SBAG Asteroid Redirect Mission Special Action Team

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SBAG ARM SAT Activities

- **January 21** – Opening discussion with ARM RCIT; discussion of task list
- **January 23** – SBAG ARM SAT telecon; action items for members
- **January 30** – SBAG ARM SAT telecon; discussion of completed actions and of further items needed
- **February 3** – SBAG ARM SAT telecon; discussion of compiled slide set and additions needed
- **February 4** – Discussion with ARM RCIT of draft slide set, task list items, and additions needed
- **February 10** – SBAG ARM SAT telecon; discussion of slide set and recent additions
- **February 13** – Discussion with ARM RCIT of revised slide set
- **February 19** – Presentation to ARM formulation team

January 21, 2014, Task List items addressed by SBAG ARM SAT to date:

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

- Assessment of likely physical composition of near-Earth asteroids <10m 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 <10m boulders on Itokawa
- Current relevant findings based on meteorites collected on Earth

- Findings relevant to ARM from open community SBAG meetings from July 10-11, 2013, and January 8-9, 2014, are available on the web and in back-up (http://www.lpi.usra.edu/sbag/findings/)
- This presentation addresses the above Task List items
- Extensive back-up slides provide details

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.

See back-up slides for details

SBAG
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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.

See back-up slides for details

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.

See back-up slides for details

- **The original task list was presented as being in priority order, and the SBAG ARM SAT worked the items with that guidance**
- **Additional task list items that have not been addressed to date are:**

To inform mission formulation, we request your scientific assessment in these areas:
  - Sample selection, e.g. identification of objects/areas on a specific asteroid that would be of most interest from a science perspective
  - Science considerations for sample collection, e.g. important aspects and techniques

In addition, provide input for the science and planetary defense figure-of-merit (FOM) assessments of the robotic mission. As part of these assessments, please address the following:
  - **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?
  - **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?

- **The SBAG ARM SAT would be happy to continue to work these items, or others, if such input would be useful**
  - Additionally, input could be provided related to resource utilization, in addition to science and planetary defense, if desired

BACK-UP

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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

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

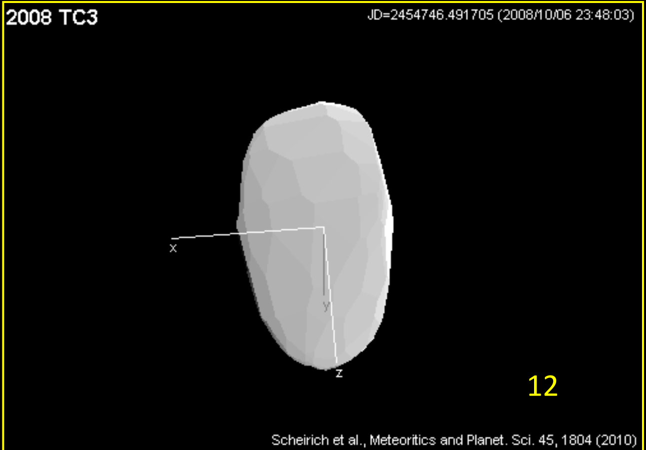
From: Cat. of Meteorites, 5th Ed

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

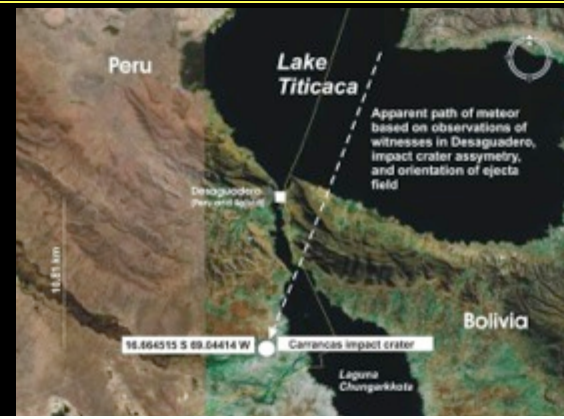


Scheirich et al., Meteoritics and Planet. Sci. 45, 1804 (2010)

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

Summary from other meteorite showers

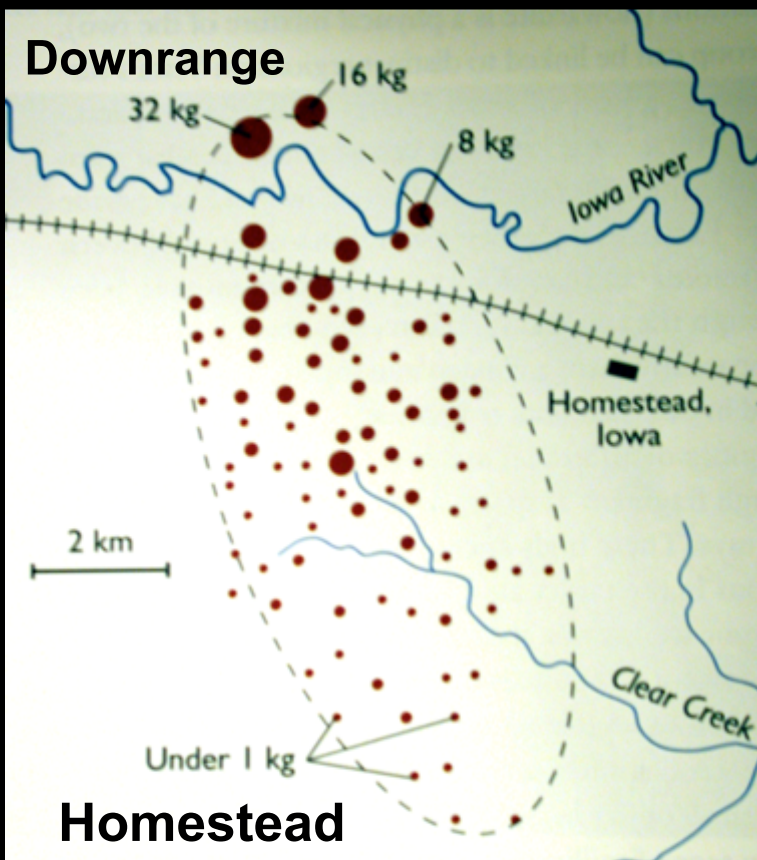
- **Carancas, Peru (Near Lake Titicaca), 3800 m (12,500 ft.) elevation.**
- **Fall: 15 September 2007, ~16:45 UT**
- **Crater 4.5 m (15 ft) deep, 13 m (43 ft) wide**
- **Meteorite was ~ 3 m in diameter before breaking up**
- **H 4-5 ordinary chondrite breccia**
- **Residents complained of illness from 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.

