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# Harvesting NEOs: The Mining Engineering Perspective

# Outline

- Mining terms
- Small-body classification for mining
- Unit operations
- Stages in the life of an asteroid mine
- Mining methods

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# Mining

- mining = extraction of geologic materials for use

- mining engineering = applying science, engineering fundamentals, and appropriate technology to recover geologic materials

# Mining Terms

- mineral deposit = a naturally occurring concentration of geologic material
  - ore = anything that can be mined for a net benefit
    - may include one or several target substances
  - most mineral deposits are not ore, because
    - the concentrated material is not of interest; or
    - the deposit is too small; or
    - the material is in an un-extractable form
  - gangue = unwanted material intermixed with the target substance

# More Mining Terms

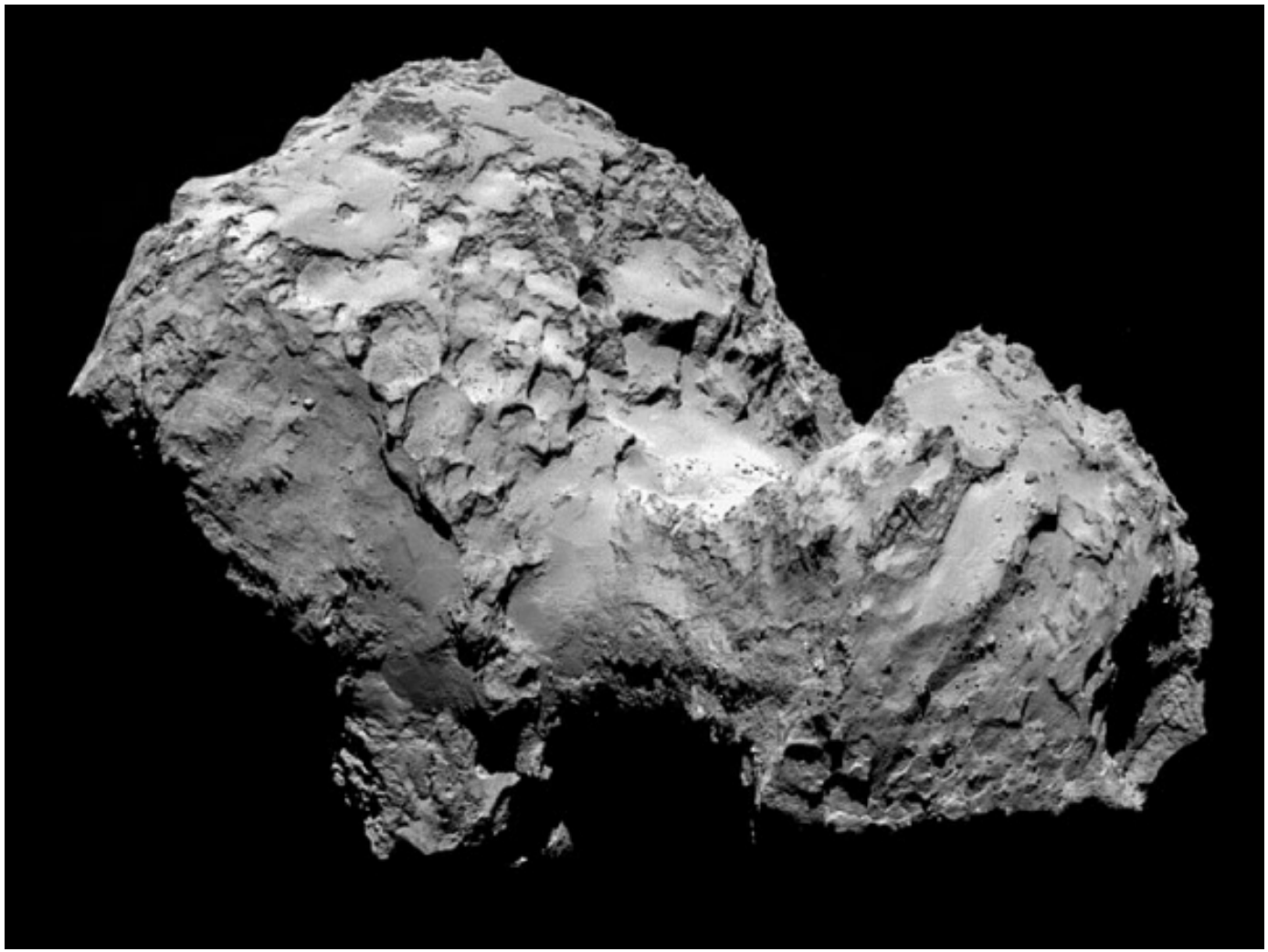
- reserves vs. resources
  - reserves = ore known to exist, and available to mine
  - resources = potential ore
- recovery = proportion of in-place target substance that can be separated from waste material
- dilution = amount of waste material inextricably bound to target substance

