Ocean Mining
Potential and Technological Challenges

Adi Kurniawan

23 April 2013
Outline

Is there gold underwater?

Why ocean mining?

Is it feasible?

Conclusion
Is there gold in sea water?
Is there gold in sea water?

Yes, nearly 20 million tons of it.
Is there gold in sea water?

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Is there gold in sea water?

Yes, nearly 20 million tons of it.

But it is so dilute (on the order of parts per trillion).

In 1920s, Fritz Haber, Nobel laureate in Chemistry, tried to extract gold from sea water, but concluded that it was uneconomic.
What about the sea floor?
Offshore placers: Oldest example of offshore mining

- The minerals are eroded from rocks and transported by rivers to the ocean
- Concentrated by waves, tides, and currents to form placer deposits in relatively shallow waters (less than 400 m)
- Metals: gold, tin, iron, etc.
- Non-metals: diamonds, sand, gravel
Offshore placer deposits

Erry et al. (2000)
Phosphorites

- Water depths: 400–500 m
- Supply of phosphates, for fertiliser

www.oceanflore.com
Manganese nodules

Halbach & Fellerer (1980)
Manganese nodules

- Water depths: 3000–6000 m
- Metal contents: nickel, copper, cobalt, manganese
- Contain more nickel and cobalt and almost as much manganese as all known metal deposits on land

Hein et al. (2013)
The nodules remained a geological curiosity until 1965

Mero estimated the amount of manganese nodules on the Pacific deep-sea floor to be over one trillion tonnes.

More recent estimates (Morgan, 2000) indicates 34 billion tonnes of nodules:

- 7.5 bt of Mn
- 78 mt of Co
- 340 mt of Ni
- 265 mt of Cu
The first pilot mining of manganese nodules (1978)

- Location: south of Hawaii
- About 800 tonnes of nodules in total were harvested
- A modified drill ship (SEDCO 445) was used as the mining platform
Manganese nodule deposits

Erry et al. (2000)
Ferro-manganese crusts

- Up to 25-cm thick layers found on the sides and summits of seamounts
- Water depths: 400–4000 m
- Similar composition to manganese nodules, but higher in cobalt content

Hein et al. (2013)
Metalliferous sediments

Water depths: 2000–3000 m

Resource potential of the Atlantis II Deep, Red Sea

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<tr>
<th>Metal</th>
<th>Grade (wt. %)</th>
<th>Weight (tonnes)</th>
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<td>Metalliferous sediments</td>
<td></td>
<td>89,500,000</td>
</tr>
<tr>
<td>Zn</td>
<td>2.06</td>
<td>1,838,000</td>
</tr>
<tr>
<td>Cu</td>
<td>0.45</td>
<td>404,000</td>
</tr>
<tr>
<td>Ag</td>
<td>38.4 g/t</td>
<td>3432</td>
</tr>
<tr>
<td>Au</td>
<td>0.5 g/t</td>
<td>45</td>
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Rona (2008)

Bertram et al. (2011)
Seafloor massive sulfides (SMS)

- Water depths: 1000–4000 m
- Located around hydrothermal vents, which are volcanic hot springs on the seafloor
- High concentrations of copper, zinc, lead, gold, and silver
The first hydrothermal vents were discovered in 1977

Researchers discovered them in the Pacific Ocean off the coast of the Galapagos Islands.
Massive sulfide deposits

Erry et al. (2000)
Methane hydrates

- A mixture of natural gas and water compressed into solids
- Has the potential to satisfy world energy needs for centuries

Erry et al. (2000)

Wikipedia
Hydrate deposits

Erry et al. (2000)
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Increasing world demand for metals

Manganese price trend

Morgan (2011)
Increasing world demand for metals

Copper price trend

Morgan (2011)
Increasing world demand for metals

Nickel price trend

Morgan (2011)
Increasing world demand for metals

![Cobalt $/Ton chart]

International Seabed Authority
The potential is huge

- The deposits can yield as much as ten times the desirable minerals as a seam that is mined on land.
- The deep sea contains enough mineable gold that there is nine pounds (four kilograms) of it for every person on Earth.
Example calculation of potential return from a nodule mining site (Sharma, 2011)

