Good practices of Industry 4.0 in the mining and raw material sector

26 April 2024

Supported by eit RawMaterials Connecting matters
Funded by the European Union
EIT HEI Initiative
HEI4S3 RM

GeoZS
Geološki zavod Slovenije

USE OF ROBOTICS AND AUTOMATION FOR THE EXPLORATION AND EXPLOITATION OF MINERAL RESOURCES

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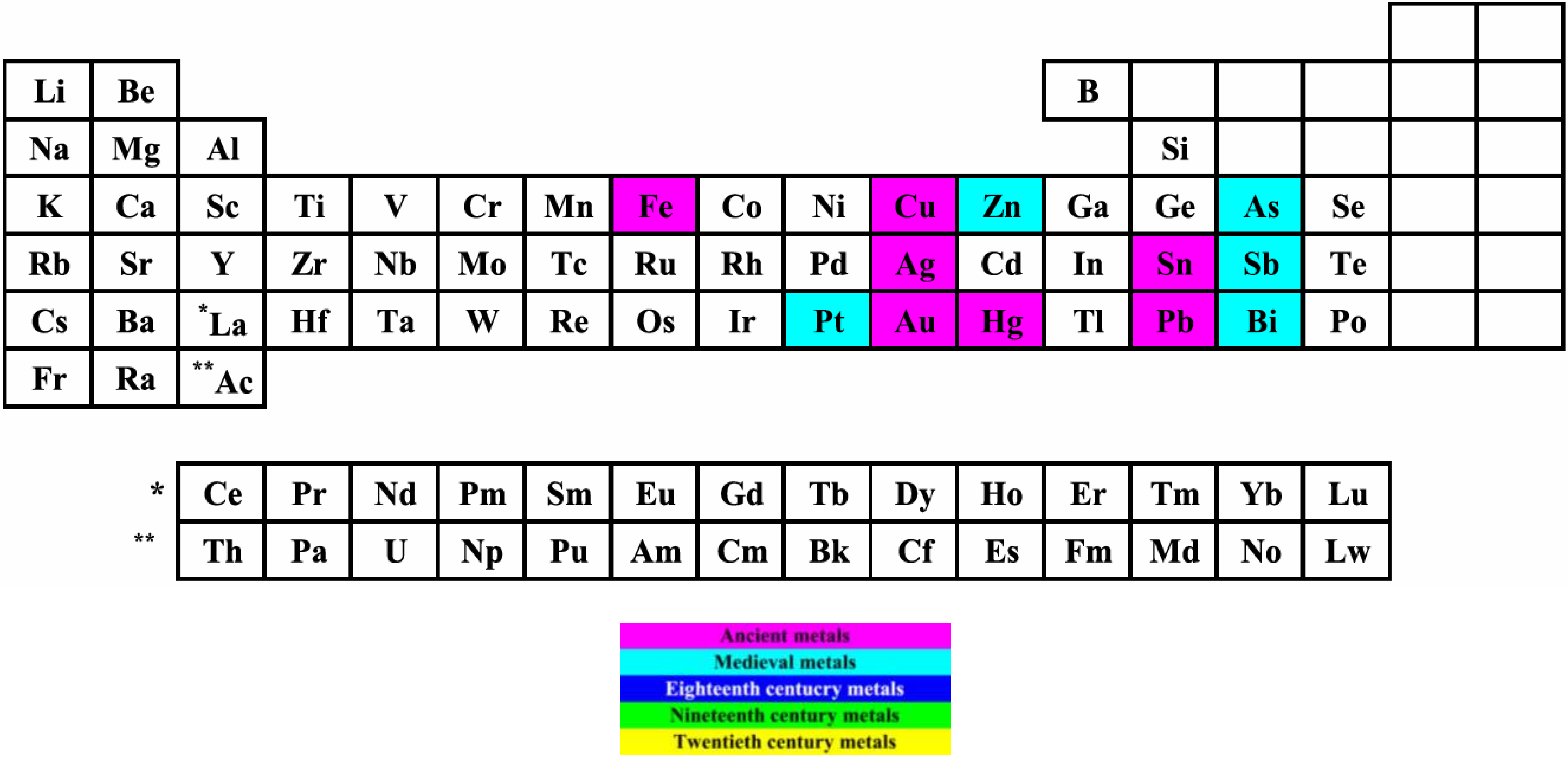
Geological Survey of Slovenia

gorazd.zibret@geo-zs.si

Li	Be											B					
Na	Mg	Al											Si				
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te		
Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po		
Fr	Ra	**Ac															

*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw

Ancient metals
Medieval metals
Eighteenth centucry metals
Nineteenth century metals
Twentieth century metals


Li Be B
Na Mg Al Si
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te
Cs Ba *La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po
Fr Ra **Ac
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** Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lw
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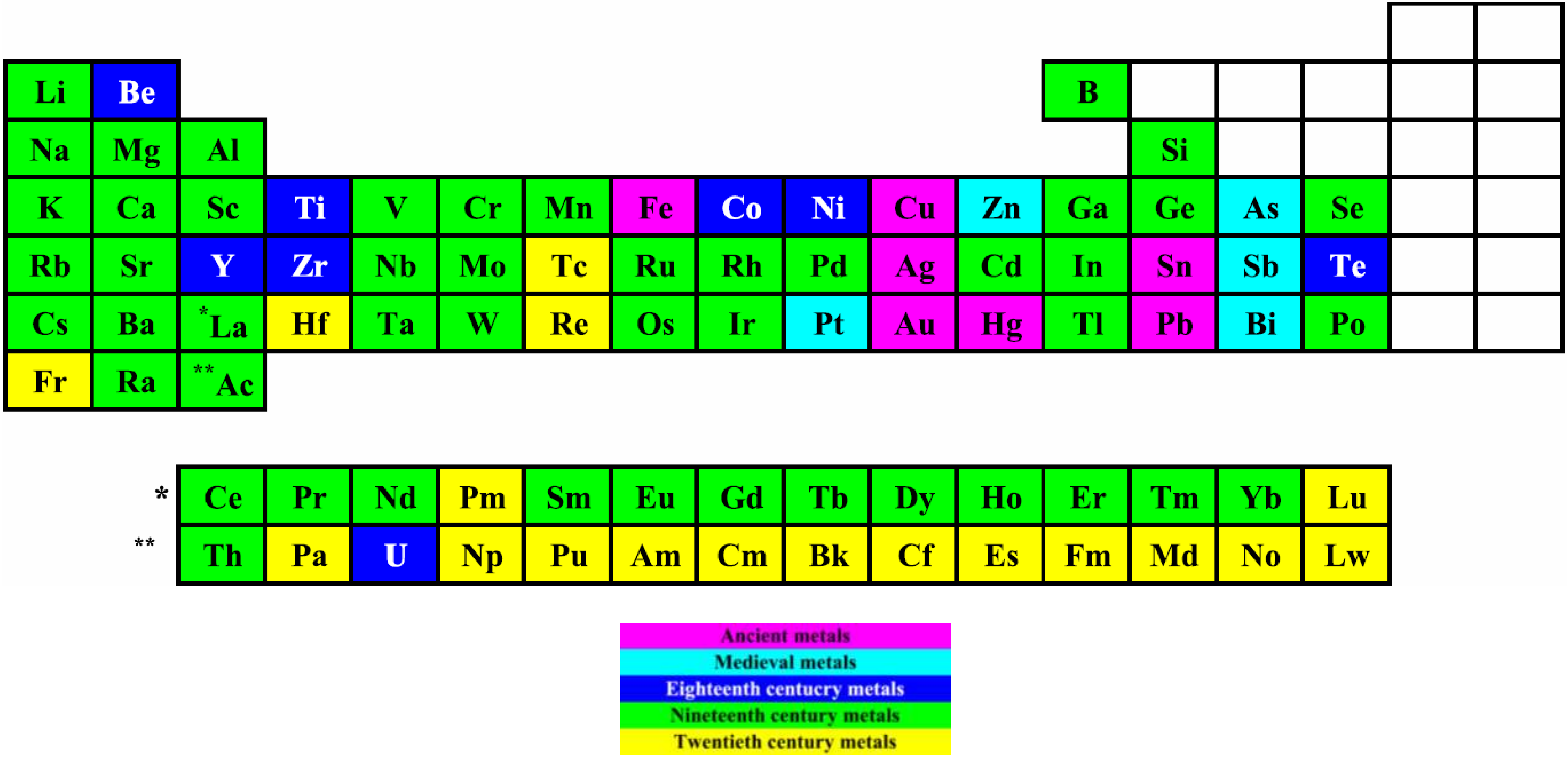
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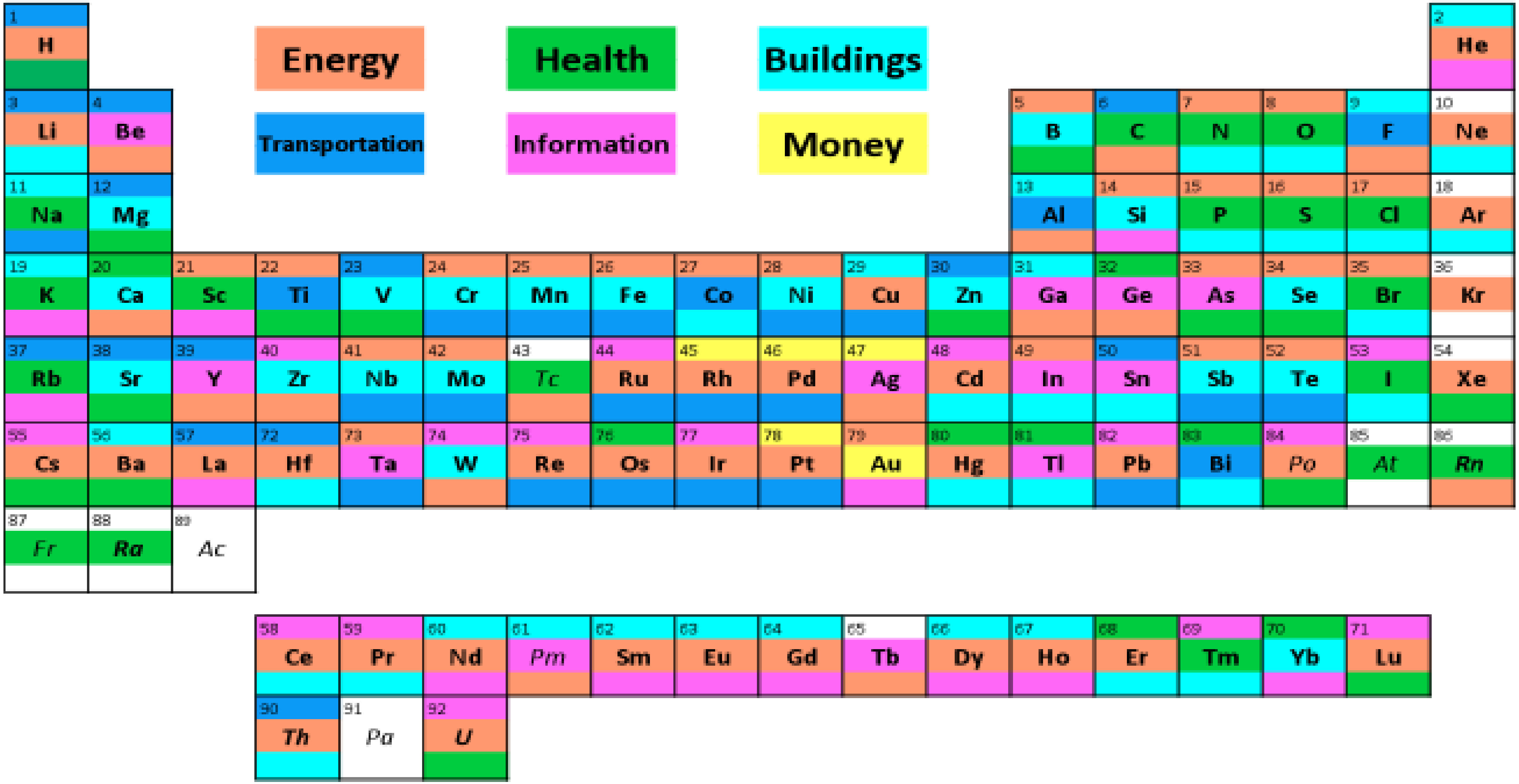

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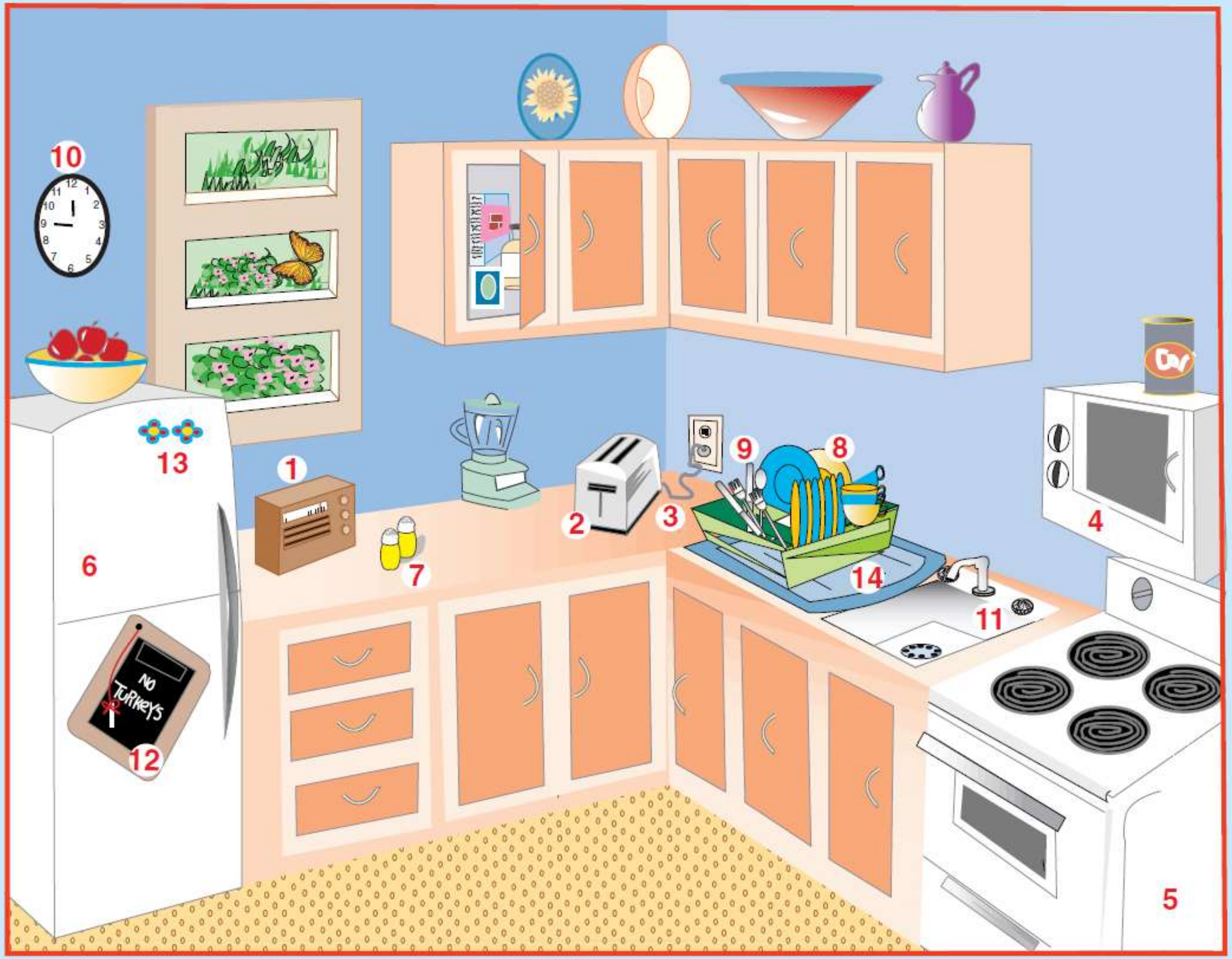

1. RADIO: Includes aluminum, copper, gold, iron and petroleum products.
2. TOASTER: Includes copper, iron, nickel, mica, chromium and petroleum products.
3. ELECTRICAL WIRING: Includes copper, aluminum and petroleum products.
4. MICROWAVE: Includes copper, gold, iron, nickel and silica.
5. STOVE: Includes aluminum, copper, iron, nickel and silica.
6. REFRIGERATOR: Includes aluminum, copper, iron, nickel, petroleum products and zinc.
7. TABLE SALT: Includes halite; light salt can be made from sylvite. Most salt has added iodine.
8. PLATES: Includes clays, silica and feldspar.
9. CUTLERY: Includes iron, nickel, silver and chromium.
10. CLOCK: Includes iron, nickel, petroleum products and silica.
11. STAINLESS STEEL SINK: Includes iron and nickel.
12. BLACKBOARD: Includes clays. Chalk includes limestone or petroleum products.
13. MAGNET: Includes cobalt.
14. DISH RACK: Made of petroleum products.