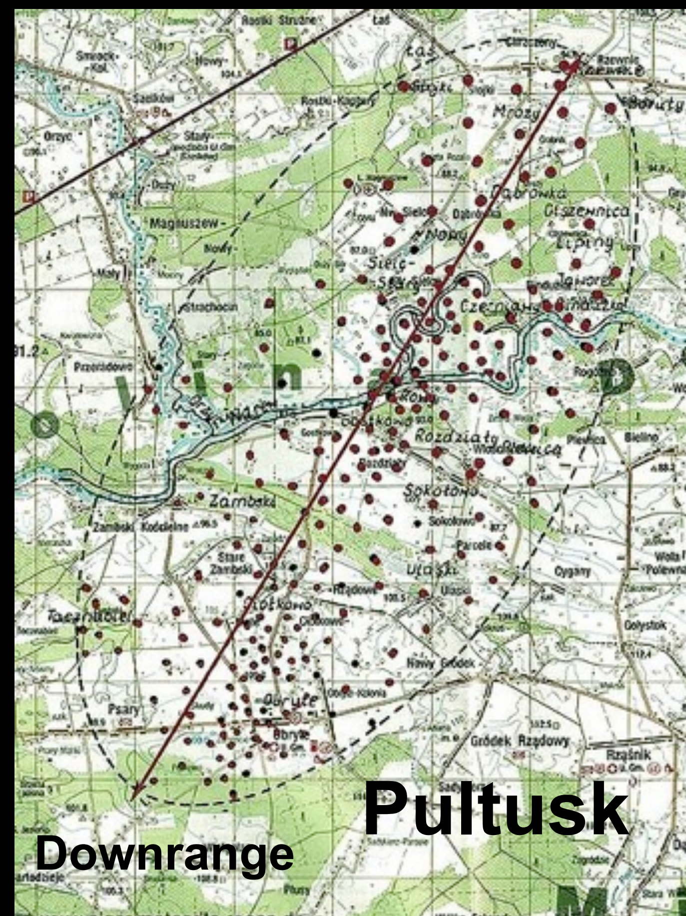


Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

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

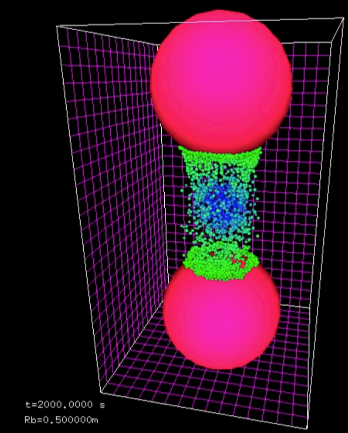
- Average period: 12 min (dominated by 1 object)
- Median period: 3.6 min

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

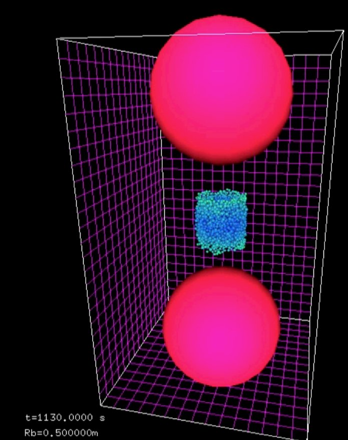
Assessment of likely physical composition of near-Earth asteroids <10m mean diameter:

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



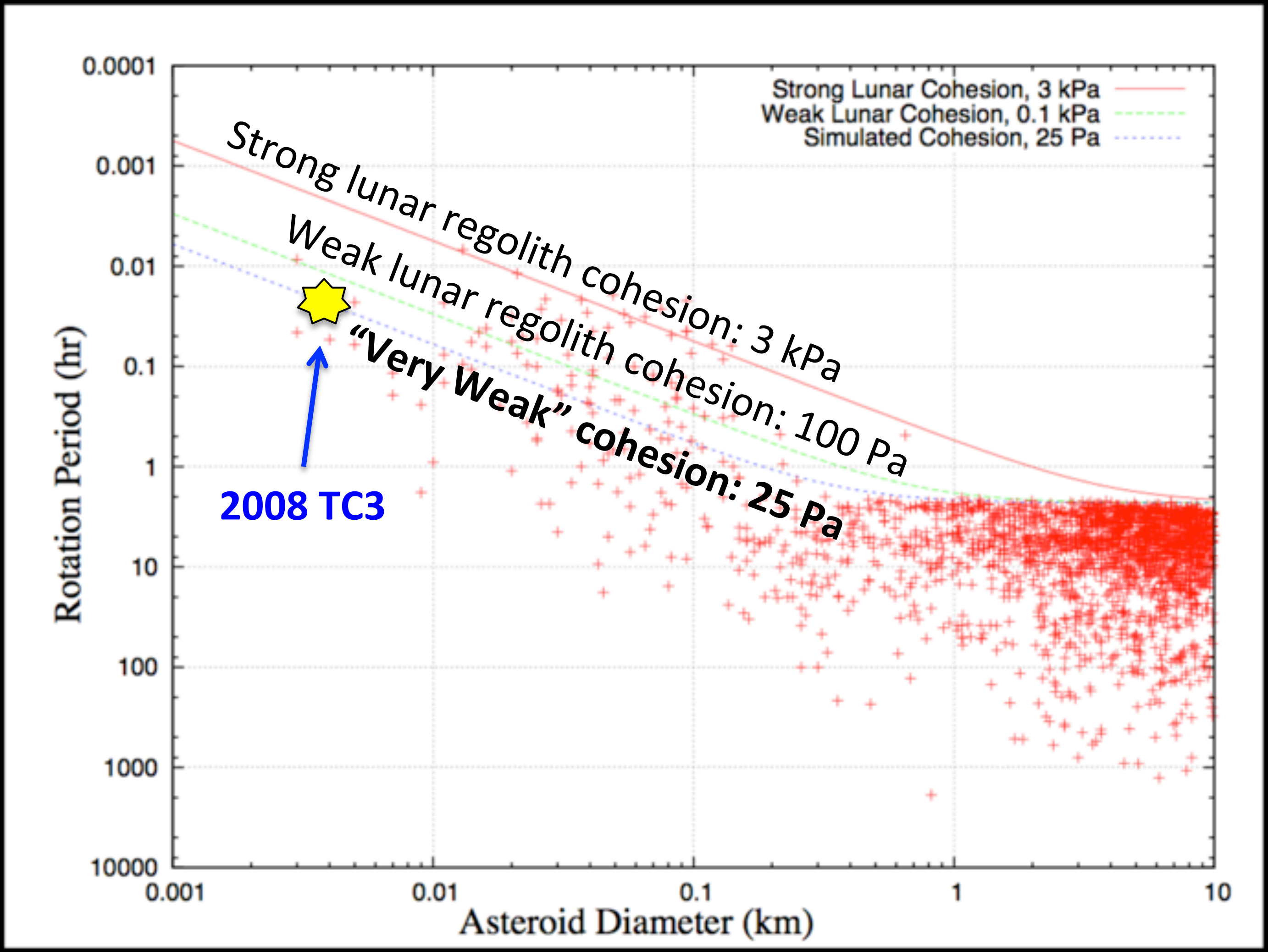
Cohesive Regolith



Cohesionless Regolith

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

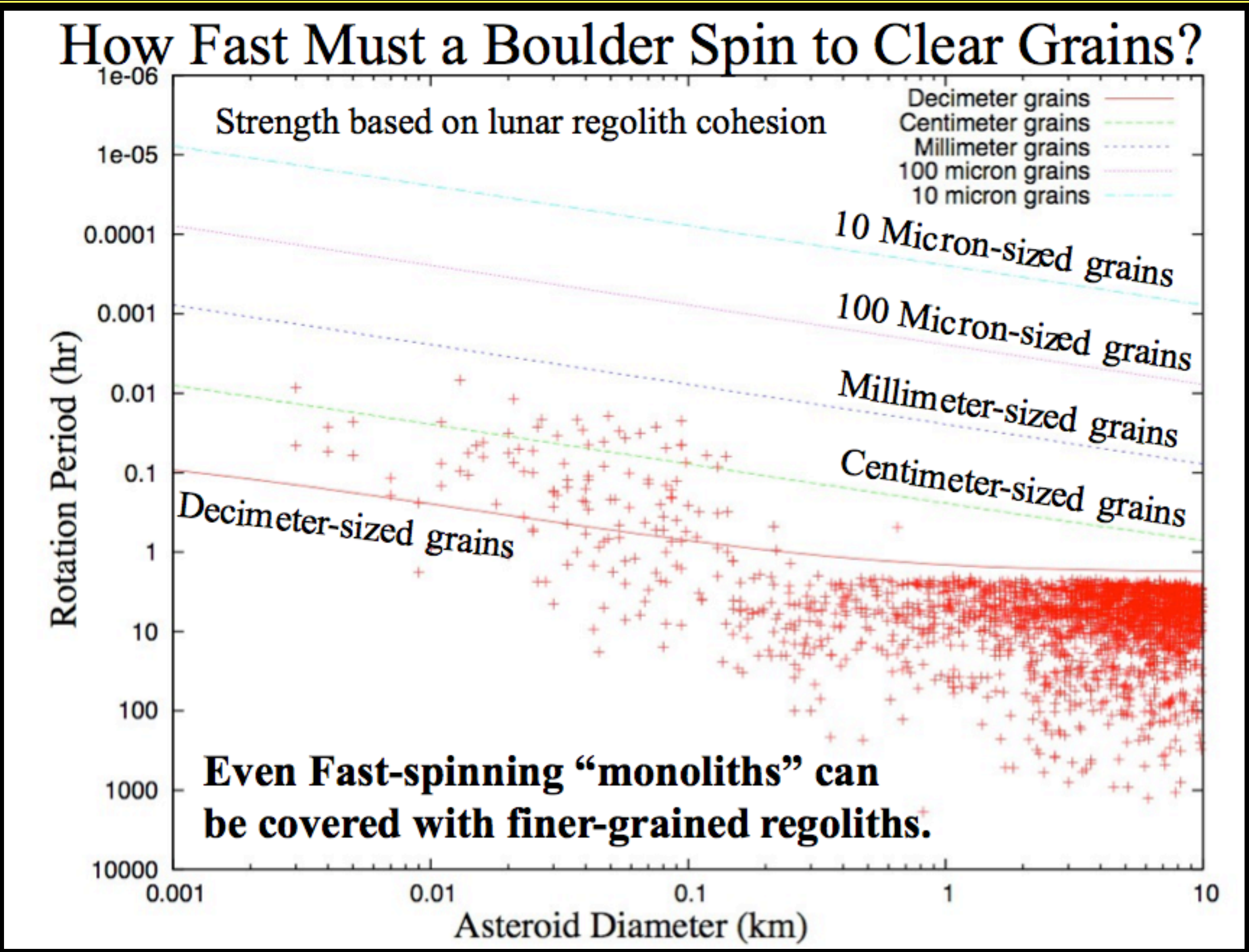
Summary from rotation periods and strength models



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

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

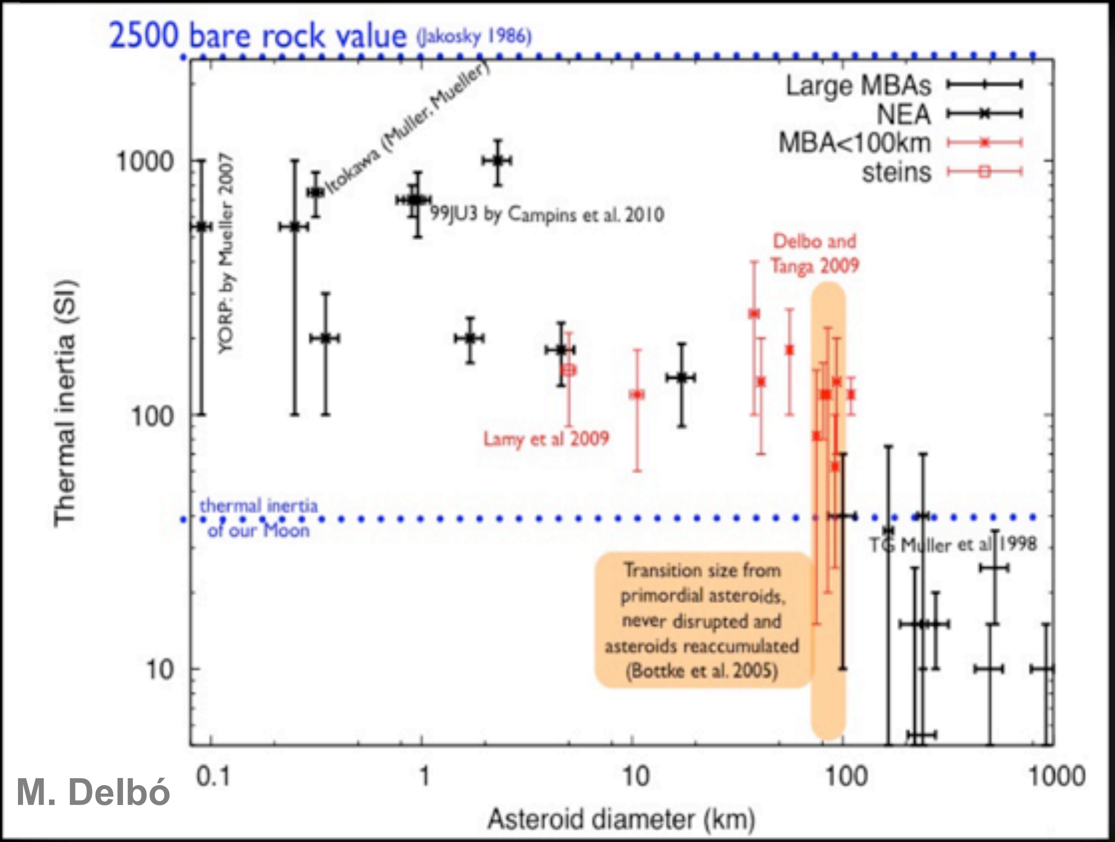
Summary from rotation periods and strength models



