August 31, 2014

Report of the Small Bodies Assessment Group Asteroid Redirect Mission Special Action Team

In January 2014, the Asteroid Redirect Mission (ARM) Robotic Concept Integration Team (RCIT) engaged the Small Bodies Assessment Group (SBAG) community by presenting a list of tasks for which input was requested. In response, a SBAG ARM Special Action Team (SAT) was assembled to address the task list items. This report addresses that task list through a combination of written assessments and detailed charts.

Though this report provides input to aid assessments of the ARM robotic mission concepts, previous findings by SBAG that relate to ARM are also still valid. In particular, the findings from the SBAG 11 meeting in July 2014 state:

"The portion of the ARM concept that involves a robotic mission to capture and redirect an asteroid sample to cis-lunar space is not designed as an asteroid science mission and its benefits for advancing the knowledge of asteroids and furthering planetary defense strategies are limited and not compelling.

Limits in the current knowledge and large uncertainties in the properties of near-Earth asteroids contribute significantly to schedule and cost risk, and to the risk of mission failure, of either Option A (redirect an entire small asteroid) or Option B (capture and return a large boulder from a larger asteroid) of the robotic ARM concept. Current surveys, observing programs, and other projects are not positioned to sufficiently bridge this knowledge gap within the allotted schedule."

The SBAG ARM SAT continues to support these and other previous SBAG findings.

The SBAG ARM SAT consisted of:

Nancy Chabot, *Johns Hopkins University Applied Physics Laboratory (SBAG Chair and SAT Science Lead)*
Paul Abell, *NASA Johnson Space Center*
Dan Britt, *University of Central Florida*
John Dankanich, *NASA Marshall Space Flight Center (SAT Resource Utilization Lead)*
Josh Emery, *University of Tennessee*
Andrew Rivkin, *Johns Hopkins University Applied Physics Laboratory*
Dan Scheeres, *University of Colorado (SAT Planetary Defense Lead)*

This report summarizes discussions and findings of the SBAG ARM SAT. The SBAG ARM SAT echoes the statement in the CAPTEM ARM report: of necessity, this is a preliminary report. If such a mission goes forward, we recommend that the prioritization of the science, planetary defense, and resource utilization requirements be refined through a more comprehensive process.

<u>Complete SBAG ARM Special Action Team Task List</u>

We request your technical assessment for the following areas to support assessments of the robotic mission concepts:

- **Science:** What new science, beyond what's already planned for missions in development, could be done robotically at a large (>50 m) asteroid or small (<~10) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid? As part of this assessment, we request your scientific assessment in sample selection and collection. What is the value to the Science community of characterization of a large >50 m NEA that hasn't been visited before? Also what is the value of re-characterization of a previously visited NEA? What is the difference in value between the two options?
- **Planetary Defense:** What realistic impact threat mitigation techniques or strategies and what trajectory deflection demonstrations, if any, make sense to be performed by the asteroid redirect robotic mission?
- **Resource Utilization:** What key resource utilization demonstrations could be done robotically at a large (>50 m) asteroid or small (<~10) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid?

To inform mission formulation, we request your scientific assessment in these areas:

- Assessment of likely physical composition of near-Earth asteroids <10 m mean diameter
- Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids
    - Presence of "free-standing" boulders
    - Friability of boulders for various asteroid types
    - Also, assessment of <10 m boulders on Itokawa
- Current relevant findings based on meteorites collected on Earth
- Provide information/data regarding the range of expected regolith surface properties (surface cohesive, porosity, compaction, etc.) of large NEAs of various types to support analyses for assessing surface contact, interaction during boulder collection, and mechanical push planned for ARRM Option B.
- Two small meteorites (Park Forest and Grimsby) were estimated to be 1.8 meters and 0.13 meters diameter, respectively, that had very low compressive strengths at first breakup (~0.03 MPa). What does this imply about the lower limit on the strength of small NEAs or boulders on larger NEAs?
- What do models of rubble piles say about their range of compressive strengths?
- What does the latest paper on thermal cycling of NEAs (Delbo, M. *et al. Nature* **508,** 233–236 (2014)) say about the expected strengths of 10-m-class NEAs and 1- to 4-m sized boulders on 100-m-class NEAs?
- What remote sensing instrumentation is available that is capable of determining the structural integrity of a boulder? What is the resulting uncertainty?
- What is the effectiveness of C-type and S-type asteroid material for radiation shielding?
- What is the maximum acceptable contamination level of an asteroid or boulder returned to lunar DRO?

TOPIC 1: Science

What new science, beyond what's already planned for missions in development, could be done robotically at a large (>50 m) asteroid or small (<~10 m) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid? As part of this assessment, we request your scientific assessment in sample selection and collection.

Follow-on related request:
What is the value to the Science community of characterization of a large >50 m NEA that hasn't been visited before? Also what is the value of re-characterization of a previously visited NEA? What is the difference in value between the two options?

- **The type of asteroid sampled is of major scientific importance.** The Decadal Survey outlines the top science-driven priorities and emphasizes the importance of the type of asteroid sampled. Primitive asteroids associated with prebiotic materials (water, C, organics) are prioritized for science. Such materials may address important science questions related to the inventory and delivery of such materials to the inner Solar System. Such materials also may not be fully represented in meteorites, due to losses related to passage through Earth's atmosphere, necessitating the need for sample return missions to acquire such materials. A substantial mass of asteroid samples are already available for scientific study by examination of meteorites, and thus the scientific priority is to sample asteroids that have the highest potential to provide new materials not available in meteorite collections. For science, target composition is a much higher priority than target mass returned.

- **Characterizing and returning a sample from an asteroid not already, or planned to be, sampled is of greater science value than characterizing and returning a sample from one that has been.** The asteroid population is numerous and diverse, and meteorite samples further support the widespread diversity present between asteroids. Characterizing and sampling that diversity has scientific value. Only samples collected from Itokawa are currently in our collections, and samples from Bennu and 1999 JU3 are planned. Samples from asteroids other than these three would provide new scientific insights and hence are of greater science value. The value to the science community is greater for characterizing a previously unexplored NEA than re-characterizing one that has been previously visited.

- **Involvement of a science team is critically important to maximize the science, including during the concept development portion of the mission.** The science team should be involved in all aspects of the mission and its development, including target selection, scientific instrument development, the robotic asteroid encounter, and characterization and sampling by the crewed mission. The early application of the best available science insight can reduce complexity, cost, and mission risk. A science team, or science advisory group, should be integrated into current and ongoing ARM development efforts independent of there being any science objectives.

- **Ground-based characterization of the target asteroid is scientifically important.** Along with providing crucially important operational and tactical information that will be used to implement the mission, an extended ground-based observing campaign provides unique scientific context in which to interpret the robotic spacecraft characterization observations and the returned sample.

- **Remote characterization prior to, during, and following sampling provides scientific context.** Remote characterization can cover many aspects, included but not limited to surface morphology, compositional characterization, and physical properties. In particular, diversity characterization may influence subsequent science driven sampling decisions. Remote characterization can be done robotically but may be complicated if the sample is enclosed by the capture mechanism. Input from the science community should be used to define the requirements, needs, and instruments for such robotic characterization. Involvement of an active science team is needed for sample selection decisions based on the robotic characterization of the asteroid. Sample collection should aim to minimize the disturbance to the sample, be recorded and documented to understand aspects that were not preserved, and strive to minimize contamination. Characterizing the surfaces of a larger host body after sampling has science value for evaluating surface properties of the asteroid.

- **The CAPTEM findings on sample selection and collection by the crew during EVA are very good assessments.** We support those findings and haven't duplicated that effort in this report.

- **An asteroid sample return mission offers a range of possible science investigations, both with remote characterization and through study of the returned sample.** Specific investigations depend on the nature of the target asteroid. Many open science questions exist as related to asteroids and the overall NEA population, and remote characterization investigations to any asteroid would cover investigating physical properties, composition, heterogeneity, surface morphology, interior structure, and relating the sample to meteorites. Both options also have the potential to provide additional science. A few examples for each are provided below, but this list is not exhaustive. Due to the diverse nature of the NEO population, sampling a single object will not provide definitive knowledge of all NEOs. The science community should be engaged to define the science mission of any such opportunity.

    - <u>For capturing a small (~<10 m) asteroid:</u> Much is unknown about this numerous population as it is a very difficult population to observe from Earth and has never been visited by spacecraft. What is the nature of such objects? Coherent monoliths or rubble piles? How strong are such objects? How homogenous/heterogeneous, for both composition and physical properties? How does the surface compare to the interior? How long has the object been this size? How does the object reaction to spacecraft operations and collection?

    - <u>For capturing a boulder from a >50 m NEA:</u> What is the nature of the boulder? What is the boulder population and how does it compare to the boulder sampled and to the larger surface geology in general? How strong is the boulder? How homogenous/heterogeneous is the boulder? How does the surface compare to the interior and what does this mean for space weathering? How long has the boulder been this size, at the surface? What are the characteristics of the surface below the boulder and that disturbed by its collection? How does the regolith move in response to the boulder being collected and other spacecraft operations? How does the sampled boulder relate in the larger context of the whole asteroid?

TOPIC 2: Planetary Defense

What realistic impact threat mitigation techniques or strategies and what trajectory deflection demonstrations, if any, make sense to be performed by the asteroid redirect robotic mission?

- **Involvement of the planetary defense community will be vital for optimal leveraging of the ARM mission for planetary defense studies.** Involving the wider community in order to incorporate their expertise will help ensure that any planned demonstrations are correctly scoped for the available resources and allow the most efficient leveraging of independent programs already underway.

- **All deflection technologies, except for the gravity tractor, will likely modify or transform the asteroid or boulder surface to some extent beyond that resulting from just the capture activities, which may seriously compromise scientific investigations**. The choice of a planetary defense demonstration will inevitably have implications for any subsequent science investigation, and the trade space would need to be evaluated in more detail. However, for the remainder of these findings, we treat them as independent. This could be an issue for future interaction or interpretation of the body. however we will not limit our analysis with regard to this except in one instance: We do not discuss nuclear blast approaches.

- **Neither the Option A target nor the block retrieved from the Option B target will be of a size *per se* relevant to planetary defense.** While objects as small as only a few meters in diameter can produce meteorites, and bodies the size of the Chelyabinsk impactor (~15-20 m) can cause damage on the ground, the cost and effort required to deflect such impactors combined with the likely very short warning time and limited damage they cause make them unlikely candidates for any future deflection campaigns. This is reflected in the unofficial Torino Scale, which considers all impactors less than 20 m to register as a 0 on the scale.

- **The Option B target from which the block would be retrieved is likely to be of a size of greater interest to the planetary defense community.** The candidates we are aware of have diameters in the hundreds of meters range, large enough that deflection would be seriously considered if such an object were threatening to impact Earth.

- **Demonstrations of new technologies and deployment tests may be fruitfully conducted with either Option A or Option B, though specifics depend on the particular technology/test.** The smaller size of the Option A target will lead to deflection measurements being completed more quickly than for Option B, however Option B studies may be more directly applicable to truly dangerous objects and may preserve the scientific integrity of samples more easily than Option A studies.

Appendix: Short description and discussion of selected deflection techniques

We have taken a systems engineering approach to our observations, noting that it is not necessary to carry out an end-to-end engineering demonstration of a deflection technology in order to advance the technology level of any particular deflection approach. Rather, in keeping with the spirit of advancing the Technology Readiness Level (TRL) of various methods, we note when some demonstrations short of a measured deflection could be important. With this philosophy, significant testing and development of most relevant deflection technologies can be carried out for either option. In the following, for each deflection technology we note what aspects of them could be tested for either option, if any. In all cases, if it is desired to measure a deflection, it is required that the spacecraft be tracked relative to the asteroid prior to the attempt and then after the attempt for a suitably long enough period of time to provide a statistically significant detection. These time periods can vary widely as a function of the asteroid physical properties and the deflection method. Their detailed discussion is beyond the scope of this report.

Kinetic Impactor: This option uses a second spacecraft to impact the asteroid to transfer momentum to the body. The method relies on a beta factor greater than 1 to enhance the effectiveness of the approach.

We view it as risky to apply this approach to Option A as it could severely affect the target asteroid due to its small size. For Option B we view this as a feasible approach, assuming that the boulder has first been taken from the surface, as the approach could compromise or alter key areas of the asteroid where boulder sampling is viable. For a large enough impactor, it may be feasible to estimate the degree of deflection. Carrying out a test without deflection detection could serve as a demonstration of the targeting technology and for providing an assessment of how an asteroid surface responds physically to an impact. In particular, estimates of beta can be developed based on observations of the ejecta, independent of a direct measurement of deflection.

Gravity Tractor: This option places a spacecraft or massive object in close proximity to the asteroid in order to generate a net attraction between the bodies. If the spacecraft is then maneuvered in such a way that it does not place propellant on the asteroid, the center of mass of the system can be deflected.

