Applying Mining Concepts to Accessing Asteroid Resources

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Asteroids offer both Threat and Promise –

- *Threat* of impacts delivering regional or global disaster.

- *Promise* of resources to support Humanity's long-term prosperity and expansion into the Solar System.

- The technologies to tap asteroid resources will ***also*** enable the deflection of at least some of the Impact-Threat objects

-- It is likely that the NEAs will be major resource plays of the mid 21st century

-- Thus we should seek to develop these technologies, with all due speed!!

Asteroid Resources

High and increasing discovery rate of NEAs

Growing belief that NEAs contain easily extractable products

Accessing asteroid resources is *dependent on development of market(s) for mass-in-orbit*

How to compare schemes for mining a NEA and returning the product to market??

***Capex*, *payback time*, and *net present value* are critical design drivers, in choice of <u>target</u>, <u>market</u>, <u>product</u>, <u>mission type</u>, <u>extraction process</u>, and <u>propulsion system</u>**

Huge increase in potential targets:

	Total #	> **300 m diam**	> **1 km diam**
NEAs	> 7200	> 3200	> 800
PHAs	> 1100	> 500?	> 150

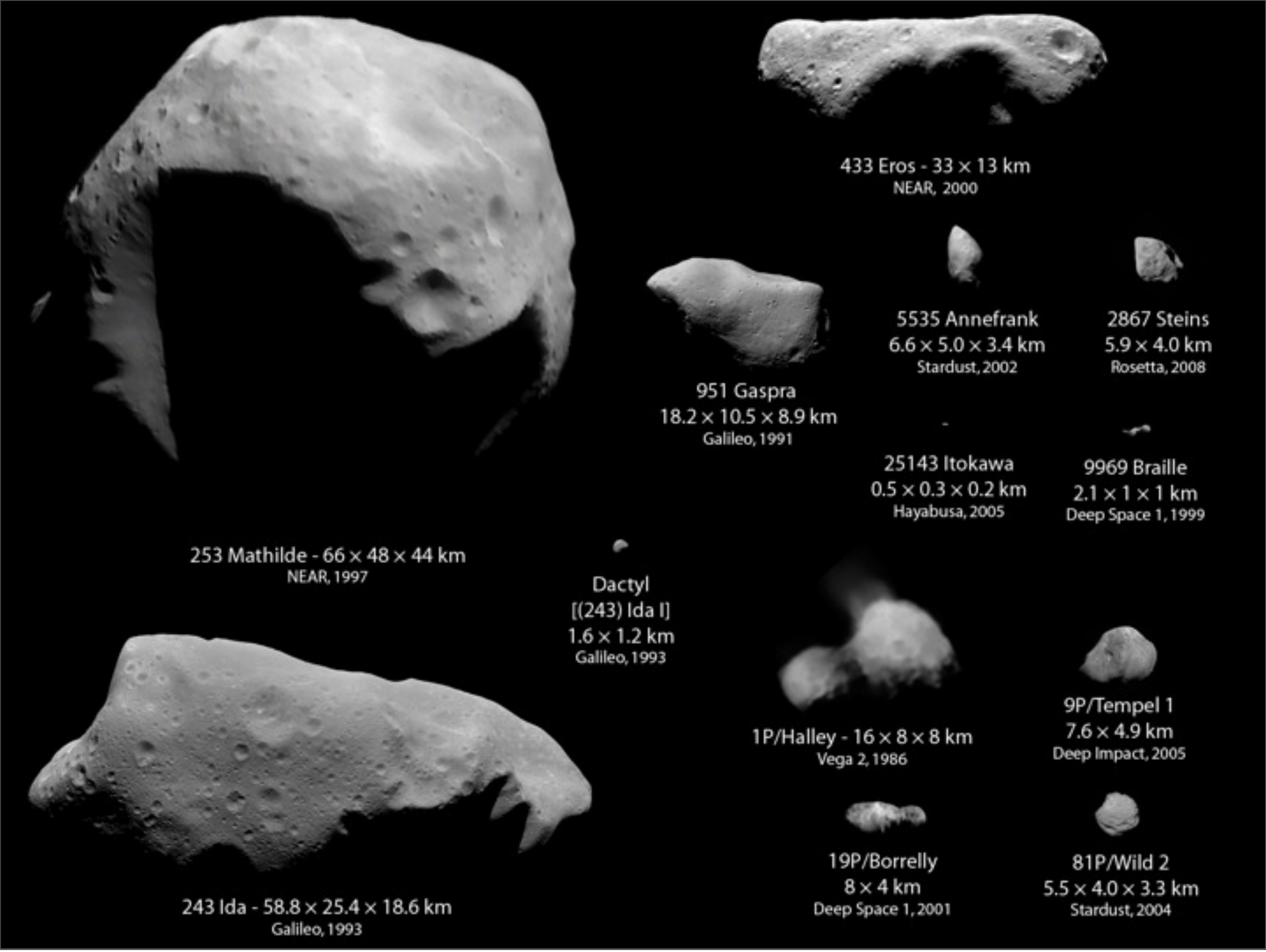
Apollos: ~ 3900

Amors: ~ 2700

Atens: ~ 590

Atiras: ~ 10

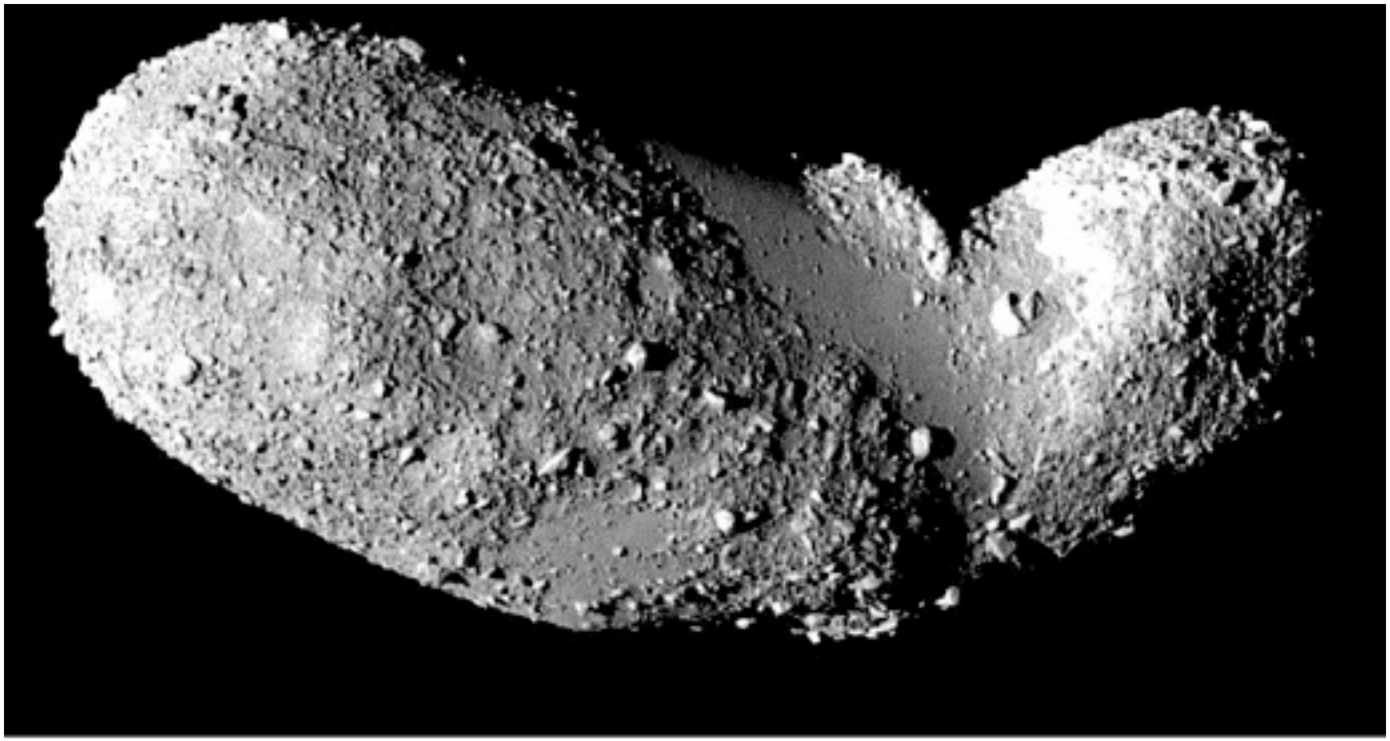
as of Oct 2010


433 Eros - 33 × 13 km
NEAR, 2000
951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993

Itokawa is close in size to a likely mining target

It's a rubble pile with lots of void space: ρ = 1.95

Regolith (!!) is gravel-size particles



We now know

- Asteroids retain deep regolith
- Often heavily fractured or rubble piles
- Have significant void space (‘macroporosity’)
- Many appear to contain H_2O in clays or salts
- Many appear to contain Ni-Fe and PGMs
- Some may be extinct comet cores

Products from asteroid mining:

- **Water, for use in space (propellant)**
- **Ni-Fe, for use in space (construction)**
- **PGMs, for return to Earth (catalyst for fuel cells)**
- **Semiconductors, for use in space (PV arrays)**
- **Raw silicate, for use in space (ballast, shielding)**

Water is an obvious product, as it can be used for PROPELLANT for the RETURN TRIP

But the in-space market is not yet in existence.......

