DYNAMICS AND GRANULAR MECHANICS OF NEAR-ZERO GRAVITY EXCAVATION OF C-TYPE RUBBLE PILE ASTEROIDS

June 2023

Dr. Curtis Purrington
Karman+ Lead Excavation Engineer

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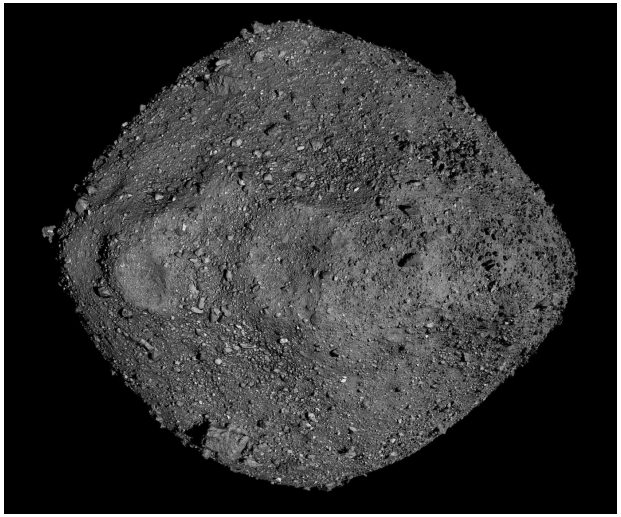
Karman+ Mining NEA C-Type

Mission 1 (2026): Learn to be Better Miners

Mission 2 (2028): Apply Knowledge and Scale



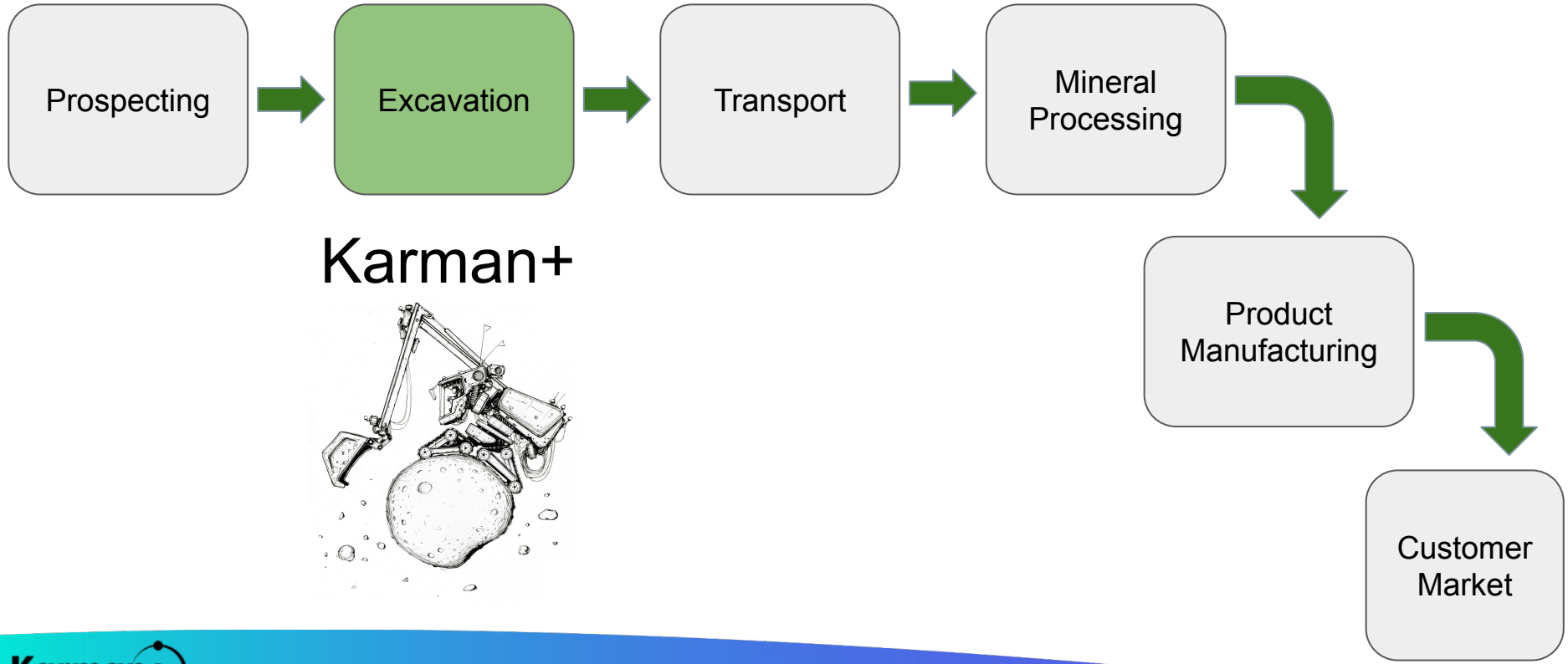
NASA OSIRIS REx (101955 Bennu) - C-Type Asteroid