This demonstration is viable for either Option A or B. For Option B, the spacecraft should use the retrieved boulder plus spacecraft as the massive object for the test. Though the physics of the interaction is well understood, demonstrating the hovering and proximity control technology would provide advances. Deflection detection may be feasible in both cases.

Ion Tractor: This option places a spacecraft with a “dual” ion propulsion system that can simultaneously thrust in opposing directions in close proximity to the asteroid. Once dual thrusting begins, the spacecraft places the asteroid in the field of one of the ion plumes, which transfers momentum to the asteroid.

This option is viable for either Option A or B. Deflection detection may be feasible in both cases, although the scaling is favorable to Option A. As the interaction of an asteroid surface with an ion beam is not fully understood, non-detection deflection experiments could still be of interest to better understand how the incident ion beams will react with the asteroid surface, if such measurements can be made.

Induced Surface Outgassing: This option heats a small region of the asteroid to high enough temperatures to induce vaporization, providing an outgassing jet on the asteroid surface, which can deflect the asteroid. Most methods either use a laser or refocused solar light to generate the surface heat.

This demonstration is viable for either Option A or B. It is unclear whether the detection of a deflection is possible, although Option A would be more favorable than Option B for this. Non-detection deflection experiments would be useful to understand the thermodynamics of vaporization in the asteroid environment and to quantify the degree to which the asteroid environment becomes filled with products from these reactions. It may create a hazardous environment for the spacecraft due to an enhanced number of particulates in the close proximity environment.

Surface Albedo Modification: This option deploys an albedo-modifying material across an asteroid to control or shut-off the Yarkovsky effect for a given body.

This demonstration is viable for either Option A or B, thought it is unclear whether either of these could yield a detection due to the possibly weak effect of this method. Non-detection deflection experiments would be of use to understand the mechanics of material deployment to the asteroid surface and its subsequent evolution due to charging effects. It may create a hazardous environment for the spacecraft due to an enhanced number of particulates in the close proximity environment.

TOPIC 3: Resource Utilization

What key resource utilization demonstrations could be done robotically at a large (>50 m) asteroid or small (<~10) asteroid? Or with crew at a captured and returned boulder from a large asteroid or at an entire small asteroid?

Motivation: NASA roadmaps and technology prioritization plans consistently include the utilization and technology development for the generation of resources found in-situ. ARM is intending to send a vehicle to a near Earth asteroid. The ARM vehicle plans to include significant power capability and potential excess mass capability. At the mission's conclusion, the mission intends to provide a small asteroid or a boulder from a larger asteroid in cis-lunar space for future crew operations. While not an exhaustive list, general findings are noted below as related to the task statement at the top of this page that was provided to the SBAG ARM SAT.

Available Resources: The solar system provides a wealth of resources for future exploitation. Carbonaceous, C-Type, asteroids have the greatest variety of resources available for extraction. Some C-type asteroids include water, primarily as hydrated minerals, metal oxides for both metal and oxygen extraction, and metals. Primitive S-Type asteroids also offer metal oxides in addition to metals. Finally Metal, associated with M-Type, asteroids offer potential for platinum group metals and also elemental metals such as iron and nickel. The desire for volatiles would prioritize a C-Type asteroid as the highest valued target, though the volatile content and other potential resource materials of C-type bodies may vary considerably, as supported by the range of abundances measured in carbonaceous chondrite meteorites.

Resource Extraction Methods: Both the resources available and the methods of resource extraction are dependent on the detailed composition of the source, which may be poorly known until the return of the ARM target. Many of the simplest methods of resource extraction are to heat the surface, subsurface, or bulk collected sample to sublimate or mobilize the constituent volatiles for separate collection. NASA has proposed methods of both solar concentrators and microwave systems for heating. Assuming successful asteroid return, the ARM spacecraft's available power could possibly be used to support microwave processing of the asteroid material. NASA has also performed experiments using ionic liquids combined with electrolysis using meteoritic material for water extraction, metal extraction, and water electrolysis for hydrogen and oxygen generation. Ionic liquid demonstrations are well suited for small-scale demonstrations. However, industrial scale extraction methods are typically higher in complexity including beneficiation, acid leach and fluorination, molten oxide electrolysis, and carbothermal regolith reduction. Industrial scale extraction methods may be challenging for autonomous operations in the near or mid-term and may create hazardous conditions during initial crew activities in an unknown environment. Table 1 is a preliminary subset of potential extraction methods for demonstration based on the desired resources and asteroid type. Several resource extraction experiments and demonstrations have been successfully performed in the lab for water and volatiles in simulated lunar and martian environments. Experiments have been proposed, but never accepted and completed, using the International Space Station (ISS) for microgravity demonstration of resource extraction. It is assumed that the highest priority resources for extraction are water and oxygen. Regardless of the highest priority resource, based on the desired extraction method to demonstrate, a C-type target should allow for the testing of the most extraction methods. Extraction demonstrations, even of small-scale methods, in a relevant environment, are useful to the ISRU community and would fill a current gap in ISRU technology development. However, methods tested on one target may not to be extensible to a general ISRU capability, given the diversity of the NEO physical and compositional characteristics, even within the same taxonomic class. It is also noted that currently there is little agency coordination to focus asteroid ISRU technology development. Worthwhile ISRU demonstrations should be conducted with present day capabilities, using a range of meteorite samples and simulants on the ISS.

Table 1: Potential extraction methods for demonstration based on desired resources and asteroid type.

Type of Asteroid	Possible Available Resources	Methods to Extract Resources
C-Type (Carbonaceous)	Volatiles (simple compounds of hydrogen, oxygen, carbon, sulfur and nitrogen) Rarely nitrogen, halogens and noble gases.	Heating: Microwave or Solar Thermal processes
	Water – primarily as hydrated minerals	A. Heating: Microwave or Solar Thermal processes B. Ionic Liquid Acid dissolution, C. H_2SO4 or HF dissolution
	Metal Oxides (for oxygen)	A. Ionic Liquid Acid dissolution B. H_2SO4 or HF dissolution C. Hydrogen Reduction D. Carbothermal Reduction E. Molten Oxide Electrolysis
	Metal Oxides (for metal)	A. Molten Oxide Electrolysis B. Ionic Liquid dissolution followed by electrolysis
	Elemental Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
S-Type (Silicaceous)	Platinum Group Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
	Metal Oxides (oxygen and metals)	A. Molten Oxide Electrolysis B. Ionic Liquid dissolution followed by electrolysis
M-Type (Metals)	Elemental Metals (Primarily Iron and Nickel)	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis
	Platinum Group Metals	A. Heating: Microwave or Solar Thermal processes B. Molten Oxide Electrolysis C. Ionic Liquid dissolution followed by electrolysis

Small versus Large Target: If all a priori knowledge is equal, ISRU demonstrations are possible for either Option A or Option B. However, compositional characterization of the target can be critical depending on the extraction method to be tested, as will knowledge of the physical surface or regolith properties. The physical properties may impact the complexity of the material collection and processing. The capture mechanism and containment of the sample may complicate acquiring knowledge of the surface properties if the sample is fully enclosed, such as if the target is weak and disturbed during the capture process. Given the diverse nature of the NEO population, demonstrations on a single object will not provide insight into the properties for all NEOs. Realizing future ISRU capabilities on an industrial scale is likely to require a number of targets of sizes larger than the asteroid sample returned by ARM, and the mechanical properties of small asteroids and boulders may not be informative of the range of mechanical properties on the surface and subsurface of larger asteroids.

Robotic versus Crewed Demonstration Advantages: A number of laboratory environment experiments with intensive human in the loop operations have validated the efficacy of small ISRU demonstrations for extraction of resources from meteoritic material. There has been minimal autonomy developed into ISRU demonstrations applicable to asteroid resource utilization. Ultimately, future ISRU can be practical only if it is robotic and automated. However, due to the limited existing autonomous systems and the current lack of maturity, it may be difficult to deliver a well-tested autonomous ISRU demonstration given the baseline ARM schedule. Small-scale ISRU demonstrations are viable for either Option A or Option B and may use crew participation for sample selection, coring or raking, and transferring into the ISRU extraction system.

Summary Findings: An initial assessment of the asteroid resource utilization demonstration potential for either the ARM spacecraft or crewed mission to the asteroid yield these summary findings:

- For resource utilization priorities, target composition is more important than target mass. A volatile-rich C-type target provides the greatest diversity for extraction method demonstrations.
- Detailed knowledge of the asteroid composition and surface and subsurface mechanical properties are critical to developing a resource extraction demonstration.
- Given the diverse NEO population, demonstrations on a single target do not provide insight into ISRU demonstrations on all NEOs. The mechanical properties of the returned ARM target may not be applicable to larger asteroids that are of future ISRU interest.
- Small-scale demonstrations in a relevant environment are viable for both Option A and Option B and would be useful to the community. However, techniques for small-scale resource extraction demonstrations are likely not optimized and are potentially dissimilar from full-scale industrial operational techniques. Focused investments are required to delivery an autonomous asteroid ISRU demonstration; there are no existing turn-key autonomous experiments readily available. It is unclear if an autonomous demonstration system can be matured for flight with appropriate testing and meet the baseline ARM launch date without immediate and modest investment.
- Worthwhile ISRU demonstrations could be conducted with present day capabilities, such as using a range of meteorite samples and simulants on the ISS. Such ISRU investments could complement and inform any ISRU demonstration on the ARM target.
- The ARM concept, with its advantageous power, may provide an opportunity to jumpstart or focus asteroid ISRU investments.

Task: Assessment of likely physical composition of near-Earth asteroids <10m mean diameter

SBAG ARM SAT provided inputs based on:

- Observations – surveys suggest "dark"/"bright" ratio of ~0.5 to ~1.6
- The meteorite population – meteorite falls are 80% "bright" ordinary chondrites
- 2008 TC3 – a 3-6 m F-class object, tumbling rubble pile, 98 sec rotation period, exploded in the upper atmosphere, collected as meteorites, which show high level of mineralogical heterogeneity
- Other meteorite showers – can show less heterogeneity in the recovered meteorites
- Rotation periods and strength models – rubble pile asteroids, though weak, still rotate; spinning monoliths may retain grains on the surface

Overall, meteorites, observations, and models show a diversity of potential properties for NEAs <10 m in diameter. Direct data are limited for objects of this size.

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Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from observations

- Visible-wavelength surveys are biased against low-albedo objects, creating the need to account for the biases in the statistics
- Debiased surveys suggest a "dark to bright ratio" of 1.6 *in all of the NEO population* (Stuart & Binzel, 2004), based on targets ≥~1 km
  - 10% C complex – "dark", ~4-10% albedo (e.g. Bennu, 1999 JU3), inferred link to CC meteorites
  - 36% S+Q complexes – "bright", ~20-40% albedo (e.g. Eros, Itokawa), direct link to OC meteorites
  - 33% X complex – can include both iron meteorite and CC-link bodies and others
    - Stuart & Binzel assumed all X complex as "dark" but acknowledged it could have a significant "bright" fraction, which would change the ratio
  - Dark cometary (D-type) spectra ~18% of NEO, concentrated in less-accessible orbits
- IR surveys less sensitive to bias against low-albedo objects
- NEOWISE IR-survey *for low delta-v objects* (Mainzer et al., 2011): ~0.5 "dark to bright" ratio in most accessible objects

Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from the meteorite population

- Meteorite *falls* (material collected shortly after impact) give information about 0.1-10 m scale objects in NEO population
  - 80% ordinary chondrite (OC) – never melted, mostly silicate minerals, high strength
  - 4% carbonaceous chondrites (CC) – never melted
    - some CC have 10-20% water, 5% organic materials, low strength
    - other CC are similar to OC in the silicate minerals and high strength
  - 8% achondrites (5% HED), 6% iron, 1% stony-iron – experienced melting, less primitive
- Notable meteorite falls with parent body diameter estimates:
  - Tagish Lake, Carancas, Peekskill, 2008 TC3: ~3-6 m
  - Gold Basin: ~6-8 m
  - Chelyabinsk: ~17-20 m
- The meteorite population may be biased by:
  - Weaker material being screened out
  - Meteorites are not constrained to be on low delta-v orbits

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Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from the meteorite population

Selected Large Meteorites

Meteorite	Date	Mass (Kg)	Fragments
Campo del Cielo (IAB Iron)	Find	100,000	~30
Sikhote-Alin (IIAB Iron)	Feb. 12, 1947	70,000	~9,000
Hoba (IVB Iron)	Find	60,000	1
Cape York (IIIAB Iron)	Find	58,000	8
Willamette (IIIAn Iron)	Find	14,500	1
Pultusk (H5)	Jan. 30, 1868	8,863	~70,000
Allende (CV3)	Feb. 8, 1969	5,000	~1,000
Jilin City (H5)	Mar. 8, 1976	4,000	100
Tsarev (L5)	Dec. 6, 1922	1,132	~40
Knyahinya (L5)	June 9, 1866	500	~1000
Mocs (L6)	Feb. 3, 1882	300	~3000
Homestead (L5)	Feb. 12, 1875	230	
Holbrook (L/LL6)	July 19, 1912	218	~14,000
Forest City (H5)	May 2, 1890	122	~2,000