Terrestrial *Project Development* Path:

- "Desktop" studies: *what* to look for, & *where*
- Open-literature and proprietary data reviews
- Reconnaissance of prospective target areas
- Identification of potential targets
- Field work identifies extended mineralization
- Drillout of prospect to define orebody
- Metallurgical testwork to confirm extractability
- Project conceptual planning / prefeasibility studies
- Bankable Costing & Feasibility Study (& EIS)
- Funding and Project Go-Ahead
- Construct and Commission

Mining Engineering and Economics

*“Material is **ore** only if you can **mine**, **process**, **transport** and **market** it for a **profit**”.*

<u>Terrestrial Mine Project Planning</u> involves **choosing** between ***competing mining*** *and* ***metallurgical extraction concepts***, to:

- Minimize Capital Expenditure (Capex)
- Minimize operating cost (Opex)
- Minimize payback time
- Minimize project risk ***-and thereby-***

Maximize Expectation Net Present Value

So must it be also, in Space Mining

Bankable Feasibility Study must develop:

- **A Mining Plan**, based on an
- **Accurate orebody model**, and a
- **Metallurgical Process Flowsheet**, based on
- **Accurate understanding of the ore,** which
- **maximises Recovery,** and
- **minimizes Capex**, **Opex**, and **Payback Time**, and
- **optimizes the Production Rate**, so as to

maximize the <u>Expectation Net Present Value</u>.

Choice of Mining Plan and Process is often surprisingly difficult--

Some cautionary tales from Oz mining scene --

Olympic Dam Cu-U-Au project: non-obvious mining and processing choices

Mulga Rocks U-base metals project: ditto

Nolans Rare Earths project: challenging process development

Beverley U ISL: need accurate orebody model…

Implications of the "Economic

Maximize Expectation NPV implies →

- Minimize project risk → Simplest possible extraction, processing, and propulsion systems – KISS
- Minimize CAPEX → single or double launch, unmanned;
- Maximize returned payload fraction → minimize return Δv including capture
- Minimize return Δv → target orbit low eccentricity and earth grazing; lunar flyby capture?
- Minimize payback time → minimum duration mission → target asteroid semi-major axis ~ 1 AU;
- Synodic period constraint → 'single season' mine mission

