Scoping Studies for Asteroid Mining Projects

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Asteroids and Comets Visited:
Near-Earth Asteroids Discovered

Total per Size Bin (as of 2017–Sep–18)

Estimated Diameter (m)

- 0-30: 3,016
- 30-100: 4,580
- 100-300: 4,208
- 300-1000: 3,860
- 1000+: 881

https://cneos.jpl.nasa.gov/stats/
Defining our Asteroid Projects:

How to identify our targets?
   By orbit, type, accessibility

What, & how big, & when, is our market?
   Water? Metal? Storable Fuels? (Silicon? PGMs? – later, only)

Delivery to where?
   LEO? GEO? E-M L1 or L2? Moon? HEEO for Mars departure?

Mining Method:
   Surface reclaim? Underground? ISR?

Beneficiation & Processing:
   Mechanical? Electrostatic? Vapour process? Pyro or hydro?

Return Propulsion & Earth Capture:
   Type & origin of propellant, lunar flyby, + other tricks?
Terrestrial Mine Project Planning:

Means choosing between competing mining & processing concepts, to:

• Provide desired production rate,
• Minimize Capex & Opex, and
• Minimize payback time, and minimize project risk,
• -and thereby-
  Maximize Expectation Net Present Value

--So must it be also, in asteroid mining...
Notes from Terrestrial Mining:

There is a vast range of orebody sizes, types, & geometries, thus vast range of mining methods & processing methods to choose from:

- Open pit (shallow / deep, soft / hard rock, strip mine, dredge)

- Underground -large vertical extent: Long-Hole Open Stoping, airleg or mechanised cut & fill, block cave;

  -large horizontal extent: room & pillar, longwall miner...

- In Situ Leach / In-Stope Leach / solution mining...

You must understand your orebody and choose correct mining and processing methods or risk project failure

Same will apply with asteroid mining...
Choice of Mining Plan and Process Flowsheet is often *surprisingly difficult*--

Some cautionary tales from Oz mining scene --

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

**Mulga Rock** U+ base metals project: *ditto ditto*

**Nolans Bore** Rare Earths project: *very* challenging process development

**Beverley** U In-Situ Leach: seriously compromised by lack of accurate orebody model...
Some terrestrial examples

Mulga Rock Uranium Project Update
1 August 2014
Presentation to Department of Mines and Petroleum
Mines Safety – Resource Safety Division

BROWNS RANGE PROJECT
Definitive Feasibility Study
Executive Summary

Our vision is to become the first significant dysprosium producer outside of China.

NOLANS DEVELOPMENT REPORT
SEPTEMBER 2014
Similarly in asteroid mining:

- Target-dependent choice of regolith model, and hence applicable mining / processing technologies
- Concept-level choices in
  - mass return
  - power & propulsion
  - processing at-asteroid / in earth-orbit
  - Delivery to market(s)
  - allowable mission timeline

As in terrestrial mining, it’s ‘horses for courses’ --
These questions are the basis of a Concepts / Pre-Scoping Study
Terrestrial Mining Project Pathway:

“Desktop” studies (includes open-literature data reviews):
- Decide what mineral to look for, & where
- Identify prospective areas & select potential targets

Theory & field work to identify mineralized ‘prospects’
Define ‘inferred mineral resource’ (tonnes, grade)

Then Concept / Scoping Study (investigate mining methods, processing options etc)

Metallurgical testwork to confirm extractability

Project planning / Prefeasibility studies - ‘PFS’
Definitive Costing & Feasibility Study - ‘DFS’

Funding & Project Go-Ahead (+ Licensing / Permitting!)
then Construct and Commission
The ‘Studies Sequence’

• Desktop / Conceptual Study -- what mineral are we chasing? - list & compare project options - feasible?

• Scoping Study -- concept? desired production rate? - can we quantify the market? Costs to +/- 50%

• Pre-Feasibility Study (PFS) -- capex and opex costs to +/- 25%

• Final / Definitive / Bankable Feasibility Study (DFS) -- costs to +/- 15%; de-risked to max extent possible
So- What is a Scoping Study?