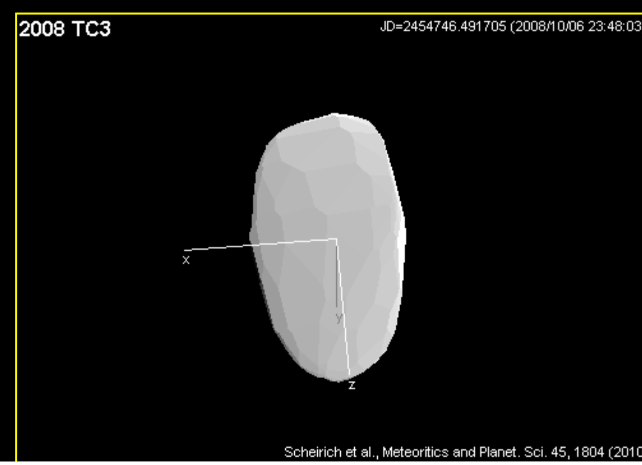
From: Cat. of Meteorites, 5th Ed

Note that some masses and number of fragments are estimates

Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from 2008 TC3

- ~3-6 m diameter body discovered 20 hours prior to impact
  - Rotation period of 98 sec
  - F-class (C-complex, “dark”) spectral classification
- Impacted over Sudan on Oct. 7, 2008; recovered as Almahata Sitta meteorites
  - Centimeter-size fragments recovered
  - Mostly ureilite meteorite type – a primitive achondrite
  - Also 20-30% other meteorite types (Jenniskens et al., 2011)
  - Despite “dark” spectral type, poor in water/OH (but organics present)
- Small tumbling rubble pile at the top of the atmosphere
  - Exploded in upper atmosphere
  - Macroporosity ~20-50% (Kohout et al., 2011)
  - Non-principal axis rotator

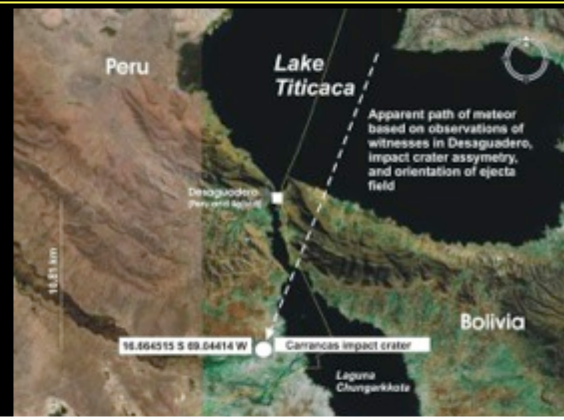


Scheirich et al., Meteoritics and Planet. Sci. 45, 1804 (2010)

Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from other meteorite showers

- **Carancas, Peru (Near Lake Titicaca), 3800 m (12,500 ft.) elevation.**
- **Fall: 15 September 2007, ~16:45 UT**
- **Crater 4.5 m (15 ft) deep, 13 m (43 ft) wide**
- **Meteorite was ~ 3 m in diameter before breaking up**
- **H 4-5 ordinary chondrite breccia**
- **Residents complained of illness from the impact-produced vapors**
  - Turns out that the local ground water is rich in arsenic (and close to the surface).
  - The illnesses were probably caused by inhaling the steam from arsenic-contaminated water generated by the heat of the impact.



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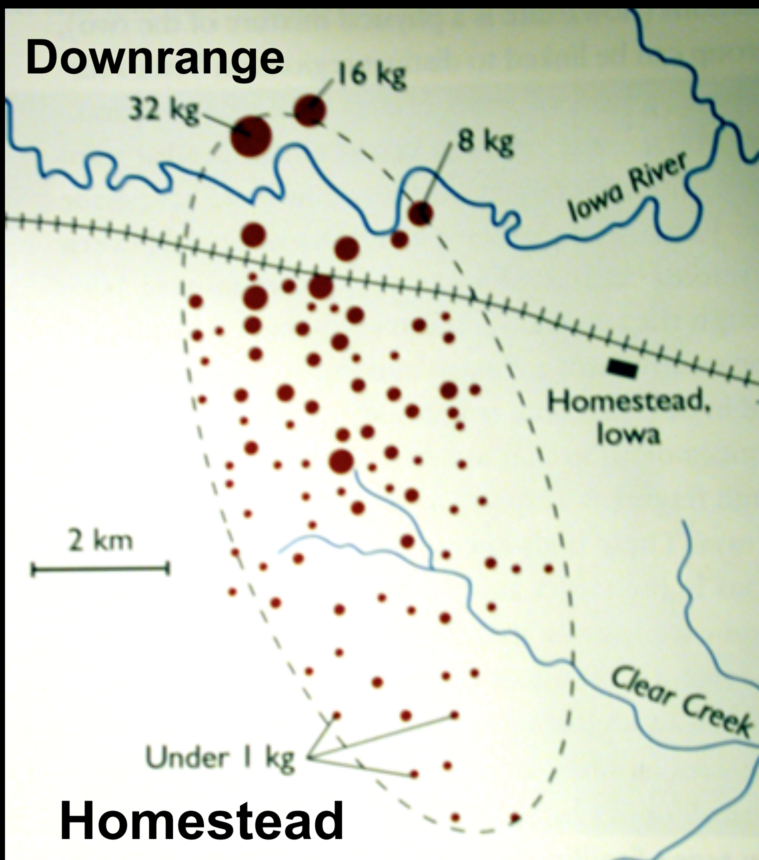
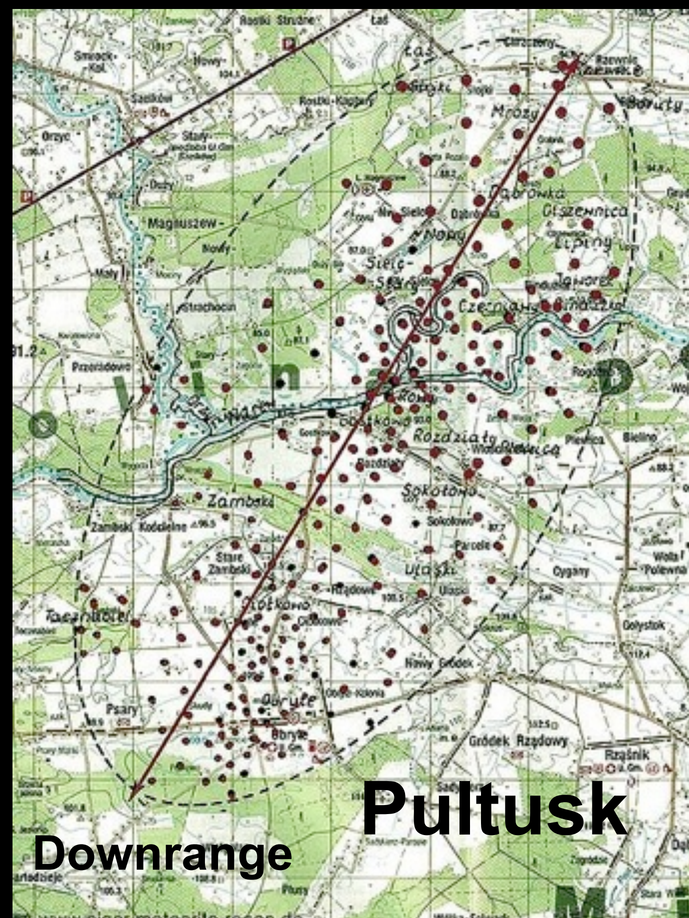
Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from other meteorite showers

- **Strewnfields are produced by breakup, atmospheric drag, and winds**
- **Larger pieces fall downrange**





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Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from rotation periods and strength models

Object Name	Diameter	H	Period (m)
2001 WJ4	0.01	27.4	54.2
2003 WT153	0.007	28	7.02
2005 UW5	0.009	27.5	14.44
2006 DD1	0.015	26.5	2.74
2006 MV1	0.013	26.8	5.71
2006 RH120	0.003	29.9	2.750
2008 JL24	0.004	29.6	3.23117
2008 TC3	0.004	30.9	1.6165
2009 FH	0.01	26.6	6.438
2009 KW2	0.014	26.6	3.412
2009 UD 2009	0.01	27.2	1.3948
2009 WV51	0.011	27.1	4.60
2010 AL30	0.011	27.2	8.796
2010 JL88	0.013	26.8	0.4098
2010 TD54	0.005	28.7	1.376
2010 WA 2010	0.003	30	0.5148
2011 MD 2011	0.007	28	11.62
2012 BX34	0.009	27.6	**108.50**
2012 KP24	0.02	26.61	2.500
2012 KT42	0.006	28.79	3.634
2012 TC4	0.014	26.7	12.23

Asteroids with H>26.5 & good quality lightcurves

Assuming albedo 0.17

- Average size: 9 m
- Median size: 11 m

- Average period: 12 min (dominated by 1 object)
- Median period: 3.6 min

- Mean amplitude: 0.69
- Axial ratio ~ 1.38:1
- ~6.4x9x9 m to ~7.2x7.2x10 m

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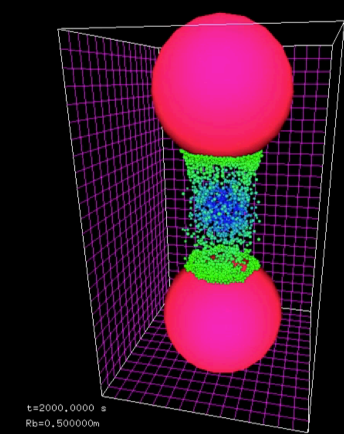
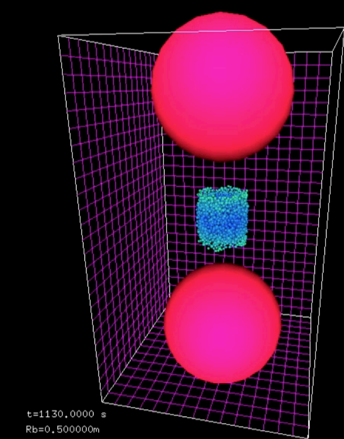
Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from rotation periods and strength models

- A rubble pile has a size distribution of boulders and grains, from ~microns to decameters
  - Small regolith “dominates” in surface area but not volume, implying that larger boulders and grains are coated in a matrix of finer grains
- Implications of cohesion for small body strength and surfaces
  - Rubble pile asteroids can be strengthened by cohesive forces between their smallest grains
  - Cohesive strength less than found in the upper lunar regolith can allow ~10 m rubble piles to spin with periods less than a few minutes
  - “Monolithic boulders” ~10 m and spinning with periods much faster than ~1 minute can retain ***millimeter to micron*** grains on their surfaces



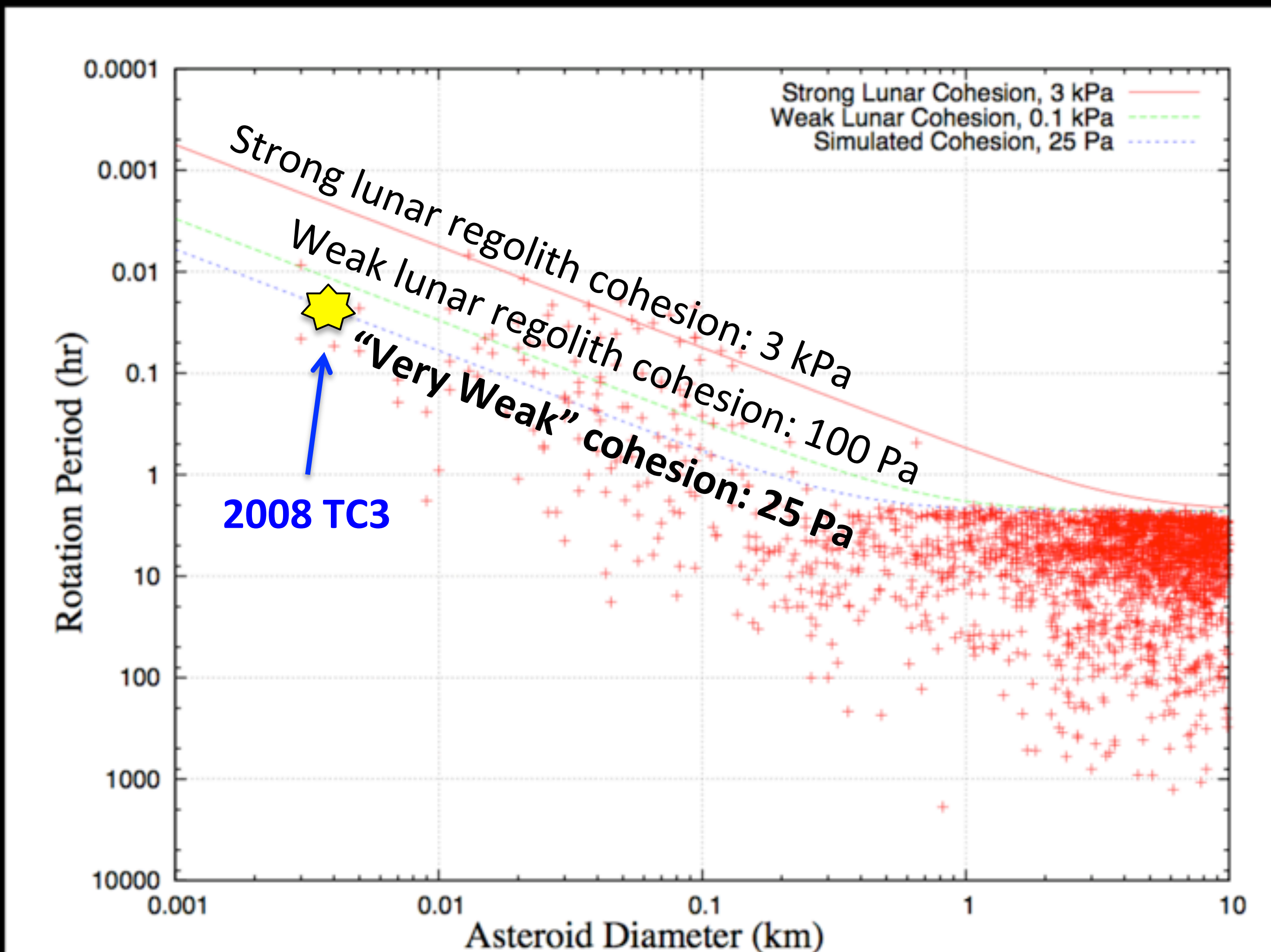
Cohesive Regolith



Cohesionless Regolith

Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from rotation periods and strength models



Rubble pile asteroids with "very weak" cohesion can be fast spinners. 2008 TC3 is an example of such an object.