Asteroid Mining Project Economics will be driven by

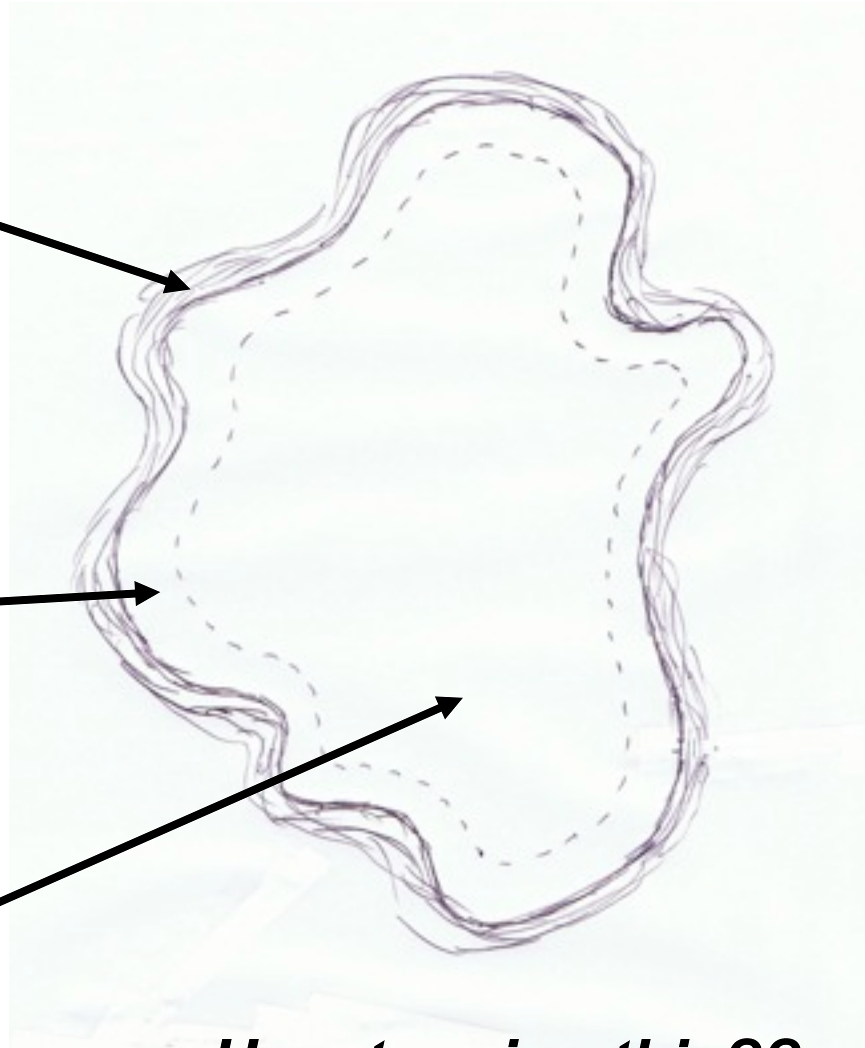
- **MINER MASS and LAUNCH COST**
- **SPECIFIC MASS THROUGHPUT OF MINER**
- **MISSION DURATION and MASS RETURNED**
- **DELTA-V for RETURN into Earth Orbit**
- **POWER & PROPULSION SYSTEM parameters**
- **VALUE PER KG DELIVERED TO LEO GEO or HEO**

Cryptocomet model:

Loose & fluffy or **cinder 'lag deposit',** insulating the underlying icy matrix (? ~1 metre)

Densified underlying ice-clay-bitumen layer of thickness ~ 2 metres

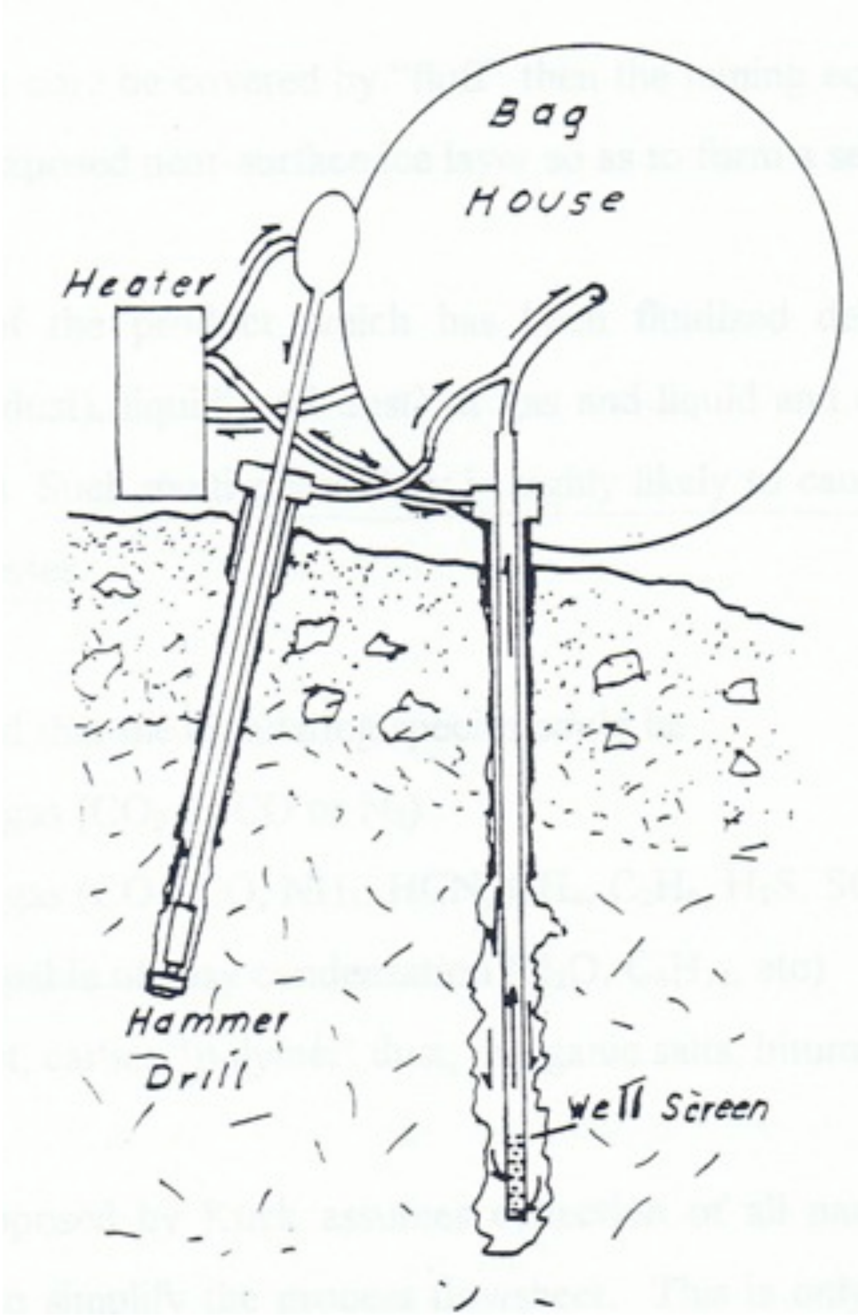
Deep porous low density ice-clay-bitumen **matrix**