It’s the First Pass at:

– Defining market
– Defining project concept alternatives & timeline
– Setting size, throughput / production
– Flowsheet & equipt functions and size
– Capex and Opex guesstimates

I have been working up a ‘Generic Pre-Scoping Study’
Typical Scoping / PFS Contents Page:

- Market & Potential Sales
- Geology, Mineralogy & Resource
- Access / Tenure
- Mining Concept(s)
- Metallurgy / Processing Flowsheet Concept(s)
- Tailings Management
- Logistics & Infrastructure
- Power, Water, & Comms
- Project plan & Implementation
- Capex / Opex
- Risk assessment
- Financial evaluation
Project concept dev:

• Market: commodity, size, location, price?
• What class of targets?
• What orbit & mission type?
• Mining season duration?
• Mission duration?
• Extraction / recovery?
• Return propulsion?
Identify Targets

Selection Rules / Figures of Merit
- gives first-pass ‘short-lists’ of targets

Probabilistic resources assessment of target(s)

Target mission profile (Apollo / Amor / Aten)

Assessment of return parameters
- gives ‘sieved’ target shortlists
## ‘Existence Proof’ Target List*

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Size (m)</th>
<th>Albedo/ Type</th>
<th>OCC</th>
<th>dV from LEO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 US16</td>
<td>500</td>
<td>K or Xc</td>
<td>0</td>
<td>4.43</td>
<td>(km/s)</td>
</tr>
<tr>
<td>1999 JU3</td>
<td>870</td>
<td>C</td>
<td>0</td>
<td>4.65</td>
<td></td>
</tr>
<tr>
<td>10955 Bennu</td>
<td>484</td>
<td>0.046 / C</td>
<td>0</td>
<td>5.09</td>
<td></td>
</tr>
<tr>
<td>65803 Didymos</td>
<td>1000</td>
<td>Xk</td>
<td>0</td>
<td>5.10</td>
<td></td>
</tr>
<tr>
<td>2002 AT4</td>
<td>300</td>
<td>0.04 / D</td>
<td>0</td>
<td>5.55</td>
<td></td>
</tr>
</tbody>
</table>

* Top 5 prospects after excluding high OCCs and sizes < 50 m

GOOD TARGETS EXIST!
Estimation of Mineral Resources

- ‘Measured’ / ‘Indicated’ / ‘Inferred’
- ‘Exploration Target’ or ‘Unclassified Mineral Inventory’
- ‘Endowment’ or ‘Contingent Resource’

Both JORC and NI 43-101 require transparency in showing how the asserted resource estimate is derived...

- Parallels with Deep Seabed Nodules & Seamount Black Smoker VMS deposits
- Parallels with coal, bauxite, & Coal Seam Gas estimates
  - I have generated robust ‘JORC-like’ asteroid resource estimates on hypothetical targets:
Spreadsheet showing *Scenario Probability Tree* calculation of Mineral Inventory Estimate for Water Recovery from top 2 m of Hypothetical Dark Asteroid ‘2016 XY’
Here’s how the oil guys assess the resulting Probability Distributions. Previous slide indicates we have a ‘discovery’...
# Mining Methods ‘Portfolio’

<table>
<thead>
<tr>
<th>Mining Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface reclaim cutter <em>accepted</em> Rassor</td>
<td>robust process; easy handling; easy to monitor</td>
<td>Problems w anchoring &amp; containment. Dust threat</td>
</tr>
<tr>
<td>Underground mole / cutter <em>accepted</em></td>
<td>reduced anchoring &amp; containment problems</td>
<td>Mechanically severe; how to move cuttings unresolved</td>
</tr>
<tr>
<td>Solar Bubble vaporizer <em>??</em> Sercel</td>
<td>Simple, Collects volatiles only</td>
<td>High membrane tension; how to (a) seal (b) anchor?</td>
</tr>
<tr>
<td>In-Situ Hot Gas <em>rejected</em> Kuck</td>
<td>simple concept; asteroid body gives containment.</td>
<td>risks loss of fluid; clogging; &amp; blowout. Heat transport probs</td>
</tr>
<tr>
<td>Reclaim via ERE <em>accepted</em></td>
<td>Provides intrinsic downforce.</td>
<td>Power reqt. may be excessive</td>
</tr>
<tr>
<td>Downhole Pressure Jet Monitoring <em>??</em></td>
<td>simple; separates mining from processing.</td>
<td>Need gas to transport cuttings. Significant blowout risk?</td>
</tr>
<tr>
<td>In-Situ Microwave <em>very promising</em></td>
<td>Simple, direct</td>
<td>Query power reqt &amp; TRL</td>
</tr>
</tbody>
</table>
Asteroid Mining Economics will be driven by **Capex, payback time, & Net Present Value**: 

- Mission duration and Mass returned
- Specific mass throughput of miner
- Miner mass and launch cost
- Delta-v for return from asteroid to Earth Orbit Capture
- Power & Propulsion systems parameters

- And VALUE PER KG delivered to **LEO, GEO or HEEO**
What is the **Minimum Viable Project**?

- Capex reduction is critical
- Show technical proof
- Make some money, draw in further investors
  - How low can we go, then bootstrap up?

Beverley Uranium Project Trial 1998
This was the Minimum Viable Project for Olympic Dam Cu-U-Au-Ag mine and treatment plant (photo 1988)

(very big!!)
What does all this mean??