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

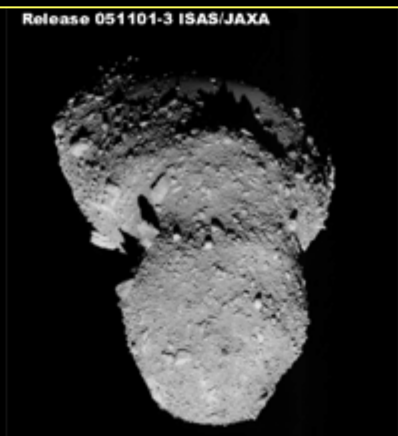
Summary from thermal inertia

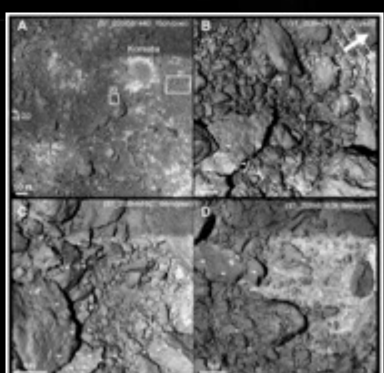
- Thermal Inertias of NEOs range from ~100 to ~1000 J $m^{-2}K^{-1}s^{-1/2}$
  - Moon: ~50
  - Large main belt asteroids: 10-40
  - Bare rock: 2500
- Implications for regolith grain sizes
  - NEO regoliths likely all coarser than the Moon's
  - Lower end likely "pebble" size (~mm)
  - Upper end have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

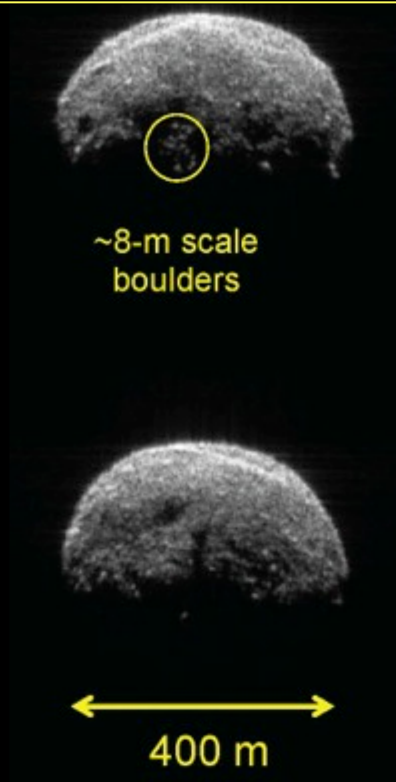


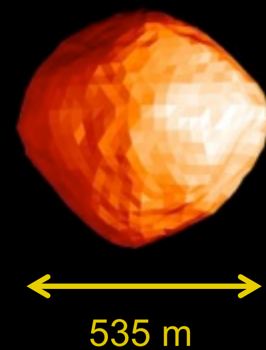
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from thermal inertia









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)

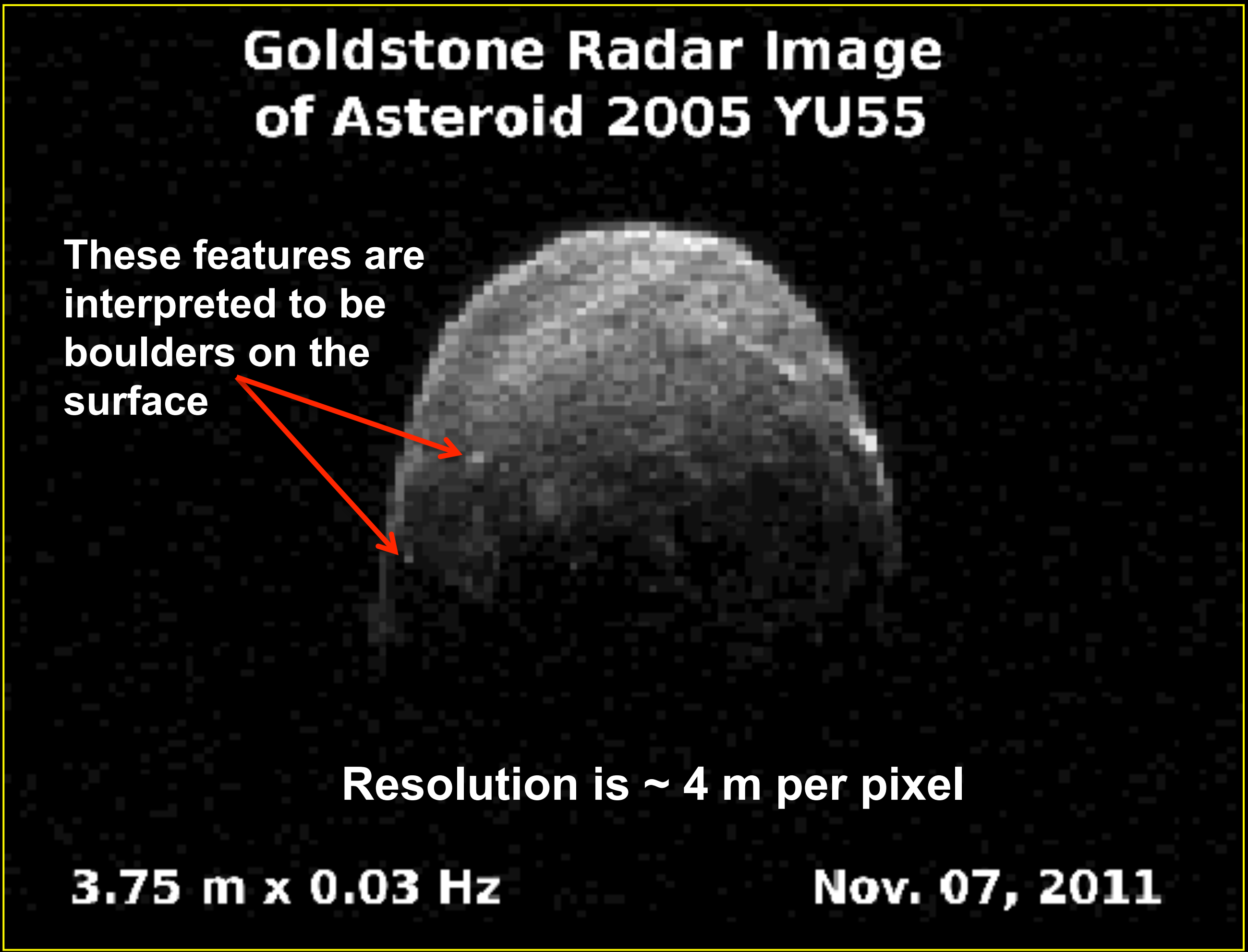
At most one 8-m scale boulder (Nolan et al. 2013)