# Small-Body Classification for Mining

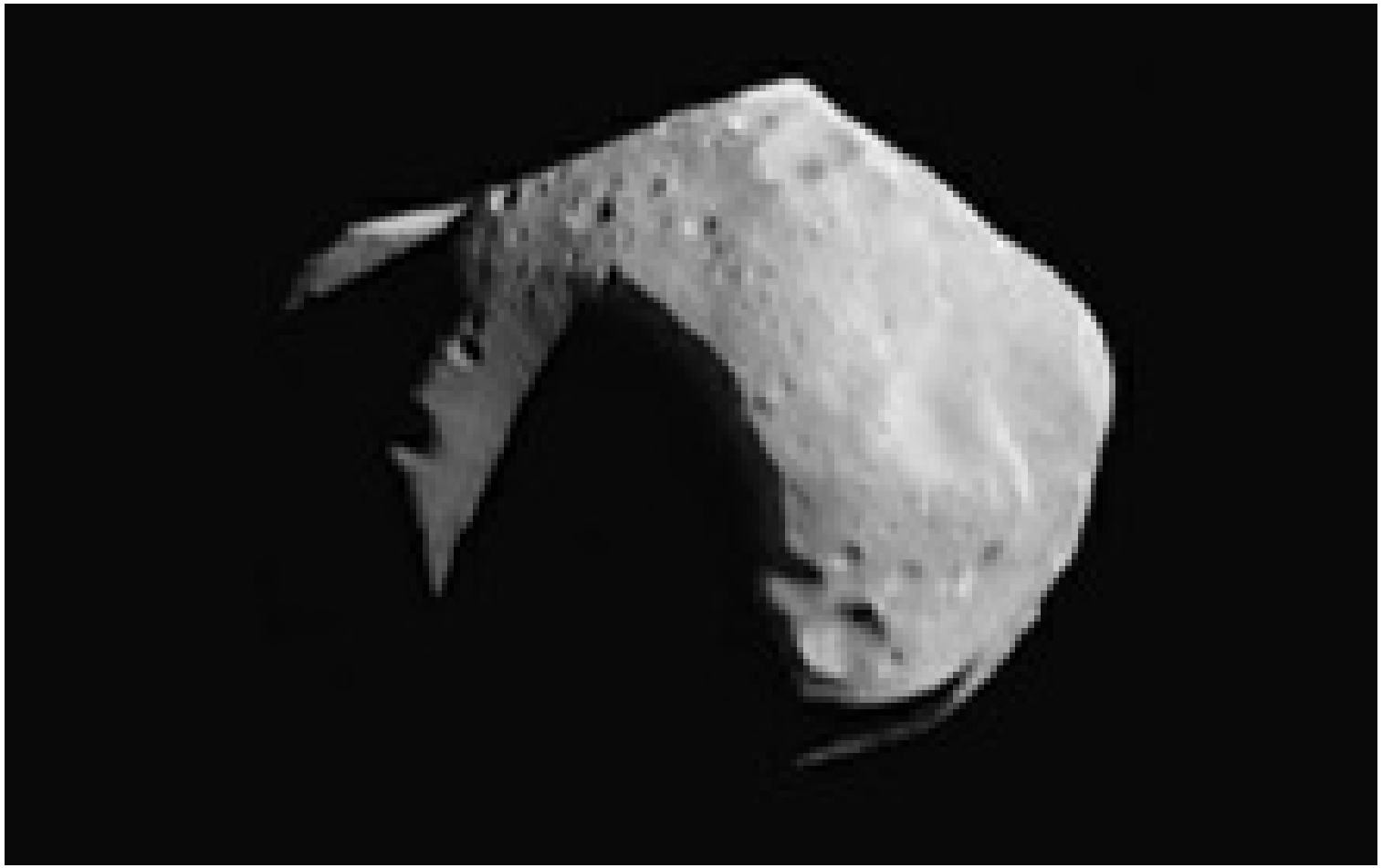
# Apply to All Asteroids and Comets

- Group 0. Ice composites
  - Very weak, mostly ices with or without organic compounds.
- Group 1. Friable rock
  - Similar to Group 0, but with low volatile amounts. Weak.
- Group 2. Hard rock
  - Strong and brittle, the most similar to materials encountered in terrestrial mining practice.
- Group 3. Metallic:
  - 3a. Massive metal – may be ductile.
  - 3b. Rock-metal composites – would fracture mainly at rock-metal interfaces.

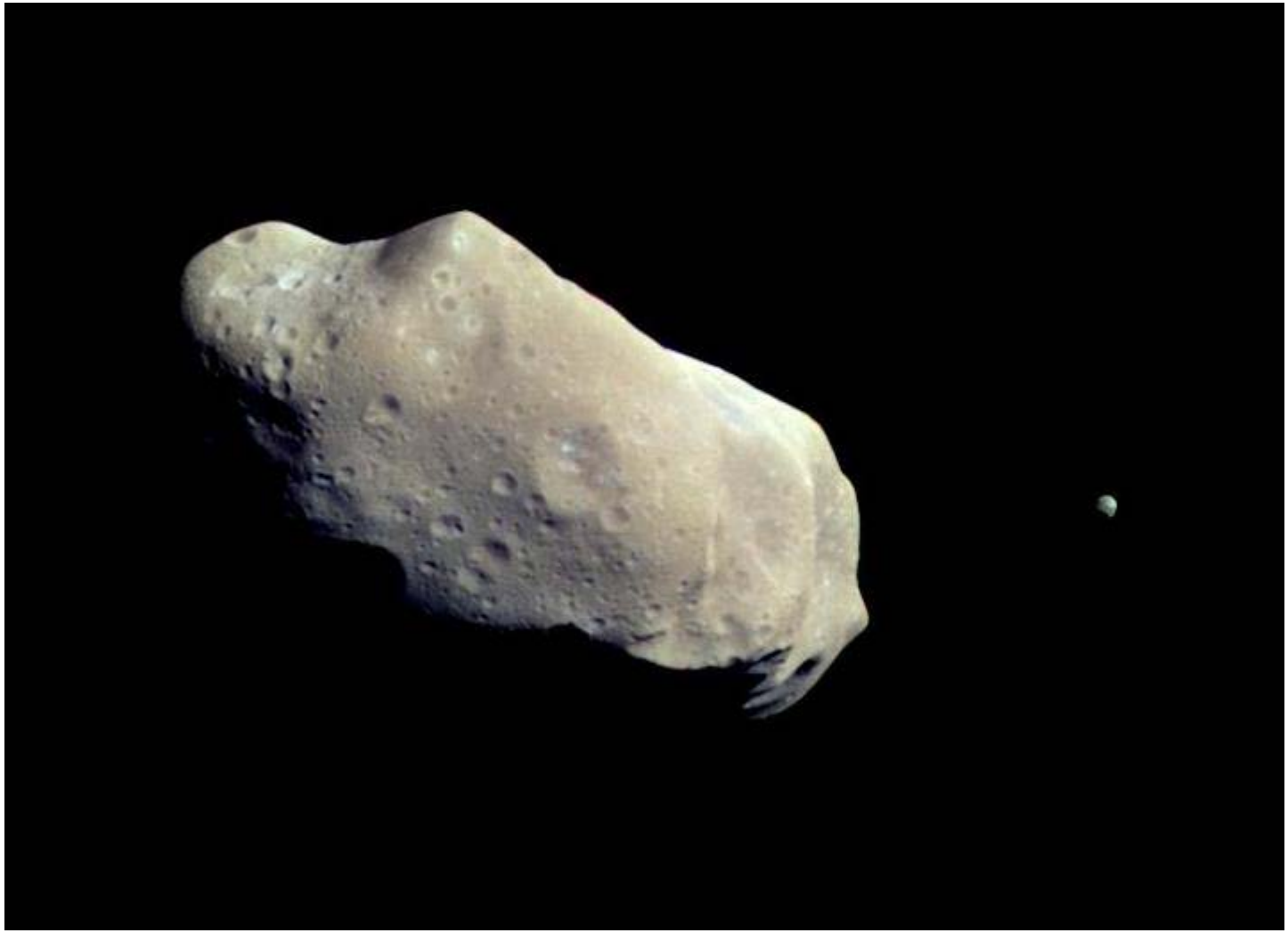
# Group 0 Example: Comet Churyumov-Gerasimenko