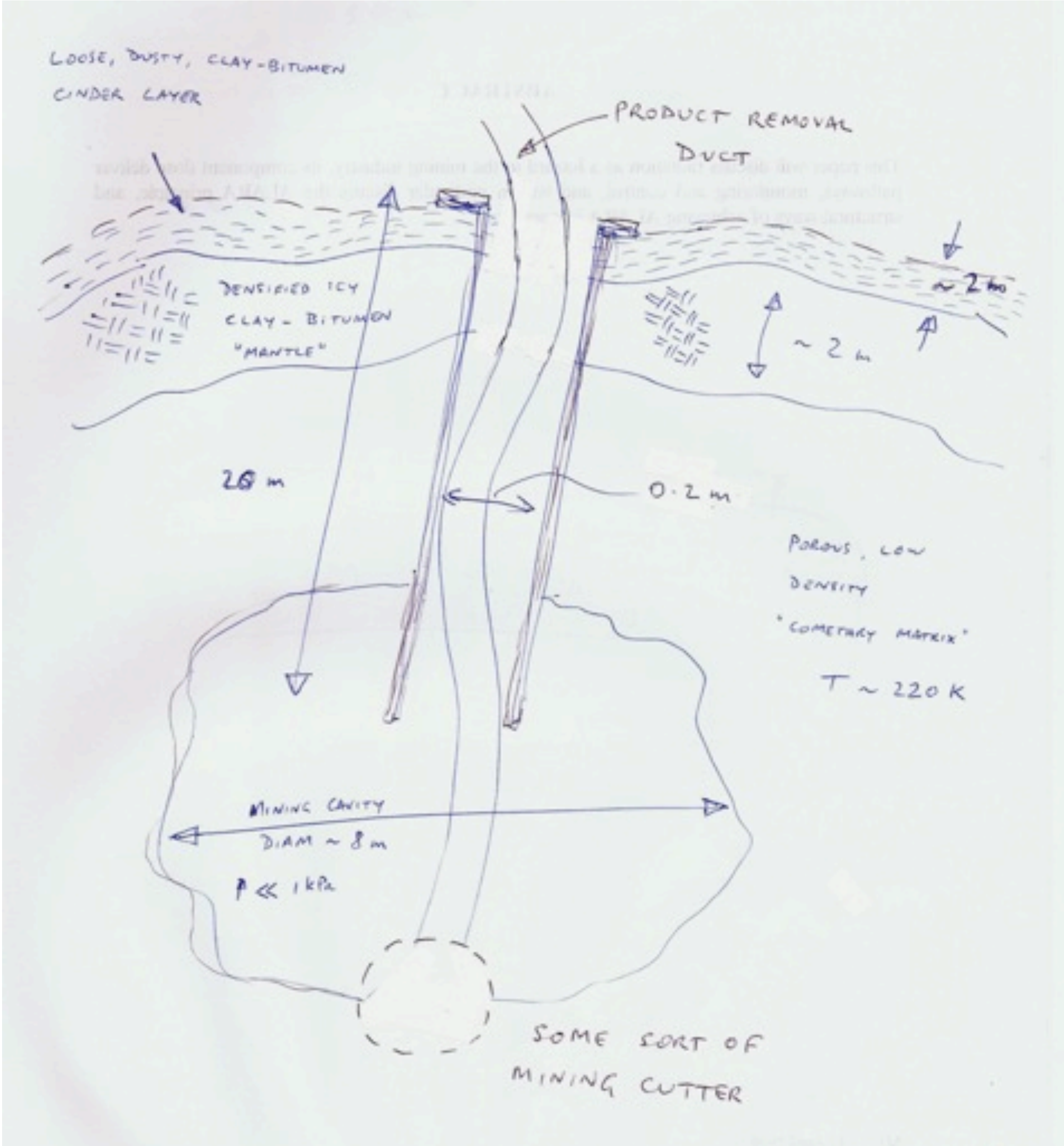
How to mine this??

David Kuck's downhole In-Situ Volatilizer miner

(based on the cryptocomet model)



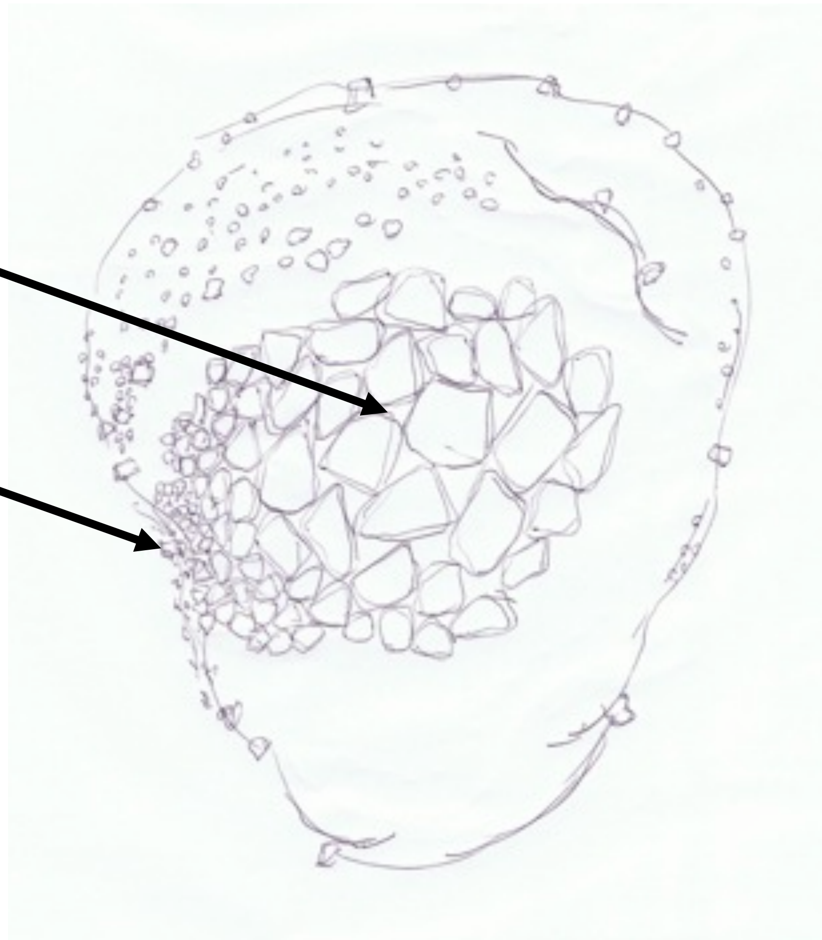
Mining Method	*Advantages*	*Disadvantages*
Surface reclaim *(rejected)*	**robust process; easy to handle loose soil; easy to monitor**	**Problems with anchoring & containment; surface will be desiccated.**
Solar Bubble vaporizer *(rejected)*	**Simple, Collects volatiles only**	**Very high membrane tension; how to anchor?**
In-Situ Volatilization *(rejected)*	**simple concept; asteroid body gives containment.**	**needs low permeability; risks are loss of fluid; clogging; & blowout.**
Explosive excavation *(rejected)*	**Very rapid release of mass, short timeline.**	**Capture of material and processing is unsolved.**
Downhole Jet Monitoring *(rejected)*	**Mechanically simple; Separates mining from processing task.**	**Need gas to transport cuttings to processor. blowout risk high.**
Underground mining by mechanical 'mole' *(accepted)*	**reduced anchoring & containment problems; physically robust**	**Mechanically severe; hard to monitor; must move cuttings to surface plant**


