rehearsal phases (as well as the final TAG approach) will provide progressively higher-resolution data to refine the maps in local areas.

Data Product Structure and Organization

What is the structure of the data product?

ShapeFile format

How is the product organized?

ShapeFile format details information for each individual mapped feature, which are separate pieces of data.

Data Format Descriptions

Header information for the safety map will include:

Version number

Time and date of generation

Map scale / resolution in m per pixel of the underlying shape model used as the framework for the ma

Metadata or extra notation related to various qualities found on the feature will use the Geologic Mapping notation, with keys found in the Spreadsheet below and on the RDWG Google Doc.

https://docs.google.com/spreadsheets/d/1y6ty57ybfV1zH0hYJTbaSArLK5Qa5HuLRp0f7R4-K4M/edit?usp=sharing

The core of the data product will be a table that consists of measured parameters for each boulder/rock that are generated in the initial boulder/rock assessment for mission-critical activities and for longer-term science assessment (i.e. these data are acquired in both stage 1 and stage 2, described above):

- Geometric center in x, y, z coordinates and in latitude, longitude, radius
- Dimension of long-axis
- Dimension of short axis
- Maximum boulder height above local reference surface (if sufficient resolution in topographic data)

Each observed boulder will subsequently be analyzed relative to other science data products to include additional data (i.e. these measurements and analyses are stage 2 described above):

- Radius of geometric center relative to mean asteroid reference
- Height relative to geoid
- Local acceleration value
- Geopotential value
- Orientation of long axis relative to local acceleration gradient
- Orientation of short axis relative to local acceleration gradient
- Thermal inertia of local area (from MRD-155 or MRD-540)
- Color value
- Space weathering “value”
- Compositional information

Data Product Generation

The central element of the data product is the identification and measurement of the boulder population. This is done on image data and with OLA data that have been calibrated and tied to the shape model (or map projection). The IPWG and ALTWG, respectively, are responsible for generating the calibrated and projected data, and assigned members of the RDWG (Bierhaus et al.) make the measurements using an agreed-upon Project tool (e.g. the APL Small Body Mapping Tool, or SBMT). Furthermore the IPWG has automated detection techniques and a Citizen Science effort to populate a Boulder Database that will be made available to the RDWG.

Additional remote sensing data, and derived data products, add context and value to the crater measurements. The supporting data correspond to existing science data products as follows:

Inputs for time-sensitive "Global Crater Feature Map"

- Global Mosaic @ 21-cm resolution (MRD-121)

- Global Topographic map (MRD-122)

Inputs for long-term science "Global Crater Geology Map"

- Global Color Ratio Maps (MRD-141)

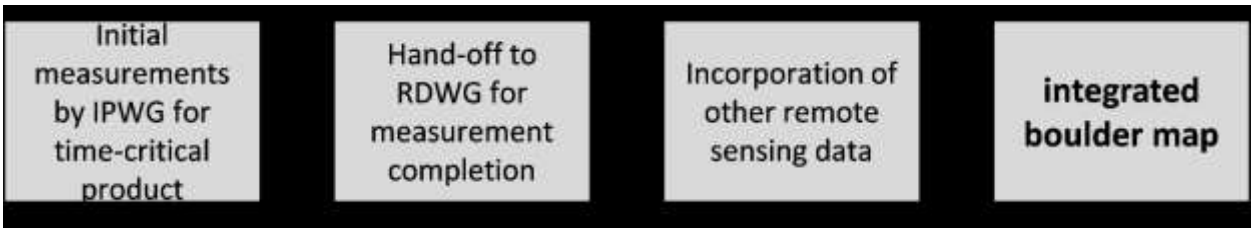
- Global Reflectance Factor Maps (MRD-154)

- Global Bond Albedo Map (MRD-154)

- Global mineral and chemical maps (MRD-140)

- Global Thermal Inertia Maps (MRD-155)

Members of the RDWG will lead the development of the final boulder map(s), although interim stages of the product will involve other working groups, and the final product will utilize information from other science products, see Figure 1.