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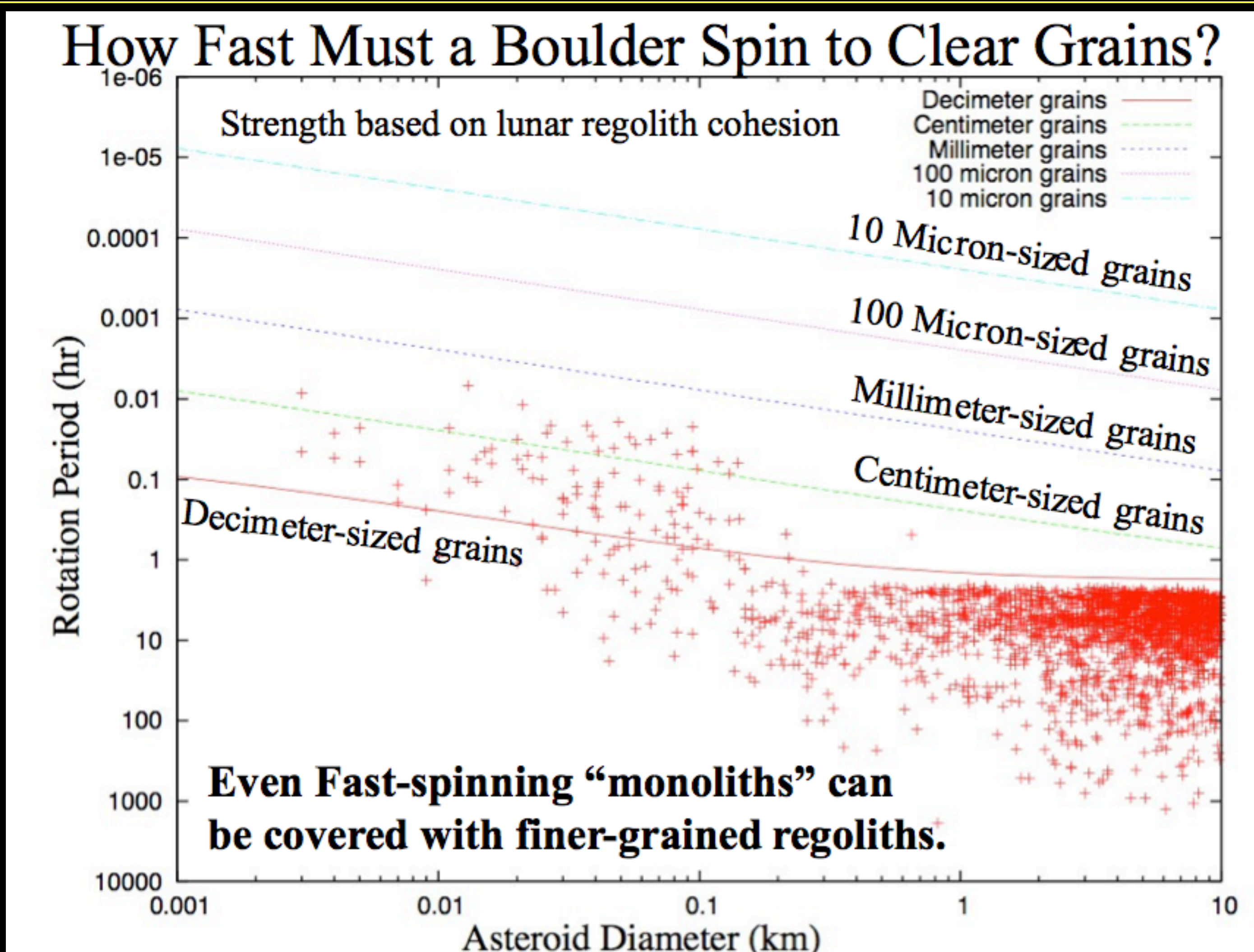
Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

Summary from rotation periods and strength models



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Task: Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

SBAG ARM SAT provided inputs based on:

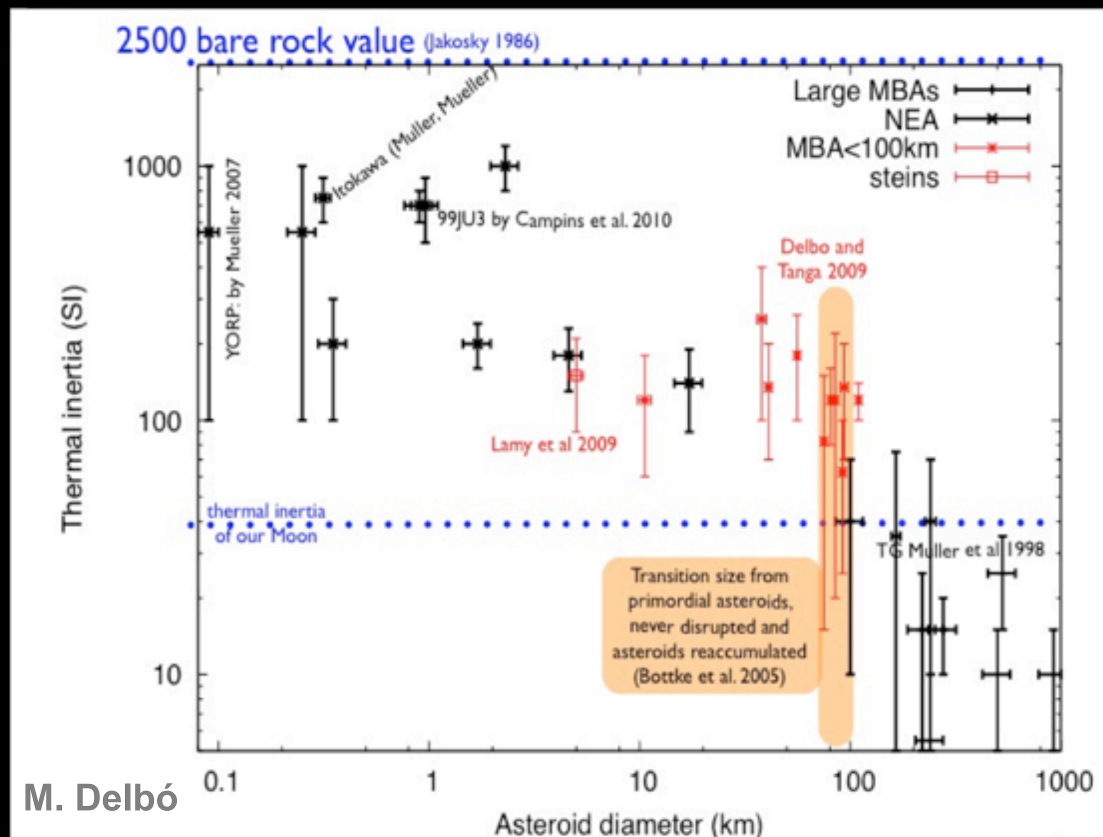
- Thermal inertia – NEOs are not bare rock and have regoliths likely coarser than the Moon, consistent with abundant boulders
- Radar – Ground-based radar, when viewing is optimal, has imaged some boulders at ≥4 m/pixel
- Spacecraft imagery – Numerous boulders are seen in images (including of the “dark” martian moons); size frequency distribution measured down to <1 m on regions of Itokawa. Highest-resolution of Eros interpreted as boulders partially buried, of Itokawa as free-standing boulders, though images do not provide direct knowledge of the subsurface

Overall, boulders are thought to be generated by impact processes and appear to be common on near-Earth asteroids. Direct data are lacking for the presence of boulders on objects <350 m.

Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

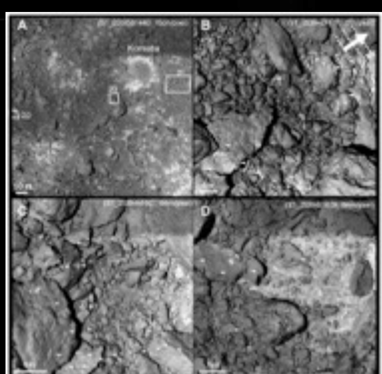
Summary from thermal inertia

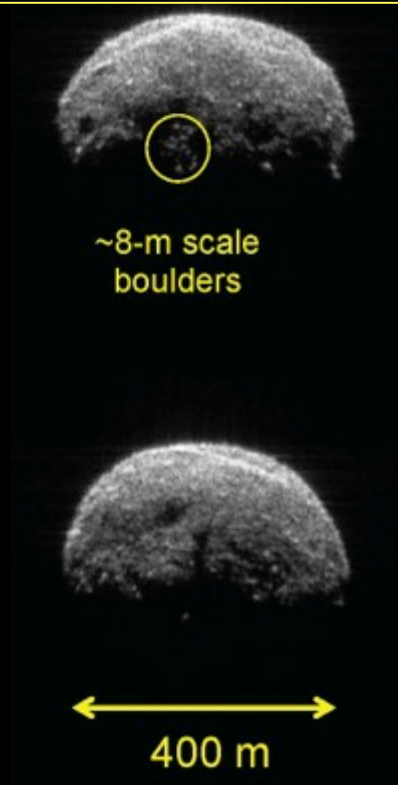
- Thermal Inertias of NEOs range from ~100 to ~1000 J $m^{-2}K^{-1}s^{-1/2}$
  - Moon: ~50
  - Large main belt asteroids: 10-40
  - Bare rock: 2500
- Implications for regolith grain sizes
  - NEO regoliths likely all coarser than the Moon's
  - Lower end likely "pebble" size (~mm)
  - Upper end have abundant boulders (> 0.5 m)



Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from thermal inertia





<u>Itokawa</u>: TI~750
(Müller et al. 2005)

Boulder-rich, with finer-grained regions

<u>YU55</u>: TI~600
(Müller et al. 2013)

Many 8-m scale boulders

<u>Bennu</u>: TI~310
(Emery et al. 2014)

At most one 8-m scale boulder
(Nolan et al. 2013)

<u>Eros</u>: TI~150
(Müller et al. 2007)