Water

Carbon

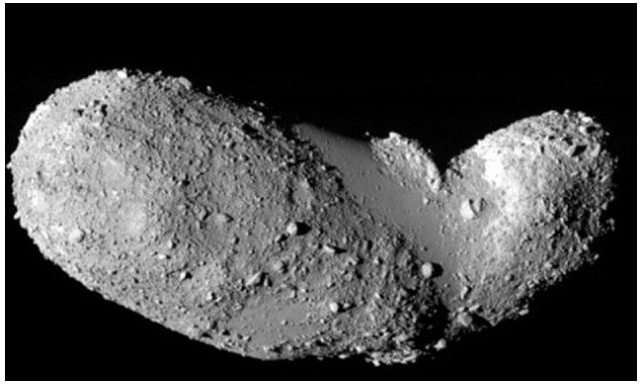
Clay

Asteroid Mining Value Chain



Asteroid Sample Missions

Itokawa (S) - Hayabusa1 JAXA

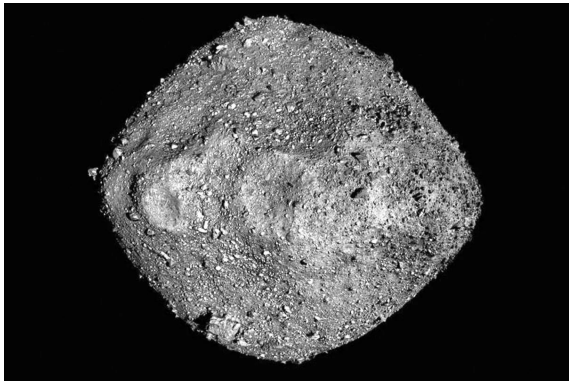


<1g

Ryugu (C) - Hayabusa2 JAXA

~5.4g

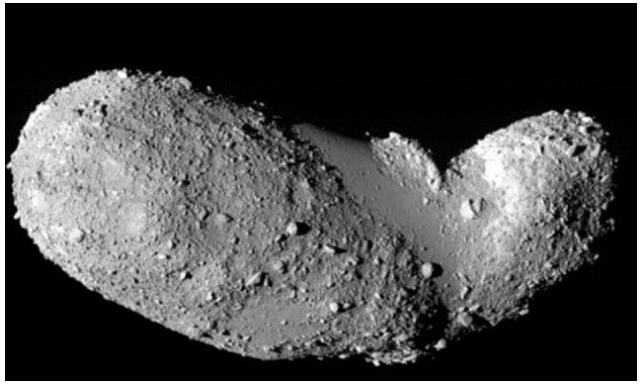
Bennu (C) - OSIRIS-REx NASA



0.5-2kg

Asteroid Sample Missions

Itokawa (S) - Hayabusa1 JAXA



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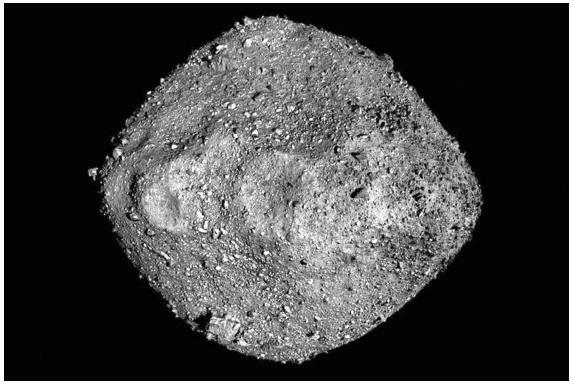


0.5-2kg

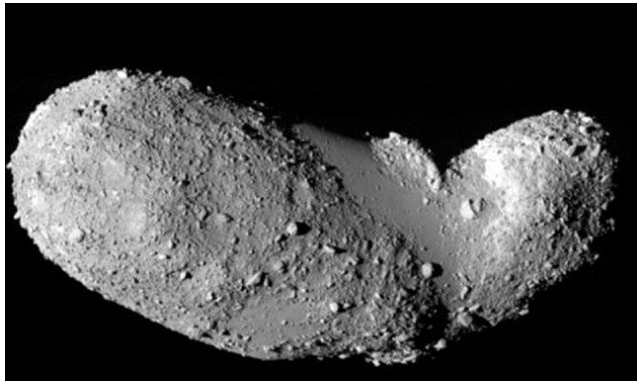
CO Molybdenum Mine

18,500,000 kg/day (215 kg/s)

Karman+

Asteroid Sample Missions

Itokawa (S) - Hayabusa1 JAXA



<1g

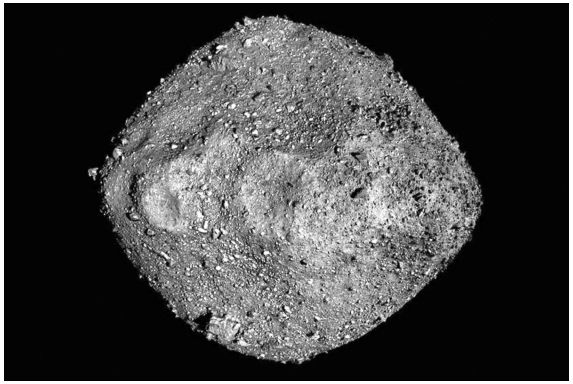
$150 billion/kg

Ryugu (C) - Hayabusa2 JAXA

~5.4g

$27.7 billion/kg

Bennu (C) - OSIRIS-REx NASA



0.5-2kg

$0.58 billion/kg

CO Molybdenum Mine

$0.024/kg 18,500,000 kg/day(215kg/s)