Source: USGS

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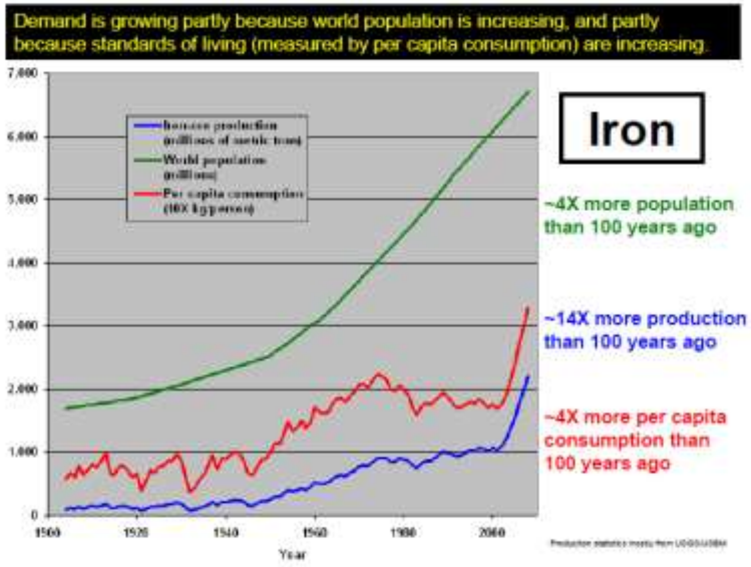
1 lbs = 1 pound = 0,45 kg

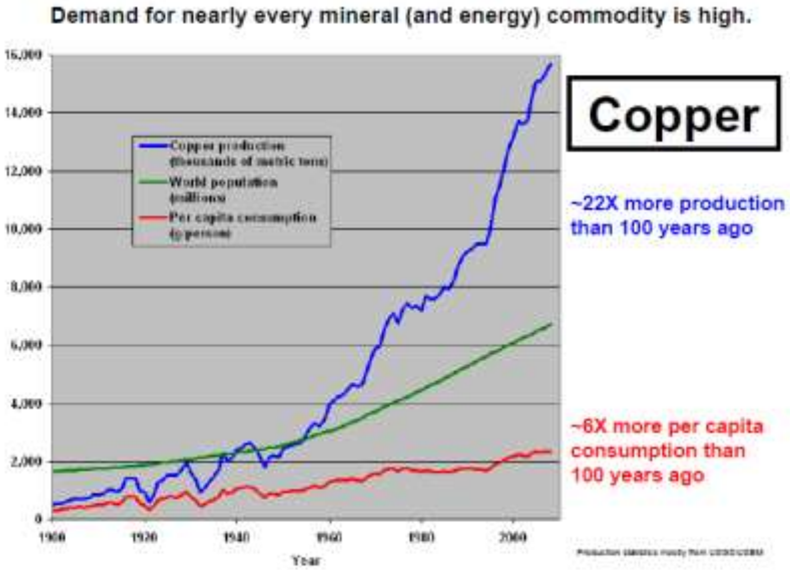
How do we obtain mineral resources?

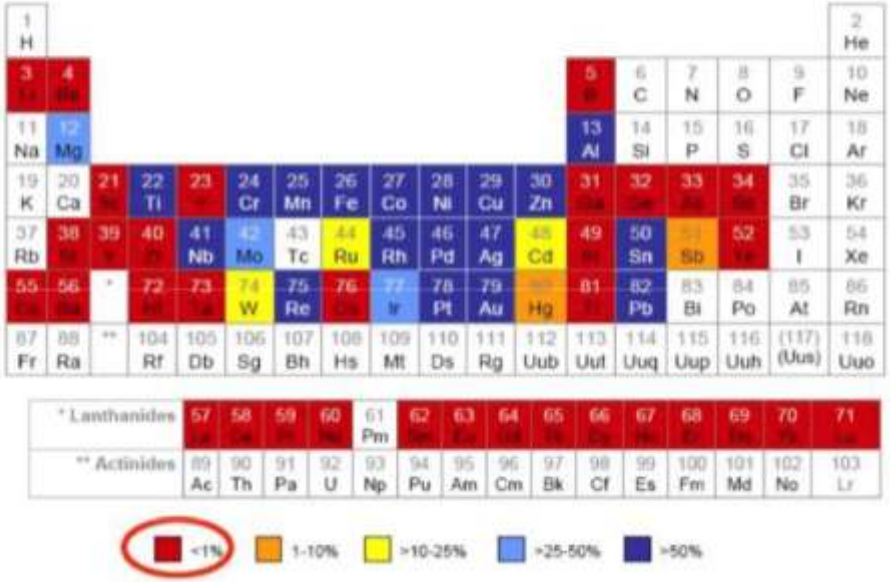
(1) RECYCLING. But it is a problem here.

Recycling cannot meet the ever-increasing demend for raw materials (until 2050 there will be 9.7b people, global metal extraction needs to be increased by 50% and the production of non-metallic raw materials by 100%). By recycling all of the waste we would met around 20% of the demand!

Some commodities can not be (economically) recycled.







Source: Graedel et al. (2011) What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology, 15*, 355-366

How do we obtain mineral resources?

(2) MINING - it is an activity of extraction of raw materials from the Eart, where an useful substance is concentrated in high enough quantities and is of good enough quality for economic extraction

a) prospection (geological mapping, geophysical exploration, drilling), mining project and permits

b) extraction (blasting, cutting & grinding, leaching, pumping etc.)

c) loading, crushing (primary, secondary)

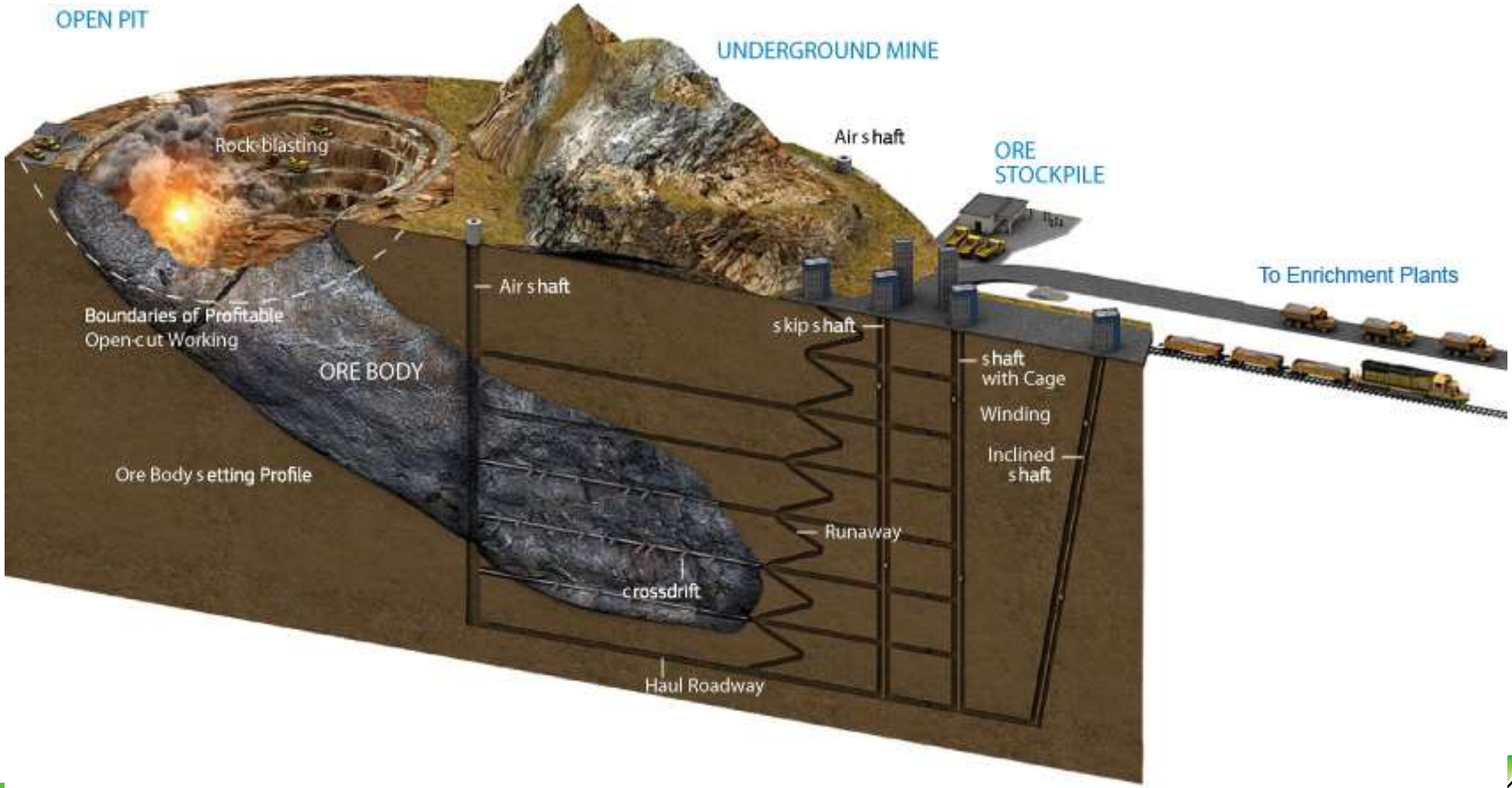
d) ore beneficiation (i.e. flotation, gravitational or magnetic separation etc.)

e) metallurgical processing - hydro- or pyrometallurgical processes, bioleaching

f) purification - using chemical or metallurgical procedures to get the desired output

g) mine closure and land recultivation (BUT!!! IN THE VAST MAJORITY OF CASES NOT BECAUSE THERE IS LACK OF ORE, BUT BECAUSE EXTRACTION IS NOT ECONOMICALLY VIABLE ANY MORE)

Mining process



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Mining process

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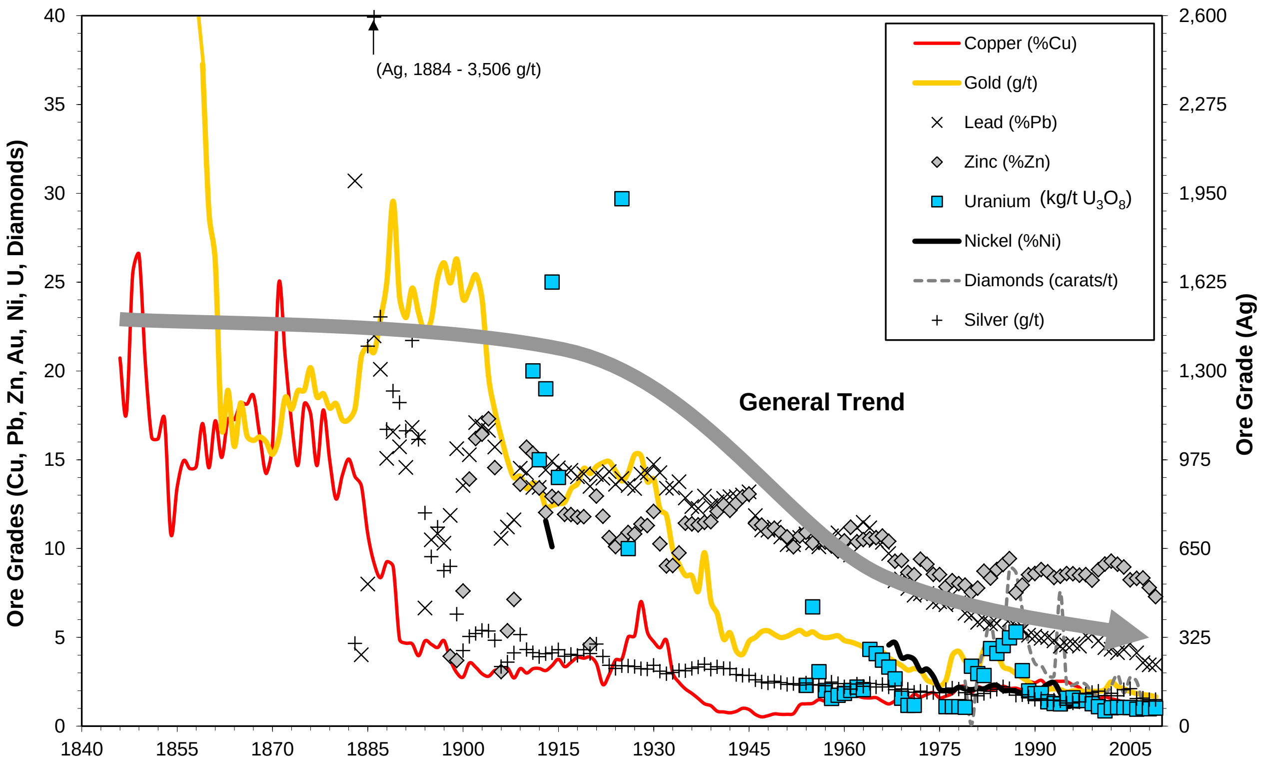
Mining process

