30 April - 6 May | Perth, Australia

27TH Annual Conference Proceedings

In-Situ Recovery Conference

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In-Situ Recovery Contents

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IN-SITU RECOVERY KEYNOTE

CONSIDERATIONS FOR HARD ROCK IN-SITU MINING IN AUSTRALIA

By

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ABSTRACT

In-situ recovery (ISR) is typically defined as drilling from the surface to access ores that are amenable to chemical lixiviants. When these lixiviants flow through a porous and fractured orebody they extract the mineral content to various degrees, which is separated from the fluids. Hard Rock In-Situ Mining (HRISM) has been proposed since the 1980s with early work performed at the US Bureau of Mines. Access may be from the surface or of the underground and use new or existing infrastructure. In most cases, uranium has been a target mineral for ISR due to favourable geology and issues for conventional mining. Currently, mines extract other metals such as copper; mostly in Kazakhstan and starting in the USA. These orebodies are favourable for ISR mining due to their large oxide content and high permeability.

ALTA conference series has, since about 2016, been considering the ISR work carried out in Australia and other countries. Research continues to evolve to develop a range of lixiviant and access technologies. The energy transition is driving intensive searches for novel and energy-efficient methods of extracting minerals so this paper will explore some of the recent Australian developments and implications for HRISM operations locally.

As part of the identification of HRISM opportunities, we consider the geological framework of Australia as a start to understanding the location of ores, challenges, and opportunities. We briefly consider the stress, strength, and temperature regimes that would be encountered in Australian conditions and the implications for HRISM. Some ideas for linking HRISM to the energy transition and implications are the object of considerable research within CSIRO. For fun, we look at what Artificial Intelligence/Machine Learning (AI/ML) image generation suggests as technology options and find out that interpolation of the past cannot predict the future.

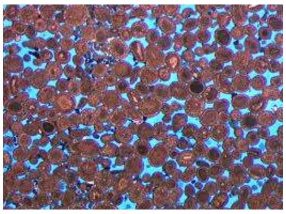
Keywords: In Situ Recovery, ISR, Hard Rock, In-Situ Mining, (HRISM),Uranium, Copper, Artificial Intelligence, Machine Learning, (AI/ML)

Accessing ore in hard rock?

https://www.excelsiormining.com/project

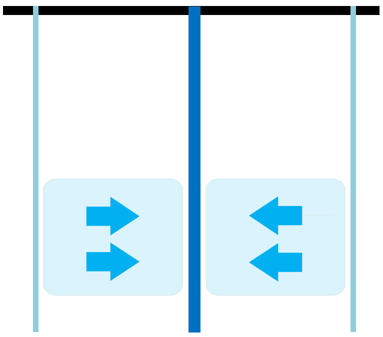
Naturally fractured with copper oxide minerals mostly on the fracture surfaces.

- Hard rock is jointed, stronger, not porous and less permeable. Needs to be fractured – usually by blasting
- Can we use modify conventional methods?
- To access the ore we need to reimagine what a mine looks like and use traditional mining methods in new ways

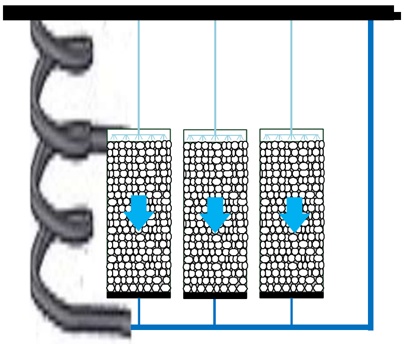


A new approach to underground mining

- In situ mining considers drill holes from surface and flow fluids through permeable strata
- **Hard Rock In Situ Mining (HRISRM)** needs to create it’s own permeability at depth



From surface
e.g. Kapunda



From underground

http://encyclopedia.che.engin.umich.edu/Pages/SeparationsChemical/DistillationColumns/DistillationColumns.html

How to gain access?

Access Creation

- Automated Mining – ROES 2011

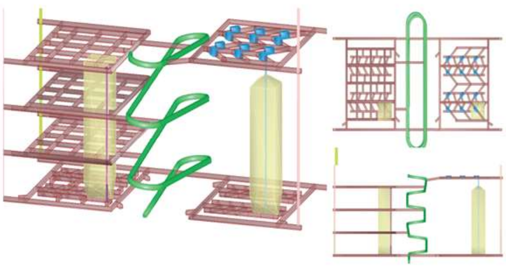


FIG 1 - ROES® overview.

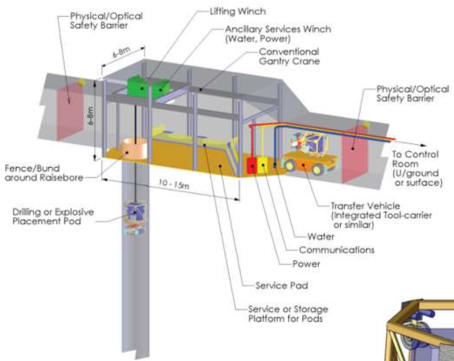


FIG 2 - ROES® chamber.

I Gipps and J Cunningham

SECOND INTERNATIONAL FUTURE MINING CONFERENCE / SYDNEY, NSW, 22 - 23 NOVEMBER 2011

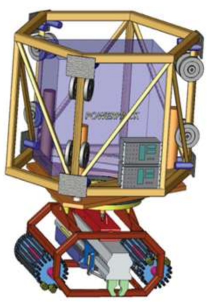
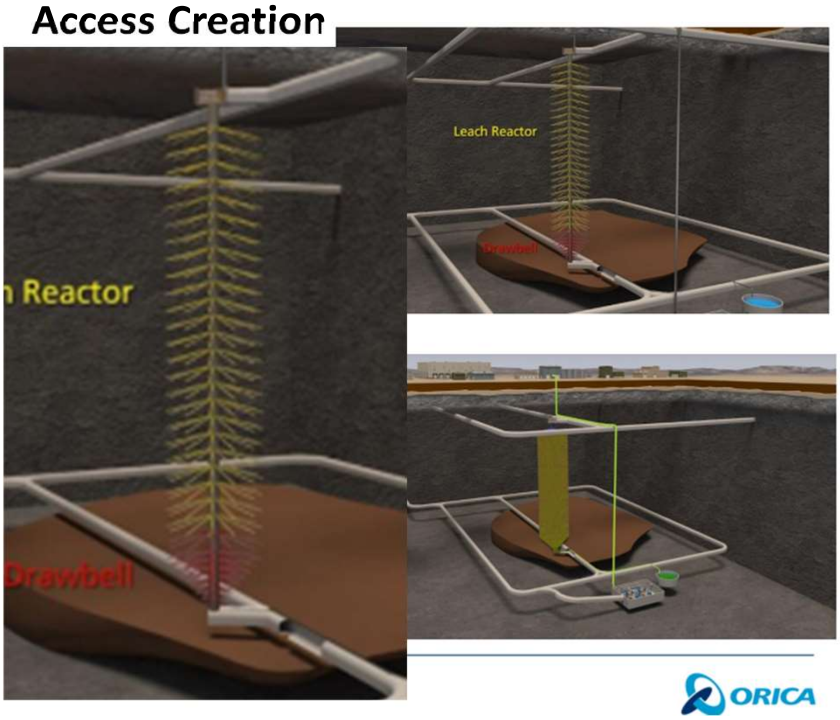


FIG 3 - Drill platform.

Access Creation

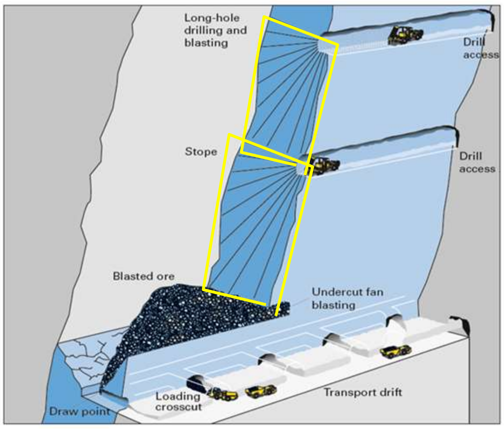
- Taking ROES to HRISM
- Supported by wireless detonators
- Challenged by geotechnical conditions

ALTA 2017: Fragmentation & Fracture From Blasting For Insitu Recovery, Stephen Boyce, Alan Minchinton

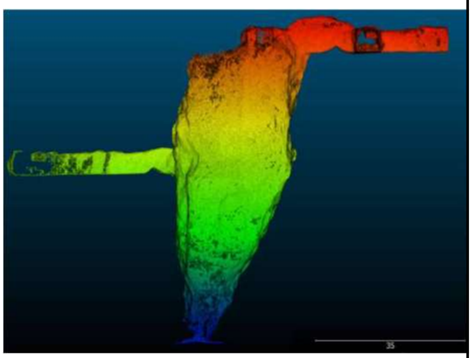


Access creation

Creating permeability underground using standard stoping methods?



Sublevel open stoping (SLOS) (Atlas Copco, 2007)

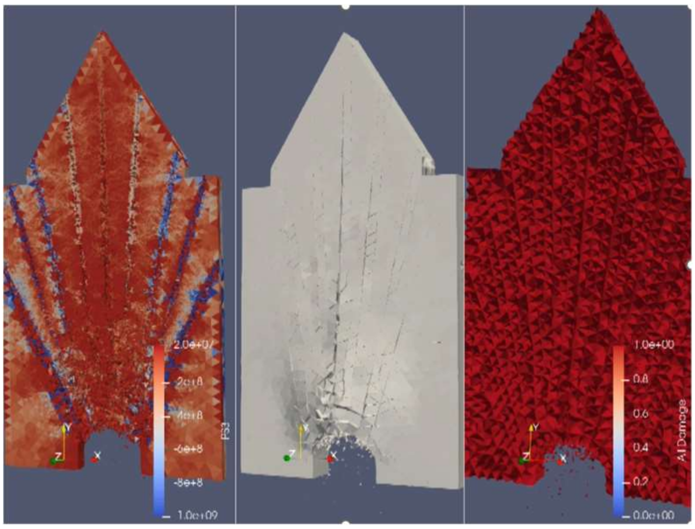


Canales and Sellers, Massmin, 2020

Access creation

Creating permeability underground using standard stoping methods?

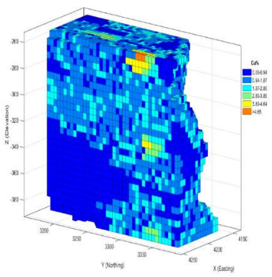
Numerical modelling: At what stage is permeability and fragmentation sufficient?



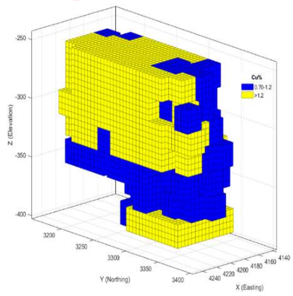
Sellers and Salmi, UMT2020; Liu et al, IOP 2021

Hybrid Open Stope / IMR for Marginal ore recovery

Block Model



Stope Model



NPV Improvement: 40%

- Positive NPV
- Many assumptions

	# Stopes	NPV(m$)	# Mined Stopes	Ave Cu(%)
Hybrid OS/IMR	196	5.47	157	1.57 1.12
OS	196	3.91	98	1.12

Mousavi & Sellers, Resources Policy, 2019

Value of Recovery of stranded ore – Actual gold mine

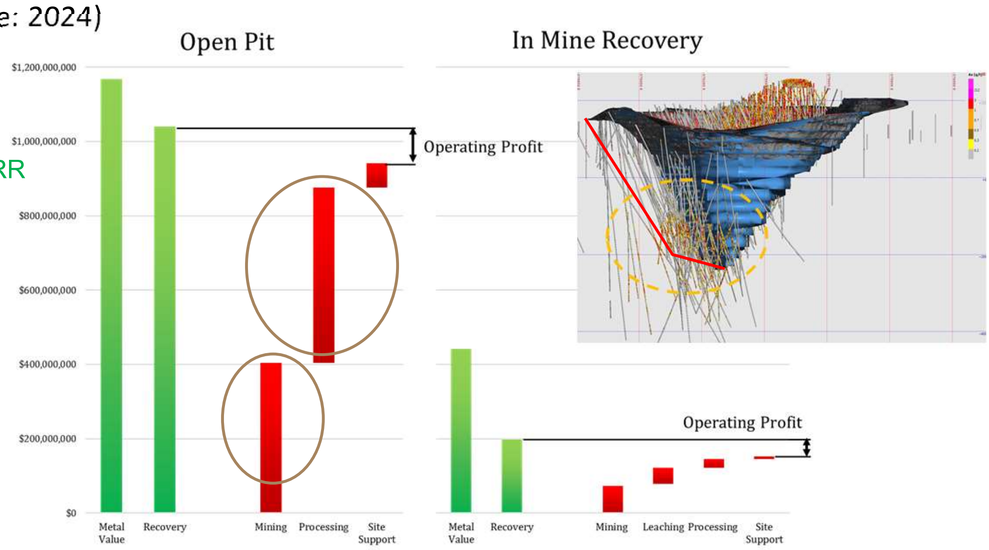
- 6 years (Mine closure: 2024)

NPV

u/g = -560M$
Pit cutback = -140M$
IMR = +27M$ @ 44% IRR

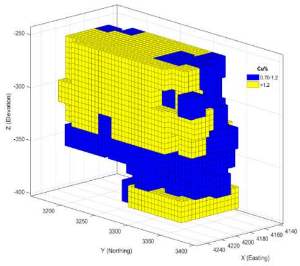
Similar profit
Triple ROCE

Benefits in removing diesel (transport) and comminution energy



Case study: energy and diesel benefits

- Save 2.8 Billion kWh on Milling @ 20KWh/t (5% efficient)
  - **~ 1 Adelaide / yr**
- Save 12 megalitres of diesel (equivalent electricity)
  - Australia consumed a total of 34,170 megalitres of fuel in 2018.



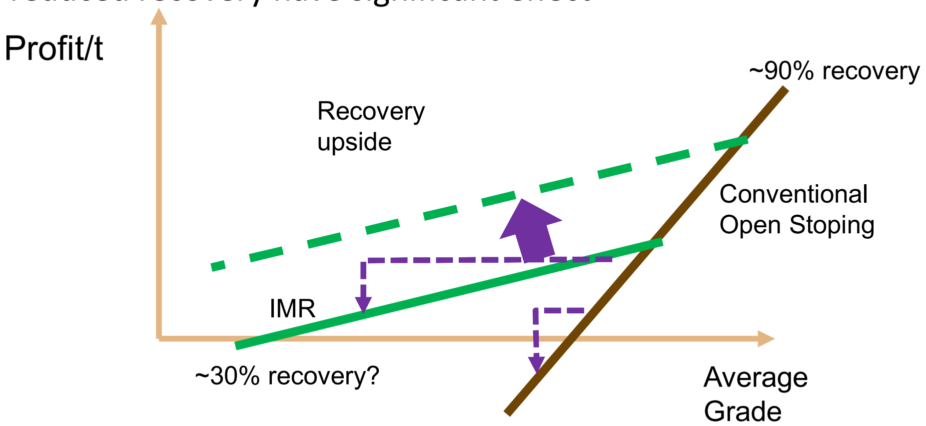
600KW @ 20km/h @ .1 L/KWh

….needs testing

Sellers and Lever, ALTA, 2020

Value of IMR

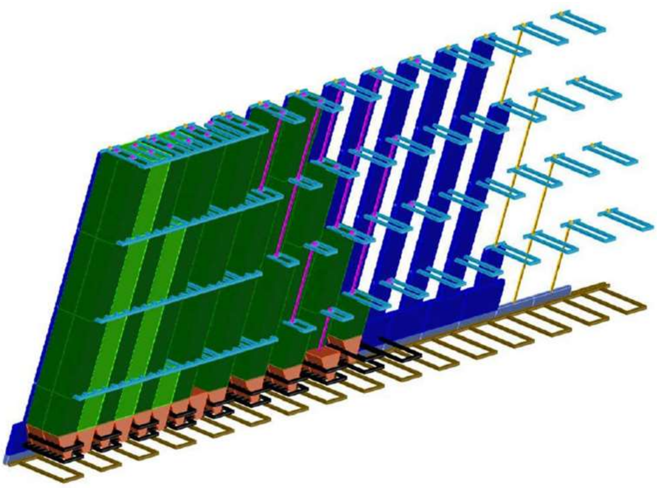
- In a conventional u/g operation, high energy costs mean that unexpectedly lower grade or reduced recovery have significant effect

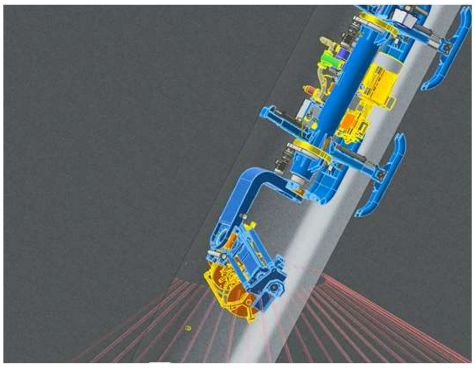


- IMR is more resilient to grade. Recovery is expected to increase in future

Sellers and Lever, ALTA, 2020

Access Creation





Ladinig, T., Wagner, H., Karlsson, M. *et al.* Raise Caving—A Hybrid Mining Method Addressing Current Deep Cave Mining Challenges. *Berg Huettenmaenn Monatsh* **167**, 177–186 (2022). https://doi.org/10.1007/s00501-022-01217-3

Access Creation

- **New drilling technology**

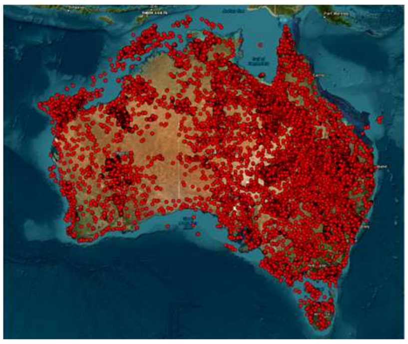
Coiled tube drill rig (MinexCRC, 2023)

- Potential for coiled tube drill rigs to access ore at much faster rates. MinexCRC (2023)
- Anglo American project - 12 holes into basement rock with 400 -450m of regolith cover.
- penetration rates > 100 m – 232m/12h
- Working on 1000m and steering to target straight holes and designed deviation at depth.

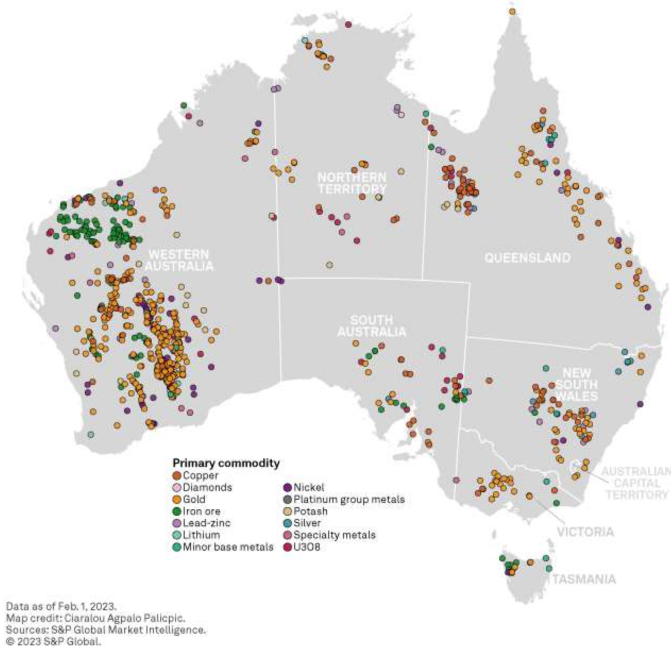
Where to mine?

Minerals in Australia

- Significant exploration
- Wide range of minerals
- More opportunity



Drill holes - https://portal.ga.gov.au/persona/eftf

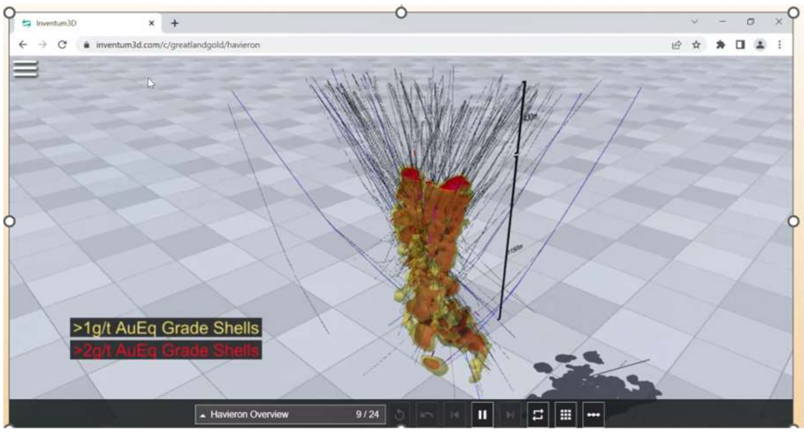


Australian Geology

- Consider some new projects
- Gold
- Critical Minerals

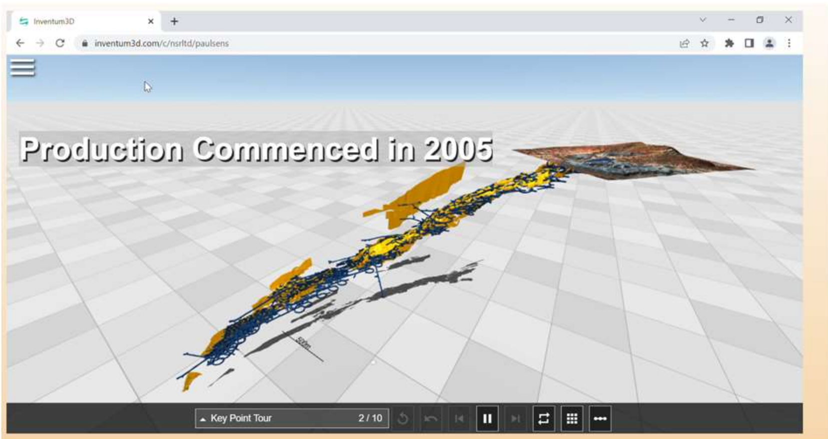
- Disclaimer: Projects discussed here for illustrative purposes only. This does not imply in situ mining will occur, or is being considered, or provide any investment advice

Gold mining



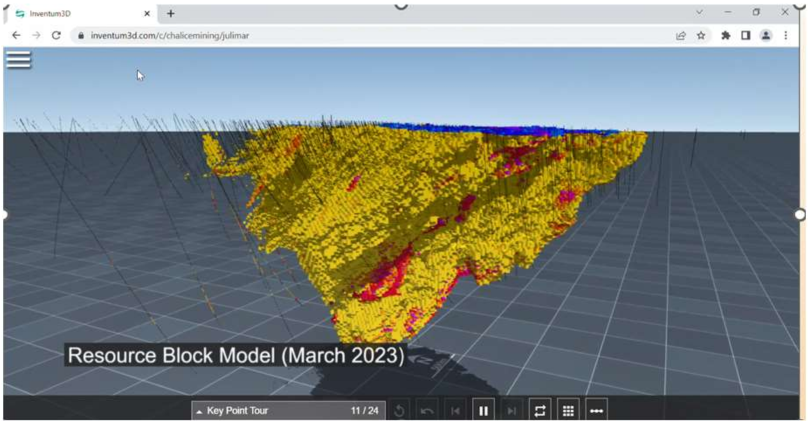
https://inventum3d.com/c/greatlandgold/havieron

Gold mining



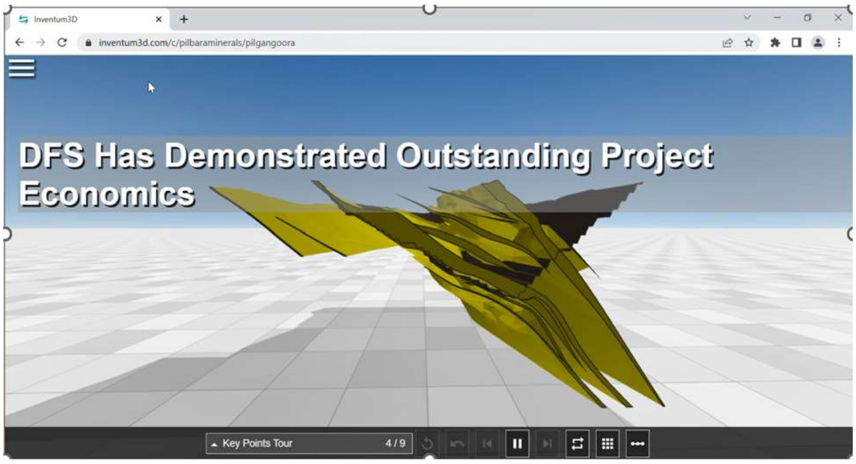
https://inventum3d.com/c/nsrltd/paulsens

Cu, Ni, PGE



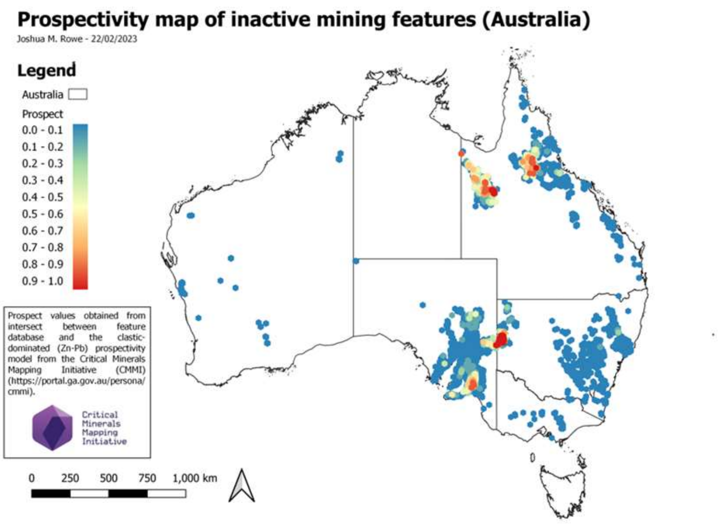
Julimar Ni, Cu, PGE https://inventum3d.com/c/chalicemining/julimar

Li



https://inventum3d.com/c/pilbaraminerals/pilgangoora

Where else? Abandoned mines?



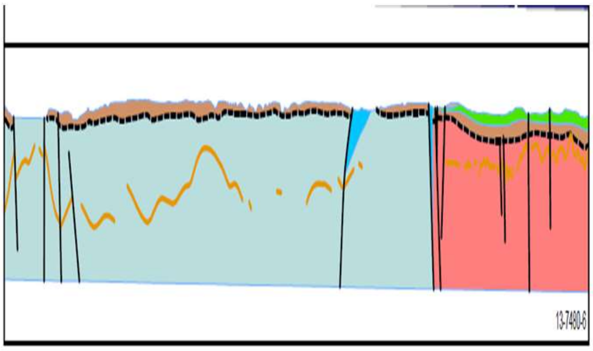
Notes:

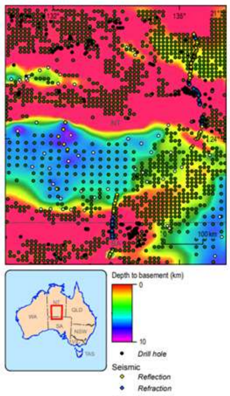
- 10,759 sites were identified to have some sort of prospect via the clastic-dominated model.
- 586 fall exclusively in significant urban areas.
- 574 fall exclusively in CAPAD areas.
- 32 fall in both CAPAD and SUAs.

The challenge of Regolith

- Large regions of Australia are covered by Regolith
- Sandstones and mudstones with limited mineralisation
- Hard to explore through
- Varies over short distances

Near surface basement / deep basement





0 10km

stretched vertically for visibility

Cu Ore under Cover

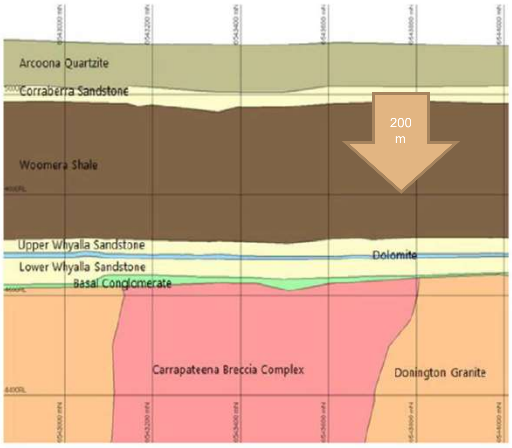
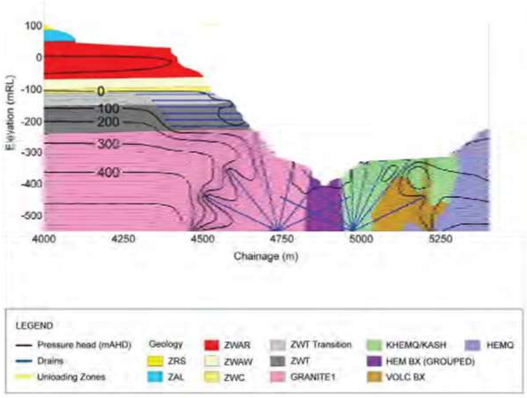


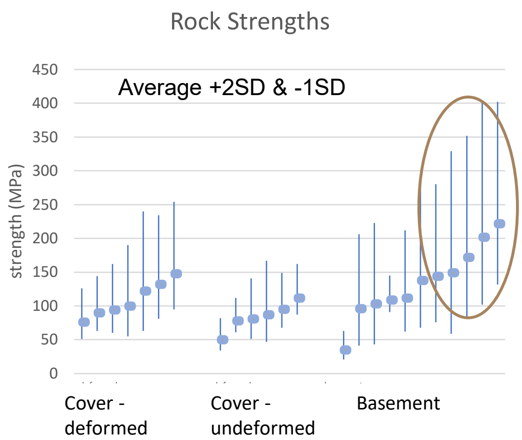
Figure 21: Stratigraphy and cover sequence at Carrapateena mine (Chauvier, 2022; Hocking et al., 2020).



https://www.bhp.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/0000/supplementary-eis-appendices/appendix-c_description-of-the-proposed-expansion.pdf
(PKM2011)

Strength

- Basement rocks are:
- Stronger

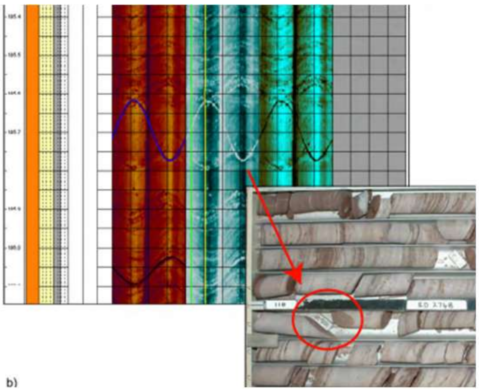


Data from PKM, 2011

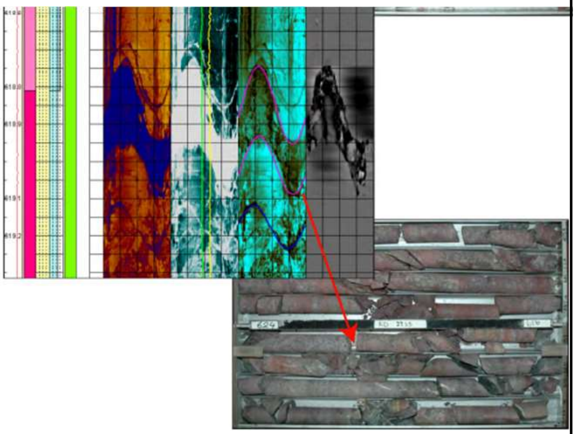
https://www.bhp.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/0000/supplementary-eis-appendices/appendix-c_description-of-the-proposed-expansion.pdf

Permeability

- Basement rocks are:
- Stronger
- Less permeable



Controlled by horizontal layers



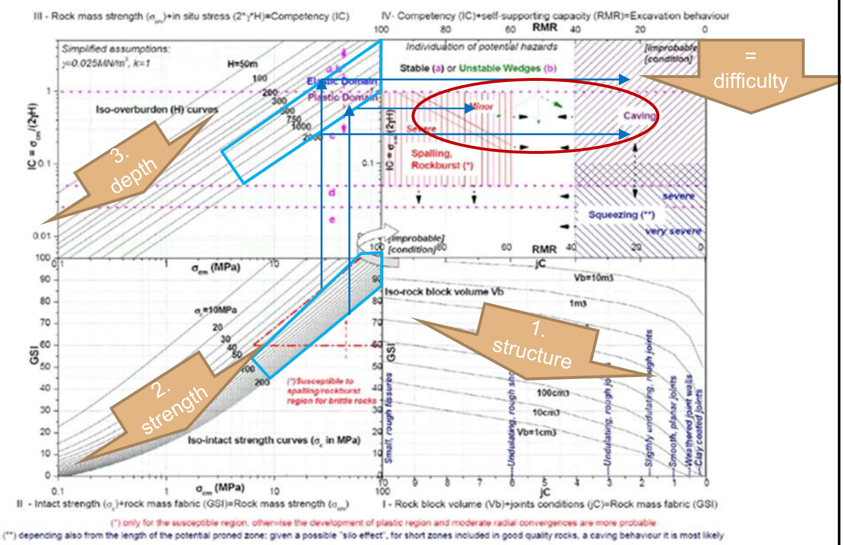
Controlled by joints and faults

Data from PKM, 2011

https://www.bhp.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/0000/supplementary-eis-appendices/appendix-c_description-of-the-proposed-expansion.pdf

The challenge of stress

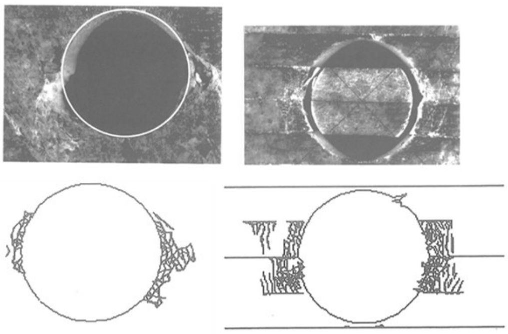
- > 500m deep
- How to keep holes open?



Adapated from Russo (2014)

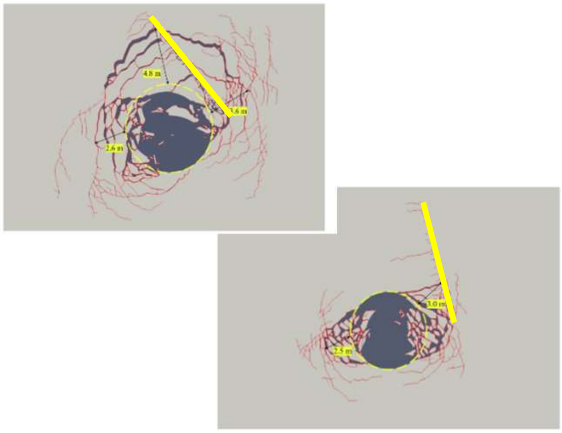
The challenge of stress

- Influence of jointing



(Sellers, Klerck, TUST, 2003)

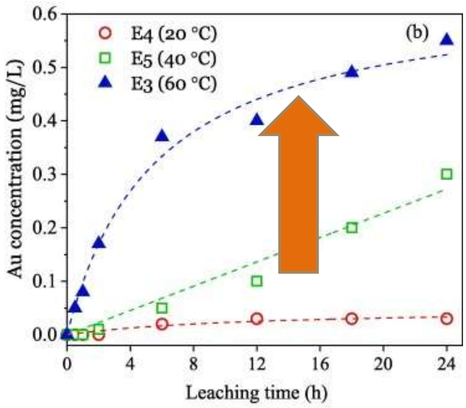
- Influence of Faults



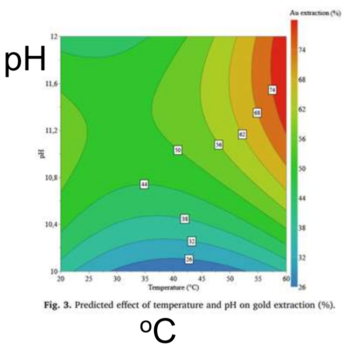
(Han et al, Computers and Geotechnics, 2021)

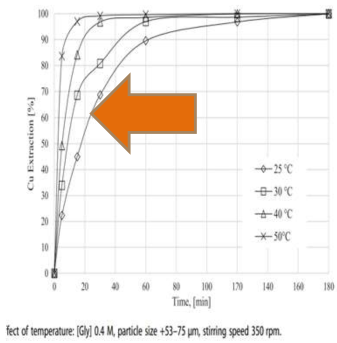
Is temperature an opportunity?

Increased, and/or faster leach recovery with temperature



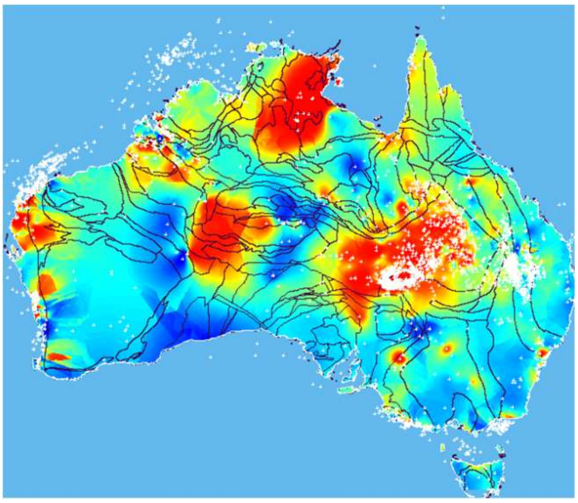
Gold : Altinkaya et al, 2020)





Copper: (Tanda et al, 2018)

Australian Rock temperature



- Gradient ~ 20°C/km
- Temperature at 5km depth in Australia (Chopra and Holgate, 2005)
- Blue is ~100°C and red >~200°C (1/10 @500m
- Lower temperatures where the basement (mineralised) rocks have surface exposure (Yilgarn Block, Gawler Craton and Lachlan Fold Belt). = shallow ore
- Higher temperature at depth associated with regolith cover (Basins) = deep ore
- Implies temperature improvement for deeper ore bodies that are harder to find and access

Where Next?

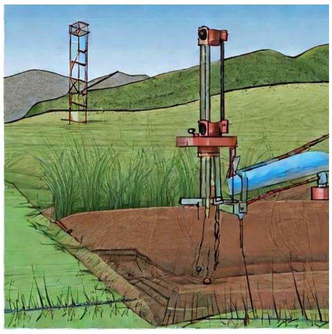
Research

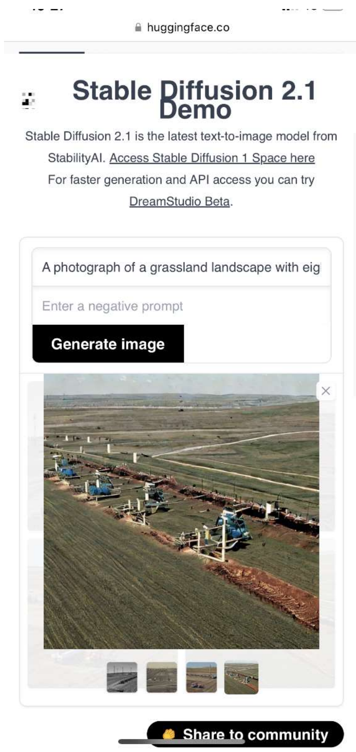
- MRIWA M0519
- Mining3, CSIRO, Curtin, Murdoch
  - Hydraulic and gas fracturing is possible
  - Leaching is possible from fractures
  - Leach recovery depends on:
    - Mineralogy
    - Liberation
    - Lixiviant
    - Deleterious gangue minerals

Kuhar (ALTA, 2019),
Karami et al (2021/2022),
Sun (ALTA, 2022)

- MRIWA M0545
- Curtin　　Mawire et al, (ALTA 2021)
  - Evaluation of in-situ barrier technology
  - Cementitious
    - Biotechnology
- MRIWA M0529
- Murdoch
  - Lixiviant access creation

AI experiments





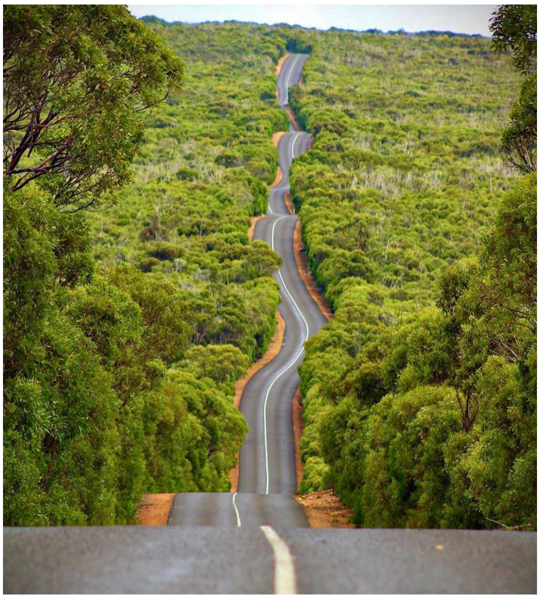
Research Challenges

Key questions remain to be answered:

Breakage: how to create the correct size distribution
Ore characteristics: Deeper and different mineralization
Recovery: less recovery, but higher return?
Temperature: more recovery with higher?
Geometry: Can we have higher stopes/silos?
Aeration: Alternative oxidant transport mechanism?
Particle size: Size distribution of blast-fragmented ?
Leach Time: Months or years?

Conclusions

- A long road ahead for Hard Rock In Situ Mining in Australia
- Opportunities exist in Australia. Near-surface, conventional ISR opportunities and tailings dams likely to be first.
- Identify and prevent future environmental issues
- Change management for miners, regulators and society
- **Need to pilot test at scale for confidence**



https://southaustralia.com/travel-blog/south-australias-top-6-instagrammable-roads

Acknowledgements: CSIRO, MRIWA, Ivor Bryan, Laura Kuhar, Mohammad Sarmadivaleh

IN-SITU RECOVERY – PROGRESS OVER THE LAST FIVE YEARS

By

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ABSTRACT

In-situ recovery (ISR) transfers hydrometallurgical processing of mineralised bodies to the subsurface to directly obtain solutions of commodities. As a result, there is little surface disturbance. For ISR to be successful, however, deposits need to be permeable. Furthermore, commodities need to be readily amenable to dissolution by leaching solutions over a reasonable period of time, with an acceptable consumption of leaching reagents.

CSA Global presented an overview of ISR for non-uranium metals at the ALTA-2019 conference. The ISR industry rapidly changes and material updates are now available for presentation.

Uranium. ISR accounts for more than 50% of world uranium production. The main uranium ISR regions are Kazakhstan, Uzbekistan, USA (Wyoming, Nebraska) and South Australia. Ukraine, a pioneer of the ISR industry, returned to applying this technology through pressure air/oxygen gas uranium leaching, initially developed in Uzbekistan. This technology is most suitable in the Kalahari Desert (Namibia) where new uranium deposits were discovered.

Copper. Copper is extracted by sulfuric acid, however, ammonium-base lixiviants may be used if sulphuric acid is not suitable due to a high carbonate content. Florence Mine and Gunnison Mine in Arizona started ISR copper production in 2019-2020. Moonta and Kapunda deposits in South Australia have been extensively investigated and are close to pilot plant ISR operation.

Gold and Silver. These commodities are extracted by chlorine or sodium hypochlorite. The Gagarskoe and Dolgy Mys deposits in the Urals are currently subject to the successful application of ISR. Several projects in the weathering crust and deep placers in Russia are nearing production, and some projects in Australia and the USA are currently being assessed for ISR potential.

Nickel, Cobalt, Manganese. The most significant recent progress has been made regarding the development of ISR for nickel and cobalt laterite projects in Kazakhstan. Pilot operation from 2019 to 2020 was performed on the Gornostay deposit. Four field cluster tests have been completed to assist with the preparation of a program to achieve a PFS level investigation. Sulphurous acid is used as a lixiviant for leaching with the production of pure metals. Sulphuric acid was not economical for the ISR of nickel and cobalt. Manganese is also a commodity which can be mined by a similar lixiviant, as has been demonstrated in field tests.

A successful push-pull test for tungsten using a complex lixiviant with hydrochloric and ethanedioic acids was completed in Kazakhstan. This technology was patented by Dala Mining company.

Forty Cady project (California) started ISR pilot operation at a boron deposit at the end of 2020. The aim was to produce boric acid using hydrochloric acid as the lixiviant.

Scandium is extracted as a by-product from pregnant uranium solutions at Dalur in Russia. ISR of Rare Earth Elements from ionic clays is used in China, however environmental issues exist which could potentially be resolved through adequate planning and organising of the ISR process.