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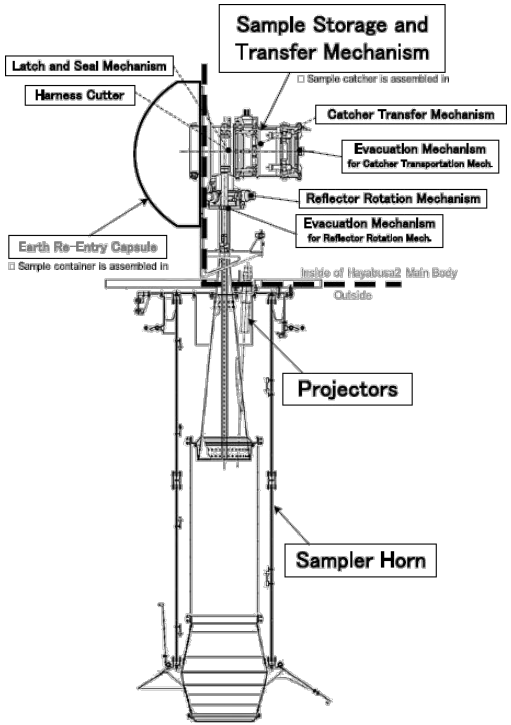
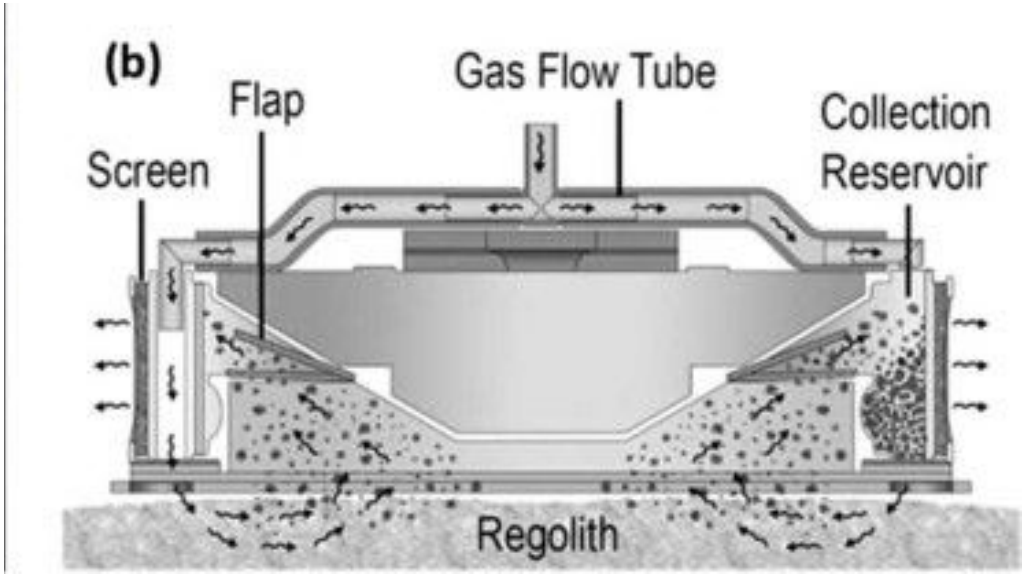
State of the Art

JAXA - Hayabusa2, Ryugu



NASA - OSIRIS-REx, Bennu



Debris Fields

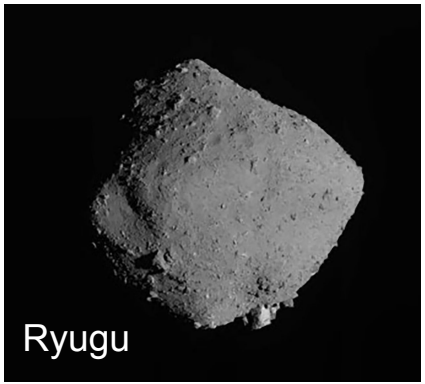
Hayabusa2 - 5.4g

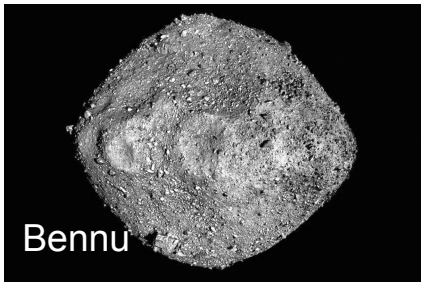
OSIRIS-REx - 0.5 - 2kg

Debris Fields - Silver Lining

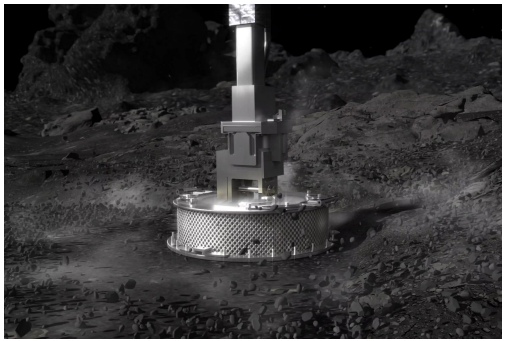
Goal: 150g
Captured: 0.5 - 2kg
Mobilized Particles - 6000kg
over 5 seconds
(1200 kg/s)

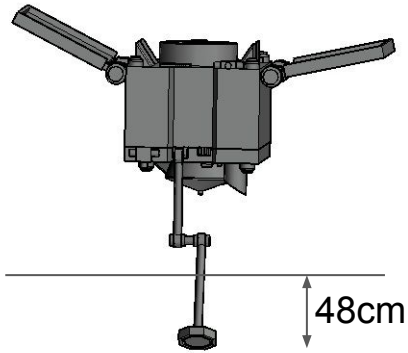
Unconsolidated Surfaces (Rubble Pile)