Of the >15,000 known NEAs, approx 50% are ‘big enough’ (100m diam) to (a) grow and retain mineable regolith, and (b) to ‘visually acquire’ on the way out

Of these known 7500, an identified 1400 or so are intermittently ‘more accessible than the Moon’ (<6 km/sec outbound from LEO to rendezvous)

Of these 1400, about 10-20% give intermittent very low delta-v’s for return to Earth-capture (dv < 2 km/s)*

* Capture via lunar flyby or aerobraking

Of these known 200 or so, statistically 50% are dark (‘C-complex’, including D and P class), and thus potentially water and volatiles rich (but we don’t yet have spectra to know which ones..)

Thus, we have a 50% chance of any chosen target being a ‘water orebody’, even without spectral or albedo information
Finally-
Can we ‘close the business case’?

- Positive NPV
- Minimize CAPEX & OPEX
- Minimize payback time
- Meet acceptable price points

Only the PFS / DFS can tell us this...

But first we have to do the Concepts / Scoping Study..
Concepts Development & Pre-Scoping Study gives the basis for choosing viable missions, & identifying knowledge gaps to be addressed, & sets the basis for Pre-Feasibility and Final (Bankable) Feasibility Studies.

A necessary step along the way...
Thanks!

Questions?
Mining 101 … a browse around ‘projects I have known’ and other stuff…

The Kalgoorlie ‘Super-Pit’
Cobar Copper

Note (a) old u/g workings showing in side of pit
(b) decline portal at base of open pit ..
Even smaller: Nabarlek, mined out in 7 months, 1979, processed 1980-90
Orebody interpretation & Reserve estimates are important and depend on price.
Need to understand your orebody...
What about ‘underground’: ‘Old School’ airleg miner

...your stainless steel cutlery are thanks to this sweaty guy in Kambalda, drilling out little one-man stopes chasing veins of 15% nickel sulphide... *they still do this stuff...*

The Kambalda story:

Discovery drillhole: 28 Jan 1966;

First concentrate shipment: 15 July 1967...

*18 months for shaft-sink, develop mine, construct concentrator, and first shipment!!*
Now: automated stope drill, will drill a whole fan of blastholes without human intervention.. set-and-forget; get man out of hazard area...
This is a ‘two-boom development jumbo’
Load-Haul-Dump & 50-tonne haul truck

Olympic Dam 1988
Thinking in three dimensions...

Open Stopes are massive voids the size of large skyscraper office blocks
Yep, this is the famous Olympic Dam, biggest underground mine in Oz...
Beverley Field
Leach Trial 1998
(Pilot Plant)
How the Beverley ISR Mine Works

Mining Process:
1. Groundwater pumped to surface
2. Small amount of acid and oxidant added
3. Water pumped back into aquifer
4. Uranium dissolved
5. Water pumped to surface
6. Uranium taken out of the water
7. Water recycled back to 2
Beverley ISL Uranium mine
Then there’s dredge mining, like here on North Stradbroke Island (‘Straddie’)

Heavy Mineral Sands, for zircon, rutile, and ilmenite.
I got involved due to the presence (as in all HMS) of radioactive monazite, a rare earths-thorium phosphate.
Comparisons with Terrestrial Mining

Best comparisons are NOT with large low grade high tonnage mines but with Remote, high grade, high margin, small throughput, very high value product operations…..

see following slides:
BHP-Billiton Ekati Diamond mine, NWT, Canada:

10 weeks ice road access per year....
At the height of the Mt Kare gold rush in the highlands of PNG, these villagers would *flag down passing helicopter taxis to fly them to the bank*…

Rio, who had the mining lease, couldn’t do a thing about it…
Andamooka opal fields, South Australia

Rule # 1:
Behave, there’s lots of open mine shafts...
Bulolo Goldfields, 1930's

Read ‘Not a Poor Man’s Field’ by Waterhouse, Halstead Press
Diamond dredging, Namibia
Shinkolobwe, Belgian Congo

..real Joseph Conrad "Heart of Darkness" setting..

-- now subject to ‘artisanal’ (uncontrolled) mining for ‘coltan’ for mobile phones.. (niobium/tantalum)
Exploring for **Seabed Massive Sulphides** offshore PNG

(in active and extinct Black Smoker chimney strewnfields on seamounts) - at 1.5 km depth.

Metal grades can be +50%
Lessons for asteroid mining?

- Mineralization, ore, orebody, ore reserve..
- Asteroid resources are very **high value**..
- Probability of successful search **very high**..
- Very non-trivial nature of project definition..
- Do not choose between options too soon..
- Progression of de-risking studies: Scoping, Pre-Feasibility, and Bankable Feasibility Studies..
- Need to focus, *focus* on CAPEX reduction..