Keywords: in-situ recovery, copper, gold, silver, nickel, cobalt, manganese, tungsten, scandium, rare earth, yttrium, boric acid

AGENDA

Introduction – History of ISR

1950s - 1960s

Discovering ISR for U

ISR was developed independently in the former USSR (Ukraine, 1959 and Uzbekistan, 1960s) and the USA (Wyoming, 1958) by acid leaching and alkaline leaching

1970s - 1980s

Initial development ISR for Uranium

Ddiscovering ISR for Cu, Au Pilot test for leaching by-products at the U Mines

ISR mining ramp up the USSR (Uzbekistan, Kazakhstan) and USA (Wyoming, Texas). Period for major sand-stone type uranium deposits discoveries

Test for ISR the following elements as by-products at the uranium Mines: Sc, Re, REE, Y, Mo, V, Se. First ISR tests and mines for Cu in USA (Arizona) and Australia, Au in Canada

1990s

Stagnation in U ISR industry

Developing ISR at the new types of deposits including new commodities (Ni, Co, Mn)

Stagnation period for uranium ISR after Chernobyl disaster and collapsing USSR, development small projects in Russia

Closing the first ISR copper mines in USA, Australia. Developing ISR Mines for Au, Cu in the new regions. Identification of chemical reagents for most effective leaching of Au.

2000s

Wide development ISR for uranium, the displacement of conventional mines

Uranium ISR boom in Kazakhstan (8 new mines). New ISR mines in Uzbekistan, USA, Russia, Australia, including difficult nature conditions

Development ISR technology for new commodities (Ni, Co, Mn) by new lixiviants. Development ISR to new types Cu, Au deposits including tailings

2010 - 2017

Development ISR, discovering of new types non-uranium deposits for ISR (B, W, REE, Sc), development of new methodologies

New ISR uranium mines in Kazakstan, USA, Australia, ISR production share increased to 51% of World uranium production

Non-uranium ISR was spread locally by enthusiasts for Au, Cu, Ni, Co. Development technologies for leaching and extraction metals from pregnant solutions Return to test and pilot operation for ISR of Sc and REE

Definition of general approaches for exploration, modelling and estimation deposits for ISR. Definition criteria and discovering of new types of deposits which can be operated by ISR

2018 - 2023

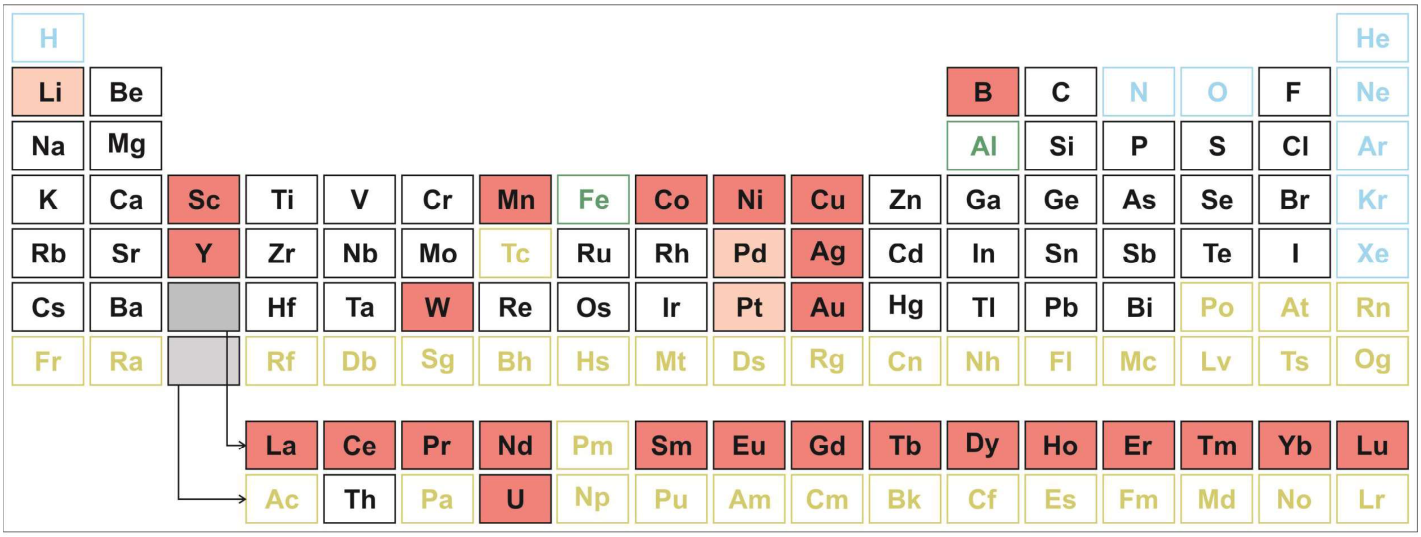
Discovering new deposits / basins for uranium ISR, development new technologies for uranium ISR

Commercial operations (Cu, Au, Sc, REE) and preparation (Ni, Co, Mn, B, W) to commercial operations for new ISR non-uranium deposits

Development of ISR for new types of uranium deposits (unconformity in Athabasca), discovering new deposits and basins suitable for ISR, development of new technologies of ISR, returning Ukraine for investigation and operation of ISR uranium deposits

Start of commercial operation of new copper ISR projects in USA (Arizona), preparation new ISR copper projects in South Australia, depletion of Gumeshevskoye deposit with start of transformaton to gold ISR project. Commercial operation of gold deposits in Russia, depletion the first gold ISR deposit (Gagarka).
Development of ISR technological scheme for Ni-Co-Sc laterite project with evidences of economic profitability on Scoping Study level and start of pilot operations
(Kazakhstan) Development of tungsten ISR, successful push-pull test with evidences of economic profitability on Scoping Study level Development and pilot test for boron project in USA (California), currency project is on construction stage.
Development if REE&Y ISR for ionic clays

Introduction – Activity in the last 5 years

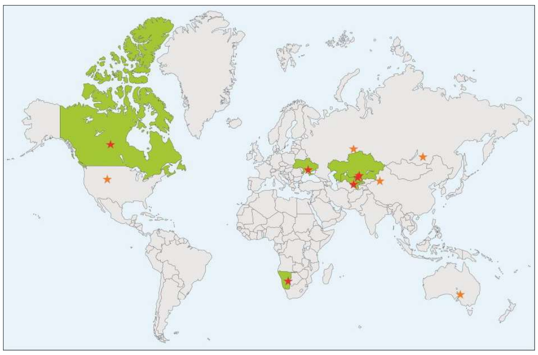


Co ISR was developed in the last five years

Pd ISR tested in the last five years

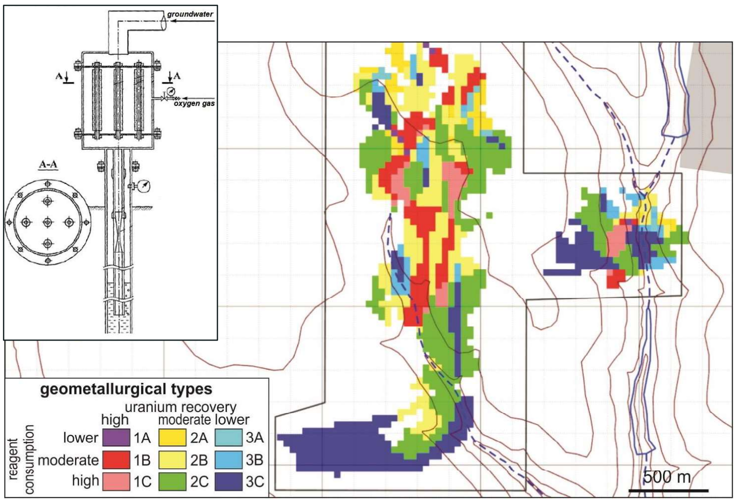
Uranium

- Uranium is the most common commodity extracted by ISR.
- Uranium ISR developed since 1960s and despite this at the last 5 years:
  - Was discovered new major uranium Aranos basin in Namibia.
  - Oxygen gas leaching without or with low grade of sulphuric acid was developed in Uzbekistan and can be used for other projects.
  - ISR technology was developed for unconformity type deposits.
  - Methodology of modelling of roll-front deposits were improved.



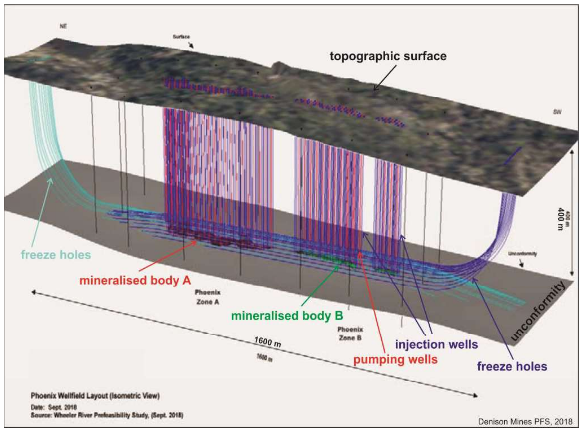
Uranium – Uzbekistan, Sanonovka deposit, Aranos basin

- Tests with oxygen gas, without sulphuric acid, were performed in Uzbekistan (Shiyaev et al., 2020).
- Tests were performed using pressured air with displacement of groundwater from the productive horizon using an ejector and increasing pressure of the ejection of pressured air (Shiyaev et al., 2020).
- Method was proposed for Ukranian Safonofka deposit and Aranos basin in Namibia due to strict environmental limitations.



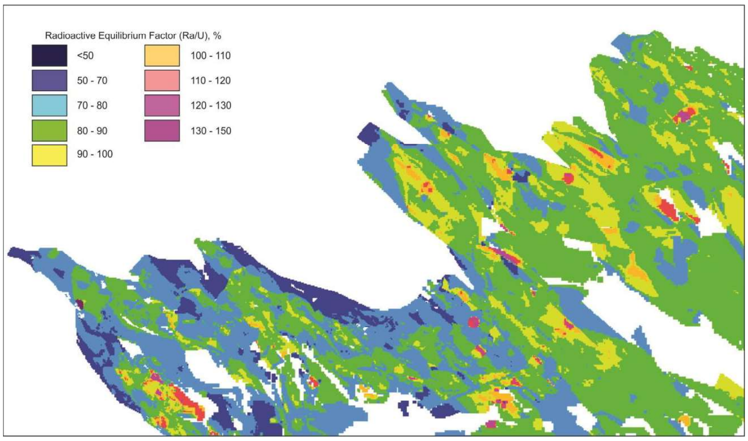
Uranium – Phoenix deposit

- Dennison Mines Corp. successfully investigated ISR for Phoenix uranium deposit of unconformity type in the Athabasca Basin (PFS Report, 2018) and plans to start natural pilot operation.
- Phoenix deposit is located in complicated geological and hydrogeological conditions, uranium grade is high (19% U_3O_8), not favourable for ISR.
- Hydrogeological tests and laboratory leaching tests demonstrated applicability of ISR for this deposit.
- Horizons above and lower uranium mineralisation will be frozen for creating artificial aquicludes for avoiding wide distribution of leaching solutions.
- ISR in cold conditions (< 5°C) was proved earlier at the Khiagda ore field.



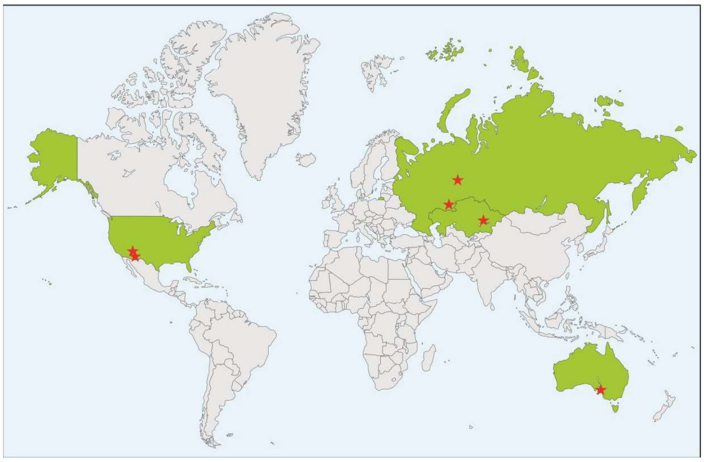
Uranium – Chu-Sarysu and Syrdarya basins

- Subsidiary mines of Kazatomprom improved methodology of modelling and estimation variability of uranium grades.
- The most of roll-front deposits in Kazakhstan has not equilibrium between radium and uranium.
- Estimation of REF variability is required for correct estimation of uranium grades using gamma logging.
- Developed methodology allows to estimate variability of REF using sparce exploration grid with following applying to operation wells.



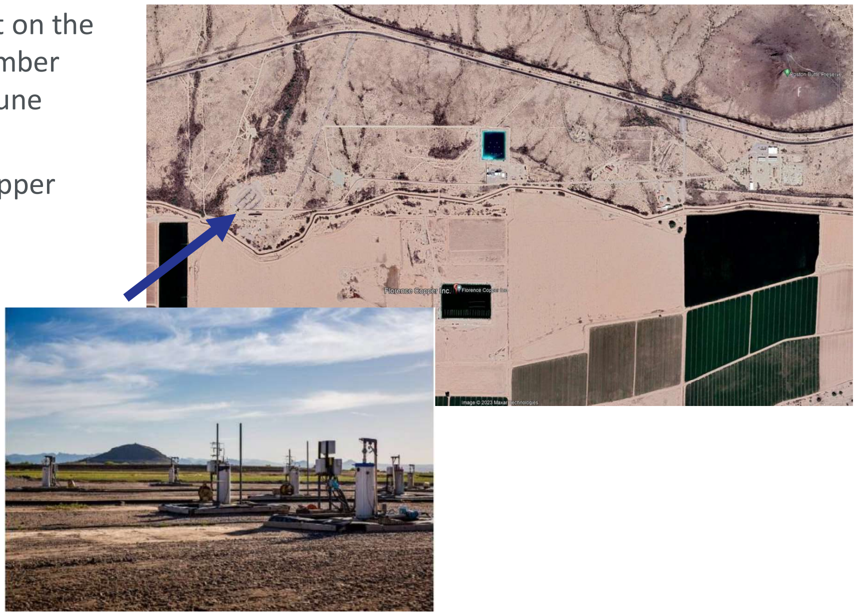
Copper

- Copper ISR initially used on the San-Manuel deposit as additional method to underground operation. Project was closed in the 1990s.
- New ISR copper projects were developed since end 1990s and especially in 2000-2010s.
- Total capacity of Florence and Gunnison projects may reach 100 kt copper per year .



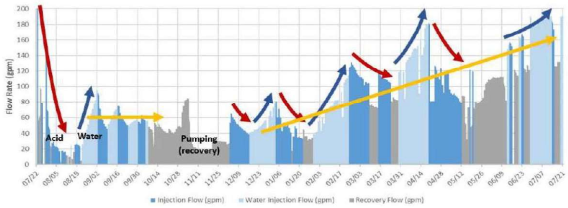
Copper – Florence

- Taseko mining started operation test on the Florence copper ISR project in December 2018 and commercial operation in June 2020 (NI 43-101 report, 2023).
- Proposed full capacity is 38-40 kt copper per year for period at least 22 year.
- Final product is cathode copper.



Copper – Gunnison

- Excelsior mining started pilot operation the Gunnison copper ISR project in Q4 2020 (NI 43-101 report, 2023).
- Proposed full capacity is 55-60 kt copper per year for period at least 24 years.
- Company met with blockages by carbon dioxide gas colmatation due to high grade of carbonate material in copper bearing veins and fractures.
- Company plans to resolve this issue by alternating periods of acidification and neutralisation of solutions, this will probably lead to increasing acid consumption.
- Another option was used in the high-carbonate conditions was tested on the Kharasan mine – soft acidification before dissolution of carbonates.



NI 43-101 report, 2023

Copper – Kapunda and Moonta

- Enviro Copper extensively tested the Kapunda and Moonta copper ISR projects.
- Completed comprehensive hydrogeological tests, prepared hydrodynamic model, performed leaching tests by different lixiviants.
- Processing of pregnant by ion-exchange (IX) process developed by company is safer and better than common SX process using now for treatment of copper pregnant solutions.
- Company is ready to commence pilot operation.

Copper - Gumeshevskoye

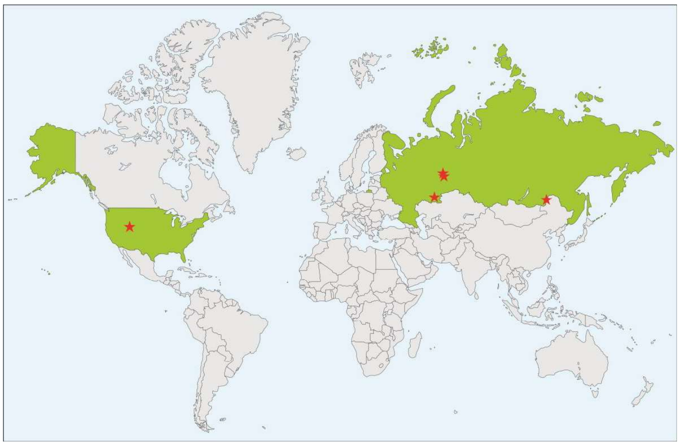
- UralHydroCopper operates the Gumeshevskoye copper ISR project since 1998.
- Capacity of project reached 5-7 kt copper per year however now deposit is almost depleted.
- Copper grades in pregnant solutions is 200 mg/L, this is close to breakeven cut off.
- Company completed extensive program of gold leaching investigations and consider construction of chlorine gas production module as well as processing plant for gold pregnant solutions.

Copper – waste dumps

- ISR technology was successfully applied to copper waste dumps by private companies at the Kounrad deposit in Kazakhstan and Gaysky deposit in Russia.
- This technology addresses to profitable production of cathode copper with resolving of environmental issues by leaching oxide copper which may contaminate superficial water and groundwater.

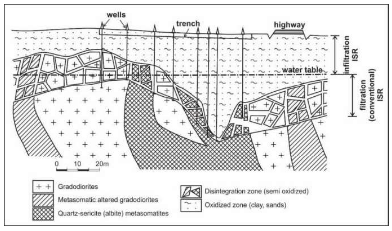
Gold

- Gold ISR was developed last 30 years but still used for small deposits with small capacity by private companies.
- Annual capacity of new Tuba-Kain ISR project may reach 15kOz.
- Carlin type of gold deposits considered for ISR in 2018 and this idea is productive and may be realised in the nearest future.
- Deep gold placers are suitable for ISR too!



Gold (continued)

- Gold ISR was realised by small private companies on the Urals. Lixiviants are chlorine gas or sodium hypochlorite.
- Annual capacity of gold ISR miners is 2-6 kOz however on the Tuba-Kain will be increased up to 15 kOz per year. This capacity is not intersecting for bigger mining companies.
- The first gold ISR Gagarka mine is depleted and in remediation process now.
- Gold ISR was considered by Nornickel on the Bystrinsko-Shirinskoye deposit but this project was suspended in 2019 due to low dynamics of leaching.
- The project demonstrated that production of fresh lixiviants on mining sites are the best option for ISR.

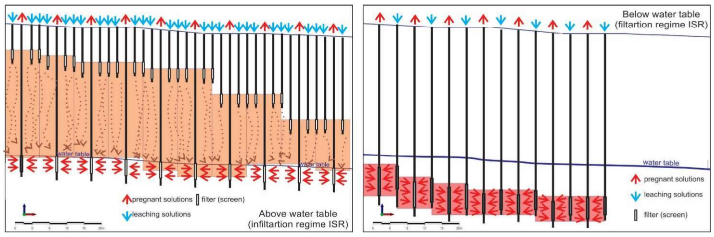


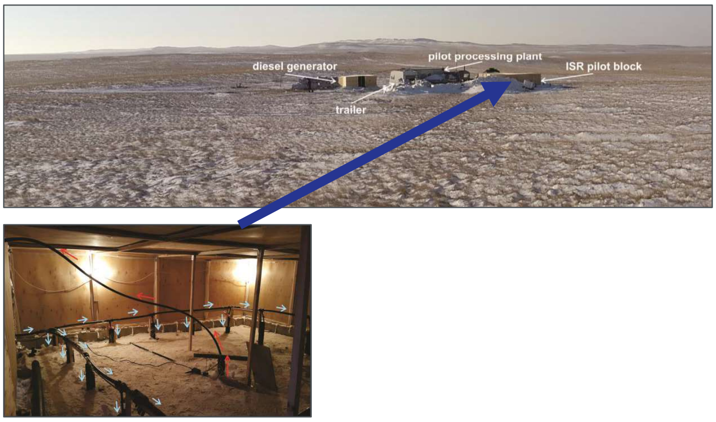
Nickel-Cobalt-Manganese-Scandium

- Nickel-Cobalt-Manganese-Scandium ISR from laterite deposits was extensively developed last 5 years.
- This technology is close to realisation at Pre-Feasibility Study.
- This technology is widely applicable to laterite Ni-Co-Mn-Sc deposits due to quite similar geological conditions.

Nickel-Cobalt-Manganese-Scandium

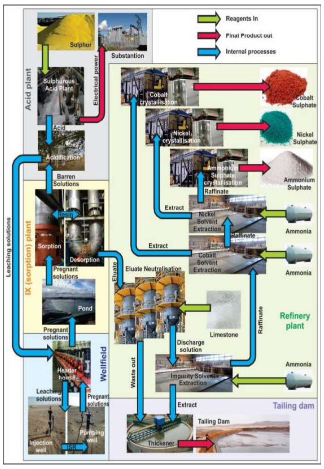
- ISR of Nickel and Cobalt from laterite mineralisation was developed by private companies in Russia since 2000s due to uneconomic of pyrometallurgy method.
- Sulphurous acid as the best lixiviant was discovered in 2011-2013 and field tested at the Ekibastuz-Shiderty deposit in 2018.
- Sulphurous acid was used for leaching of cobalt-manganese ore on the open pit Mt Thirsty project in Western Australia.
- Manganese and Scandium can be leached from laterite deposits too.





Nickel-Cobalt-Manganese-Scandium

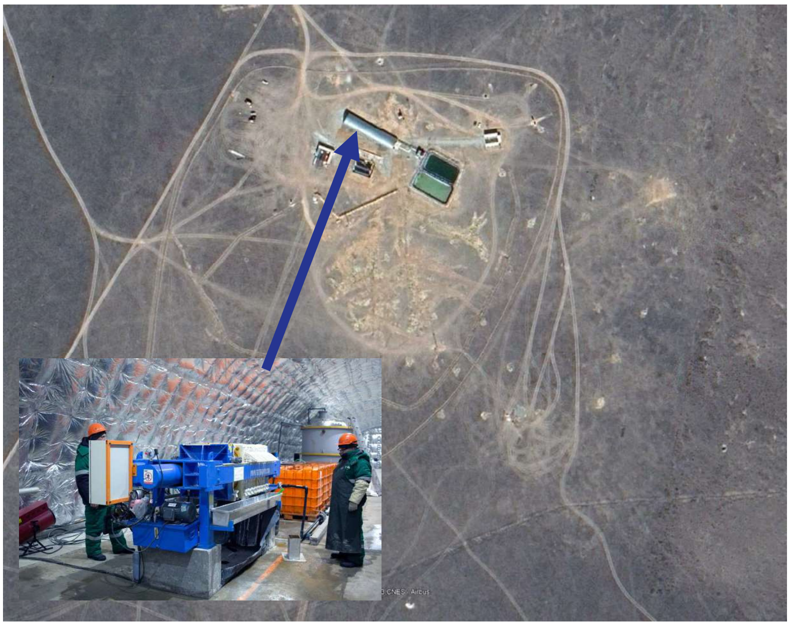
- Processing of pregnant solutions in pilot ISR test allowed to produce from poor pregnant solutions (100-120 mg/l) Ni-Co eluate with composition comparable with eluate in SunRise project (CleanTeQ) produced from pregnant solutions after HPAL process.
- Comparable composition of eluate allows to use processing flowsheet detailly designed by CleanTeQ use for processing pregnant solutions after ISR.
- CSA Global integrated technologies for ISR projects in 2019.



Component	SunRise (Fairfield, 2018)	Ekibastuz-Shiderty
Ni, g/l	31	22
Co, g/l	3	10
Mn. g/l	0.7	4
Sc, mg/l		50
Fe, g/l	4	5
Al, g/l	2.9	1.5
Mg, g/l	0.4	3

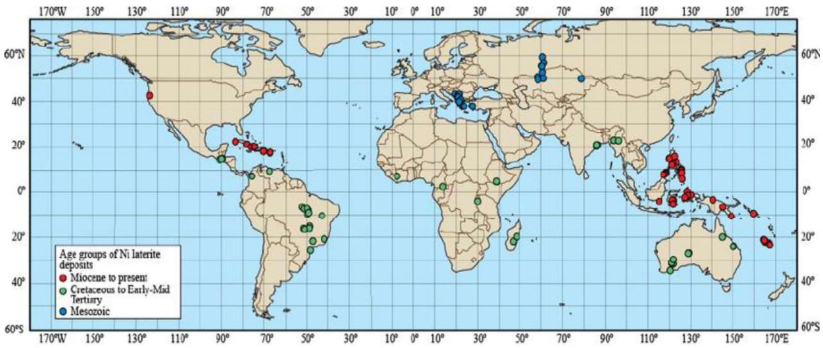
Nickel-Cobalt-Manganese-Scandium

- Kaznickel constructed the first Ni-Co pilot ISR plant in 2019 and performed operations in 2019-2021.
- Tested different lixiviants and ion-change processes for selection the most suitable technology.
- Demonstrated successful operation above the water table.



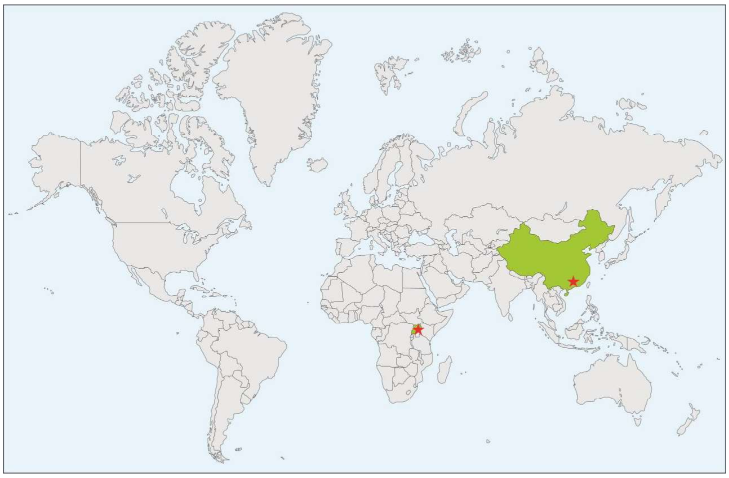
Nickel-Cobalt-Manganese-Scandium

- Nickel-Cobalt-Manganese-Scandium ISR from laterite deposits may be developed to widely distribute technology similar to uranium
- ISR due to similar geological conditions on laterite deposits across the world.



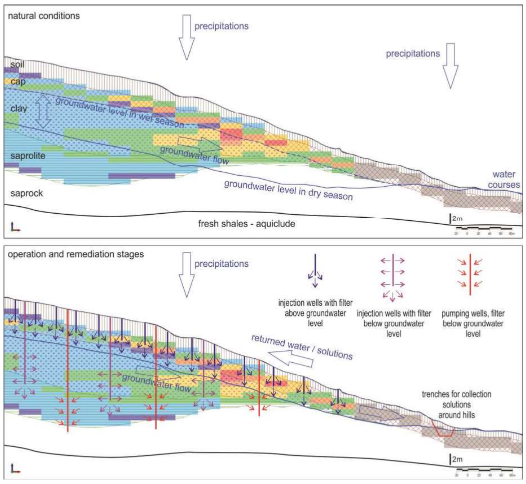
Rare Earth Elements & Yttrium

- ISR technology is very prospective for ionic rare earth clays and applied in China - ready for reducing impact of REE mining.
- Australian companies has interest to development of REE ISR for ionic rare earth clays due to identifying many this type projects in Australia and Africa.



Rare Earth Elements & Yttrium

- Rare Earth and Yttrium ISR technology was developed in China due to conventional mining impacted to environmental very strongly up to disaster situation.
- Leaching of rare earth can be described as desorption from clays by sodium carbonate or sulphate solutions and quite effective.
- Potential re-soluble issue is high fluctuation of groundwater level during year cycle.



Tungsten

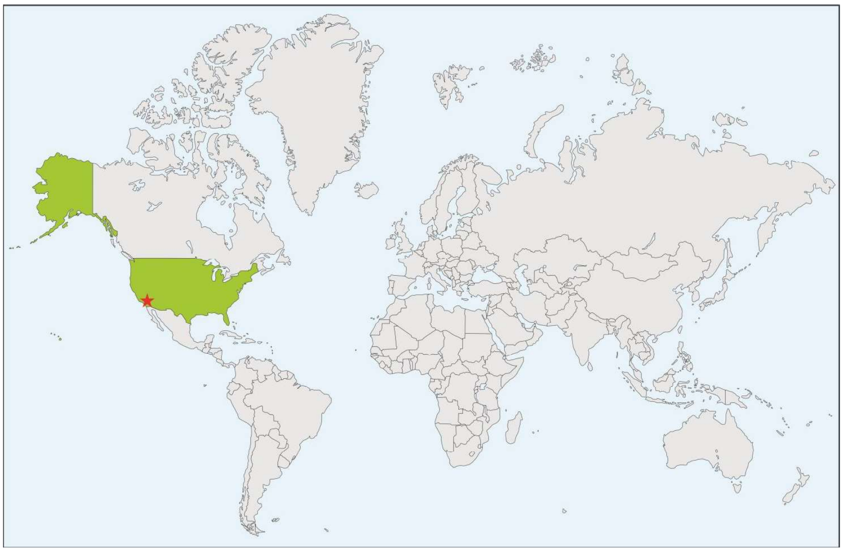
- New ISR technology was developed for tungsten mineralisation in weathering crusts and skarns.

Tungsten - Koktenkol

- ISR was developed by Dala Mining in 2019.
- Lixiviant with based on Oxalic acid and hydrochloric (or sulphurous) acid allows to extraction of tungsten to solutions in oxalate complexes.
- Technology was tested by push-pull test, tungsten grade in pregnant solutions reached to 250-300 mg/L.

Boron

- ISR technology was applied to boric-lithium mineralisation in the last five years.



Boron – Fort Cady

- American Pacific Borates company developed ISR technology for leaching of boron from colemanite mineralisation on the Fort Cady project in California (Corporate Presentation, 2019).
- Lixiviant is heated hydrochloric acid, process is push pull due to colemanite mineralisation is impermeable.
- Final product is boric acid, lithium is in pregnant solutions as by product, leached from clay interbeds.
- Mine and processing plant is in construction stage now and company is almost ready for start of commercial operations.

Conclusion

Commodity		Price	OPEX	Wellfield construction	Unit of capacity	Plant and infrastructure construction	Level of technology development
Uranium	Acid ISR, roll-front	122 US$/kg U	12 – 35 US$/kg U	5 – 10 US$/kg U	1000 tpa U	30 – 150 MUS$	Commercial operation
	Acid ISR, paleochannel	122 US$/kg U	35 – 65 US$/kg U	15 – 25 US$/kg U	1000 tpa U	50 – 130 MUS$	Commercial operation
	Alkaline ISR	122 US$/kg U	25 – 55 US$/kg U	10 – 30 US$/kg U	1000 tpa U	25 – 110 MUS$	Commercial operation
Copper. Sulphuric acid ISR		9.6 US$/kg Cu	1.8 – 2.5 US$/kg Cu	0.4 – 0.7 US$/kg Cu	1000 tpa Cu	4 – 7 MUS$	Commercial operation
Gold and Silver. Sodium hypochlorite ISR		1,850 USD$/oz Au	250 – 300 USD$/oz Au	100 – 300 USD$/oz Au	1 tpa Au	1 – 4 MUS$	Operation
Nickel & Cobalt. Sulphurous acid ISR		28 USD$/kg Ni	5 – 8 USD$/kg Ni	2 – 5 USD$/kg Ni	1000 tpa Ni	25 – 40 MUS$	Scoping level, pilot tests
Tungsten. Oxalic acid ISR		42 USD$/kg W	16 – 27 USD$/kg W	0.8 – 2 USD$/kg W	1000 tpa W	20 – 50 MUS$	Scoping level, push-pull test

BENEFITS OF COLLABORATION TO ADVANCE ISR TECHNOLOGIES AT THE KAPUNDA COPPER PROJECT

By

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ABSTRACT

EnviroCopper's Kapunda copper in-situ recovery (ISR) project in South Australia, is leading the way in applying technological advances for In-Place Mining. The project, located in an historic mining jurisdiction, with a JORC compliant resource of 47.4 Mt @ 0.25% Cu for 119,000t of Cu, will see a stranded mineral deposit revitalised as Australia's first fractured rock copper ISR project.

Our long developmental stages have been well presented at ALTA since 2017. Close to pre-feasibility, EnviroCopper has overcome a number of regulatory hurdles in order to open up more opportunities for projects in stranded deposits so other junior companies can follow suit in the growing ESG space.

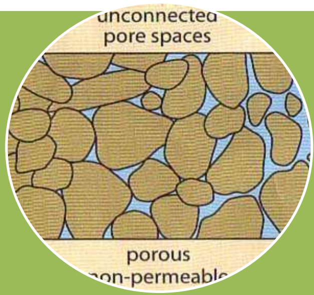
This presentation will summarise the key outcomes of ECL's development of a Copper ISR template using Kapunda as a demonstration site and how collaboration with industry and institutions over the years has significantly contributed to our success, leading to partnering with OZ Minerals for $2.5M for the next step in realising the economic potential of smaller, low grade copper deposits with an inground Site Environmental Lixiviant Trial (SELT).

Under the umbrella of the Think and Act Differently (TAD) innovation team, OZ Minerals' partnership seeks to complement the work of ECL at the Kapunda site by enabling both companies to build capabilities that can be used to explore the potential at other undervalued orebodies.

TAD's broader program works towards building an ecosystem of partners who explore and accelerate themes that prioritise social and environmental responsibility for the development of modern mines. Central to TAD's success is the active participation of a network of people from across multiple industries, organisations, community groups, governments, research organisations and others who want to play a role in solving complex challenges in the resources sector.

Keywords: in situ recovery, copper, collaboration, SELT, TAD, partnerships

Pillars of ISR



Technical

- Hydrogeological
- Groundwater Modelling
- Fate Transport Modelling
- Fracture/Flow Modelling
- Benign Lixiviant

Location

- The Kapunda project sits 90 km North of Adelaide with an inferred ISR-amenable copper resource of 119,000 tonnes
- Historic mine site from 1840s, currently used primarily as a tourist site managed by local council
- Potentially one of the first non-uranium ISR projects in Australia, being developed in a fractured rock environment

Challenges

- Hydrogeological properties
- Managing ground water environmental risks
- Community acceptance being so close to town

EnviroCopper is leading the way in developing minimally invasive, low footprint exploration and mining techniques

Benefits of Working Together

1. Access to people and skills you don't currently have in house
2. Potentially access additional funding for your project/technology

Since 2017 EnviroCopper have collaborated with;

- ✓ Cth and State Govt research grant $3M, inc. Cooperative Centre Research – Project (CRC-P)
- ✓ CSIRO – Inground Vesi™ Sensors for commercialisation of continuous, automated environmental monitoring for Copper ISR operations
- ✓ 3 x MRIWA research programs – benign lixiviant system design, fate transport modelling, and fluid/rock/lixiviant interactions
- ✓ MinExCRC - Coiled Tube directional drilling
- ✓ In 2022 partnered with Think & Act Differently powered by BHP team with $2.5M
- ✓ And this year research partner with Ekion Pty Ltd in developing EK for ISR hard rock potential

Benefits of Working Together

Not just technical benefits……………..

EnviroCopper have identified 900 deposits just in SA that could be ISR amenable for Gold and Copper but,

We can't do it all ourselves.

Many companies are in this space, some Tier 1s hold their cards close to their chest……..

Developing Smarter Mines means employing Smarter Business Strategies

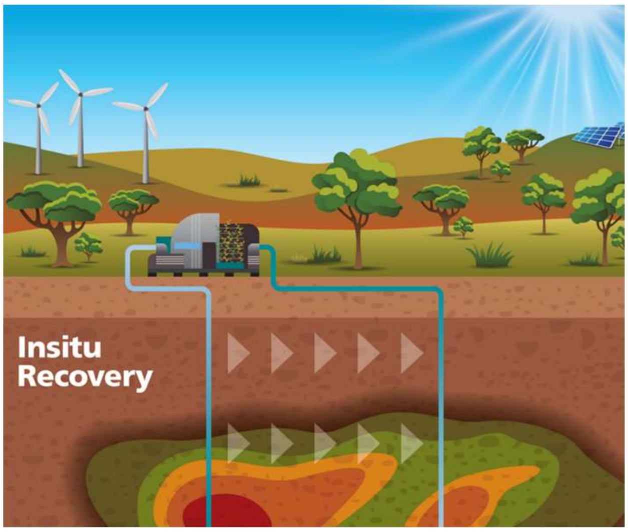
Collaborating gives you industry credibility, providing for evidence-based decision making and comfort with investors and regulators.

Looking at new ways to extract metals

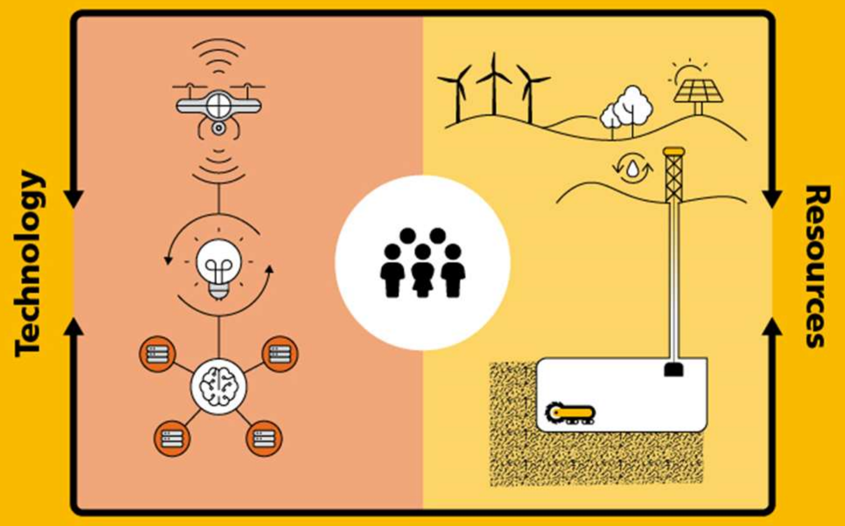
Partnership with EnviroCopper to investigate advances in In-Situ Recovery

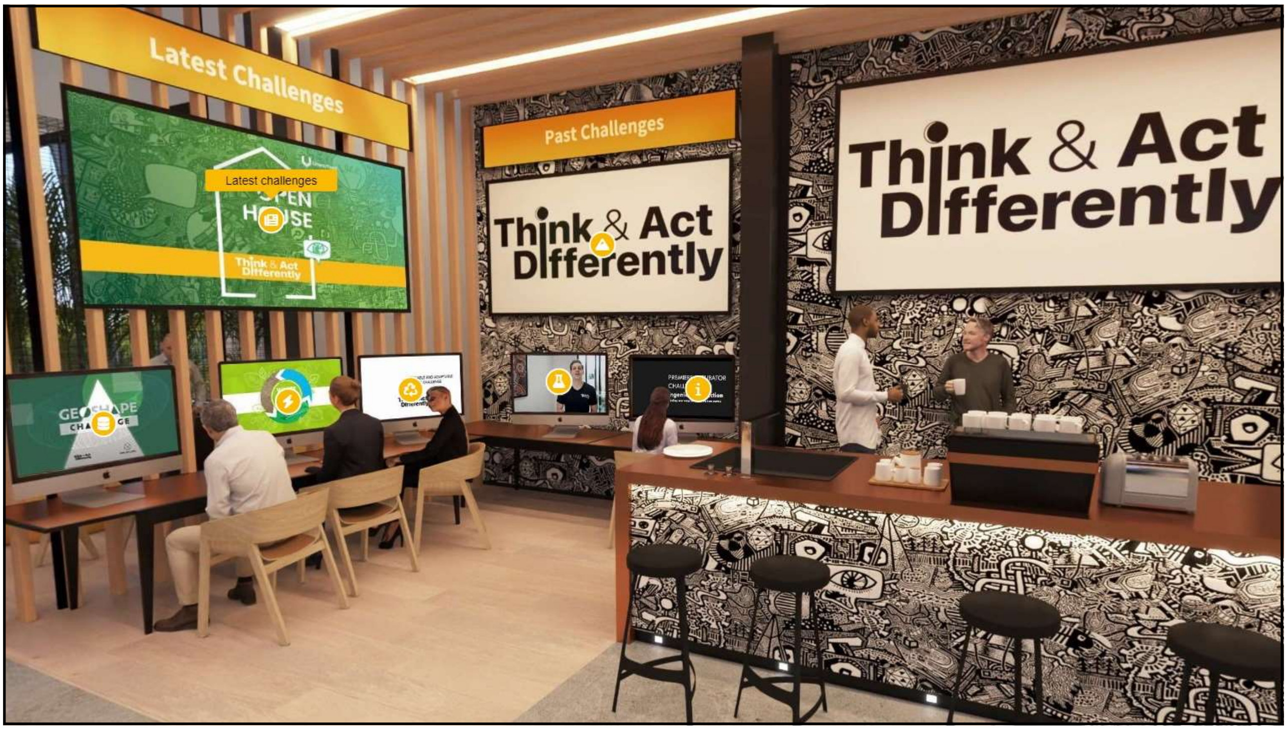
Understand the economic extraction of copper from deposits that cannot be mined conventionally.

Develop a copper ISR demonstration site at Kapunda to enable both companies to employ similar approaches to explore undervalued orebodies



- A Modern Approach to Technology & Resource Development




Latest Challenges
Latest challenges
Past Challenges
Think & Act Differently
Think & Act Differently

IN SITU EXTRACTION OF PRECIOUS METALS AND MINE REMEDIATION WITH POLYSULFIDES

By

Drummond Earley III

D3 Geochemistry LLC

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ABSTRACT

It is estimated that cleanup of metal bearing wastes from abandoned mine lands across the U.S. alone will cost tens of billions of dollars. Recovery of valuable metals by reprocessing of mining wastes in conjunction with water treatment has been considered but hindered by the potential risk of incurring liability in the commercial remediation of abandoned mine sites. Recent US EPA interest in this idea has heightened in the aftermath of the Gold King mine spill because of the potential for mine reclamation that pays for itself by secondary recovery of metal values. At one Superfund site in the southeastern US a pilot test is being developed to test polysulfides for recovery of precious metals while remediating mobile metal contaminants in mining wastes and mine influenced water. Polysulfides are unique in that they have been used to both recover precious metals from ores and for in situ reduction and chemical stabilization of metals during remediation of contaminated sites. In situ treatment of mine pool waters and mine wastes is becoming more common to avoid perpetual water treatment. Polysulfides could be used for in situ recovery (ISR) by stope leaching, for example, while reducing acid generation and metal leaching from abandoned underground mines.

Polysulfides are generally recognized as safe, non-toxic, non-polluting and are routinely used in agricultural applications as well as remediation. Furthermore, polysulfides can be inexpensively produced from ARD and mining wastes themselves. The sulfur saturated system is self-buffering and maintains the optimal chemical environment for leaching precious metals and stabilization of metals such as mercury and base metals. Solvent extraction technology has also been developed to recover gold from polysulfide solutions while recycling and conserving water for sustainable use in metal remediation and recovery.

Demonstrated recovery of precious metals from mined lands using acceptable lixiviants and methods and possibly a first step towards the wider application of ISR for precious metals in undeveloped ores. This paper also touches upon some of the concepts that may lead to the expansion of successful in situ recovery projects.

Keywords: In situ, precious metals, polysulfides, mine remediation

INTRODUCTION

Cyanide has been the reagent of choice to recover gold and other precious metals through leaching since the system was patented the system in the late 1800's[1]. However, it is generally accepted that cyanide would not be allowed for in situ recovery (ISR) of precious metals in most jurisdictions and gaining social license to operate would be very difficult [2]. Hence, there has been considerable interest in developing alternative lixiviants for ISR[3][4]. In the early 1990s the US Bureau of Mines investigated several alternatives to cyanide. One of these technologies involves leaching gold with a polysulfide lixiviant at moderately elevated temperatures where polysulfides are more stable than at ambient temperatures[3][5][6].