Eros: TI~150
(Müller et al. 2007)

Fine regolith with boulders

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

Summary from radar

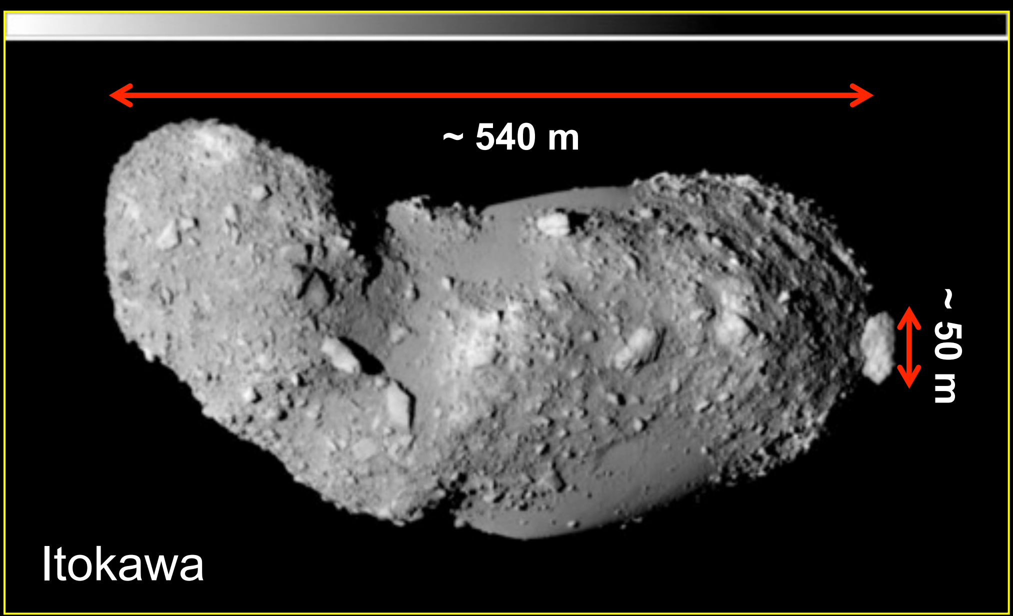


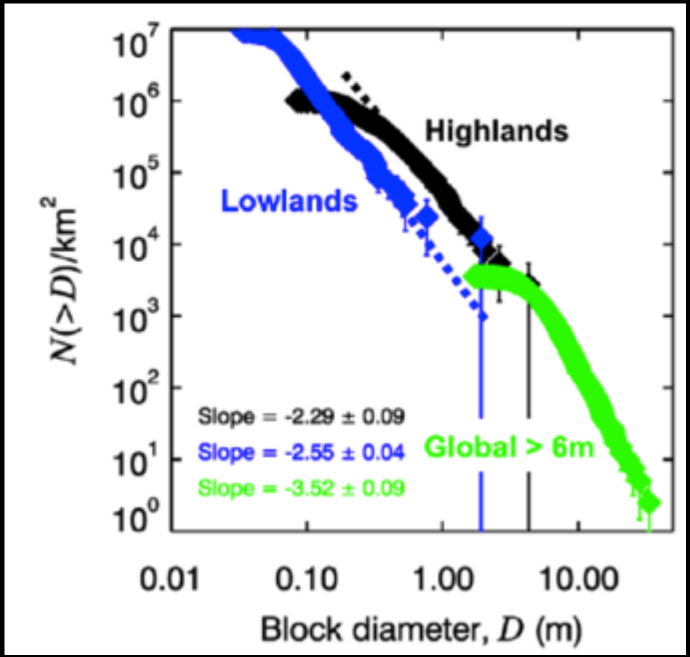
- Ground-based radar can image features to ~4 m/pixel
- The near-Earth asteroid has to be in a good viewing geometry, including relatively close, for radar imaging of small scale features such as boulders

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





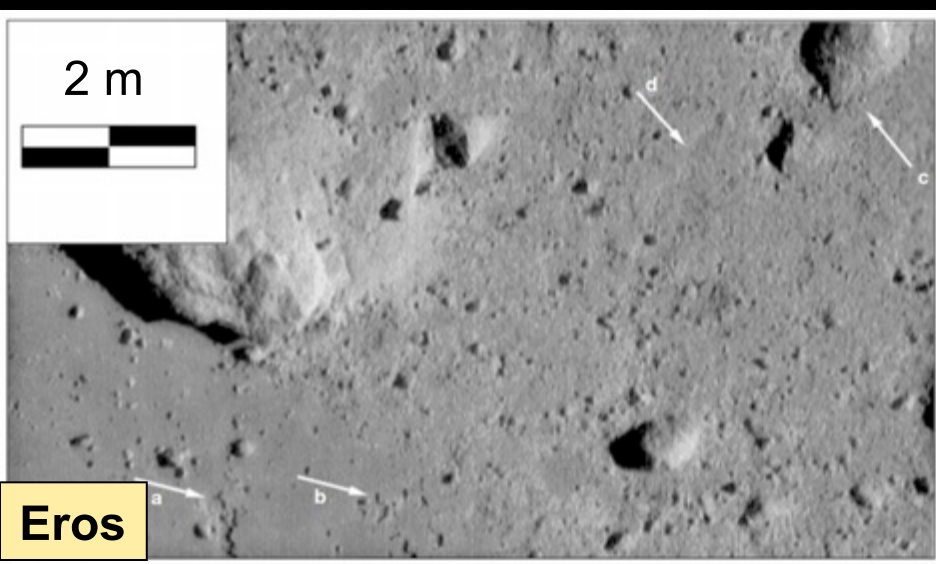
Noviello et al. (2014)

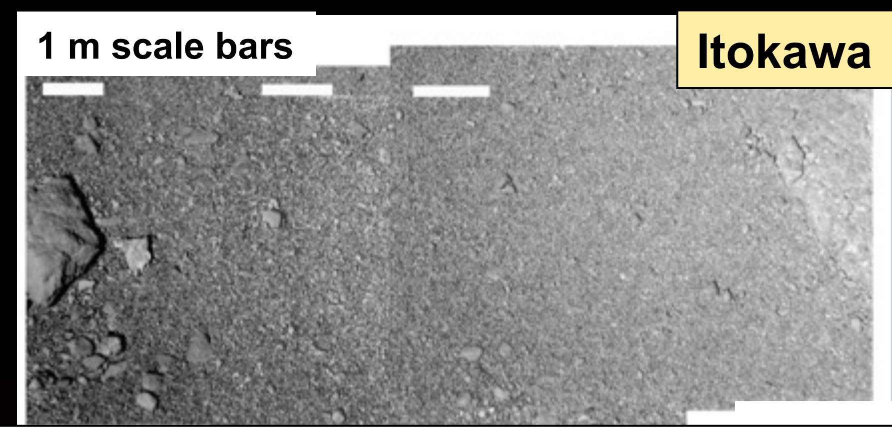
Assessment of likelihood and diversity of boulders on larger (>50 meter) near-Earth asteroids

