Fluxed Melting for Rapid Regolith Digestion

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Fluxed Melting Overview

To separate the elements in regolith:

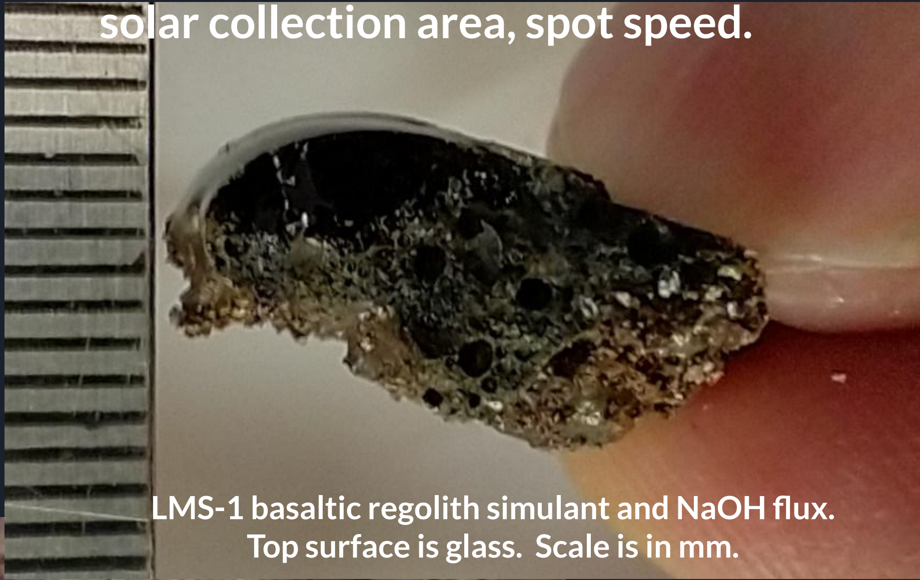
1. **Melt** the regolith using a sodium hydroxide flux (10-30% works)
   - Solar or microwave or induction melting all work fine
   - Difficult-to-process crystalline minerals dissolve into the glass
2. **Leach** the resulting obsidian glass in hot HCl acid
   - The precipitate contains most of the silicates
   - The red acid solution contains most of the metals
     - Neutralize to pH 8 to precipitate Fe and Al
     - Neutralize to pH 11 to precipitate Ca and Mg
     - Brine electrolysis regenerates NaOH and HCl from $NaCl+H_2O$
3. Use the separated materials to sustainably explore space!

- Visual Summary
- Flow Diagrams
- Downstream Processing

Solar Melting Step

Melt depth depends on composition, solar collection area, spot speed.

0.5 square meter fresnel lens



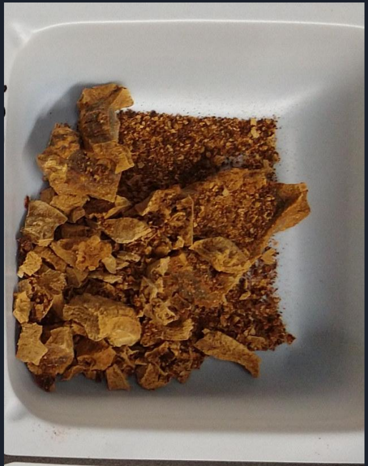
LMS-1 basaltic regolith simulant and NaOH flux. Top surface is glass. Scale is in mm.

NP-1 basaltic regolith simulant melted to glass in wide swath by moving spot slowly.

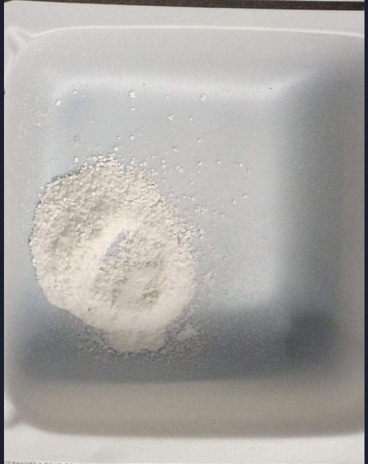
Acid Leach Step

Leach metals from the melted regolith glass with hot concentrated HCl.
Black glass turns to fluffy white silicates.
50-80 °C @ 33% for 1 hour
10:1 acid:glass ratio

Metal oxide recovery from acid with NaOH



Fe and Al precipitate at pH 5



Ca and Mg precipitate at pH 11

Precipitates after Acid Leach

No flux
No melting

(Most minerals intact.)

Melted with
10% Sodium Hydroxide

(Black glass remains.)

Melted with
20% Sodium Hydroxide

(Nearly all silica.)

Precipitates after Alkali Bake

No flux
No melting

(Most minerals intact.)

Melted with
10% Sodium Hydroxide

(Large glass chunks left.)

Melted with
20% Sodium Hydroxide

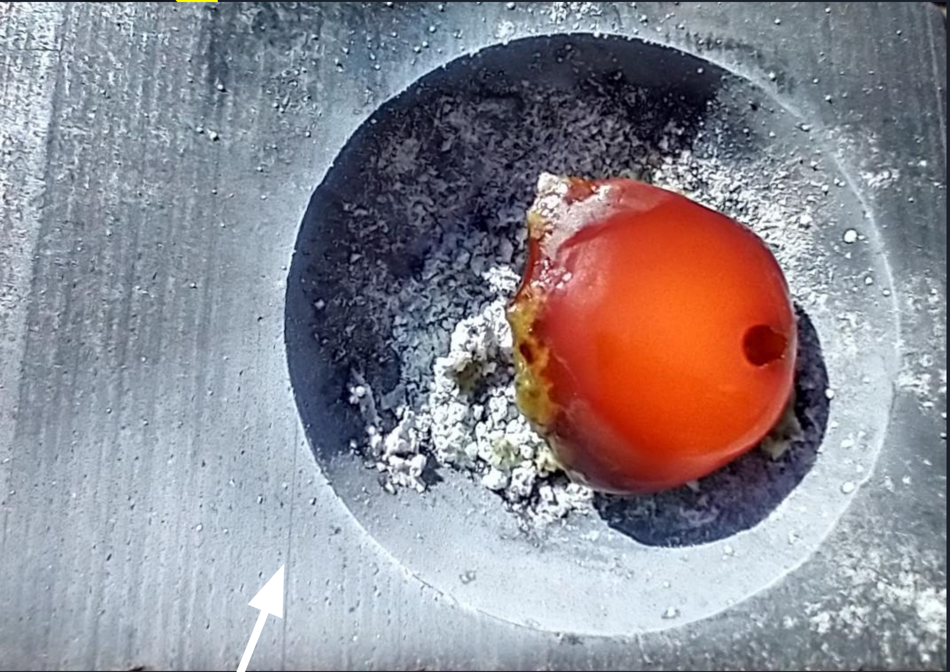
(Most glass dissolves.)

Vacuum Melting

LHS-1 +20% NaOH @ 1 mbar

LHS-1 +20% NaOH @ 1 atmosphere

Sodium Loss



Sodium loss is higher with more NaOH flux
(LHS-1 +100% NaOH @ 1 atm)

Sodium loss is higher in vacuum
(LHS-1 +20% NaOH @ 1 mbar vacuum)