The polysulfide lixiviant can be deployed as a dilute, non-toxic, aqueous, solution which operates optimally at neutral pH and elevated temperatures (75 to 150 degrees Celsius (^{o}C)[5]. Polysulfides are still effective at ambient conditions but the solution is not stable and precipitates sulfur[3]. However, the cost of heating solutions and ore would not be prohibitive for some deposits if leach solutions are managed to retain heat in an ISR system[5]. Furthermore, deep deposits naturally attain such conditions and polysulfide compounds injected into these deposits could help stimulate natural dissolution processes and enhance precious metals recovery. It is probable that polysulfide lixiviants can be inexpensively produced from readily available chemical reagents and even mining wastes which has been demonstrated for sulfide leaching[7]. The polysulfide lixiviant is self-buffering and maintains the optimal chemical environment for leaching without extensive operator maintenance[5]. Yet long term rinsing and site monitoring are not necessary because the lixiviant itself is not toxic and breaks down as the system cools and equilibrates after mine closure.

Polysulfide lixiviant systems are promising for ISR of gold and some of the disadvantages of polysulfide leaching by heaps and vat leaching like off gassing and decomposition[3] are less detrimental in ISR systems. However, obtaining permits and social license to operate has always been a “tough sell” for any ISR project[2] owing to public skepticism and concerns over groundwater protection in particular. However, in situ remediation has become a best available technology for groundwater restoration and polysulfides are effective for in situ chemical reduction (ISCR) of metals and inorganic contaminants[8]. Given that abandoned gold mines are often the source of mine influenced water, the author proposes that it may be possible to use ISR and ISCR in tandem to recover gold and reclamation costs for cleanup of these sites while stabilizing metals and reducing treatment costs and longevity. The U.S. Environmental Protection Agency is interested in the potential for mineral and cost recovery at its cleanup sites and has approved a pilot study at the Barite Hill Superfund site in the southeastern US. ISR is not the primary method that will be used at this former heap leach facility but polysulfide recovery of gold from abandoned underground gold mines is a logical extension of the concept. At these sites gold can be recovered from gob and tunnel collapse materials using stope leaching. Furthermore flooding can be used to evoke ISR from tunnel walls and extensions of vein systems where leachable gold occurs in permeable vugs and fractures[9].

Conceptually, ISR and ISCR can be used simultaneously to recover gold and stabilize mine waste and exposed wall rock. The current progress, technical challenges, economics and permitting issues will be outlined in the remainder of the paper.

RESEARCH AND DEVELOPMENT

Leaching Experiments

Ammonia polysulfides have been used for gold leaching and has a fast leaching rate and high leaching ratio of gold in alkaline solutions[3]. It is effective in treating low-grade gold ores and As- and Sb-containing refractory ores. The US Bureau of Mines and University of Minnesota conducted laboratory experiments that showed that polysulfides (S_nS^{-2} where n = 1 to 7) complex with and dissolve gold in sulfur saturated solutions under intermediate H_2S and O_2 partial pressures and neutral pH (Figure 1) according to the following mass balance equation:

$$2Au + H_2S + nS_2 = 2AuS_nS^- + 2H^+$$

The association constants (log K) for aurous polysulfide complexes are between 21 and 26 at temperatures of 100 to 150 ^{o}C. Furthermore, because gold simultaneously forms strong complexes with multiple polysulfides polymers and bisulfide in solution the cumulative association constant is higher than cyanide.

Laboratory tests on pure gold and gold quartz mixtures conducted at 75 to 150 °C and 10 to 100 bars showed the solubility of gold in the presence of polysulfides in of 10 to 50 ppm with a solution containing approximately 500 to 1,600 ppm total dissolved sulfur[(6)]. Gold solubility is higher with increasing temperature and sulfur concentrations. Extrapolation of these results indicate that gold loadings of 5 ppm can be achieved with a sulfur concentration in solution that is below the equivalent EPA sulfate aesthetic standard of 500 mg/L. Polysulfides ultimately break down into sulfate in relatively oxidizing groundwater conditions.

In another set of experiments some common ore types were "salted" with gold to test the stability of polysulfide in the presence of gangue minerals[(10)]. The ore samples were collected from the Round Mountain (oxide ore, Nevada), Bullfrog (carbonate hosted, Nevada), and Summitville mines (sulfide ore, Colorado). Because the samples were grab samples and may not be representative of the average ore owing to the "nugget effect", the samples were reacted in a gold pressure vessel to ensure that maximum solubilities could be determined. Rock samples were powdered in a ball mill to <325 mesh grain size in order to accelerate fluid/mineral reactions and to allow more rapid identification of the key processes affecting the integrity of the leach solutions.

The ore samples were reacted with bisulfide and polysulfide bearing solutions at 100-125°C and 100 bars pressures using the autoclave facilities at the University of Minnesota, Department of Geology. Reactants were loaded into a cell (70 ml total volume with a fluid to rock ratio of 3:1 to 10:1) composed of Au and Ti which is itself loaded into an autoclave. The entire autoclave is loaded into a furnace assembly. Fluid samples were periodically withdrawn from the cell so that changes in solution chemistry could be monitored. Fluids were also injected into the reaction cells midway during some of the experiments in order to replace solution removed by sampling and/or to facilitate a needed change in solution chemistry. Experiments involved the injection of relatively simple NaHS solutions(1000 to 1500 mg/l) and if needed a dilute (0.1 M) HCl solution which lowered the pH to the region of polysulfide stability. Solutions were monitored for a large suite of elements including major elements, sulfide sulfur, total sulfur, sulfate, pH (25°C) and dissolved metals (Au, Fe, Cu, Zn) in addition to many other elements.

The maximum and minimum measured gold concentrations during these experiments are tabulated in Table 1. All reported concentrations are economically viable by comparison with typical gold concentrations in standard heap and vat leaching systems. The Round Mountain and Bullfrog ore types required acid and bisulfide additions to achieve optimal gold concentration owing to sulfide oxidation by hematite and dissolution of carbonate. The Summitville samples had natural native sulfur which buffered the solution chemistry at optimal leaching conditions which are approximately neutral as shown in Figure 1 as compared to the alkaline conditions needed for other alternative lixiviants. The fact that this assemblage contained elemental sulfur suggested that to produce polysulfide solutions all that was necessary was to inject NaHS solution. Production of polysulfides by reaction with elemental sulfur would then occur naturally via a process such as:

$nS + HS^{-} = S_nS^{-2} + H^{+}$.

When NaHS solutions were reacted with this ore specimen, the gold concentrations to be quite high throughout the experiment: up to 18 ppm at 125°C and approximately 8 ppm later in the experiment when temperature was reduced to 100°C. Sulfur can also be readily introduced into an ore by precipitation from supersaturated solutions and will likely result in ISR operations involving polysulfide leaching. While too much sulfur can clog pore space the material can be redissolved by adjusting the injection solution as was the case for the Summitville experiment. Hence chemical buffering at optimal pH and Eh conditions (Figure 1) is achieved readily.

Chemical Stability

One drawback of polysulfides is that they are inherently stable and more effective at dissolving gold under elevated temperature conditions (≥75°C) than typical ambient temperatures[(3)(6)]. However, other lixiviants for precious metals also have stability problems. Polysulfides are potentially more stable than other lixiviants in situ because confining pressures and elevated temperatures can be maintained more readily. ISR usually involves saturated conditions which prevent gas exsolution and polysulfide decomposition if hydraulic pressure is high enough. The modest temperatures required to make polysulfides more effective can be attained cost effectively owing to the insulating properties of rock once heated.

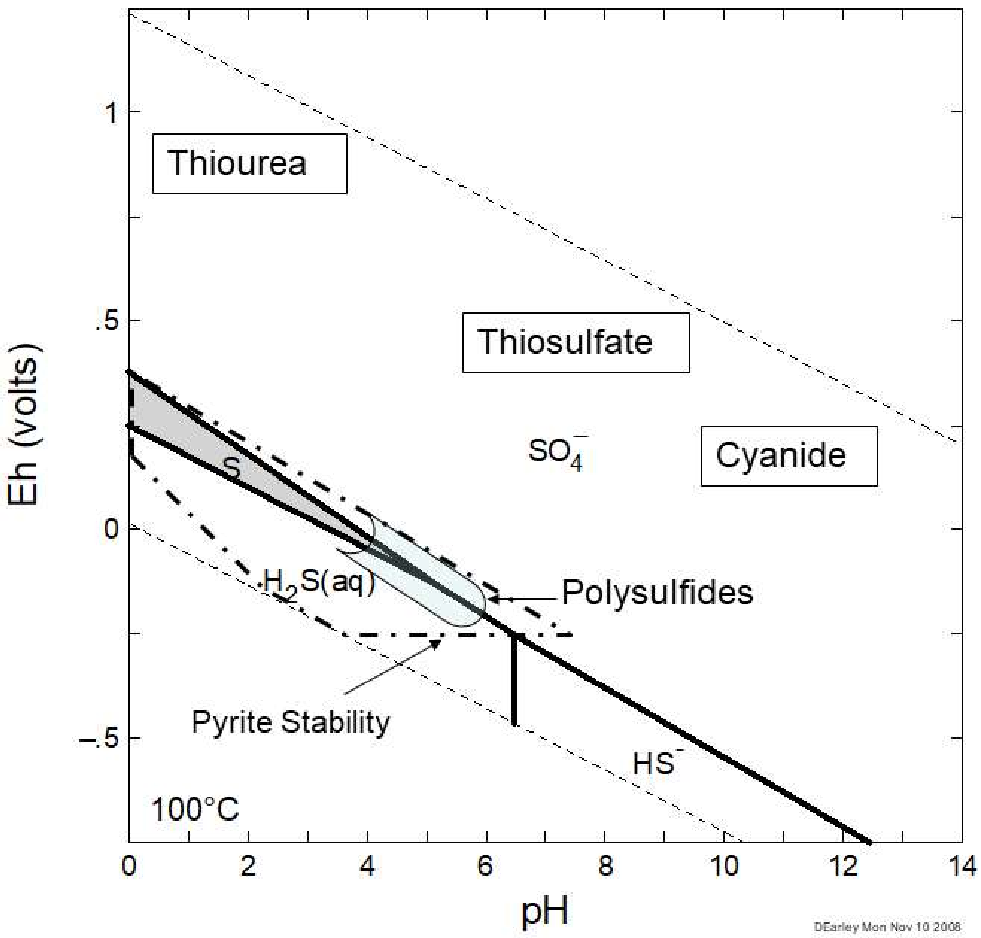

Figure 1: Eh pH Diagram for Sulphur and Polysulfide Aqueous Complexes

IN SITU RECOVERY

Wellfield and Underground Leaching

Traditional wellfield injection and recovery systems can apply to gold and other precious metals for specific disseminated ore deposit types such as placer and Carlin Type ores with sufficient permeability. However alternative gold leaching systems involving bonanza type veins could also be candidates for ISR. At the Ajax underground mine in Colorado, USA an ISR test was conducted with a chloride plus iodine solution injected into a gold-bearing vein(10) The solution was injected at the top of the vein and allowed to flow under gravity to drifts where they could be collected. Solution losses and metallurgical complications resulted in poor recovery and test termination. However, it may be possible to conduct a similar test with polysulfides a more favourable deposit and using better solution tracking and control technology. Certainly the potential for stope leaching in inactive or abandoned underground mines is promising.

So far there have been few studies of the hydraulic properties of gold ores for ISR. The results of porosity and permeability testing of representative samples from the Phoenix Mine in Colorado, USA are provided in Table 2. The hanging and footwall rocks show very low permeabilities that are for the most part lower than the detection limit of the method. However, the vein sample, which hosts most of the gold mineralization, shows the highest permeability which agrees with the observed friability of the vein material. This friability may be a result of fault motions along the plane of the vein(11). Conversely the low permeability of the vein walls ensures solution containment.

Table 1: Polysulfide Leach Test Results

Sample Source	Ore Type	Gold Concentration (mg/L)	
		Maximum	Minimum
Round Mountain Mine, Nevada USA	Oxide	16.8	0.22
Bullfrog Mine, Nevada USA	Carbonate	6.6	3.3
Summitville Mine, Colorado USA	Sulfide	17.9	8.4

Gold Recovery and Processing

Recovery of gold from high temperature solutions can be achieved by simple closed system boiling[5]. Familiar solvent extraction of gold from leach solutions is also possible[12]. Potentially solution grades may be diminished ("preg-robbed) from equilibrium values by co-precipitation of gold with metal sulfides if ISCR results in precipitation of contaminant metal sulfides.

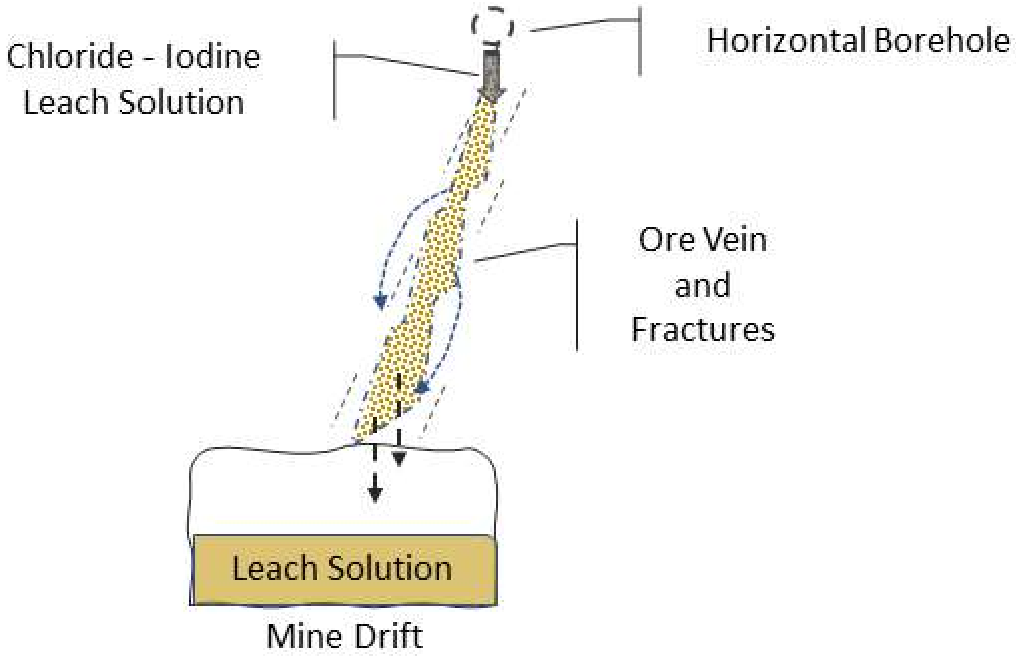

Figure 2: Ajax Mine, Colorado, USA, ISR Test Schematic[10]

Table 2: Hydraulic Properties of the Phoenix Mine Ore and Host Rock, Colorado USA

Sample	Porosity	Permeability	Lithology
	volume %	md	
PH5-1	6.16	2.95E-01	pyrite+quartz vein
PH7-3	6.15	nd	bostonite
PH7-2	7.74	nd	bostonite
PH8-1	8.43	nd	bostonite
PH4-1	6.74	nd	gneiss
PH2-1	3.57	nd	gneiss
PH4-3	7.40	4.86E-01	pegmatite
PH3-2	5.21	nd	pegmatite
md=millidarcy			
nd=not detected			

IN SITU REMEDIATION AND ECONOMICS

In the past few decades in situ remediation has been developed and used extensively for the treatment of organic and metal contaminants. Polysulfide is one of the chemical reagents used for in situ chemical reduction (ISCR) and is recommended by the US Environmental Protection Agency(8). Polysulfides can passivate chrome, mercury and many metals by ISCR and can even treat cyanide in wastewater(13). Moreover, injection of ISCR chemicals into a contaminated site is much easier to permit than injection into uncontaminated aquifer under Underground Injection Control and other regulations in the US. Given that there are tens of thousands of abandoned mines across the US alone many sites are likely to be amenable to ISR and ISCR under cleanup actions. These sites have been developed by mining which provides access and enhanced permeability for ISR. Given that these sites are already developed, characterized, and need restoration regardless of metal recovery potential the capital and regulatory risk of attempting ISR at these brownfield projects is considerably lower than for an undeveloped deposit. However, the risk of being involved in responsible party cost recoveries for cleanup may discourage mining companies and other interested parties from the project creating a “Catch 22”.

CONCLUSIONS

Several alternative lixiviant systems for precious metals have been developed and researched thoroughly, but none have contributed significantly to production or facilitated ISR. New mine project investment instruments and regulations lack the flexibility necessary to allow for innovative technology. Hence, the mining industry has not readily embraced alternative leaching technologies such as polysulfides and other alternatives to cyanide for conventional systems much less ISR. Even mature technologies such as thiosulfate and other alternative leaching systems that have been under development for several decades(3) have not yet been been used for ISR. However, the incentives for development of sustainable mining technologies has never been higher. An ISR project based on a leaching system such as polysulfides, which is thought to be a natural agent for mobilizing gold in nature(6), is more likely to gain social license to operate than systems that require artificial chemicals. Indeed, polysulfide solutions could conceivably be derived from mining wastes thereby incorporating the principal of recycling. Moreover, polysulfides can also be used to stabilize and treat mine wastes in situ while potentially recovering metals of value. Mine reclamation cost recovery and water protection could help ISR gain favor and allow ISR to expand to yet undeveloped deposits. However, continued research and development is needed to support trials of ISR for gold and other precious metals. It is not known yet if gold can be selectively mobilized and recovered during precipitation of contaminant metal sulfides. However, polysulfides are polymers of sulfur and are amenable to advanced formulations may prevent preg-robbing.

ACKNOWLEDGMENTS

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PHOENIX RISING: THE APPLICATION OF ISR FOR HIGH GRADE URANIUM MINING IN THE ATHABASCA BASIN

By

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ABSTRACT

Denison is pioneering the use of the In-Situ Recovery (ISR) mining method in the Athabasca Basin region of northern Saskatchewan (Canada), at the company's Phoenix Uranium Deposit located on the Wheeler River property. Given the unique geology and high grades of the Phoenix deposit (Reserves of 59.7 M lbs. U_3O_8 grading 19.1% U_3O_8), Denison is using a unique application of existing and proven technologies from both the mining and oil & gas industries to engineer field conditions for an innovative application of the ISR mining approach – pairing the world's most utilized and lowest cost method of uranium mining with one of the world's highest-grade undeveloped uranium deposits.

Proven freeze technology is planned to be used to surround the high-grade Phoenix deposit, within which an ISR wellfield of over 300 wells are planned to be installed. Permeability enhancement techniques from the pump and injection wells can be used to augment the natural hydrogeological flow paths facilitating a higher degree of contact of lixiviant with uranium ore. Injection pressure and pumping rates are the primary tools to be used to direct the lixiviant through the wellfield pattern, simulating, to some degree, the natural "sweep" of traditional ISR operations. Wells are expected to be outfitted for both pumping and injection, allowing reversal of flows to facilitate a higher recovery of the deposit.

The successful application of ISR in any geological environment largely hinges on three fundamental requirements: 1) permeability (of the deposit), 2) leachability (of the mineralization), and 3) containment (of the mining solution). Denison has systematically advanced several staged technical programs at Wheeler River, to reduce the project risk associated with these requirements.

In-ground permeability tests conducted via a series of commercial scale wells (CSWs) have evaluated the physical flows and connections through the groundwater systems within the orebody, demonstrating the positive application of ISR and the amenability of the Phoenix deposit. Subsequent hydrogeologic modelling incorporating the results of the in-ground permeability tests produced the "proof of concept" for the application of the ISR mining method at Phoenix, with respect to potential operational extraction and injection rates.

The high-grade nature of the Phoenix deposit at the Wheeler River Project is expected to produce a high-grade Uranium Bearing Solution (UBS) from the wellfield which facilitates the use of direct precipitation for on-surface processing. Specialized core leaching tests have been undertaken to simulate expected field conditions and the characteristics of recovered UBS. Test results to date have far exceeded the UBS grade estimated in Denison's Prefeasibility Study of 10 g elemental uranium per litre of UBS, and long-duration testing has demonstrated overall estimated recovery of uranium in excess of 97% and an average recovered solution uranium head grade of 18.3 grams per litre – demonstrating excellent recovery of uranium from intact high-grade core without the use of permeability enhancement.

In October 2021, Denison completed an ISR field test program which included an ion tracer test utilizing a five-spot pattern of CSWs. The program was successful in demonstrating production flowrates assumed in the Pre-Feasibility Study, confirming hydraulic control of injected solutions during the ion tracer test, establishing breakthrough times between injection and recover wells consistent with previous ‘Proof of Concept’ modelling, and also showcasing the ability to remediate the test pattern by completing a ‘clean up phase’ following the tracer test.

In September 2022, after several years of de-risking field investigations, Denison completed a Feasibility Field Test (“FFT”) which was designed to assess the effectiveness and efficiency of the leaching process in the ore zone. The first component of the test included the controlled injection of an acidic mining solution into the ore zone within a portion of the CSW test pattern installed in 2021 and the recovery of the solution back to the surface (‘Leaching Phase’). The FFT recovered approximately 14,400 lbs U_3O_8 over 10 days of active leaching following completion of initial acidification of the leaching area.

A Neutralization Phase, designed to reverse the residual effects of any remaining acidic solution from the Leaching Phase, was undertaken in October 2022. Overall, the results of the Neutralization Phase achieved the key pH restoration parameter outlined in the applicable regulatory approvals for the FFT, and verified the efficiency and effectiveness of the process for returning the leaching area to environmentally acceptable pH conditions.

Test and design work, to further evaluation and optimize the application of ISR at Phoenix are ongoing in support of a future Feasibility Study.

Keywords: in-situ recovery, core leach tests, permeability enhancement, Athabasca Basin, freeze technology, high-grade uranium

Outline

- **Company Background**
- **PFS summary**
  - **Selection of ISR Mining Method**
- **Deposit Setting**
- **4 Year De-risking Plan**
  - **2019 through 2022**
  - **Focus on Containment, Permeability and Leaching**
  - **Optimizations and Trade-Off Studies**
    - **Freeze Containment**
    - **UBS Head Grade**

Diversified Athabasca Basin asset base with superior development leverage

95%[(1)]
effective interest in
Flagship Wheeler River project

PFS stage development project[(2)]

Largest undeveloped uranium project in the infrastructure rich eastern Athabasca Basin

Feasibility Study in progress[(3)]

Draft Environmental Impact Statement ("EIS") submitted[(7)]

22.5%
interest in
Strategic McClean Lake Uranium Mill

Strategic regional asset

+11% of global uranium production

Excess licensed annual capacity

Licenced for expansion of tailings management facility ("TMF") [(4)]

67.41%
interest in
Emerging Waterbury Lake project

PEA stage development project[(5)]

Tthe Heldeth Túé ("THT") deposit (formerly J Zone) highlights potential for future development project pipeline

Participating interests in key development-stage assets operated by uranium "majors"
Includes 22.5% in McClean Lake (Orano), 25.17% in Midwest (Orano), and an effective 15% in Millennium (Cameco) through 50% ownership of JCU[(6)]

~300,000
hectares of exploration ground

PHOTO:

Aerial view of Denison's 22.5% owned McClean Lake mill facility

NOTES:

(1) Denison increased its effective interest in Wheeler River as part of the acquisition of 50% of JCU (Canada) Exploration Company, Limited. See Denison's news release dated August. 3, 2021.

(2) Refer to the Wheeler River Technical Report titled "Pre-feasibility Study Report for the Wheeler River Uranium Project, Saskatchewan, Canada" dated September 24, 2018.

(3) See news release dated September 22, 2021.

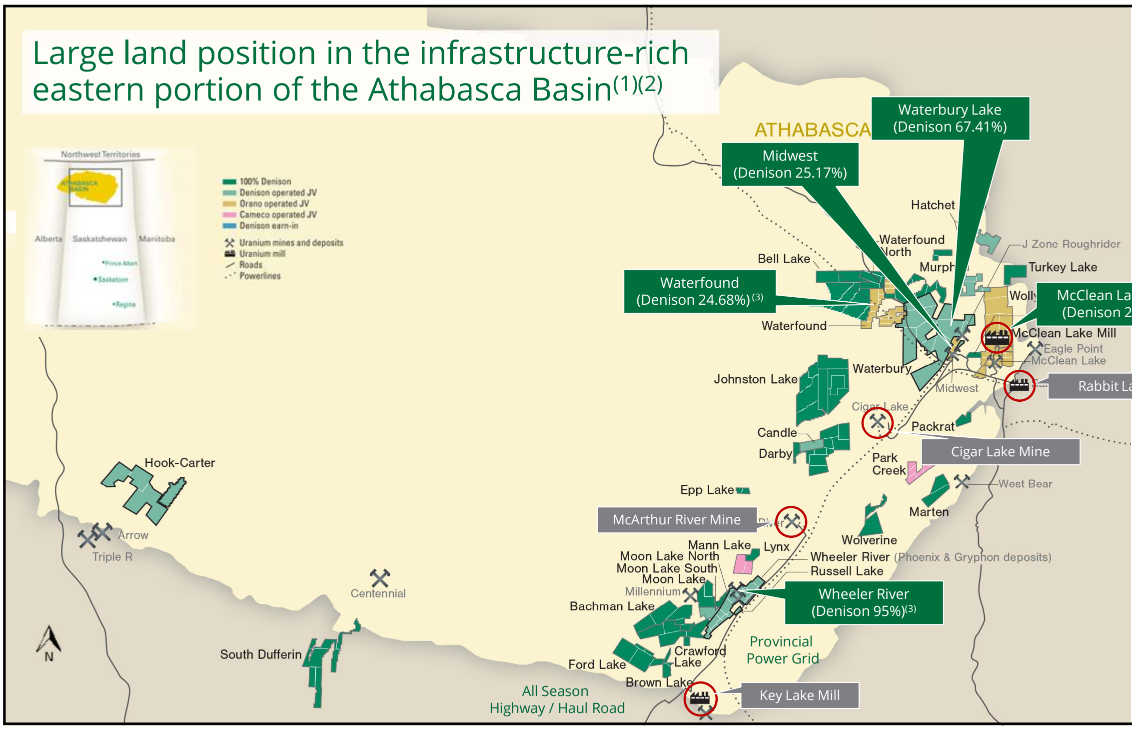
(4) See news release dated January 19, 2022.

(5) Refer to the Waterbury Lake Technical Report titled "Preliminary Economic Assessment for the Tthe Heldeth Túé (J Zone) Deposit, Waterbury Lake Property, Northern Saskatchewan, Canada" dated October 30, 2020.

(6) See news release dated August. 3, 2021.

(7) See news release dated October 26, 2022.

Large land position in the infrastructure-rich eastern portion of the Athabasca Basin[(1)(2)]



NOTES:

(1) Denison direct land position shown as of December 31, 2022.

(2) Excludes interests held only through 50% ownership of JCU – See Denison news release dated August 3, 2021.

(3) Reflects Denison's effective interest, including a portion attributable to Denison's 50% ownership in JCU (Canada) Exploration Company, Limited. See Denison's news release dated August. 3, 2021.

Wheeler River Project

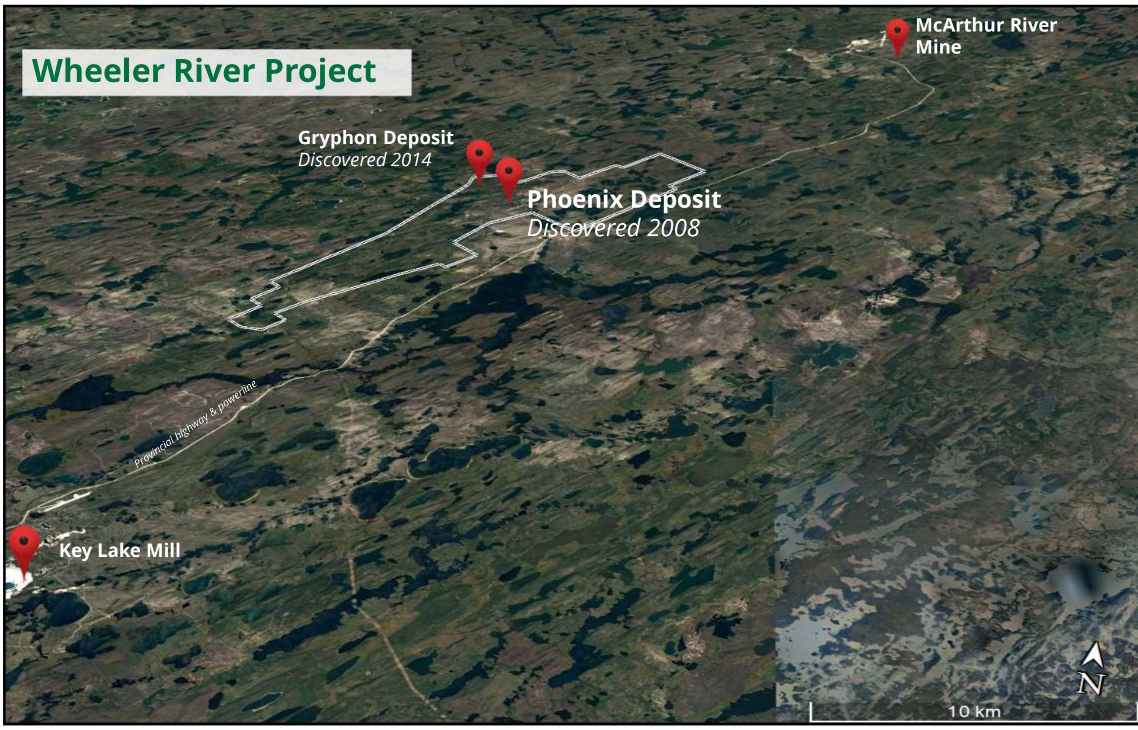
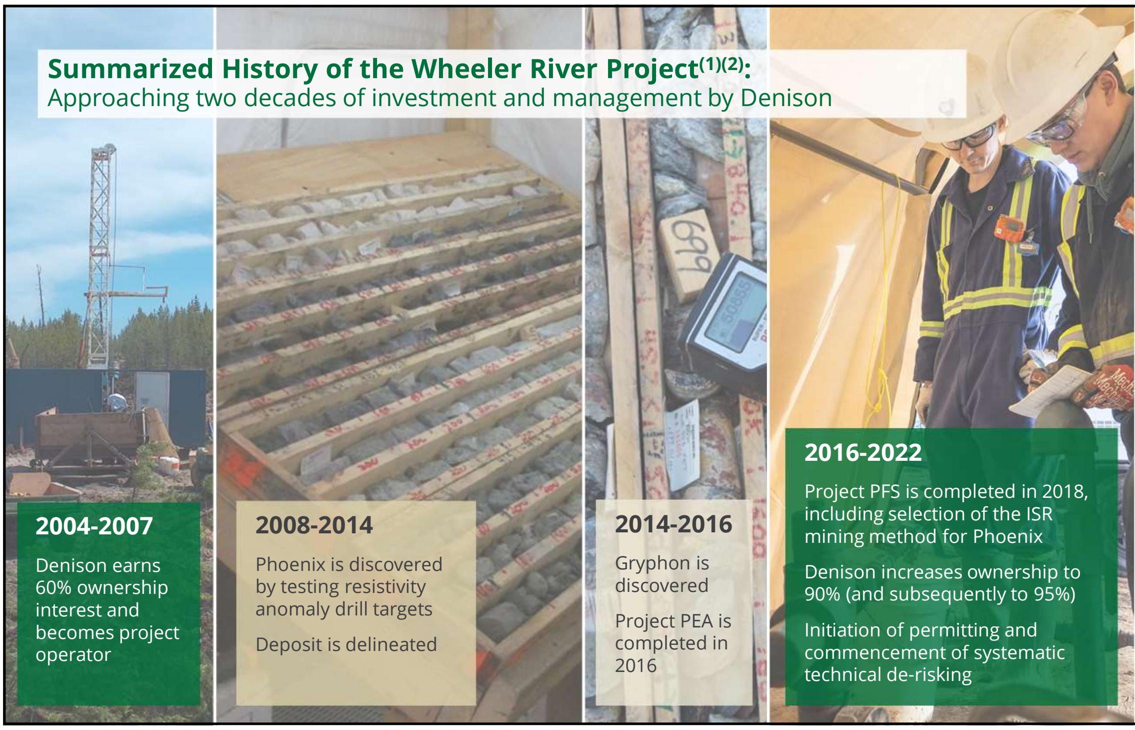


PHOTO:

Aerial view of Denison's 95.0 % owned Wheeler River Project. Highlighting the Phoenix and Gryphon deposits relative to existing infrastructure.

Summarized History of the Wheeler River Project[1][2]:
Approaching two decades of investment and management by Denison



2004-2007

Denison earns 60% ownership interest and becomes project operator

2008-2014

Phoenix is discovered by testing resistivity anomaly drill targets

Deposit is delineated

2014-2016

Gryphon is discovered

Project PEA is completed in 2016

2016-2022

Project PFS is completed in 2018, including selection of the ISR mining method for Phoenix

Denison increases ownership to 90% (and subsequently to 95%)

Initiation of permitting and commencement of systematic technical de-risking

PHOTOS (Left to Right):

Drill rig carrying out exploration at the Wheeler River site in the mid 2000s; Core logging from discovery of Phoenix; Drill core and handheld scintillometer from discovery of Gryphon; monitoring of commercial scale ISR test wells at Phoenix in 2021.

NOTES:

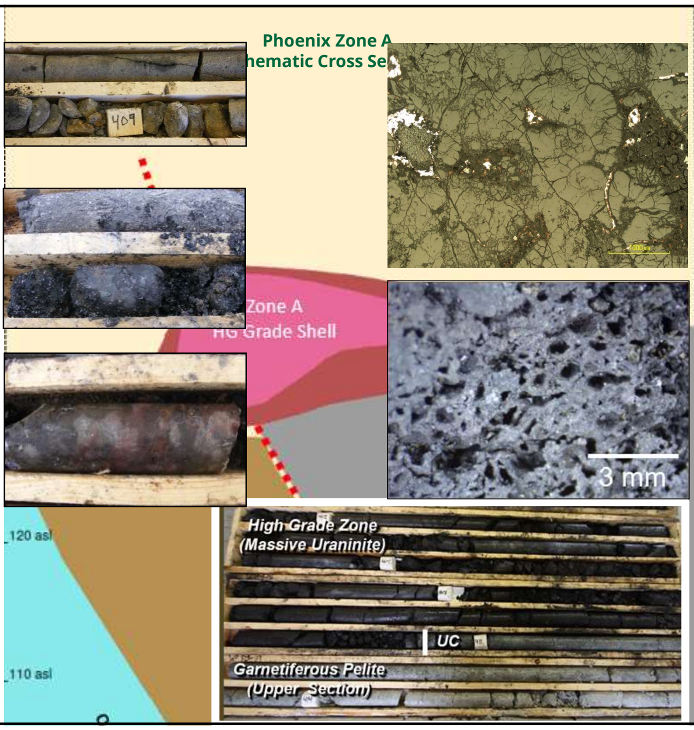
(1) See Denison's current Annual Information Form for additional details regarding the history of the Wheeler River project.

(2) The source for uranium price data included on this slide is UxC LLC.

Phoenix Geology:
Unique uranium deposit with exceptionally high grades

- **Highlights[1]:**
- Mineralization is situated at or immediately above the unconformity("UC")
- Two distinct zones – Phoenix A + B
- Approximately 400m below surface
- World's highest-grade undeveloped uranium deposit
- **70.2 million pounds U_3O_8 @ 19.14% U_3O_8** Indicated mineral resources (166,400 tonnes)[2]
  - Zone A High-Grade Core contains an estimated **59.9 M lbs U_3O_8 @ 43.2% U_3O_8** (62,900 tonnes)
  - Cut-off grade of 0.8% U_3O_8
  - 1.1M lbs U_3O_8 in Inferred mineral resources (8,600 tonnes @ 5.8% U_3O_8)[3]

✓ **Geological setting expected to be amenable to ISR mining, with ~90% of the mineral resource (contained metal) hosted in sandstone**



NOTES:

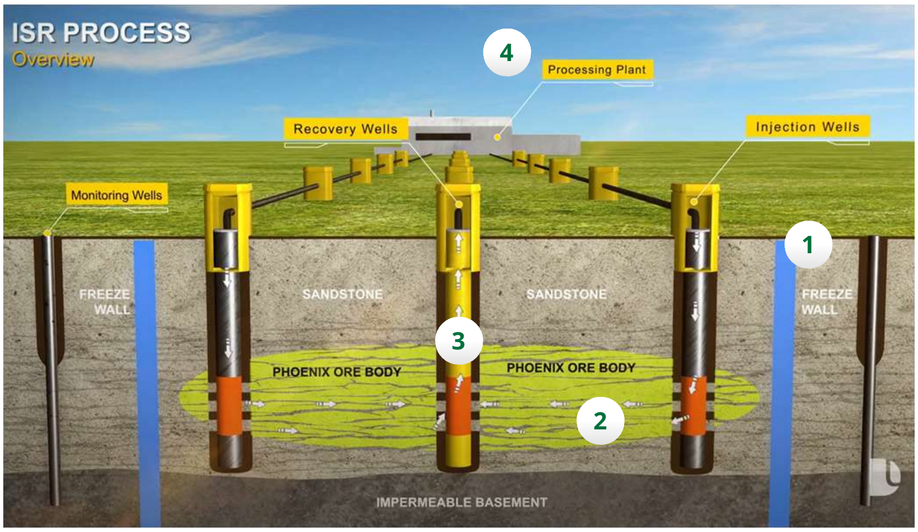
(1) Refer to the Wheeler River Technical Report titled "Pre-feasibility Study Report for the Wheeler River Uranium Project, Saskatchewan, Canada" dated September 24, 2018;

(2) Indicated resources are inclusive of Reserves

(3) The PFS does not include any economic analysis based on estimated Inferred resources.

Phoenix ISR De-Risking:

First principles of successful ISR mining in the Athabasca Basin

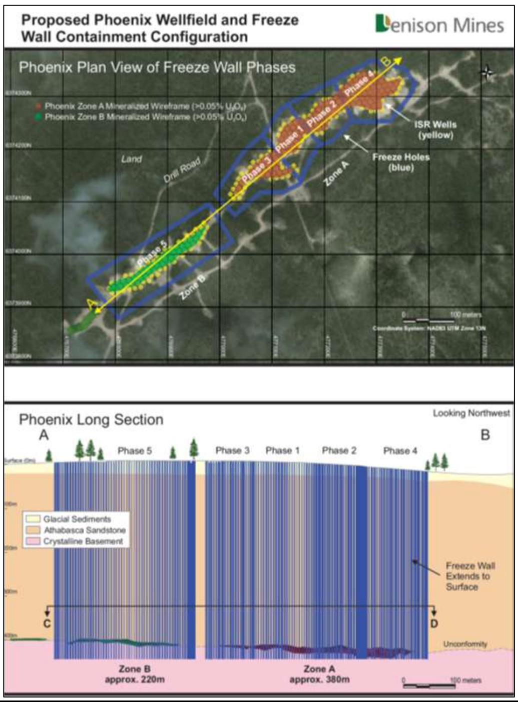


1. **Containment:** ability to contain the mining solution injected into the formation
2. **Permeability:** ability to establish hydraulic connections between injection and recovery wells to move the mining solution throughout the deposit
3. **Leachability:** ability to complete leaching of the uranium mineralization while it is in the ground (in-situ);
4. **Processing:** ability to recover a suitable finished product from the uranium bearing solution recovered from the wellfield.

Phoenix De-Risking:

Conventional freeze wall design adopted for Phoenix ISR to replace novel freeze cap / dome design

- **Post-PFS trade-off study supports decision to adopt freeze wall design to provide hydrogeologic containment(1)**
  - Parallel vertical cased holes drilled from surface and anchored into impermeable basement rock surrounding the Phoenix deposit
  - Circulation of low-temperature brine solution through cased pipes will freeze groundwater in sandstone surrounding the deposit
  - 10-metre-thick freeze wall, together with basement rocks will encompass Phoenix vertically from surface to basement rock underlying the deposit
  - ✓ **Eliminates common environmental concerns with ISR mining and facilitates controlled reclamation**

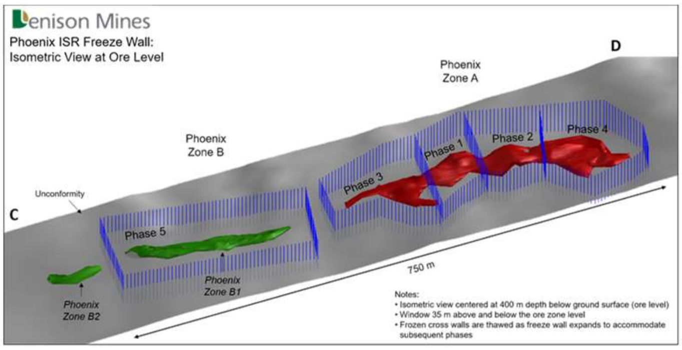


NOTES:

(1)) See Denison's news release dated December 1, 2020 for additional information on the freeze wall design for Phoenix.

Phoenix De-Risking:
Freeze wall design shows potential for significant advantages[1][2]

- ✓ **Enhanced environmental design**
  - Full hydraulic containment of ISR well field to surface
  - Defined area for reclamation
- ✓ **Lower technical complexity and operational risk**
  - Existing diamond drilling methods
  - Reduction of intersection of freeze holes and ISR wells[1]
- ✓ **Expected reduction in initial capital**
  - Lower cost drilling
  - Phased mining approach
- ✓ **Strengthened project sustainability**
  - Diamond drilling widely employed in northern Sask.
  - Ability to leverage existing skilled workforce
  - Drilling over life of mine



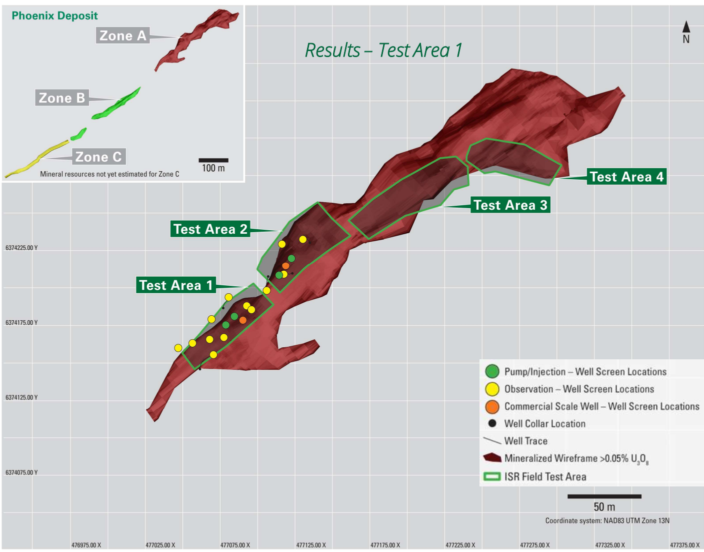
NOTES:

(1) For additional information on horizontal freeze cap design included in PFS, refer to the Wheeler River Technical Report titled "Pre-feasibility Study Report for the Wheeler River Uranium Project, Saskatchewan, Canada" dated September 24, 2018

(2) See Denison's news release dated December 1, 2020 for additional information on the freeze wall design for Phoenix.

Phoenix ISR Field Test Program
Preliminary Test Work

Phoenix Zone A Plan View – ISR Field Test Areas



- ✓ **Initial ISR Field Test work (2019-2020)**
- ✓ De-risking **permeability**
- ✓ Installation of several **small diameter wells** ("SMWs") utilizing existing exploration boreholes
- ✓ Athabasca Basin's first large-diameter **Commercial Scale Wells** ("CSWs") designed for commercial ISR production
- ✓ Long-duration **hydrogeological tests** allowed for the characterization of fluid flow under conditions similar to an envisioned commercial production environment

NOTES:

(1)) See Denison's news release dated August 27 2019, September 19 2019 and October 31, 2019 for additional information on the ISR field test work.

Phoenix ISR Field Test Program:
Installation of Small Diameter Wells[1]

PHOTO:

ISR field testing at Wheeler River Phoenix Deposit, Summer 2019

NOTES:

(1)) See Denison's news release dated August 27 2019, September 19 2019 and October 31, 2019 for additional information on the ISR field test work.

Phoenix ISR Field Test Program:
Advancement to installation of Commercial Scale Wells[1]

PHOTO:

CSW being installed at Wheeler River Phoenix Deposit, Summer 2901

NOTES:
(1)) See Denison's news release dated August 27 2019, September 19 2019 and October 31, 2019 for additional information on the ISR field test work.