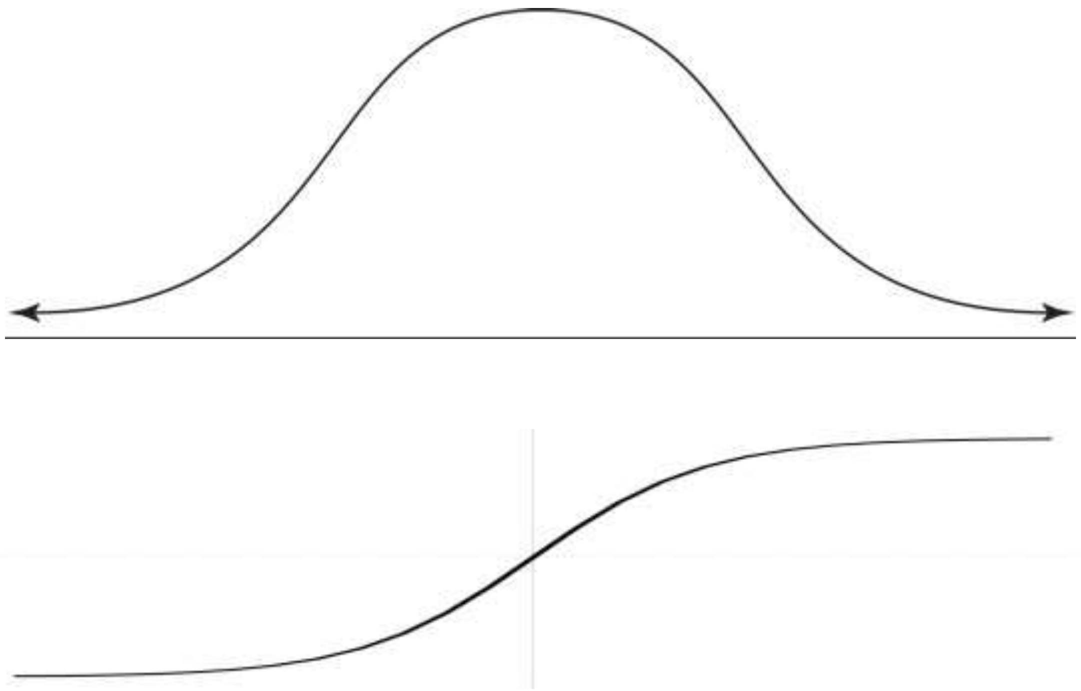
NEGATIVE INFLUENCES

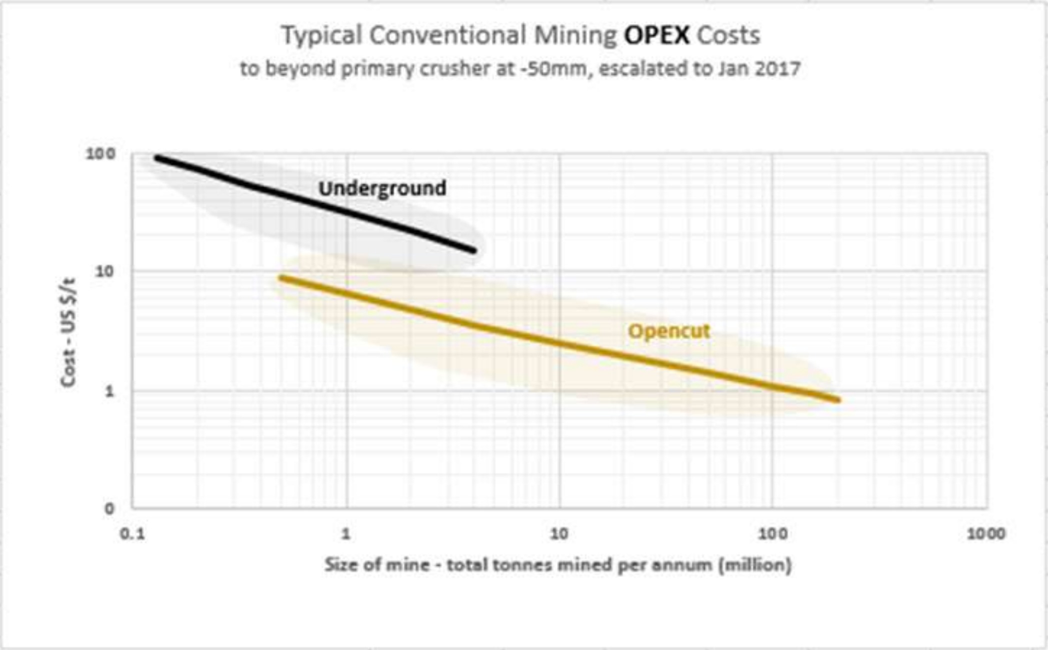
- land use, infrastructure, transport
- energy-intensive industry, water and chemical use
- large quantities of waste
- emission of harmful substances (natural or man-made)
- secondary effects: land subsidence, instability, water regime, econsystems

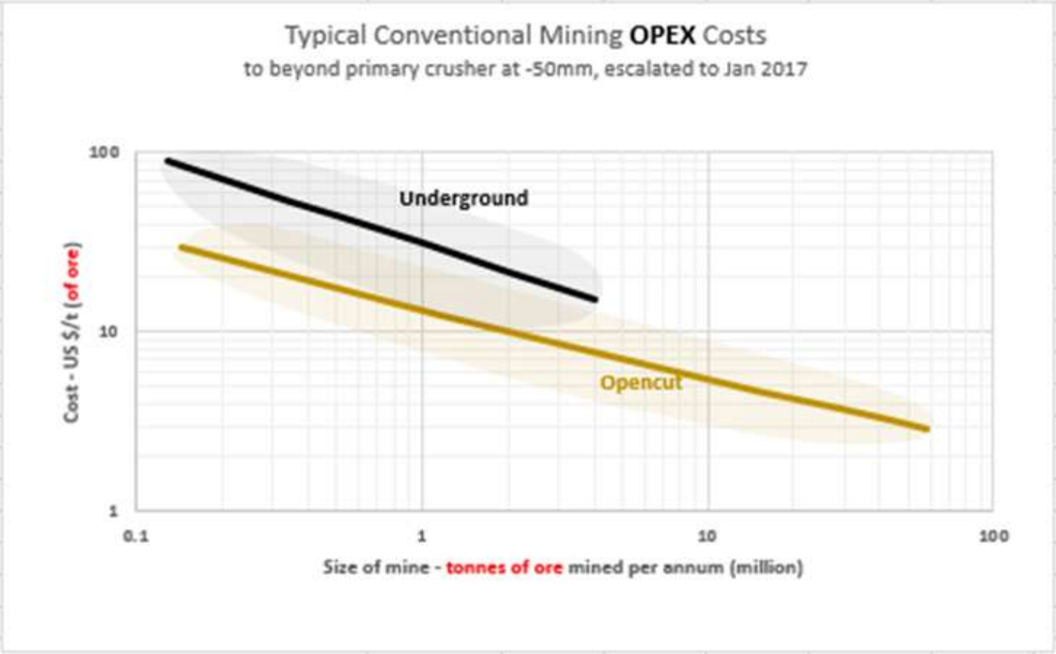
Mining is the future! If it's Not Grown, It Must Be Mined.

We will not run out of mineral resources. The only question is at what price are we going to extract and process them! Economical extraction is a function with numerous variables: prices, environment, taxation, geology, price of energy, workforce etc.





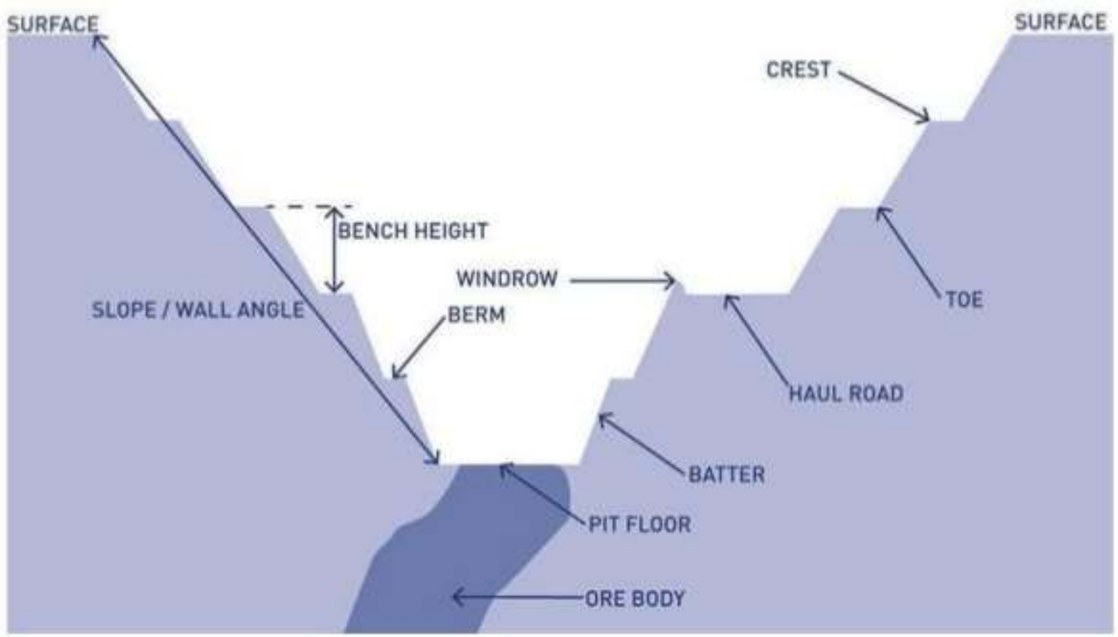

Typical Conventional Mining OPEX Costs
to beyond primary crusher at -50mm, escalated to Jan 2017
Underground
Opencut
Cost - US $/t
100
10
1
0
0.1
1
10
100
1000
Size of mine - total tonnes mined per annum (million)


Typical Conventional Mining OPEX Costs
to beyond primary crusher at -50mm, escalated to Jan 2017
Underground
Opencut
Cost - US $/t (of ore)
100
10
1
0.1
1
10
100
Size of mine - tonnes of ore mined per annum (million)

What are the factors which dictates mine opening and closure?

Economical factors for mine closure:

- ore prices on global markets
- decrease of raw material content
- increased mine depths lead to increased costs (water, people)
- decreased stripping ratio



Main factors for mine opening:

- required infrastructure (water, energy, workforce...)
- local community, social licence fto operate
- environmental impacts
- workforce
- geomechanical stability

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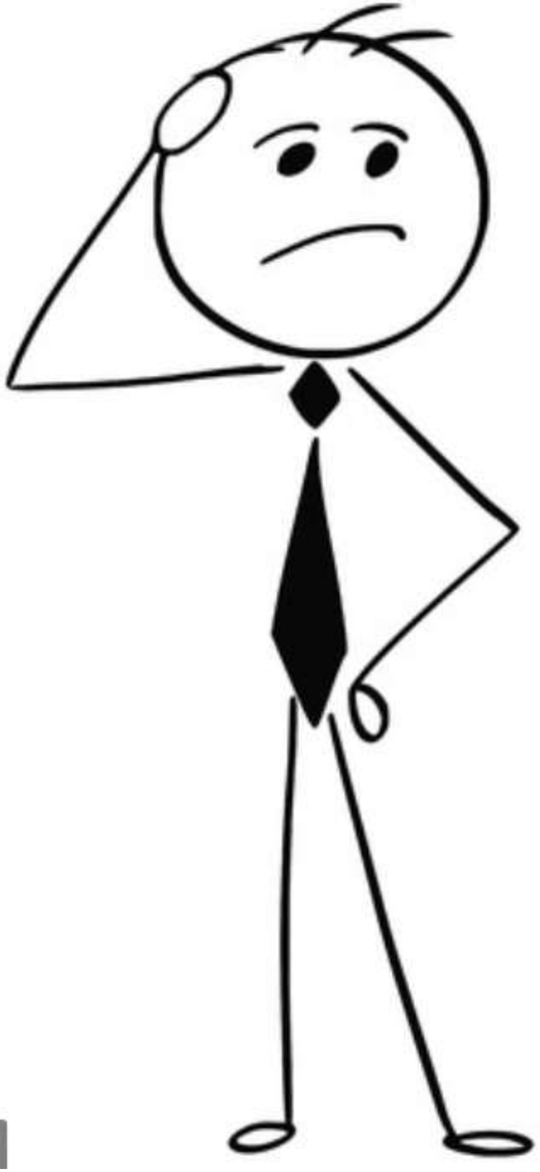

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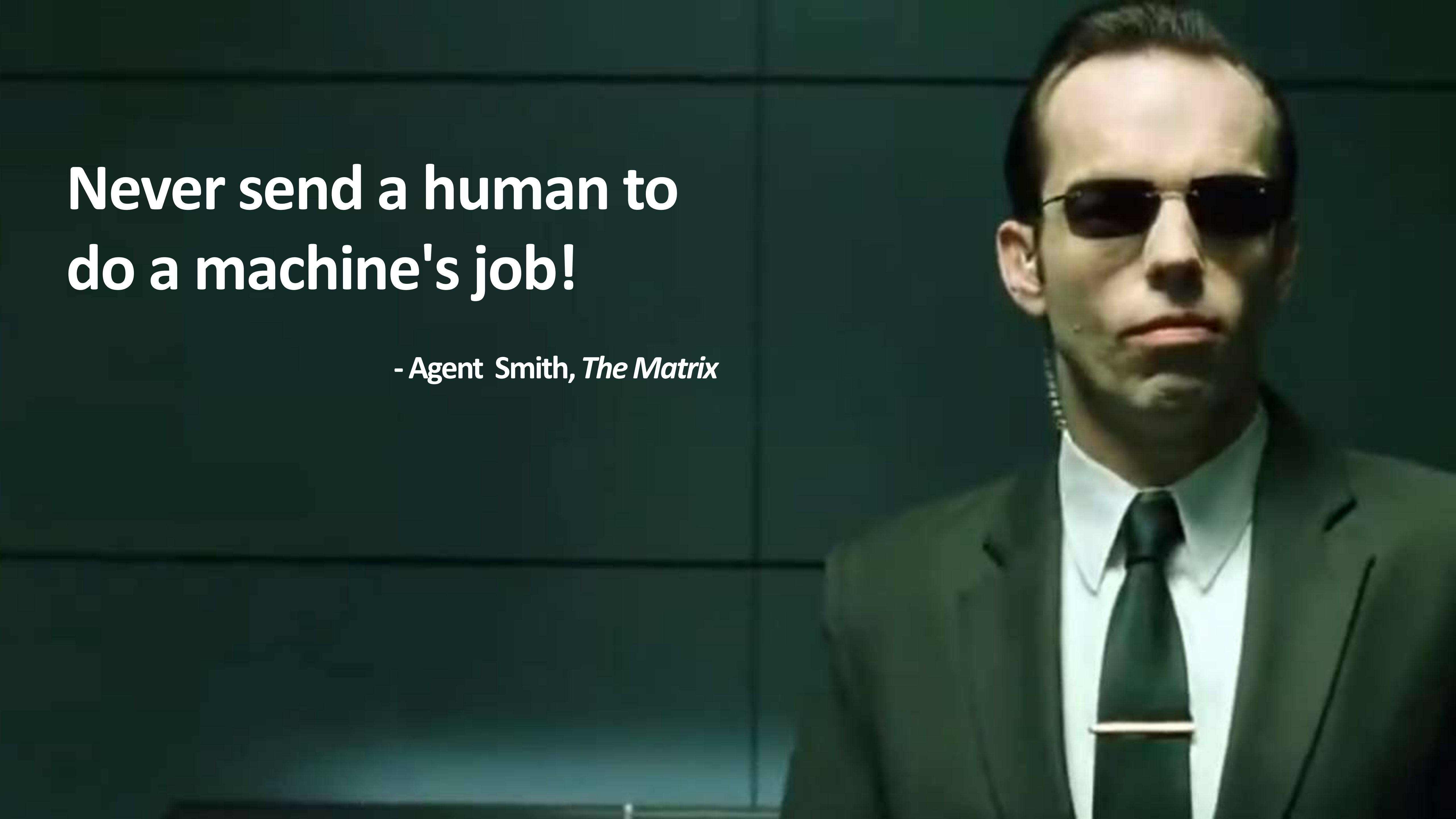
Let's mine big low-grade ore deposits in big mines by using big machines, and leaving big environmental footprints!

https://sac.edu.ph/no-to-mining-anthonians/


Never send a human to
do a machine's job!
- Agent Smith, *The Matrix*

What's next?

- **selective mining**, let's (selectively) mine small high-grade deposits

- **autonomous / remotely-controlled mining**: let's mine deposits where humans can not go

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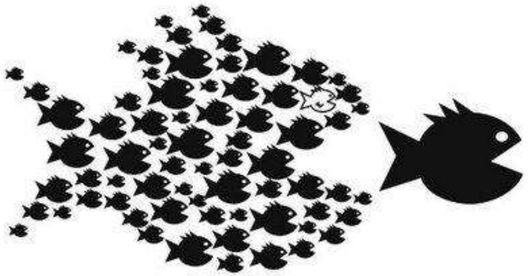
Benefits of selective mining

- **selective mining**, let's (selectively) mine small high-grade deposits

- get rid of humans from the excavation face
- significantly less amounts of waste
- better geotechnical stability
- can unlock many small, but reach deposits which are not the main target for conventional mining
- can be used in active mines in areas not attractive for conventional mining



Benefits of autonomous / remotely-controlled mining?