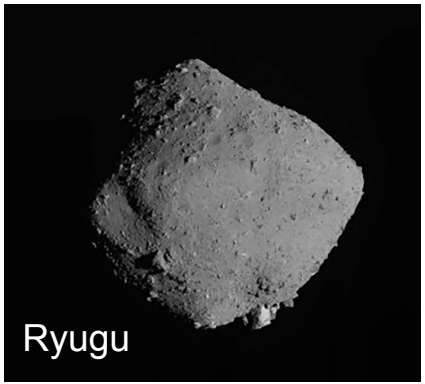


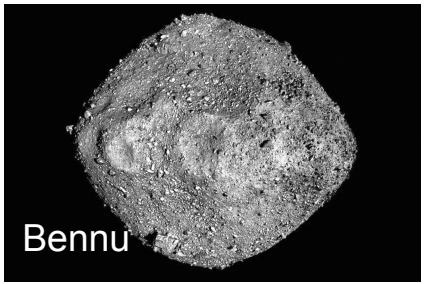
Density	Bulk Porosity	Gravity
1.27 g/cm^3	44%	0.00011m/s^2
1.19 g/cm^3	55%	0.000098m/s^2





Unconsolidated Surfaces (Rubble Pile)





Density	Bulk Porosity	Gravity
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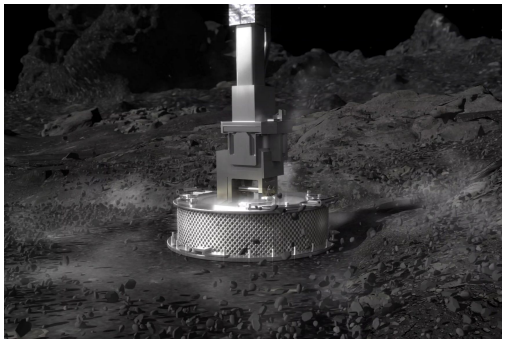
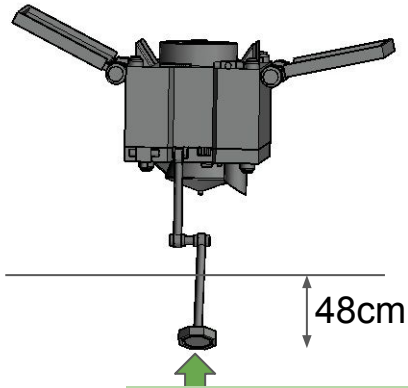
1.19 g/cm^3	55%	0.000098m/s^2

Estimated Cohesion Strength: ~1Pa





~0.006 PSI

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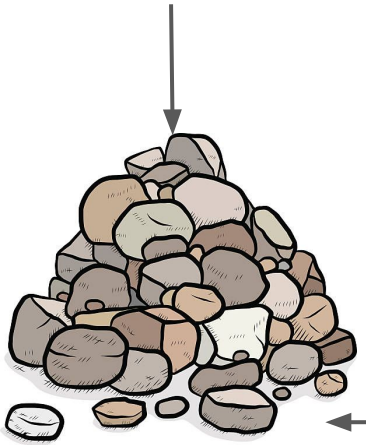
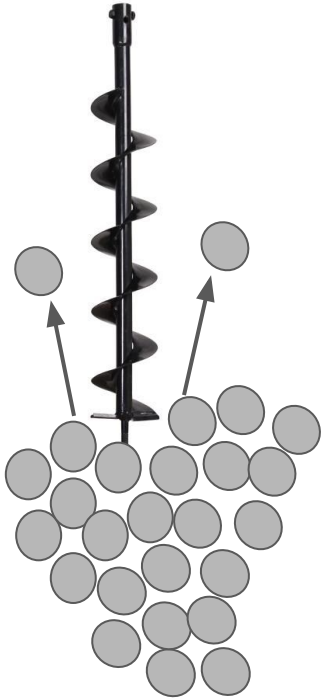
Reaction Forces