- Visual Summary
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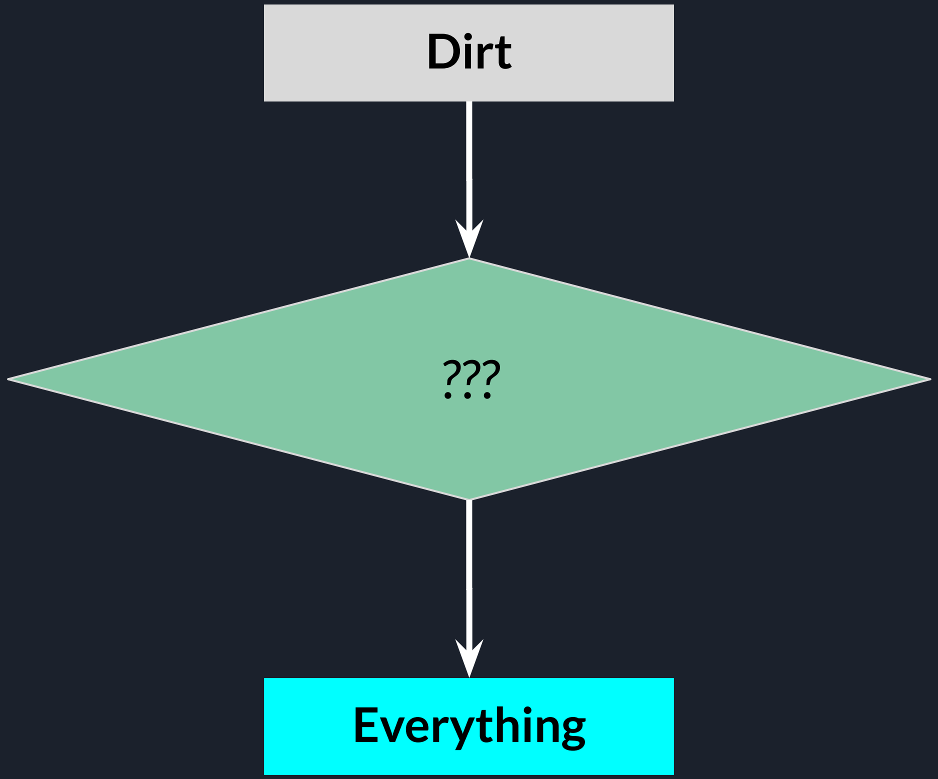
- Downstream Processing


Dirt
???
Everything

What's in Moon / Mars / Asteroid Dust

	Earth Basalt	Lunar Basalt	Mars Soil	H Chondrite
SiO_2	50	41	42	34
Al_2O_3	15	10	10	2
CaO	11	12	6	2
FeO	10	19	21	35
MgO	8	7	9	22
Na_2O	3	0.4	3	1
TiO_2	2	10	1	0.1
Sulfur	0.1	0.1	2	2

What's in Moon / Mars / Asteroid Dust

molten dust = cast basalt, basalt fiber

		Earth Basalt	Lunar Basalt	Mars Soil	H Chondrite
SiO_2	Glass, solar panels	50	41	42	34
Al_2O_3	Aluminum, refractory	15	10	10	2
CaO	Concrete, glass	11	12	6	2
FeO	Steel	10	19	21	35
MgO	Magnesium, refractory	8	7	9	22
Na_2O	Glass	3	0.4	3	1
TiO_2	Titanium, solar panels	2	10	1	0.1
Sulfur	Sulfuric Acid	0.1	0.1	2	2