Phoenix ISR De-Risking:
2019 and 2020 ISR field test programs[1][3]

~35
small-diameter wells

installed into and around the Phoenix deposit

All holes generally equipped with a down-hole pressure transducer or vibrating wire piezometer ('VWP') to measures hydraulic pressure during test work

Two
large-diameter commercial-scale wells

First installed in the history of the Athabasca Basin

~40
Pump and injection tests

completed to collect extensive data for development of hydrogeologic model

Containment:

Tests show minimal vertical travel of injected fluids

Support decision to adopt "Freeze Wall" design[4]

Permeability:

Hydrogeologic model build and calibrated by third-party

Achieved ISR **"Proof of Concept"[2]**

PHOTOS:

ISR field testing at Wheeler River Phoenix Deposit, Summer 2019.

Inset photo shows close up view of downhole pressure transducer.

NOTES:

(1) See Denison's news release dated Dec.18, 2019.

(2) See Denison's news release dated June 4, 2020.

(3) See Denison's news release dated Oct. 28, 2020.

(4) See Denison's news release dated Dec. 1, 2020.

"Proof of Concept" Achieved for Application of ISR Mining Method at Phoenix[1]

- **Comprehensive hydrogeologic model:** Developed, using 2019 ISR Field Test data
- **Calibrated:** models compared to actual 2019 Field Test data, such that the "head" changes resulting from simulations in the models were similar to observed changes in the actual field tests
- **Parameters:** 18 extraction / recovery wells and 33 injection wells modelled across Test Area 1 and Test Area 2, nearly balanced operational flow; 180-day simulation was completed with approximately 80% of the injected fluids estimated to be captured during the simulation period
- **Report Conclusions:** modelling provided **"Proof of Concept"** for application of ISR to Phoenix with respect to potential extraction and injection rates
- **2020 ISR Field Test Program:** Developed to further validate the model completed by Petrotek, and to prepare for field tests in future years, using existing test wells in Test Area 1 and Test Area 2

NOTES:

(1) See Denison's news release from June 4, 2020 for details

PHOTO:

ISR field testing at Wheeler River Phoenix Deposit, Summer 2019

Phoenix ISR De-Risking:
Commercial-scale test pattern and tracer test[1]

5-spot
large-diameter commercial scale test pattern

installed in expected Phoenix mining Phase 1

Tracer Test
First known completed ion tracer test for ISR mining in the history of the Athabasca Basin

Permeability Enhancement Tools Tested
On a larger-scale than previous tests, verifying increased hydraulic connection where needed

Highlights of highly successful tracer test:

- ✓ Achieved commercial-scale production flow rates
- ✓ Demonstrated hydraulic control of injected solution
- ✓ Established breakthrough times consistent with hydrogeological modelling
- ✓ Completed 'clean-up' phase consistent with hydrogeological modelling

PHOTOS:

ISR test pattern and commercial scale well-head (inset) at Phoenix during field tests / tracer test completed in 2021.

LINKS:

2021 ISR Field Test Video

NOTES:

(1) See Denison's news release dated Oct. 28, 2021

Phoenix ISR De-Risking:
Validating in-situ leachability through specialized metallurgical testing

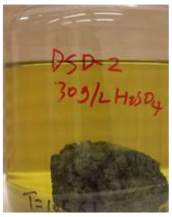
Core Leach Testing
Saskatchewan Research Council ('SRC') uses a specialized 'core leach' machine to simulate in-situ leach conditions by forcing the leach solution through the natural permeability of multiple representative in-tact core samples

50%
increase in ISR mining head grade[1]

Core leach test results support decision in 2021 to increase the mining head grade assumed in the 2018 PFS

Plant design advancing
Metallurgical testing using roughly 1000L of uranium bearing solution to support bench-scale evaluations for plant design is well advanced

Hydro-metallurgical test work
Progressing to support water effluent quality for ongoing environmental assessment.



PHOTOS:

Specialized 'Core Leach" apparatus at the SRC labs in Saskatoon.

Inset photo shows 9" sample of in-tact high-grade drill core from Phoenix prior to insertion into the testing apparatus.

Bottom right, shows static leaching of uranium from undisturbed core sample.

NOTES:

(1) See Denison's news release dated August, 4, 2021.

Fully Permitted In-Situ Recovery Feasibility Field Test (FFT):
Multiple catalysts from first-of-its-kind test in the Athabasca Basin[1, 2]

The Phoenix FFT was designed to validate and inform various feasibility study elements for use of **In-Situ Recovery (ISR)** mining, including production and remediation profiles, and is planned to occur in three phases. The first phase commenced in **H2'2022**:

Leaching
Completed ✓
successful injection of acidic solution and recovery of uranium bearing solution using a portion of the test pattern installed at Phoenix in 2021[3].

Neutralization
Completed ✓
successful injection of mild alkaline solution to reverse the leaching process and return test area to protective conditions[4].

Recovered Solution Management
Separation of recovered solution into mineralized precipitates (temporarily stored in tanks on surface) and neutralized treated solution (re-injected into sub-surface).

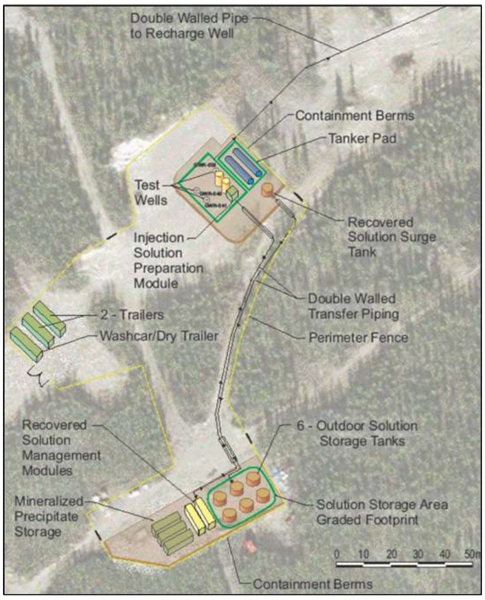


PHOTO:

Inside FFT coverall structure during commissioning – including view of commercial scale test wells, monitoring wells, and injection solution preparation module (left) and plan map of Phoenix FFT site (right).

NOTES:

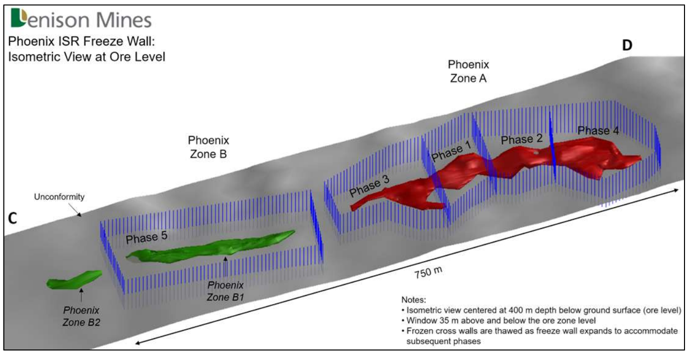
(1) See Denison's news release dated July 12, 2022.

(2) See Denison's news release dated August 8, 2022.

(3) See Denison's news release dated October 17, 2022.

(4) See Denison's news release dated December 12, 2022.

Phoenix ISR Feasibility Study:
Wood PLC selected to lead + author independent Feasibility Study in accordance with NI 43-101[1]



50% increase
to ISR mining uranium head-grade in PFS[3]

Updated
Estimate of Mineral Resources
including results from GWR-045[4] and GWR-049[5]

Process
Plant Optimization
Including increase in ISR mining head-grade

Mine
Design Optimization
Including results from multiple field tests

Freeze wall design shows potential for significant advantages[2]

Conventional freeze "wall" design selected to replace novel freeze dome / cap design in 2018 PFS

- Enhanced environmental design – full containment of ISR wellfield to surface
- Lower technical complexity and operational risk – using existing diamond drilling methods
- Expected reduction in initial capital costs with introduction of phased mining approach
- Strengthened project sustainability

Superior
Standard of Environmental Stewardship
Incorporating technical work and feedback from ongoing EA

Class 3
Capital Cost Estimate
AACE international standard with an accuracy of -15%/+25%

PHOTO:

Isometric view of planned ISR Freeze Wall for Phoenix, including illustration of phased mining approach

NOTES:

(1) See Denison's news release dated September 22, 2021.

(2) See Denison's news release dated December 1, 2020.

(3) See Denison's news release dated August 4, 2021.

(4) See Denison's news release dated July 29, 2021.

(5) See Denison's news release dated Feb. 16, 2022.

Cautionary Statements & References

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Qualified Persons
The disclosure of a scientific or technical nature within this presentation, including the disclosure of mineral resources, mineral reserves, as well as the results of the Wheeler PFS and Waterbury PEA, was reviewed and approved by Chad Sorba, P.Geo, Denison's Director Technical Services, and Andy Yackulic, P.Geo, Denison's Director Exploration, each of whom is a Qualified Person in accordance with the requirements of NI 43-101.

Technical Reports

- For further details regarding the **Wheeler River project**, please refer to the Company's press release dated September 24, 2018 and the technical report titled "*Prefeasibility Study for the Wheeler River Uranium Project, Saskatchewan, Canada*" with an effective date of September 24, 2018 ("Wheeler PFS").
- For further details regarding the **Waterbury Lake project**, please refer to the Company's press release dated November 17, 2020 and the technical report *titled "Preliminary Economic Assessment for the Tthe Heldeth Túé (J Zone) Deposit, Waterbury Lake Property, Northern Saskatchewan, Canada"* with an effective date of October 30, 2020 ("Waterbury PEA"). **The PEA is a preliminary analysis of the potential viability of the Project's mineral resources, and should not be considered the same as a Pre-Feasibility or Feasibility Study, as various factors are preliminary in nature.** The PEA includes inferred mineral resources that are considered too speculative geologically to have the economic considerations applied to them that would enable them to be categorized as mineral reserves, and there is no certainty that the preliminary economic assessment will be realized**. Mineral resources are not mineral reserves and do not have demonstrated economic viability. Scheduled tonnes and grade do not represent an estimate of mineral reserves.**

For a description of the data verification, assay procedures and the quality assurance program and quality control measures applied by Denison, please see Denison's Annual Information Form dated March 27, 2023. A copy of the foregoing is available on Denison's website and under its profile on SEDAR at www.sedar.com and on EDGAR at www.sec.gov/edgar.shtml.

ACCURATE PRODUCTION PREDICTION GUIDING BUSINESS DECISIONS

By

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ABSTRACT

Heathgate has been mining uranium for the last 23 years using the unique and low impact in-situ recovery (ISR) method. The company has produced millions of pounds in the past and is looking to produce millions more in the next 10 years. To continue business growth the company applies latest methods and technology to generate accurate insight towards future planning. In the next 2 years the company is undergoing it’s biggest expansion, which has all been planned out by Heathgate’s internal expertise.

To generate accurate insights into the future, there needs to be a reasonable amount of confidence, competency and accuracy in the modelling processes. There are some fundamental parts to predicting ISR production, one is the design of the production curve, the other the software to predict the operation.

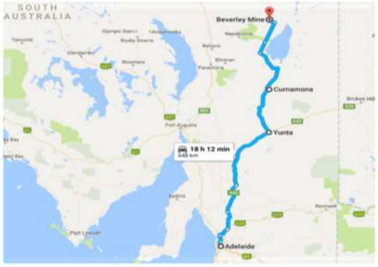
There are many inputs that contribute to the makeup of the production curve design, some have more influence than others, but in the end, all are important for that accurate design/estimation. This presentation will highlight some of those key inputs and how they influence the production curve design, all of which are used to test the economics of future production before being used for Life of Mine (LOM) planning.

Production forecasting using the decline curves is done with an in house custom ISR software PathCAD. PathCAD has been designed to cover all aspects of the ISR operation, including: planning, analysis and forecasting. Heathgate has been using PathCAD for last 12 years, during which the program has provided accurate short- and long-term production estimates for planning and insight into business decisions. PathCAD’s reliability comes from the well calibrated constraints within the program that provide a true simulation compared with reality.

Keywords: In-Situ Recovery, Uranium, Production Prediction, PathCAD

Introduction
Heathgate Overview

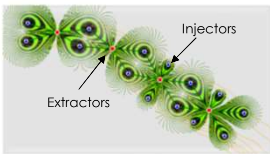
- Heathgate is a privately owned company
- Producing uranium for 23 years using *In Situ* Recovery (ISR)
- Beverley Mine is roughly 650km North of Adelaide, 1 hour flight
- Main office in Adelaide CBD
- Fly from Adelaide airport to private airstrip at mine
- Has 300 employees
- Plant 1km away from camp



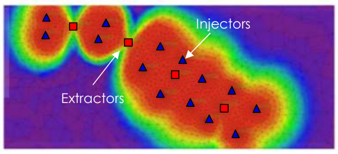
Production Estimation
Software (PathCAD™)

- To accurately plan future production in ISR, you need specific software to consider all aspects of mining
- For Uranium ISR mining, the software should be dynamic in all applications, as ISR mining is very much a dynamic environment
- Heathgate is turning on new wellfields every 2 months, this requires rapid analysis and planning
- Heathgate has trialled and uses many software's, but PathCAD is still the primary software for all production modelling
- PathCAD™
  - Founder Craig Bartels, 50 years experience in ISR
  - Originally designed to optimise wellfield patterns
  - Program continually upgraded since 1980
  - **User friendly, quick processing, accurate estimates**
  - Functions cover all aspects of an ISR project development
    - ❖ resource estimation, wellfield design, decline curve design, production assessment, production forecasting and plant optimisation.
  - No other software at the time; still unique for Sandstone Uranium ISR
- Key functions in PathCAD used for accurate production prediction are:
  - Modelling of the Decline Curve (Production Curve)
  - Production Forecast

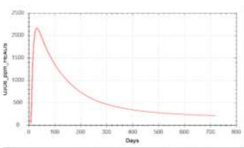
PathCAD™ Icon



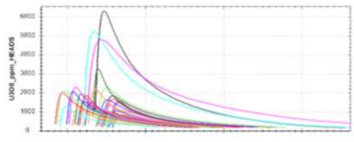
PathCAD Model Of 4 Patterns



FEFLOW Model Of Patterns



PathCAD Decline Curve

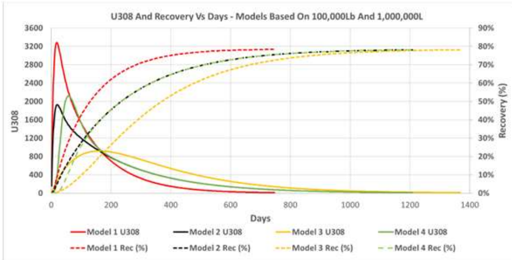


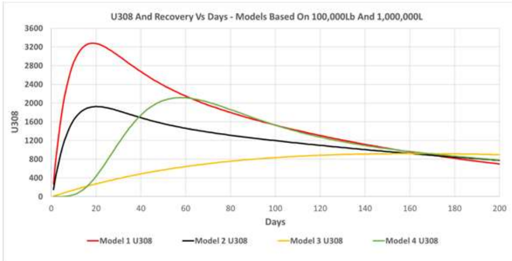
PathCAD Forecast

Production Estimation

What is a "Decline Curve"

- Decline curve is a production curve, comes from the Petroleum Industry
- PathCAD decline curve is an **Exponential Decline Equation**, which uses first order rate kinetics or first principles
- Decline curve design is based on the **relationship** between the inputs
  - Resource, Pore Volume (PV), Kinetics (Reductants, DEF, Reagents, etc), Permeability, Porosity, Zoning, etc.
- Pore Volume (PV) is a standard PathCAD variable, which defines the size of the leaching volume
- All inputs condition the model in the design of decline curve
- Incorrect inputs can generate variety of results
  - Example on right showing 4 models based on same Resource and PV (Liters) but varying conditions
- All inputs have an influence on the design of the curve, some more than others: Data, Mining Zones, Resource Estimation And Kinetics





Production Estimation

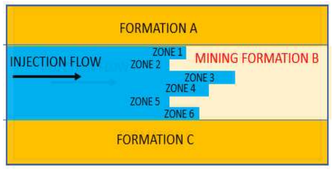
Data -Advanced Prompt Fission Neutron (APFN⁺) tool

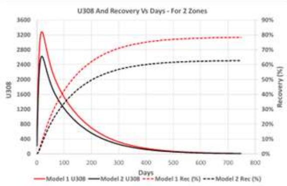
- Accurate production prediction starts with accurate data
- APFN tools have been used for the last 10 years
- Developed by UIT in Dresden, Germany
- This tool is used to estimate the following:
  - U grade
  - Disequilibrium
- Tool is regularly calibrated on-site using calibration pits and test holes
- Reliable quantitative estimates
- Provides confidence in resource estimates

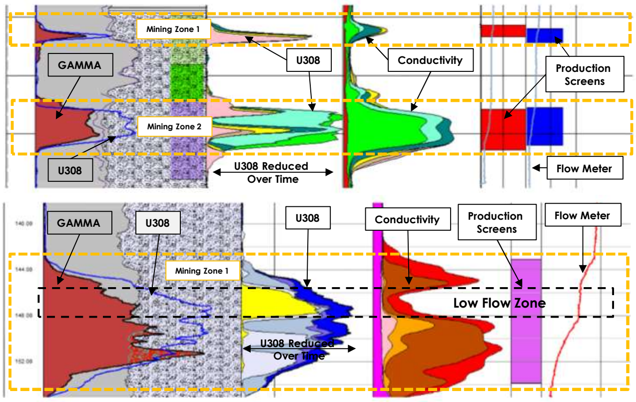
Production Estimation

Mining Zones

- Zoning is the most fundamental step when designing a model for estimation of a decline curve
- The number of mining zones should reflect the different characteristics or variability in the formation
- Mining Zones are determined by correlating the geology and mineralisation
  - normally identified by uranium roll-fronts (APFN or GAMMA), geophysics and lithology
  - Resistivity is used to estimate permeability using Petrophysics, good insight towards vertical and horizontal variability
- Selected zones are pump tested for permeability
  - Permeability is later used to estimate flow rate
  - Flow meters are used to define flow across production screens







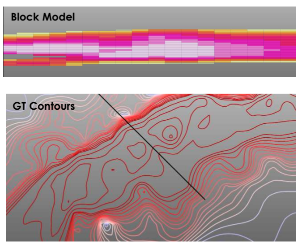
Geophysical Logs In WellCAD

Production Estimation

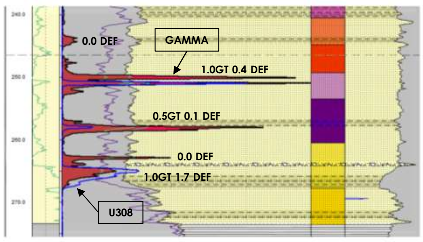
Resource Estimation

Disequilibrium Factor
DEF = U308/GAMMA
Negative <1.0 DEF

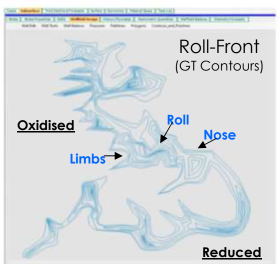
- Resource estimation is done for each zone
- Only minable or leachable resource are used in estimates
- Negative DEF is not used as part of the resource estimation
- PathCADs decline curve estimation is done with input of GT contours (Grade x Thickness)
- GT Contours are generated from block models or drawn by hand
  - Conventional method of roll-front resource estimation
  - Provides a good understanding of the grade or roll-front distribution, especially when the roll-fronts are:
    - very complex in shape
    - Stacked roll-fronts
- This method has worked well at Heathgate in the past years:
  - to justify any of the new projects to be undertaken
  - to design very efficient wellfields for ISR mining
- GT contouring method has been reliable at all levels of estimation (inferred, indicated and measured)



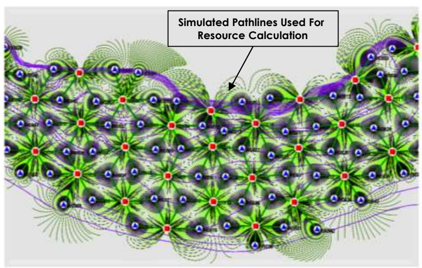
Block Model GT Contours



Log In WellCAD showing GAMMA, U308 And DEF



GT Contours In PathCAD



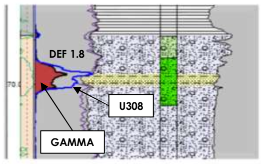
PathCAD Resource Calculation Using Pathline Simulation

Production Estimation

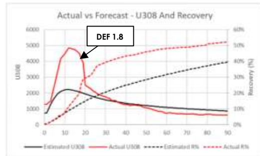
Kinetics

- To predict recovery, you need to understand recovery rate or kinetics
- Column Leach Test or Beaker Test provide insight to kinetics
  - Tests should be done on all identified mining zones
  - Upscaling of CRT data is complex
- DEF is an excellent guide in kinetic change
- Core drilling is performed in all new deposits
- Typically 1 core hole is drilled per wellfield in a representative location, but in more complex areas (variable permeability, etc.) may require additional holes
- Core drilling is challenging due to the unconsolidated nature of the sediments
- The core is logged and sent away for external analysis
  1. Geochem
  2. Permeability and Porosity
  3. Bulk density
  4. Mineralogy

Column Leach Test



Log Showing GAMMA And U308



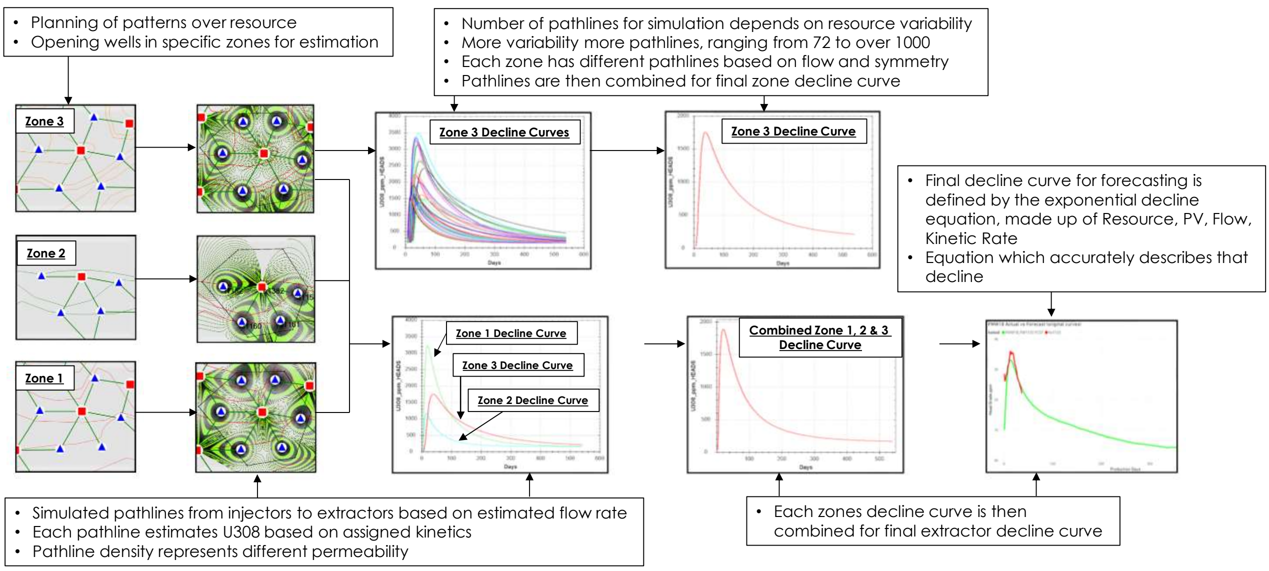
Actual vs Estimated

Beaker Test

Four Mile West Core

Production Estimation

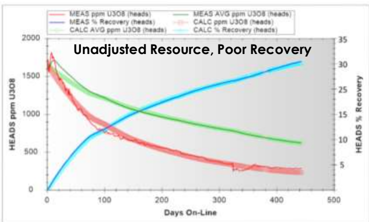
Decline Curve Estimation - "Composite CRT Kinetics" function



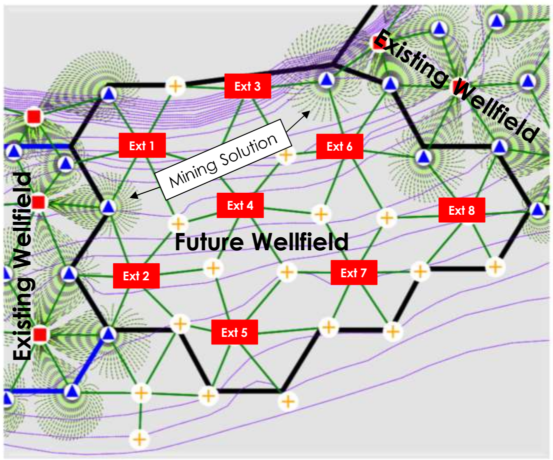
Production Estimation

Decline Curve Resource Adjustment

- Future wellfields or patterns are likely to be next to active patterns
- Existing wellfields which have produced for a while have no doubt robbed adjacent resources
  - High permeability equals large flaring, equals lots of robbing
- Future decline curves if contacted require resource adjustment
  - Review of Mining solution spread over future patterns, chems, geophysics and induction
  - Statistical analysis is used to adjust the resource for the decline curve equation



PathCAD Extractor Modelling

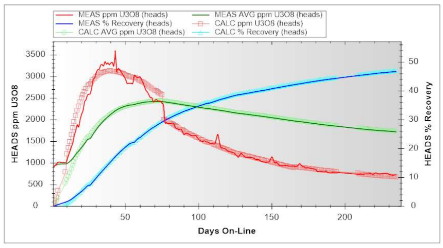


PathCAD model showing flare of mining solution

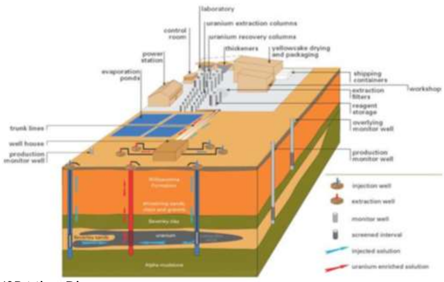
Production Estimation

PathCAD™ – Production Forecast

- Forecast generated monthly or when required
- Generates short term and long term production estimates
- Forecasts are based on all exiting and future decline curve
- Provides information of when new projects/wellfields are starting
- Is calibrated to real time operational events
- Is constrained to actual individual satellite plant and processing plant capacities/capabilities
  - Number of IX Vessels, Number of Elution Trains, Elution Cycle, Resin Loading, IX Tail Re-circulation, etc.
- Estimates production for Years, Months and Days for:
  - ❖ Existing and future wellfields or wells
  - ❖ Number of wells, wellfield costs, Start and Finish date, % Recovery
  - ❖ Max U ppm, Ave U ppm, End U ppm, Months on line
  - ❖ Reagents use (Volume), Cost of reagents per pound
  - ❖ Operational expenditures



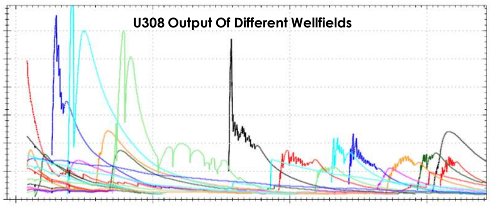
PathCAD U308 Decline Modelling



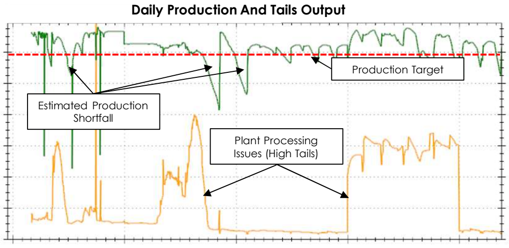
ISR Mine Diagram

Production Estimation
Forecast Outputs

- The production forecast generates a variety of outputs for review
- Production prediction is reviewed in detail to understand if company is on track to meet production targets
- When predicted shortfalls are identified, new project options are prioritized to get production back on track
- The long-term production forecasting is targeting different deposits with different flow rates, grades and kinetics to make expected production targets
- Plant processing is reviewed to understand efficiency
- Many iteration of scenarios are modelled to best understand future business needs



Forecast Output U308



Forecast Output Daily Production And Tails

Conclusion

- To make any future business decisions, you need to have accurate predictions
- Heathgate has been lucky to have PathCAD as it has guided the business to many key decisions
- PathCAD or any other software to be accurate in predictions require a lot calibration
- Calibration starts with quality in the data and setting up of models
    - Zoning, Resource Estimation and Kinetics
- No quality, no accuracy

NEW PREDICTIVE MODELLING APPROACH TO URANIUM IN SITU RECOVERY

By

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ABSTRACT

Boss Energy are entering into an exciting new phase of development, with the Enhanced Feasibility Study completed in 2021, and the project on track for production of 2.45Mlb of U_3O_8. Boss Energy's Honeymoon project is supported by highly skilled hydrogeologists, geologists, and management with proven operational experience. To further enhance their position, Boss Energy, in collaboration with WGA, have identified an innovative approach to determine recovery of In-situ (Leach) Recovery (ISR) deposits from data available during exploration. Boss Energy and WGA were granted an Accelerated Discovery Initiative (ADI) grant by the South Australian Government to deliver this tool, which has the potential to be rolled out to other operations.

The tool takes information available at the exploration stage of the project to predict ISR decline curve and uranium extraction. The tool has the potential to assist operations in wellfield planning, and be integrated with process plant models for economic optimisation of uranium production. WGA have employed a machine learning approach' tool, based on review of literature, Honeymoon operational datasets, and current modelling methodology. Our key findings are:

- Application of our machine learning approach to predicting decline curve is novel. Although machine learning is used in adjacent applications, such as prediction of mineralisation, iron deposits, stratigraphy, and lithology within the vicinity of the uranium body, it has not been used to predict decline curves in uranium ISR.
- Our approach leverages faster and more simple algorithms than current modelling techniques to predict uranium recovery. Current practices in the industry require a detailed profile of the deposit and require significant computing power: Most of the models use Reactive Transport Modelling (RTM), which couples numerical models of the metallurgical and hydrodynamic processes occurring underground. These sophisticated models can produce and track production curves to a high level of integrity. The disadvantage is that these models use a high level of computing power to produce results, and since they require a detailed understanding of the spatial distribution of both physical and chemical properties within the deposit they can be very sensitive to this data.

We assessed and ranked the suitability of several machine learning models, and progressed a hybrid metallurgical, hydrodynamic and machine learning model, to leverage both known relationships, and the potential increase in accuracy provided by machine learning algorithms. We also identified a second approach that can be leveraged during operations to further boost the model. Systems, also known as compartment, model, which is a mathematical approach to describing material transmission across a system.The systems modelling approach may be used for near real time operational modelling, where the deployed model can learn from and react to the wellfield and plant data as it is collected

We have also identified the following opportunities which have the potential to improve production planning and well field development tooling:

- In this phase of works, the potential for this model to be used in wellfield planning was demonstrated by overlaying several decline curves. This could be further progressed to enhance productivity of the wellfield planning team, enabling them to focus on their core business through integration with a plant production model and operating costs, to create optimised wellfield planning, and operational setpoints, to maximise production and revenue.
- Given that the response of a heap leach extraction process is similar to an ISR profile, the modelling approaches proposed in this study could be used to more simply predict heap leach performance.
- The dataset generated by Boss Infill drilling during feasibility evaluation of the deposit contains extensive information (Borehole magnetic resonance tool, and density and neutron logs). This data will be very useful at later stages of the development to link to future production data.

This presentation will summarise the final project reporting and interactive model test interface, aligned with our commitment to the knowledge share requirements of our ADI grant.

Keywords: Uranium, ISR, Machine Learning, South Australia,

INTRODUCTION

Project Appreciation

Sedimentary uranium deposit evaluation for ISR is challenging due to the difficulty in determining reasonable prospects for eventual economic recovery input to reporting exploration results under the JORC Code 2012, and more so, difficulty in determining the proportion (if any) of the mineralisation that can be recovered by ISR methods and reported as a reserve. Boss Energy (Boss), in collaboration with WGA, have identified that there may be opportunities to improve the evaluation process by using novel methods such as machine learning (ML) in conjunction with other innovative tools in exploration. WGA and Boss have been granted an Accelerated Discovery Initiative (ADI) grant by the South Australian Government, to further develop this concept. If successful, this tool has the potential to be rolled out to other operations.
Boss own the Honeymoon site, which was previously owned by Uranium One and operated from 2012 to 2013. Boss has completed an Enhanced Feasibility Study (EFS) after an extensive test work program, on the restart of the Honeymoon In-situ Recovery (ISR) Project in the Curnamona district of South Australia. The existing Honeymoon processing facility will be re-developed and expanded, with fast-tracked production within 12 months and a target production of 2.45 Mlb/annum U3O8 by the second year of the expansion.

Project Objectives

The objective of this project is to deliver a ‘proof of concept’ geophysical data processing tool for sedimentary uranium deposit evaluation for recovery by In-situ Recovery (ISR) during Greenfields exploration.
The proposed geophysical data processing tool was initially projected to a machine learning model that uses the data from downhole geophysics logs, specifically new and innovative tools such as the borehole magnetic resonance tool in conjunction with density and neutron logs and onsite XRF data to derive the amenability for leaching of a deposit. The implementation of the tool has the potential to improve the exploration efficiency; reduce cost; and resources needed for exploration, hence reducing the overall exploration footprint. This ‘proof of concept’ study aimed to prove that advanced data analysis techniques can predict uranium recovery based on field data produced in a drilling program. This technology is enabled by the development of machine learning models to predict leach recovery, and ultimately, predict surface plant production from exploration drill hole geophysical and geochemical data. Rapid scenario generation using the developed technology will drive focus for further exploration programs.

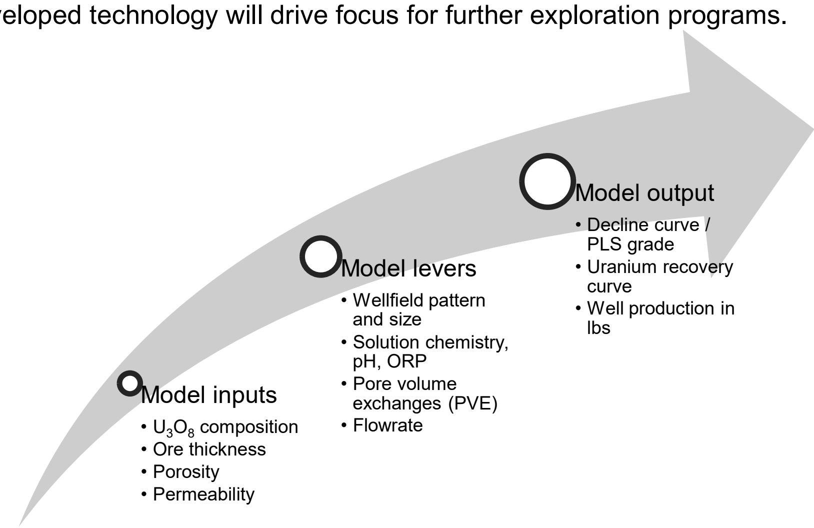


Figure 1: Proposed Geophysical Data Processing Tool Inputs, Levers, and Outputs

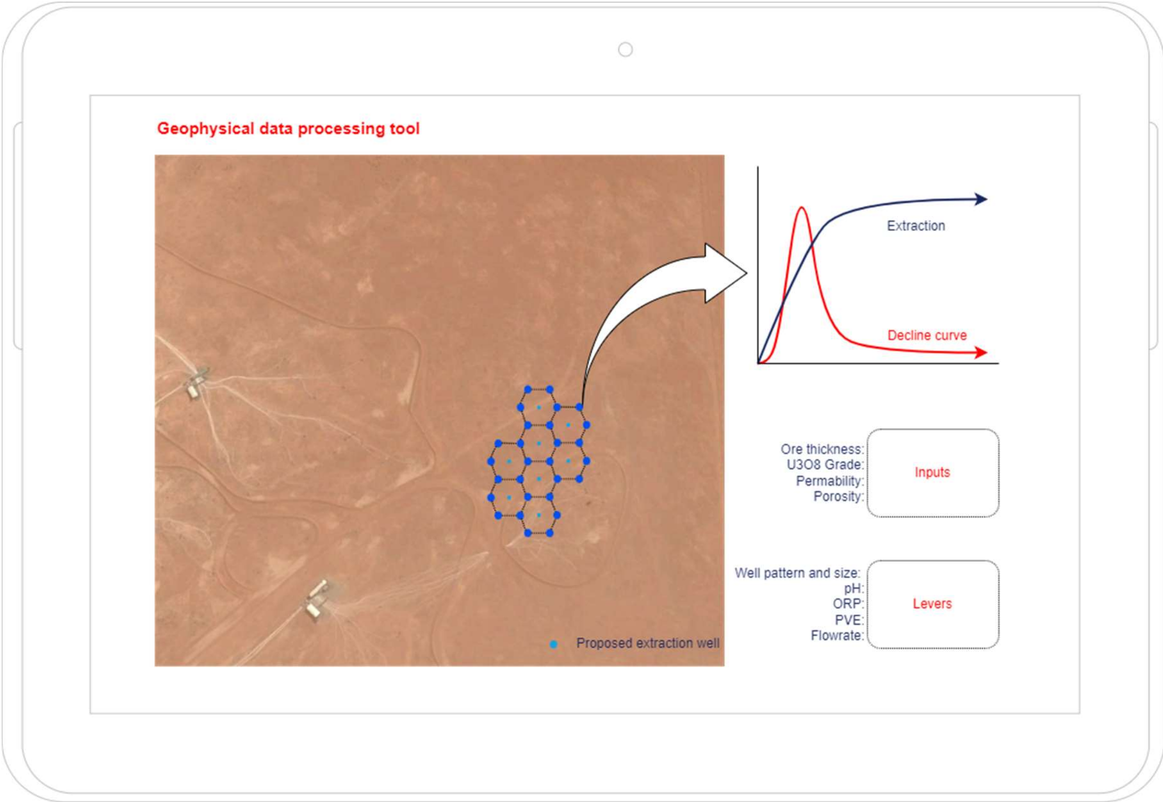
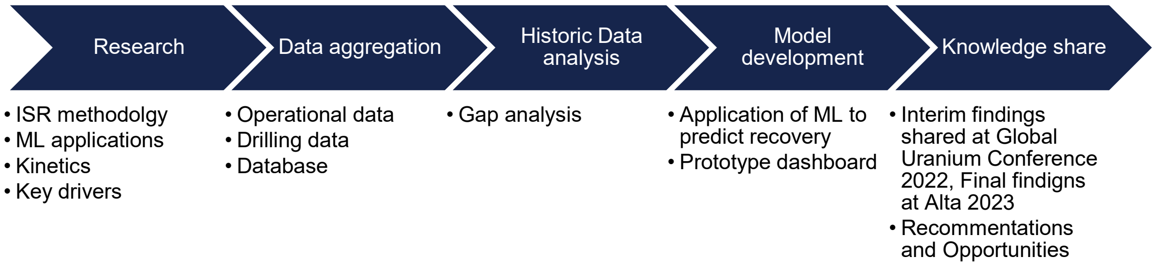


Figure 2: Idealised Version of The Tool Interface for A Single Well

The proposed tool will predict wellfield performance from exploration data for the Boss resource, and the methodology for tool development could be deployed on other operational sites. That is, although the tuned model parameters may be specific to the Boss Honeymoon mineralisation, the model development algorithm may be able to be rapidly deployed and tuned at other sites

METHODOLOGY



Research

Information gathering and literature review, including data, publications, operational information were collected, consolidated, and reviewed, including:

- Literature review on ISR modelling, including available data on other operational sites
- Review on Honeymoon operations historic datasets and modelling
- Machine learning applications to ISR and similar applications

As model development progresses the key model inputs and outputs will be further defined, and Honeymoon operations data collection gap analysis will be delivered, to inform recommendations for data collection for future operations.

Data Aggregation

The data framework has been developed as a basis for predictive modelling. Boss have historical and recent data, including drillhole collars, downhole geophysics, PFN data, water bores and screen depths, lithology, analytical results and well construction data which currently exists in a SQL server database. Available data has been transferred, using scripts where possible to increase efficiency, into a standardised format and loaded in a secure AWS database. The data that is not included in the current SQL database, including data still in excel sheets, may also be included in the database. The key features of the data aggregation include:

- The database schema has been developed that will enable use in future operations
- An aggregated dataset for modelling has been produced. As modelling is developed, additional iterations of data cleaning, and interpolation may be required
- Statistical analysis of data to better understand data and inform data cleansing requirements
- Development of a data framework and database for machine learning

LITERATURE REVIEW

Overview of ISR Mining

In Situ Recovery (ISR) mining methods are applicable to scenarios where the orebody is straddled between two impermeable layers, allowing for either acidic or alkaline leaching solution to be injected and recovered from the orebody. In uranium ISR, the acidic or alkaline solution is injected in the orebody via injection wells where the solution contacts and dissolves the uranium ore. The Pregnant Leach Solution (PLS) is recovered using pumps in extraction wells and sent to a processing plant for further extraction and purification of the uranium, as shown in Figure 3 below. To ensure the leaching fluid is contained within the mining zone, water quality in monitoring wells is analysed and mediating actions to taken if required.

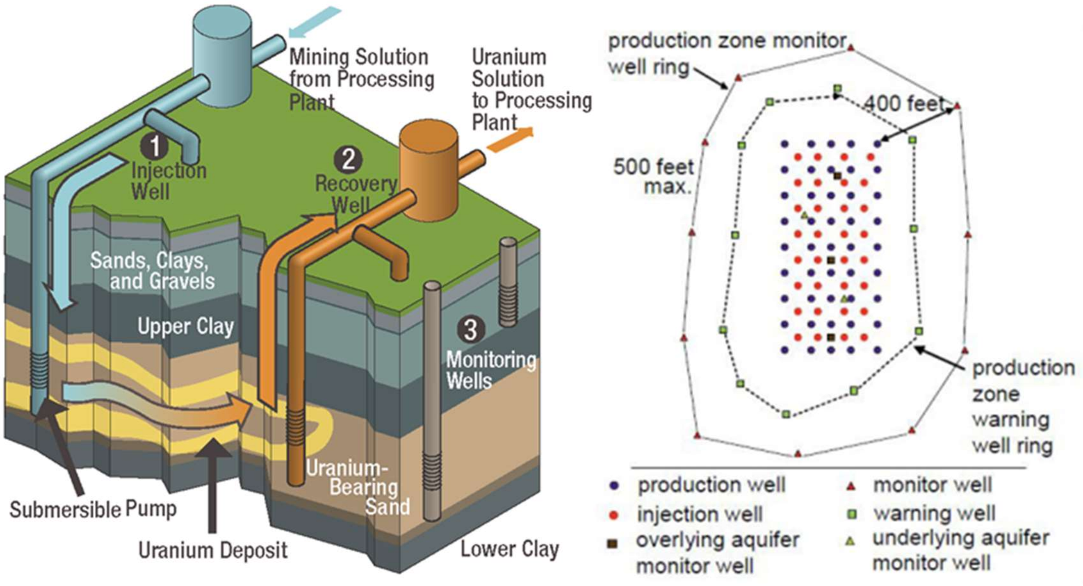


Figure 3: Uranium ISL Mining Method and Wellfield Layout [1] [2]

Unlike conventional open cut mining, the uranium is extracted entirely in-situ. This approach to mining is cost-effective and low impact to the surrounding environment [3] [4]. The leaching process occurs underground, and the extent and process chemistry are only measurable at the extraction wells. The PLS chemistry is used by operators to control and optimise production [5]. The layout of injection and extraction wells is typically aligned with one of the 'spot' patterns shown in Figure 4. After a period of operation, the wells may be switched from injection to extraction to establish new path lines and boost recovery from the pattern.

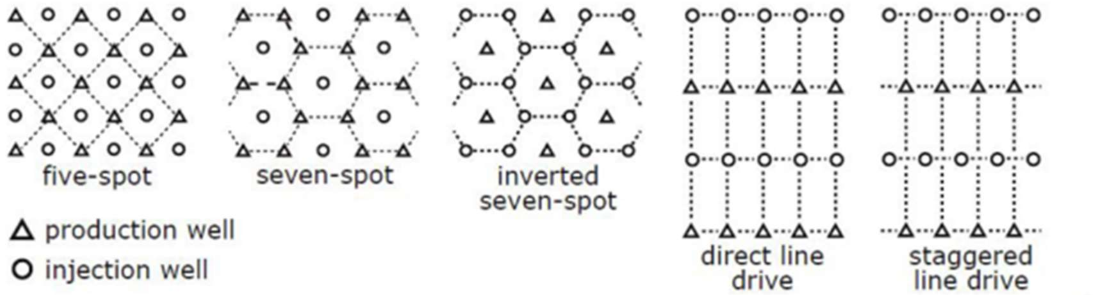


Figure 4: Well Field Pattern Layout Nomenclature [2]

Modelling ISR Production

Uranium PLS grade curves, know often in industry as Decline Curves (as the uranium grade typically declines over time), are typically obtained from a kinetic model of the ISR process. The key operational output metrics are permeability, leachability, and the predicted uranium production curve. This information enables the operators to plan and optimise the overall production process. In the case of greenfield exploration, an accurate prediction of production can be used to gauge the the initial economic and commercial value of the project. Predictive models capture the following characteristics and dynamics of the system:

- Geochemical reactions
- Kinetics of primary and secondary reactions associated with the injected chemicals
- Hydrodynamic transportation properties

These variables are coupled together, and the governing system of equations is solved to generate a Decline Curve. This modelling approach is described as reactive transport modelling [6] which has been applied to systems with geochemical and aquifer properties, and reviewed by various authors [7] [8] [9]. This model has been used to predict the PLS curve [6] using operational parameters associated with leaching reaction kinetics, aquifer properties and wellfield configurations [10].