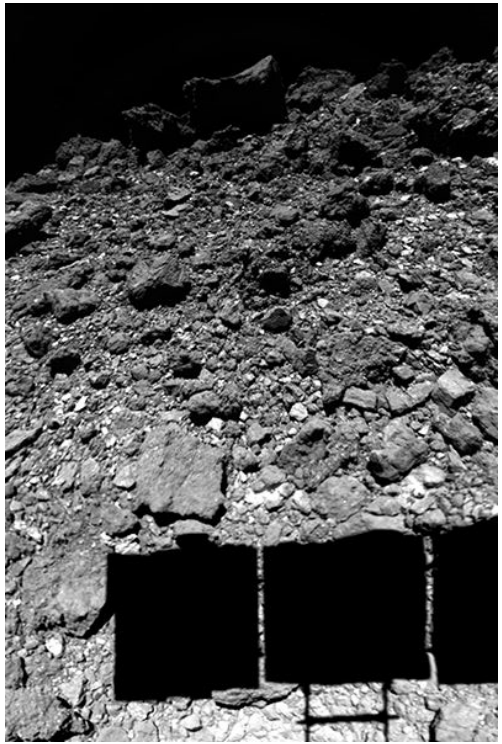




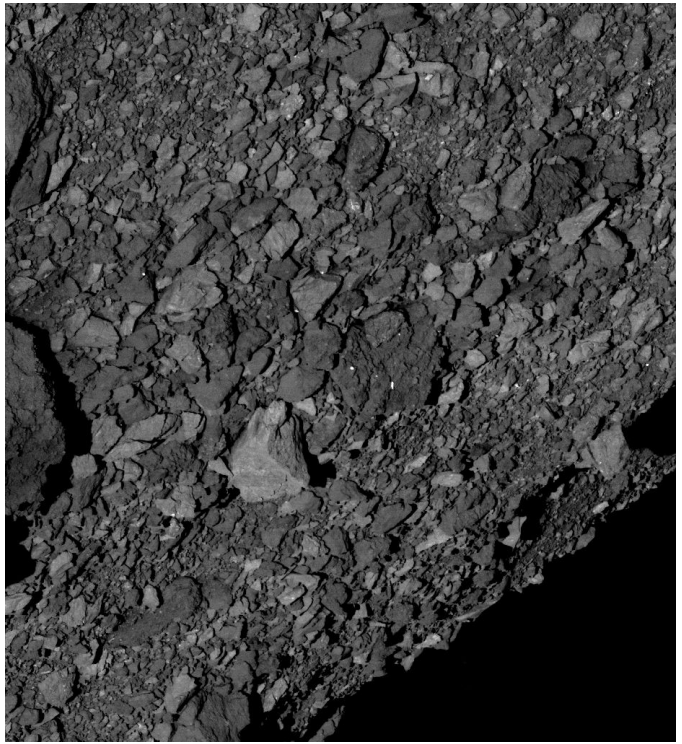
F_{exc}

Cohesion Forces
Interparticle Contact Forces (Friction)

Surface Particle Size

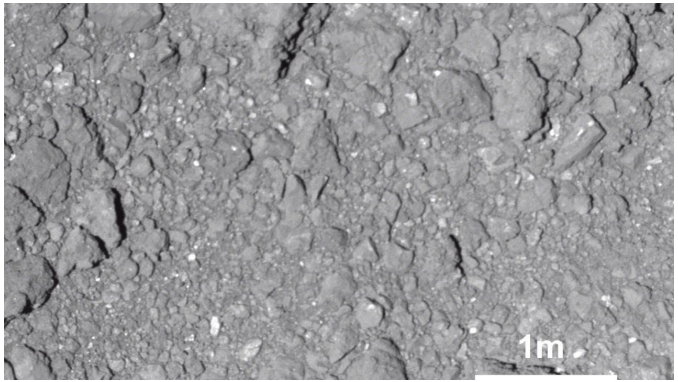


Ryugu (JAXA)



Bennu (NASA)

Surface Particle Size



Bennu (OSIRIS-REx Tagsam) NASA

Upper: Ryugu Impact Site, Lower: Frame Prior to Impactor (JAXA)

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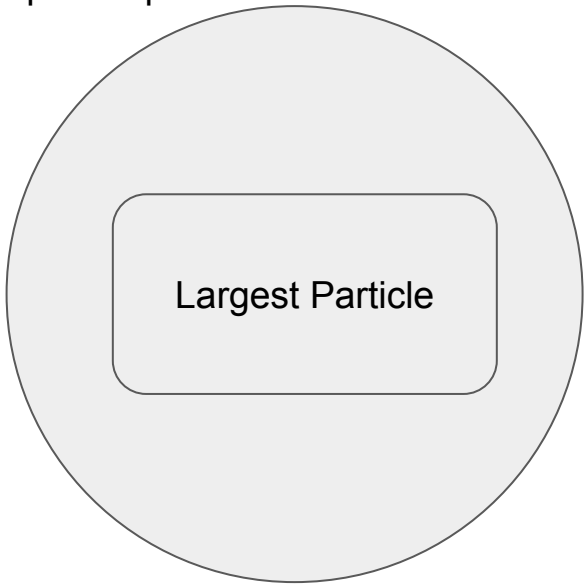
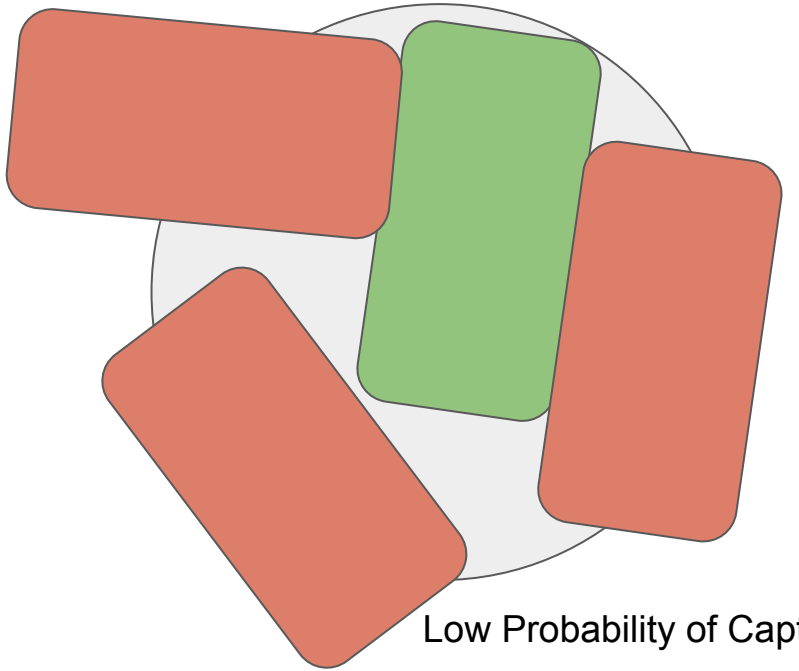
Particle Size Impact on Capture Efficiency