Dust is 30% Oxygen by mass

	Earth Basalt	Lunar Basalt	Mars Soil	H Chondrite
SiO2	50	41	42	34
Al2O3	15	10	10	2
CaO	11	12	6	2
FeO	10	19	21	35
MgO	8	7	9	22
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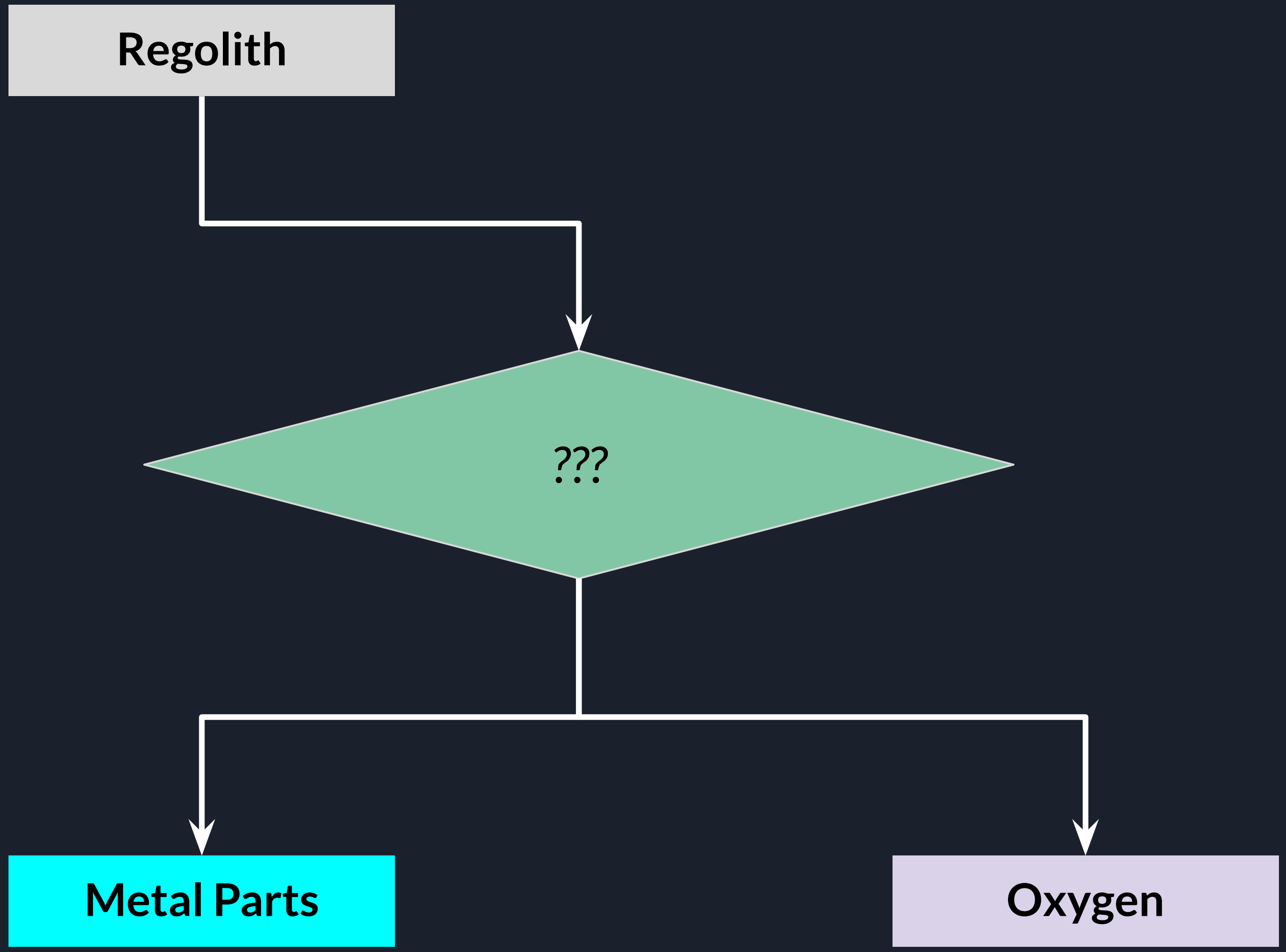
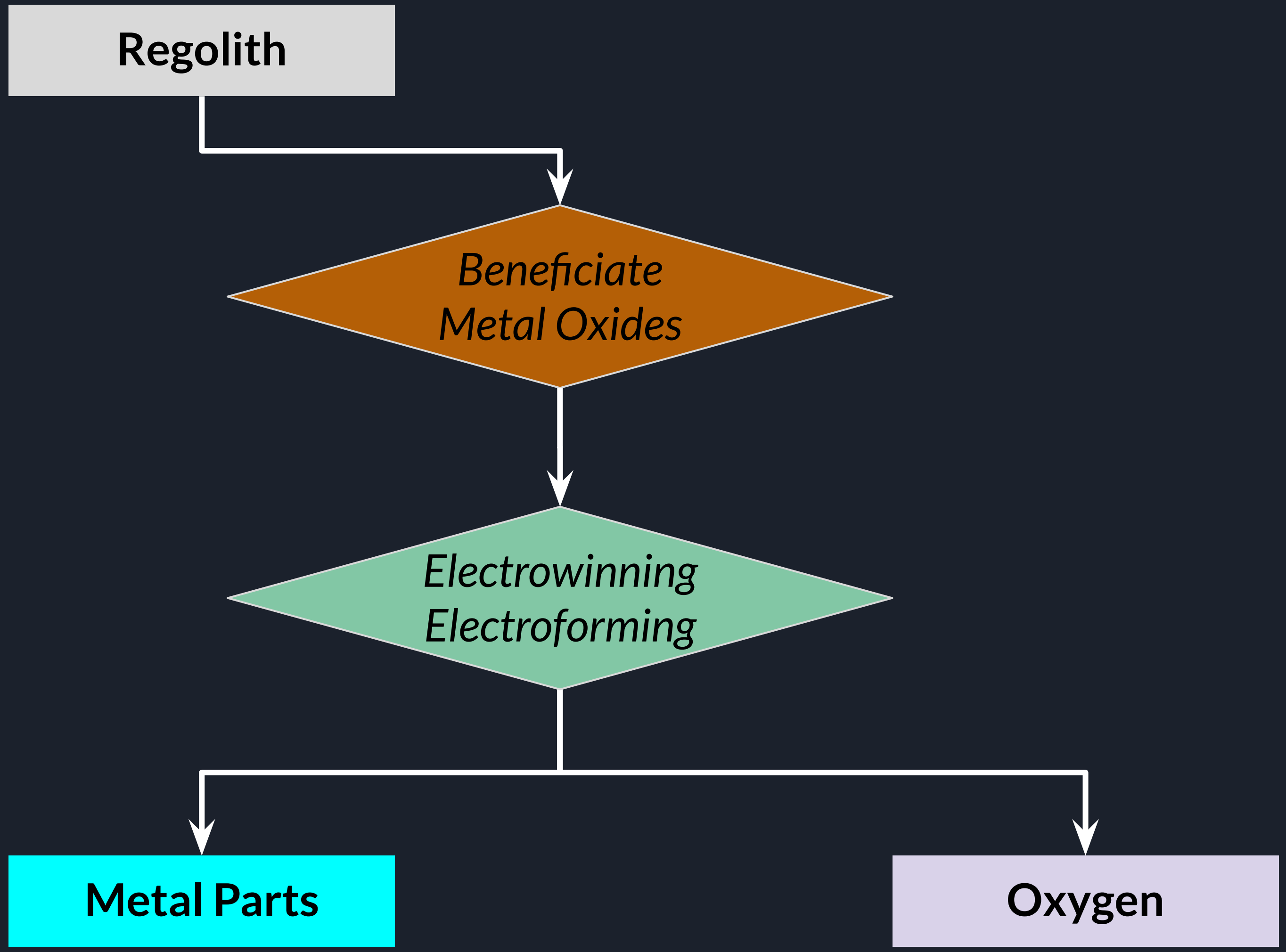
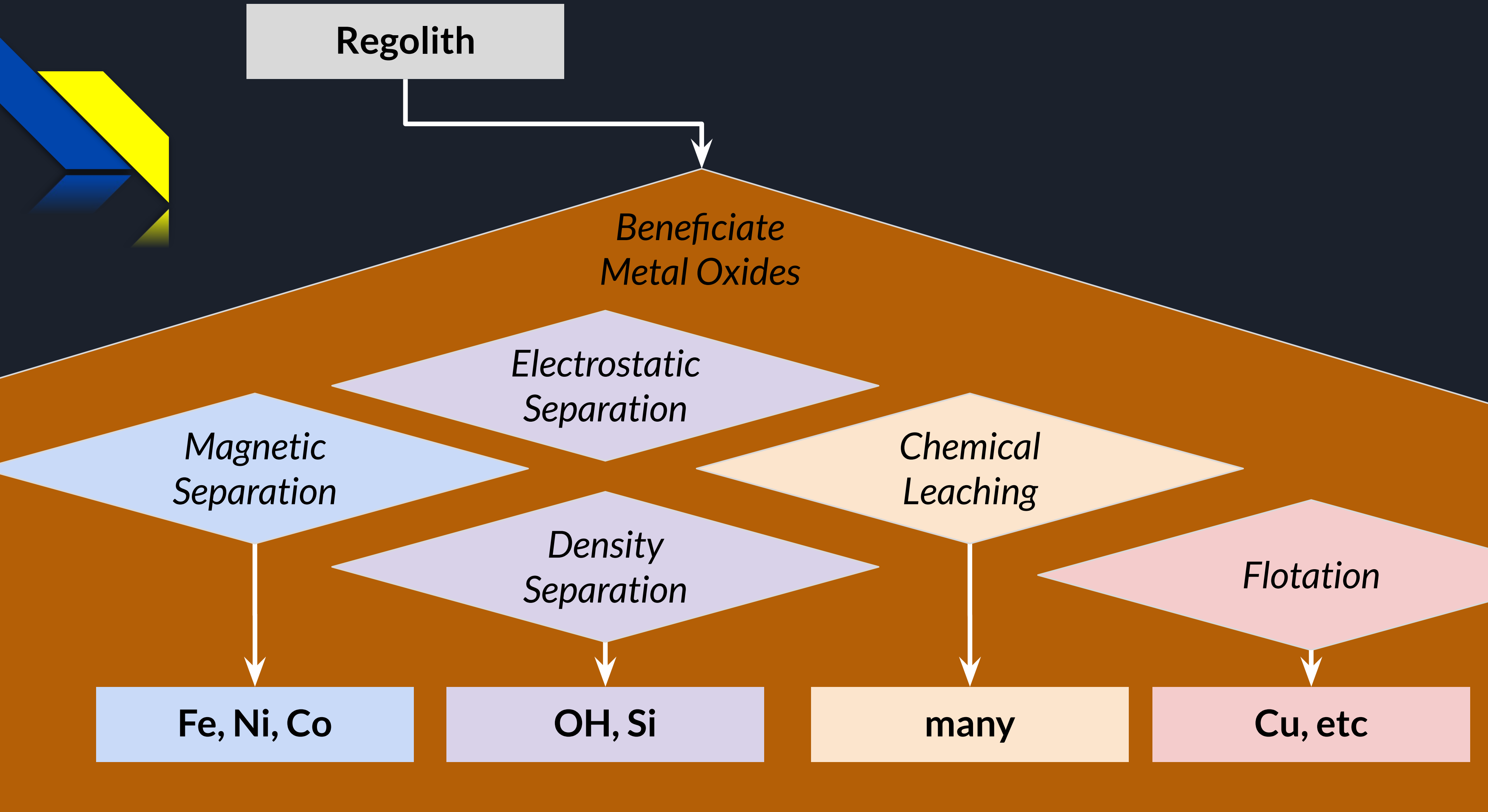
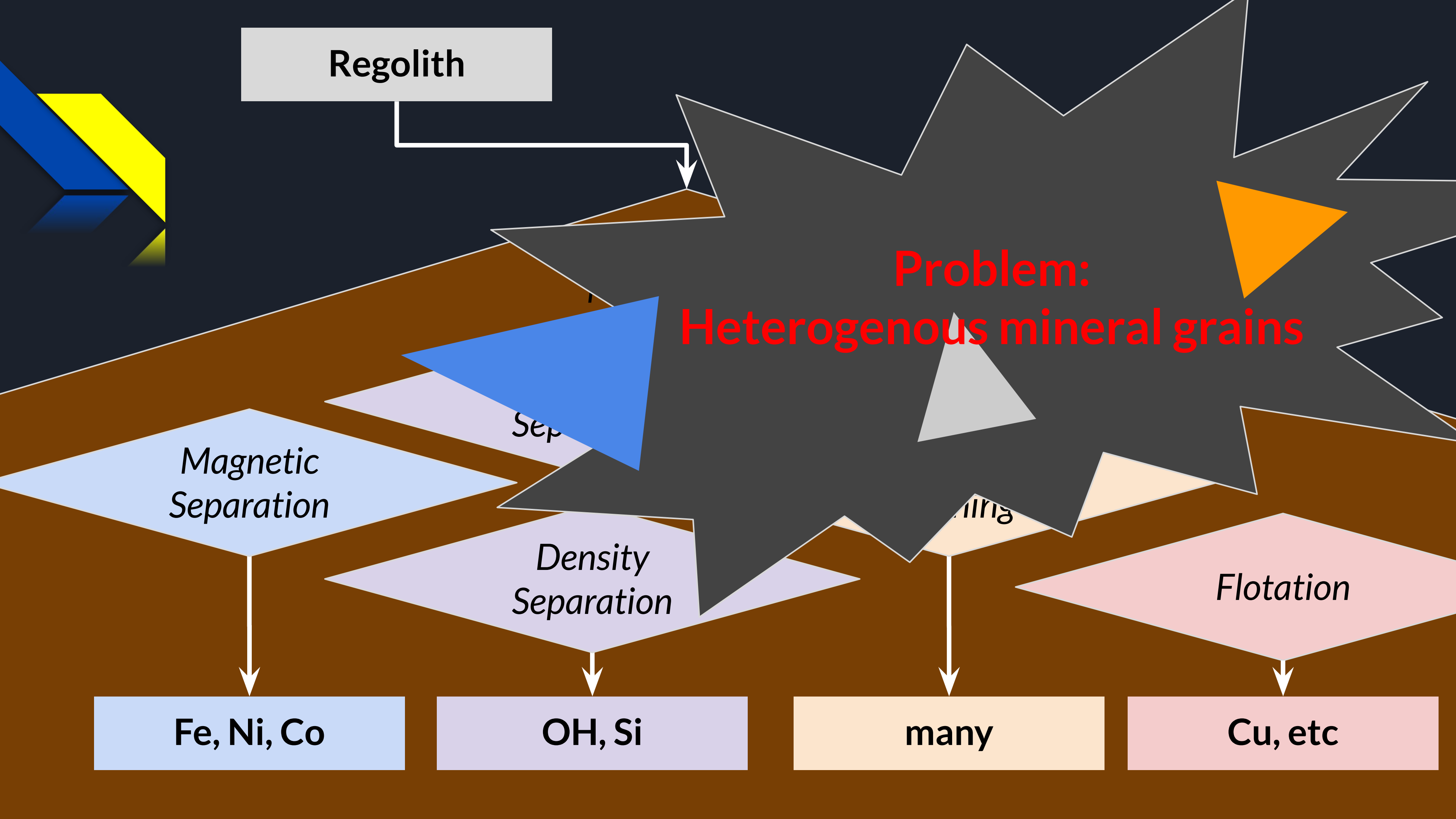
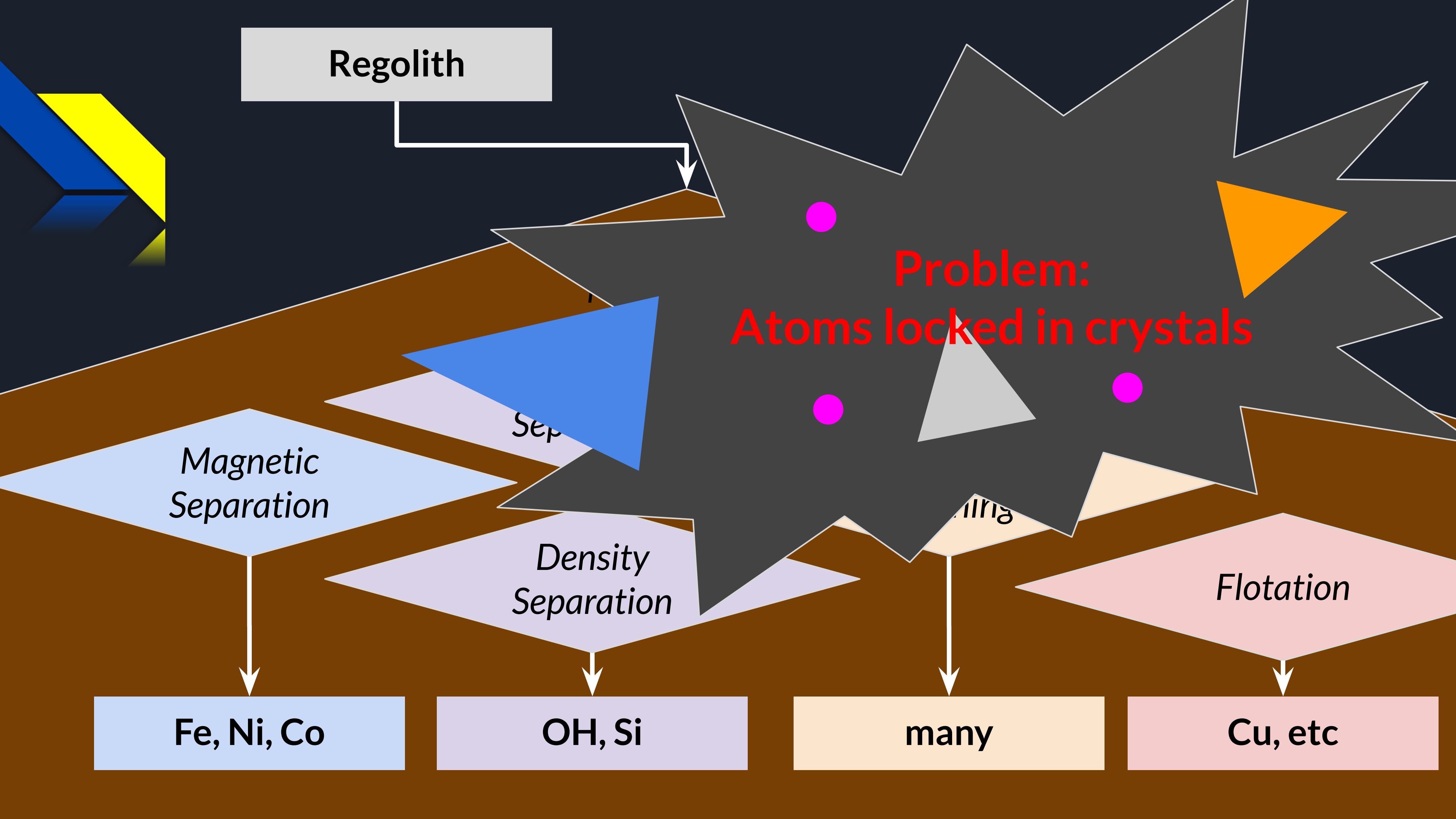