- **autonomous / remotely-controlled mining**: let's mine deposits where humans can not go

- get rid of humans from the excavation face
- less costs for workers health & safety
- unlocking ultra-deep deposits, ocean floor, even asteroid
- more attractive sector for workforce
- more productive work

What's next?

- **selective mining**, let's (selectively) mine small high-grade deposits

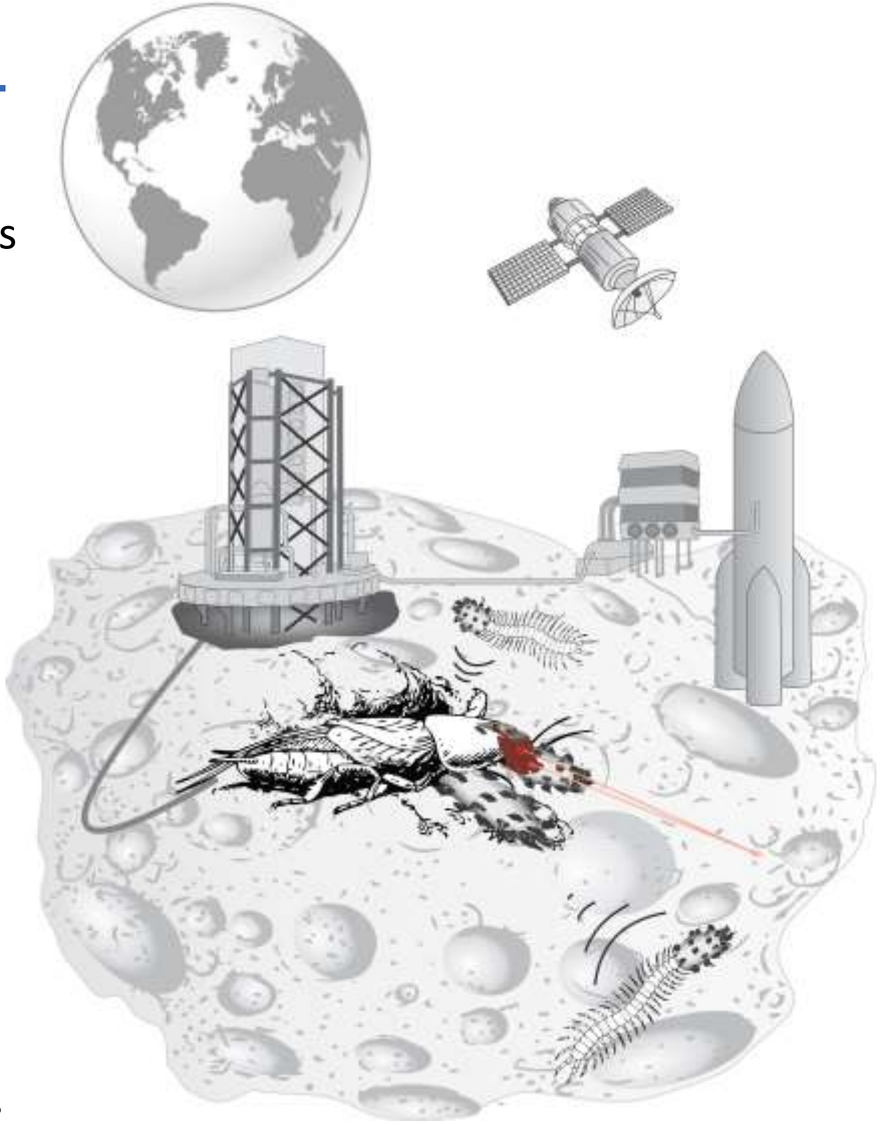
- **autonomous / remotely-controlled mining**: let's mine deposits where humans can

Technologically very challenging!

Vision of the mine of the future:

Mining:

- is completely automated, no humans needed underground; human interventions are needed, but can be done remotely,
- machines are modular, can self-assembly and self disassembly, are able to use various tools and to replace worn-out parts,
- machines are able to distinguish between ore and waste, and are able to make decisions accordingly,
- minerals are extracted precisely, in all 3 directions, with much less waste,
- have complex, or fractal-like mine layout, increased stability,
- mining machines can start digging from the surface, and can operate in various environments, even underwater, in fresh or saline waters, in corrosive environments etc.,
- mineral separation is occurring underground, with in-situ backfilling if needed,
- ore concentrate is transported to the surface,
- downstream industries (concentration, processing, metal extraction) are also automated,
- can operate in extraterrestrial environments (like on the Moon, Mars, asteroids).



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Technological challenges

It could be stated, that underground autonomous mining is bigger challenge than the exploration of extraterrestrial bodies.

- **energy supply** (crushing of rocks requires enormous amounts of energy)
  - batteries???
  - if we use fuels we need oxygen or ventilation
  - hydraulic systems, compressed air, problem with pipes
  - explosives, danger of accidents
  - nuclear / fuel cells / fusion?

- **motoric, locomotion**
  - legs or wheels?
  - 3D environment, must be able to climb
  - substance independent (walk, crawl, swim, climb, float etc. in air, fresh/salt water, gas, oil...)

- **communication** (rocks absorb EM waves)
  - cable communication (cables again!)
  - autonomous or semi-autonomous machines
  - wireless routers - straight corridors are needed (generates waste!)

Technological challenges

It could be stated, that underground autonomous mining is bigger challenge than the exploration of extraterrestrial bodies.

- **cutting of hard rocks, productivity**
  - how to assure backforce (especially for smaller machines)
  - anchoring?
  - buoyancy in the case of water environment
  - replacement of worn-out parts
  - transportation of extracted ore to the processing plant

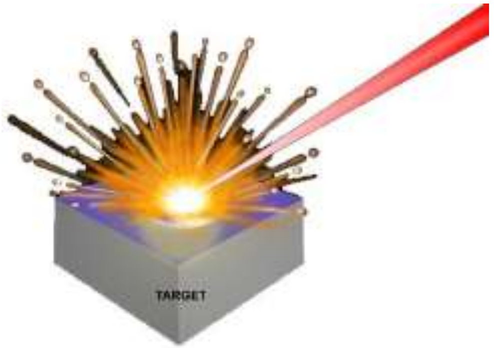
- **big data handling**
  - data storage, data processing
  - information & feature extraction
  - communications, data transfer
  - algorithms development (feature detection, artificial intelligence)

- **human-machine interaction**
  - virtual reality
  - data integration
  - decision-support sytems & autonomy

Technological challenges

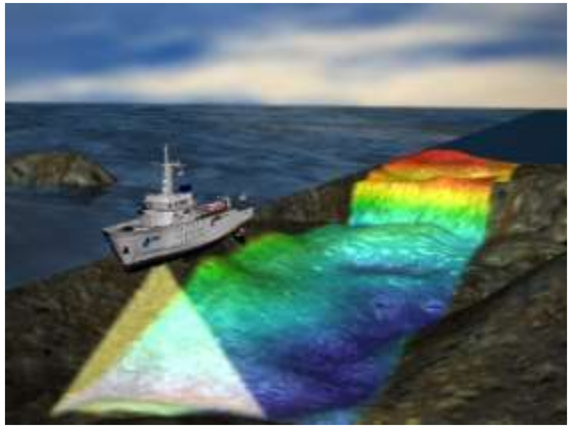
It could be stated, that underground autonomous mining is bigger challenge than the exploration of extraterrestrial bodies.

- **robustness and resistance to corrosion**
    - presence of corrosive gasses and liquids (i.e. H_2SO_4)
    - tolerant to malfunctions; back-up systems
    - tolerant to impacts, roof collapses
    - tolerant to magnetic and electric fields, radiation
    - tolerant to high temperatures



- **modularity** (a lot of different tasks in the mine)

- **sensors**
    - positioning, environmental sensing, manoeuvering (GPS does not works underground)
    - mineral and ore detection system
    - high noise environment, dust, dirt, water, suspension, gasses...



“The man who moves a mountain begins by carrying away small stones.” (Confucius)

- **automatization of tasks, remote control of machines (co-existence of humans and machines)**

- sensors, virtual reality environments

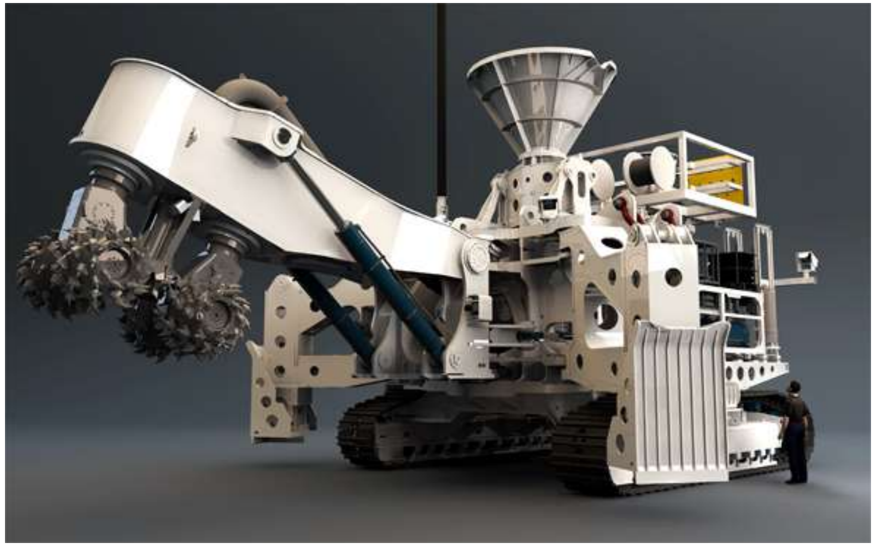
less issues with health and safety of workers

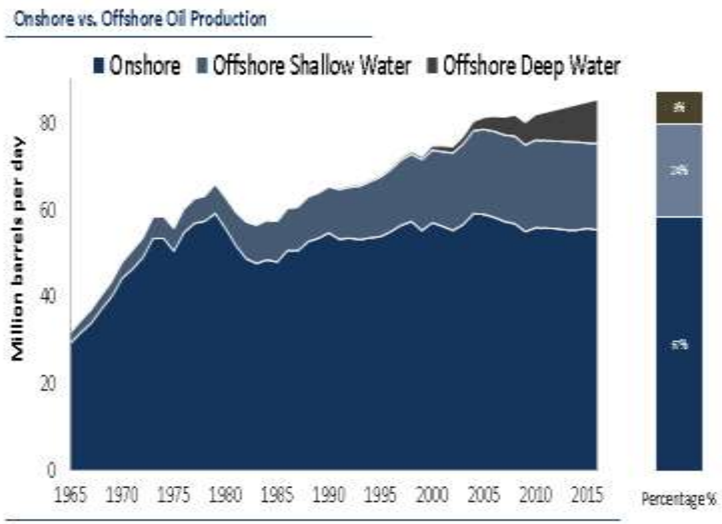
better working environment

Sandvik AutoMine

Soil Machine Dynamics

Off-shore mining





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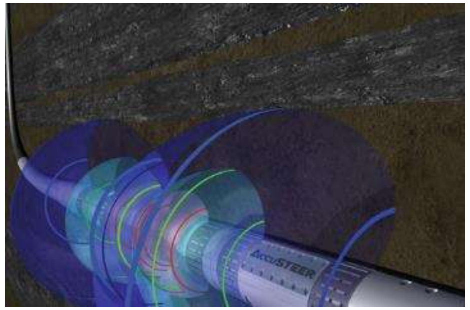
First commercial steps

Sandvik Mining DD320s



Accusteer MWD

Atlas Copco Mobile Miner

Julius robot - Innok Robotics

Joy DynaCut

Longwall automatic mining

Sandvik Rapid Mine Development System

And many many others...

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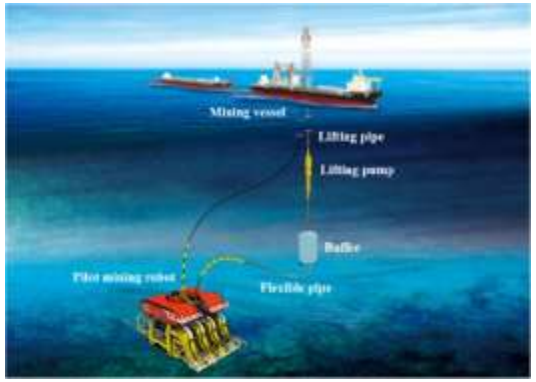
Sea floor mining & Various projects



KRISO underwater mining machines

NAUTILUS

DAMEN dredging

Pipebots

Badger

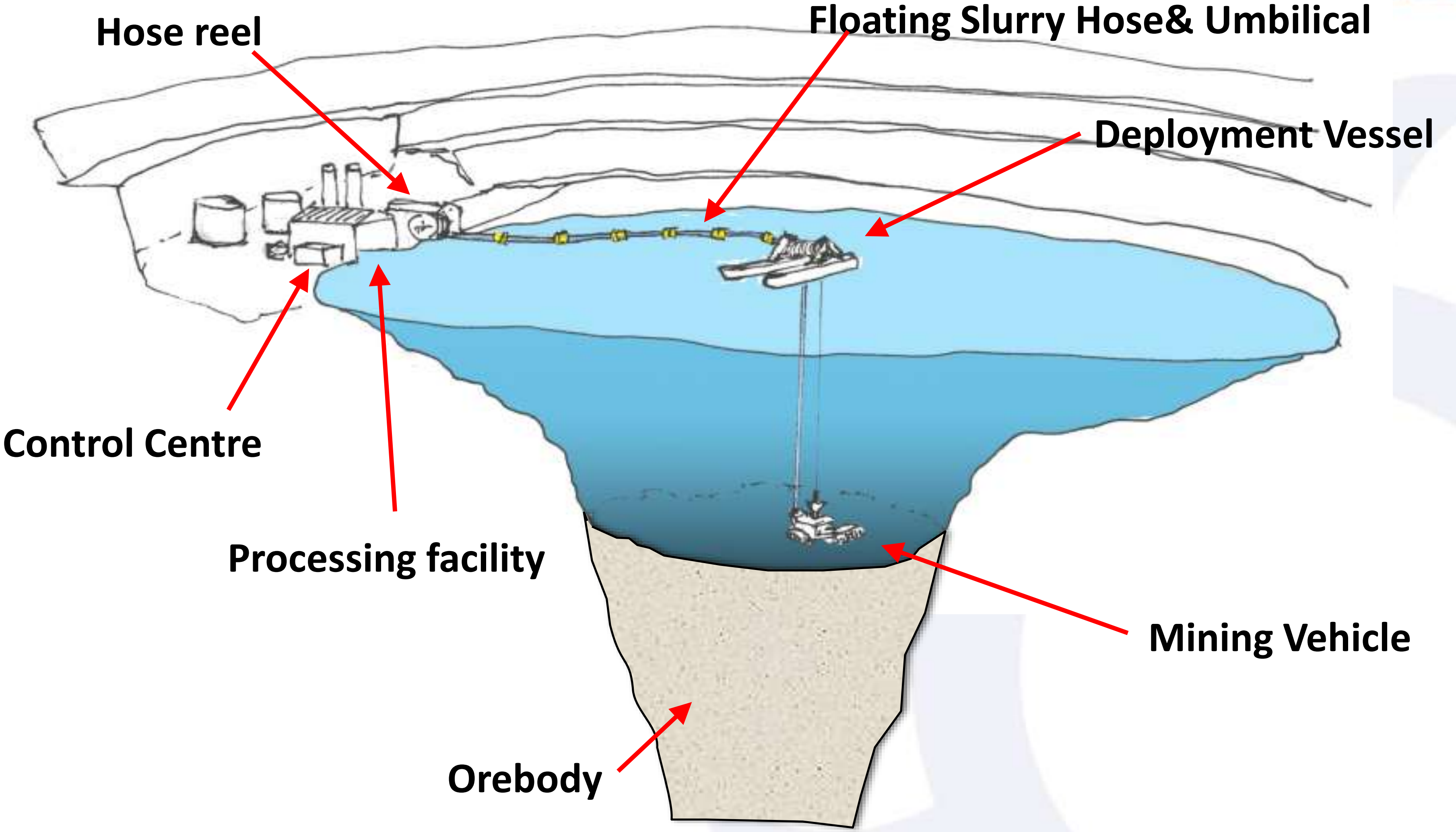
AutoFlyMap

And many many others...