The IPWG will populated a Boulder Database with a first-look distribution of boulders that effectively are a "triage" of high- and low-density rock populations. These initial measurements will consist of location and size (long- and short-axis). For regions that have unacceptably high rock populations (where "unacceptably high" is TBD), the measurements will stop at some threshold size and/or density.
Subsequent measurements for the science version of the boulder map will expand the measured sizes down to the completeness limit allowed in the data, and will incorporate the supporting measurements (e.g. thermal inertia, local acceleration) into the data set.

Currently the most reliable method to identify the features is manually, and the program asteroid visualization tool, J-Asteroid, is tasked to have this capability. (If appropriate, APL's Small Body Mapping Tool could also be used. It has been effectively used to look at global block distribution on Itokawa and already possesses many of the outputs described above). A typical implementation of the measurement effort is to display images on a computer screen, with the ability to adjust magnification and brightness/contrast (see below), and mark boulder location, diameter, height, and other key morphological features; these data are stored in an ascii file and easily imported to a variety of analysis tools. Its significantly easier to undertake this mapping if it possible to move the image as they sit on a topographic surface.

Image data: OCAMS images, both low-level (i.e. L1), and high-level (i.e. reprojected and tied to the shape mode) will be used. The radiometrically corrected but not geometrically reprojected

images provide "spot checks" for candidate populations, i.e. sometimes using less processed versions of the data allow for a more definitive identification of feature(s). In general, however, the measurements will utilize images that have been radiometrically calibrated, reprojected, and combined into image mosaics. The image mosaics should not be whole-body mosaics, rather regional mosaics that span blocks of longitude and latitude. It is important that these mosaics are tied to the appropriate reference frame (e.g. the shape model or a particular 2D projection).

Altimetry/Topography products: OLA altimetry data enable an independent assessment of the boulder population, which will be particularly valuable in regions where feature identification in the image data suffers from poor lighting (e.g. high latitudes). In addition, altimetry data from both OLA and OCAMS (stereo-photoclinometry) enable estimates of boulder heights, which will require estimating a local surface plane beneath the boulder for which to baseline the boulder thickness, where thickness means "height" in the sense of how tall or short an object is. ("Thickness" is used here, rather than "height", since we use "height" in the altitude-sense of the word – how high up it is relative to the geoid – rather than a physical dimension associated with shape – i.e. length, width, height.) This is possible by selecting >3 points adjacent to the boulder, fitting a plane to the radius value at those points, and removing that radius value from the radius value of the boulder. This only works if the topographic resolution allows it, where the topography is not smoothed between rocks, or block constructs are difficult to sort of remove from one another.

Other corollary data: the map products associated with other remote sensing data can be associated with the boulder data through a common map projection.

Beau Bierhaus will lead a team of colleagues on this effort, including Barnouin, Daly, Risk, Lauretta, Walsh and McCoy.

Version Control
Global and local versions of the product will be generated.
For the global map, it is important that the images used for measurements be as uniform as possible to minimize bias in the derived population; uniform applies to resolution, lighting, and viewing geometry. Thus it is expected that detailed survey OCAMS images, and OLA Orbital Phase B data, will be the preferred data for developing the global measurements.
Ideally the local, higher-resolution data would also be consistent in resolution, lighting, and viewing geometry, but because of the closer range between the spacecraft and the asteroid, the finite level for navigation errors – and thus relative geometry between the spacecraft and the asteroid – will be proportionally larger, and the inherent geometry of the reconnaissance passes means that local/site-specific data likely will have greater inherent variability in lighting angle, resolution, and viewing geometry. As a consequence, it will be necessary to select the data the provide the most consistency possible, and evaluate that data to ensure a reasonable completeness limit for the minimum size is determined.

Observational Requirements
The imaging data should have the following characteristics.

Plate scale: the images should be <= 1 m/pix. In conjunction with the other imaging parameters listed, we need at least 4 pixels across a feature to have sufficient confidence of its existence and origin.

Incidence angles > 40 deg and < 75 deg: The magnitude of the solar incidence angles determines the presence and length of a shadow. Incidence angles > 40 deg ensure sufficient shadowing to define the characteristic circular/elliptical shape of craters. Incidence angles > 75 deg result in excessive shadows, masking the terrain.