Regolith
???
Metal Parts
Oxygen

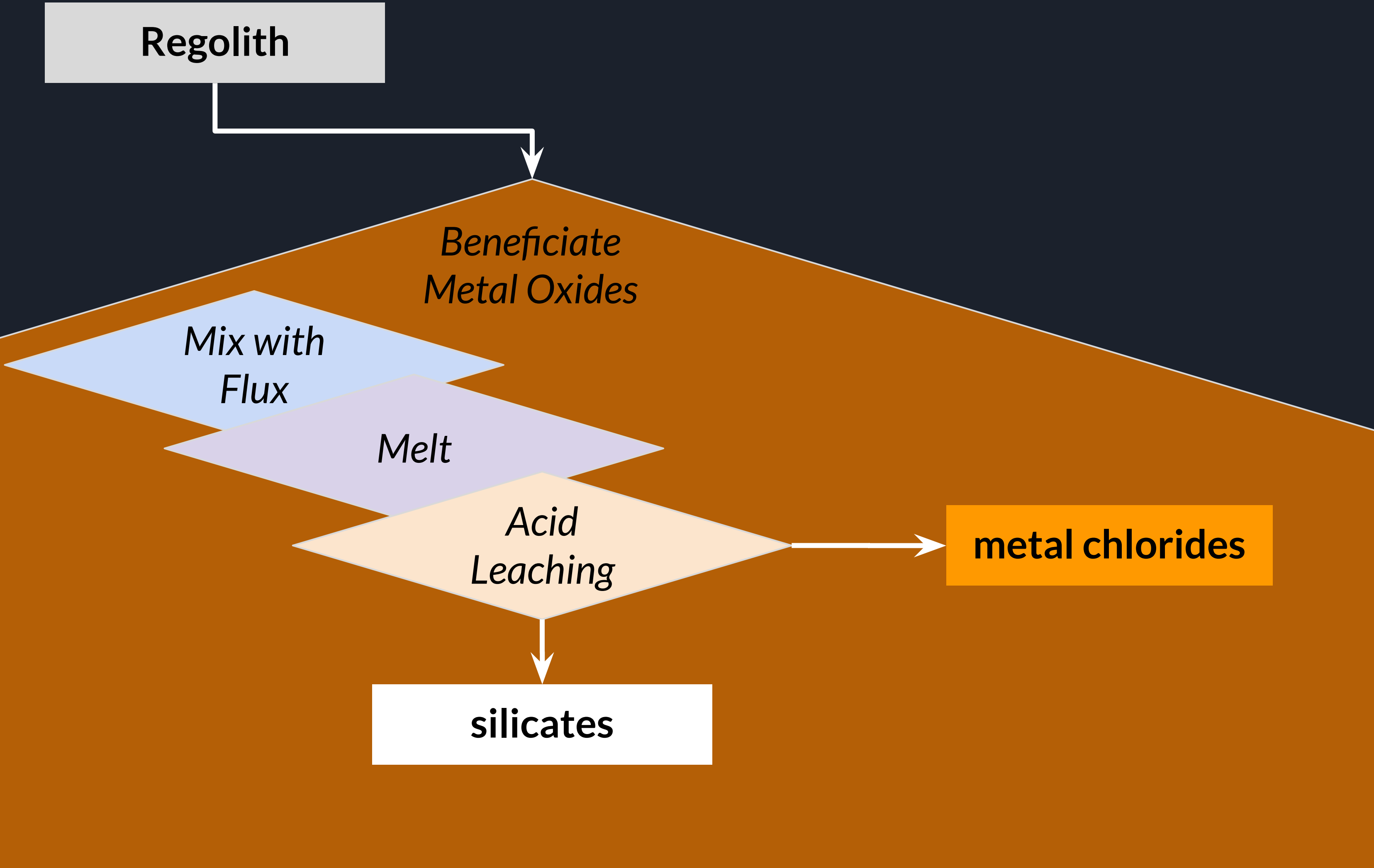

Regolith
Beneficiate
Metal Oxides
Electrowinning
Electroforming
Metal Parts
Oxygen

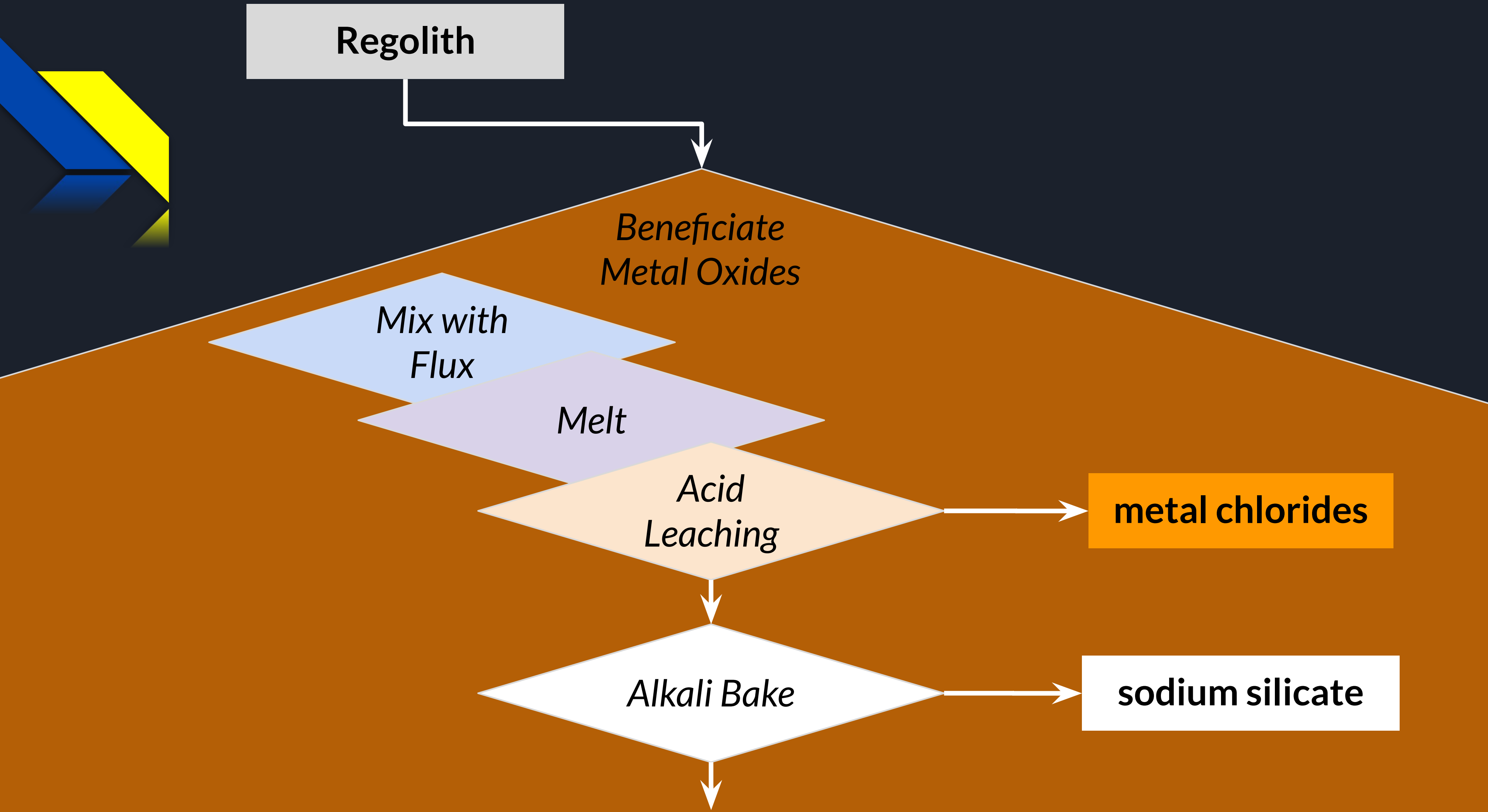


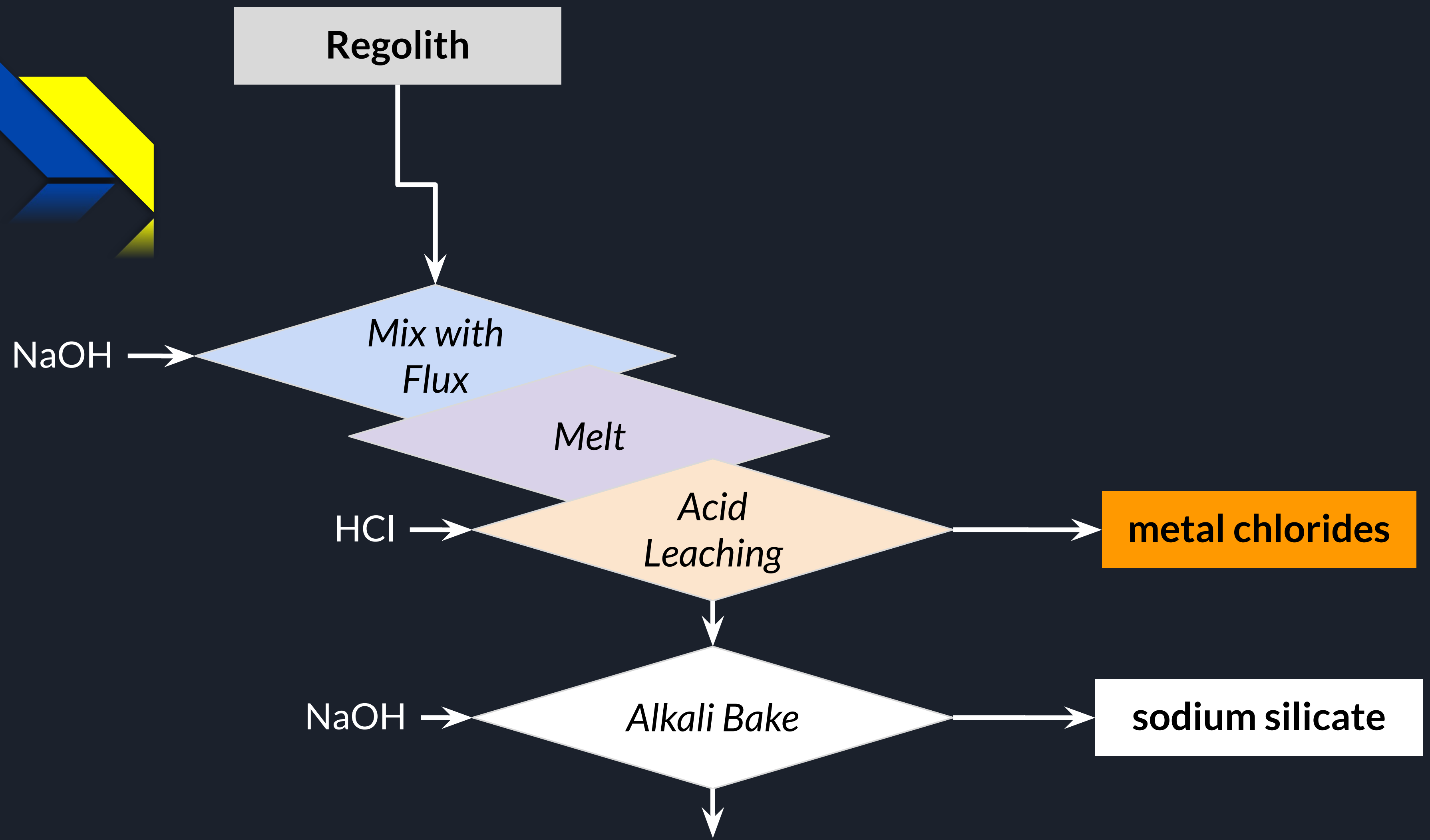
Regolith
Beneficiate
Metal Oxides
Electrostatic
Separation
Magnetic
Separation
Chemical
Leaching
Density
Separation
Flotation
Fe, Ni, Co
OH, Si
many
Cu, etc