- Mineable area: 75,000 km²
- Abundance: 5 kg/m²
- Grade (%): Mn = 24, Ni = 1.1, Cu = 1.04, Co = 0.1
- Mining rate: 1.5 mt/year
- Duration: 20 years
- Price ($/kg): Mn = 1.32, Ni = 23, Cu = 8.30, Co = 39.20

Total resource: 375 mt (wet) or 206.25 mt (dry)
Value of total metals produced annually: $1.04 billion/year
Total yield in 20 years: $20.85 billion
Total estimated cost (capital and operational): $11.90 billion
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Ocean mining activities

- exploration
- mining
  - collection
  - lifting
  - disposal
- transfer & transport
- processing
Exploration

Aim:
▶ locate a mineable site

Function:
▶ map sea-floor
▶ collect samples
▶ estimate grade and abundance
▶ observe marine life
Mining

\[ \sim 5000 \text{ m} \]
Mining

\[\sim 5000 \text{ m}\]
Mining

We need:

- collector
- surface platform
- lift system
- disposal system

\[ \sim 5000 \text{ m} \]
Surface platform

Function:
- storage and deployment of equipment
- pre-processing, storage, and transfer of ores

Requirement:
- mobility in any direction, and station-keeping ability
- motion compensation for mining equipment at the moving surface
- economy of power

Challenges:
- static and dynamic loads
Surface platform

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Collector

Function:
- collect ores
- pre-process for lifting

Requirement:
- need to cover an area of \( \sim 1 \text{ km}^2 \)/day
- must have high collection rates of \( \sim 5 \text{ tons/min} \)
- collector has to track-keep and minimise wandering
- must minimise waste and maintain high concentration of ores

Challenges:
- uneven sea-floor topography
- extreme pressure and temperatures
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Collector design

Handschoh (2001)
Collector design

Archimedean-screw-propelled collector inside Hughes Glomar Explorer during test in 1976 (Chung, 2010)
Collector design

Archimedean-screw-propelled collector inside Hughes Glomar Explorer during test in 1976 (Chung, 2010)
Remotely-operated machines for SMS

Track-keeping

Successive learning track-keeping control (Chung, 1999)
Hyperbaric cutting of rock

Materials that give a brittle failure at low hydrostatic pressure often give a ductile failure at very high hydrostatic pressures, resulting in much higher cutting forces.
Lift system

Function:

▶ lift ores from sea floor to the surface

Challenge:

▶ water depth of $\sim 5000$ m
Lift system

Function:
  - lift ores from sea floor to the surface

Challenge:
  - water depth of $\sim 5000$ m
Lift system

Function:
  ▶ lift ores from sea floor to the surface

Challenge:
  ▶ water depth of $\sim 5000$ m

Various lift systems:
  ▶ continuous line bucket (CLB)
  ▶ shuttle
  ▶ air lift
  ▶ hydraulic lift
Continuous line bucket (CLB)

- Simple and mechanically more reliable
- Low efficiency because of difficulties in track-keeping
Shuttle

- Independent battery-powered vehicles would **dive on their own** to the ocean floor
- After collecting, they would drop ballast and rise to the surface
- Has no need of any riser system
- Expensive
OMI Pilot mining test system (1978)

Deep Sea Mining Vessel
SEDCO 445

Pump System

Air Lift System

Pipe String

Nodule Collector

Flexible Hose

Water Depth around 5000m
Air lift vs. hydraulic lift

- Air lift has higher energy consumption, but easier to maintain.
- Hydraulic lift needs less power, but difficult to maintain.
- Hydraulic lift allows higher transport densities and hence smaller pipes.

Deep-submersible pump

Chung & Tsurusaki (1994)
Challenges in lifting

- Differences in particle properties (size, density, shape) → differences in transport velocities of the particles.
- The riser might get **blocked** due to particle clustering and plugging.
- Particle size and its distribution should be limited.
- Preconditioning the mixture at the seafloor is therefore important.
Riser dynamics

- Drag
- Axial stretching
- Vortex-induced vibrations

Chung and Whitney (1981)
Sea water temperature changes with water depth

Chung and Felippa (1981)
Dynamic viscosity changes with water depth

Chung and Felippa (1981)

Chung and Felippa (1981)
Reynolds number changes with water depth

Chung and Felippa (1981)
Drag coefficient as a function of Reynolds number

Chung and Felippa (1981)
Drag coefficient and drag force as a function of water depth

Chung and Felippa (1981)
Axial stretching

FULL-SCALE MEASUREMENT OF VERTICAL PIPE IN THE NORTH PACIFIC OCEAN - AXIAL AMPLITUDES OF PIPE'S BOTTOM/BUFFER

PIPE LENGTH ≈ 16,000 FT

- o - MEASURED
- - - WITHOUT HEAVE COMP
- -- - WITH HEAVE COMP
- --- - CALCULATED

Chung (2010)
Elastic joints and axial dampers

May reduce deflections, axial stress, bending moments, and torsional deformation.