Emission angles < 30 deg: The magnitude of the emission angle determines the extent of foreshortening present in the image. Greater emission angles correspond to increasing foreshortening, degrading the resolution along the line of site, and introducing potential "feature confusion" as objects start to obstruct one another between near- and far-field, as well as affecting the perceived geometry of a feature on the ground. As emission angle increases, there is insufficient information in the line-of-site direction to accurately render the surface in reprojections that create a different, e.g. nadir, view of the surface.

Topographic (OLA) Observational Requirements

Spot size: The spot size should be <= 1/3 the size of the feature. Image data contains information content beyond just the dimensions of the feature, because of the shadows cast by the feature, and the distinctive light/dark shading made by illuminated and shadowed edges. The OLA spot size for boulders / rocks is less stringent than for craters because the intent of this measurement is to know a feature is present, as opposed to characterizing the morphology and origin in detail.

Spot spacing: The spots should be adjacent, and sample the crater in both dimensions on the surface.

Range precision: The range precision should be <=0.2 the mean feature dimension to ensure that low-profile features are resolved with a precision that resolves their height from the mean plane around the feature.

When in the DRM are the observations that make the data product scheduled to be taken?

- Starting at the Preliminary Survey phase, ending during Detailed Survey.

How long does it take to produce the data product?

- The Global Boulder Feature Map - locations and sizes of boulder - can be generated in 4-6 weeks of work as imaging is analyzed and processed, completed at the end of Detailed Survey.
- The long-term science product, the Global Boulder Geology Map, will take months.

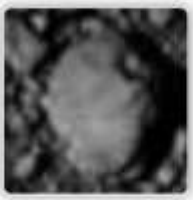
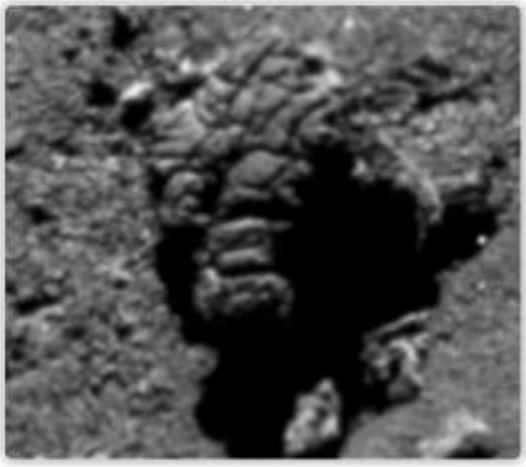
Is this product used for sample site selection, science value, or long-term science?

- The rapidly produced feature map is used for sample site selection as an input to Global Science Value Geologic Feature Map (MRD-114). The long-term

Global Boulder Geology Map is and for long-term science as an input to the Global Geology Map (MRD-195a).

Taxonomy/Metadata

Since many different mappers/scientists may be the researchers to first see and map a crater, we propose building a simple taxonomy for people to indicate interesting or important physical traits of boulders. This could be helpful for the final inspection of all boulders and composition of the long-term science products. A starting point is proposed here, and can evolve as we find weird stuff. We can handle multiple designations, separated by a comma - so that a clearly angular boulder that is associated with a weird linear feature would be "BA,BL".

Code	Feature	
BA	Clearly Angular	
BB	Clearly smooth or rounded	
BC	Fractured or cracked - yet coherent (mappers should draw a path along the dominant fracture)	
BD	Fractured and clearly split (Mappers would map the rock with a circle/polygon, and indicate them with this label)	
BL	Associated linear feature - trail - landslide	