Fine regolith with boulders

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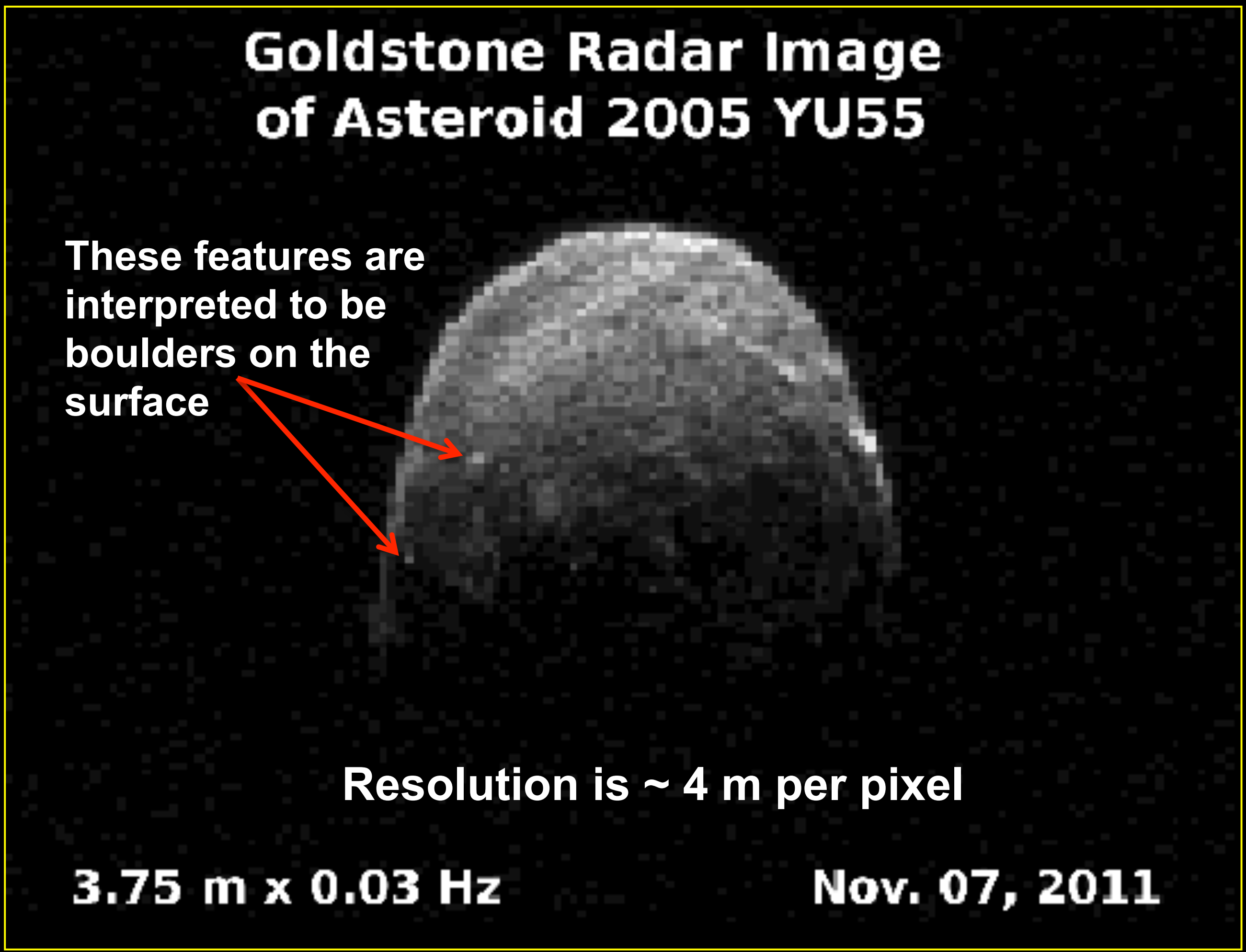
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from radar



- Ground-based radar can image features to ~4 m/ pixel
- The near-Earth asteroid has to be in a good viewing geometry, including relatively close, for radar imaging of small scale features such as boulders

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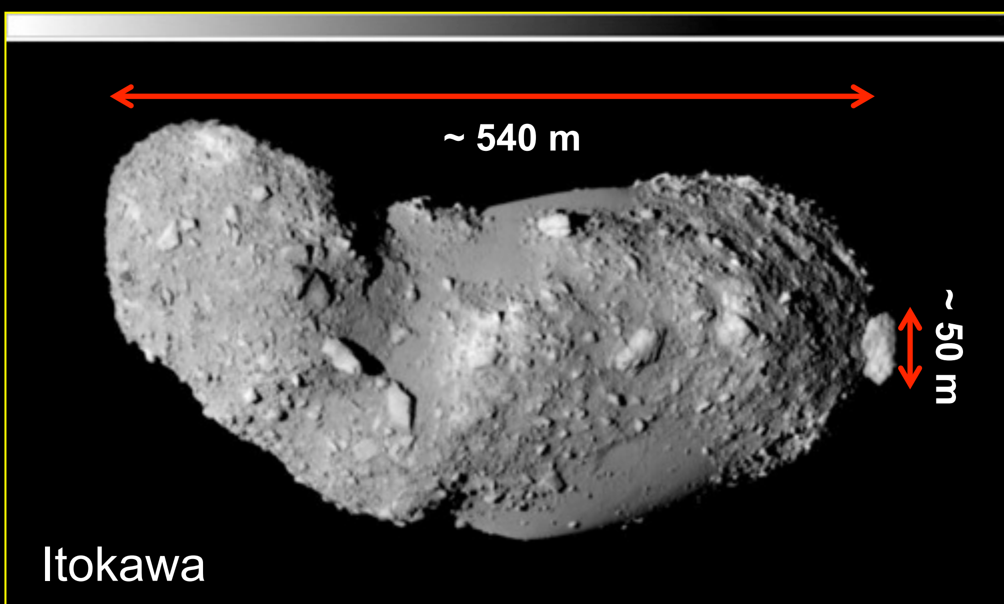
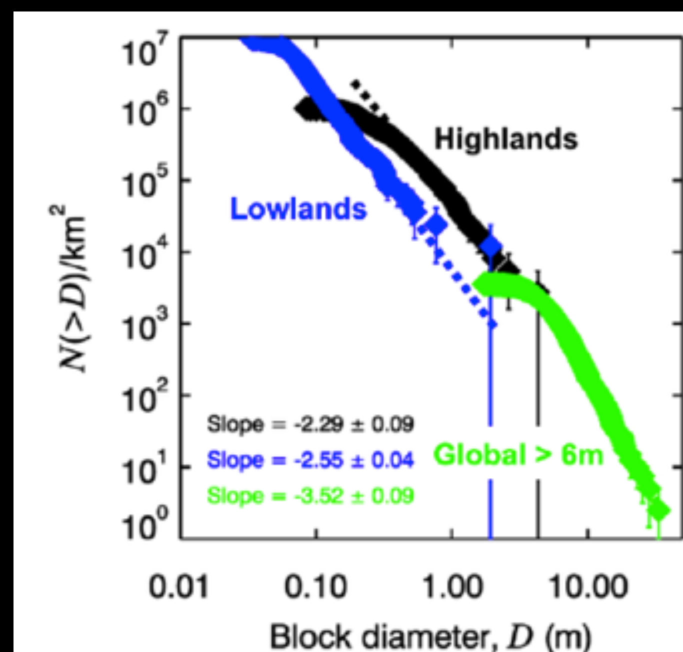
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from spacecraft imagery

- All spacecraft encounters of near-Earth asteroids with sufficient imaging resolution have shown the presence of boulders
- The size-frequency distribution of boulders on Itokawa follows a power law behavior
  - ~1-2 boulders >6 m per 1000 m^2 (Mazrouei et al., 2014) (Itokawa = ~400,000 m^2)
  - Many more blocks <6 m, but mapping completed for local regions only





Noviello et al. (2014)

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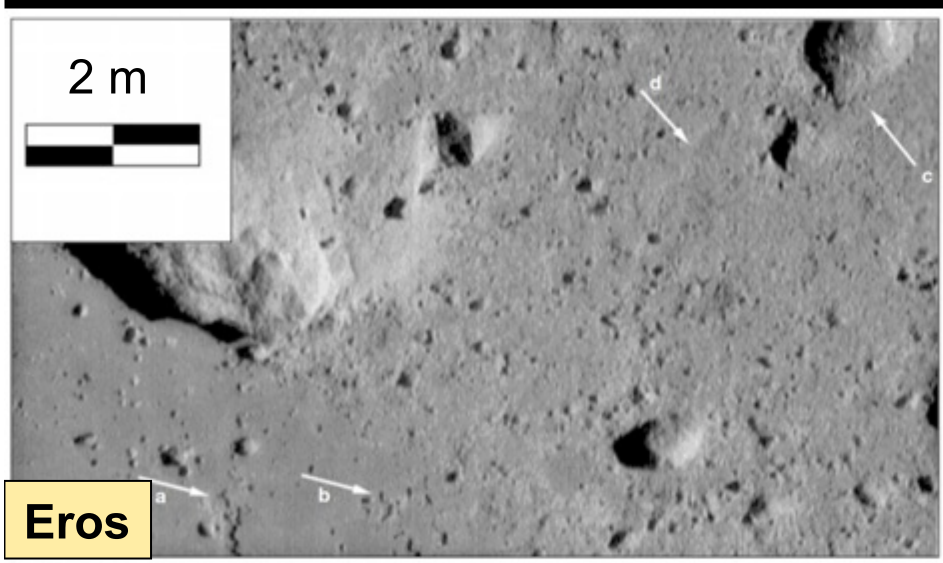
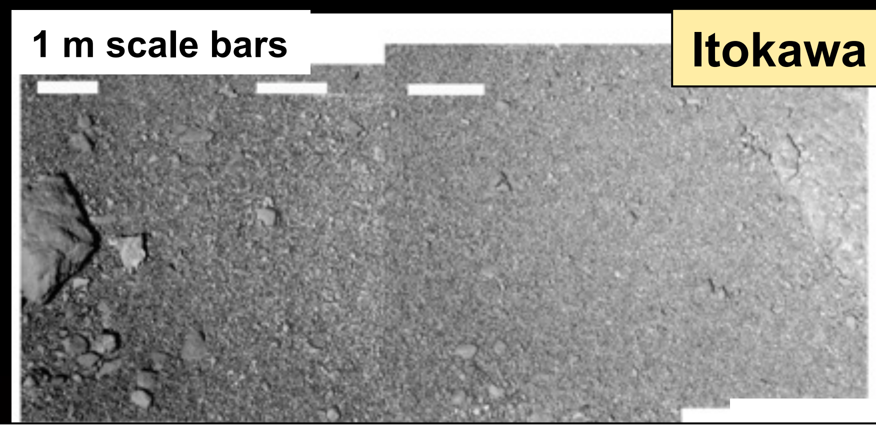
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from spacecraft imagery

- NEAR-Shoemaker obtained images of Eros (34x11x11 km) to 1.2 cm/pixel in 2001
- Many blocks of a range of sizes
- Interpreted "all of the larger ejecta blocks in this region are partially buried" (Veverka et al., 2001)

- Hayabusa obtained overlapping images of Itokawa (540x295x210 m) to 6 mm/pixel in 2005
- Many blocks of a range of sizes
- Interpreted "boulders sitting on top of fines in gravitationally stable orientations" (Miyamoto et al., 2007)





Stereo analysis enabled by overlapping images

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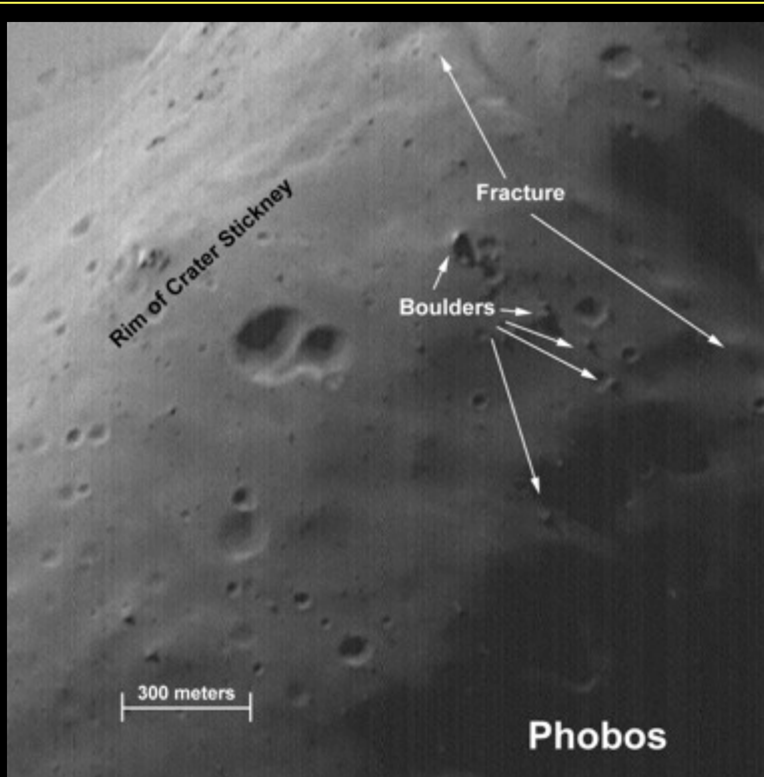
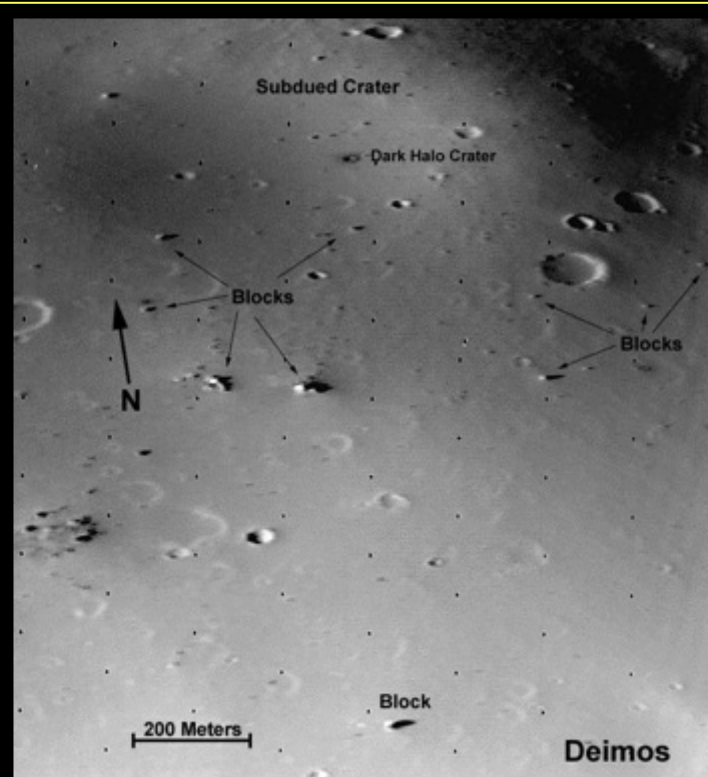
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from spacecraft imagery