Cheng and Chung (1997)
Vortex-induced vibrations

- In contrast to short pipes, higher modes of pipe vibration can be excited even at low towing speeds.
- Flow-induced torsional moments on pipe with cables can cause pipe detorque.

Chung et al. (1994)
Vortex-induced vibrations

Shroud and two-helically-wound cables perform best

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Shroud 1</th>
<th>Shroud 2</th>
<th>Model 12</th>
<th>Model 7</th>
<th>Model 5</th>
<th>Model 6</th>
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<tbody>
<tr>
<td>$C_D = 0.4-1.1$</td>
<td>$C_D = 1.1$</td>
<td>$C_D = 1.12$</td>
<td>$C_D = 0.96$</td>
<td>$C_D = 1.11$</td>
<td>$C_D = 1.17$</td>
<td>$C_D = 0.98$</td>
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<tr>
<td>$C_L = 0.210$</td>
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Chung et al. (1994)
Disposal system

Function:
▶ Dispose debris and sediment back to the sea after initial processing on the platform

Challenge:
▶ What is the best depth to dispose the material to minimise environmental disturbance?

Kim (2010)
Transfer & transport

Function:

▶ transfer ore to carrier vessels that would transport it to port for processing
▶ transport of personnel, supplies, and fuel

Bath (1989)
Transfer & transport

Function:
- transfer ore to carrier vessels that would transport it to port for processing
- transport of personnel, supplies, and fuel

Challenges:
- dynamic loads during transfer
- mining sites may be far away from land, involving ~10 days of travel time
Need for novel metallurgical processes to extract and separate the metals

What are the potential hazards of materials that are left after metal extraction?

What are the potential uses?
Deep sea ecosystem

Armour-plated snail

Yeti crab

Psychropotes semperiana

Pale octopus
Minimising environmental impact

Erry et al. (2000)
Minimising environmental impact

- Lift as minimum sediment as possible to the surface
- Dispose sediment at sufficient depth below the surface
- Constructive use of unwanted material after metal extraction
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# Manganese nodules vs. crusts

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<td>Found in deep waters</td>
<td>Found in shallower waters, but in more concentrated areas and more unevenly distributed</td>
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### Manganese nodules vs. seafloor massive sulfides

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<td>Situated just on the seabed and can be collected more easily</td>
<td>Can be considered as rock and the high hydrostatic pressure will make it difficult to excavate</td>
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</table>
Ocean mining vs. land mining

- Unlike mining on land, no need of an infrastructure of roads and buildings
- This infrastructural advantage could be offset by operational costs for long-distance transport (several thousand kilometres).
## Ocean mining vs. oil and gas

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- **Pipe is free at its bottom end**
- **Pipe bottom is connected to the seafloor equipment**
- **More concerned with instantaneous pipe position**
- **More concerned with pipe strength and buckling**
- **Sea floor vehicle maintenance**
- **Subsea system maintenance**
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Ocean mining must deal with extreme environmental conditions

- Freezing temperatures
- Total darkness
- Hydrostatic pressure $\sim 500$ times atmospheric
- Varying wind
- Varying waves
- Varying currents (with time and water depth)
- Variable seafloor characteristics
An integrated dynamic model is essential

The platform-riser-buffer-collector should be studied as an integrated system.

- Platform’s motion
- Pipe response
- Collector’s impact with obstructions
- Internal fluid flow effect on the pipe
Control and automation are essential

- The technology of ocean mining should be geared towards automation to achieve economy.
- During deployment and retrieval of pipe string and collector, the platform should station-keep over a fixed point.
- During mining, the platform and the pipe bottom-end should be controlled to stay close to the collector on the sea floor.
- Uncertainties in pipe response prediction is a challenge.
Current deep-ocean mining contracts

Hein et al. (2013)
Thank you