Summary from spacecraft imagery

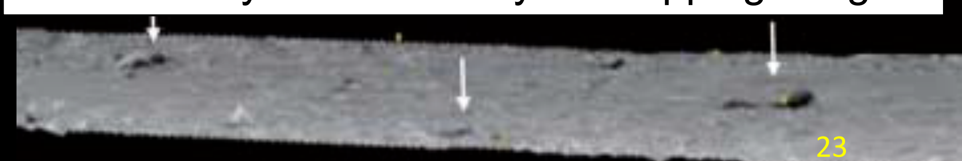
- NEAR-Shoemaker obtained images of Eros (34x11x11 km) to 1.2 cm/pixel in 2001
- Many blocks of a range of sizes
- Interpreted “all of the larger ejecta blocks in this region are partially buried” (Veverka et al., 2001)

- 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)



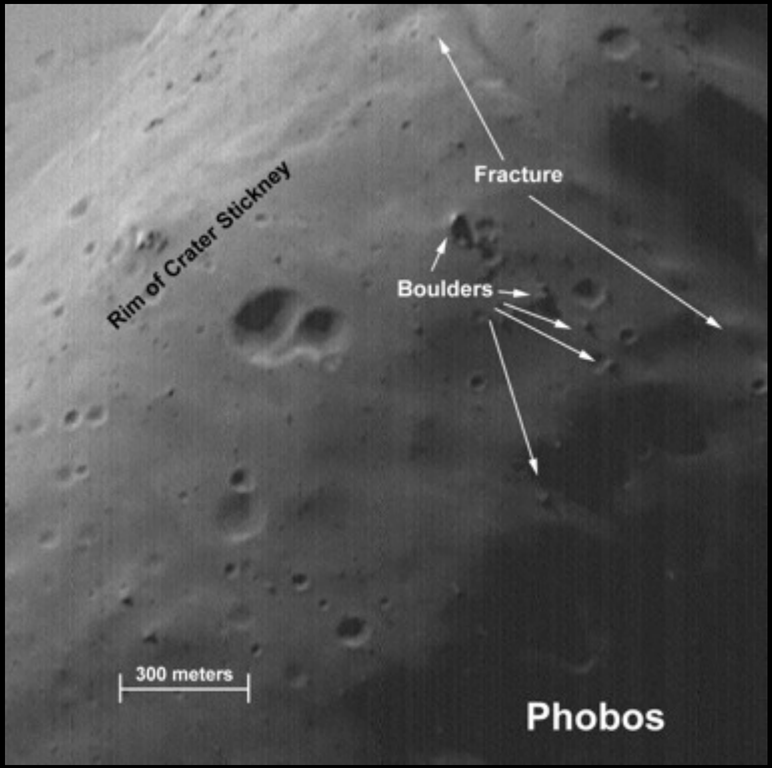


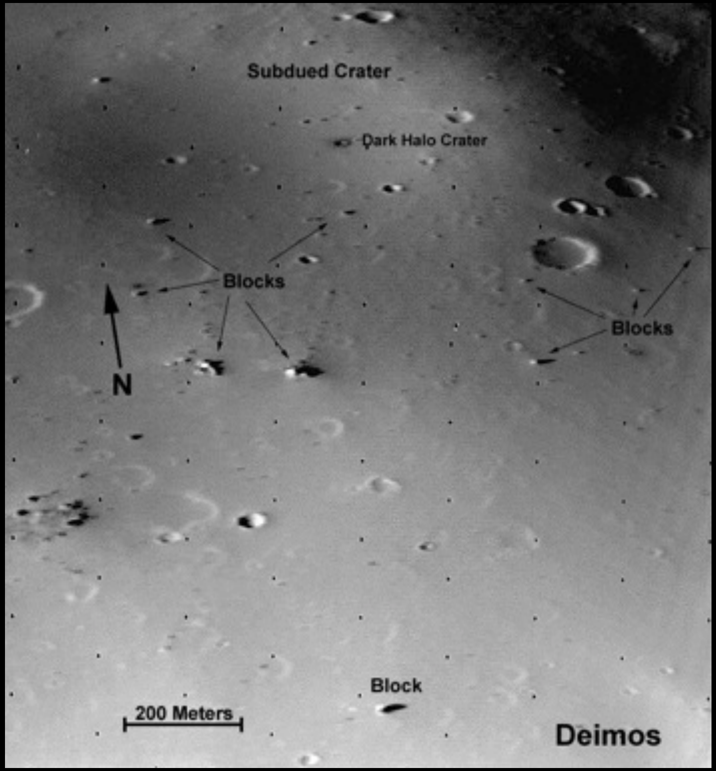
Stereo analysis enabled by overlapping images



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

Summary from spacecraft imagery





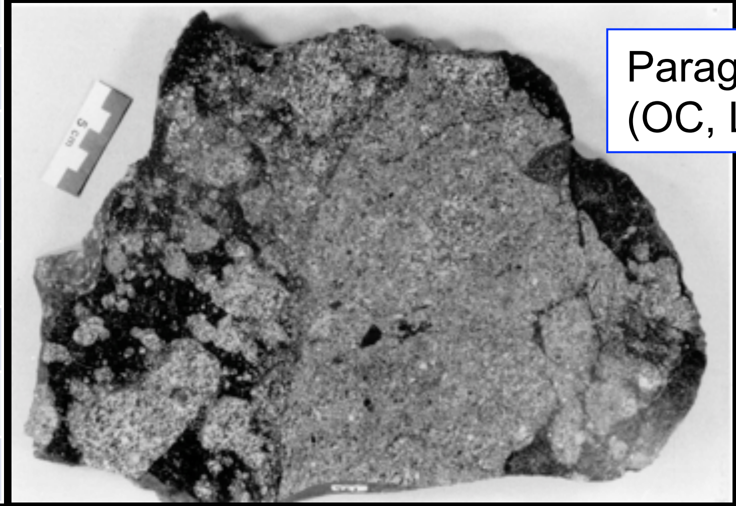
- The martian moons, Phobos and Deimos, are “dark”, in contrast to “bright” Itokawa
- Boulders on Phobos give cumulative slopes consistent with distribution on Eros (Thomas et al., 2000; 2001)
- Best resolution images of Phobos and Deimos: ~1.5 m/pixel, resolves blocks ~3-4 m