¡vamos!

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 642477

Inland Submerged Mining (Concept Prototype)



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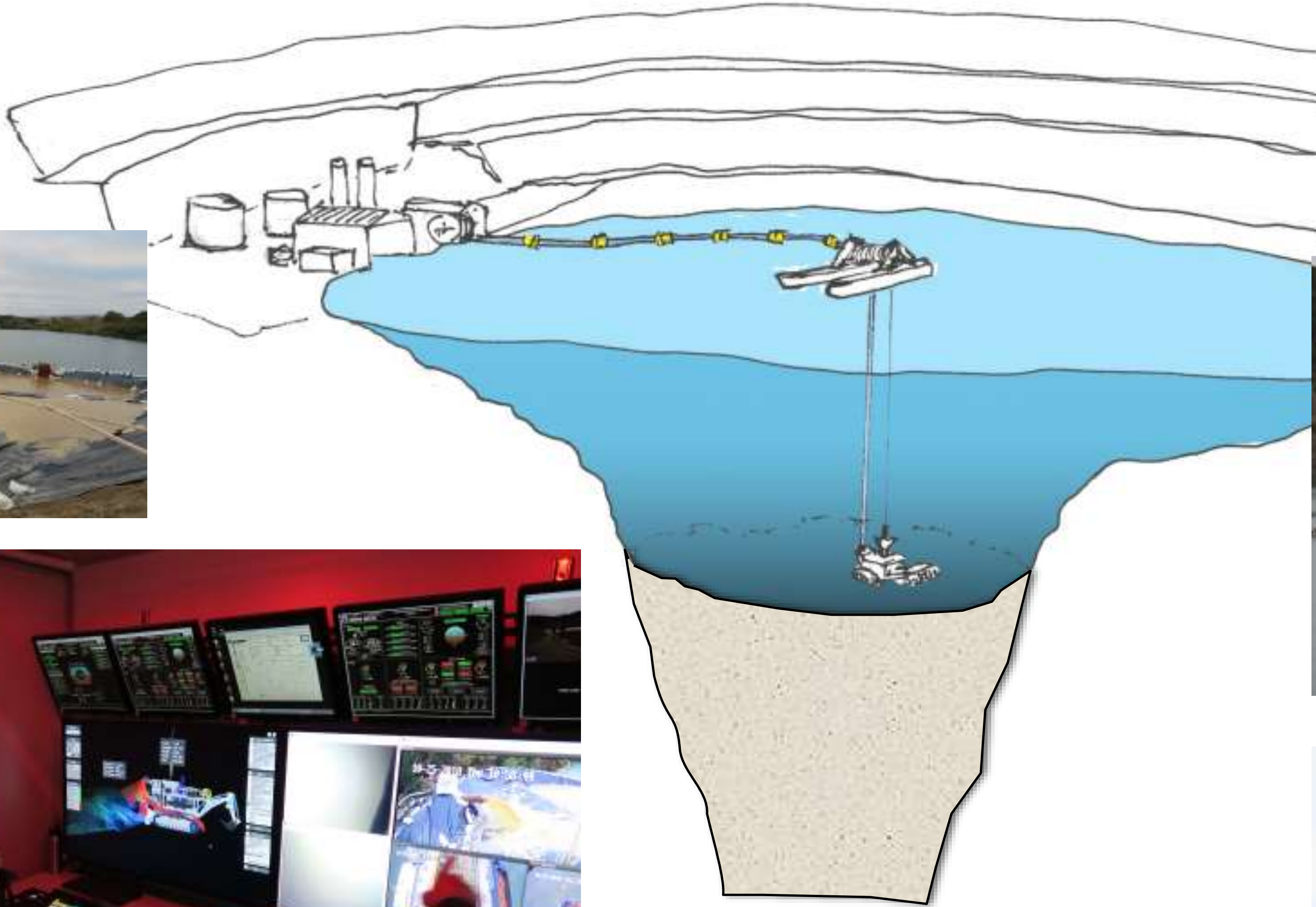
DAMEN

¡vamos!



UNEXUP

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Autonomous exploration of flooded mines (UNEXMIN & UNEXUP projects)

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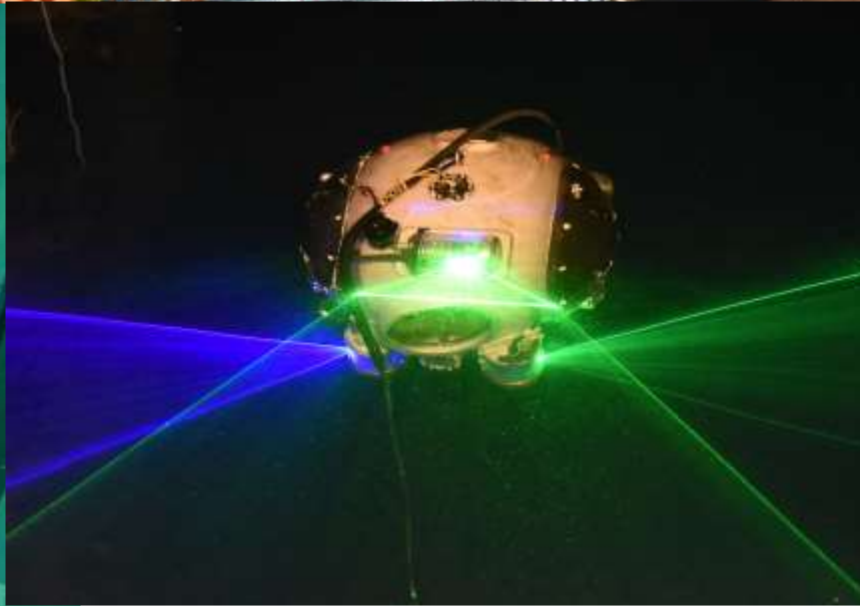
This activity has received funding from European Institute of Innovation and Technology (EIT) , a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation.

Prometheus, 2012



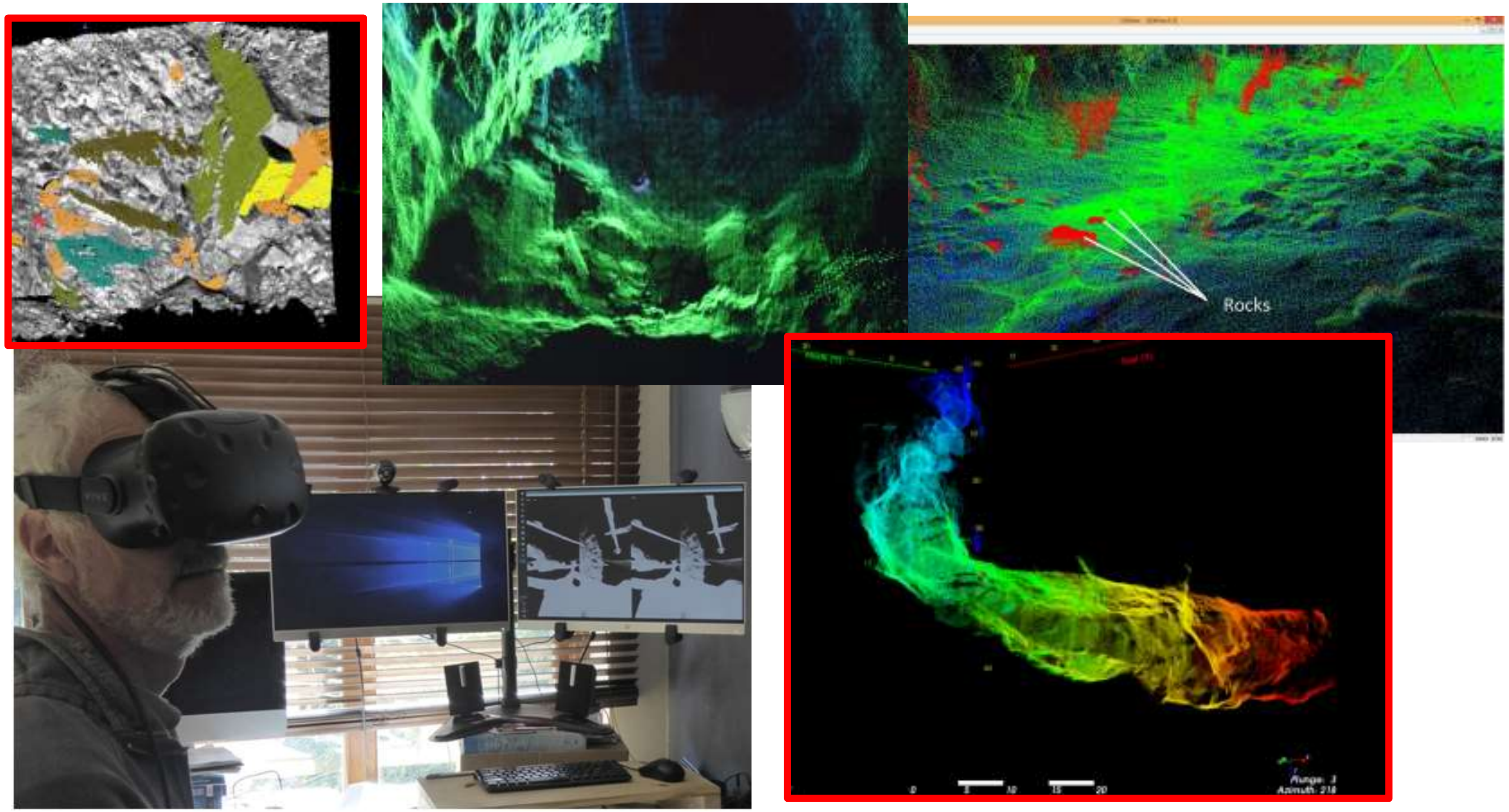
Geology





Scientific payload

- visual and multispectral cameras
- scanners and sonars
- water sampler
- pH/EC unit
- gamma-ray detector
- PLANNED: rock sampler, magnetic field sensors, increased operational range and depth
- more versatile and effective hardware on the field (decreased downtime)



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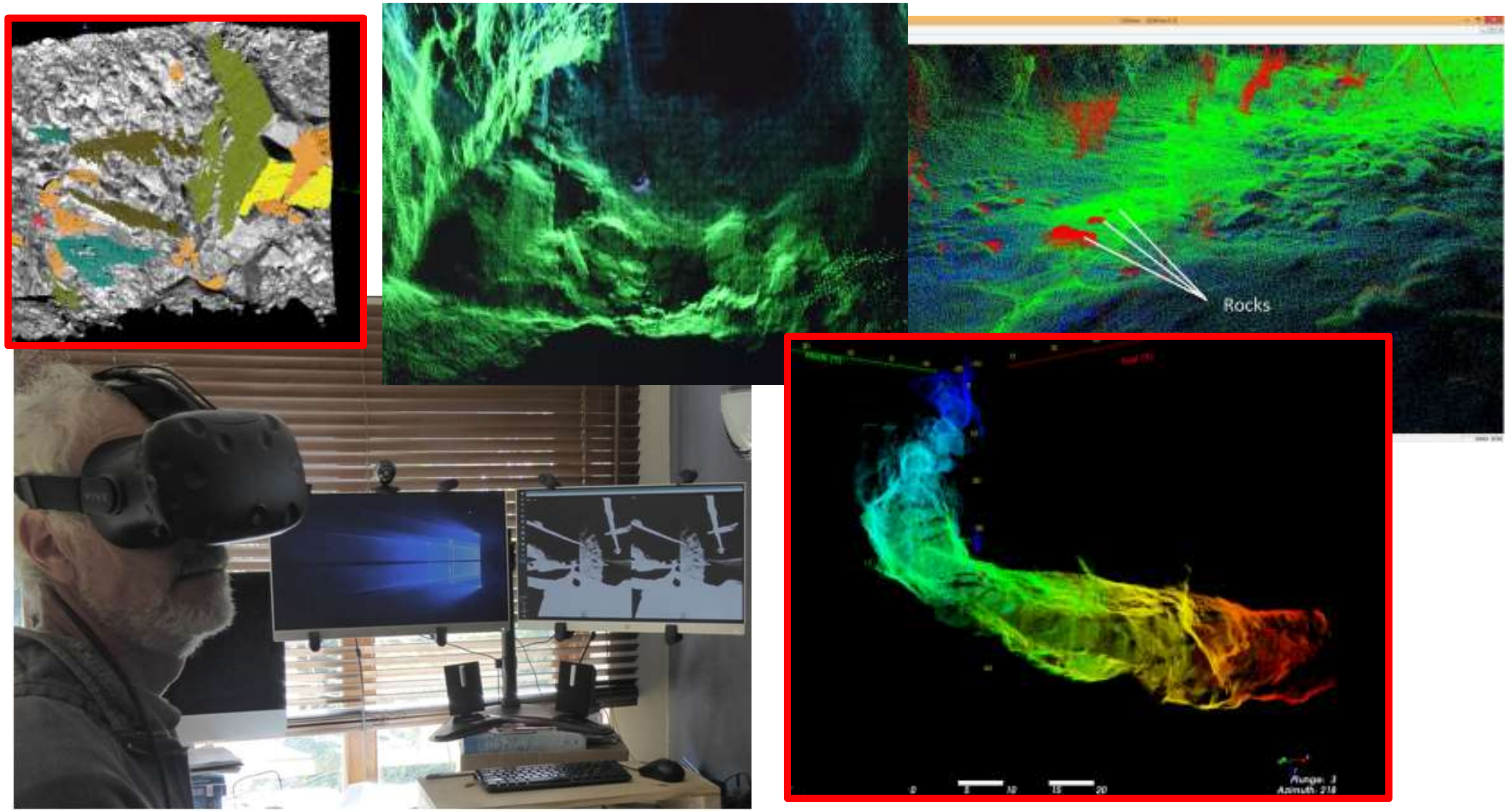
Connecting matters

UNEXUP

This activity has received funding from European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation.