Capture Aperture



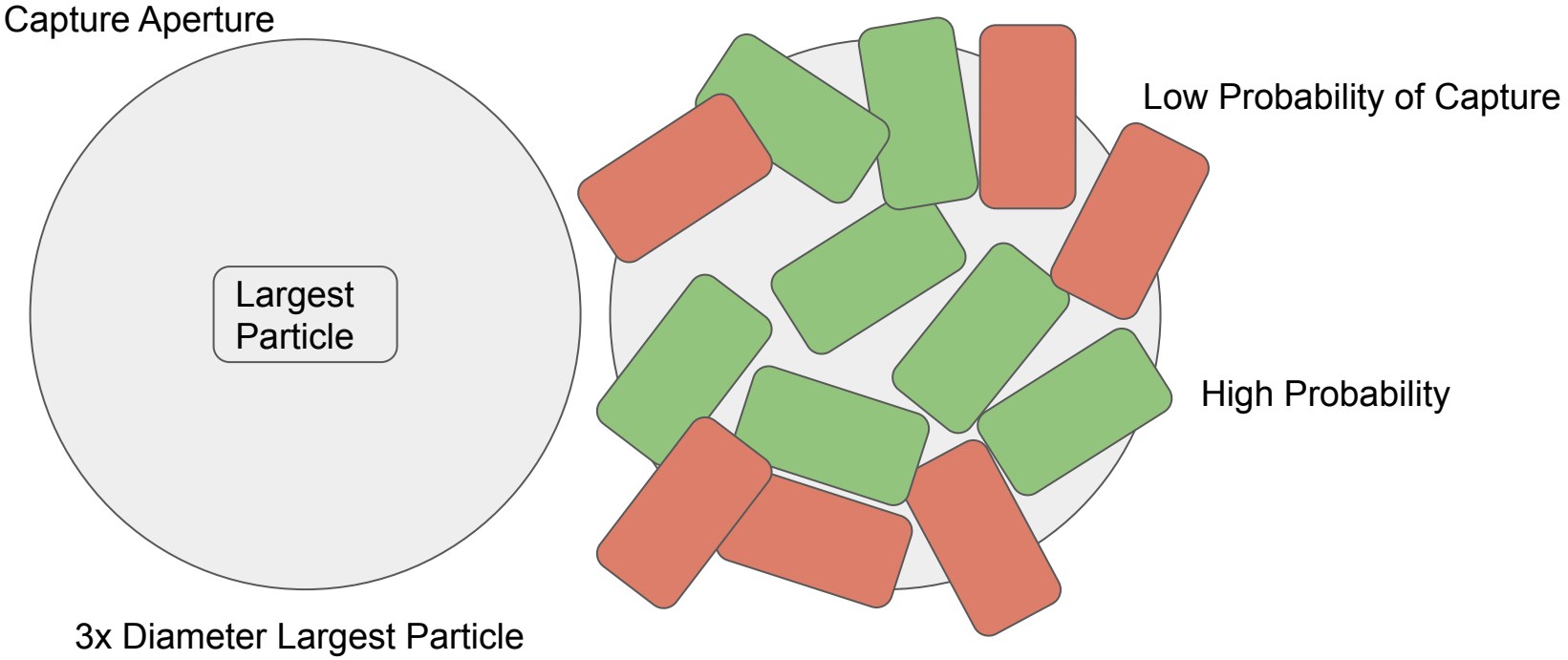
1.5x Diameter Largest Particle

High Probability

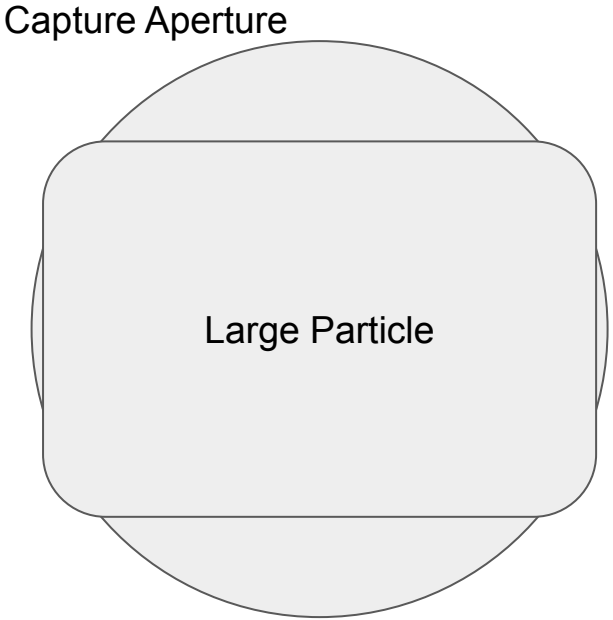


Low Probability of Capture

Particle Size Impact on Capture Efficiency

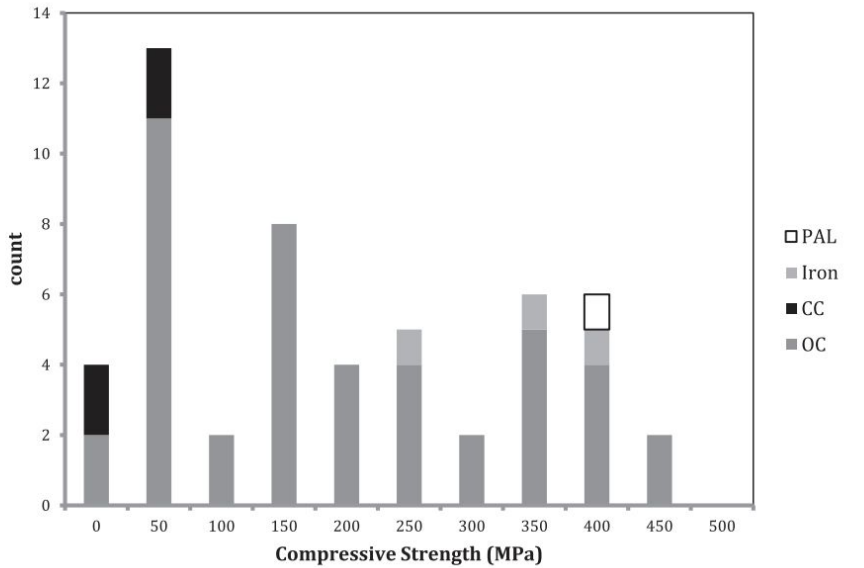


Particle Size Impact on Capture Efficiency



~9% World's Energy
Big Rocks into Little Rocks

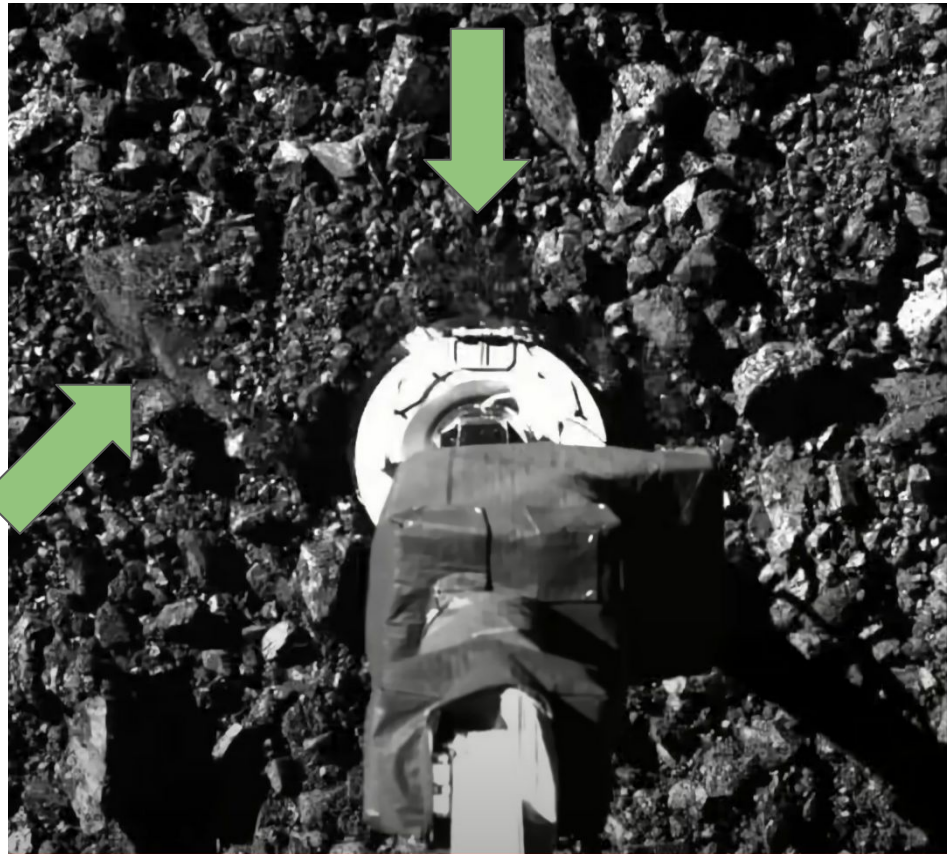
C-Type Material Strength



"Physical Properties of Meteorites" D. Ostrowski 2019