- The martian moons, Phobos and Deimos, are "dark", in contrast to "bright" Itokawa
- Boulders on Phobos give cumulative slopes consistent with distribution on Eros (Thomas et al., 2000; 2001)
- Best resolution images of Phobos and Deimos: ~1.5 m/pixel, resolves blocks ~3-4 m

Task: Current relevant findings based on meteorites collected on Earth

SBAG ARM SAT provided inputs based on:

- Meteorite compressive strength – coherent ordinary chondrites have high compressive strengths, while some (but not all) carbonaceous chondrites are weaker. Meteorites are pervasively fractured down to cm scale.
- Bolide strength – the large majority of bolides are weak and break-up high in the atmosphere, including ordinary chondrites
- Porosity – meteorites and asteroids exhibit a wide range of porosities
- Altered chondrites – have darker albedos but similar chemistry as unaltered ordinary chondrites

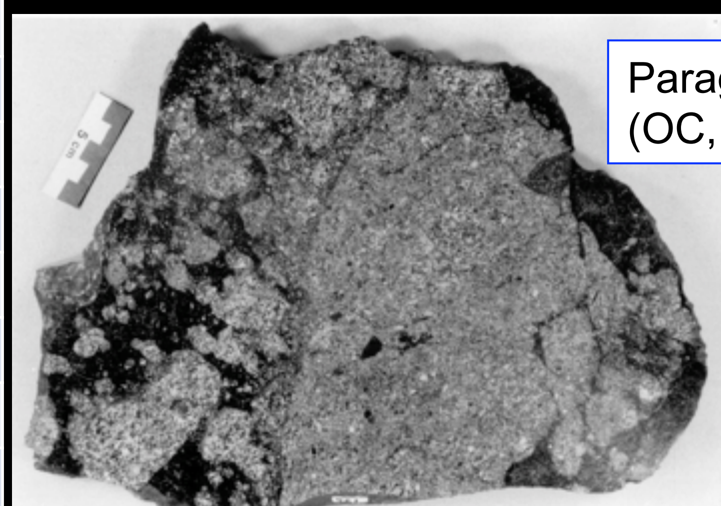
Overall, coherent meteorites can have a range of strengths but the most common are quite strong. Bolides are observed to be significantly weaker, consistent with being rubble piles, pervasively fractured, and/or having high porosities. Such observations have relevance to both NEAs <10 m and small boulders on NEAs.

Current relevant findings based on meteorites collected on Earth

Summary from meteorite compressive strength

Material	Meteorite Type	Compressive Strength (MPa)
Concrete (Unreinforced)	Typical Sidewalk	20 (3000 psi)
Quartz	Single Crystal	1100
Granite		100–140
Medium dirt clod		0.2-0.4
Holbrook, AZ (porosity 11%)	OC (L6)	6.2
La Lande, NM	OC (L5)	373.4
Tsarev	OC (L5)	160-420
Covert (porosity 13%)	OC (H5)	75.3
Krymka	OC (LL3)	160
Seminole	OC (H4)	173
Tagish Lake	CC (C2)	0.25-1.2
Murchison	CC (CM)	~50
Bolides	?	0.1-1

- Most OC meteorites are very tough when coherent
- Volatile-rich CC meteorites tend to be much weaker
- However, volatile-poor CC can be as strong as OC
- Meteorites are pervasively fractured down to cm scale



Paragould (OC, LL5)

Current relevant findings based on meteorites collected on Earth

Summary from bolide strength

- Coherent meteorites may be strong, but many bolides are very weak and break up high in the atmosphere, consistent with being rubble piles

Meteorite	Comp. Strength range of Met. Type (MPa)	Initial Mass (Metric Tons) / Diameter (Meters)	Compressive Strength at First Breakup (MPa)	Max. Compressive Strength (Mpa)
Pribram (OC - H5)	77-247	1.3 / 0.9	0.9	
Lost City (OC - H5)	77-247	0.16 / 0.45	0.7	2.8
Innisfree (OC - L5)	20-450	0.04 / 0.28	0.1	3
Tagish Lake (CC - C2)	0.25-1.2	65 / 4.2	0.3	2.2
Moravka (OC - H5-6)	77-327	1.5 / 0.93	<0.9	5
Neuschwanstein (EL6)		0.3 / 0.55	3.6	9.6
Park Forest (OC - L5)	20-450	10 / 1.8	0.03	7
Villalbeto de la Pena (OC- L6)	63-98	0.6 / 0.7		5.1
Bunburra Rockhole (Ach)		0.022 / 0.24	0.1	0.9
Almahata Sitta (Ure, OC)		70 / 4	0.2-0.3	1
Jesenice (OC - L6)	63-98	0.17 / 0.45	0.3	3.9
Grimsby (OC - H4-6)	77-327	0.03 / 0.13	0.03	3.6

Note that all data are estimates that are inferred from observations of the bolide, breakup altitude, and the pattern of the breakup. Popova et al., 2011

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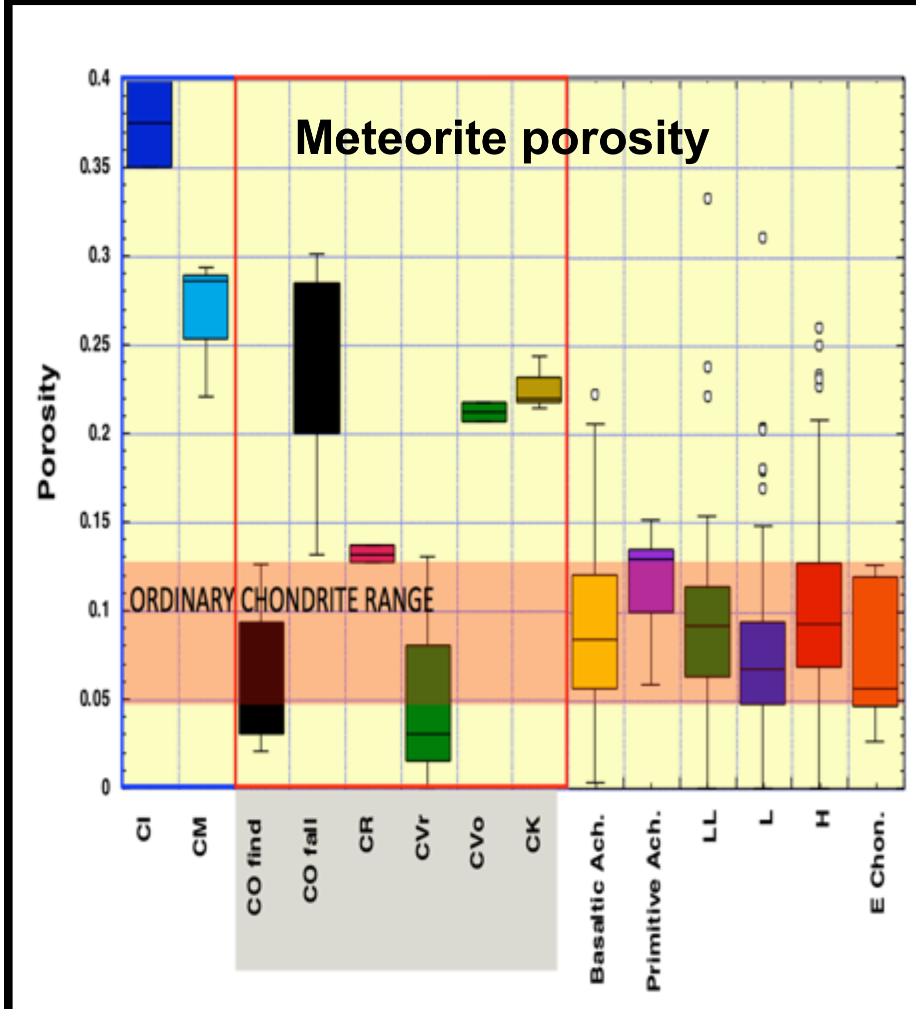
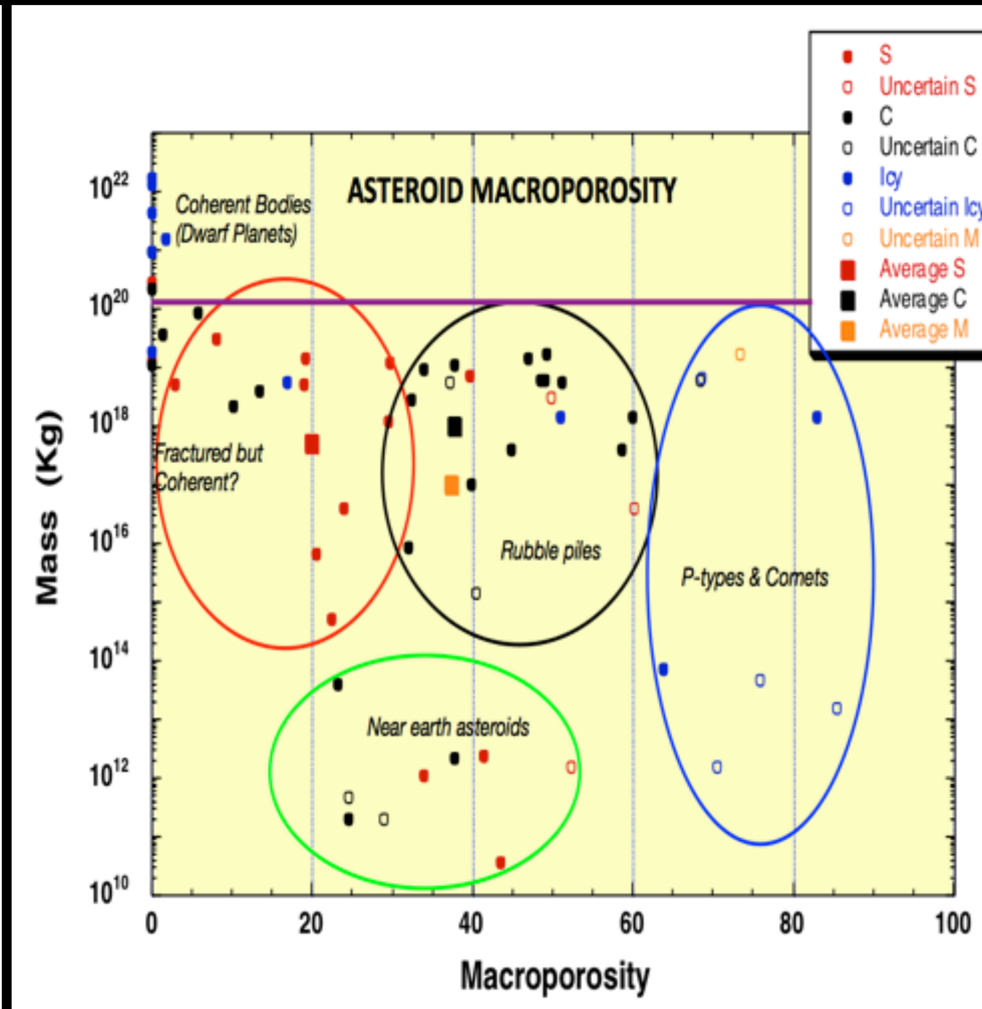
Current relevant findings based on meteorites collected on Earth