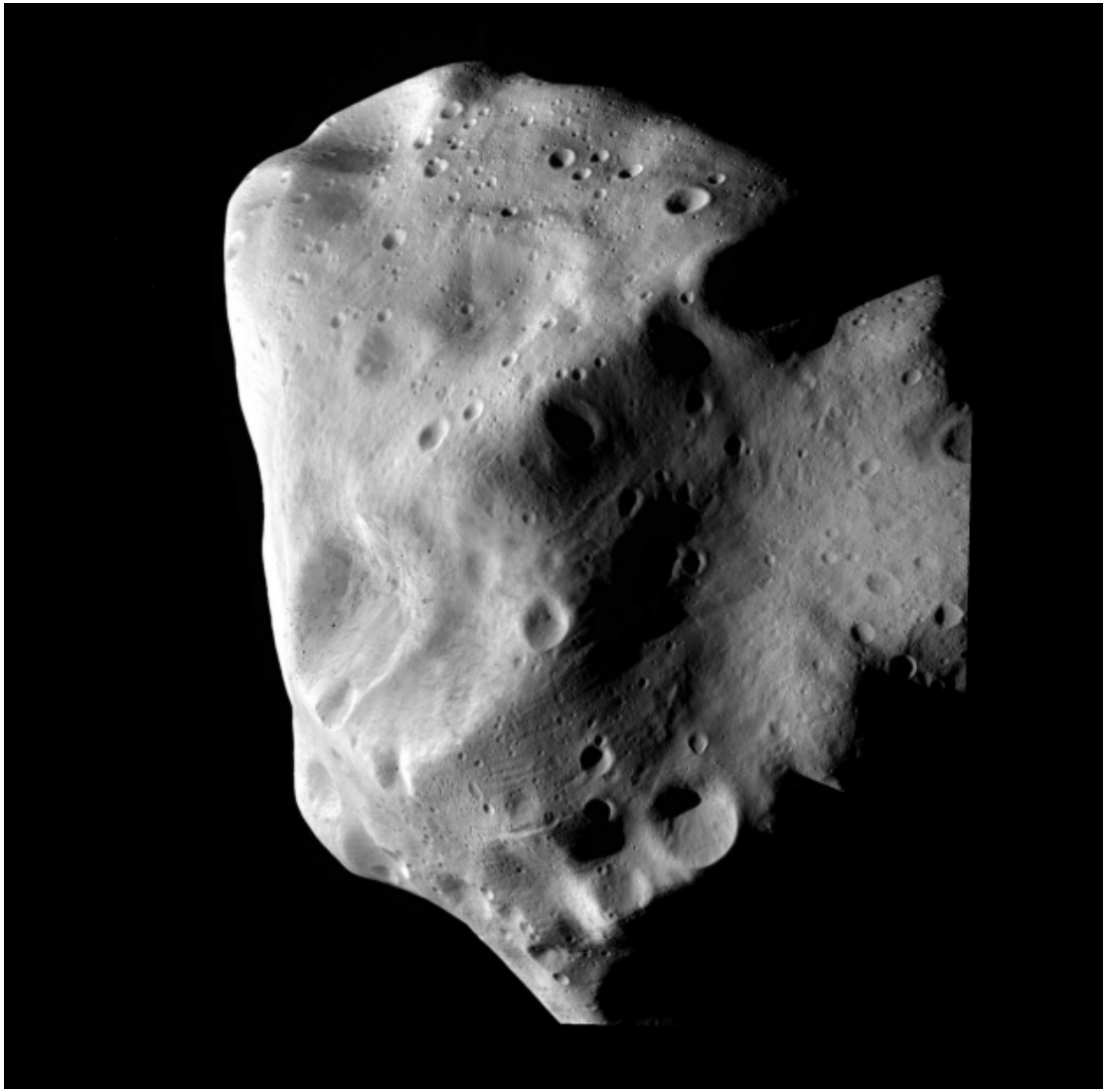
# Group 1 Example:  Mathilde(?)



# Group 2 Example:  Ida(?)



# Group 3b Example:  Lutetia(?)



# Unit Operations

# Mining Unit Operations

- generic fundamental activities to acquire ore while minimizing handling of gangue
- terrestrial basics:
  - fragmentation – detach ore from surrounding mass
  - excavation – remove ore from surroundings – often combined with fragmentation
  - transportation – move ore through the process
  - beneficiation – increase the concentration of target substance
  - support activities

# Fundamental Constraints

- terrestrial:
  - unidirectional, constant-magnitude gravity vector
  - energy scarcity
  - mass abundance
  - difficult deposit access
  - originally derived from human physical capabilities
- asteroids:
  - variable gravity vector
  - energy abundance
  - launch mass limitations
  - difficult location access
  - difficult human participation

# Example: Sand & Gravel Pit

- fragmentation, excavation, and some transportation accomplished by track hoes
- beneficiation is by simple size separation
- further transportation is by truck
- site maintenance is by bulldozer

# Example: Large Open-Pit Gold Mine

- fragmentation is by drilling-and-blasting
- excavation is by hydraulic excavator
- transport is by truck
- liberation is by crushing and grinding
- separation is by carbon adsorption & cyanide leaching