LOOSE, DUSTY, CLAY-BITUMEN
CINDER LAYER
PRODUCT REMOVAL
DUCT
DENSIFIED ICY
CLAY - BITUMEN
"MANTLE"
~ 2 m
~ 2 m
20 m
0.2 m
POROUS, LOW
DENSITY
"COMETARY MATRIX"
T ~ 220 K
MINING CAVITY
DIAM ~ 8 m
P ≪ 1 kPa
SOME SORT OF
MINING CUTTER

Rubble pile model:

Large boulders, voids, '**macroporosity**' at depth

Grading finer to **gravel regolith at surface**



?? Ices in voids??

How to mine this??

Mechanical miner – 'SpaceMole'?

- Cutting / comminution
- Ground control (even in micro-g)
- Containment of cuttings
- Transport of cuttings to Process Plant
- Separation and storage of product(s)

Comparisons with Terrestrial Mining

- Large, low grade, high throughput, low margin ‘commodity’ operations….

  - are not so relevant

- Remote, high grade, very high value, high margin, small throughput, exotic product operations….

  - more comparable, see following slides:

The Kalgoorlie Super Pit –

100 years of gold mining

NOT useful comparison

Value of ore at today's gold price

~ $140 / tonne

Terrestrial Remote High Value Mines

- Ekati diamond mine, Canada (access by ice road, 10 weeks per year)
- Namibia offshore diamond dredging (Skeleton Coast)
- Garimpeiro (illegal) goldminers in Brazil and elsewhere
- Bulolo goldmines, New Guinea, 1930's (more airfreight than *entire rest of world total*, to build 3 x 1200 tonne dredges)
- Port Radium, Canada, 1930's (Radium was $50,000 / gram!)
- Nautilus Deep Sea Massive Sulphides (Manus Basin, PNG)

BHP-Billiton Ekati Diamond mine, NWT, Canada:

10 weeks road access per year, over ice roads….

Molybdenum mine in the Bolivian Andes

At the height of the Mt Kare gold rush in the highlands of Papua New Guinea, these villagers would flag down passing helicopter taxis to fly them to the bank…

Andamooka opal fields

Bulolo Goldfields, 1930


Papua New Guinea (PNG)
and Northern Australia

Notes from Terrestrial Mining (2)

Vast range of orebody types & geometries, thus vast range of mining methods:

- Open pit (shallow or deep, soft or hard rock, strip mine, dredge, …)
- Underground (room & pillar, Long-Hole Open Stoping, cut & fill, block cave)…
- In Situ Leach...

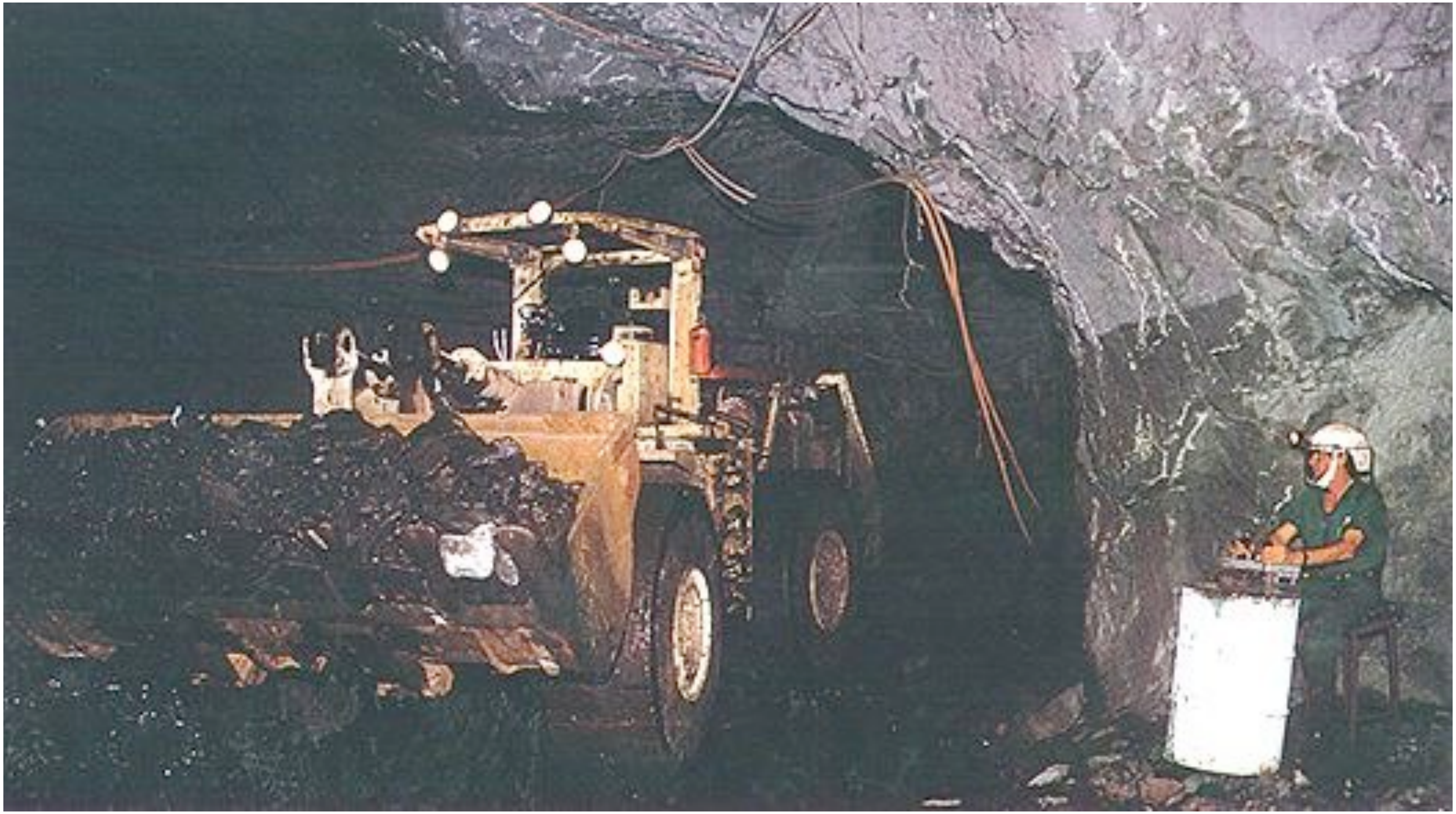
Must choose correctly or risk your project