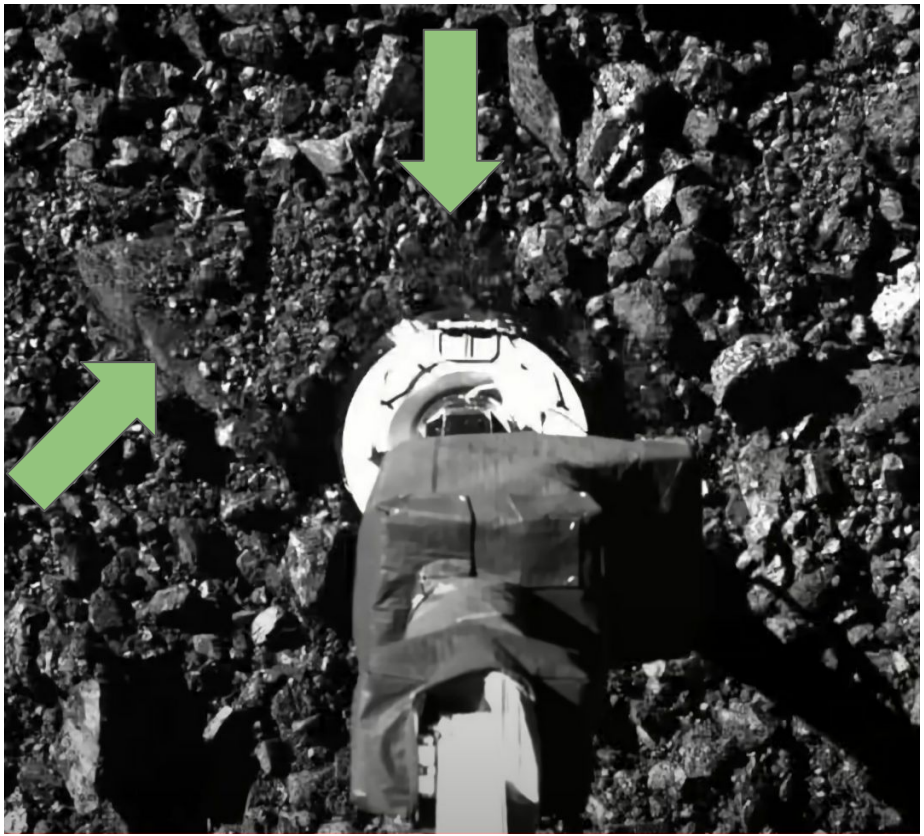
Meteorite Compressive Strength

Material	Meteorite Type	Compressive Strength (MPa)
Concrete (Unreinforced)	Typical Sidewalk	20 (3000 psi)
Charcoal Briquette		~2
Granite		100–140
Medium dirt clod		0.2-0.4
La Lande, NM	L5	373.4
Tsarev	L5	160-420
Covert (porosity 13%)	H5	75.3
Krymka	LL3	160
Seminole	H4	173
Holbrook, AZ (porosity 11%)	L6	6.2
Tagish Lake	C2	0.25-1.2
Murchison	CM	~50
Bolides	?	0.1-1