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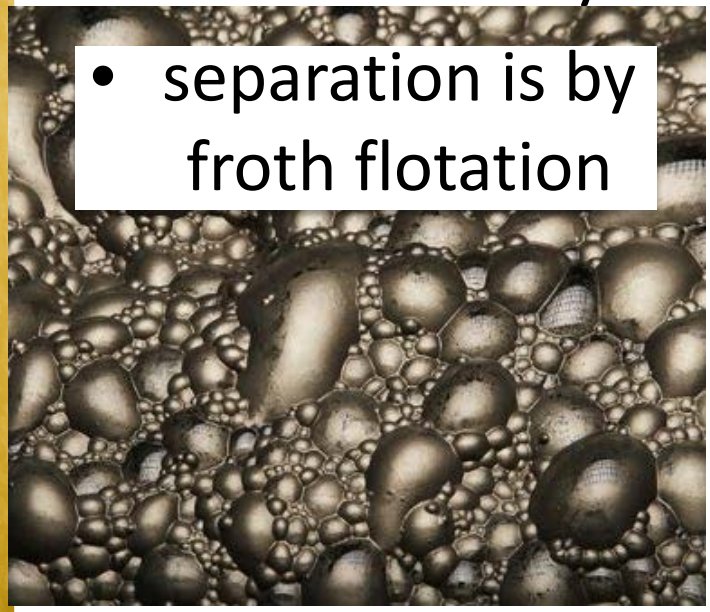
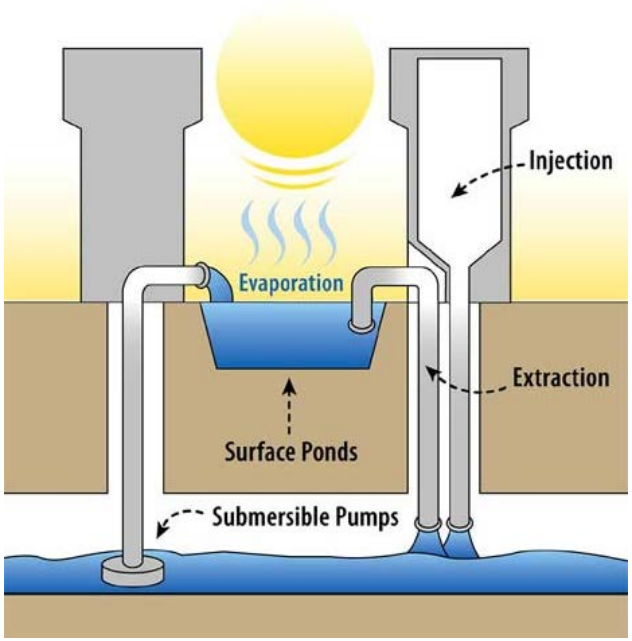
# Example: Underground Copper Mine

- fragmentation is by drilling-and-blasting
- excavation is by load-haul-dump
- transportation is by truck, conveyor, & hoist
- liberation is by crushing and grinding
- separation is by froth flotation



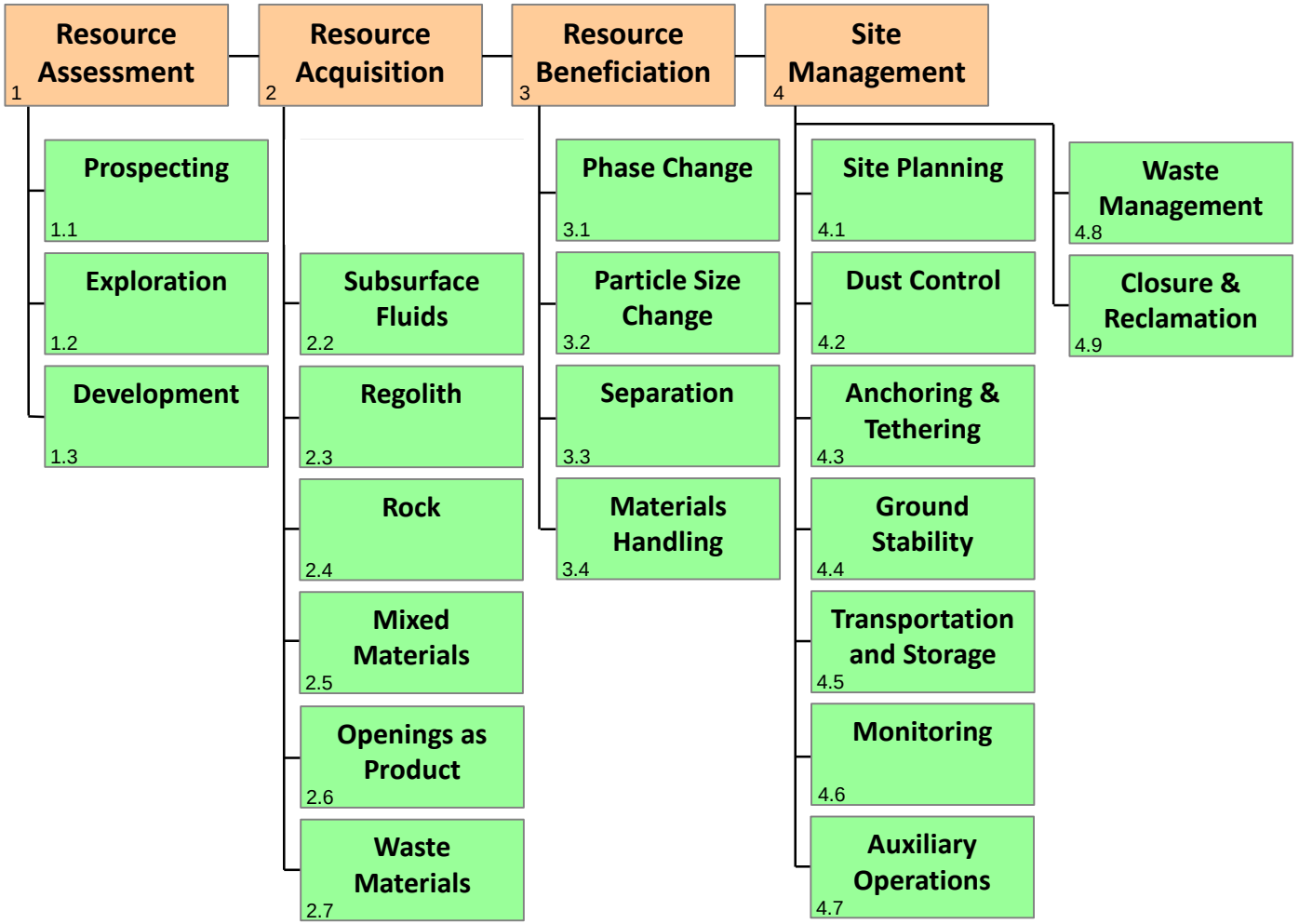
# Example: Underground Salt Mine

- liberation is by chemical dissolution
- transport is by slurry pipeline
- concentration is by evaporative precipitation




# Stages in the Life of an Asteroid Mine

# Asteroid Mining Phases



# Asteroid Mining Sequence:
# **Prospecting**

1. **decide on target substance**
2. **locate target NEOs**
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation

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# Asteroid Mining Sequence: **Exploration**

1. decide on target substance
2. locate target NEOs
3. **gain access to NEO**
4. **characterize NEO**
   a) **surface properties**
   b) **internal properties**
   c) **orbital properties**
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation

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# Asteroid Mining Sequence: **Development**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. **prepare NEO**
   a) **anchor and tether**
   b) **control NEO motion**
   c) **restrain NEO**
   d) **install operations platforms**
   e) **bag all or part of NEO**
   f) **install support equipment**
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation

# Asteroid Mining Sequence: **Acquisition**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. **mining operations**
   a) **access the ore**
   b) **remove the ore**
7. ore beneficiation
8. transport
9. closure & reclamation

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# Asteroid Mining Sequence: **Beneficiation**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. **ore beneficiation**
   a) **liberation**
   b) **separation**
8. transport
9. closure & reclamation

# Asteroid Mining Sequence: **Transport**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. ore beneficiation
8. **transport**
   a) **supplies & support**
   b) **mining**
   c) **processing**
   d) **marketing**
9. closure & reclamation

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# Asteroid Mining Sequence: **Closure**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
9. **closure & reclamation**
   a) **remove/recycle equipment**
   b) **prevent future problems**

# Mining Methods

# Mining Method

- how the unit operations are accomplished for a given deposit type
  - same unit operations can be accomplished by various technologies
  - take advantage of environment and orebody characteristics – terrestrial examples:
    - block caving uses gravity and the fracturability of the rock mass to fragment and excavate the ore
    - longwall mining uses differences in fracturability of coal and sandstone to control stability of the rock mass
    - mills built on hillsides use gravity to transport ore through beneficiation steps


Churyumov-Gerasimenko

# Target: Volatile Ices

- mining method derived from in situ solution and block caving
- likely asteroids:
  - Group 0
- mining sequence:
  - primary fragmentation
  - bagging of major fragments
  - heating
  - fragmentation of refractory portion(s)
  - repeat as needed

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Matilde

# Target: REEs

- mining method derived from bulk mining of disseminated metal orebodies
- likely asteroids:
  - Groups 1-3
- mining sequence for spin caving:
  - maintain or increase body spin
  - set up two opposing bags sized for half the body
  - blast even-massed layers off both ends simultaneously – repeat
  - wind up and release inter-bag tether to segregate fragments


Ida

# Target: PGEs

- mining method derived from narrow-vein deposit methods
- likely asteroids:
  - large, cohesive Group 2 bodies
- mining sequence:
  - locate vein outcrops
  - fragment & excavate with gripper-based continuous miner


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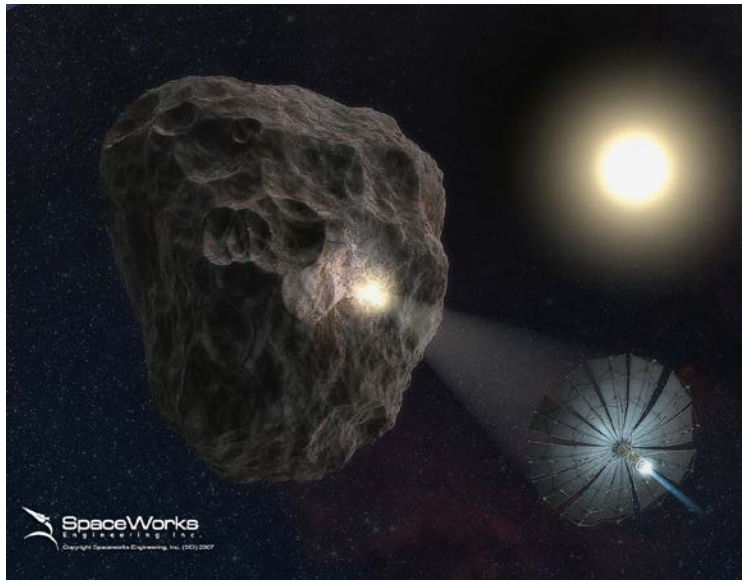
# Target: Native Metals

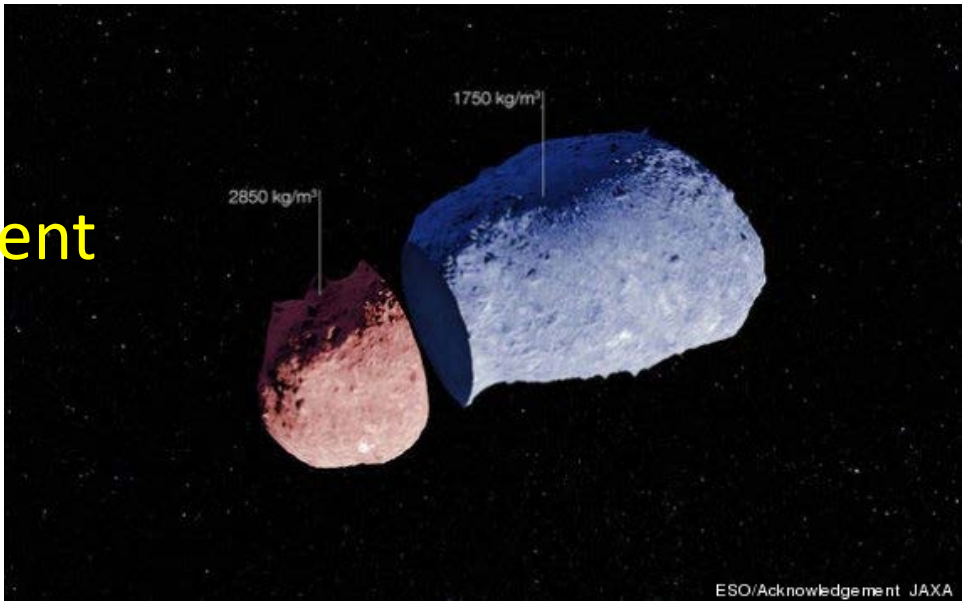
- mining method derived from smelting
- likely asteroids:
  - Group 3a, some Group 3b
- mining sequence:
  - bag the body
  - solar concentrator for differential heating




Itokawa

# What About Rubble Pile Asteroids?

- it depends on particle compositions & sizes
- gain experience with small, monolithic bodies
  - mineral economics determines minimum size
  - orbital dynamics and rock strength determine maximum size
- then “move up” to multi-component bodies



# Mining Method w.r.t. Asteroid Size

- smallest bodies likely to be monolithic and free of regolith cover
- intermediate-sized bodies may require hierarchical approach:
  - fragment into sizes amenable to small-body methods
- largest bodies may be amenable to underground mining techniques
  - especially if ore occurs in narrow veins