Haul truck, Prominent Hill Copper Mine, 200 km NW of Woomera, South Australia: Cu grade = 2%; 0.2 g/t Au

Value of ore at today's Cu price = $170 / tonne

Heavy Mineral Sands mine, Stradbroke Island, Brisbane

(Titanium, Zircon)



Miner (in Airstream helmet) bogging out a Trough Undercut using a radiocontrolled Front End Loader

Pilot Plant (above)

General Atomics' Beverley Uranium *In-Situ Leach* Operation in South Australia

Notes from Terrestrial Mining (2)

Metallurgical flowsheet: how to separate the product(s) from the waste - More complex if trying to extract multiple products:

Solid / solid separation : density or electrostatic

Solid / liquid sep’n: by dissolution / precip’n

Solid / vapour sep’n: volatilization, eg Mond process
(nb Vapour processes are *limited by low massflows)*

Liquid / liquid: smelting, melt electrolysis etc

-- *Must choose correctly or you may lose your project*

Ore grade is measured in…

- Gold: grams per tonne (ppm)
- Uranium: kg per tonne
- Pb, Ni, Cu: %

But in reality, mining engineers talk about ore grade in terms of -- ***$ per tonne***

So should we… for example, see next:

PGMs or Water?

- Assume we have a target asteroid which contains ***50 ppm PGMs*** and ***10% H_2O:***

- ***PGMs value*** ~ $4,000 / tonne of regolith
- ***H_2O value*** ~ $1,000,000 / tonne of regolith

  (at $10,000 per kg cost delivered in LEO)

Is this *"ore"* ?

- ***Only if we can mine, process, transport, and sell the product, AT A PROFIT…***

Comparisons with Terrestrial (2)

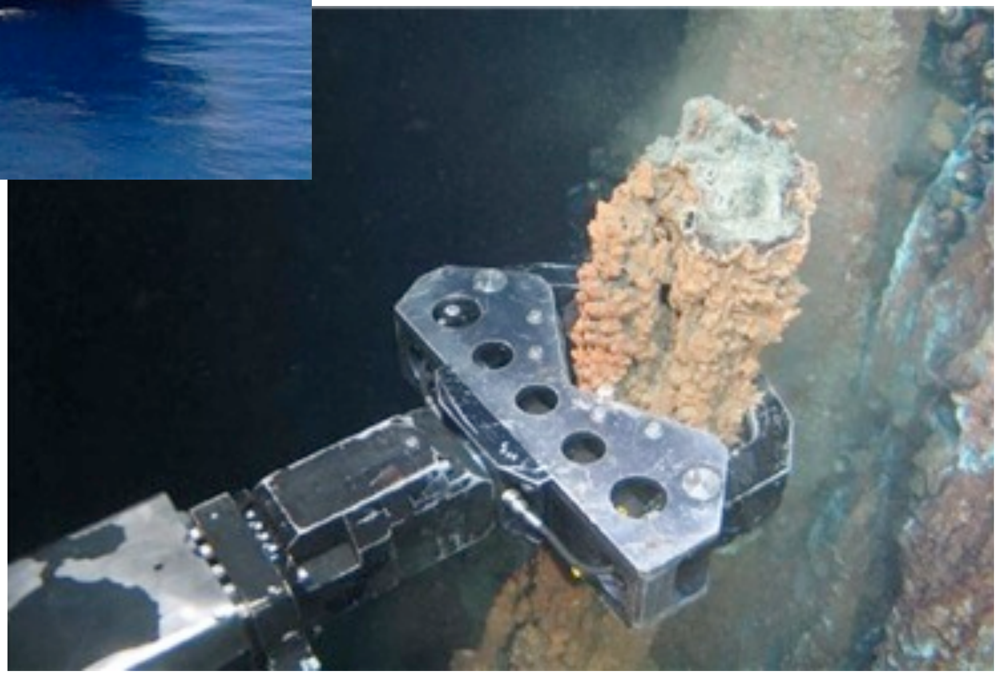
Seabed Mining of Massive Metal Sulphides in Volcanic Black Smoker Vent chimneys

Some interesting parallels ---

- very high value ore
- small multiple deposits
- low mass throughput (down by factor of 50)
- mobile, teleoperated equipt

Seabed Massive Sulphides …

Metal grades can be +50%



Exploring for ***Seabed Massive Sulphides*** offshore PNG

(in active Black Smokers and extinct Black Smoker chimney strewnfields)

Why Seabed Massive Sulphides --

- Lower discovery costs: exposed, easy sampling
- Low cost / easy trial mining
- Shorter development lead time: easy ore access (no shaft, decline, or prestrip)
- No landowner compensation costs
- Cheaper beneficiation, easier metallurgy, less materials handling: all due to ultra-high grade
- No ‘pit to port’ infrastructure: major Capex item in terrestrial mining

Seabed Massive Sulphides (continued)

- Cheaper plant: build in shipyard, sail to site
- FPSO vessel can even be *leased*: removes single biggest Capex item!
- Single plant can access several deposits sequentially, hence -
- Lower feasibility hurdle: access to multiple deposits plus plant mobility means not necessary to confirm full ‘mine life’ reserves
- Much less waste & enviro impact due to low mass throughput: thanks to ultra-high grades

(adapted from presentation by Julian Malnic, Nautilus CEO, 2000)