ISO 14688-1:2002

Name				Size range (mm)	Size range (approx. in)
Very coarse soil		Large boulder	LBo	>630	>24.8031
		Boulder	Bo	200–630	7.8740–24.803
		Cobble	Co	63–200	2.4803–7.8740
Coarse soil	Gravel	Coarse gravel	CGr	20–63	0.78740–2.4803
		Medium gravel	MGr	6.3–20	0.24803–0.78740
		Fine gravel	FGr	2.0–6.3	0.078740–0.24803
	Sand	Coarse sand	CSa	0.63–2.0	0.024803–0.078740
		Medium sand	MSa	0.2–0.63	0.0078740–0.024803
		Fine sand	FSa	0.063–0.2	0.0024803–0.0078740
Fine soil	Silt	Coarse silt	CSi	0.02–0.063	0.00078740–0.0024803
		Medium silt	MSi	0.0063–0.02	0.00024803–0.00078740
		Fine silt	FSi	0.002–0.0063	0.000078740–0.00024803
	Clay		Cl	≤0.002	≤0.000078740

Caption: This is the international standard for names of grain sizes (see https://en.wikipedia.org/wiki/Grain_size). This is a guide for our preferred nomenclature throughout the mission - TO MAKE SURE WE ARE SPEAKING THE SAME LANGUAGE PEOPLE!

Vocabulary for Particle Size descriptions for observed particles on Bennu's surface.

Size Range	Proposed name	Notes
20cm and larger	Boulder	This size is set because they are all Hazards and larger than the TAG head opening. Things over 2m would be a "Large Boulder".
2cm to 20cm	Cobble	Typical language from the international standard. These objects can frustrate sampling by tilting the TAG head.
0.2cm to 2cm	Granules	Ingestible particles! This upper size range is right around the resolution limits from Recon, so some Granules will be observed.
0.02mm to 2mm	Sand	Can't resolve them, but can infer their presence, and need to differentiate them from mm-cm scale ingestible particles. This is the size scale expected to be collected by the contact pads.
Below 0.02mm	Dust	