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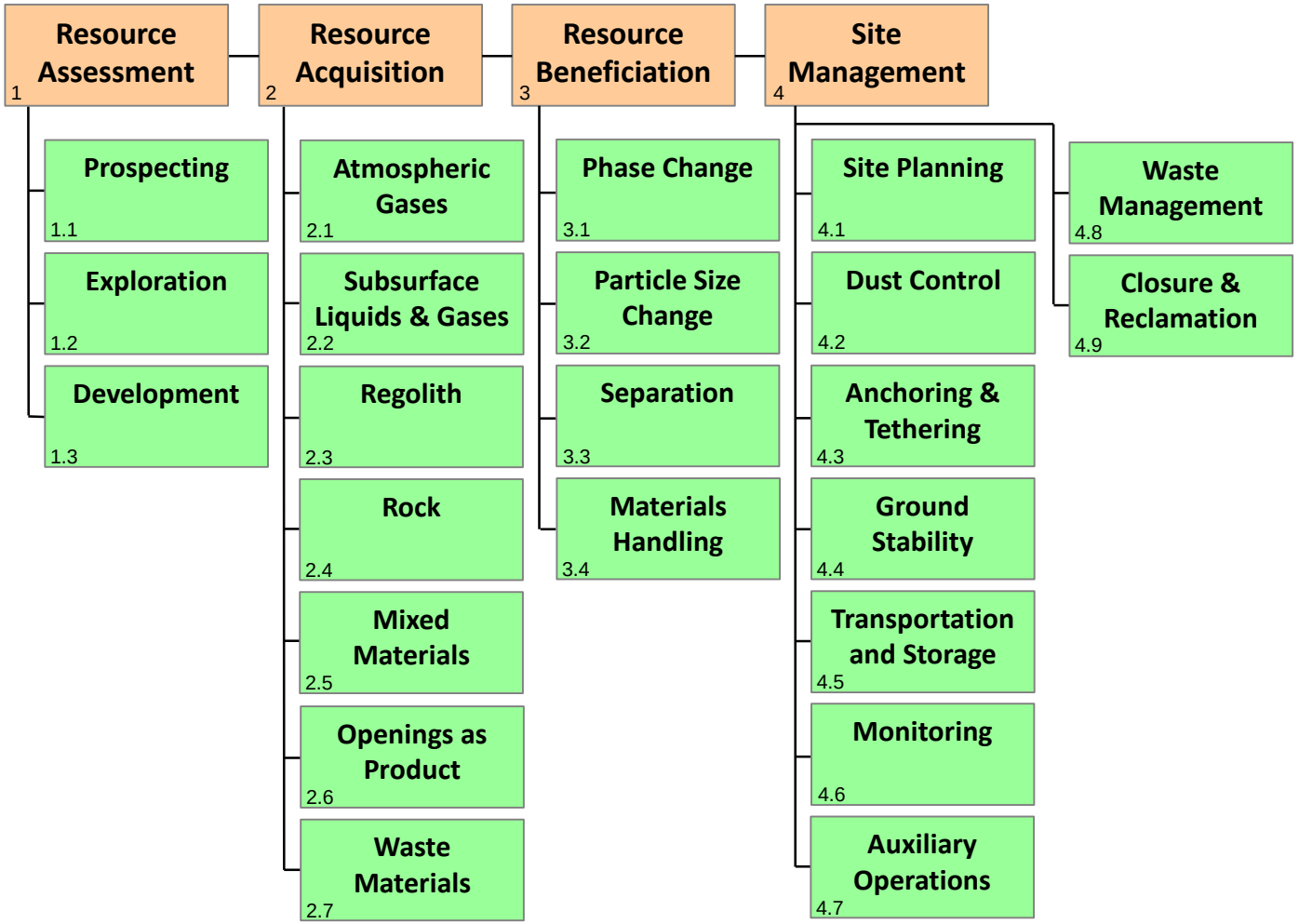
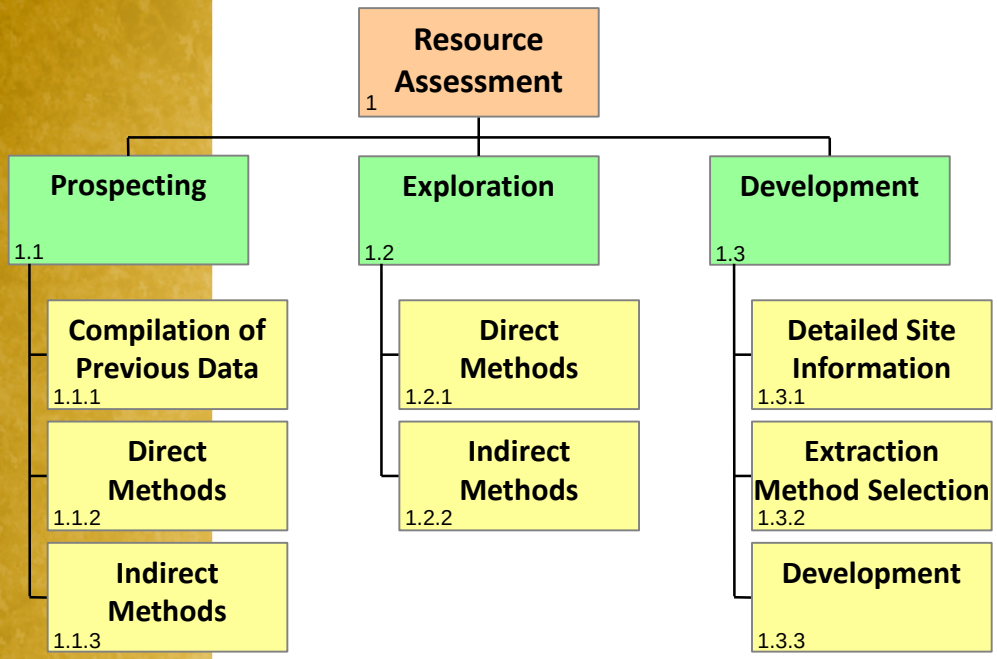
# Questions?