Data processing development

- less people needed in the field
- reducing weight, while increasing operational range and depth
- on-line dive monitoring, remote control
- faster battery replacement
- better localisation
- faster data retrieving protocols & data processing (less time from raw data to the product)
- development of data post-processing algorythms



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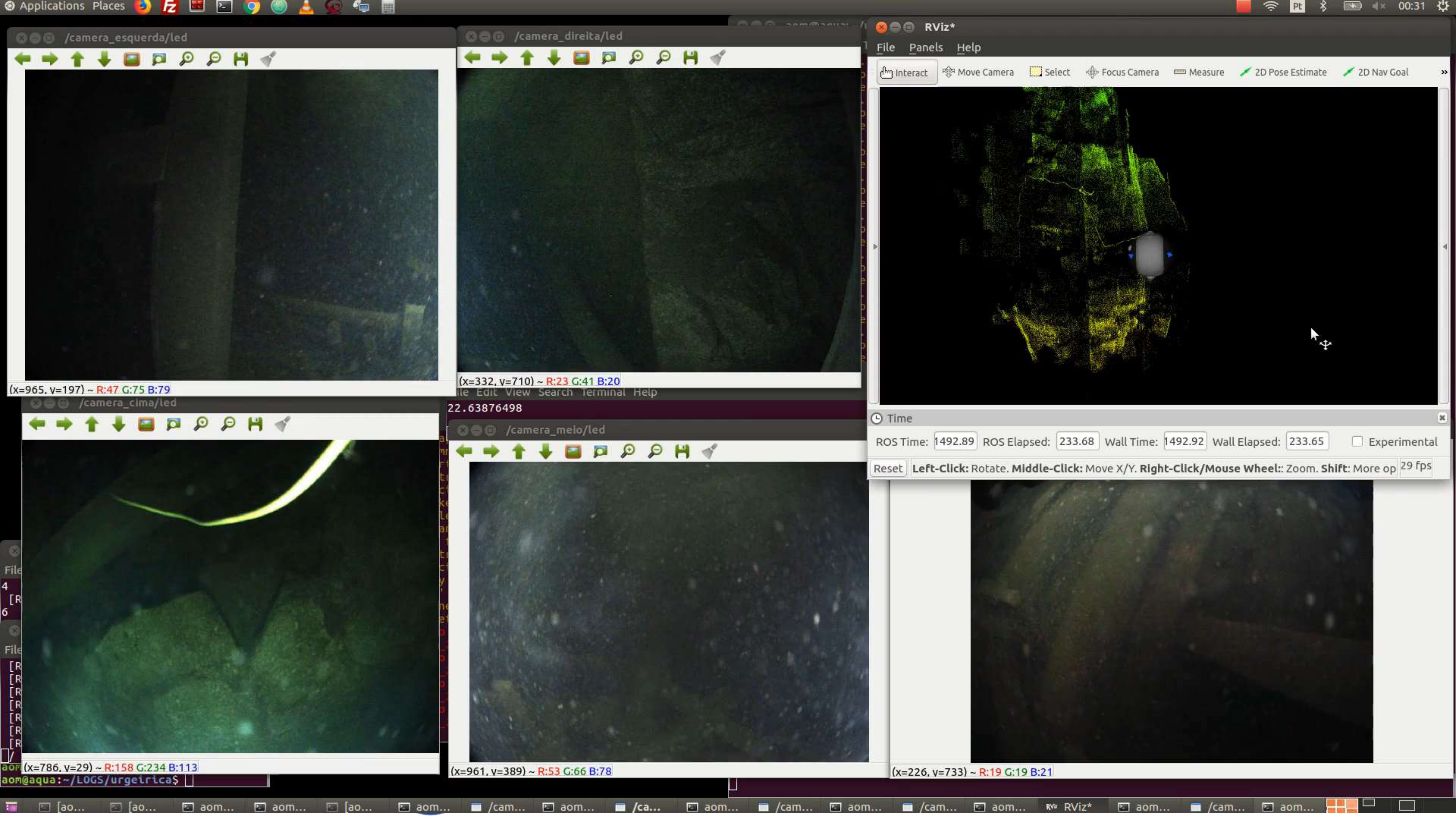
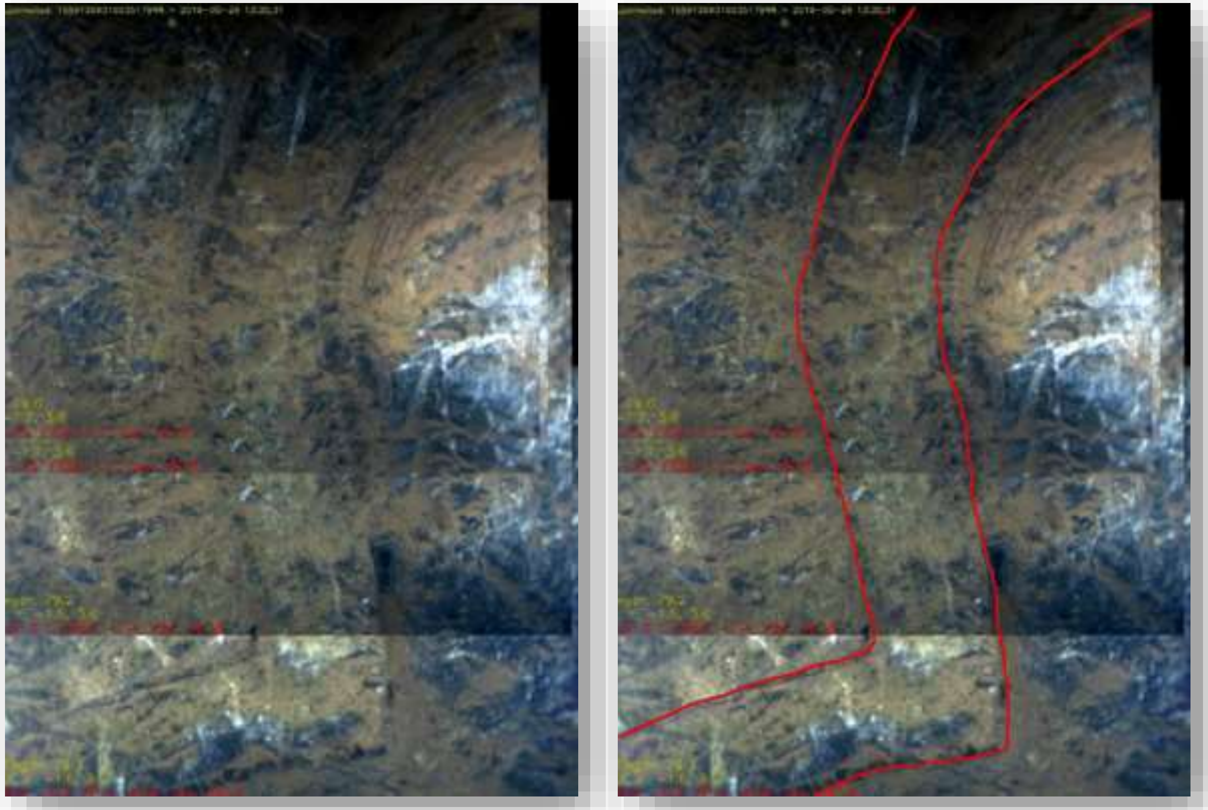


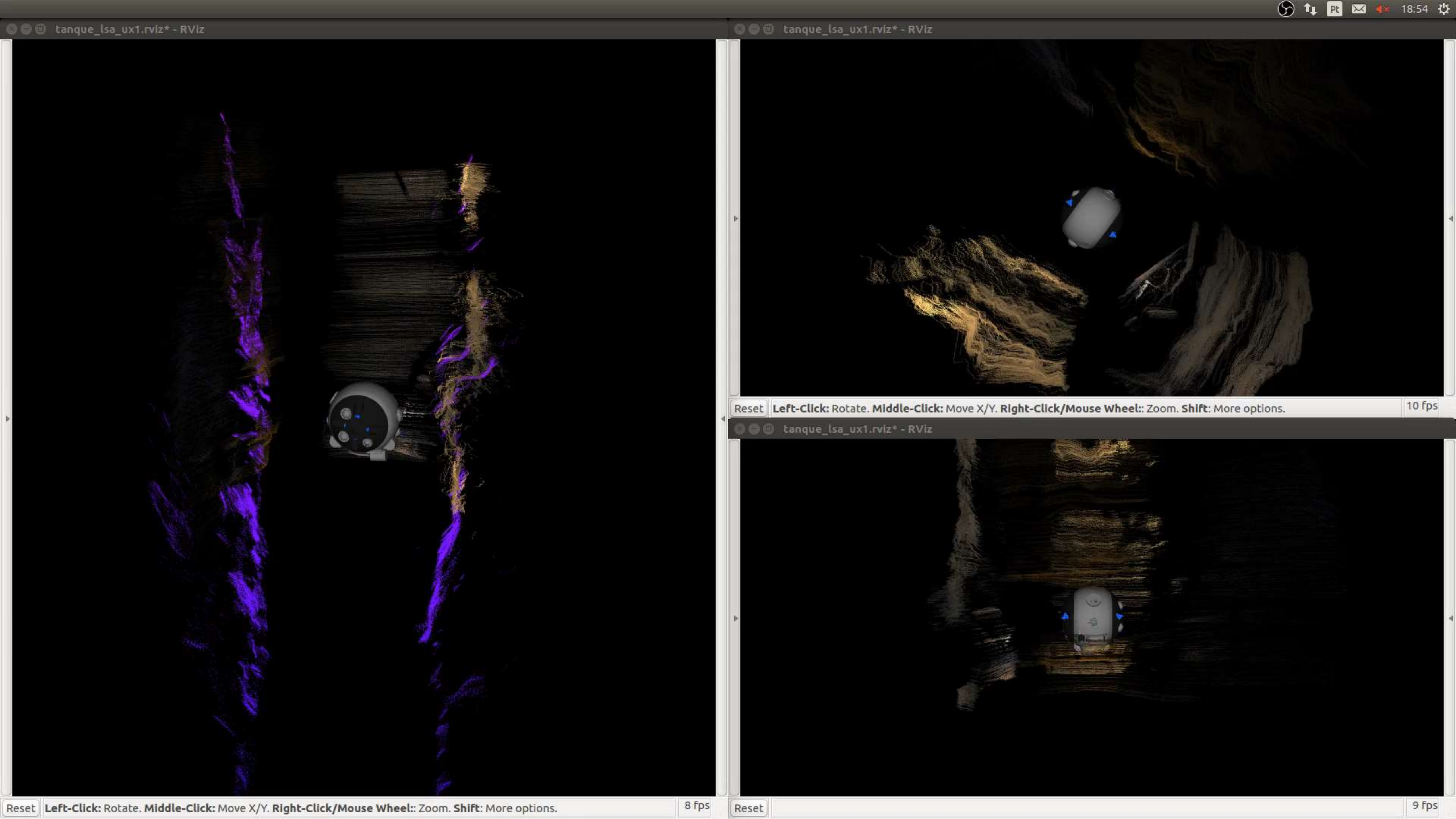
Applications
Places
00:31
/camera_esquerda/led
(x=965, y=197) ~ R:47 G:75 B:79
/camera_direita/led
(x=332, y=710) ~ R:23 G:41 B:20
RViz*
File
Panels
Help
Interact
Move Camera
Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Time
ROS Time:
1492.89
ROS Elapsed:
233.68
Wall Time:
1492.92
Wall Elapsed:
233.65
Experimental
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click/Mouse Wheel:: Zoom. Shift: More op
29 fps
/camera_cima/led
(x=786, y=29) ~ R:158 G:234 B:113
22.63876498
/camera_meio/led
(x=961, y=389) ~ R:53 G:66 B:78
(x=226, y=733) ~ R:19 G:19 B:21
aom@aqua:~/LOGS/urgeirica$
RViz*

Structural geology observations in Ecton

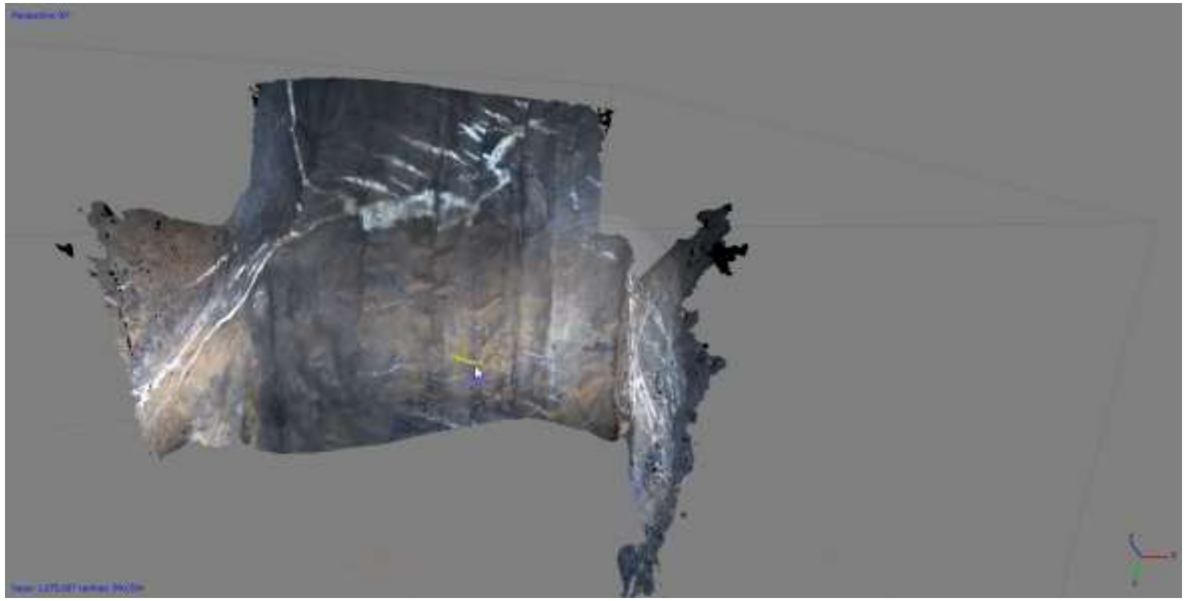


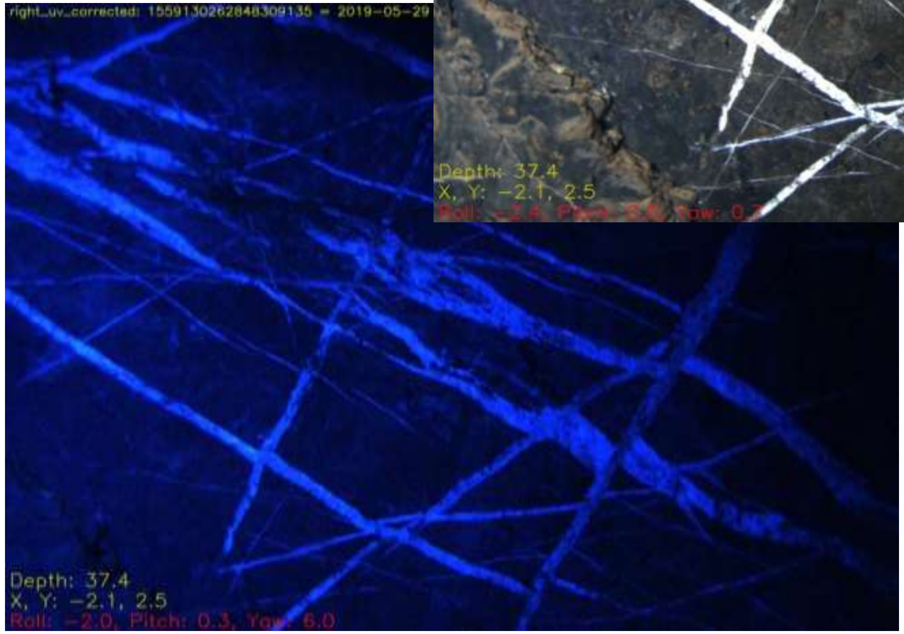
Folding, winding shaft (-79 m)

Syncline with calcitized tension cracks, winding shaft (-46-48 m)


18:54
tanque_lsa_ux1.rviz* - RViz
tanque_lsa_ux1.rviz* - RViz
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click/Mouse Wheel:: Zoom. Shift: More options.
10 fps
tanque_lsa_ux1.rviz* - RViz
Reset
Left-Click: Rotate. Middle-Click: Move X/Y. Right-Click/Mouse Wheel:: Zoom. Shift: More options.
8 fps
Reset
9 fps

Ecton mine, calcite veins in the winding shaft (-37.4m)





Field mission: Hranice Abyss

On the 1st August 2022 UX-1Neo dived and mapped the deepest known underwater cave Hranice Abyss in Czech Republic to the depth of -450m

TECHNOLOGY EXPLOITATION

UNEXMIN GeoRobotics Ltd.