Comparisons with Terrestrial (3)

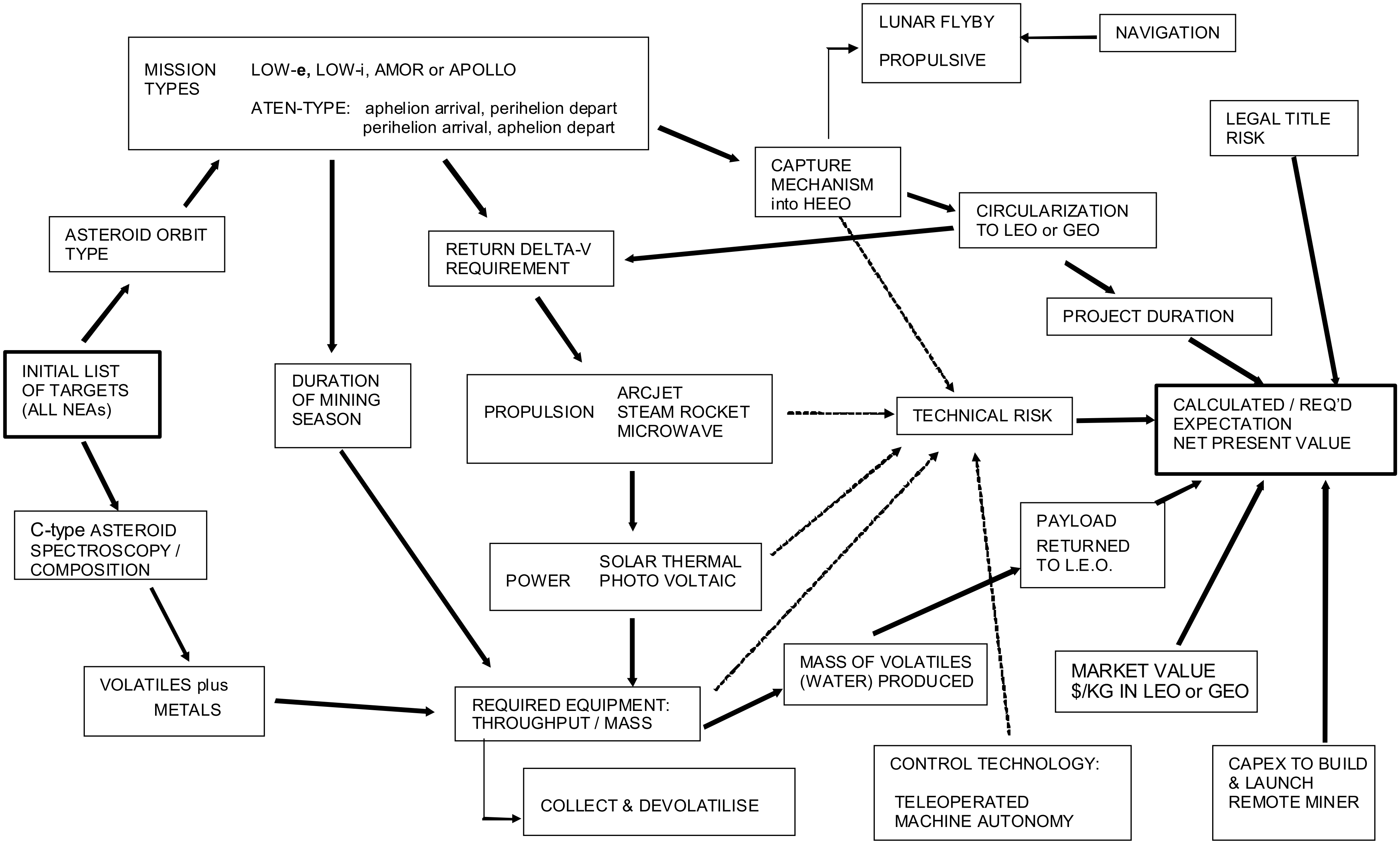
- NEAs *prolific*, with subset having low Δv
- Many are prospective for H_2O, Ni-Fe
- *Very* valuable ore ($\$1 \times 10^6$ / tonne)
- *Easy* extraction (??)
- Target return parcels ~ 1000 tonnes

- ***Analogous to short campaign Trial Mining***

So what will an Asteroid Miner look like?? – I don’t know, but:

- Design depends on target orebody ‘model’
- Small, highly integrated, digger plus processor
- Almost certainly reliant on ISPP for return
- Almost certainly solar powered