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

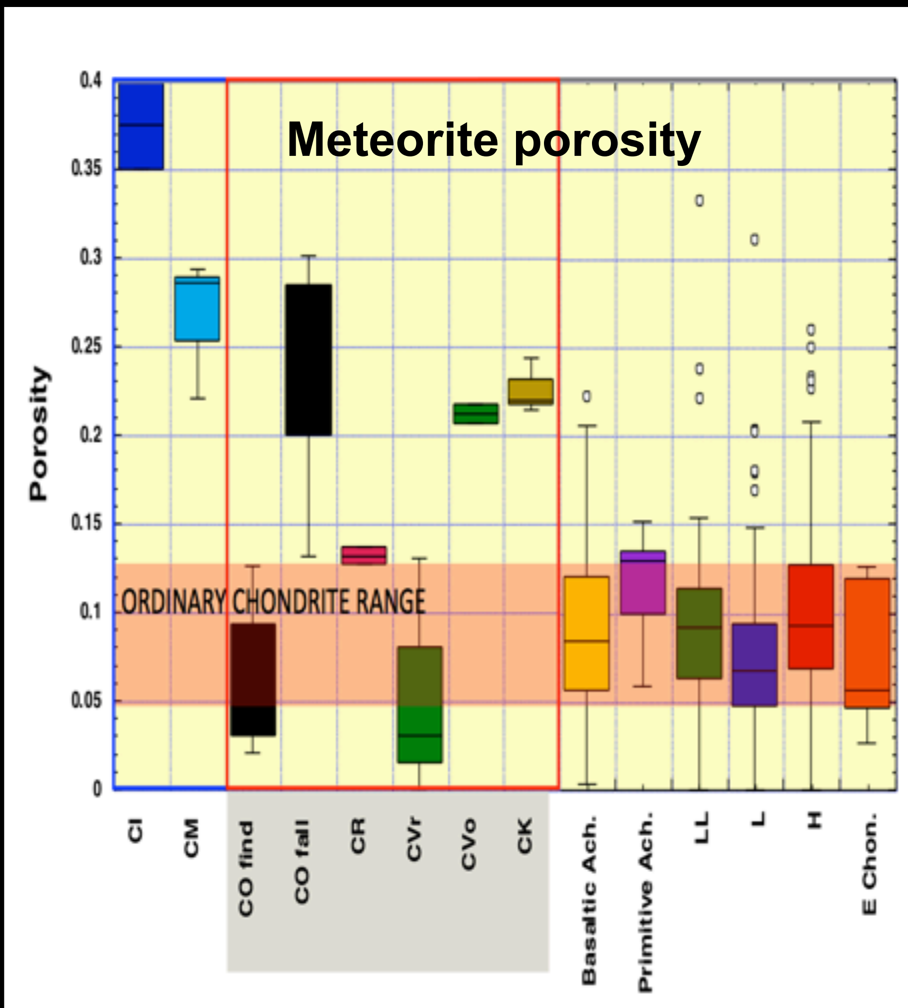
Meteorite	Comp. Strength range of Met. Type (MPa)	Initial Mass (Metric Tons) / Diameter (Meters)	Compressive Strength at First Breakup (MPa)	Max. Compressive Strength (Mpa)
Pribram (OC - H5)	77-247	1.3 / 0.9	0.9	
Lost City (OC - H5)	77-247	0.16 / 0.45	0.7	2.8
Innisfree (OC - L5)	20-450	0.04 / 0.28	0.1	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

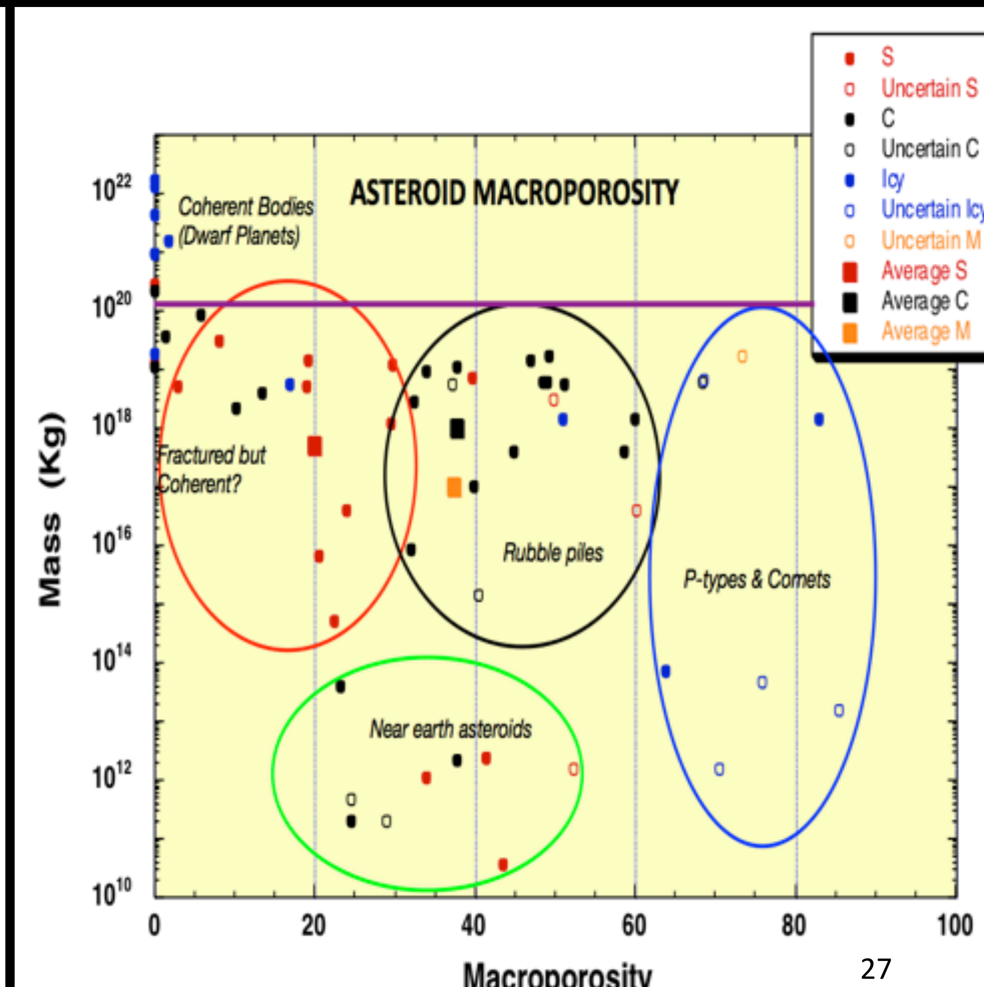
Note that all data are estimates that are inferred from observations of the bolide, breakup altitude, and the pattern of the breakup. Popova et al., 2011