Summary from porosity

- Meteorites and asteroids exhibit a wide range of porosities

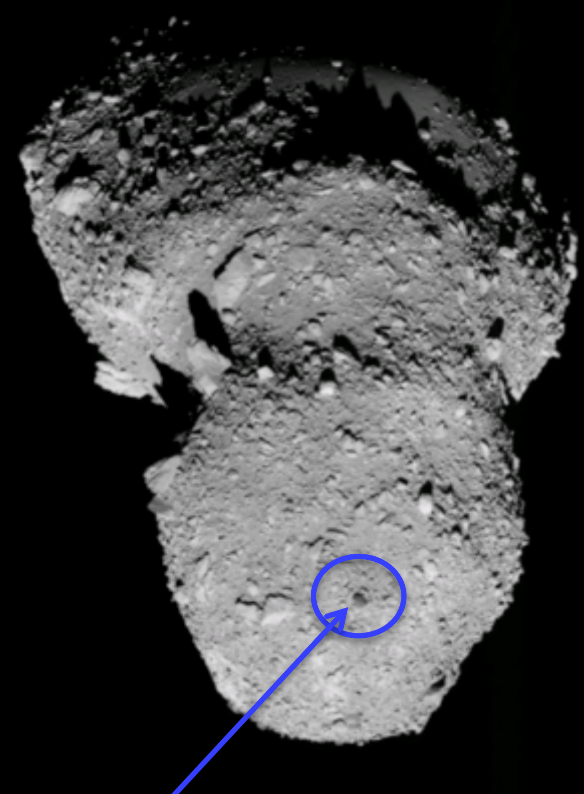




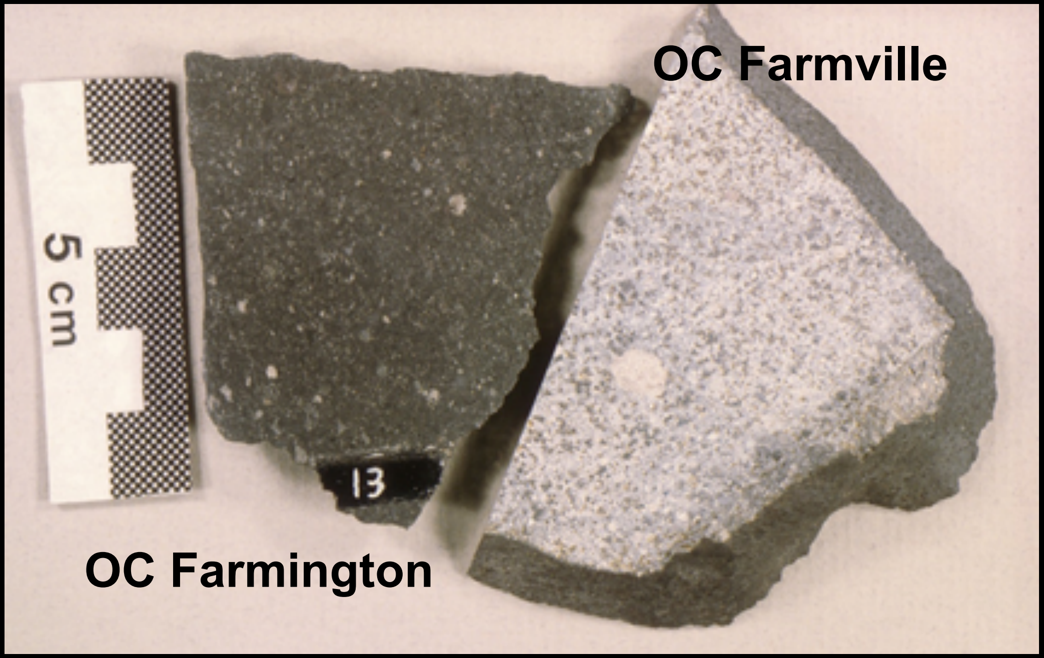
Current relevant findings based on meteorites collected on Earth

Summary from altered chondrites

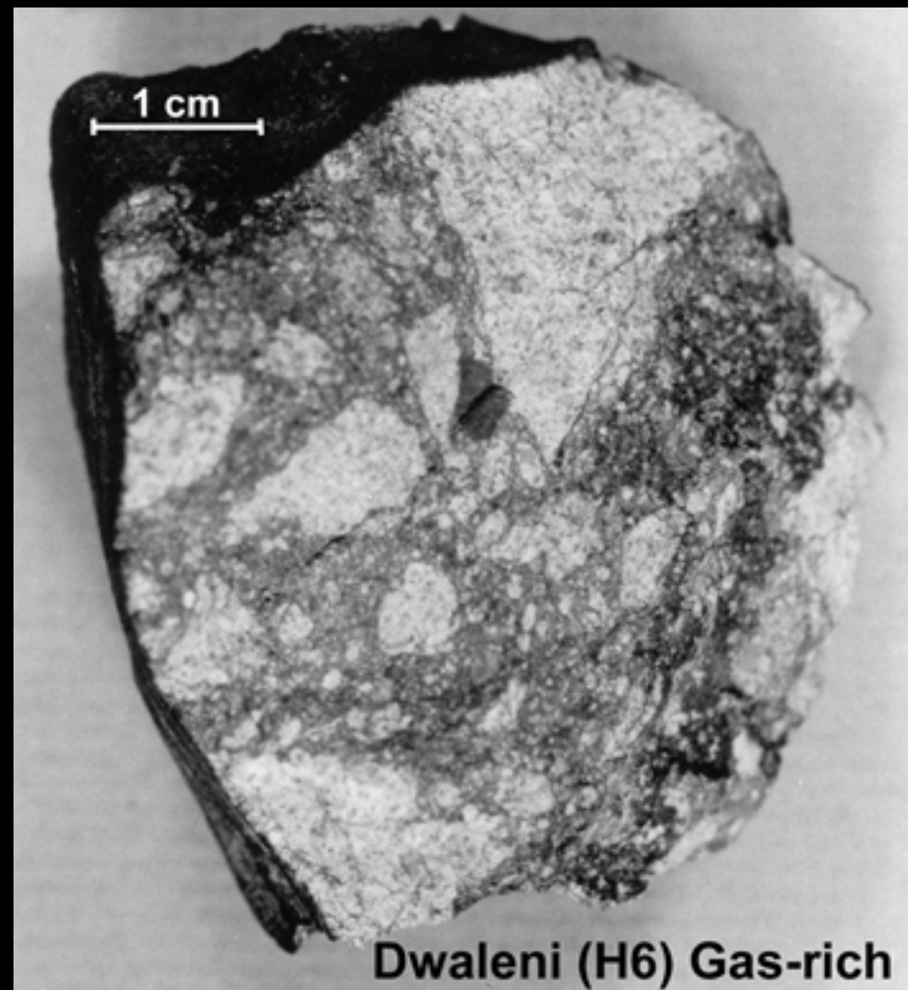
- ~15% of OC meteorite falls are dark, altered by shock
- Altered chondrites have similar chemistry to other OC meteorites
- Dark boulders on Itokawa may be altered OC material



~6 meter dark boulder on Itokawa

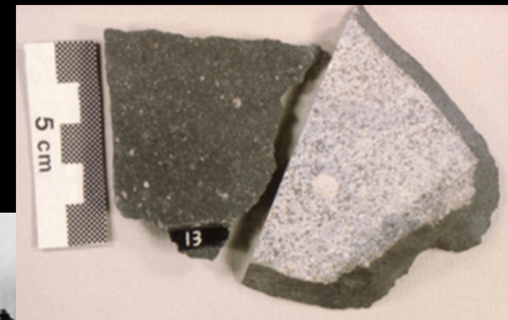


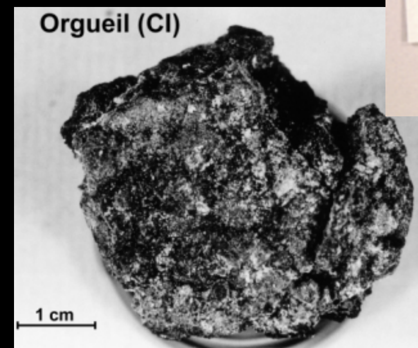
Provide information/data regarding the range of expected regolith surface properties (surface cohesive, porosity, compaction, etc.) of large NEAs of various types to support analyses for assessing surface contact, interaction during boulder collection, and mechanical push planned for ARRM Option B.



Meteorite Types

- Chondrites (ordinary, enstatite)
  - Stones, chondrules, olivine, pyroxene, metal, sulfides, usually strong
- Volatile-rich Carbonaceous Chondrites (CI, CM)
  - Hydrated silicates, carbon compounds, refractory grains, very weak.
- Other Carbonaceous (CO, CV, CK, CR, CH)
  - Highly variable, chondrules, refractory grains, often as strong as ordinary chondrites
- Achondrites
  - Igneous rocks from partial melts or melt residues
- Irons
  - Almost all FeNi metal
- Stony-irons
  - Mix of silicates and metal





Porosity

- Most NEAs are probably rubble piles with very weak cohesion
  - Bolide, spin rate, and bulk density observations support rubble pile structure
  - Inter-particle forces on small particles literally hold asteroids together.
  - Volatile-rich asteroids somewhat more likely to be rubble piles
- Macroporosities of ~ 25-50%
- Angle of Repose will depend on local gravity field, but should be in the range of ~ 45%

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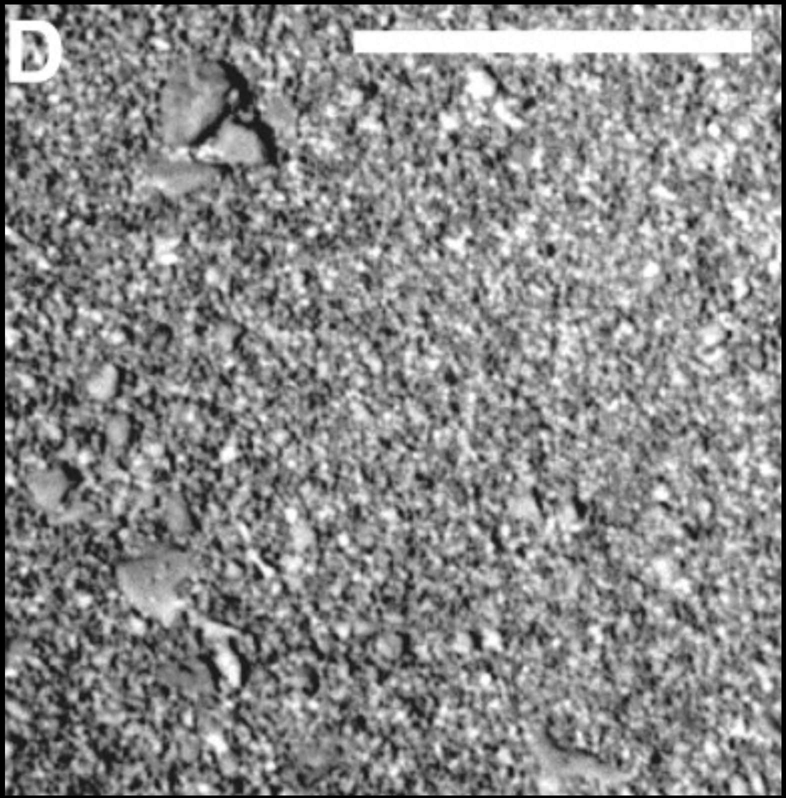
Soil Structure

- Relative to Lunar Soil NEAs have....
- Much higher thermal inertia, much lower gravity
- Expect courser soils, more boulders
- Micro-impacts and regolith gardening can result in size segregation. The solar wind may deplete the smallest size fraction and the larger materials are preferentially retained on the surface of the asteroid.
- Fine materials may be retained at depth in the soil profile.

Itokawa 1 meter



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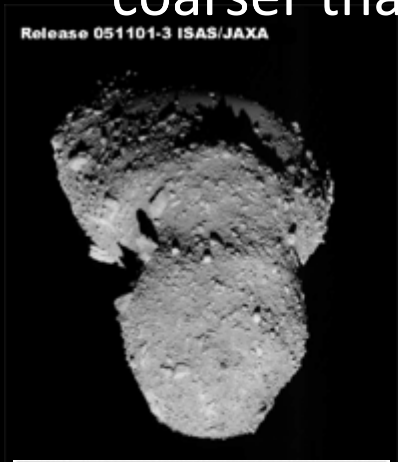
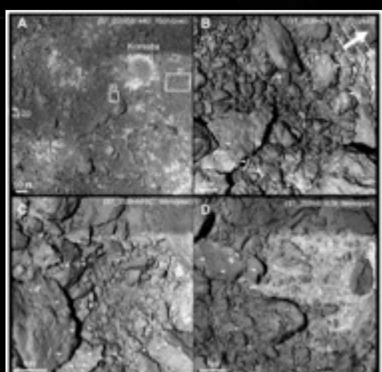
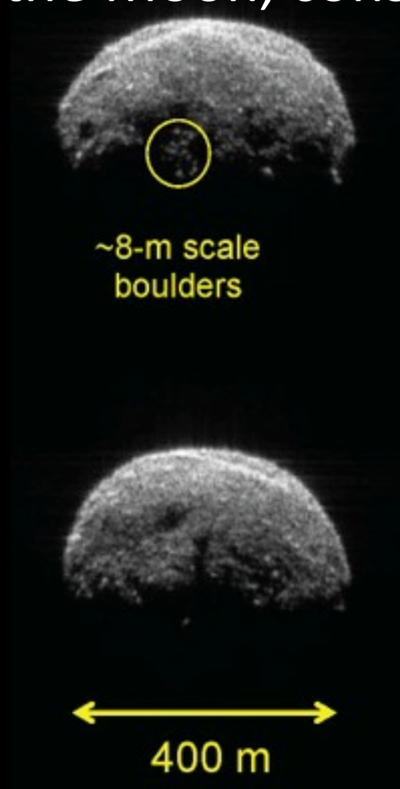
Thermal inertia – NEOs are not bare rock and have regoliths likely coarser than the Moon, consistent with abundant boulders