Reactive transport modelling of ISR [6] is based on rigorous numerical models of all physical processes, from the fluid flow dynamics through to the geological properties of uranium bearing sand and the chemical processes occurring at the fluid-solid interface. Previous work has shown that the production curve can be predicted to a high level of fidelity but at the cost of increasing the complexity of the overall model [11] [12]. Disadvantages of this kind of modelling include both the computational power required to perform it, and the detailed inputs required including a complete three-dimensional model of the orebody. In general, the uncertainty in the ISR extraction extent is mainly attributed to uncertainty in the 3D geological model, and when used as a key input to 3D reactive transport ISR modelling, can result in execution of computationally expensive statistical methods [13] [14].

Fundamental to the modelling ISR process and the overall objective of generating a useful PLS curve require the understanding of the underlining metallurgical processing occurring during the in-situ leaching, reviewed in the following sections.

Metallurgical Processes

The rate and extent of uranium extraction from the host ore body by the applied solution is influenced by several mineralogy and metallurgical factors:

- Uranium mineralogy, oxidation state and ore composition
- Solution composition and impurity precipitation
- Acid concentration measured as pH
- Oxidation Reduction Potential (ORP)
- Temperature
- Pressure
- Solution residence time

The impact on the leaching kinetics of uranium concentration in the ore, acid concentration, ORP, temperature and leach duration are described in the following generic kinetic equations. The effects of these variables are interdependent and should be considered collectively. The rate coefficients ko, and exponents to pH and ORP, can be derived from literature or empirically from test data.

Table 1: Kinetic Equations Describing Uranium and Gangue Dissolution

General Leaching Rate Law	$\frac{dX}{dt} = k(T)f(C)w(1-X)$	**Equation 1**
Arrhenius Equation	$k(T) = k_0 \exp\left(\frac{-Ea}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right)$	**Equation 2**
Concentration function for uranium mineral dissolution	$f(C) = [H^+]^a[ORP]^b$	**Equation 3**
Concentration function for gangue dissolution	$f(C) = [H^+]$	**Equation 4**
Topology function	$w(1-X) = (1-X)^{\phi}$	**Equation 5**

Table 2: Combined Kinetic Equation for Uranium Dissolution

General Leaching Rate Law	$\frac{dX}{dt} = k_0 \exp\left(\frac{-Ea}{R}\left(\frac{1}{T} - \frac{1}{T_o}\right)\right)[H^+]^a[ORP]^b(1-X)^{\phi}$	**Equation 6**

Table 3: Descriptions of Kinetic Parameters

SYMBOL	DESCRIPTION	UNITS
a	pH coefficient	**-**
b	ORP coefficient	**-**
$-Ea$	Activation energy	**kJ/mol**
$[H^+]$	Hydrogen ion concentration	**M**
k_0	Reaction rate constant, or Rate coefficient	**Order dependent**
ORP	Oxidation Reduction Potential (ORP)	**mV**
ϕ	Phi – reaction order, or topology factor	**-**
R	Universal gas constant	**J/K.mol**
T	Temperature	**K**
T_o	Temperature at standard conditions	**K**
X	Conversion extent, or Extraction	**%**

The topology function in the general leach equation is typically used for heap leach kinetic evaluation and accounts for the changing surface area over time, with a parameter phi ϕ that varies to account for the complexity of leaching from the heap leach material which is not spherical or uniform size. The value of phi is between 0.5 and 2 for a heap leach kinetic function [15].

Uranium extraction is a diffusion process, and therefore the overall rate is proportional to the rate of diffusion through the solution layer adjacent to the solid surface [16]. The kinetic model can be combined with physical factors that impact leaching, such as particle size, and permeability, which may have equivalent proxies for ISR compared to the traditional slurry leach modelling kinetics. A key challenge with modelling the kinetics of ISR extraction is that while the injection and production solution chemistry is monitored, the profile of the solution chemistry within the ore body cannot be monitored in real time.

Uranium Mineralogy and Oxidation State

The mineralogy and oxidation state of uranium influence the kinetics and leachability of the deposit. Mineralogy by QEMSCAM on samples submitted to ANSTO as part of the Honeymoon Field Leach Trial (FLT) study identified that most of the uranium present in the orebody is a uranium phosphate mineral in

tetravalent form U(IV) [17]. The key uranium mineral was tristramite. $(Ca,U,Fe)(PO_4,SO_4).2H_2O$, with other uranium minerals not able to be identified due to small grain size and phase intergrowth. Tristramite is known to occur in association with sulphides, which presents as pyrite in the Honeymoon ore.
Tetravalent uranium must be oxidised to hexavalent uranium for dissolution to occur. An oxidant, hydrogen peroxide, is added to the solution prior to wellfield injection to indirectly oxidise the uranium by first oxidising ferrous to ferric, as described in the reactions below. The magnitude of the ratio of ferrous to ferric is measured using an ORP probe, and for typical conditions the logarithmic relationship can be described by the Nernst equation. ANSTO test work has shown that maintaining the ORP around 450mV, in conjunction with low pH, is effective at uranium dissolution for the Honeymoon ore [17], and typically satisfactory for most ores [18].
The concentration of iron in the solution is maintained by a combination of iron dissolution from the ore and iron sulphate injection into the solution. The total iron concentration and the ferric/ferrous ratio are both important to extraction. Higher iron content will mean higher oxidant addition required to maintain a target ORP. High ORP, more than 475mV, was shown to cause high oxidant consumption in the Honeymoon ore, likely due to pyrite oxidation since oxidant consumption increased with increasing feed sulphide content.

Table 4: Uranium Dissolution Chemical Reactions

Ferric oxidation	$2 Fe^{2+} + H_2O_2 + 2H^+$	"	$2Fe^{3+} + 2H_2O$	**Equation 7**
Tetravalent uranium oxidation to hexavalent uranium	$UO_2 + 2Fe^{3+}$	"	$UO_2^{2+} + 2Fe^{2+}$	**Equation 8**
Uranyl sulphate formation	$UO_2^{2+} + 3SO_2^{2-}$	"	$[UO_2(SO_4)_3]^{4+}$	**Equation 9**
Pyrite dissolution	$FeS_2 + 8H_2O + 14Fe^{3+}$	"	$15Fe^{2+} + 2SO4^{2-} + 16H^+$	**Equation 10**

Acid Concentration, Solution Composition and Gypsum
Acid added to the solution is consumed in the dissolution of the ore, and consumption is largely driven by gangue concentration since these are typically at much higher concentrations than the uranium minerals. Acid consumption is a key economic driver in the ISR uranium production process, and addition rates are optimised based on evaluation of uranium extraction, acid costs and gangue dissolution, which can impact operability from precipitated impurities, risk product quality and increase oxidant consumption. Mineralogy by ANSTO showed that varying amounts of clay phases such as kaolinite were present, while the main silicate gangue material was quartz [17]. Complex aluminosilicates, if dissolved, may precipitate as a gel [16], causing plugging, reduced permeability and reduced access to ore and uranium extraction.
A pH of 1.5 was recommended by ANSTO for the Honeymoon ore [17], with higher pH having a negative impact on dissolution, and increasing the risk of ferric precipitation [18]. Gypsum precipitation was found to be minimised by maintaining low pH, ORP>490mV, and Cl >8.5g/L.
Sulphuric acid is added to the solution prior to injection, and the pH of the injection and production streams are typically monitored.

Solution Residence Time, Temperature and Pressure
The rate of diffusion is inversely proportional to the square root of the rate of motion of the phases relative to each other [16]. In ISR, the ore is stationary, and the fluid moves past the ore, at a rate determined by the pumping rate, and influenced by the permeability of the ore body. The solution residence time is often normalized to a ‘Pore Volume (PV)’, which is simply the time taken to circulate a volume of solution that is equal to the volume of formation within the leaching pattern multiplied by the effective porosity. Uranium recovery of a pattern is typically tracked in ISR against the number of ‘Pore Volume Exchanges (PVE)’ as opposed to time. Diffusion is negatively impacted by formation of slimes and gypsum.
Temperature increases the rate of dissolution of uranium and gangue minerals according to the Arrhenius equation. In ISR, the temperature in not typically controlled. Target ORP, pH, and residence time must be evaluated in conjunction with operational temperature to optimise the process.

Hydrodynamic Processes
Fluid flow dynamics, or hydrodynamics, must be incorporated into ISR process models since the dynamics of the leaching solution from the injection channel to the path taken to reach the extraction channel influence access to ore and overall recovery [19] [20]. The cross section of flow paths from the two injection wells to the extraction well is shown in Figure 5. With the inclusion of hydrodynamics in 1D, 2D or 3D, the resulting model can predict performance at multiple injection points with different flow rates and inhomogeneous material properties associated with geology of the mine site, including porosity and permeability. The inclusion of fluid dynamics increases in the complexity of model, and computing power required to solve the model.

Hydrodynamics are governed by the following dynamic equations [21]:

- Mass conversation law
- Diffusion equation
- The constitutive relationship
- Darcy law

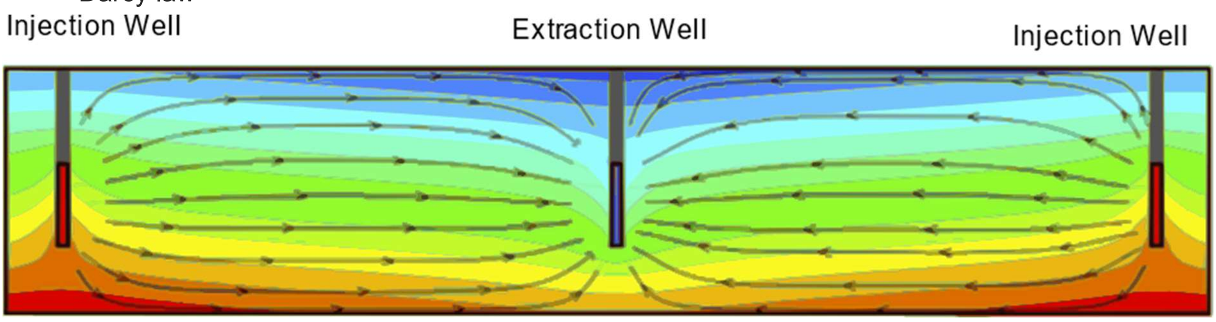


Figure 5: 2D Cross Section View of Flow Path Lines [11]

Ideally, the flow through the orebody would resemble a plug flow reactor (PFR), which would produce the highest grade PLS in the lowest volume of extraction fluid. The PLS grade curves generated by operations resemble residence time distribution (RTD) of tanks in series, which describes a cascade of n tanks in series and accounts for effects such as dead zones, non-ideal back mixing, and/or bypassing effects [22]. The term tau used in the equations below to determine the distribution, is equivalent to the total pore volumes passed. The gamma function can be applied to the RTD function to permit an analytical solution, as shown in Equation 12. The conversion and PLS grade can be defined from the segregated model that combines the kinetic and RTD equations in Equation 13.

Table 5: Residence Time Distribution (RTD) Modelling

Tanks in series, where n is an integer [22]	$RTD(t)$	=	$\frac{t^{n-1}}{(n-1)!}\left(\frac{n}{\tau}\right).e^{\left\{-\frac{t\,n}{\tau}\right\}}$	**Equation 11**
Tanks in series, where n is any decimal number [22]	$RTD(t)$	=	$\frac{t^{n-1}}{\Gamma(n)}\left(\frac{n}{\tau}\right).e^{\left\{-\frac{t\,n}{\tau}\right\}}$	**Equation 12**
Mean conversion X for mixed kinetic X(t) and RTD E(T) function [23]	$\frac{d\bar{X}}{\mathrm{dt}}$	=	$X(t).E(t)$	**Equation 13**

Current Practice in Uranium ISR Modelling

ISR uranium producers have developed and applied custom models for ISR wellfield production. These models typically use a theoretical basis including:

- Reaction kinetics
- Residence time modelling
- Reactive transport modelling
- User selected wellfield patterns, well spacing radius, and dimensions, that describe the pattern area

Boss have developed a theoretical/empirical model to describe the kinetics of wellfield extraction, with output shown in Figure 6. This typical wellfield output profile has a sharp initial peak followed by a long decay tail [24]. The grey and orange lines represent the measured data and the green and blue lines the modelled results, both in terms of uranium concentration in the PLS and uranium extraction as a function of PVs treated.

This theoretical/empirical approach works well for performing wells but does not consider all operational factors that may influence the recovery. The limitations of the modelling are:

- Variation in ore body composition means using averages for kinetic modelling may produce misleading results. This is because the orebody genesis contributes greatly to the high spatial variability in the chemical kinetics, which in turn affects the shape and accuracy of the PLS model [25].
- Limited data for validation of the model.

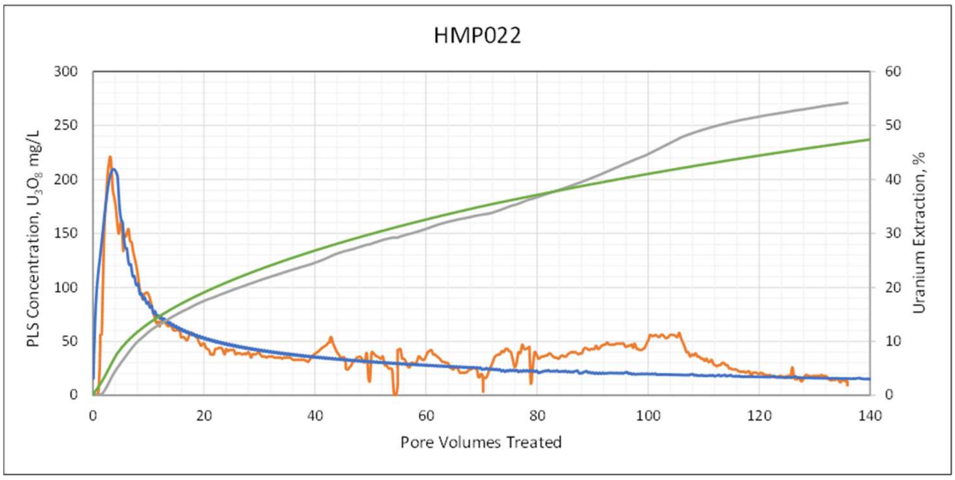


Figure 6: Typical Wellfield Output Profile with Sharp Initial Peak Followed by a Long Decay Tail [24]

KATCO mine, the world's largest ISR mine, have used reactive transport software HYTEC developed by MINES ParisTech [26], to simulate and predict the PLS curve [6]. The tool is written in C++ with the system solved using iterative numerical methods. In this application, the model's parameters were based on known and assumed operational leaching kinetics, aquifer properties, and wellfield configurations [21]. These model's parameters, for example leaching kinetic and aquifer properties, are not time invariant which implies new system parameters will need to be used to recalibrate the model. Although HYTEC allows for easy manual tuning upon deviation of the model from operational data, it is still a tedious exercise to recalibrate the multiple individual patterns for a given wellfield during the mining exploitation phase.

Due to the need to continuously re-adjust the model parameters of HYTEC code, HYSR was created which a graphical user interface (GUI) to the program to provide a friendlier user experience to mine operators, and clear presentation in the output of the program [6]. The GUI does not require initial or boundary conditions and imports a block model or well specifications [27].

These models can be used in short term and long-term planning, as well as to assess the environmental footprint of an ISR mining site to minimise environmental impact [27].

Other Similar Processes

Non-Uranium ISR

ISR mining is also employed in copper and gold recovery. A recent scoping study on reactive transport modelling of copper ISR demonstrated that a full reactive transport model was developed using the COMSOL Multiphysics package to full scale simulations of the whole ore body [10]. The model included modelling existing underground workings as 2D fractures, and parametric studies at the block scale with a five spot well field design. The parametric models allowed the investigation of the key factors affecting PLS recovery, and the full-scale simulations shows a practical modelling example of how to use Reactive Transport Modelling (RTM) for production prediction, albeit without calibration from ongoing production data.

Heap Leach

In heap leaching ore is typically crushed and stacked as it comes out of the mine without any additional grinding like traditional mining flowsheets. A leach solution is then applied to the ore surface and permeates through the ore pile using gravity to be collected in a sump. Weeks or months elapse before the solution is reapplied to the heap. Due to the permeation of leaching solution through ore, this presents similar physical interactions as ISR but on different timescales. Physical models accounting for the kinetics of the ore are typically in the forms described in Table 1 and will be applicable to ISR.

In the heap bioleaching process, the system has been model using three fundamentals intercoupled subprocess including chemical reactions, temperature, and bacterial activity [29]. Additionally, Kalman filter was added (i.e., a recursive estimator method) to estimate the system time varying system parameters. In an application setting, the initial model derived from first principles did not work very well. A solution is to add empirical adjustments to the equations to add in the missing dynamics.

Machine Learning Methods

Artificial intelligence and machine learning have been instrumental in driving technical advances across many industries in the past 10 years. This has been driven by both large computing resources available to companies such as Google and Microsoft, as well as the availability of large datasets. In some domains, such as image recognition or speech recognition, (deep) machine learning is a solved problem and real-world applications abound. This growing trend has led to a suite of accessible machine learning methods and tooling applicable to mineral exploration and extraction processes.

Machine learning is a data driven approach to process modelling, used to solve regression or classification problems, where a target variable or class from a training dataset is inferred from a set of input variables. Once the training process is completed and validated, the model can be used to predict new targets from new input variables.

There was no literature found in the application of machine learning to predict the PLS curve of the ISR process. Several examples of ML application in geology assessments were reviewed, including ML to predict mineralisation, iron deposits, stratigraphy, and lithology within the vicinity of the uranium body [28]. Another application of ML was using downhole measurements to learn filtration coefficients, which is used as model input parameter to the ISR model [29].

The complexity of machine learning methods can vary from simple, such as linear or logistic regression, through to very complex and computationally intensive methods such as deep neural networks, where large amounts of input data are fitted with the target labelled data.

The quality and ability to generalise (give accurate predictions when used with new data that it has not been trained on) of supervised models depends on the quality and quantity of the data available ideally a large data set will assist in the training the model to an acceptable degree of accuracy for deployment of the model.

The dataset provided by Boss contains 48 Decline Curves, which is insufficient amount of data to model the PLS curve purely using machine learning method. With small data sets such as in this project, machine learning can overfit [30]. To reduce the risk of overfit, the machine learning problem can be constrained with extra information. Constraining the model can be done by regularisation [31], or by explicitly including constraints based on the underlying geophysical and chemical problem.

Table 6 lists several supervised learning methods considered for this project. They are assessed in terms of:

- complexity - how much computational effort is required in fitting the model
- accuracy - is the model, once fitted, able to accurately represent the process
- interpretability - are the parameters of the model able to be related easily to physical processes
- applicability - can we use this model in this project

Table 6: ML Techniques Ranked for Suitability to ISR Process Modelling

MODELLING TECHNIQUE	COMPLEXITY	ACCURACY	INTERPRETABILITY	APPLICABILITY
System Modelling	**Low**	**Medium**	**High**	**Yes**
Support Vector Regression	Low	Medium	Medium	Yes
Random Forest Regression	Medium	High	Medium	Yes
XGBoost Regression	Medium	High	Medium	Yes
Deep Neural Network Regression	Very High	High	Low	No
Time Series	Low	Medium	High	Yes
Adaptive Models	Low-medium	Medium	High	Yes

DATA AGGREATION

Data from several sources was aggregated into a database in preparation for modelling. The purpose of data aggregation was to both assess the quantity and quality of the data and identify any gaps in knowledge.

Two key datasets were provided:

- BIF (Boss In-fill drilling data)
- Historical production data, including 3 wellfields – 16 patterns each, 48 Decline Curves

The historic operations data is key to understanding what the key outputs that operations require to plan, operate, and optimise production. Key information includes

- Calculated PLS grade decline curve and extraction
- Resource estimate of uranium in pounds
- Injection and extraction solution chemistry and flow (NTU, ORP, pH, composition, Flow)
- Pore volume

The following gaps were identified and represent opportunities to improve the model in future applications of the model:

- There is currently no way to use the extensive information contained in the BIF data (Borehole magnetic resonance tool, and density and neutron logs), as it was not obtained in the historical wellfields. This data will be useful in future applications of the predictive tool.
- Resource estimate of other key elements and mineralogy for the existing dataset were not available. This data may inform other aspects of the ore amenability to leaching and improve the prediction.
- Porosity, ore thickness, and wellfield area, and pattern, which are used to derive the pore volume was not available. Pore volume was provided in the historic data without the input data.

The dataset provided by Boss Energy contains 48 PLS curves, which is insufficient amount of data to model the PLS curve purely using machine learning method. With exclusion of data where there is no flow, or backflow, this data set reduces further. To prevent overfitting, the model must be constrained by regularisation [31] or by available information such as kinetics, hydrodynamics, and ore body characterisation.

MODELLING SELECTION AND METHODOLOGY

Model Selection

Because of the limited data sets available, and the sensitivity of complex machine learning approaches to overfitting on small data sets, a hybrid approach to modelling was progressed through to development. Two different lumped parameter models were proposed:

- System modelling – using a compartment modelling approach to generates the correct shape predicted curve, with simple but potentially not interpretable parameters.
- Mixed kinetic and RTD model – this model leverages theory and interpretable parameters in a simple model.
- The mixed kinetic – ML model was selected to go forward to development into a predictive model, because it has directly interpretable parameters that enable the user to understand the impact of key mineralisation characteristics, well construction and injection solution chemistry.

The inclusion of theoretical-empirical models in the kinetic-ML model introduced rigidity to the model, which in some cases resulted in lower accuracy results when compared to the highly flexible systems modelling approach. System modelling allowed more flexibility in shape of curves produced, which enabled it to fit historical decline curves that had operational issues, and skew parameters. The systems model was not taken forward in this project because the model does not meet the objective of the study which was to produce a predictive model from data at the exploration stage, and parameters are not directly interpretable. Systems modelling is a more suitable approach for near real time operational modelling, where the deployed model can learn from and react to operational issues on the fly.

Modelling Methodology

The mixed kinetic- ML model leverages the kinetic equations, and known residence time distribution (RTD) functions, to find the kinetic rate constants that are used for prediction. This approach was selected since:

- The inclusion of theoretical modelling maintains impact of key operational levers on the predictive model, such as lixiviant composition, and wellfield patterns.
- Use of machine learning models to derive functions for the rate constants will leverage a greater portion of the data provided than conventional regression, and therefore has the potential to produce higher accuracy predictions than achievable with the theoretical modelling.

Fitting kinetic models to noisy data can be difficult, and it can be necessary to move from simple least squared loss functions to more sophisticated techniques that reduce the influence of outliers, penalise model complexity and find globally optimal solutions [32] [33].
The proposed model methodology will use error minimisation, 'curve fit', across all tests to find the kinetic equation constants, k1, a1, b1, phi, described in Equation 1 to Equation 5, and the residence time distribution constants N and tau described in Equation 11 to Equation 13. The RTD input n, theoretical number of tanks in series, will change with each well, i.e., poor flow will be characterised by back mixing, and short circuiting. Machine learning will be used in conjunction with all available data to derive the 'functions' for the constants. Feature importance is used in the derivation of the machine learning models to develop the understanding of the key drivers on the ISR process.

RESULTS

The mixed kinetic – ML model was developed using the following approach:

- An algebraic solution to mixed kinetic-RTD model was produced
- Model equation was fit to the decline curve data set, to obtain a set of k0, N and tau to describe the kinetic and flow pattern of the decline curves
- The key mineralisation and injection solution chemistry drivers for the parameters k0, n and tau were investigated using machine learning. The most important features, were:
  - Resource estimation: The uranium resource drives the size of the decline curve peak,
  - U3O8 in injection solution: The BLS grade will boost the PLS grade
  - pH: Acidity impacts rate of uranium dissolution
  - ORP: Uranium oxidation is required to leach
  - Potassium: Potassium is likely desorbed from clay in the ISR leach process under the leaching conditions. The extent of potassium in the injection liquor and PLS may be an indication of the effectiveness of the leach.
  - Turbidity: The concentration of dissolved solids may impact precipitation, permeability, and fluid flow paths.
- Machine learning models were developed to predicted k0, n and tau across the decline curve data set, using gaussian, SVR, linear and decision tree. The key findings were:
  - Number of theoretical tanks was shown to be typically between 1.5 and 2. This produces a response consistent with flow bypassing, which is consistent with an understanding of complex ISR flow paths. Higher n would imply the system is approaching perfect mixing, which is unlikely for ISR.
  - Mean residence time, tau, was in the range 25-30 days. This implies that the peak of PLS grade occurs in this timeframe, which aligns with operational experience.
  - k0 the kinetic coefficient was in the range 5.10-5.12 x 10^{-5} L/mol/h which is a reasonable order of magnitude for uranium dissolution.
- The accuracy of the models was inspected visually and using the mean squared error. An example of a curve fit is shown in Figure 7.
- The kinetic parameters a, b and k were interrogated and adjusted to ensure the response of the decline curve met understanding of the metallurgical fundamentals

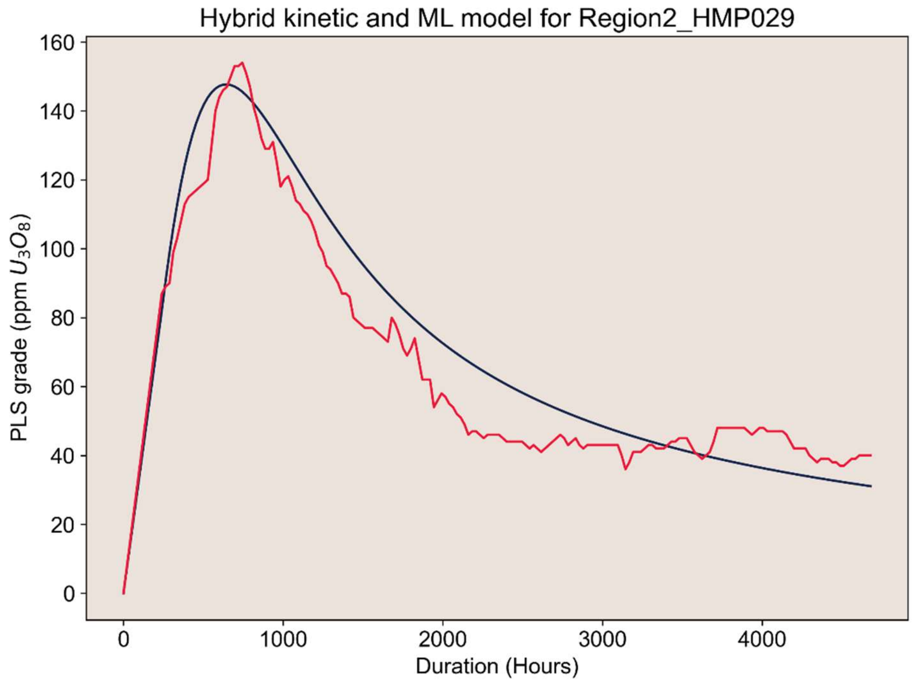


Figure 7: Mixed kinetic- ML model fit to historic well HMP029. This is a test data decline curve, meaning it's data was not used to train the model

The model was deployed in an interactive dashboard in MS Excel, to enable users to adjust mineralisation, well construction and injection solution characteristics, to determine PLS grade and extraction over time, shown in Figure 8.

To demonstrate the potential of the model to simplify wellfield planning, several decline curves were overlayed and the aggregate PLS grade calculated over time. The resulting aggregated uranium grade in the PLS and total flowrate are shown in Figure 9.

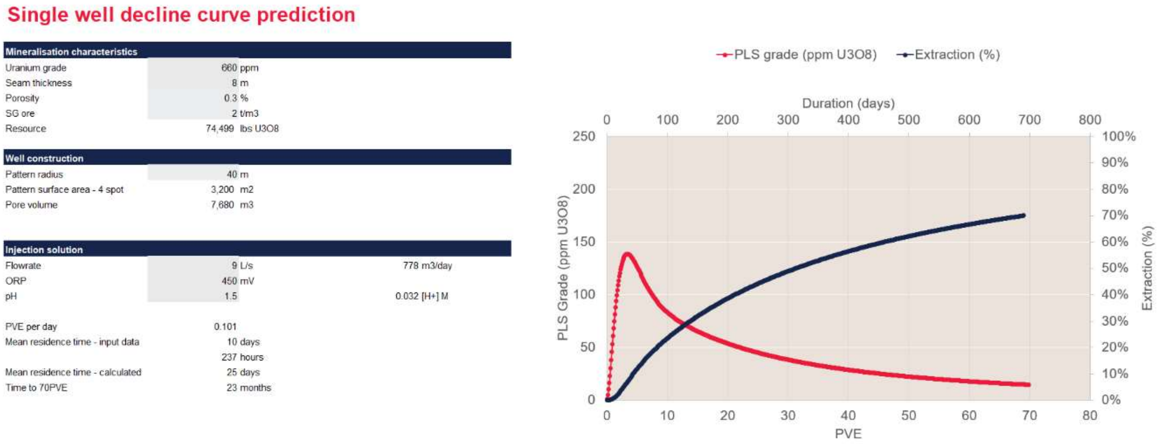


Figure 8: Mixed Kinetic – Machine Model deployed in Excel. mineralisation, well construction and injection solution characteristics, can be adjusted to determine PLS grade and extraction over time

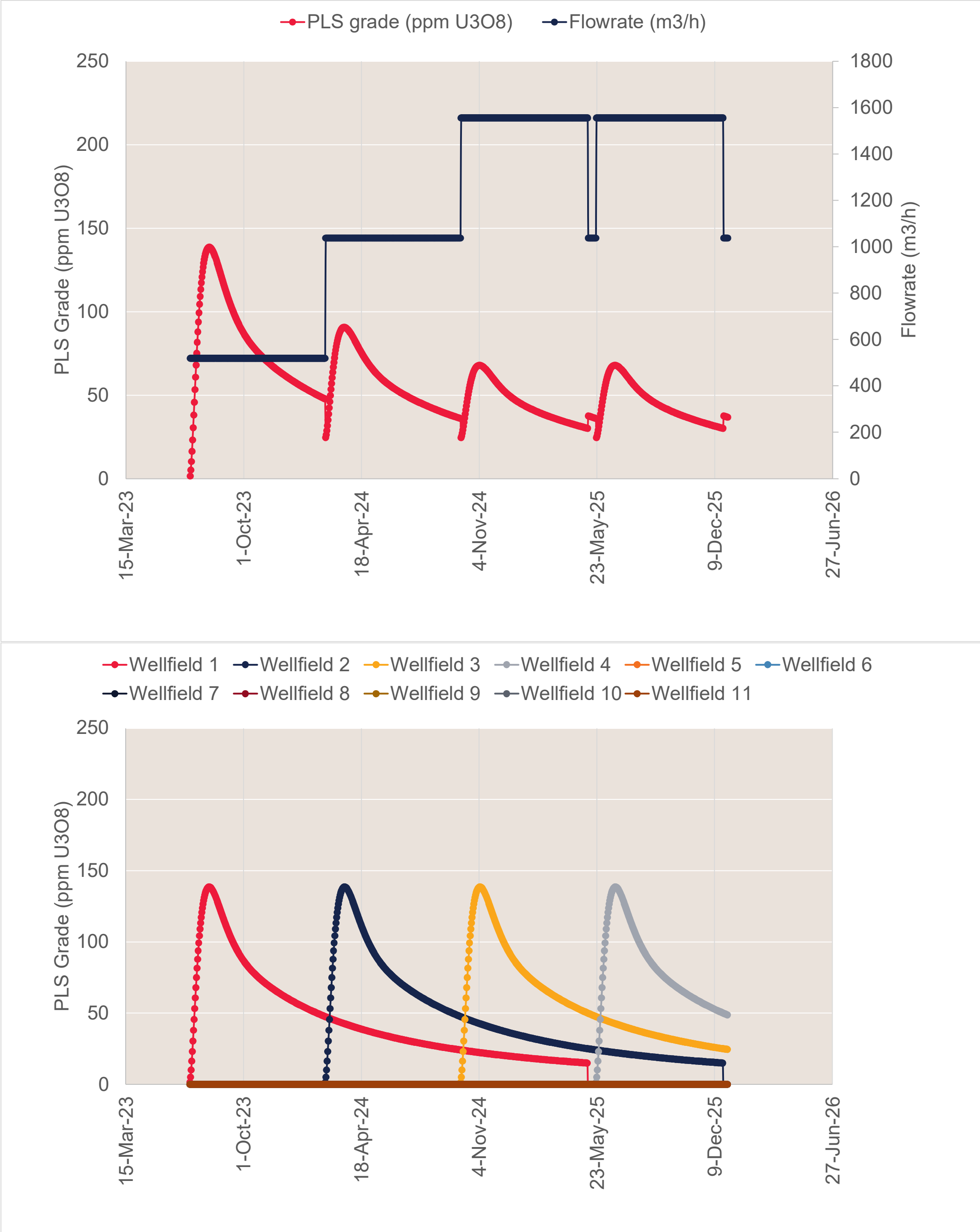


Figure 9: To demonstrate the potential of the model to simplify wellfield planning, several decline curves were overlayed and the aggregate PLS grade calculated over time

OPPORTUNITIES

Integration of New Innovative Exploration Tools

Borehole magnetic resonance tool, and density and neutron log data can be used to further train and tune the model as operational data relating to those wells becomes available. Given the additional information and potentially higher accuracy of these instruments in assessing the mineralisation, the use of these inputs in model tuning may result in a higher accuracy decline curve and extraction rate. This approach is applicable to other ISR amenable uranium deposits.

Wellfield Planning and Cost Optimisation

In this phase of works, the potential for this model to be used in wellfield planning was demonstrated by overlaying several decline curves. This could be further progressed to:

- Optimise number of patterns and wellfields online using an automated algorithm
- Integration with a plant production model to maximise production
- Integration with a plant production model and operating costs to create optimised wellfield planning, and operational setpoints, to maximise revenue

The development of a streamlined model that leverages automation of the wellfield planning and production forecast, will enhance productivity of the wellfield planning team, enabling them to focus on their core business.

Real Time PLS Grade and Extraction Forecast During Operations Using the Systems Modelling Approach
The systems modelling approach may be used for near real time operational modelling, where the deployed model can learn from and react to the wellfield and plant data as it is collected. Since mineralisation characteristics, permeability, gangue composition and operational approach may change over time, the model will experience drift. This issue can be outcome by updating the well system parameters (α, β, μ, N). There are various adaptive filtering techniques which could be implemented to automate the process of updating of the system parameters α, β, μ, and N. A recommended approach is the use of Kalman filter, which has successfully been used in an SIR epidemiological model, which shares similar system characteristics as ISR.
In the implementation of the systems modelling technique for each well, the initial system parameters can be estimated by using machine learning utilising well construction characteristics, injection chemistry, and flowrates. During ISR operation, operational data such as PLS and BLS assay data, pump speed and pressure, real time flowrates, can then be used to map operational values to the model system parameters, adjusting and correcting for drift in the model.
In an operational setting, there are multiple cells or patterns that are individually modelled. The process of auto-adjusting the individual well system parameters to match the changes to the ISR operational conditions can be automated. The result is a more accurate prediction of the well PLS curve in a production setting.

Implementation in Heap Leach Modelling
Given that the response of a heap leach extraction process is similar to an ISR profile, the modelling approaches proposed in this study could be used to predict heap leach performance.

CONCLUSION

WGA and Boss' joint study into the development of a novel tool to predict the amenability of a deposit to ISR met the key project objects:

- A model was developed to predict the extent of uranium extraction and PLS grade over time from data available during exploration. This model also has the potential to be used for wellfield planning and cost optimisation, and operational control, at Honeymoon and other sites, and could be deployed in other similar processes such as heap leach.
- Knowledge share of the project discoveries at the Global Uranium Conference 2022 and Alta 2023.
- The project was completed within budget and ahead of schedule.
- The development of an interactive tool exceeded the expectations of the original scope of the ADI grant to deliver a 'proof of concept' geophysical data processing tool for sedimentary uranium deposit evaluation for ISR during Greenfields exploration.

The development of the model was supported by a thorough review of literature, Honeymoon historic operational datasets, and current modelling methodology, as well as a robust understanding of the process enabled by collaboration of experts from Boss and WGA.

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ESTIMATING RESOURCE AND OPTIMISING PRODUCTION IN ISR AND BRINE MINING USING NUCLEAR MAGNETIC RESONANCE

By

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ABSTRACT

Understanding the Hydrogeological setting of ISR and Brine Deposits is vital to defining the available resource, as well as aiding in the optimisation and prediction of production results. Porosity, being the percentage of void space within a rock, can be used to determine resource volume (brine deposits) or understand water volumes and lixiviant concentrations for successful mining (traditional ISR). The permeability, or hydraulic conductivity, of the host rock will dictate the rate at which fluid can be extracted from the formation and consequently the rate at which the resource can be exploited. Additionally, porosity coupled with bulk density measurements can be used to calculate the dry bulk density of the host rock which directly impacts resource estimates in traditional ISR settings.

The well-established technology of Nuclear Magnetic Resonance (NMR) extensively used in other industries, has recently been made available for mining and groundwater applications, capable of resolving the complexity of hydrogeological systems at a higher resolution that alternative approaches. The Borehole Magnetic Resonance (WIREBmr™) tool is a downhole geophysical instrument that interacts with the fluid contained within the pore space directly and (i) measures the amount of fluid (total porosity), (ii) differentiates between moveable and non-moveable fractions (effective porosity) and (iii) infers how easily the fluid is likely to flow through the porous medium (permeability and hydraulic conductivity) as a continuous log. The downhole tool is environmentally friendly; there is no radiation emitted from the tool and offers considerable benefits over traditional downhole tools that estimate porosity. It works by generating magnetic fields and tipping hydrogen atoms using radio frequency pulses.

Potassium sulphate, or sulphate of potash (SOP), is mainly used in fertilisers and contains important nutrients for plant growth. It does not contain chloride which can be a detriment to plants that are chloride-sensitive such as avocados and coffee beans. Only 35% of SOP comes from natural resources and is considered a rarity. SOP is water soluble and can form mineable deposits below the subsurface hosted within hypersaline groundwater. SOP can be mined by extracting hypersaline groundwater via trenching or through boreholes and processing via evaporation ponds and s purification plant. Using data acquired from an Australian brine exploration project as a case study, we explore the advantages of using WIREBmr™ to determine aquifer properties as well as resolving the boundaries between aquifers and aquitards. This leads to better understanding of the available resource, improved decision making on production interval selection, and enhanced prediction of results during production. We further discuss how these measurements can be used across the ISR and Brine Mining spaces including the mining or copper, uranium, and lithium.

Keywords: Brine Mining, In-Situ Recovery, Sulphate of potash, borehole magnetic resonance, Porosity, Permeability

Hydrogeology in ISR and Brine Mining

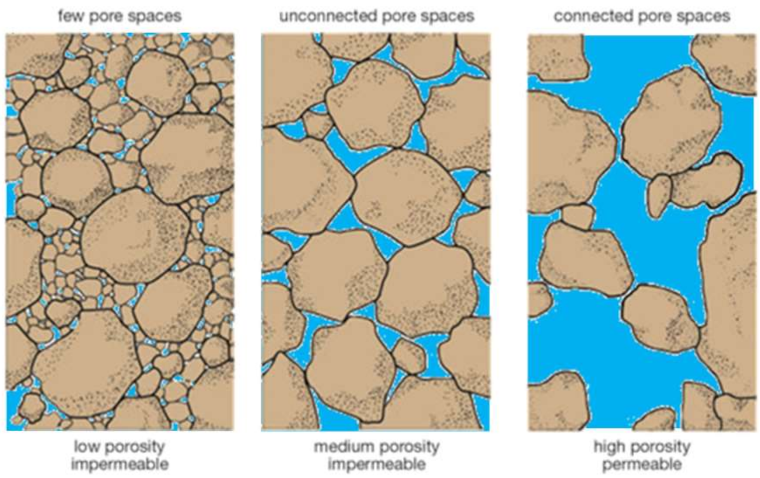
Porosity and Permeability From Wireline Data

Porosity and Permeability

Porosity: Percentage of void space in a rock. It is defined as the ratio of the volume of the voids or pore space divided by the total volume.

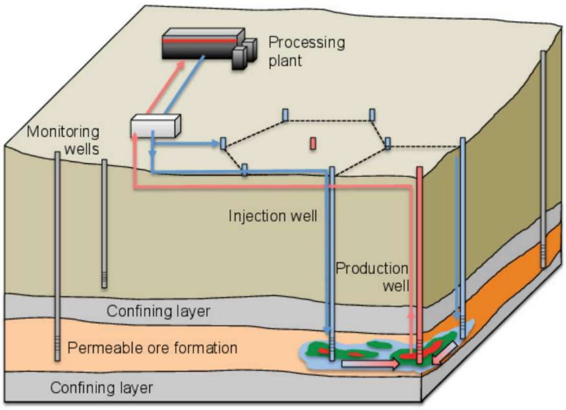
Permeability: measure of the ease of passage of liquids or gases or specific chemicals through the material.

Hydraulic Conductivity / Transmissivity: aquifer properties calculated from permeability, aquifer extent and fluid properties.



Importance in ISR and Brine Mining

- **Porosity**
  - Define resource explicitly (Brine Mining)
  - Inform the volume and chemistry required to effectively mine (ISR)
  - Calculate dry bulk density for resource calculations (ISR)
- **Permeability**
  - Quantify Production rates
  - Inform Infrastructure decisions: well spacing, pump sizing, pipe sizing …



(Lagneau et al, 2019)

Traditional Techniques

- **Core Analysis**
  - Physical lab tests can be performed to measure core scale porosity and permeability
- **Packer (Drill Stem) Testing**
  - Isolate Specific well sections using inflatable packers.
  - applying a constant hydrostatic pressure measured at the ground surface, and monitoring the water flow into the formation over time
- **Pump Testing**
  - Similar to packer testing.
  - Extract/inject water from/into a completed well and measure its effect on nearby wells

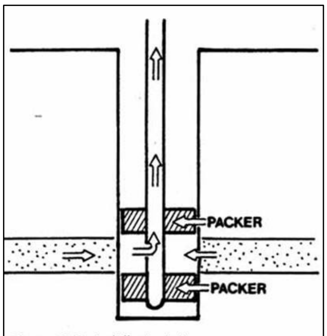
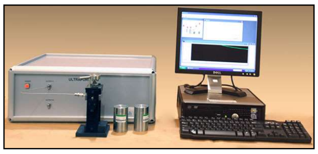


Figure 18-2 A drill stem test.