More details on the naming system here: See PDF below

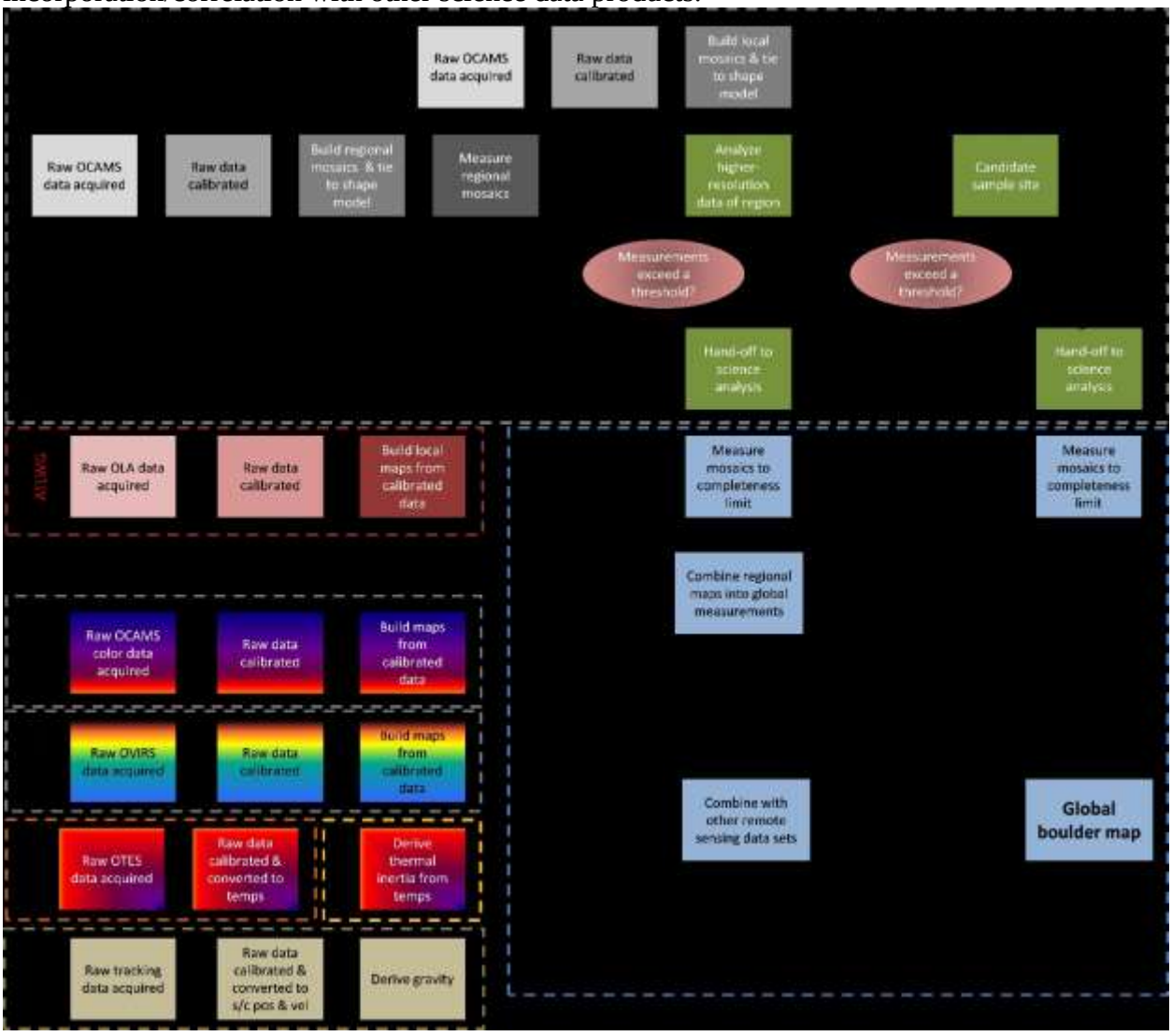
Data Product Validation

Boulder population validation can be done against synthetic surfaces for which the number and sizes of the features are known a priori. We also have validated many of these approaches through peer-review (Mazarouei et al. (2013, in press))

The other remote sensing products have their own validation process before incorporation into the boulder map. Ultimate validation will occur through the generation of peer-reviewed publications.

Data Flow

Figure 2 expands Figure 1 to include further details on the source data used, the distinction between IPWG mission-critical measurements and the science measurements, and incorporation/correlation with other science data products.



Standards used to generate data product

Time (e.g. times are all converted to UTC)

- Either spacecraft time or UTC.

Coordinate System

[Asteroid coordinate system (MRD-125)]

Data Storage Conventions (i.e. byte order, compression, machine dependence)

- Little Endian with either PackBits or LZW compression

ISO 14688-1:2002

Name				Size range (mm)	Size range (approx. in)
Very coarse soil		Large boulder	LBo	>630	>24.8031
		Boulder	Bo	200–630	7.8740–24.803
		Cobble	Co	63–200	2.4803–7.8740
Coarse soil	Gravel	Coarse gravel	CGr	20–63	0.78740–2.4803
		Medium gravel	MGr	6.3–20	0.24803–0.78740
		Fine gravel	FGr	2.0–6.3	0.078740–0.24803
	Sand	Coarse sand	CSa	0.63–2.0	0.024803–0.078740
		Medium sand	MSa	0.2–0.63	0.0078740–0.024803
		Fine sand	FSa	0.063–0.2	0.0024803–0.0078740
Fine soil	Silt	Coarse silt	CSi	0.02–0.063	0.00078740–0.0024803
		Medium silt	MSi	0.0063–0.02	0.00024803–0.00078740
		Fine silt	FSi	0.002–0.0063	0.000078740–0.00024803
	Clay		Cl	≤0.002	≤0.000078740

	A	B	C	D	E	F	G	H	I	
1										
2	**Boulder**	note		**Craters**			**Regolith**			**Lin**
3	BA	Angular		CA	Pristine/Young		RA	Finest Pond		LA
4	BB	Smooth		CB	Nearly Pristine		RB	Size sorting evident		LB
5	BC	Centrally cracked		CC	Less Pristine		RC	Imbircation		LC
6	BD			CD	Degraded/Old		RD			LD
7	BE	Edge crack		CE	Ambiguous		RE			LE
8				CF	Overlapping					
9				CG	On Slope					
10										
11										
12										
13										
14										
15										
16										
17										