# Backup Slides

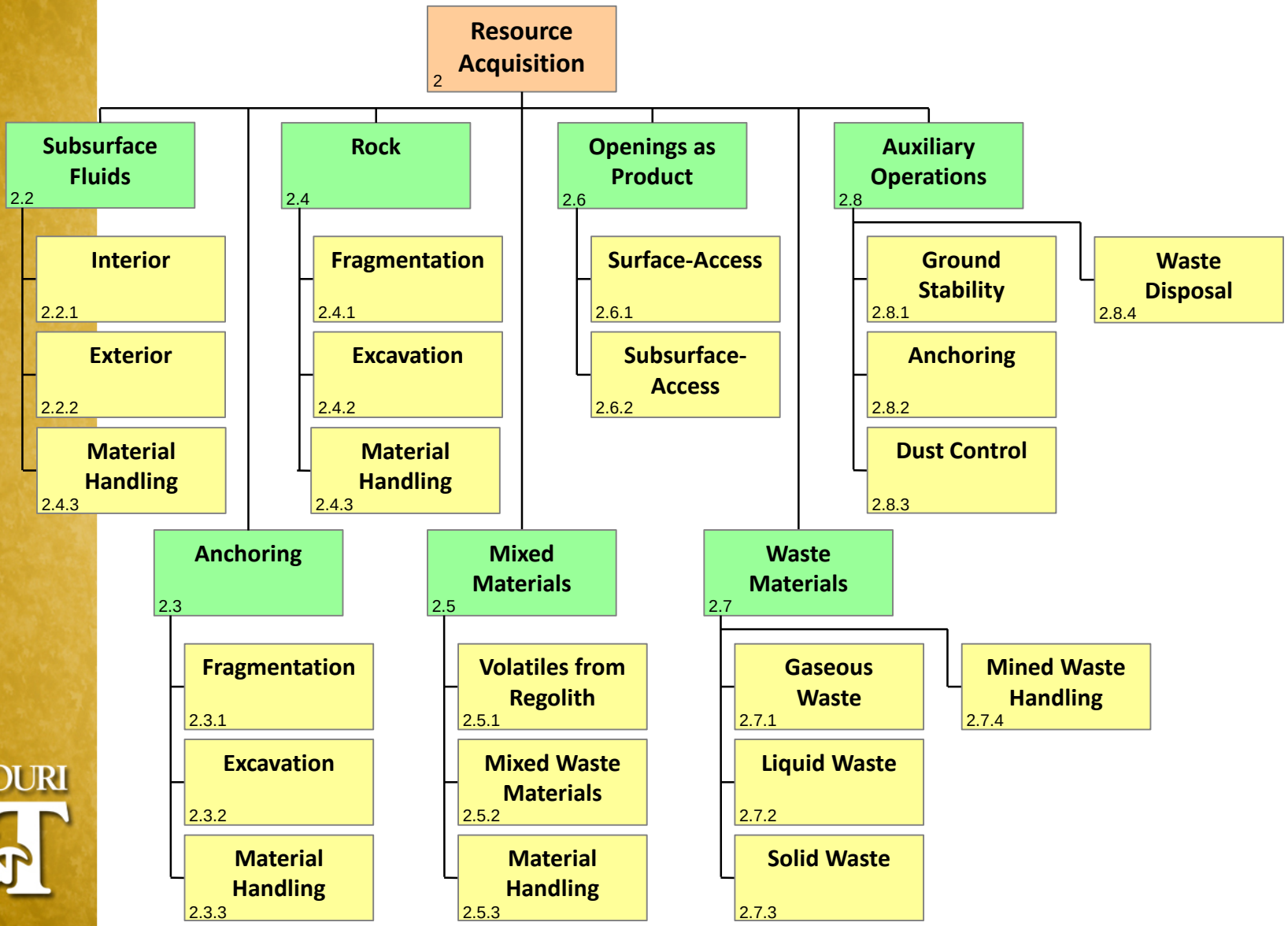
# Generic Resource Extraction



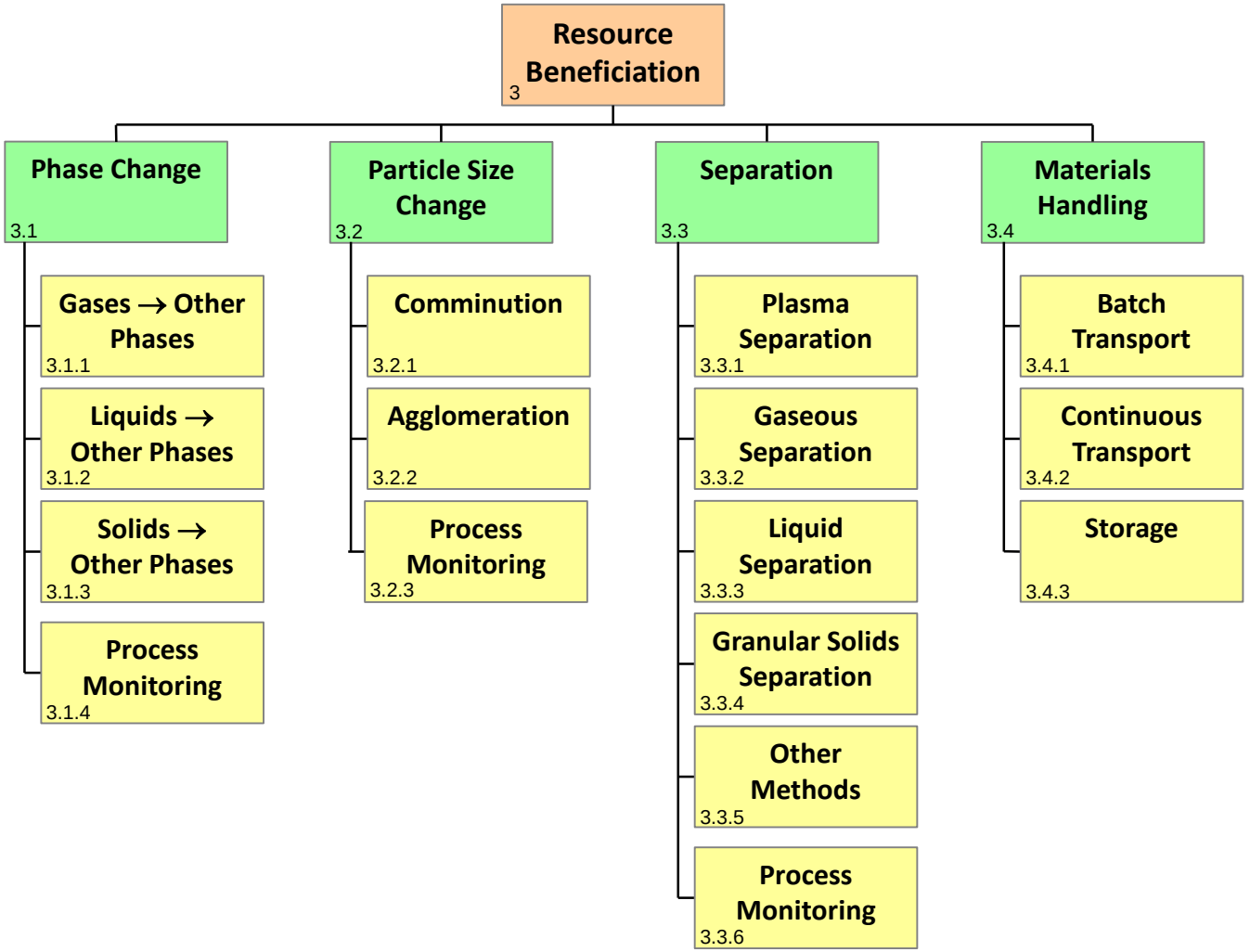
# Resource Assessment Components



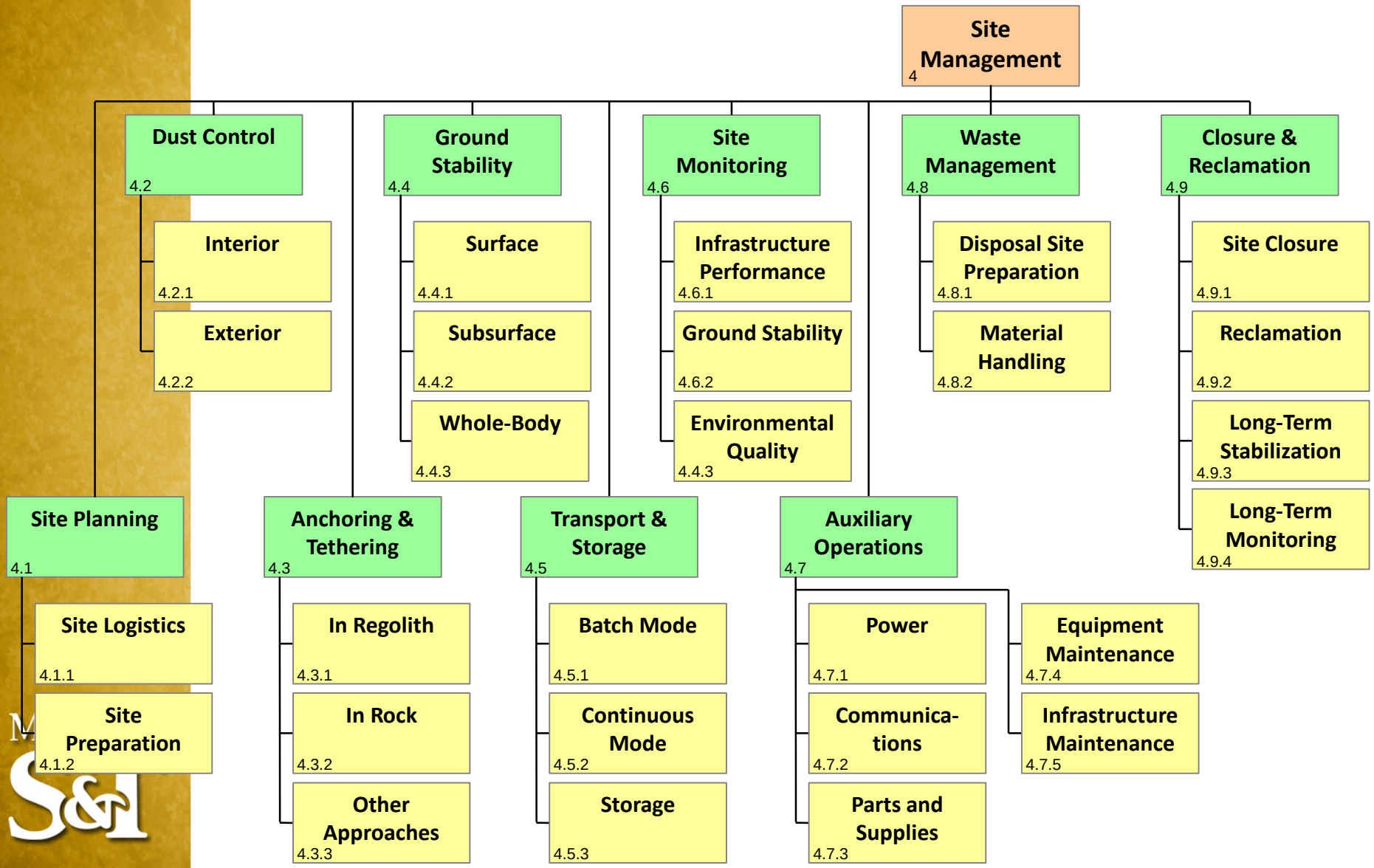
# Resource Extraction Components



# Resource Beneficiation Components



# Mine Site Management



# Mining

- mineral deposits form when natural processes segregate substances
  - if it's a substance humans can use, then the deposit is a potential orebody
  - most mineral deposits are not of interest, so aren't studied or mined
- natural segregation accomplishes part of the beneficiation required for extraction
  - can be as simple as the carbonaceous chondrite proportion of the NEO population
  - or as complex as PGE* veins in multi-lithology breccia

*platinum-group element

# Mining Methods

- classified by access type
  - surface
  - underground
- classified by ground support type
  - naturally supported
  - artificially supported
  - unsupported, allowed to fail
- classification by deposit type
  - same unit operations often accomplished by various technologies / methods

# Mining Methods by Access

- surface
  - open-pit
  - quarry
  - area mine
- underground
  - categorized by support type (next slide)

# Mining Methods by Support Type

- naturally supported
  - room-and-pillar
  - sublevel stoping
  - longhole open stoping
- artificially supported
  - cut-and-fill
    - overhand
    - underhand
  - shrinkage stoping
  - vertical crater retreat
- unsupported – allowed to fail
  - longwall/shortwall
  - sublevel caving
  - block/panel caving

# Mining Methods by Deposit Type

- fuel minerals
  - coal
  - uranium
- nonfuel minerals
  - base metals
  - precious metals
  - industrial minerals
  - construction materials
- rock type
  - hard rock (> 50-100 MPa)
  - soft rock
- petroleum
- water
  - fresh surface water
  - salt surface water
  - groundwater