Regolith
Problem:
Heterogenous mineral grains
Magnetic Separation
Density Separation
Flotation
Fe, Ni, Co
OH, Si
many
Cu, etc

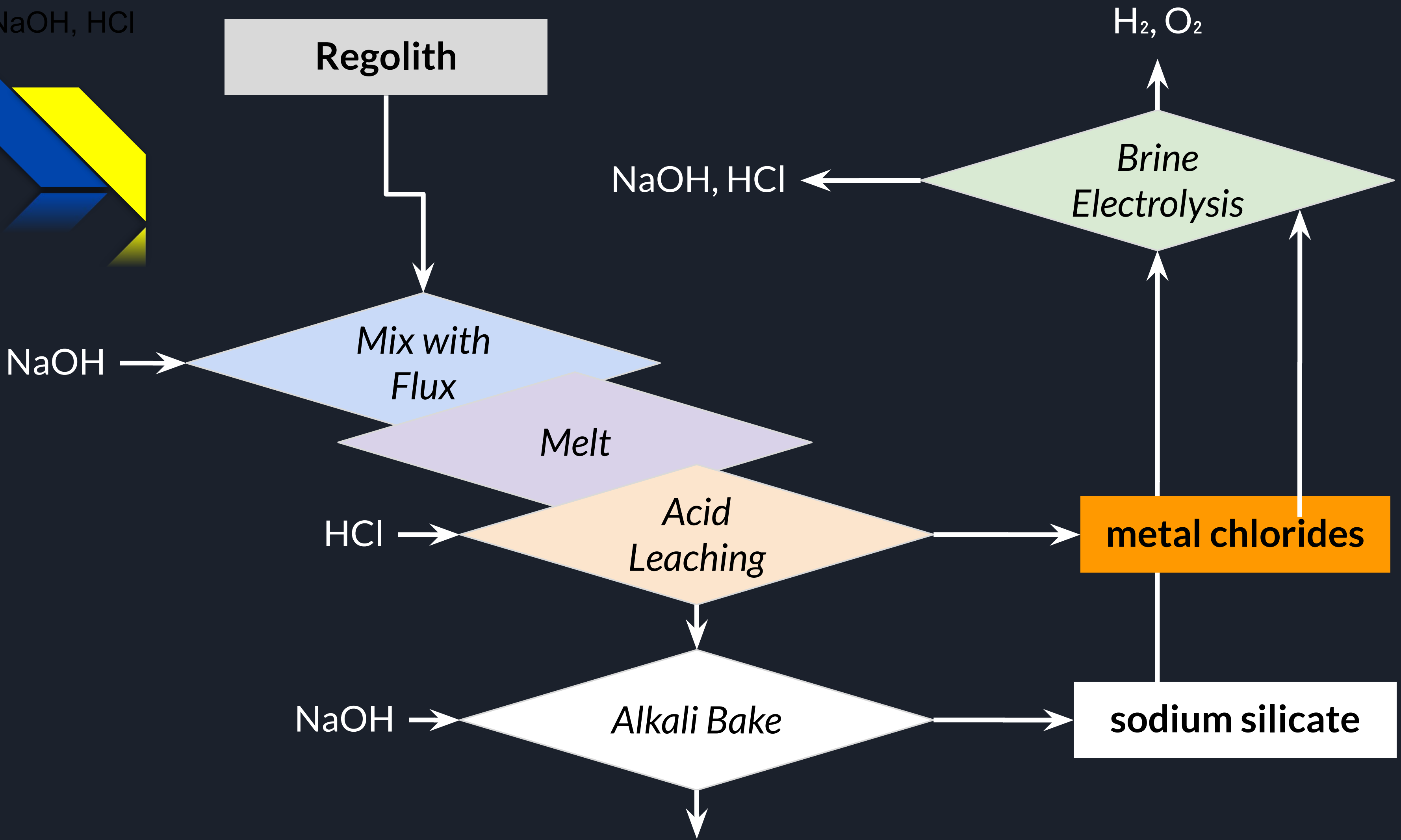

Regolith
Problem:
Atoms locked in crystals
Magnetic Separation
Density Separation
Flotation
Fe, Ni, Co
OH, Si
many
Cu, etc


Regolith
Beneficiate Metal Oxides
Mix with Flux
Melt
Acid Leaching
metal chlorides
silicates

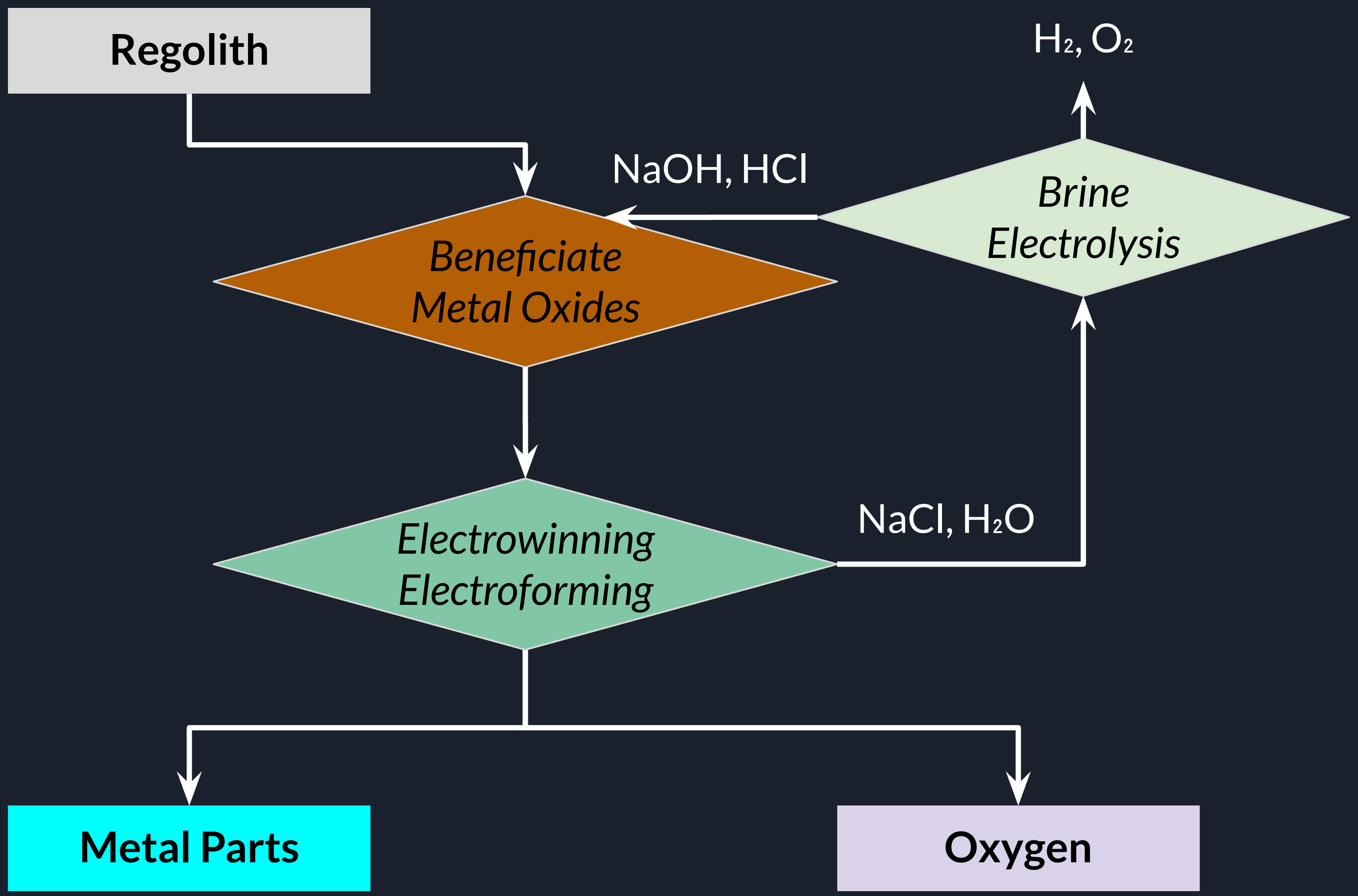

Regolith
Beneficiate
Metal Oxides
Mix with
Flux
Melt
Acid
Leaching
metal chlorides
Alkali Bake
sodium silicate