Packer Test Example (Left). Grain volume apparatus (Bottom Left), pore volume apparatus (Bottom Right)

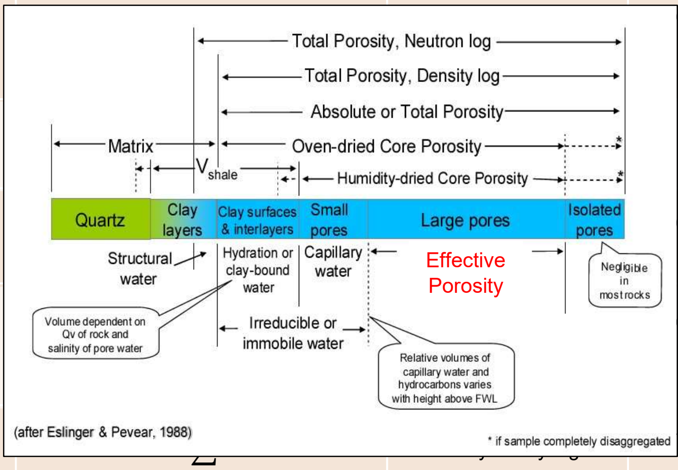


How to Estimate Porosity Downhole

Tool	Porosity Relationship	Additional Information	Drawbacks
Gamma-Gamma Density	$\rho_{bulk} = \emptyset\rho_{fluid} + (1-\emptyset)\rho_{matrix}$	Fluid, matrix density	Requires active radiation source Spurious results in gamma producing zones
Resistivity	$\frac{R_t}{R_w} = a\emptyset^{-m}$	a, m, fluid resistivity	Constants formation specific
Sonic	$\frac{1}{v} = \frac{\emptyset}{v_{fluid}} + \frac{(1-\emptyset)}{v_{matrix}}$	Velocity of fluid and matrix	Matrix velocity often formation specific
Neutron	$\log\emptyset \propto \textit{Neutron Count Rate}$	Salinity Formation chemistry	Requires active radiation source Complex tool dependent relationship, clay effect
Borehole Magnetic Resonance (BMR)	$\emptyset = \sum T2$	Salinity if very high	Sensitive to magnetic / conductive / chargeable material

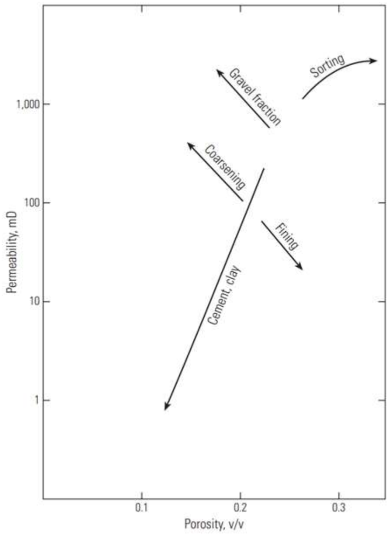
How to Estimate Porosity Downhole

Tool	Porosity Relationship	Additional Information	Drawbacks
Gamma-Gamma Density			equires active radiation source Spurious results in gamma producing zones
Resistivity			Constants formation specific
Sonic			Matrix velocity often formation specific
Neutron			equires active radiation source Complex tool dependent relationship, clay effect
Borehole Magnetic Resonance (BMR)			nsitive to magnetic / conductive / chargeable material



How to Estimate Permeability Downhole

- Any measure of porosity can be used to estimate permeability empirically.
  - Generally: $\log k \propto \emptyset^b$
  - Limited by understanding of local lithology, chemistry and geometry
- Petrophysical Approach using the **Kozeny-Carman Relationship** that describes pore space as a bundle of independent, tortuous tubes of different radii.
  - Can be leveraged to estimate permeability using results from BMR.



Generalised Poro-Perm relationships
Nelson PH (1994) Permeability-porosity relationships in sedimentary rocks.

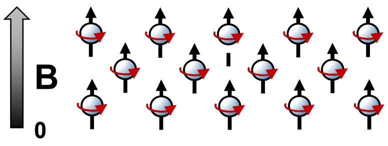
Nuclear Magnetic Resonance

Science and Application

NMR BASICS

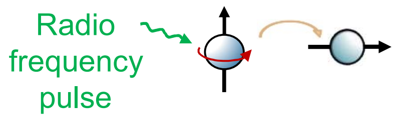
Nuclear magnetic resonance (NMR) is a physical phenomenon in which nuclei in a **strong static magnetic field** are **perturbed by a weak oscillating magnetic field** and respond by **producing an electromagnetic signal** with a frequency characteristic of the magnetic field at the nucleus.

1. Polarisation



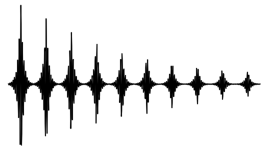
Atoms interact with a magnetic field

2. Excitation



Magnetised atoms are excited using electromagnetic radiation

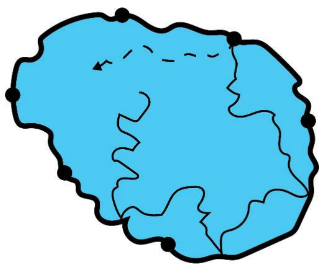
3. Detection

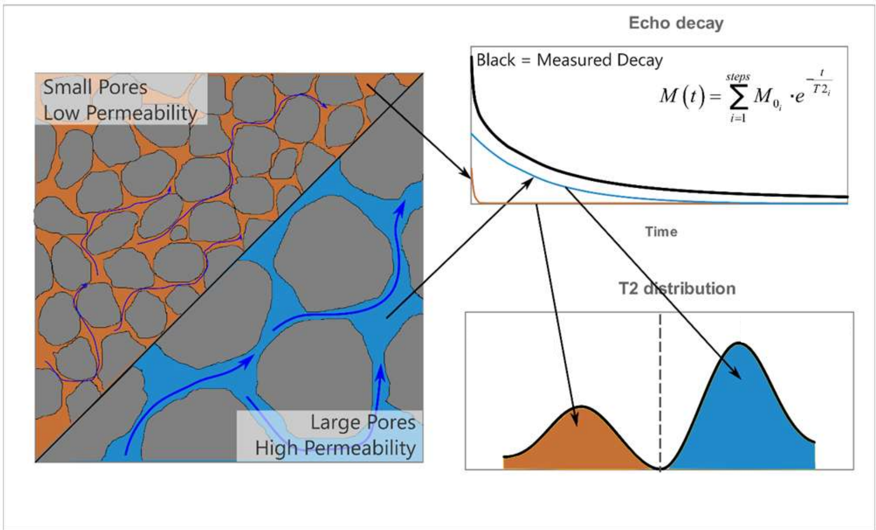


Excited atoms resonate and emit a detectable signal

NMR and Pore Interactions

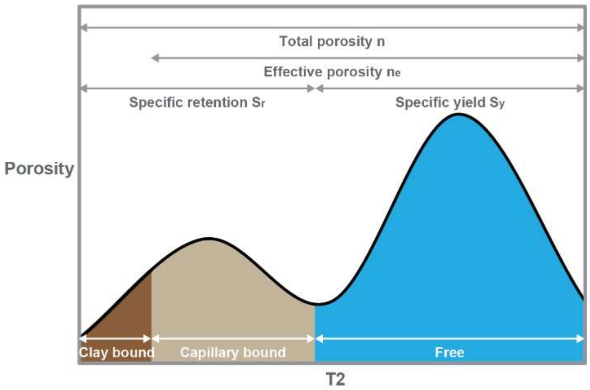
Primary control on energy loss is interaction with pore boundaries (surface relaxation)





Porosity, Cutoffs, and Fluid Volumes

- Total area under T2 represents the total porosity.
- Pore geometry information in magnetic resonance comes from surface relaxation effects.
- Driven by two properties
  - Pore geometry
  - Surface relaxivity
    - Variations in surface relaxivity related to concentration of paramagnetics (iron, manganese, …)

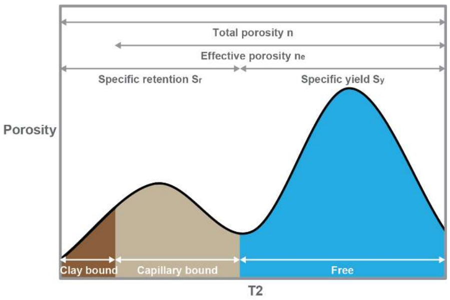


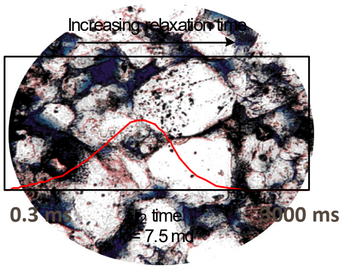
Permeability Estimation

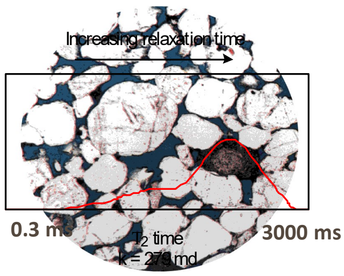
Permeability relates to porosity, surface to volume ratio, and a lithology geometry factor.

$$k_{Timur-Coate} = a \cdot n^b \cdot \left(\frac{S_y}{S_r}\right)^c$$

$$k_{SDR} = a \cdot n^b \cdot {T2_{LM}}^c$$



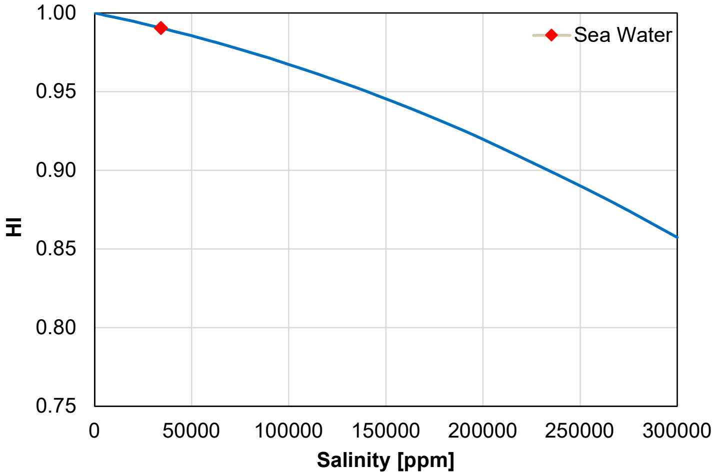




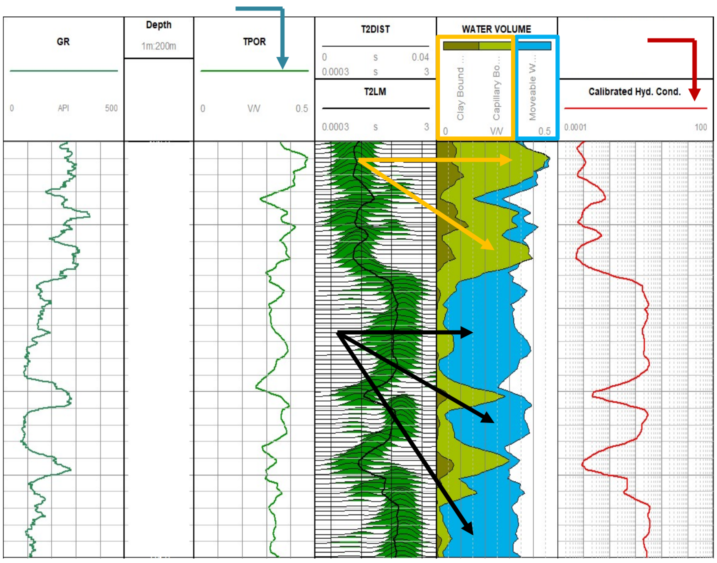
Correcting For Salinity

$$Apparent\ (Measured)\ Water\ Volume = HI\ \times True\ Water\ Volume$$

- Tool response lower than true water volume.
- Relevant in Brine Mining. Regularly see 250,000 ppm
- Calculate Hydrogen Index (HI) by calculating an effective sodium solution density.
- Definition: *The number of hydrogen atoms per unit volume divided by the number of hydrogen atoms per unit volume of pure water at surface conditions.*
- HI of pure water is 1.



Downhole BMR Data



- Aquifer / Reservoir
- Aquitard / Aquiclude
- Permeability / Hydraulic Conductivity
- Total Porosity
- Moveable Fluids (Specific Yield)
- Irreducible Fluids (Specific Retention)

Potash Brine Mining

Lake Throssell

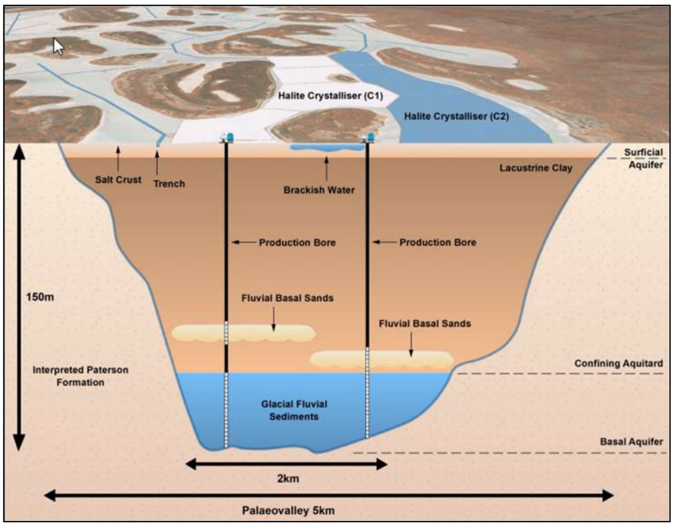
Potash Brine Mining

- Potassium sulphate, or sulphate of potash (SOP), is mainly used in fertilisers and contains important nutrients for plant growth. It does not contain chloride which can be a detriment to plants that are chloride-sensitive such as avocados and coffee beans.
- Only 35% of SOP comes from natural resources and is considered a rarity.
- SOP is water soluble and can form mineable deposits below the subsurface hosted within hypersaline groundwater.
- SOP can be mined by extracting hypersaline groundwater via trenching or through boreholes and processing via evaporation ponds and a purification plant.

(Images courtesy Trigg Minerals)

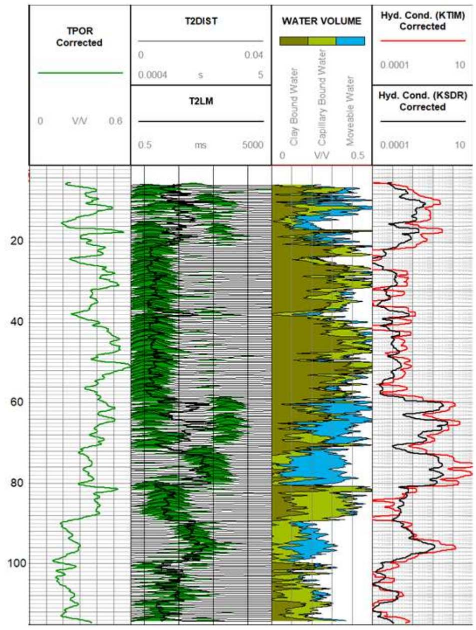
Lake Throssell

- The Lake Throssell Project covers an area of 1,085km² approximately 180km east of Laverton, Western Australia.
- The Project contains a total drainable Mineral Resource Estimate of 13.3Mt of SOP with an initial 21-year mine life.
- The salt lake acts as a point of discharge for the regional groundwater system. Groundwater flow in the shallow sediments within the lake's catchment flows towards the lake surface where evaporation is dominant and there is a net loss to the system making the groundwater hypersaline in nature.
- Average grade of 4,760 mg/L potassium.



ASX Announcement 1/02/2023: Positive Brine Assay and Borehole Magnetic Resonance Results from Lake Throssell
ASX Announcement 5/10/2021: Scoping Study Results Presentation

BMR Results



- Clear delineation of sand / clay and bound / free fluid intervals
- Allow calculation of specific yield (defined as movable water)
- Estimate hydraulic conductivity to inform aquifer performance.
- Salinity Correction on HI=0.908, i.e increase of fluid volumes of 10%.

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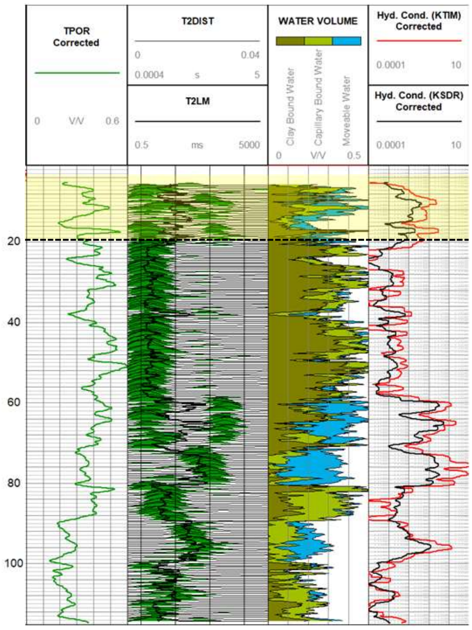
Alluvium



- Upper clay dominated aquifer
- Dual T2 peaks indicate presence of small and large pores. Dominated by small pores.
- Sy=0.11

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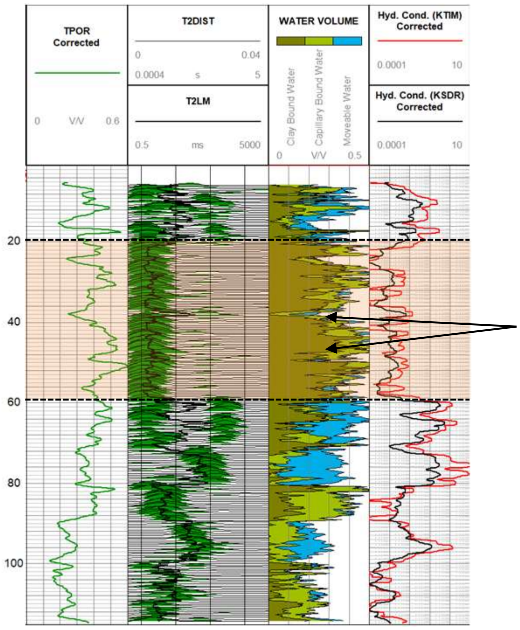
Lacustrine Clay



- Short single peak T2 indicated clay lithology
- Clay Dominated
- Notable Calcrete bands with which will yield brine
- Sy=0.03

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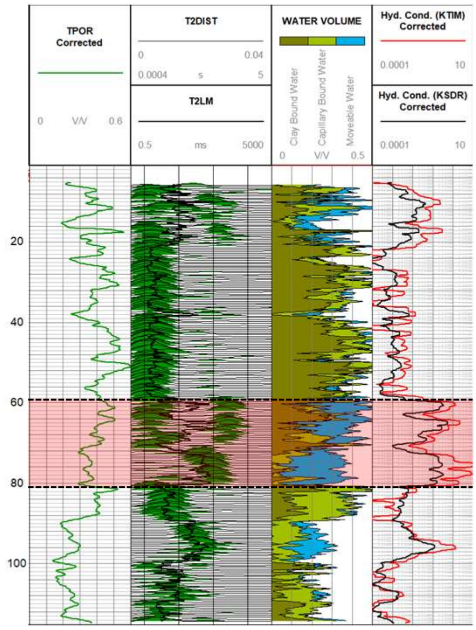
Fluvial Sand



- Primary production aquifer
- Dual peak at top of unit with clay peak not present further down. Indicates clay/sand transition into sand dominated unit.
- Fluvial / Clayey sands
- Sy=0.20

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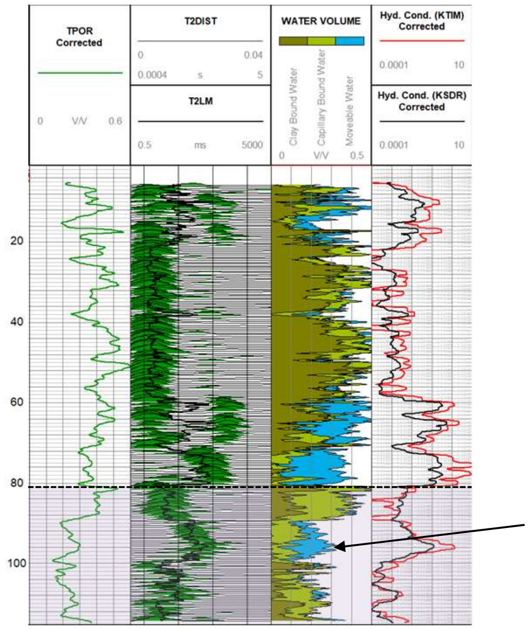
Saprolite



- Intermediate T2 peaks indicate capillary bound water / silt dominated lithology.
- Basal Aquifer
- Minor gravelly sand zone
- Sy=0.05

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Conclusions

Conclusions and Outcomes

- Poro-perm measurements are critical in knowing whether an ISR project is feasible.
- Traditional Hydrogeological data acquisition is time consuming, requires specialized expertise and can be expensive.
- BMR using NMR principles can give:
  - Differentiate bound and free fluid
  - Can provide lithological characterisation.
  - Logged without use of radioactive sources.
- Case study outcomes:
  - The BMR measurements confirm the presence of high free fluid aquifer units.
  - Enable Estimation of Specific Yield on an aquifer-by-aquifer basis.
  - Directly inform resource estimate.
  - Account for BMR logging in flowing sands during planning (case in PVC)

(Images courtesy Trigg Minerals)

Acknowledgements

Aquifer Resources
HYDROGEOLOGY | BRINE RESOURCES

- Aquifer Resources for insight into the workflow for BMR data at Lake Throssell.
  - **Adam Lloyd**

TRIGG

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  - **Jonathan Ross**
  - **Benjamin Birt**

REVIEW OF POTENTIAL FRACTURING METHODS (MICROWAVES, HIGH-VOLTAGE PULSES AND CRYOGENIC FLUIDS) FOR ACCESS CREATION IN LOW-PERMEABILITY HARD ROCKS FOR IN SITU METAL RECOVERY

By

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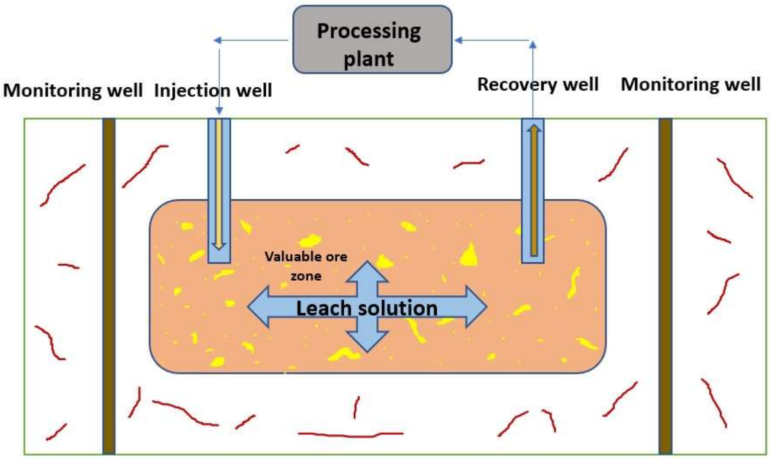
ABSTRACT

Rising mining costs and fewer high-grade ore deposits have necessitated a search for alternative methods for the recovery of metals from deposits that are no longer economically or environmentally exploitable by conventional mining. One such alternative method is in-situ recovery (ISR). Although ISR has typically been used for mining uranium ores that are not economic to mine with conventional methods, it has also been used less frequently for the treatment of other low permeability rocks, such as hard rocks containing copper, nickel and gold. The reason for the limited uptake of the technology for hard rock mineralisations is primarily due to the low natural rock porosity and permeability and hence limited ability of a lixiviant to permeate the rock and contact the minerals.

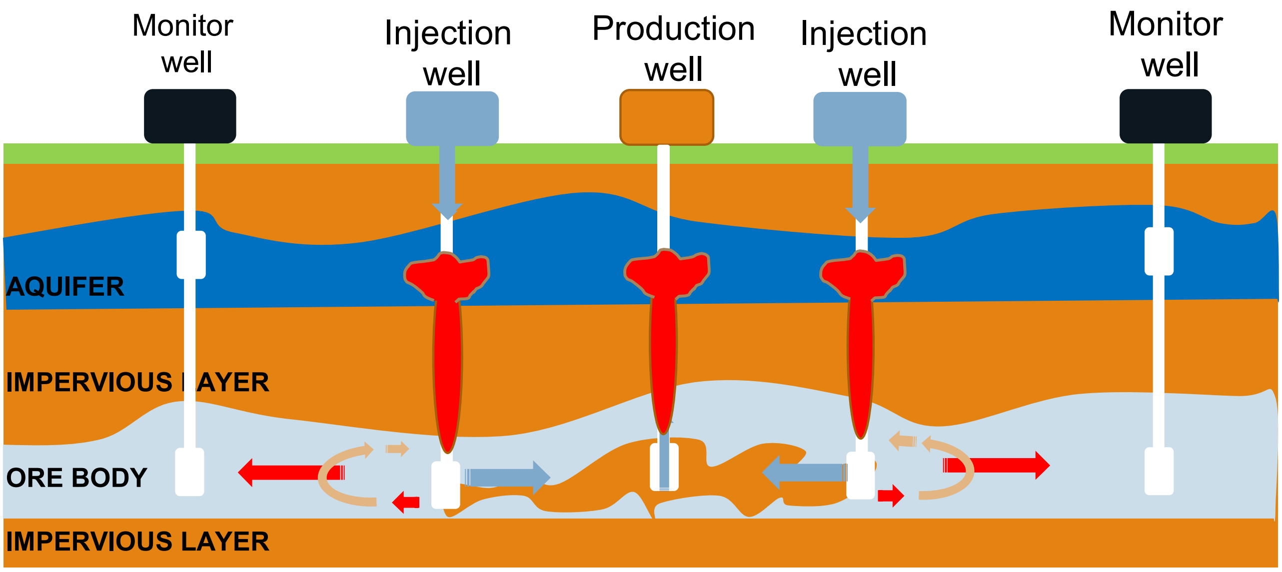
This review focuses on three potential access creation methods: microwaves, high-voltage pulses and cryogenic fracturing procedures. Microwave applications in mining and process metallurgy have been the subject of many research studies over the past two decades. Most have focused on energy savings in comminution, but little research has been done on the application of microwaves in ISR. Further, only preliminary investigations have been conducted to understand the factors that influence the change in permeability of rocks by high-voltage pulse breakage and cryogenic fracturing. The aim of this review is to summarize available information on these three methods for increasing the permeability of hard rocks and thereby improving the rate of lixiviant-mineral contact and mass transfer in in-situ recovery. The review will start with an overview of considerations for use of ISR. The mechanisms of microwave, high-voltage pulse and cryogenic fracturing methods will then be discussed.

Keywords: In situ recovery; Fracturing; Microwave; High-voltage pulse; Cryogenic fluid; Permeability.

In situ leaching

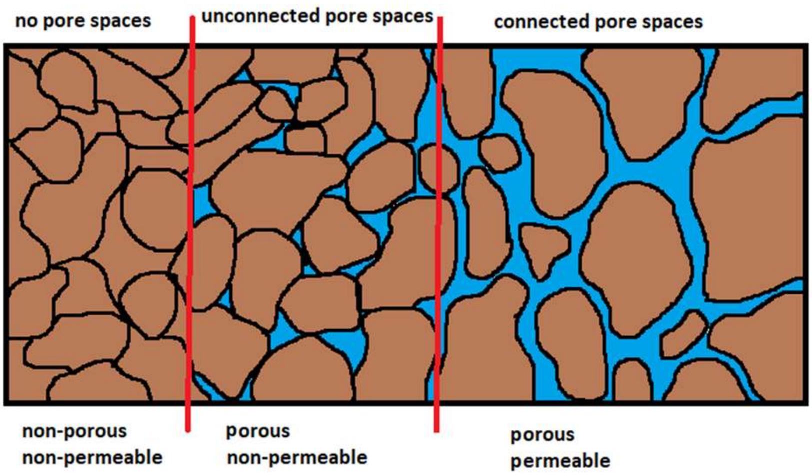


ISR lends itself to the commercial recovery of soluble salts and uranium from permeable, readily leachable "palaeochannel" deposits. However, no commercial processes exist currently for the in-situ recovery of copper, gold and nickel, Zinc and Silver as these commodities often exist in compact, impermeable rock.



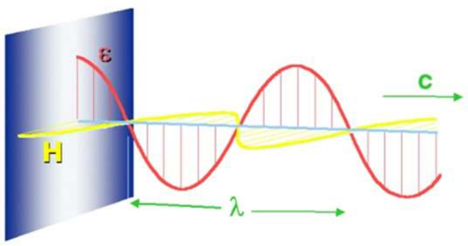
Access Creation

- Why we need for access creation in low-permeability hard rocks for in situ leaching



Microwave fracturing

Microwaves have extensive usage in processing engineering materials from assisting in comminution to leaching them.



leaching

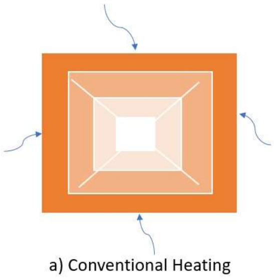
- ✓ Increasing surface area of material
- ✓ Oxidizing Mineral’s surface
- ✓ creation of large convection thermal currents
- ✓ Heating

assisting in comminution

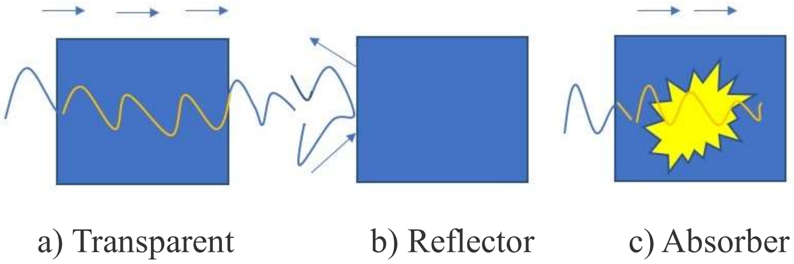
Heating

- ✓ Reduce in mechanical strength (point load index) which renders the ore more amenable to comminution

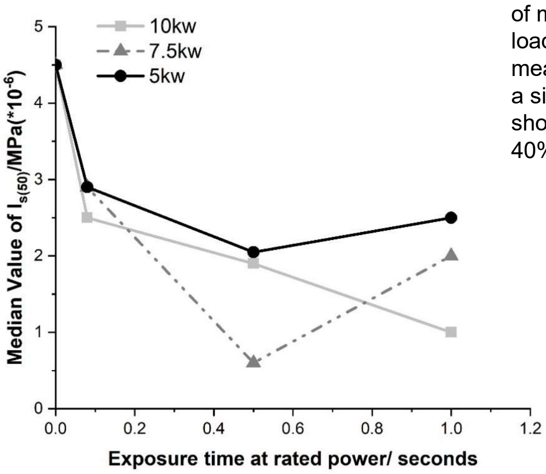
Microwave fracturing



In conventional heating, the material surface gets heated first. Subsequently, heat transfers inside the material by conducting or convection; however, in microwave heating, heat is generated internally within the material by molecular interaction and volumetric heating is achieved in a short time.

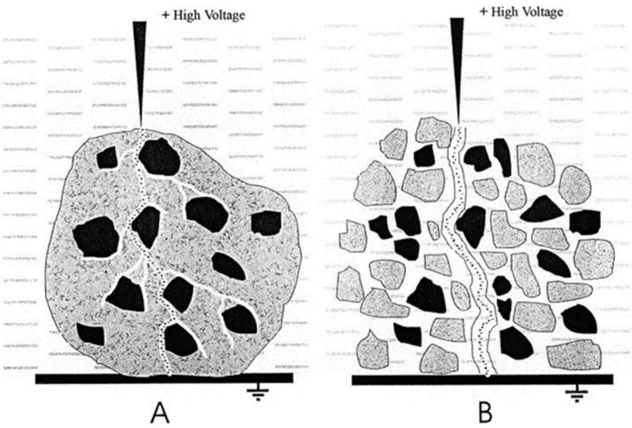


Microwave fracturing



Kingman et al. (2004) carried out tests to measure the influence of microwave power density on change in ore strength. Point load index and drop weight tests were two procedures used to measure this effect. It was shown that microwave treatment has a significant effect on the strength of the ore, with exposures as short as 0.1 s reducing the point load index by approximately 40% (Figure 5).

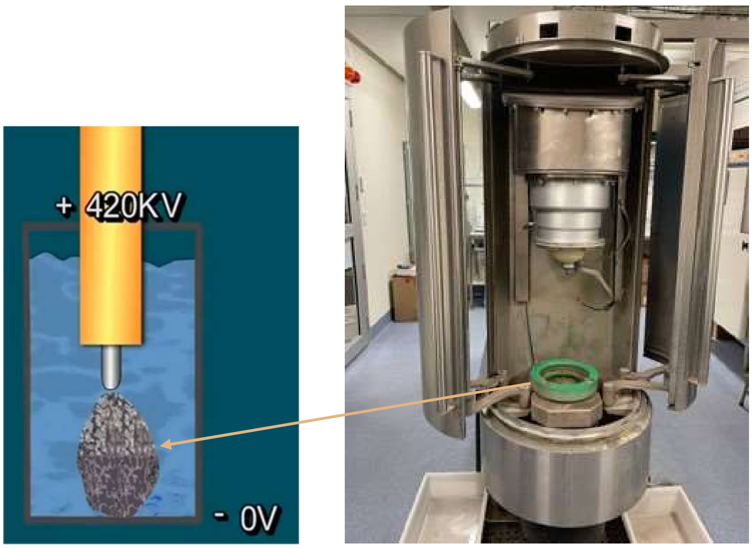
High Voltage pulse fracturing



SELFRAG machine is one of the High Voltage (HV) braking machines that uses HV pulse generators to apply extremely energetic electric discharges to solids placed between two electrodes which disintegrate and/or weaken the particles' structure by strong tensile forces due to the differences in mechanical or electrical properties of different components.
The water acts as a special electrical insulator to prevent electrical discharge occurring outside the rocks.

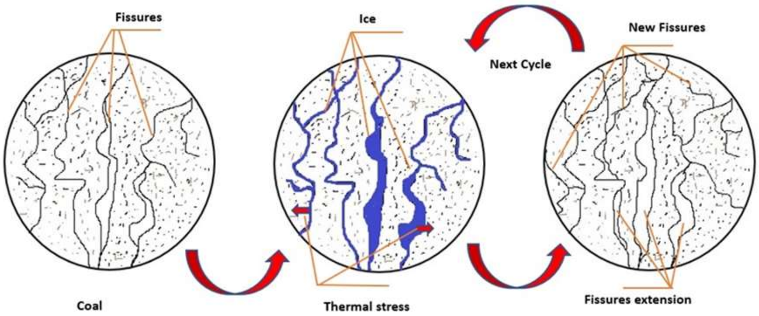
Due to different conductivity of material, current flows differently within that and heats them, and then thermal gradient causes breaking the material.

High Voltage pulse fracturing

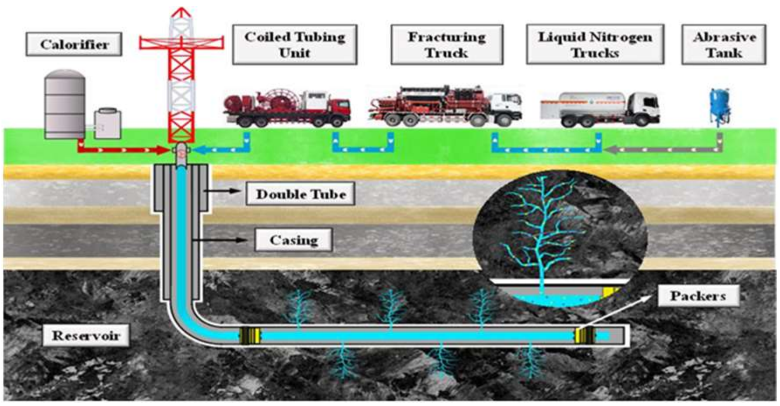


Cryogenic fluid fracturing

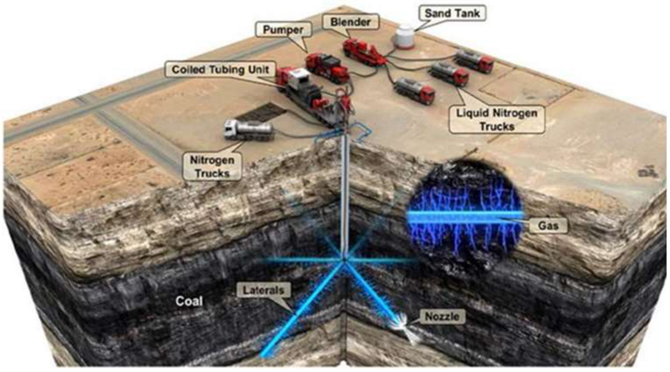
Rapid cooling of a rock surface results in a non-uniform temperature distribution, which builds considerable thermal stresses. These stresses are due to tension on the surface of the rock and compression in center of its body.



Cryogenic fluid fracturing



Cryogenic fluid fracturing



Conclusion

MW, HV and CF may be promising technologies to increase the permeability of hard rocks, such as copper- and gold-bearing ores, and thereby create access for lixiviants and promote mass transfer in ISR processing. This review focused on factors that could be important for application of the three methods in ISR environments.

All three methods MW, HV and CF, are rapid and environmentally friendly fracturing methods that are potentially applicable in ISR systems. These three methods can be used for access creation as well as for selective separation minerals grain separation and to improve leaching.

ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF UNDERGROUND IN-SITU LEACHING PROCESSES UTILISING DRILL AND BLAST TO ACHIEVE HIGH PERMEABILITY

By

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ABSTRACT

In-Place Recovery (IPR) involves blasting a stope, dissolving the metal-bearing minerals within the stope using an appropriate leach solution, and pumping the pregnant leach solution (PLS) to the surface for further processing. While the IPR concept is applicable to various metals, this study was focused on copper extraction mainly to address the future challenge of accessing lower grade and more complex ore bodies in a sustainable manner. In this work, an economic assessment and an environmental impact assessment were conducted to compare copper extraction via IPR with that of conventional mining methods and extraction routes.

A high level economic assessment was completed for a hypothetical 50,000 tonnes per annum copper operation with a head grade of 1% copper from a deposit 500 m deep. Capital investment and the operating cost of the sublevel open stoping (SLOS) method was compared against IPR with three different blast design methodologies. The results showed that both mining and processing capital costs of an IPR operation are significantly lower than that of SLOS. IPR benefits from lower direct operating cost, despite lower recoveries and a higher number of stopes in operation to equate the production rate of SLOS. Lowered haulage and the reduced amount of development were the main contributing factors to the cash cost saving. A sensitivity analysis was performed to assess the response of net present values (NPV) to copper grade, operating cost, initial capital cost, and copper price. The results showed that SLOS is more sensitive to all four parameters. Hence, for an increase in head grade or copper price SLOS is more profitable, while at lower grades and copper prices IPR is more profitable. While an optimum technology choice can only be made upon detailed consideration of the relevant facts for each specific project, the economic assessment in this work revealed that at low grades of copper an IPR operation is more profitable than conventional SLOS method due to the reduced operational cost and initial capital investment. As the stope configuration in IPR can be aligned with conventional mining methods, there is scope to run a hybrid operation where high-grade ore is mined and processed conventionally, and the low-grade ore is recovered through IPR. This allows the IPR technology to be an addition to an existing operation.

Environmental concerns such as greenhouse gas emissions, energy consumption, water consumption, and land disturbance play a governing role in restricting future operations. The environmental impacts of IPR were compared to conventional underground (UG) and open-pit operations combined with either pyro- or hydro-metallurgical processing. When comparing the CO_2 per tonne of Cu for a range of mining-processing streams, IPR with solvent extraction/electrowinning (SX/EW) is significantly less polluting than a surface mining operation with heap leach pads and SX/EW or an underground operation with concentrators, smelter, and electro refining. Technologies such as IPR allow the targeted extraction of metals from the ground resulting in significantly reduced land disturbance and other environmental impacts. The technology could be a significant contributor in underground operations achieving a net zero target by 2050.

Keywords: underground mining, Copper, In-Place Recovery, Cash Flow analysis, Environmental impact

INTRODUCTION

Population growth, increase in living standards, and transition to green energy through electrification is anticipated to skyrocket the demand for critical minerals. Meeting this growing demand is made more challenging considering that miners are facing more complex and deeper ore bodies at lower grades. Traditional surface mining methods with a large footprint are becoming unviable economically, and unacceptable socially and environmentally, resulting in a transition to underground operations. Yet, increased sustainability, enhanced efficiency, waste reduction, and a strong focus on safety requires the underground mining industry to look at cleaner approaches to meet the growing demand and ESG (Environmental, Social, and Governance) requirements. Both costs and the environmental impacts of conventional mining methods rise noticeably with deepening deposits and lowering ore-grades.

In contrast to conventional mining methods, with in-situ metal extraction operations, the mineral is extracted without moving the rock to the surface. In-situ Leaching (ISL) consists of the underground circulation of a solvent (lixiviant) through an ore deposit with sufficient permeability, dissolution of target metal(s) forming a pregnant leach solution (PLS) and pumping the PLS to the surface. The metal is then recovered from the fluid at a surface processing facility. Limited permeability affects the exposure of the ore minerals to the lixiviant, reducing recovery. While there are several permeability enhancement technologies available that can aid metal recovery from naturally permeable formations, there are no ISL operations in production for low permeability hard rock deposits. A means of leaching hard rock deposits in-place is to access the deposit through conventional underground mine development, blast the ore in a stope, dissolve the metal-bearing minerals within the stope using an appropriate leach solution, and pumping the PLS to the surface for further processing. While the application of this In-Place Recovery (IPR) technology is described in this paper in relation to copper recovery this concept is not limited to copper but extends to other base metals such as nickel and cobalt, and precious metals such as gold.

The type of ore being mined is a deciding factor in how the elemental metal(s) are extracted from the mineralogy. The two common processing routes for extracting base metal from its ore can be described as the pyrometallurgical route and the hydrometallurgical route. The pyrometallurgical process consists of beneficiation (crushing, milling and floatation) and smelting while the hydrometallurgical route involves leaching the metals from the ore followed by solvent extraction or an ion-exchange process. The hydrometallurgical path is often selected for oxidised minerals, whereas primary sulphides cannot be easily dissolved in aqueous solutions and are typically extracted via the pyrometallurgical path. However, miners face penalties when selling concentrates with high levels of impurities to smelters since certain elements (e.g. lead, arsenic and mercury) cause issues, such as occupational health exposure of smelter workers, increased operating cost by necessitating removal processes, increasing disposal cost, and reducing cathode purity. The smelters often blend high impurity concentrates with “clean” concentrates to dilute the level of impurity. However, with the growing level of impurities and shortage of adequate clean concentrates, diluting is becoming more challenging for smelters(1).

The majority of metal produced through hydrometallurgy is via heap leaching, consisting of building head pads with crushed/agglomerated/cured ore, and percolating leach solution through the heap pads by gravity. Heap leaching operations are vulnerable to weather conditions. Daily and seasonal temperature fluctuations, rain, snow, and storms can potentially have detrimental effects on the performance of a heap leaching process. The overall metal recovery depends on the sweep efficiency, as defined as the fraction of metal bearing species contacted by the leach solution, and the metal dissolution governed by the leach kinetics.

Hydrometallurgical treatment has found extensive application for leaching copper from copper oxide and secondary sulphide ores using acid solutions due to its simplicity, relatively high extraction recovery, low capital and operating cost, and ease of operation. Secondary sulphides can suffer from slow dissolution of copper, which can be improved through the work of microorganisms, termed bioleaching. Hydrometallurgical processing reduces the marketing risk associated with high-impurity concentrates(2). On the other hand, leaching copper from primary copper sulphides is at the early stages of development and research. The slow dissolution rate and formation of a passive layer, hindering further recovery, has encouraged mine operations to select pyrometallurgical process for such ore types. Also, leaching typically does not recover any precious metals as by-products from the ore, and high acid consuming gangue minerals can increase the operating cost and detrimentally effect leach performance.

IN-PLACE RECOVERY

The concept of forming an underground 'heap' of broken ore which is leached within the mining operation is not new. Middlin and Meka[3] reported on the successful underground heap leaching at the re-started Mammoth Mine near Gunpowder in Queensland. The operation employed long-hole stoping to blast the sulphide ore, and utilised bioleaching to recover ~5000-6000 tpa of LME Grade 'A' in the first few years of operation. Bioleaching was also applied in a stope leaching trial of a sulphidic ore at Ilba Mine in Romania[4]. The stope was 10 m long, 10 m high and 1 m wide (the thickness of the ore vein), and dipped at 75°. However, the field trial recovery was lower than what was achieved in the laboratory due to only the top portion of the stope leaching as the dip angle caused the lixiviant to flow down the footwall for most of the stope, this also resulted in loss of lixiviant. In 1994 the U.S. Bureau of Mines[5] posted a bulletin on stope leaching in underground mines to reduce surface environmental impacts from underground mining. O'Gorman[6] proposed a large-scale low-cost mining method where a relatively shallow ore body has underground development to access the bottom. The deposit is then drill and blasted from the surface, and the lixiviant irrigated on the surface and the PLS recovered from the underground workings. Broken ore is slowly removed from underground to eliminate channelling and enhance the contact between the ore and the lixiviant (sweep efficiency).

More recently Orellana[7] assessed the feasibility of an IPR operation for two deposits, Tkoi and Quetena, in Chile. Various stope configurations were assessed based on operating cost and operability. Costing of the operations were based on data from two sub-level open stoping operations in Chile. Previous studies for the deposits found them uneconomical for conventional underground mining methods, and an open-pit operation with heap leach would not be sufficiently profitable. Orellana showed that an IPR operation would be more profitable than the proposed open pit mine. Mining3 coined the term In Mine Recovery (IMR) for IPR and conducted a thorough analysis of the potential to utilise IPR in conjunction with a conventional stope mining operation to increase the net present value (NPV) of the operation[8]. A reserve block model was generated for a hypothetical deposit and a mine planning model created and applied to the block model to sequence which stopes should be mined conventionally or using IPR to maximise the NPV. Including IPR in the operation significantly increases the number of stopes mined, due to IPR being more profitable for lower grade stopes, and increases the profitability of the operation. The value of the project was found to be very sensitive to the assumed metal recovery.