Current relevant findings based on meteorites collected on Earth

Summary from porosity

- Meteorites and asteroids exhibit a wide range of porosities



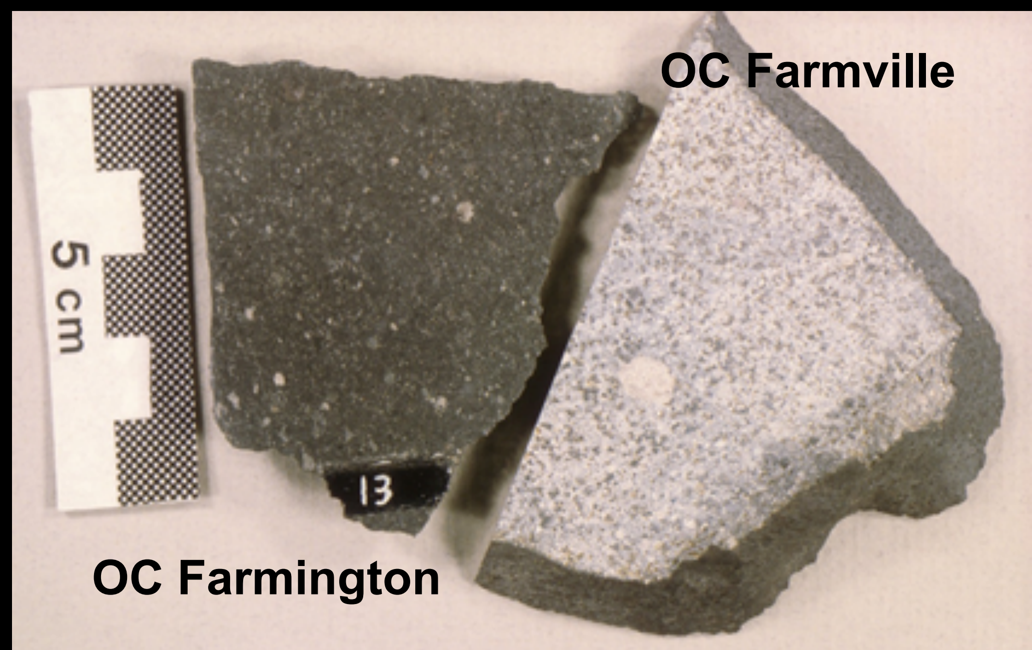


Current relevant findings based on meteorites collected on Earth

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



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SBAG
SMALL BODIES ASSESSMENT GROUP

Findings are summarized. Full findings available at: http://www.lpi.usra.edu/sbag/findings/

- **FINDINGS FROM SBAG MEETING, JANUARY 8-9, 2014:**
- ***Asteroid Redirect Mission.*** Though SBAG acknowledges that the Asteroid Redirect Mission (ARM) is continuing to evolve as the concept development matures, the current formulation has not resolved the issues detailed in previous SBAG findings of July, 2013. The objectives, requirements, and success criteria for the ARM are not clearly defined, including the relevance to planetary defense. There are substantial issues and challenges associated with the identification and characterization of potential targets. Together these combine for considerable schedule and cost uncertainty and risk for the ARM. As requested, SBAG in the near term will provide input for key small body science areas to inform NASA and the ARM formulation team, though we note that SBAG would be willing to provide input at earlier stages in the future.

- ***Support of Target NEO 2 Findings.*** The Target NEO 2 workshop had widespread and broad community participation and enabled open discussion and debate of the Asteroid Redirect Mission (ARM) concept. The Target NEO 2 final report finds the need for: ARM requirements and mission success criteria to be clearly defined; an independent cost estimate; competition and peer review; reconsideration of the aggressive schedule; a well-constrained understanding of the target NEA population and the distribution of their physical characteristics; improvement of ground-based observatories and remote characterization follow-up procedures; and a robust NEO survey. SBAG finds that the Target NEO 2 workshop was highly valuable and successful at bringing together experts in the fields pertinent to the ARM concept, supports the well articulated findings in the final report, and urges that the report be used to inform and evaluate further ARM efforts.

Findings are summarized. Full findings available at: http://www.lpi.usra.edu/sbag/findings/

- **FINDINGS FROM SBAG MEETING, JULY 10-11, 2013:**
- **(a) *Planetary Science.*** ARRM has been defined as not being a science mission, and it is not a cost effective way to address science goals achievable through sample return. Support of ARRM with planetary science resources is not appropriate.
- **(b) *Searching for Potentially Hazardous Objects.*** There is great value in enhancing NASA's capabilities in small body discovery and characterization. The enhancement to NEO discovery and characterization efforts proposed as part of the Asteroid Initiative would be greater still if it were to be continued for more than one year. There is concern that a focus on acquiring ARRM targets can come at the expense of the detection rate and follow-up observations of 140m and larger asteroids.
- **(c) *Relevance of ARRM to Planetary Defense.*** Given the size of the ARRM target (< 10m), ARRM has limited relevance to planetary defense.
- **(d) *Mission Objectives.*** ARRM does not have clearly defined objectives, which makes it premature to commit significant resources to its development. Firm baseline and minimum requirements must be set. SBAG finds that formation of *an independent Mission Definition Team (MDT)* prior to commitment of significant resources and mission confirmation would allow for community participation in the relevant fields for the mission and provide a non-advocate peer review of the expected benefit if mission success criteria are met.

Findings are summarized. Full findings available at: http://www.lpi.usra.edu/sbag/findings/

- **FINDINGS FROM SBAG MEETING, JULY 10-11, 2013:**
- **(e) *Target issues*.** The population and physical characteristics of low delta-velocity targets having diameters less than 10m are poorly constrained by observations. It is impractical to begin the planning and design of any mission to capture such an asteroid in the absence of a pre-existing study on the population and the physical characteristics of its members**.** *A robust characterization campaign is imperative*. Target characterization will be challenging and is expected to be of the utmost importance to mission success.
- **(f) *Schedule risks*.** Because of long-synodic periods, a missed launch window will not be recoverable for the same ARRM target. Therefore, multiple targets meeting orbital and physical characteristic requirements and having appropriately phased launch windows will need to be discovered. Given the poor knowledge of the population of these objects, this is a significant mission risk. The stated schedule for the ARRM, which posits funding of a ~$100M study in FY14 and launch in 2017, is unrealistic.
- **(g) *Cost risks.*** As a mission that serves as a technology and operations demonstrator, the management approach and acceptance of risk needs to be better defined to determine the feasibility of the aggressive schedule and its impact on cost and mission success criteria. The full-cost target, funding profile, and funding sources are not provided and limit any credible assessment of the schedule and mission cost to the various directorates. Lack of clarity of both resources available and resources required limits any determination of mission value, merit, and/or whether the mission is the most efficient use of available resources to achieve NASA's objectives.