Regolith
NaOH
Mix with Flux
Melt
HCl
Acid Leaching
metal chlorides
NaOH
Alkali Bake
sodium silicate

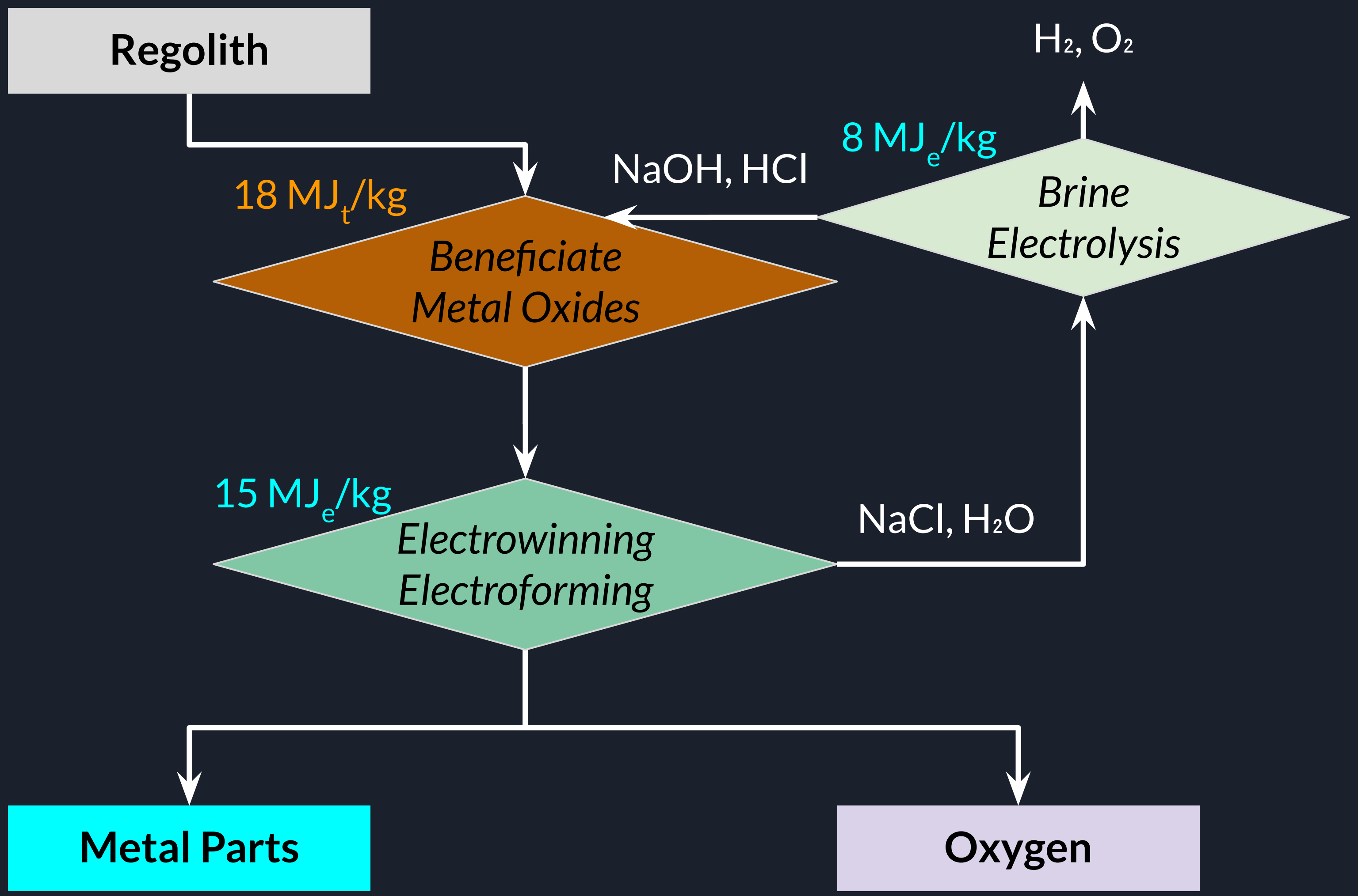
NaOH, HCl



Regolith
Mix with Flux
NaOH
Melt
Acid Leaching
HCl
Alkali Bake
NaOH
metal chlorides
sodium silicate
Brine Electrolysis
NaOH, HCl
H_2, O_2



Regolith
NaOH, HCl
Beneficiate Metal Oxides
H_2, O_2
Brine Electrolysis
Electrowinning Electroforming
NaCl, H_2O
Metal Parts
Oxygen



Regolith
18 MJ$_t$/kg
Beneficiate Metal Oxides
NaOH, HCl
8 MJ$_e$/kg
Brine Electrolysis
H_2, O_2
15 MJ$_e$/kg
Electrowinning Electroforming
NaCl, H_2O
Metal Parts
Oxygen

- Visual Summary
- Flow Diagrams
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Split oxygen and metal?

1.) Dissolve dust's metal oxides in acid

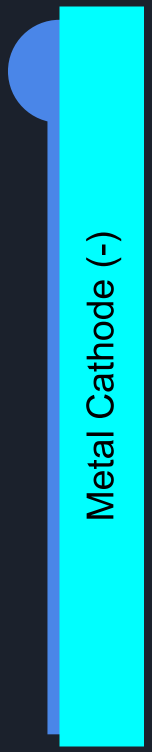
2.) Electrolysis of metal oxides in acid makes:

- Oxygen gas bubbles at anode (+ terminal)
- Metal* deposits at cathode (- terminal)

3.) Electrolysis actually regenerates the acid!

Keep adding electricity (from solar panels) and dust (mined by robots) to make oxygen and metal

*You either get metal, (hydr)oxides, or hydrogen gas, depending on the metal, the applied voltage, cathode material, etc.



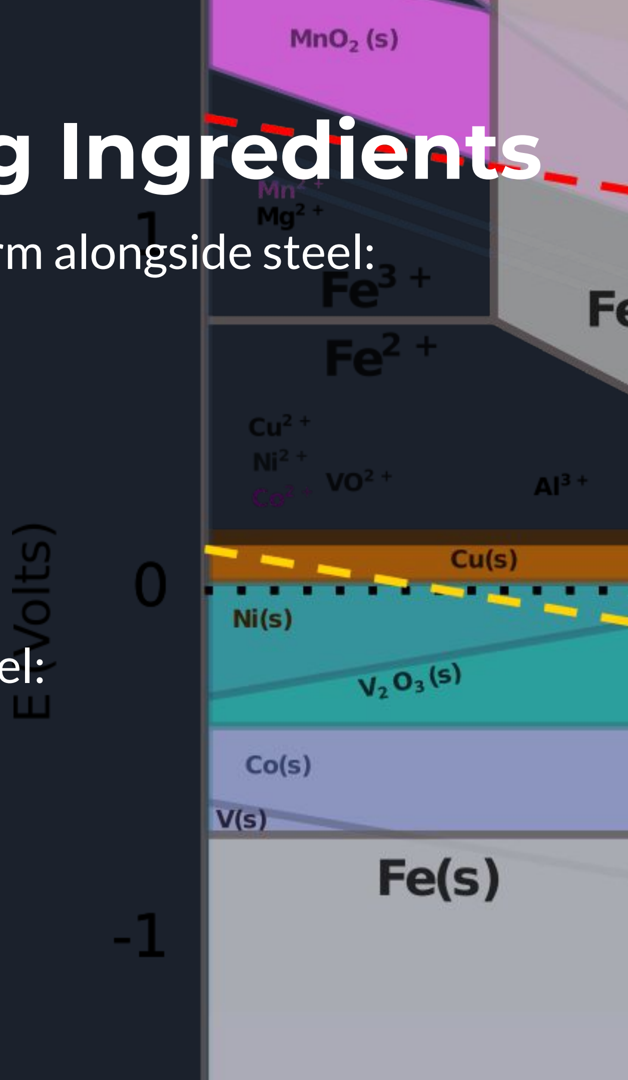
Steel = Iron plus Alloying Ingredients

Several useful metals will naturally co-electroform alongside steel:

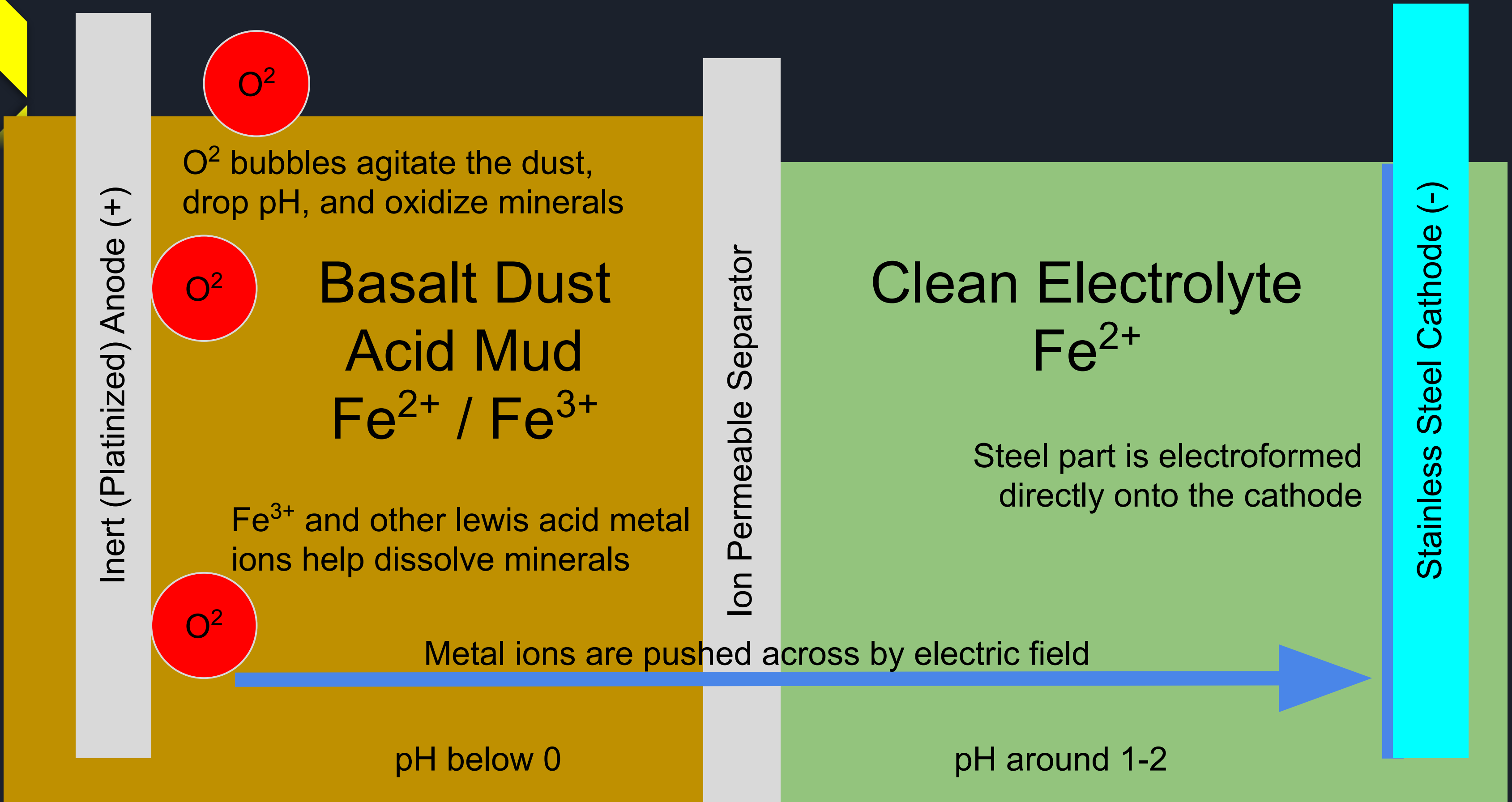
- Nickel, making stainless or maraging steel
    - Extremely common on asteroids
- Cobalt, for superalloys
- Molybdenum, for maraging steel

Other elements could be co-deposited in the steel:

- Oxygen or sulfate, to pin grain boundaries
- Basalt fiber inclusions for tensile strength



One-Pot Dust to Steel Process



3D Printed Guides for Electroforming

Electrolytic sheets or tubes are made commercial on Earth right now.

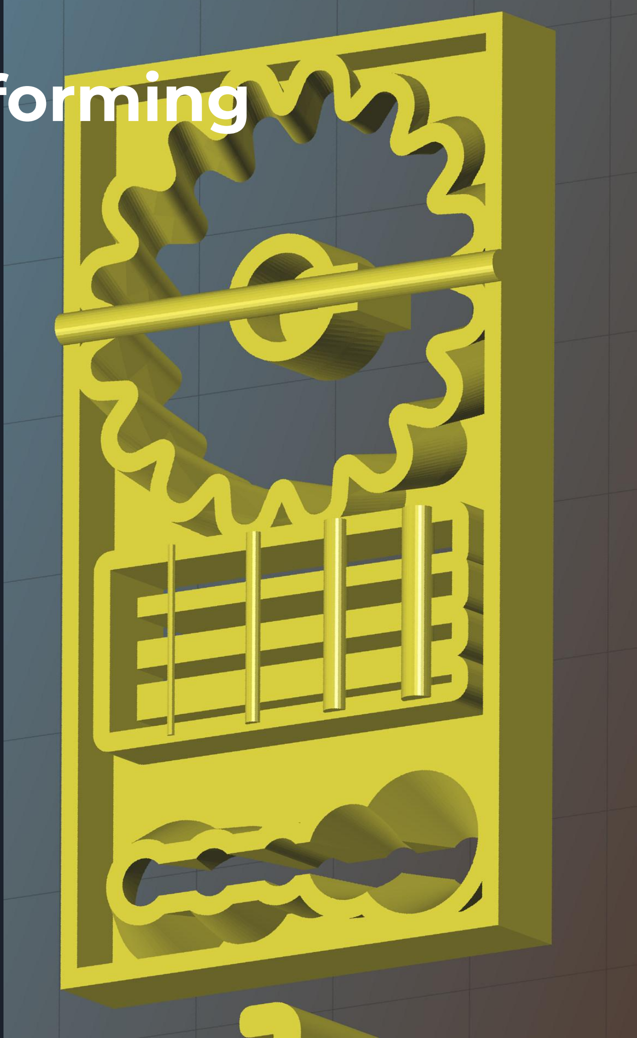
Electroforming more complex shapes is done, but mostly for tiny or high-cost objects using disposable machined mandrels.

3D printed (nonconductive) guide objects block the electrolyte, guiding the deposit

- Allows reusable stainless sheet cathodes
- Grow custom shape finished steel parts

(In space, use reusable wax, or in situ plastic.)

3D printed conductive mandrels work too.



Fluxed Regolith Melting Summary

It is possible to recover metals and silica from basalt or feldspar using this approach.

Future work: Make clear glass from the recovered silica (talk to coauthor Samuel Lucas about his work on this!). Measure the flux rate/melt time/acid time/recovery tradeoffs. Test other fluxes (lithium?). Full quantitative analysis (XRF/ICP-MS) of products and losses.

We're excited about scaling this up for use on Earth or in space!

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Backup Slides

Electrochemistry world map:

Pourbaix Diagram (data from Materials Project.org)