A method of creating stopes of broken rock for leaching in an IPR operation based on the remote ore extraction system (ROES)[9] provides a safe means of automating the drill and blast process[10] (Figure 1). ROES is a mechanised variant of the Horidiam mining method, where horizontal rings of blastholes are drilled and blasted from within a raise while retreating vertically upward. Further work demonstrated other methods of blasting ore bodies to provide broken stock for leaching[11].

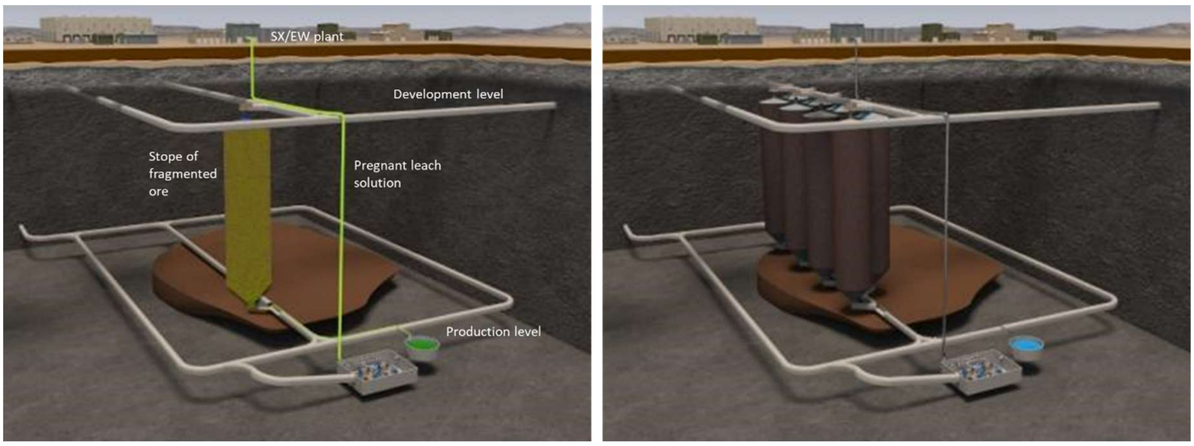


Figure 1. Example of a single stope (left) and array of primary production stopes (right).

Rossien[12] completed an economic study of IPR and determined the NPV for a hypothetical copper deposit, the presentation of the NPV data and sensitivity analysis in the paper was considered very clear and thus the format was utilised by the authors in this paper. A second part of the study assessed the value of IPR, conventional underground, and an expansion of the current open pit, to access ore beyond the current ultimate pit limit for an Australian gold mine. IPR was the only method to return a positive NPV for the deposit, however, the grade distribution and the requirement not to mine up to the existing pit shell made it difficult to maximise the recovery of the higher-grade ore with the IPR stopes.

The above brief history of IPR highlights the care that needs to be taken when conducting trials. The desktop studies show the potential economic benefit of developing IPR operations alongside or instead of conventional mining methods. Despite the lower metal recovery of IPR leaching operations compared to conventional mining with beneficiation and smelting, the lower capital and operation costs of IPR allows for the economic extraction of lower grade ore.

The following study makes a direct economic and environmental comparison of IPR and a conventional underground sub-level open stoping operation for a hypothetical copper deposit. An analysis which has not been undertaken in the previous studies.

CASE STUDY

Sub-level open stoping (SLOS) is a common underground mining method that is utilised in hard rock metal mines. SLOS has the potential to produce stopes full of broken stock, therefore, it is a readily transferable mining method to IPR. As such a case study based on SLOS, with a directly transferrable mine development infrastructure and cost, allows for a directly comparable cost analysis between SLOS and an IPR design utilising the open stoping method. Further there are two large, well-documented, SLOS operations, BHP's Olympic Dam and OZ Minerals' Prominent Hill, both in South Australia, to utilise in developing a case study.

To develop the alternative mining methods, a common target of 50,000 tonnes per annum of copper concentrate/metal was selected with an initial head grade of 1% copper. All methods utilise a decline as the access to the deposit with all the required ore trucked to the surface. For a decline angle of 7° (1 in 8), to achieve a depth of 500 m, will require approximately 4 km of decline.

For the SLOS method (Figure 2), assuming 90% recovery in creating the concentrate and 5% dilution during excavation, requires 5.8 million tonnes of ore mined per annum to achieve 50,000 t Cu per annum. The operation will use 60 tonne capacity dump trucks at a rate of approximately 11 trucks per hour to move the required ore.

Stopes are 100 m high and 100,000 m^3 in volume, with a nominal width and depth of 32 m, and assuming an ore density of 3 g/cc, containing 300,000 tonnes. Therefore, to achieve the production target 19 stopes will have to be recovered per annum. Rather than go to the detail of calculating the individual development requirements per stope, a generalised development of 450 m per stope was derived based on the data from Uggalla[(13)] on the requirements for Olympic Dam.

The stopes have a sublevel spacing of 50 m, therefore up and down blasthole ring designs have a nominal 25 m ring height. A generalised blast design with 115 mm diameter blastholes on a ring pattern of a 3 m burden and 4 m toe spacing, charged with bulk emulsion, and fired with electronic initiation was used for drill and blast costings.

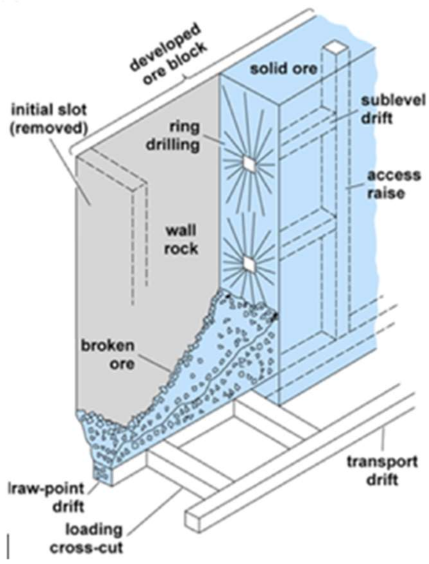


Figure 2. Example configuration of a SLOS operation, after[(14)]

For IPR, assuming an initial recovery of 50% from the leaching operation, requires 10,000,000 tonnes of ore to be in production per annum to achieve the target copper metal production of 50,000 tonnes, using the same initial head grade. It has been assumed that 20% of the ore in the stopes will be trucked to the surface, and processed in surface leach pads, to ensure sufficient void to effectively blast the remaining material in the stope.

The stope height is kept at 100 m, however, due to the required tonnes of ore to leach, the stope volume was increased to 200,000 m^3, with a nominal width and depth of 45 m, and 600,000 tonnes of ore in each stope.

Three blast design methodologies are proposed to achieve the desired fragmentation and swell to generate an effective leach environment within the stopes (Figure 3). The first method uses conventional long-hole stoping (LHS), whereby rings of blastholes are vertically orientated, similar to SLOS, however, without the sublevel and using longer blastholes, with a ring height of 50 m compared to 25 m for SLOS. As with SLOS a vertical slot will be blasted and excavated, to create the 20% void, and the rings fired into the slot. The designs can be fired with conventional electronic initiation systems, or potentially more effective designs could be fired in part with wireless initiation. The second method is an adaptation of the ROES concept where a large diameter raise is excavated up the middle of the stope, a platform is lowered into the raise, with remote drilling of the horizontal rings of holes[10]. An automated charging system loads all the holes with wireless primers and bulk explosive prior to blasting. The rings are blasted downwards in stages, with the drawbell being fired first. After each blast a small amount of material is extracted at the production level to provide relief (void) for the next stage to blast into. In the third method, again a raise bore is excavated between levels, however, with a smaller diameter than is required with the ROES technique as it is only providing void for blasting, not access to the stope[11]. Then a pattern of vertical large diameter holes (LDH), up to 229 mm in diameter, are drilled with a mobile raise bore rig around the raise. All the blastholes are loaded with wireless primers in multiple decks of bulk explosive separated by inert stemming prior to blasting. Each horizon of explosive charges is a stage which are fired sequentially from the bottom up.

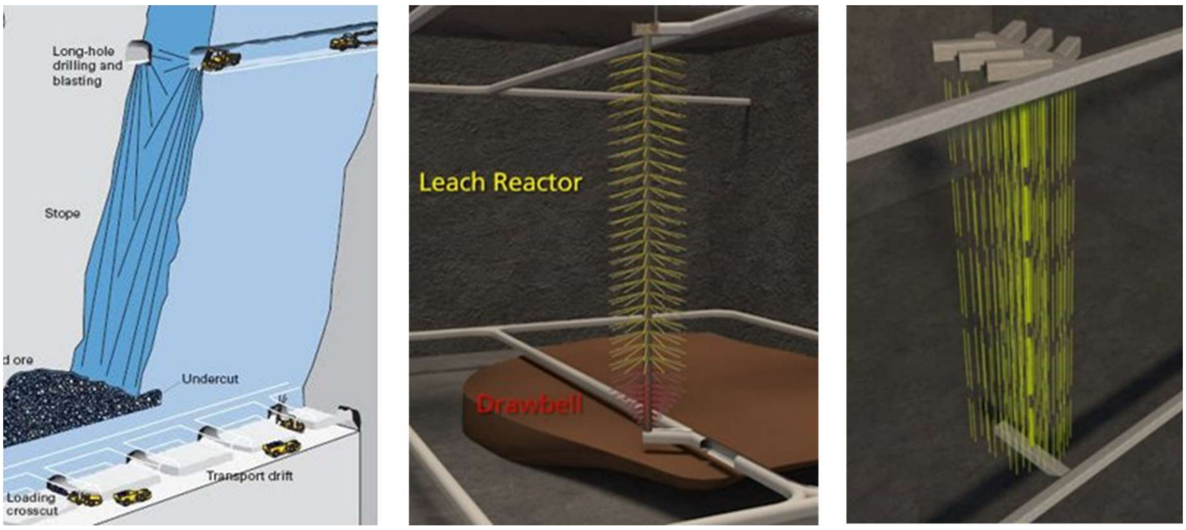


Figure 3. Design options for IPR, long-hole stoping (left, after[15]), remote ore extraction system (middle), and large diameter holes (right).

A summary of the blast design parameters for the four designs (Table 1) highlights the increase in powder factor for IPR compared to SLOS, as the IPR designs will require finer fragmentation for effective leaching compared to typical stope blasts. Correlating blast fragmentation particle size distribution to leach recovery and rate is beyond the scope of this study, therefore, the powder factors selected for IPR were based on changes in pattern that can be easily implemented, while maintaining the hole diameter in the LHS and ROES designs compared to SLOS.

Table 1. Summary of blast design parameters.

Design	SLOS	IPR		
		LHS	ROES	LDH
Stope size (t)	300,000	600,000	600,000	600,000
Burden (m)	3.0	2.0	2.0	4.5
Spacing (m)	4.0	4.0	3.0	4.5
Hole Diameter (mm)	115	115	115	229
Powder Factor (kg/t)	0.34	0.72	0.65	0.55
Drill Factor (t/m)	22.0	10.6	12.6	75.1

Economic Assessment

The operating cost (i.e., cash cost) consists of direct operating cost, sustaining capital cost, and indirect operating cost. Direct operating cash cost consists of drilling, blasting, backfill, load and haul, ventilation, and dewatering. It is apparent that the direct operating cost is a function of mining method and drill and blast design. Sustaining capex refers to the on-going cost of development in the underground area. Indirect operating cost including maintenance, and general and administration (G&A) have been calculated as a percentage of direct operating cost. The total operating cost of the mine is then added to the operating cost of the mineral processing plant.

Insurance, working capital, and deferred capital have not been included in this analysis.

Capital Cost

A significant portion of the initial mining capital cost is the same between SLOS and the IPR mine designs. For example, the ventilation shafts, dewatering station, and surface facilities are taken as the same (Table 2). Due to the significantly less ore being trucked to the surface in the IPR designs the size of the decline is taken as 5.5 m by 5.8 m compared to SLOS with a 6.0 m by 6.5 m decline, with costs of 7,000 and 9,000 $/m, respectively. The IPR mobile equipment costs were reduced by 50% of the SLOS costs considering the trade-off between the reduced ore movement and increased drilling requirement. Less ore movement to the surface results in reduced capacity and truck fleet size. However, extra capex has been allocated to consider increased production drill requirements to blast more ore at higher powder factors compared to SLOS. The engineering & management, and contingency costs were taken as percentages of the sum of the previously derived costs. Overall, the capex for IPR is approximately 25% less than that for SLOS.

To compare the capital investment requirement for hydro- and pyro-metallurgy operations side by side data from Centinela Chilean copper operations, that have both processing plants, was obtained from Wood McKenize[(16)] asset reports. This effectively normalises against variations in design, sourcing, and fabrication. The pyrometallurgy plants cost more than double the hydro plants and the data was extrapolated using the factored cost estimate to derive the data in Table 2.

Table 2. Summary of capital costs for SLOS vs. IPR.

Design	SLOS	IPR
Mining ($M):		
Decline	36.6	28.5
Three Ventilation Shafts, each	7.0	7.0
Dewatering Station	15.0	15.0
Surface Facilities	20.0	20.0
Mobile Equipment	60.0	30.0
Engineering & Management	26.0	19.5
Contingency	30.5	22.9
Mining Total	209.1	156.9
Processing Total ($M):		
Beneficiation Circuit	824.0	-
Small-scale Heap Pad	-	18.7
SX/EW	-	341.0
Lixiviant Pumping	-	5.0
Transport	15.0	10.0
Processing Total	839.0	374.7
Mining & Processing Total ($M)	1,0448.1	531.6

Operating Cost

The metres of development ($5,000/m) and ventilation requirements per stope for the SLOS was taken from Uggalla[13]. Despite the larger stope sizes in IPR compared to SLOS, the amount of development tunnels required to access the IPR stopes is considerably less due to the lack of any sub-level development required and an overall reduction in ancillary development. Therefore, the IPR development requirement was reduced by 70% (of SLOS) for the LHS and ROES designs, while for the LDH more development will be required at the production level to drill the vertical blastholes (Figure 3) and development was taken as 80% of SLOS. The ventilation requirements for IPR were reduced from the SLOS value by the same percentages as used for the development requirements. The main fan energy requirements were derived from Morla *et al*.[17].

It is common to present mining costs as $/t of ore mined, however, as the mining costs and percentage recovery of metal from the ore are very different for the two mining methods, a more meaning full comparison is $/t copper. Drilling costs were derived from the production drill metres required for the blast designs (Table 1) multiplied by the relevant drilling costs, taken as $40/m for a 115 mm diameter hole, and $200/m for the 229 mm diameter holes in the IPR-LDH design. Blasting costs were derived from the list price of detonators, primers and bulk explosives for the relevant blast designs, and a nominal charging labour cost of $10/m. Backfill costs were determined assuming 60% of the void in the stope is filled with cemented rock fill at $8/t. Haulage costs used data from Orellana[7] at $0.8/t-km, assuming a round trip of 10 km. The ventilation and dewatering costs used a grid power cost of $0.14/kWh. The auxiliary mine ventilation costs were taken as 10% of the main ventilation costs. Maintenance was taken as 28%, G&A 19%, and indirect costs 20% of the combined sustaining capital and direct operational cost. Maintenance includes upkeep of all fixed and mobile plant. G&A includes water treatment, environmental and camp costs. Indirect costs include, auxiliary electrical, process water, underground upkeep, and reconditioning.

The derived total mining operating costs (Table 3) show that all the IPR drill and blast techniques assessed have a lower cost than SLOS. Within the IPR methods the LDH has the potential to have the lowest cost, however, the technique is also the most novel. The ROES method has the highest cost of the IPR techniques, this is for the most part, due to the high cost of developing the large raise bore in the stope.

Table 3. Mining operating costs.

Design	SLOS	IPR		
		LHS	ROES	LDH
Stope size (t)	300,000	600,000	600,000	600,000
Stopes mined per annum	19	17	17	17
Development per stope (m)	450	315	315	360
Water ingress (m^3/day)	5,000	6,000	6,000	6,000
Dewatering energy (kWh/day)	14,340	17,210	17,210	17,210
Ventilation airflow (m^3/s)	2,683	1,610	1,610	1,610
Vent. power – main (kW)	6,707	4,024	4,024	4,024
Vent. energy – main (MWh/annum)	58,750	35,250	35,250	35,250
Sus. CAPEX – development ($/t Cu)	833	525	525	600
OPEX – direct ($/t Cu)				
Drilling	202	751	1,039	799
Blasting	152	507	533	205
Backfill	533	192	192	192
Load	556	200	200	200
Haul	905	326	326	326
Ventilation – main	157	99	99	99
Ventilation – aux.	16	10	10	10
Dewatering	14	18	18	18
Sub-total	2,534	2,102	2,416	1,848
OPEX – indirect ($/t Cu)				
Maintenance	941	734	822	684
G&A	644	502	562	468
Indirect costs	674	525	588	490
Total	5,626	4,389	4,913	4,090

For mineral processing operating costs associated with leaching, Table 4 assumed an acid consumption of 3 t/t Cu[1]. The acid price was set at $210/t, equating to $630/t Cu. Ferric ion concentrations were set at 6 g/l, based on Talyor[(18)], requiring Ferric sulphate at a cost of $3.6/t Cu, based on a unit cost of $200/t. PLS concentration was assumed to be 3.5 g/l[(18)]. Based on a head height of 500 m, PLS pumping will require 75.6 MW/day at a cost of $77/t Cu. The final leaching cost included 20% contingency.

The hydrometallurgical SX/EW and G&A costs, and the pyrometallurgy beneficiation (milling and flotation) and G&A costs were derived from the summary data from Chilean operations[(16)]. To express all the costs in terms of $/t Cu, an ore grade of 1% and copper recovery of 90% for SLOS and 50% for IPR were assumed. To compare the total cost of *copper cathode* production, the costs of transporting the concentrate from the plant to the smelter and the cost of smelting have been added to the pyrometallurgy route. Transport cost is a rough estimate only as it highly depends on the distance of the mine to the port and the smelters, and available transport options.

For this example of mineral processing operating costs (Table 4), from run-of-mine to metal cathode, the hydrometallurgy process is nearly 30% less expensive than the beneficiation/pyrometallurgy process. Within IPR mineral processing, the largest cost is in the leaching, specifically the acid consumption. While in pyrometallurgical processing the largest cost is in milling, specifically the energy consumed in grinding.

[1] Acid consumption depends on ore mineralogy, gangue composition, ferric ion solubility, jarosite precipitation, irrigation rate, permeability, required PLS acidity, and microorganism activity (in case of bioleaching).

Table 4. Mineral processing operating costs.

Design	SLOS	IPR
Hydrometallurgy ($/t Cu)		
Leaching		857
SX/EW		747
G&A		363
Hydrometallurgy Total		1,966
Pyrometallurgy		
Beneficiation	1,267	
G&A	232	
Beneficiation total	1,499	
Transport	320	
Smelting	900	
Pyrometallurgy Total	2,719	

The total operating costs (Table 5) combine the total mining operating costs (Table 3) and the total mineral processing operating costs (Table 4). The IPR-LHS method has an operating cost that is over 20% less than SLOS. The operational cost breakdown is consistent with the cost distribution provided by Rossien(12).

Table 5. Total operating costs.

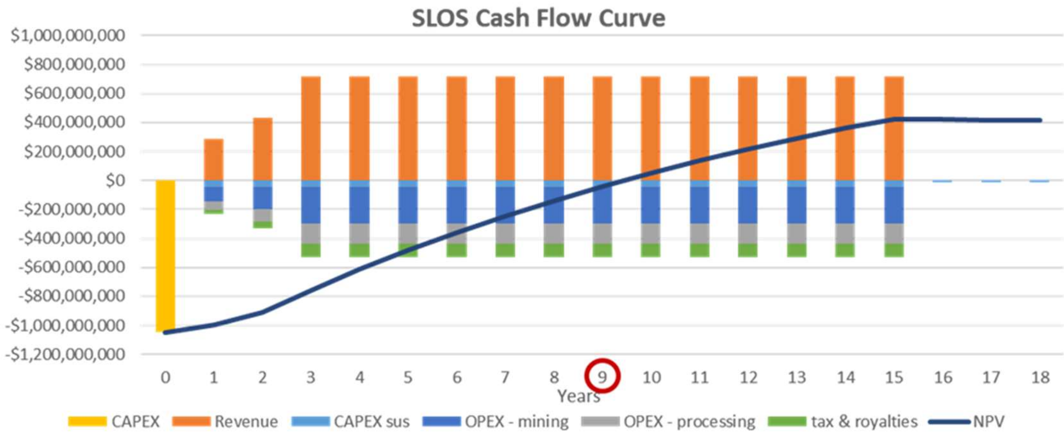
Design	SLOS	IPR		
		LHS	**ROES**	**LDH**
OPEX – Total ($/t Cu)	8,345	6,355	6,880	6,056

Cash flow analysis

A first-pass economical model was constructed for the case study, enabling NPV and input sensitivity analysis to be performed for the two mining methods. The model assumes a 15-year life-of-mine, with three years of mine closure costs at $10M per annum, costed as sustaining capital costs, after production has ceased. The tax rate was set at 27.5%, with a discount rate of 7.5% and royalties at 2%. The copper price is set at $12,000/t.

The SLOS mine is assumed to ramp up to full production over three years, while the IPR-LHS is set to take four years to reach full production (Figure 4). While the two mining methods were designed to produce the same amount of copper per year in full production, the SLOS has higher revenue due to the assumed gold and silver credits from the smelter at $1,700/t Cu, also the IPR-LHS has reduced revenue due to solution losses within the stopes, assumed to be 5%.

The SLOS operation has a final NPV of $415M and a pay-out time of nine years, compared to the IPR-LHS operation with an NPV of $689M and a pay-out time of six years.



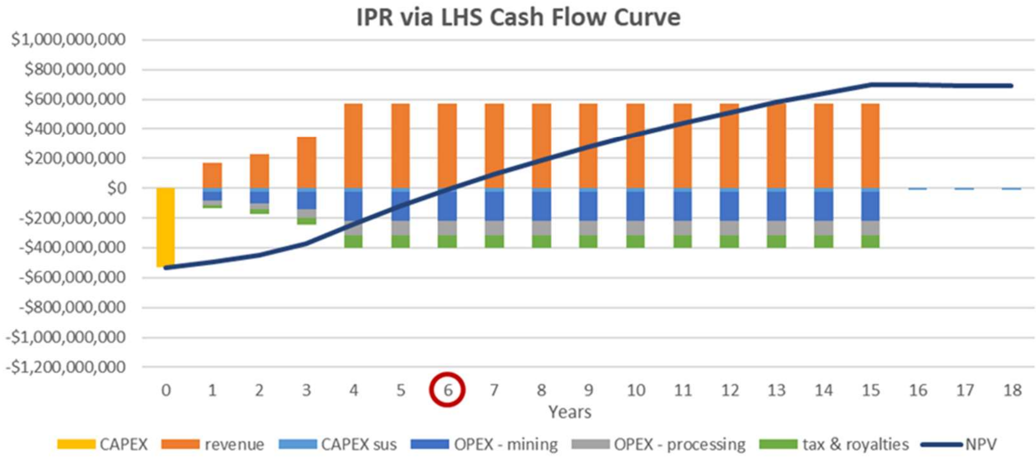


Figure 4. Comparison of cash flow curves for SLOS and IPR-LHS.

With a basic economic model constructed it is possible to perform a sensitivity analysis on a range of input parameters to determine their relative impact on the profitability of the operation. To make a clear comparison of the sensitivity analysis between the two mining methods it was considered pertinent to adjust the head grade of the deposit until the NPV's matched. This was achieved at a grade of 1.35% Cu for an NPV of $1,540M, below this grade IPR is more profitable, and above it SLOS is. The grade to match NPV's is specific to this example case study, however, the trend highlights IPR as more profitable at lower grades, due to the lower recovery and mining costs compared to SLOS. Comparing the sensitivity analysis (Figure 5), the higher capital and operating costs of the SLOS naturally are more sensitive to changes in those costs compared to IPR. SLOS is also more sensitive to grade and copper price than IPR, hence SLOS is more profitable in higher grade deposits. While IPR is more suitable to lower grade deposits with less selective stope development. For both analysis the profitability is most sensitive to the copper price, the one parameter that the operation has no control over. The operations are marginally less sensitive to grade than the copper price, hence the importance of an accurate block model and grade control program. For IPR the sensitivity for recovery is the same as grade, the recovery line in the graph has been offset a little from the grade line to improve visibility.

While in this paper, a greenfield IPR project was studied economically, the application of IPR in brownfield operations also has massive potential by increasing the total recovery and extending the mine-life, especially for less attractive mineralisation where conventional mining is uneconomic.

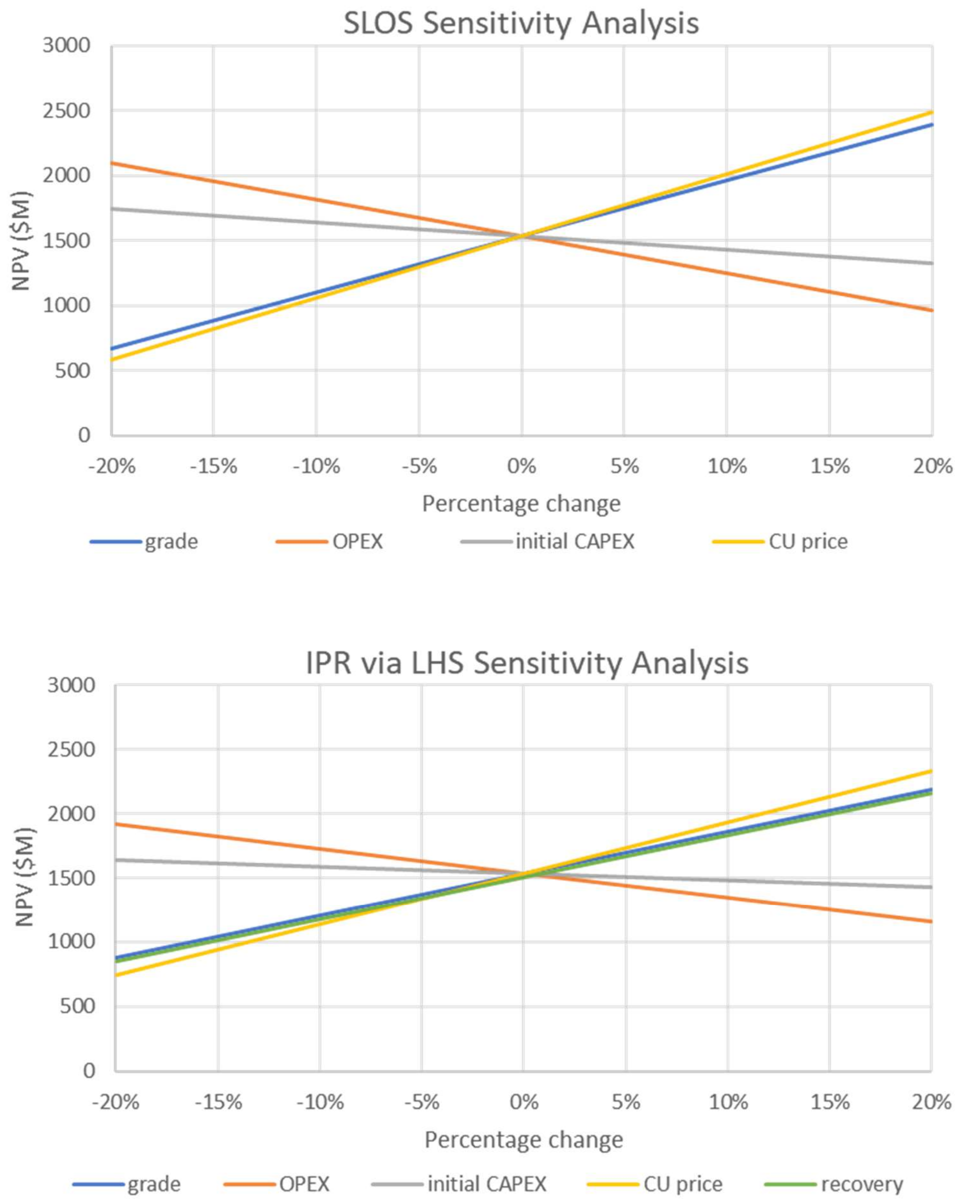


Figure 5. Comparison of NPV sensitivity analysis.

Environmental Impact Assessment

Compared with a conventional copper extraction operation, metal extraction via IPR requires minimal rock haulage and eliminates the need for costly beneficiation circuits. Some of the significant environmental advantages of IPR compared to conventional mining are as below:

- Increased safety due to reduced exposure to hazardous areas.
- Reduced energy consumption and greenhouse gas (GHG) emission due to reduction in material extraction and elimination of underground crushing and conveyance system, and elimination of the comminution circuit.
- No tailing generation
- Reduced land disturbance with much smaller surface footprint
- Reduced backfill
- Reduced dust emissions
- Lower noise level

From an environmental point of view, products and processes can be quantitatively compared through a Life Cycle Assessment (LCA) in terms of various impacts such as global warming and water use. Global warming impact is a function of both the energy consumption, and the source of energy. It is apparent the application of diesel generators and diesel-operating equipment contribute to much higher GHG emissions, and therefore, higher global warming impacts, compared to other power sources. Water use (or water footprint) is another crucial environmental indicator based on quantity of water used and its direct and indirect associated impacts.

GHG Emissions

An open-pit mining operation with Leach/SX/EW emits approximately 2.84 tonne of CO_2 per tonne of Cu, while an underground mining operation with Concentrator/Smelter/ER results in 3.3 tonne of CO_2 per tonne of Cu. It is worth noting that the values presented here are based on an average of all copper operations in Chile in 2018 which is consistent with the average literature data(19).

For an IPR copper operation, the GHG emissions of the underground operation is less intense than a conventional underground mine as much less material is extracted and transferred to the surface. With regards to leaching, the GHG emissions associated with building a heap pad including primary crushing, agglomerating, and conveying or haulage of rock will be reduced by at least 80%. However, indirect GHG emissions from pumping the lixiviant needs to be considered. The overall GHG emissions for IPR has been derived at 1.6 ± 0.4 tonne of CO_2 per tonne of Cu, which is up to 50% lower than the emissions from open-pit mining/heap leaching or underground mining/smelting operations.

Water consumption

In a beneficiation circuit, flotation is carried out at 25 to 40% solids, consuming between 1.5 to 3 m^3/ton of ore(20). In some operations, water is used to transport the concentrate as a slurry. In this case, the water used for pumping the concentrate represents 4-6% of all the water consumed in the concentrating plant(21). After delivering the slurry near the port, the water is separated through thickening and filtration prior to transporting the dry concentrate (at 10% moisture) to smelters. Depending on the distance and elevation difference, the recovered water may or may not be recirculated to the process. Nonetheless, a large portion of water used in flotation is carried over to tailings. Water recovered during thickening of the tailings and from tailing dams can be recirculated to the flotation. Yet, up to 15% of the water in tailings can be lost due to evaporation(20).

The concentrate is then dried to below 0.2% moisture content prior to smelting. At the smelters, water is used in oxygen production, cooling the produced gas during the fusion, and in the sulphuric acid plant. Depending on the closeness to the sea for sourcing cooling water, the water consumption varies. Average water requirement for smelting in Chile is around 3.6 m^3/tms[2] of cast concentrate(21).

In the hydrometallurgical process, water is used in agglomerating, heap leaching, and solvent extraction. Before building the heap pads, the moisture content of the crushed ore is increased to 10% during agglomeration. Depending on the heap pad construction method and weather conditions, significant water can be lost through evaporation off the heap pads and the PLS/LS ponds. In solvent extraction, the organic solution is frequently rinsed resulting in a high volume of water usage. Compared with a heap leaching process, it is expected that IPR will have reduced water consumption owing to elimination of crushing and agglomeration, and significantly less evaporation in an underground environment.

Overall, while the total unit consumption of freshwater in a beneficiation circuit range between 0.3 to 2.1 m^3/tonne of ore, in 2006, water consumption at a typical Chilean beneficiation plant was reported as approximately 0.8 m^3/ton ore enabled via significant water recovery and modern sealed tailings. This value can be further optimized to achieve 0.36 m^3/ton in the best operations. On the other hand, hydrometallurgical plants consume around 0.08 to 0.25 m^3/ton of ore (Santoro, Estay et al. 2021). In 2006, Chilean operations reported to consume only 0.13 m^3/ton through improved solution recirculation and minimising evaporation(21).

An IPR operation should consume less water compared with a heap leaching process given that evaporation will be significantly reduced. However, while the water consumption in terms of cubic

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[2] tms and TMS are two units of mass used interchangeably in reports published by Cochilco for processed ore and copper concentrate. On the other hand, FTM and TMF (ton of fine Cu contained material) are often used to express the mass of copper cathode. However, it is not clear to the authors whether t or T stand for metric tonne or short Ton.

metres per tonne of ore will be lower, in expressing the water usage per tonne of Cu the lower recovery in an IPR operation must be considered.

It is anticipated that water consumption of a copper IPR operation combined with SX/EW processing will be limited to 0.2 m^3/ton of ore. It is worth adding that the water consumptions presented above for pyro- and hydro- metallurgical routes did not include water use for mining. However, the estimated value for IPR/SX/EW consists of both mining and metal production.

From an ESG point of view, copper extraction via IPR has much less detrimental effects on the environment; hence, speculated to facilitate the grant of licence to operate. Additionally, the reduction in capex and opex lowers the cut-off grade allowing profitable extraction of metals such as copper and nickel from deposits which are uneconomic to mine conventionally. This assists with meeting the increased demand for copper and nickel, especially considering the role these commodities play in the transition to low carbon emissions.

FIELD APPLIACTION OF IPR

There are several variables that will influence the recovery rate of metal from a stope that need to be addressed prior to a trial within a specific deposit. As with surface leaching operations a significant program of hydrometallurgy test work from bottle roll to column tests will be required to characterise the ore over a range of lixiviant chemistry and leaching conditions. If long-period circulation of the solvent is required to achieve an economic recovery, the effect of side reactions on permeability fluctuation and short circuiting must be carefully studied over the same period in the laboratory. Blast modelling is also important to determine the fragmentation particle size distribution and heave induced permeability through the stope. And hydrology modelling to determine the fluid flow through the stope for a given modelled permeability, targeting uniform liquid, and gas if required, distribution, and assess the extent of short circuiting (channelling) or fluid entrapment prior to leaching. By combining the blast modelling, fluid flow transport and kinetics (leaching) models, a comprehensive IPR simulation tool can be developed to predict and optimise metal recovery from a stope.

Containing the solution within the stope will be in the forefront of mining operations to prevent potential environmental contamination or loss of leached metal. While the implementation of a barrier can be considered in an ISL operation targeting shallow deposits, many of the available barrier technologies are not suitable for IPR due to the lack of access from the surface. However, it is expected that once a stope within a competent rock mass is fractured, the lixiviant preferably percolates through the broken ore body.

CONCLUSIONS

While the IPR concept is applicable to various metals, this study focused on copper extraction mainly to address the future challenge of accessing lower grade and more complex ore bodies in a sustainable manner. Currently about 80% of copper is produced pyrometallurgically; however, with ongoing developments in leaching technologies and more restrictions on smelting the contaminated concentrates, the portion of copper produced from the hydrometallurgical route is increasing. Advancements in leaching copper from secondary copper sulphides has enabled more penetration of hydrometallurgical processing given its lower capital cost and operating cost requirements. Similarly, enhanced leaching kinetics of primary copper sulphides will broaden the application of IPR in extracting copper from chalcopyrite which is the most abundant copper sulphide mineral.

While an optimum technology choice can only be made upon detailed consideration of the relevant facts for each specific project, the economic assessment in this work revealed that at low grades of copper an IPR operation is more profitable than conventional SLOS method due to the reduced operational cost and initial capital investment.

Nonetheless, economic merits are not sufficient to obtain regulatory approvals for a mining operation. Environmental concerns such as GHG emissions, energy consumption, water consumption, and land disturbance play a governing role in restricting future operations. Operations such as IPR allow the targeted extraction of metals from the ground resulting in significantly reduced land disturbance and other environmental impacts.

Technological innovations in the mining industry are often adopted slowly; however, with increasing attention to ESG and ambitious net zero emission targets, the industry is expected to welcome both incremental and fundamental innovations. On the other hand, to mitigate the risk associated with the high level of uncertainty with fundamental changes, such as adoption of novel mining methods, an appropriate and in-depth pre-feasibility study must be completed. Various experts in the fields of underground mining, copper leaching, blasting, fragmentation modelling, fluid transfer modelling as well as social scientist and consultants must work closely to gain fundamental knowledge and quantify the risk and opportunities. It is also critical to establish and maintain a sustainable and trusted partnership with all stakeholders, especially the local community.

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RENEWED EXPERIMENTAL HYDRAULIC FRACTURING TECHNIQUE FOR HARD ROCK IN-SITU RECOVERY ENHANCEMENT

By

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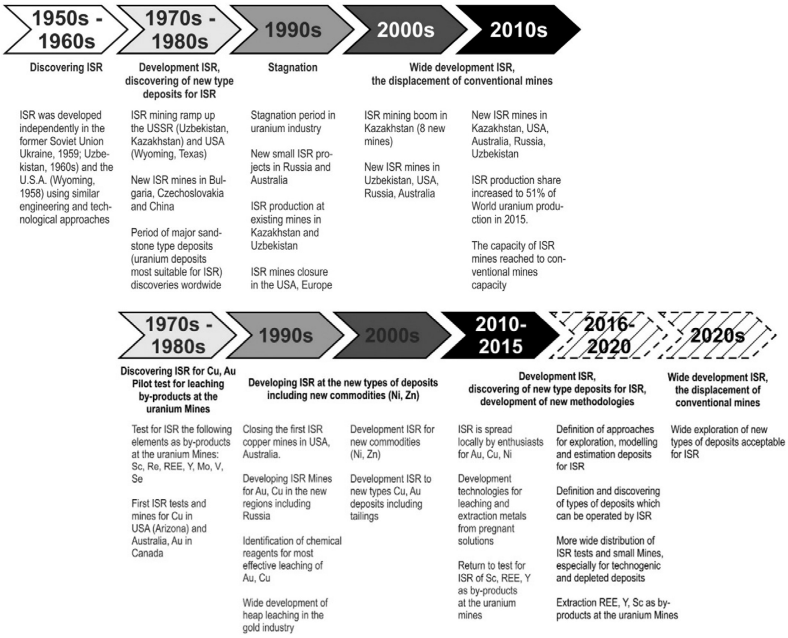
ABSTRACT

Even though the economic feasibility to continue large scale conventional mining operations is still well in place, there has been decades of time during which the mining industry has not observed revolutionary technical advancements. Given the current world economical situations, it can be foreseen that the industry will be reaching a turning point where it must refer to techniques equivalent in production while featuring smaller environmental impacts and lower costs. In-situ recovery (ISR) as a candidate for such resolution, offers an alternative for conventional mining that features a smaller footprint. The production of ISR is dependent on permeability, which can be resolved by artificial stimulation (e.g., hydraulic fracturing, blasting).

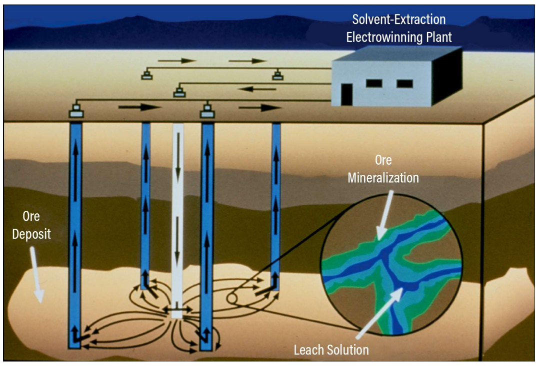
Previously in experimental research on hydraulic fracturing hard rock, the suitability of a deposit for ISR has been discussed, yet conclusions regarding injection flow rate, injection borehole size, and rock mechanical properties' influence when stress is high, remains to be determined. In this work, based on previous experimental research of hydraulic fracturing on hard rocks, further sensitivity analysis of the governing fracturing factors will be reviewed and presented. Similar to previous study, the hydraulically induced fracture geometry, strain data, injection pressure curve and X-ray computed tomography will be compared according to the conditions applied. As a direct output from hydraulic fracturing stimulation, analysis regarding fracture and lixiviant's mineral extraction interaction will also be included. With addition to already extensive number of experiments combining increased range of applied conditions, and experimental data analysis will yield a subjective point of view to evaluate hydraulic fracturing to stimulate ISR under realistic engineering background conditions.

Keywords: In-situ recovery; Hydraulic fracturing.