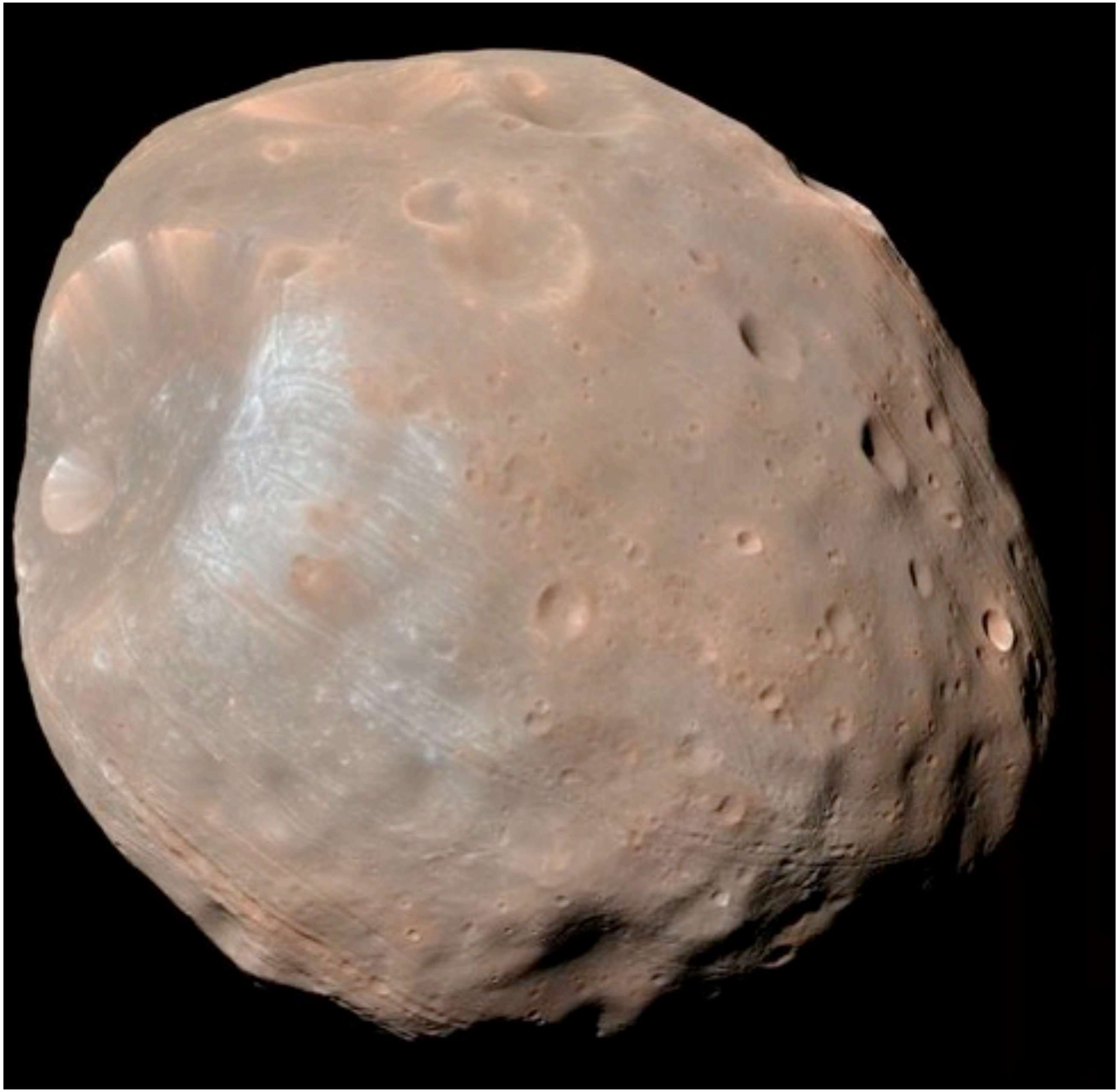
- I assume first product is H_2O, delivered into LEO, GEO, or HEEO
- *We await development of market in orbit…*



The "Sonter Spider Diagram" – for what it's worth…

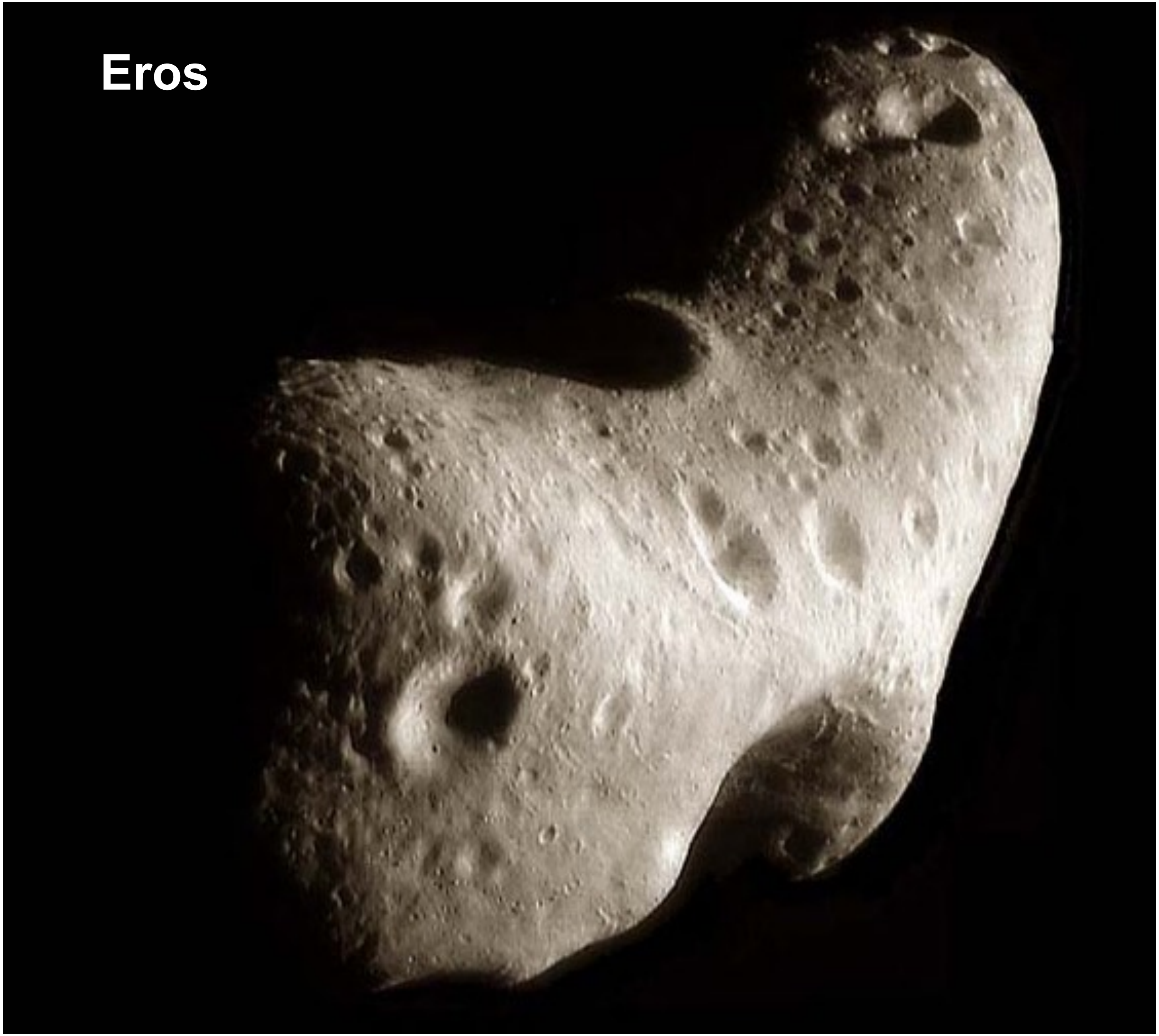
Just an afterthought:

The Mass Driver concept would still be a very powerful enabler, allowing use of untreated regolith as propellant



Thanks for your interest –

Any Comments?


Eros

Lots of new knowledge:

- Targets (generated by new search programs)
- Images, Concepts and understanding

- **But mining is *difficult*, even on Earth!**

  (we will come back to this, later--)