Itokawa: TI~750
(Müller et al. 2005)

Boulder-rich, with finer-grained regions

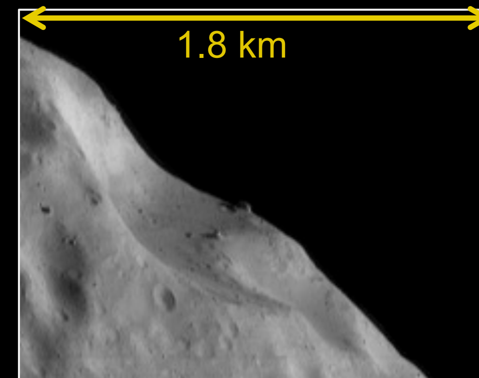


YU55: TI~600
(Müller et al. 2013)

Many 8-m scale boulders

Bennu: TI~310
(Emery et al. 2014)

At most one 8-m scale boulder
(Nolan et al. 2013)

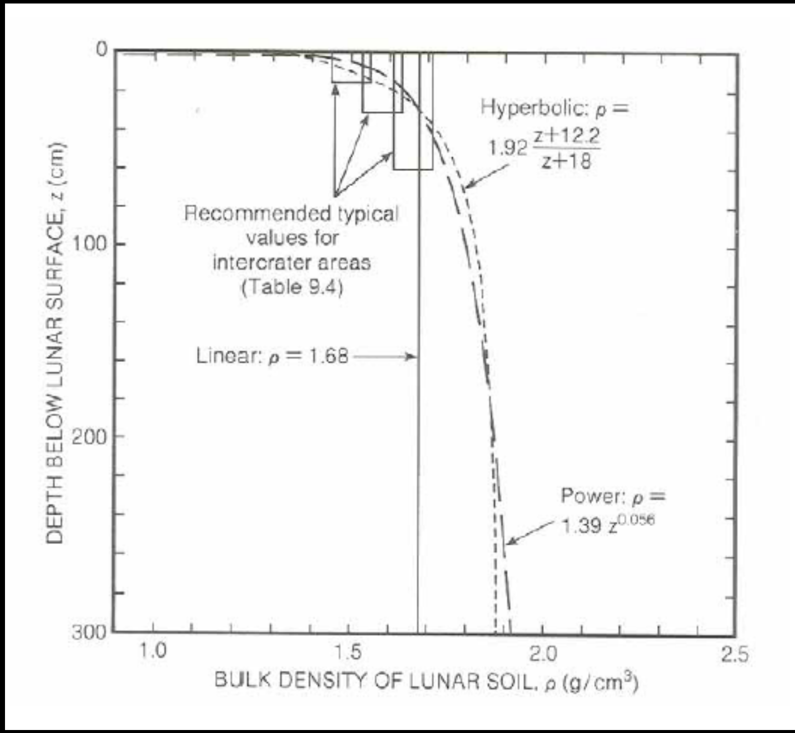


Eros: TI~150
(Müller et al. 2007)

Fine regolith with boulders

Compaction

- Lunar Regolith "Soil"
  - Fine particles, very loose, very fluffy, created by micrometeorite bombardment.
  - About 20 cm deep
  - Density about 0.9-1.1 g/cm^3. Increases with depth to about 1.9 g/cm^3. Porosity about 45%.
  - The regolith becomes progressively more compacted with depth.
- NEAs……
  - Lower gravity may make it harder to compact.
  - Interparticle forces may dominate.
  - Particle size profile with depth may be highly variable.



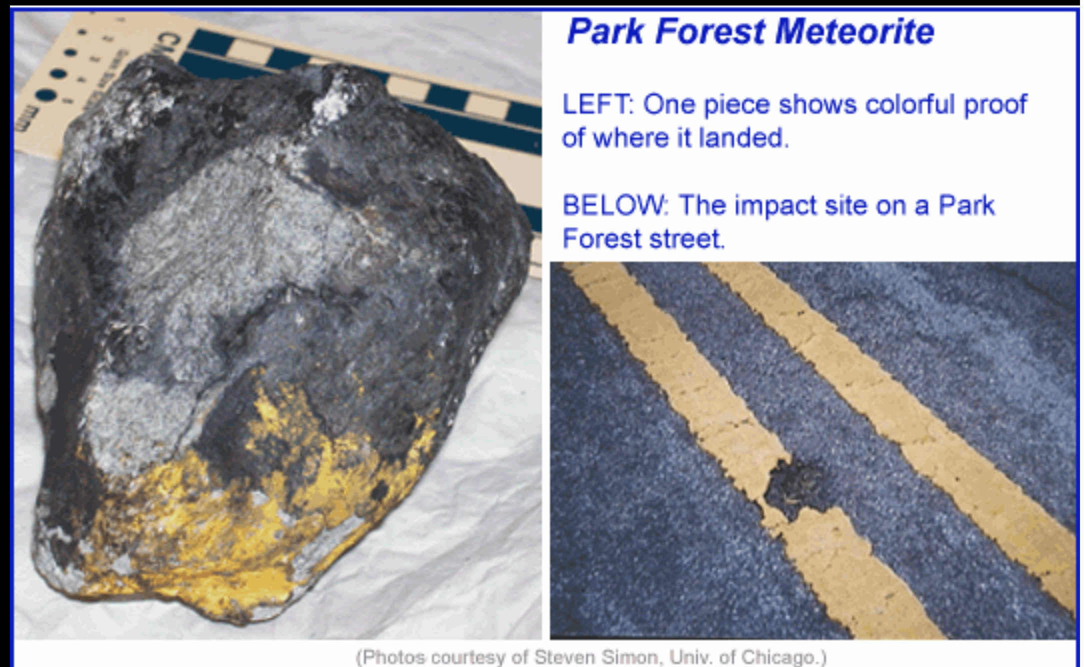
Provide information/data regarding the range of expected regolith surface properties (surface cohesive, porosity, compaction, etc.) of large NEAs of various types to support analyses for assessing surface contact, interaction during boulder collection, and mechanical push planned for ARRM Option B.

<u>Summary:</u>

Expected surface properties of “large” NEAs of various compositional types.

- <u>Porosity:</u> Mostly rubble piles, high macroporosities ~ 25-50%
- <u>Soil Structure:</u> Courser than lunar soils, more boulders, fines depleted.
- <u>Compaction:</u> Less compact relative to lunar soils, interparticle forces may dominate, particle size profile with depth may be highly variable.

Two small meteorites (Park Forest and Grimsby) were estimated to be 1.8 meters and 0.13 meters diameter, respectively, that had very low compressive strengths at first breakup (~0.03 MPa). What does this imply about the lower limit on the strength of small NEAs or boulders on larger NEAs?



Bolides with Recovered Meteorites

Meteorite	Comp. Strength range of Met. Type (MPa)	Initial Mass (Metric Tons) / Diameter (Meters)	Compressive Strength at First Breakup (MPa)	Max. Compressive Strength (Mpa)
Prıbram (H5)	77-247	1.3 / 0.9	0.9	
Lost City (H5)	77-247	0.16 / 0.45	0.7	2.8
Innisfree (L5)	20-450	0.04 / 0.28	0.1	3
Tagish Lake (C2)	0.25-1.2	65 / 4.2	0.3	2.2
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Grimsby (H4-6)	77-327	0.03 / 0.13	0.03	3.6

Note that all data are estimates that are Inferred from observations of the bolide, breakup altitude, and the pattern of the breakup.

From: Popova et al., 2011

- Park Forest and Grimsby are the lowest compressive strengths at first breakup (~0.03 MPa) in the current data.
- This is very weak cohesion and may be a lower bound for the weakest of small bodies.
- Individual pieces of Park Forest are very tough (note holes in roof). The model for this object may be a gravel or cobble bar in space.

What do models of rubble piles say about their range of compressive strengths?

Rubble piles are stronger in compression than in tension. When subject to uniaxial tension or compression, the compressive strength of a soil will be on the order of 4 times stronger than tensile strength. Minimum uniaxial tensile strength of rubble piles has been measured to range between 10-150 Pascals, but could be much larger depending on how strongly components are cemented to each other. If the compression is equal in all directions (i.e., is due purely to pressure), then the rubble pile will first go through a compaction stage. Following this phase, the final compressive strength can be on the order of the crushing strength of the material. The Table two slides prior to this one has detailed numbers on the compressive strength of various meteorites.

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What does the latest paper on thermal cycling of NEAs (Delbo, M. *et al. Nature* 508, 233–236 (2014)) say about the expected strengths of 10-m-class NEAs and 1- to 4-m sized boulders on 100-m-class NEAs?

The Delbo et al. (2014) paper does not directly address the strengths of boulders. Application of their small-scale laboratory experiments to asteroid surfaces involves <u>significant extrapolation</u> (aided by numerical modeling). Furthermore, the process may only be applicable to a few cm length scale, so may only affect the outermost layer of boulders. While intriguing, the work is should not be used as a critical factor in any mission design.

Delbo et al. (2014) do not compute a "weakening rate" for boulders from the proposed thermal fatigue mechanism. Nevertheless, the focus of the paper is on crack formation, which will weaken an otherwise coherent rock. From a combination of laboratory experiments and numerical modeling of fracture mechanics, they conclude that a 10 cm rock would survive for less than 0.1 to 1 Myr on the surface of an asteroid at 1 AU (their Fig 1) and a 100m-sized asteroid with perihelion at 0.3 AU could be completely eroded in ~2 Myr. Their models are run for rotation periods of 2.2 and 6 hrs. Fast rotators and/or asteroids with high thermal inertia will tend toward isothermal surfaces, under which condition thermal fatigue would not operate at all since temperature cycling is required. Delbo et al. define fragmentation time as the time it takes a planar crack to propagate the length of the boulder, but do not quantitatively consider other cracks opening within the rock. Presumably this would occur, but different experiments and modeling would be required to quantify the weakening of boulders from thermal fatigue.

What remote sensing instrumentation is available that is capable of determining the structural integrity of a boulder? What is the resulting uncertainty?

The structural integrity of a boulder will be intimately tied to the presence and degree of fracturing within the boulder. To assess this requires methods that can sense the degree of fracturing within the boulder. Perhaps the most applicable approach in the space environment would be the use of radar tomography to probe the boulder and its interior. Radar tomography senses discontinuities within the material, either due to gaps or to changes in refractive index. The presence of such discontinuities will be diagnostic for the strength or competence of a boulder. Alternate ways to sense a boulder’s integrity exist, such as using ultrasonic waves to measure transmission of sound waves across the body, however such approaches would require direct interaction with the boulder. Ultimately, the best way to determine the strength of a boulder is to subject it to direct mechanical tests.

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What is the effectiveness of C-type and S-type asteroid material for radiation shielding?

Shielding Potential of Meteorites:

Element (wt.%)	Volatile-rich Carbonaceous Chondrites (CI, CM)	Other Carbonaceous (CO, CV, CK, CR, CH)	Ordinary Chondrites (LL, L, H)	Enstatite Chondrites (EL, EH)
Water	15.3	1.9	0	0
Carbon	2.7	0.7	0.1	0.4
Iron	19.6	27.3	22.5	25.5
Magnesium	10.7	14	14.7	12.4
Nickel	1.1	1.4	1.3	1.5
Sulfur	4.6	1.5	2.2	4.6
Oxygen	31	32.7	38.2	29.5
Silicon	11.7	15	18.1	17.7

From Hutchison, 2004

- In general, low atomic mass elements are better. More Hydrogen, the better.
- The response of individual elements complicates the analysis
- CI & CM's are about 30-40% less dense (fewer high atomic mass minerals), rich in water and OH. <u>By far the best shielding material.</u>
- All other stony meteorites are about the same.....

What is the maximum acceptable contamination level of an asteroid or boulder returned to lunar DRO?

Contamination control is vitally important. There are many types of contamination, and each would warrant a specific investigation, with scientists involved in the assessment, to arrive at an answer to this question. The January 2014 CAPTEM report also stresses the importance of contamination control, during all aspects of sampling. The OSIRIS-REx team has valuable expertise in this topic as well that could be beneficial to future contamination discussions.

From CAPTEM January 23, 2014 report:

Finding 4: Contamination Control is vitally important. There are several aspects of contamination control. Because in practice it is impossible to eliminate contamination entirely, it is important to use materials for tools and containers that are readily recognized in the laboratory after recovery by, for example, deliberately introducing cosmochemically rare elements at minor to trace levels. It is also important to use witness materials to serve as blanks, and to develop and curate a complete list of materials to which the asteroidal samples might be exposed. Storage containers should be sealable in space. The sample containers should be purged with high purity nitrogen if a vacuum-tight seal cannot be ensured. We highly recommend the Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers (JSC-23454, LESC-26676, attached) compiled by Judy Allton as a reference. Finally, the sampling sites should not be disturbed by or contaminated by spacecraft operations (e.g., manoeuvering engine plumes).

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