Offering service with the developed equipment, further development

- **Strong focus on commercializing the technology**

- Raw materials exploration
- Water reservoirs surveying
- Cavity measurement (e.g. salt mines)
- Cave system exploration
- Cultural heritage sites investigation
- Environmental monitoring

SERVICE OFFERED

- Underwater exploration and mining
- Sensor and instrument development
- Automated measurements
- Autonomy, multi-robot platform
- Data processing, geoscientific evaluation
- 3D visualization
- Space applications

PARTIAL UTILIZATION

FURTHER DEVELOPMENT OF THE TECHNOLOGY

eit RawMaterials Connecting matters

inSITE LIBS Project Disruptive Innovation

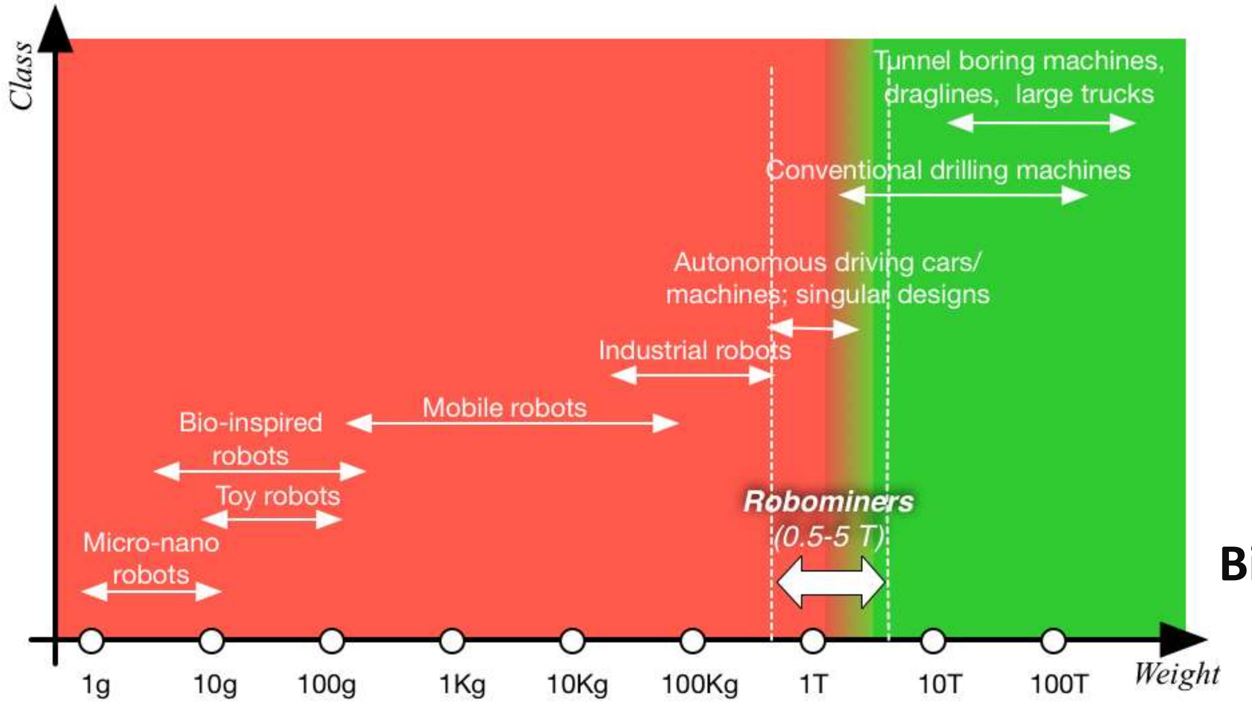
ROBOMINERS

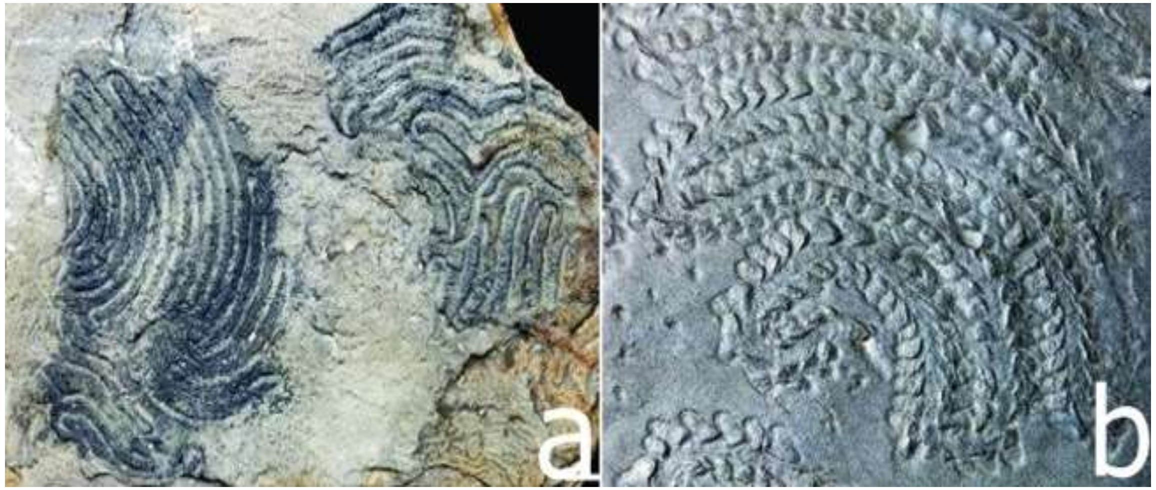
Resilient Bio-inspired Modular Robotic Miners

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820971

The robot miner – a new approach

Bio-inspired, **modular** and **reconfigurable**





2D and 3D feeding patterns as shown by trace fossils.

Big robot, small mining machine

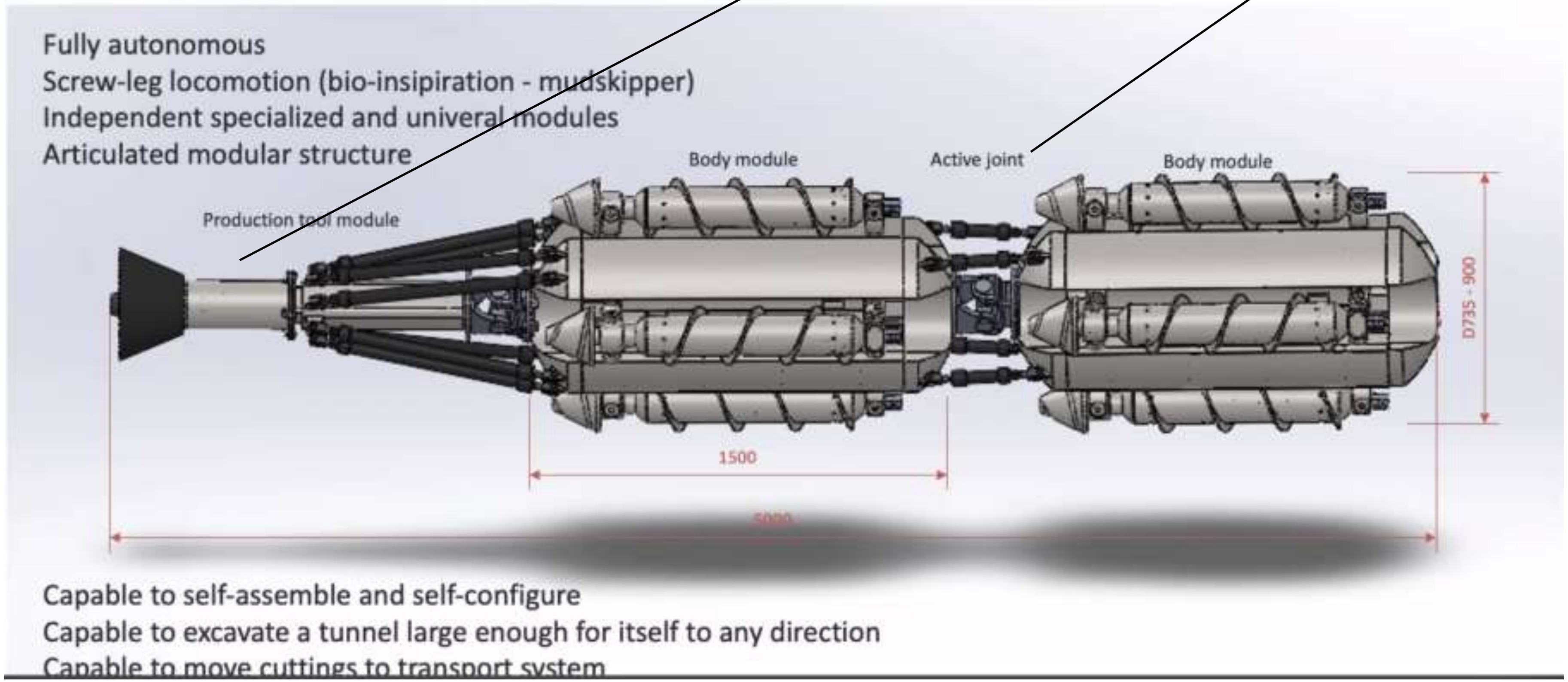
	ROBOMINERS	2030 vision	2050 vison
ROBOTICS	Demonstrator for modularity, self-assembly, perception and navigation, resilience in extreme underground environments	First industrial pilot, tethered, semi-autonomous operation	Full autonomy, self-reconfigurability, self-awareness collective robotics.
SELECTIVE MINING	New mineral perception, detection and classification, as well as new production tools, demonstrated to TRL 4/5	First industrial pilot application	Autonomous mining
MINING ECOSYSTEM	Study of a mining ecosystem of downstream and upstream processes, Identify research challenges for logistics, environment, mineral processing, borehole drilling technology, dredging & pumping	First industrial application in a “small deposit scenario” or “abandoned mine scenario” with on-site minerals processing and paste refilling	Industrial applications in “ultra-depth” scenarios Small mines deliver a considerable share of the EU’s critical minerals production
SUSTAINABILITY ASSESSMENT	Financial viability assessment, sustainability, environmental and ethical considerations Research roadmap for development of supporting technologies	Simplified permitting procedures for small-scale mining Supporting policy and legal framework for small-scale mining.	New innovation ecosystem: SMEs and entrepreneurs are working towards further miniaturisation and versatility