Mining NEA C-Type

1. Separating/Mobilizing Particles
   a. Low Gravity
   b. Low Cohesive Forces
2. Reduced Reaction Forces to Spacecraft
3. Low to Medium material Strength
   a. Improves Capture Efficiency



Payload Opportunity - 2026 and 2028

Chief of Engineering, Co-Founder
Daynan Crull
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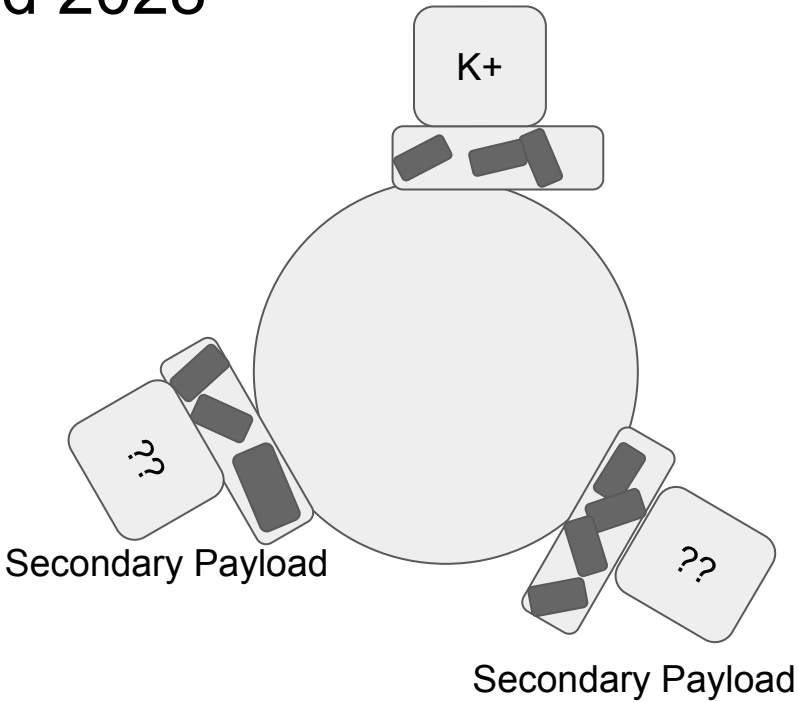
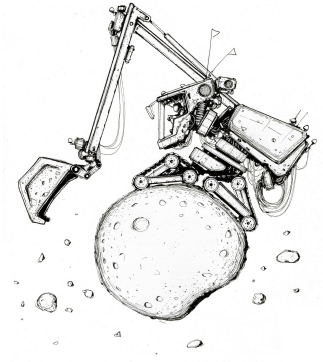
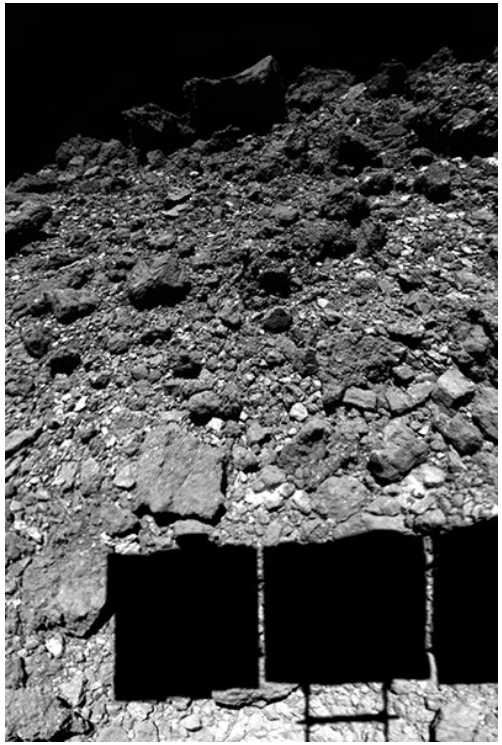
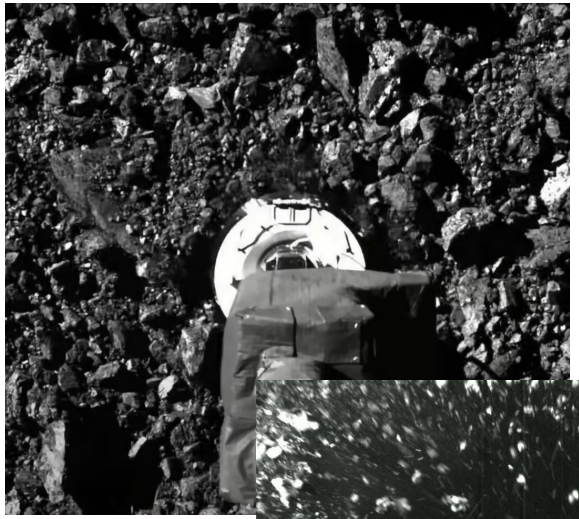


Excavation Q/A







Lead Excavation Engineer
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