ROBOMINERS

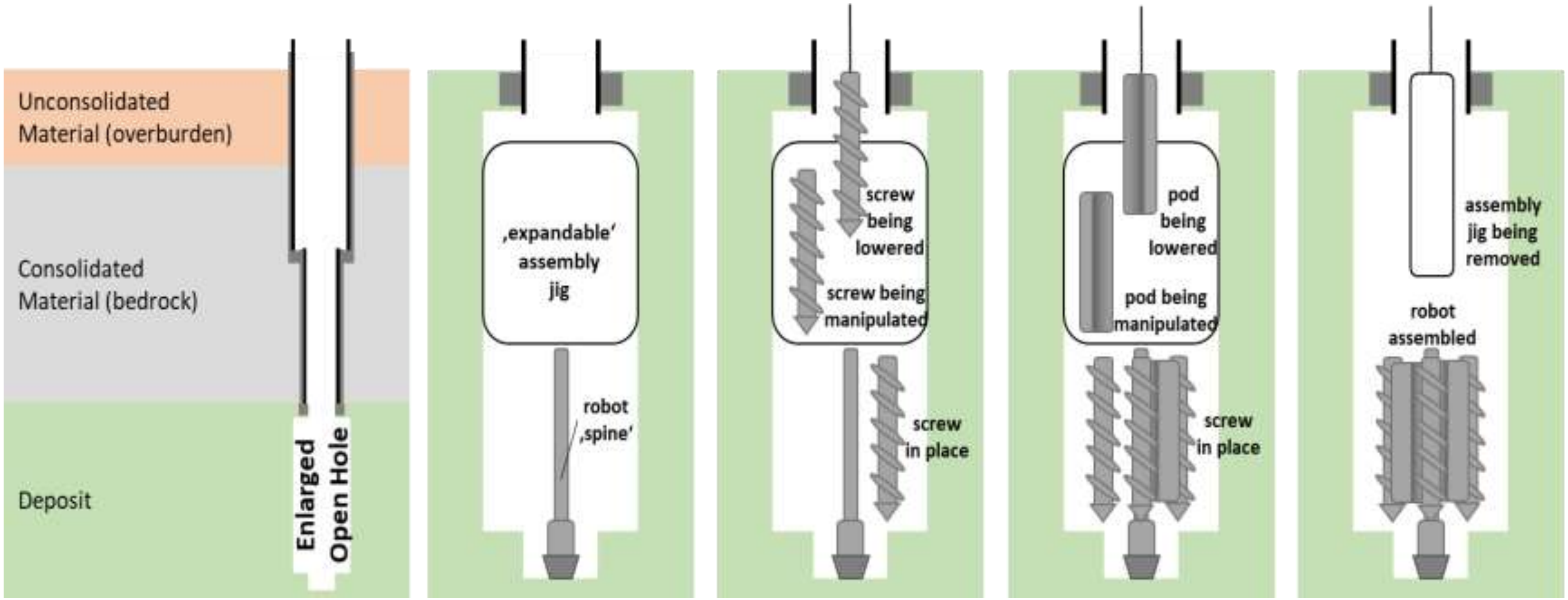
Modular and **reconfigurable**

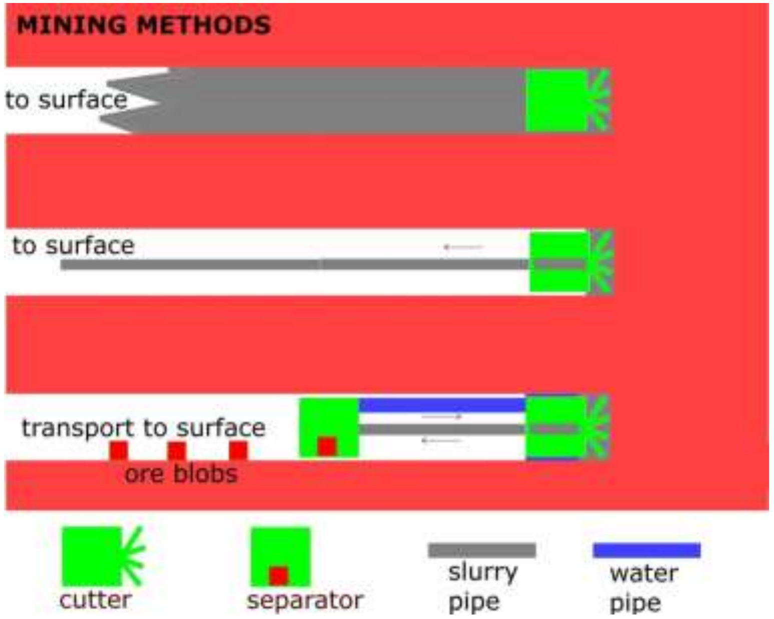
Production tool

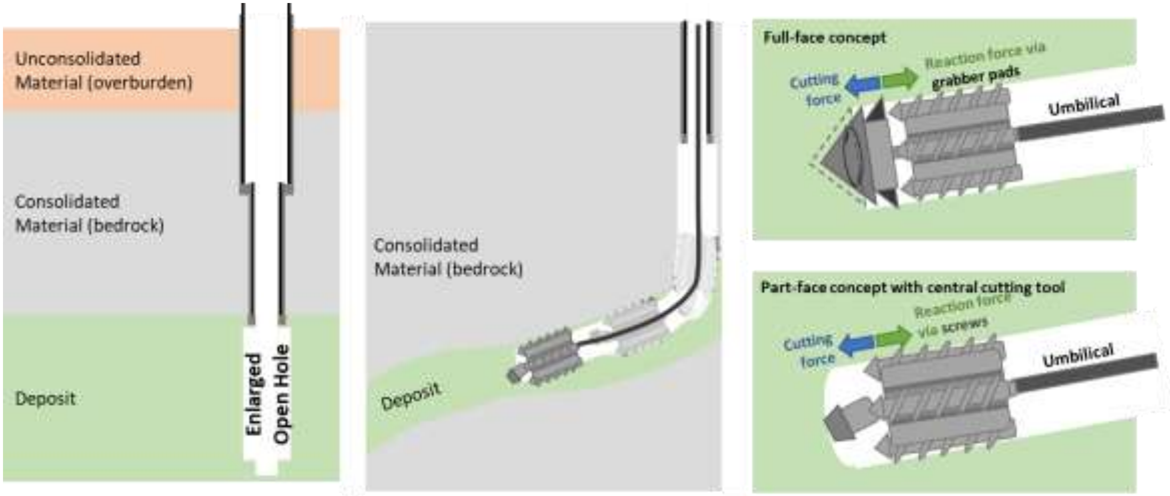
Two modules coupled



GeoZS
Geološki zavod Slovenije

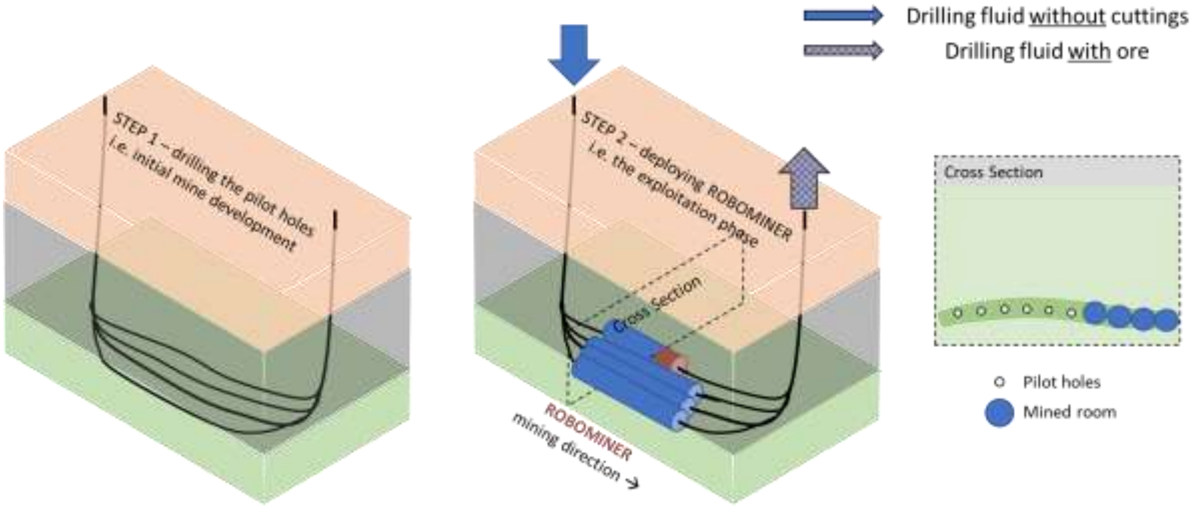

Unconsolidated Material (overburden)
Consolidated Material (bedrock)
Deposit
Enlarged Open Hole
‚expandable' assembly jig
robot ‚spine'
screw being lowered
screw being manipulated
screw in place
pod being lowered
pod being manipulated
screw in place
assembly jig being removed
robot assembled

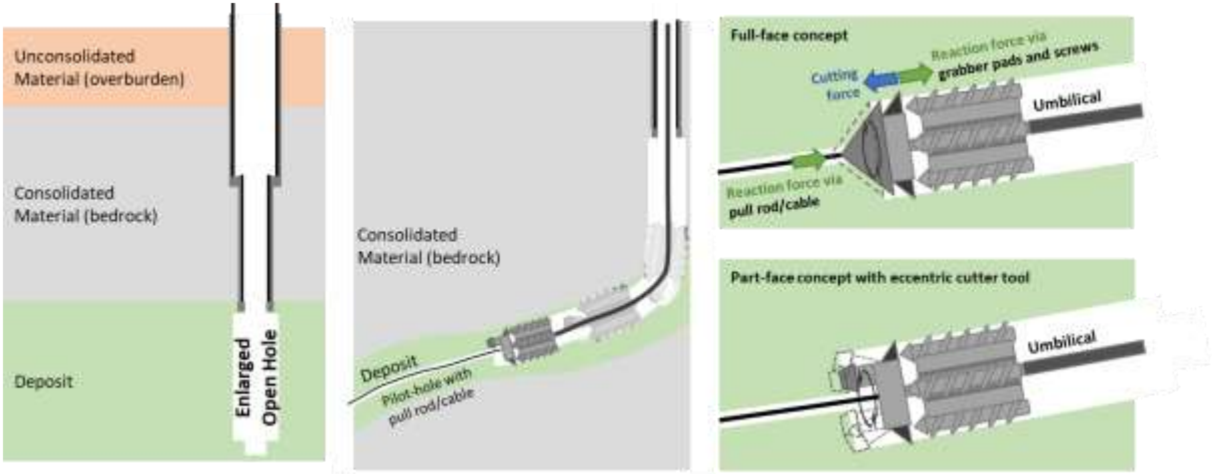

MINING METHODS
to surface
to surface
transport to surface
ore blobs
cutter
separator
slurry pipe
water pipe



'Blind' advance following the deposit using screws or grabber pads to create reaction force for the cutting action

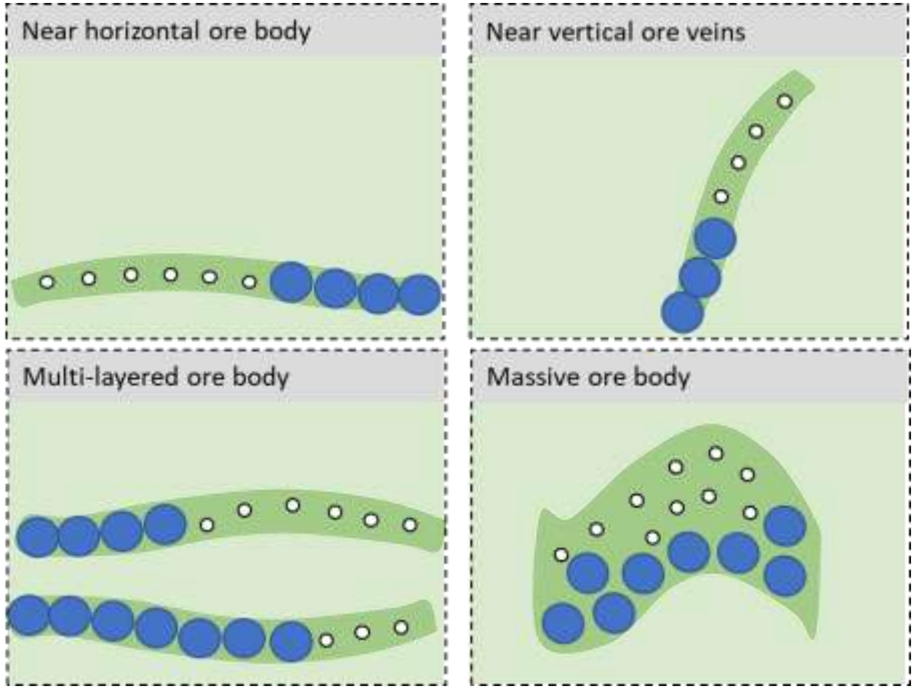
Full-face and part-face cutting tools on a screw-driven explorer/miner robot

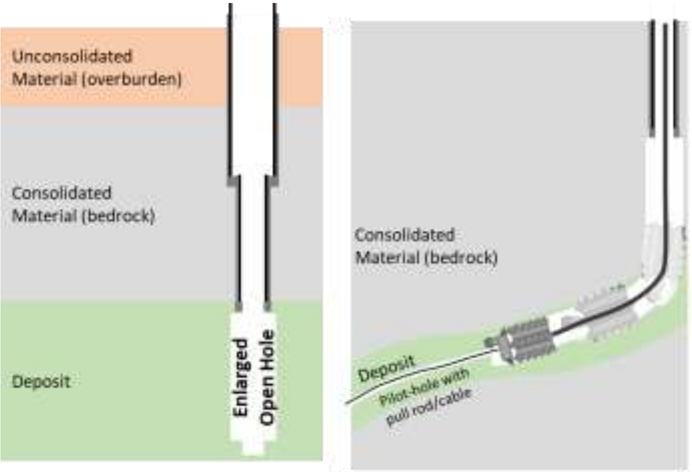




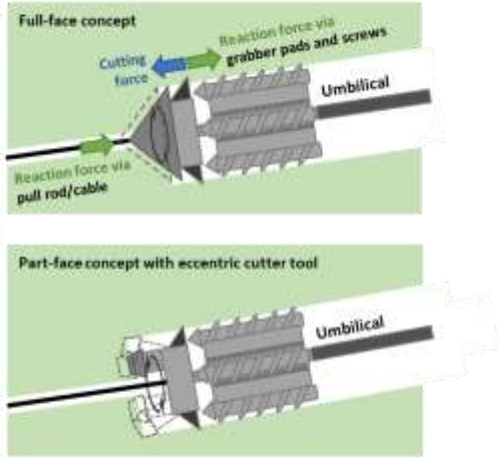
Pilot-hole assisted advance using pull rod/cable to create additional reaction force for the cutting action

Full-face and part-face eccentric cutting tools on a screw-driven explorer/miner robot with grabber pads and pull rod/cable to provide additional reaction force

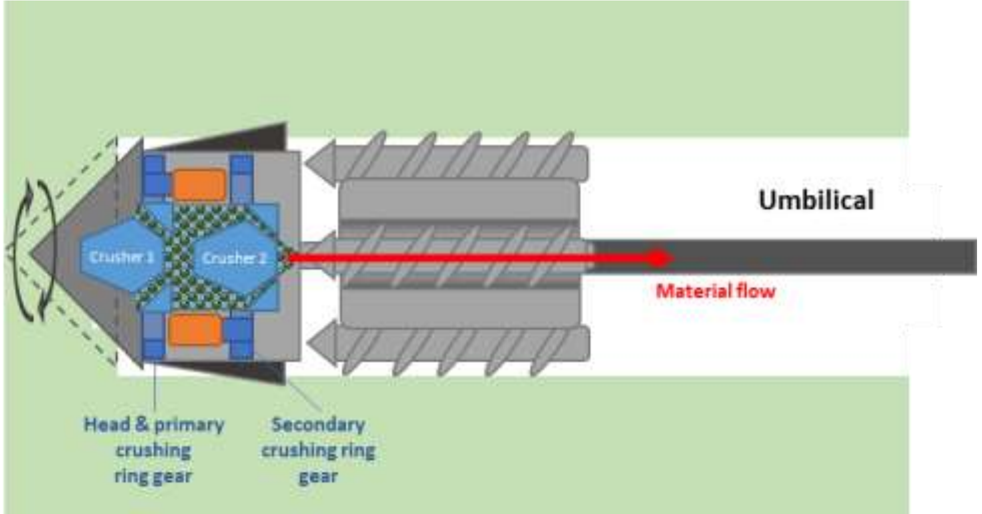


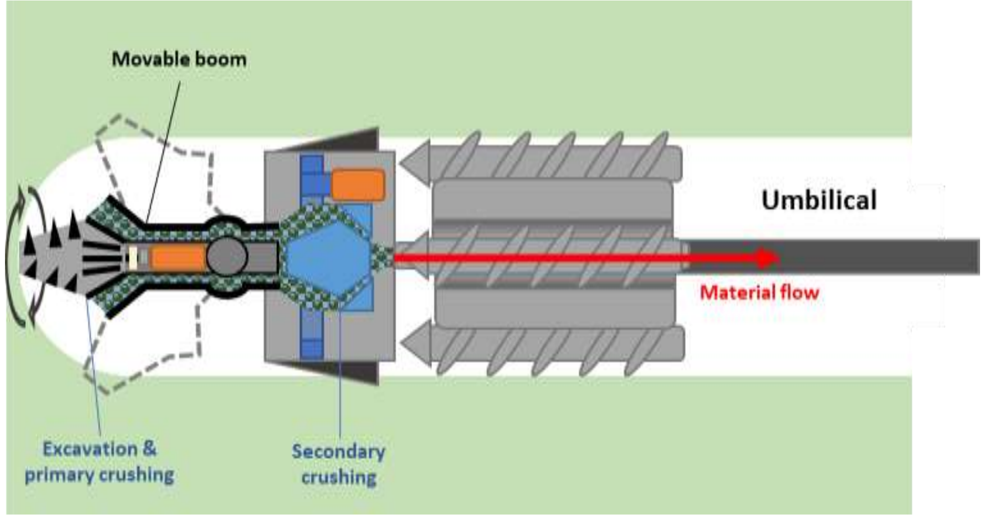


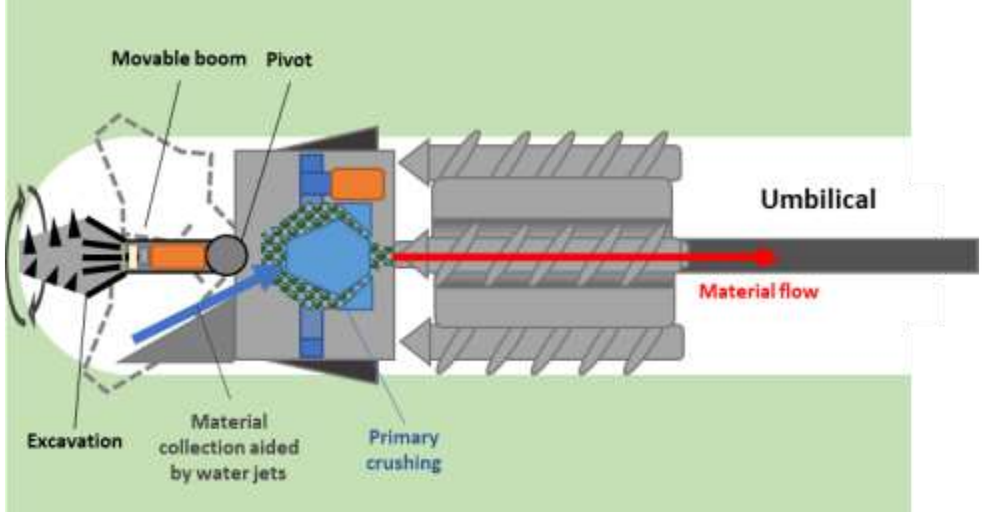
Pilot-hole assisted advance using pull rod/cable to create additional reaction force for the cutting action

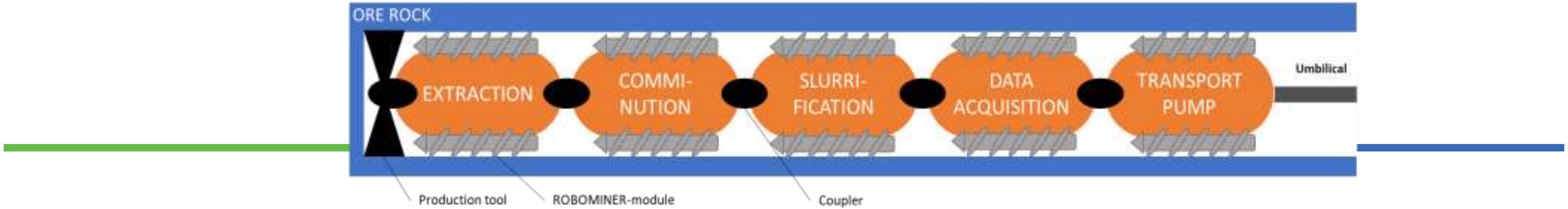


Full-face and part-face eccentric cutting tools on a screw-driven explorer/miner robot with grabber pads and pull rod/cable to provide additional reaction force









Take home message

Mining is here to stay that is why we need to make it as safe and environmentally friendly as possible

For this we will need to develop autonomous systems that will (in the long term) replace humans and will be able to mine in harsh conditions and in unfriendly environments (great depths, high T, deep sees, space….)

S R E Č N O !

Thank you for your attention!

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