ISR, developments, limitations and solutions



(M. Seredkin et al. 2016)



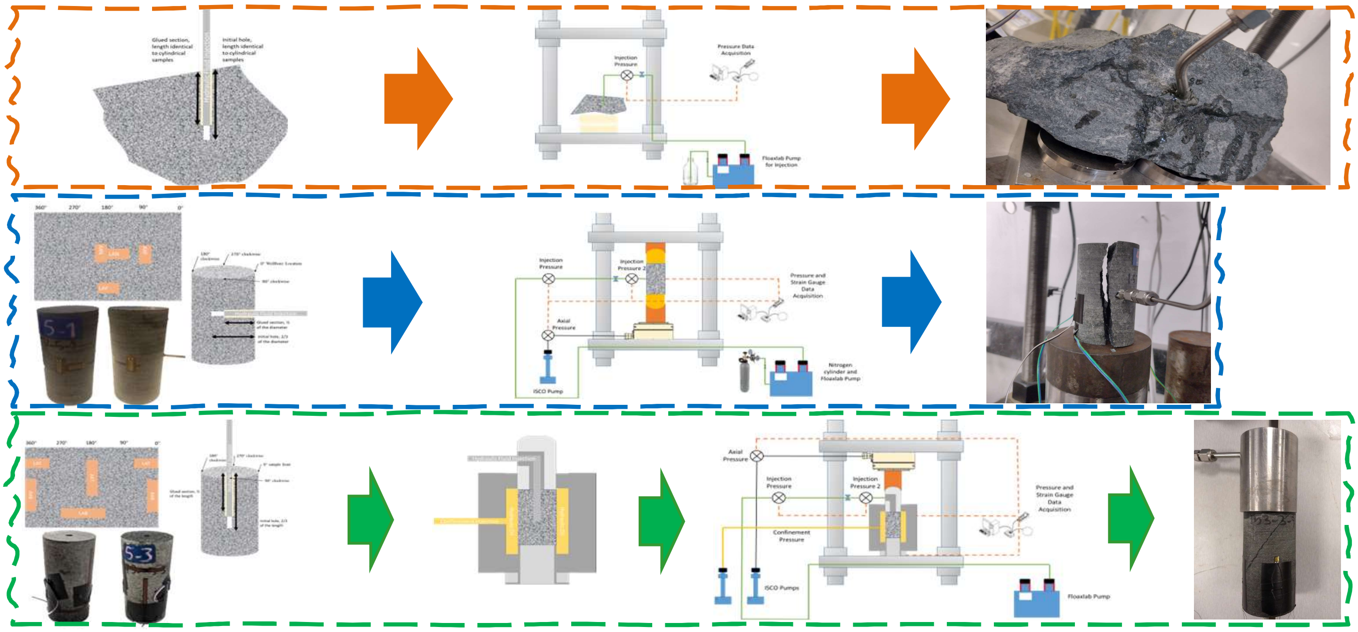
(D. Earley III. 2020)

- Artificial Permeability
  - Other Techniques
  - Hydraulic Fracturing

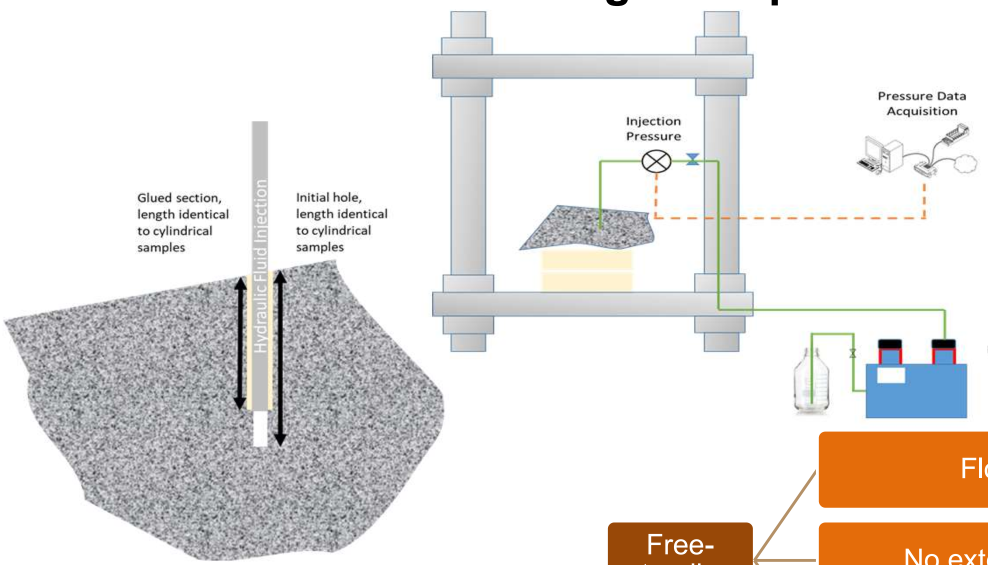
Experimental goals

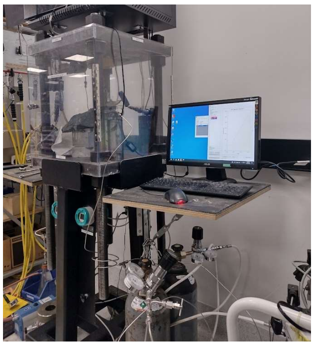
- ?
  - Flow rate — Higher injection rate is in favour of fracturing
  - No external stress
  - Rich in natural fractures — The dominant parameter is natural fractures
- ?
  - Uniaxial stress — Higher uniaxial stress will affect breakdown pressure
  - Brine vs Nitrogen comparison — Gaseous fracturing fluid has equivalent performance of liquid counterparts
- ?
  - Biaxial stress — Stress distribution will alter fracture geometry

Free-standing, Uniaxial, and Biaxial HF experiments



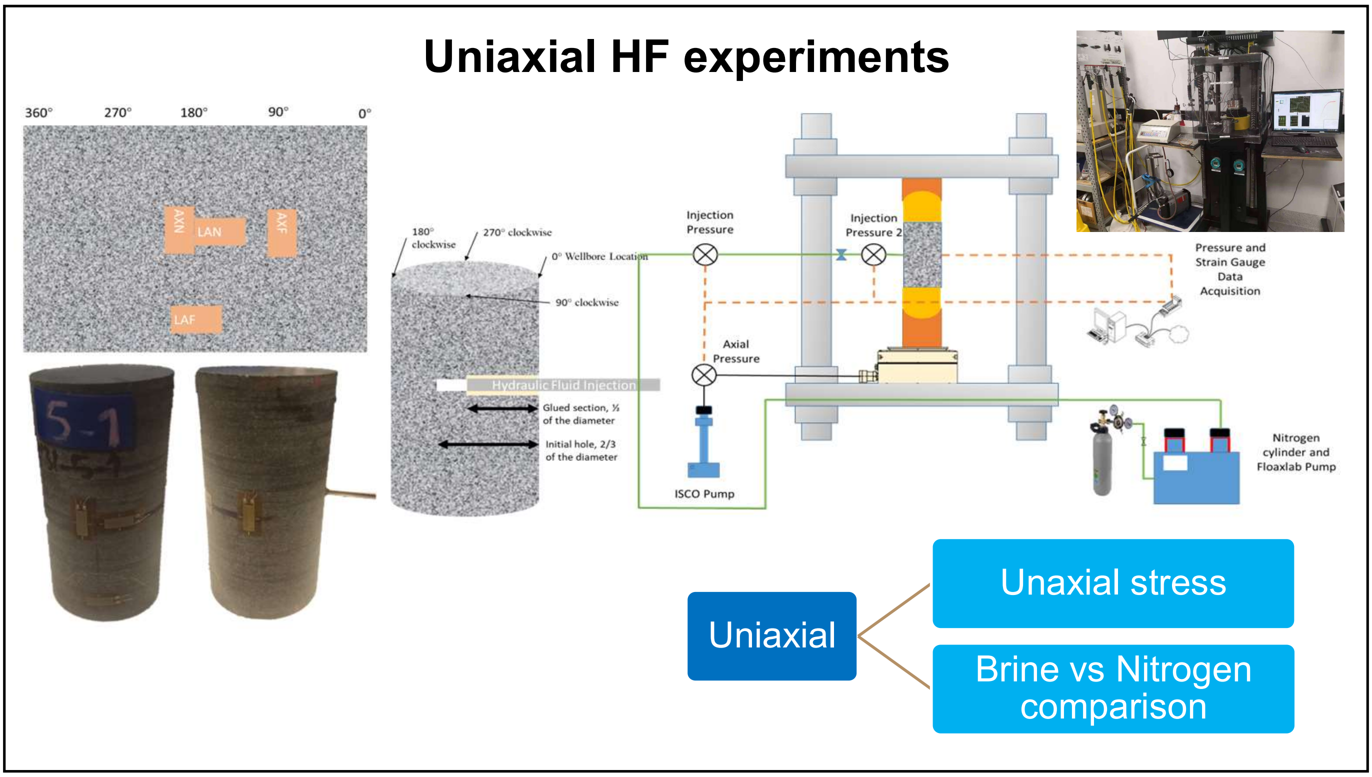
Free-standing HF experiments

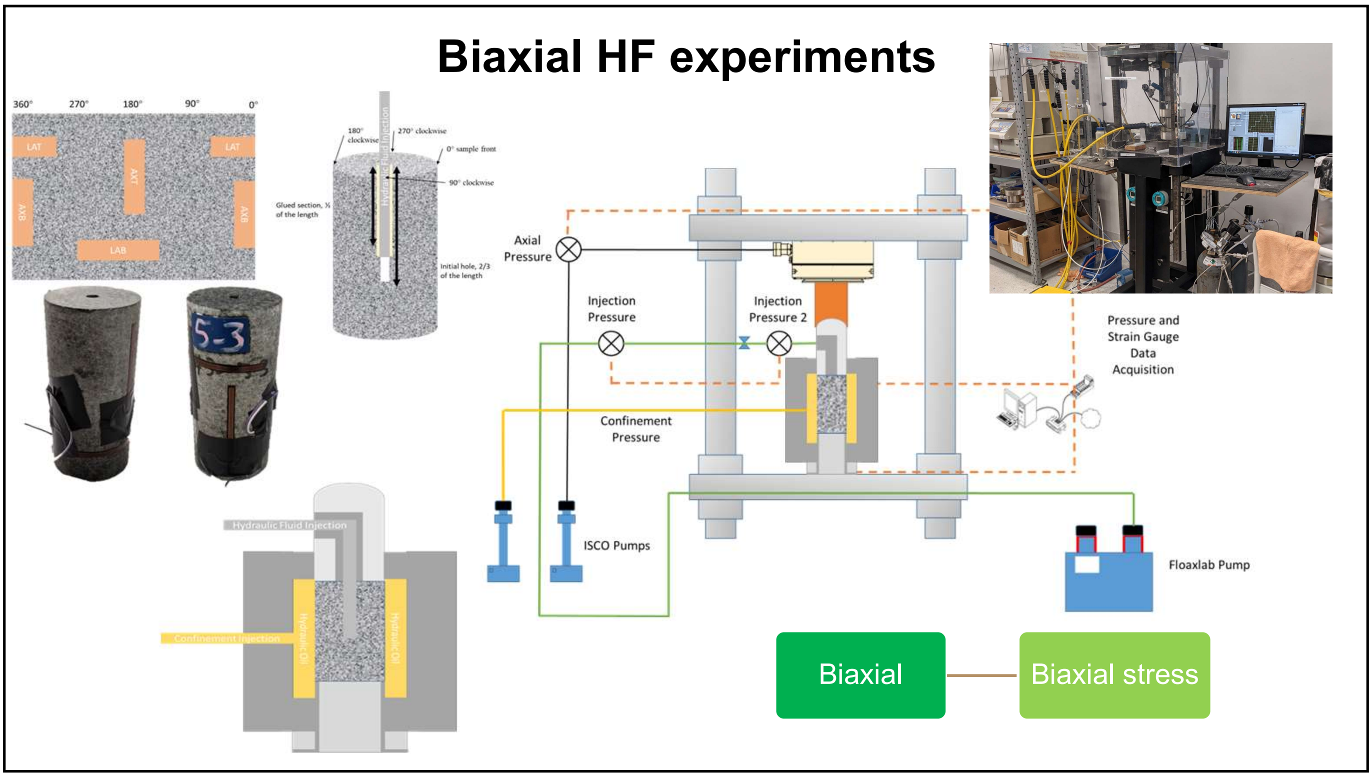




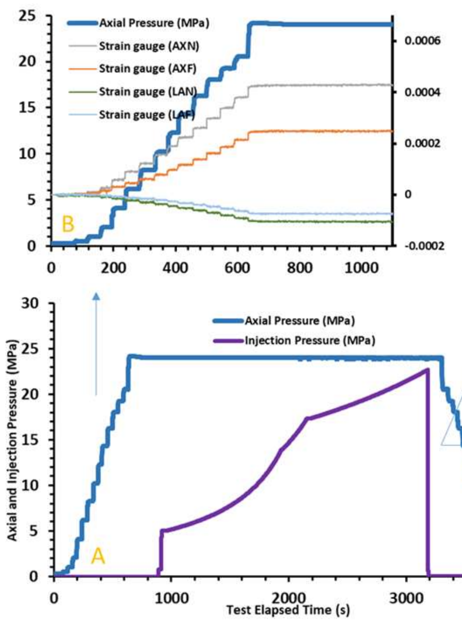
Free-standing

- Flow rate
- No external stress
- Rich in natural fractures

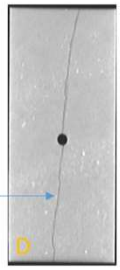

Uniaxial HF experiments
360° 270° 180° 90° 0°
AXN
LAN
AXF
LAF
180° clockwise
270° clockwise
0° Wellbore Location
90° clockwise
Hydraulic Fluid Injection
Glued section, ½ of the diameter
Initial hole, 2/3 of the diameter
Injection Pressure
Injection Pressure 2
Axial Pressure
ISCO Pump
Pressure and Strain Gauge Data Acquisition
Nitrogen cylinder and Floaxlab Pump
Uniaxial
Unaxial stress
Brine vs Nitrogen comparison

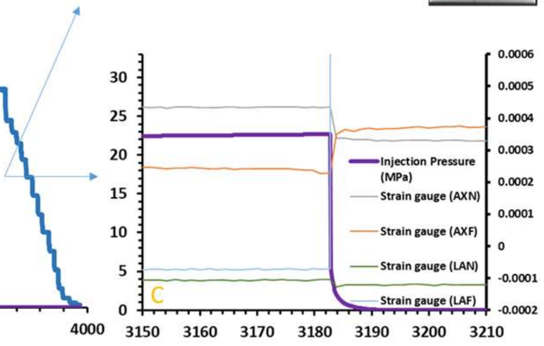

Biaxial HF experiments
360° 270° 180° 90° 0°
LAT
AXT
LAT
AXB
AXB
LAB
Glued section, ½ of the length
180° clockwise
270° clockwise
0° sample front
90° clockwise
Initial hole, 2/3 of the length
Axial Pressure
Injection Pressure
Injection Pressure 2
Confinement Pressure
ISCO Pumps
Pressure and Strain Gauge Data Acquisition
Floaxlab Pump
Hydraulic Fluid Injection
Confinement Injection
Hydraulic Oil
Hydraulic Oil
Biaxial
Biaxial stress

Datasets collected from experiments



Sample 153-4-1 was fractured with 24 MPa axial stress, at **22.68** MPa injection pressure.
CT scanning image had shown that the fracture geometry is a slightly inclined vertical clear brittle fracture.



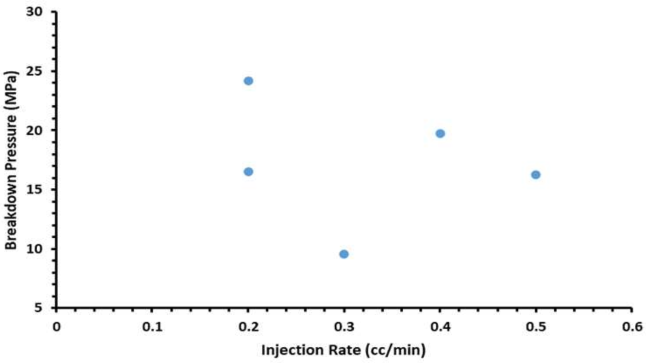


Fracture geometry

Breakdown pressure

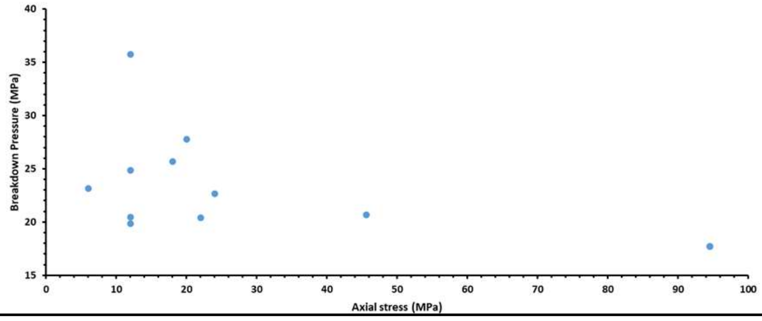
Breakdown pressure comparison (1)

Sample No.	Fracture Fluid	Flow Rate(cc/min)	Bd Pressure(MPa)	Fracture outcome
Crusher1A	Water	0.2	16.5	Fractured
Crusher1B	Water	0.2	24.19	Fractured
Crusher2	Water	0.4	19.71	Fractured
Crusher7	Water	0.3	9.56	Connected Natural
Crusher8	Water	0.5	16.23	Fractured



Breakdown pressure comparison (2)

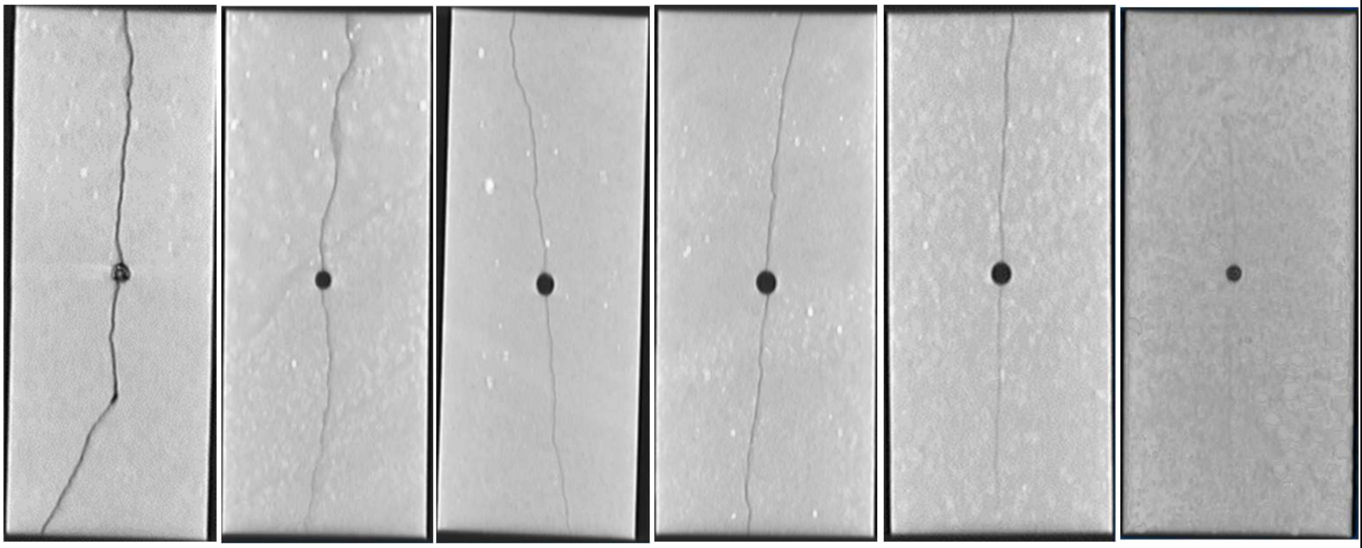
Sample No.	Axial Stress(MPa)	Conf. Stress(MPa)	Fracture Fluid	Flow Rate(cc/min)	Bd Pressure(MPa)	Fracture outcome
152-7-3	6	0	Nitrogen	1	23.13	Clear Frac
152-5-6	12	0	Nitrogen	1	24.84	Clear Frac
152-2-1	12	0	Nitrogen	1	20.46	Clear Frac
153-5-2	12	0	Nitrogen	1	19.88	Clear Frac
153-5-4	12	0	Nitrogen	1	35.76	Clear Frac
153-4-9	18	0	Nitrogen	1	25.71	Clear Frac
153-4-4	20	0	Nitrogen	1	27.8	Clear Frac
153-3-1	22	0	Nitrogen	1	20.42	Clear Frac
153-4-1	24	0	Nitrogen	1	22.68	Clear Frac
153-6-2	45.61	0	Nitrogen	1	20.7	Clear Frac
31-6-1	94.55	0	Nitrogen	1	17.68	Frac not visble



Breakdown pressure comparison (3)

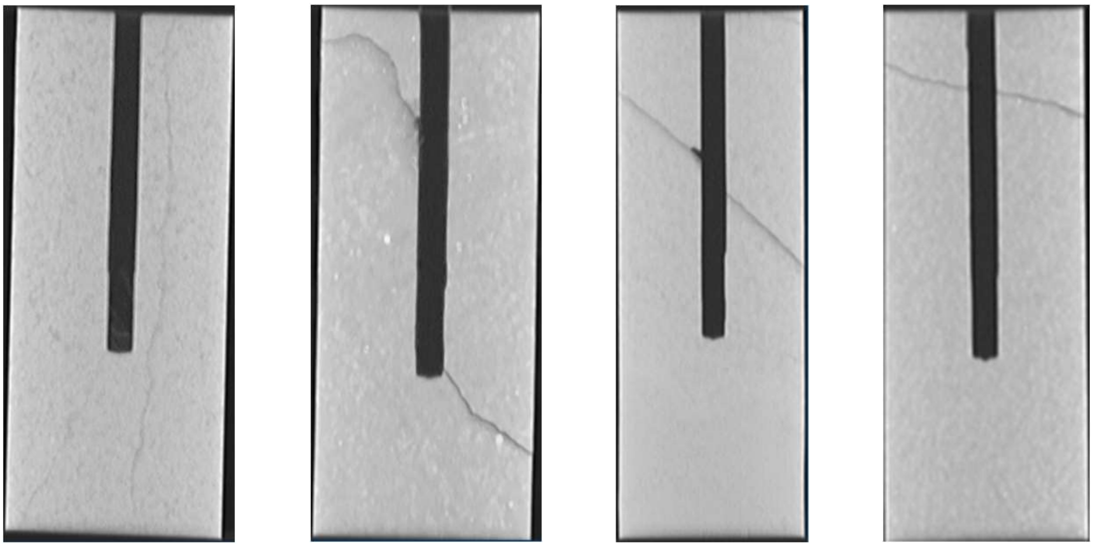
Sample No.	Axial Stress(MPa)	Conf. Stress(MPa)	Fracture Fluid	Flow Rate(cc/min)	Bd Pressure(MPa)	Fracture outcome
152-1-3	12	0	Brine	0.4	29.05	Frac
30-6-6	12	0	Brine	0.2	28	Frac
152-5-6	12	0	Nitrogen	1	24.56	Clear Frac
152-2-1	12	0	Nitrogen	1	20.46	Clear Frac

Fracture geometry results comparison (1)



153-5-4 12MPa | 153-4-4 20MPa | 153-3-1 22MPa | 153-4-1 24MPa | 153-6-2 45.61MPa | 31-6-1 94.55MPa

Fracture geometry results comparison (2)



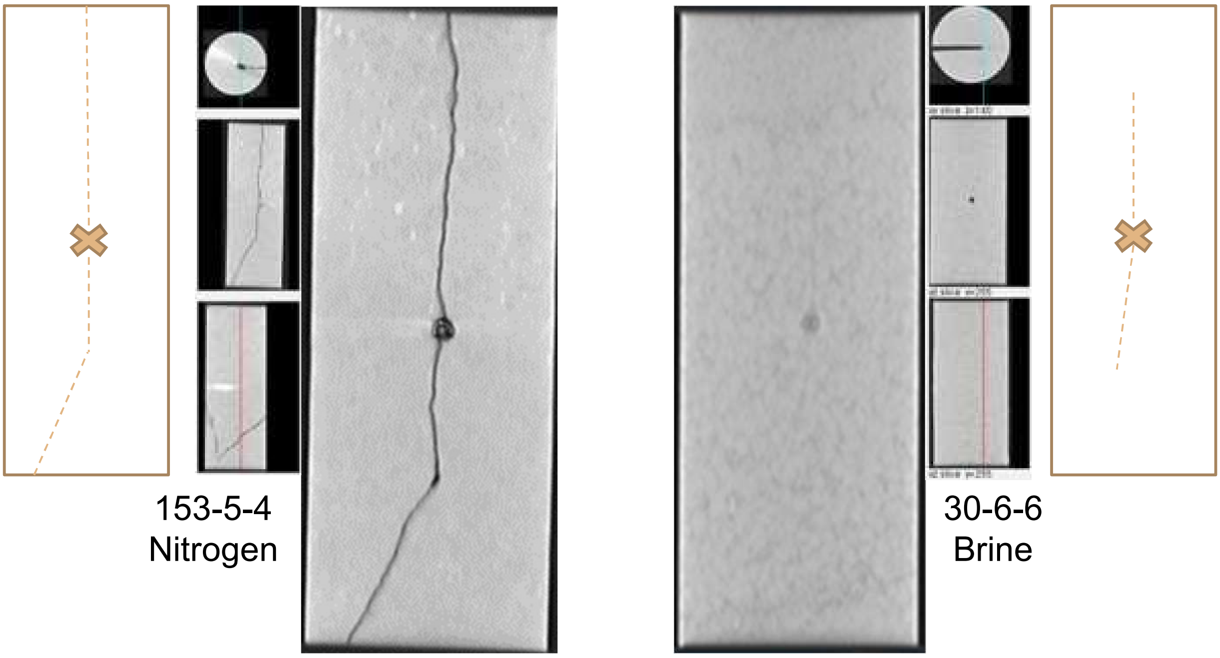
30-4-4
V:H = 4:1
V = 12 MPa, H = 3 MPa

153-4-7
V:H = 1:1
V = 15 MPa, H = 15 MPa

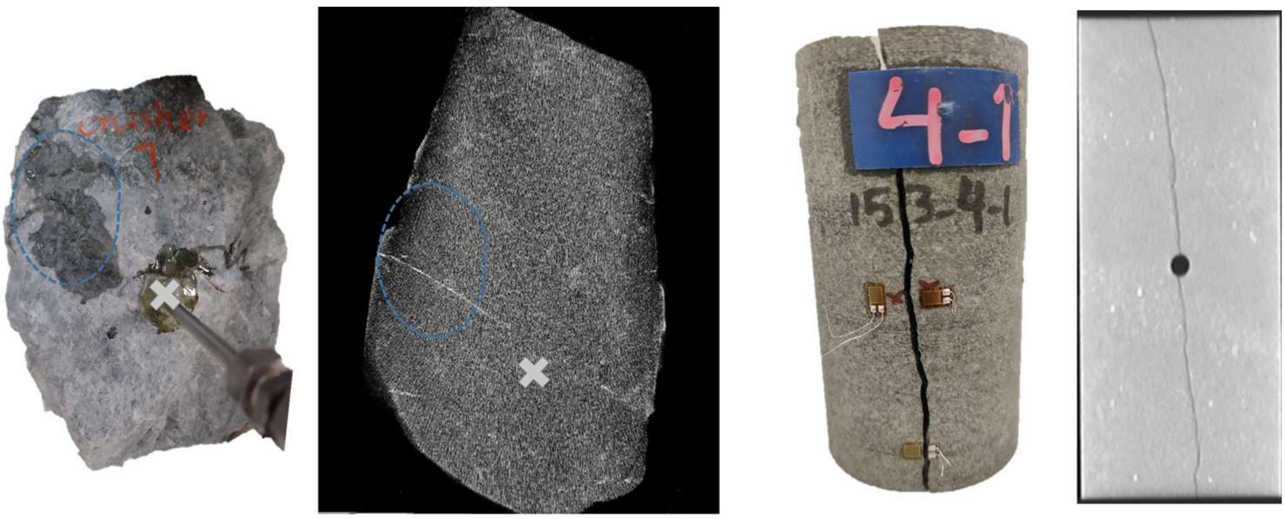
153-6-7
V:H = 1:3
V = 1 MPa, H = 3 MPa

152-7-7
V:H = 1:6
V = 0.5 MPa, H = 3 MPa

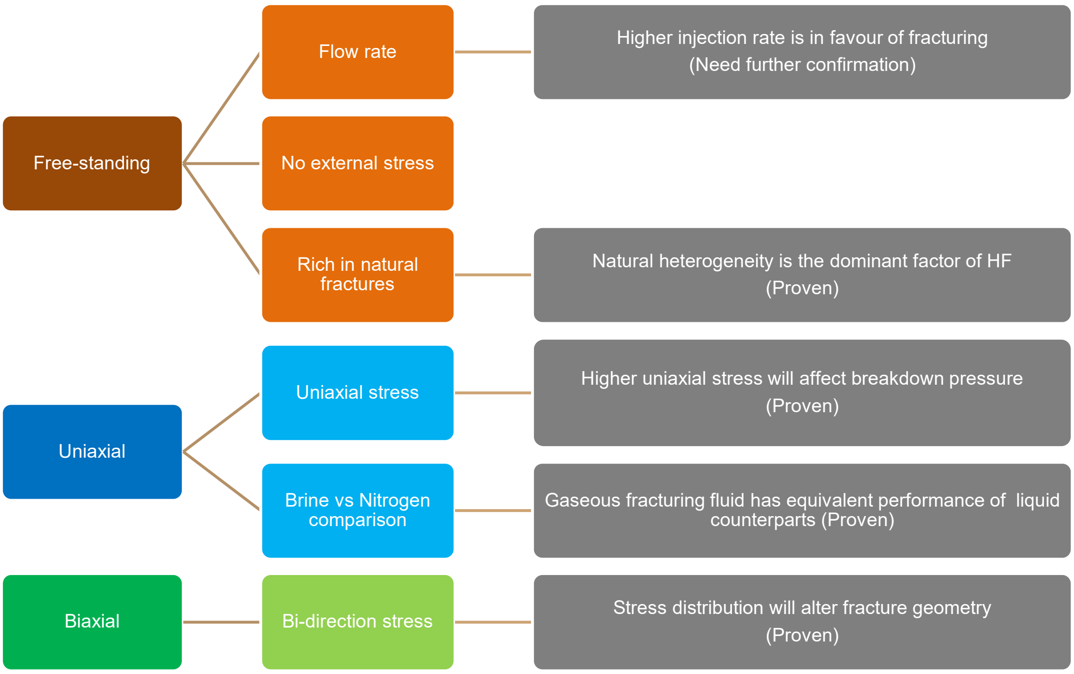
Fracture geometry results comparison (3)



Fracture geometry results comparison (4)

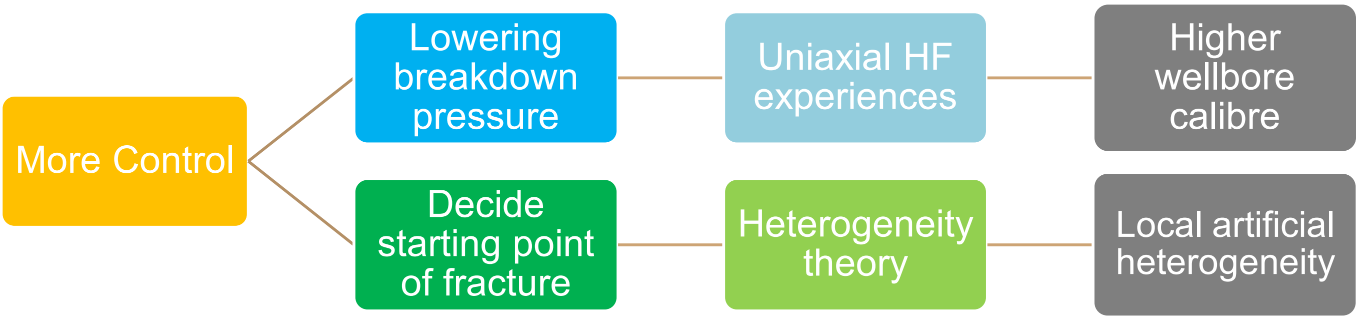


Experimental results

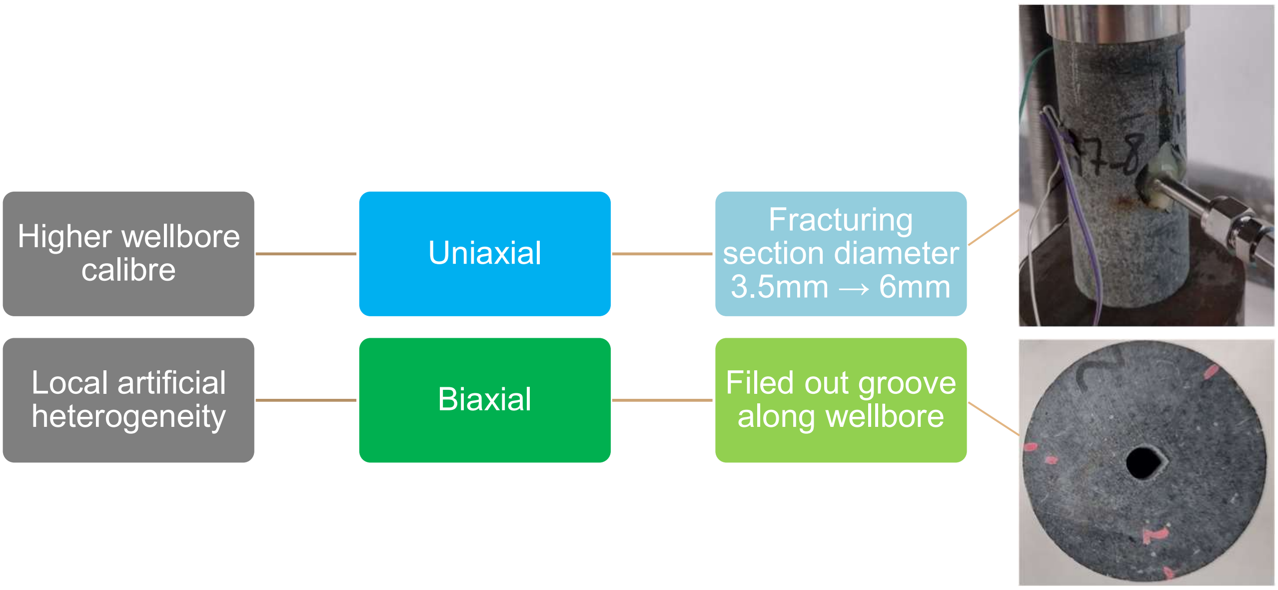


Conclusions(?)

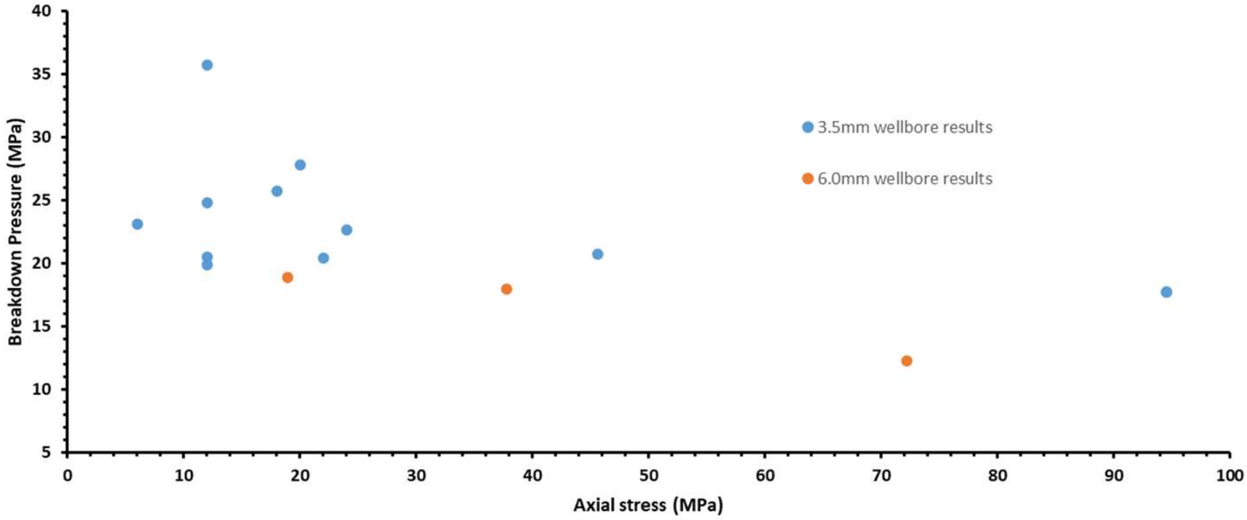
More control over HF



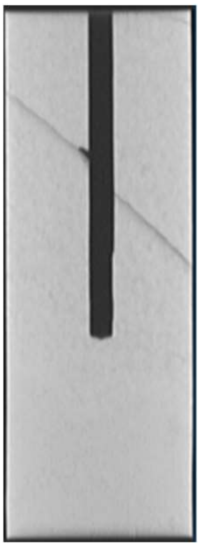
Experimental approach for more control over HF



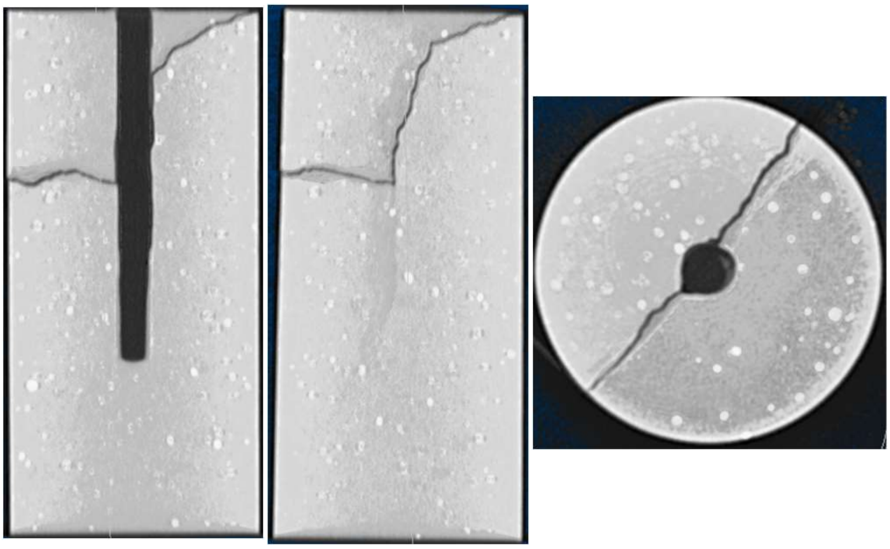
Breakdown pressure comparison (4)



Fracture geometry results comparison (5)

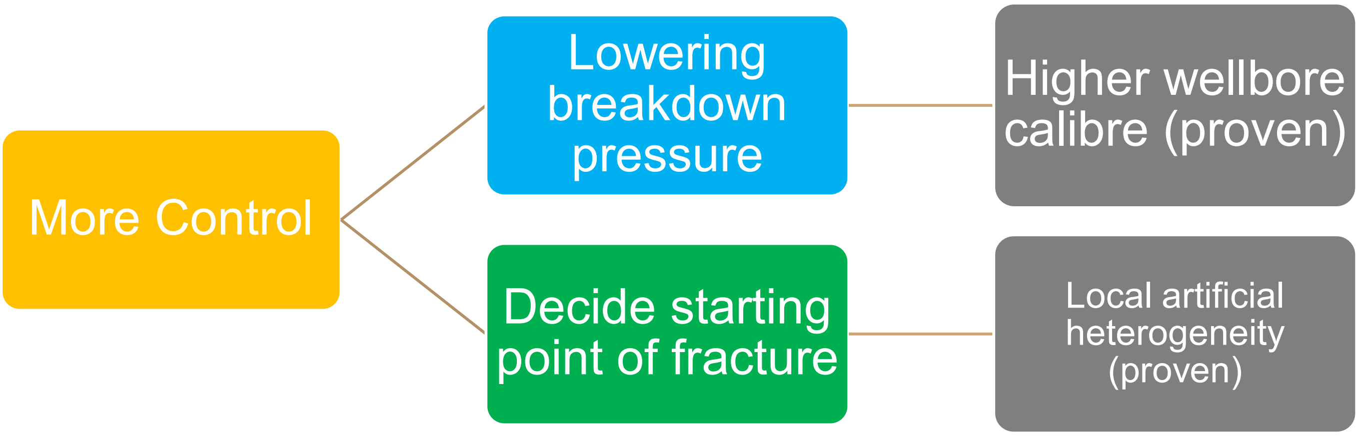


153-6-7
V:H = 1:3
V = 1 MPa, H = 3 MPa



153-3-2
V:H = 1:3
V = 1 MPa, H = 3 MPa

Control methods proven



Conclusions & Implications

- Hydraulic fracturing can be applied to create fractures in hard rock deposits
- Heterogeneities (i.e., faults, mineral veins) in hard rock dominates the fracture starting point, thus can be exploited for designating fracture starting point and further propagation direction guidance
- In-situ stress distribution ratio in hard rock will guide fracture propagation direction regardless of absolute stress values, especially when fracture point is locally intact
- High deviance in in-situ stress distribution tend to create smooth fractures without branches, thus it is recommended to apply more control over fracture process for optimum fracturing volume in hard rock deposit
- Environmental benign fluids (i.e., nitrogen) and larger wellbore diameter can be applied in HF-ISR enhancement with potentially lower breakdown pressure requirement

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ION FLUX FLOW REGIMES OF ELECTROKINETIC TRANSPORT IN LOW PERMEABILITY POROUS MEDIA RELATED TO IN-SITU RECOVERY

By

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ABSTRACT

Electrokinetic in-situ recovery is an alternative to conventional mining, relying on the application of an electric potential to enhance the subsurface flow of ions. Understanding the pore-scale ion transport under advection-diffusion-electromigration is essential for petrophysical properties estimation and flow behaviour characterization. The governing physics of the coupled transport are electromigration under electric potential, diffusion with concentration gradient, and advection due to hydraulic pressure and electroosmosis, which depend on the electric potential gradient, mineral occurrence, domain morphology (tortuosity and porosity, grain size and distribution, etc.) and electrolyte properties (local pH distribution and lixiviant type and concentration, etc.).

The governing model includes three coupled equations: (1) Poisson equation, (2) Nernst--Planck equation, and (3) Navier--Stokes equation. These equations were solved using the lattice Boltzmann method within X-ray computed microtomography images. To understand the coupled ion flow behaviour, we perform the simulation on a simple capillary tube model, a 2-dimentional heterogenous porous media, and a 3D real rock image with different corresponding length. Two dimentionless numbers (1) Peclet number; (2) a new defined Electrokinetic number are used to define the ion flow regime. The results in all three models show that 4 ion flow patterns are exist, which are (1) large channelling; (2) Uniform flow; (3) Small channelling; (4) Non flow.

With regarding to in situ recovery of minerals, with only hydraulic pressure, large channelling ion flow pattern exists where the ion prefer entering the high permeable region and cannot flow through low permeable region, which reduces the mineral extraction. However, by applying electric potential and adjusting the hydraulic pressure, the small channelling can be created, where ion prefer entering the low permeable region. The proposed study provides the fundamental understanding of the ion flow under advection-diffusion-electromigration. The result provides a potential way to control the ion flow.

Keywords: Flow regime; Advection-Diffusion-Electromigration; X-ray micro-computed tomography; Lattice-Boltzmann-Poisson Methods; ISR

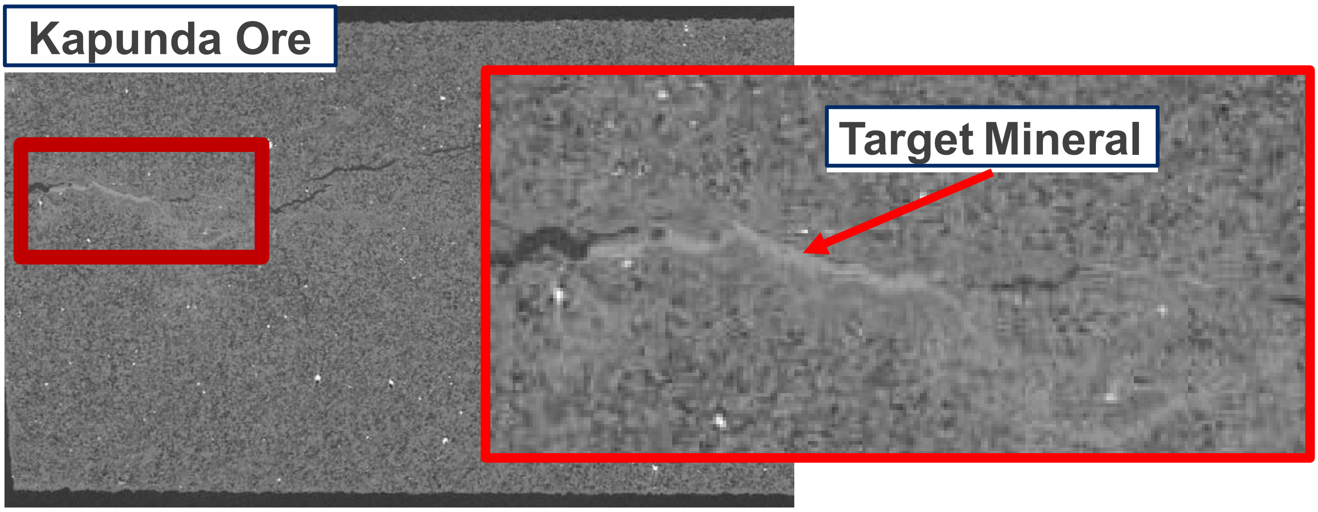
OPEN QUESTIONS:
What are the mineral compositions?
Do the minerals dissolve?
Where are the minerals located?
Does the ore have permeability?

Screening criteria:
Is this mine suitable for in-situ recovery from a pore-scale perspective?

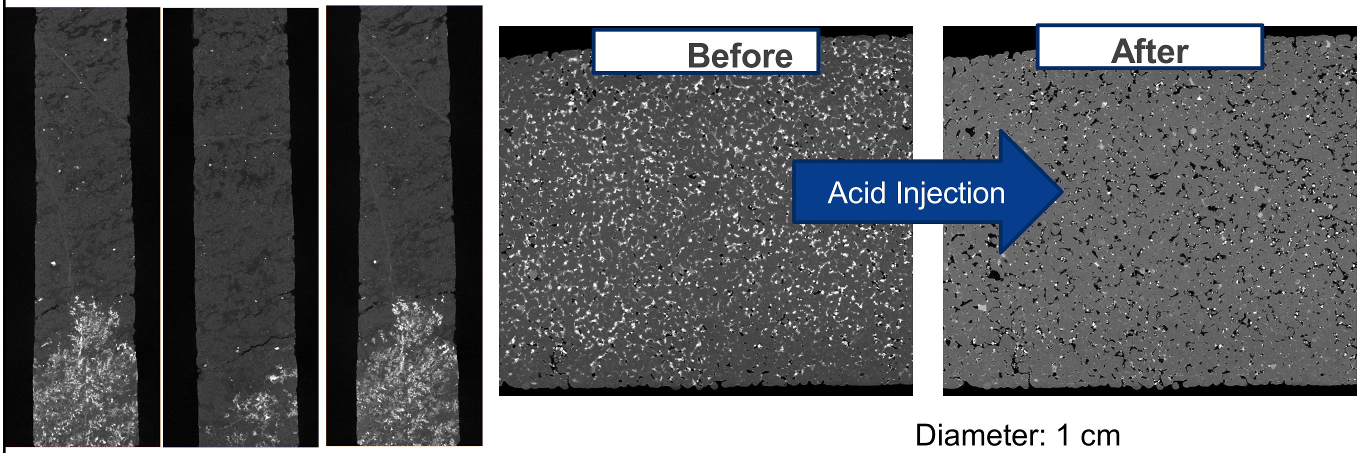
Micro-CT 3D scan of a Kapunda copper ore

Old Dutch Saying: “Wie het kleine niet leert, doet het grote verkeerd”
(S)He who does not study the small scale, will mess up the big scale

3D Mineral and fracture distribution can be characterised with micro-CT.



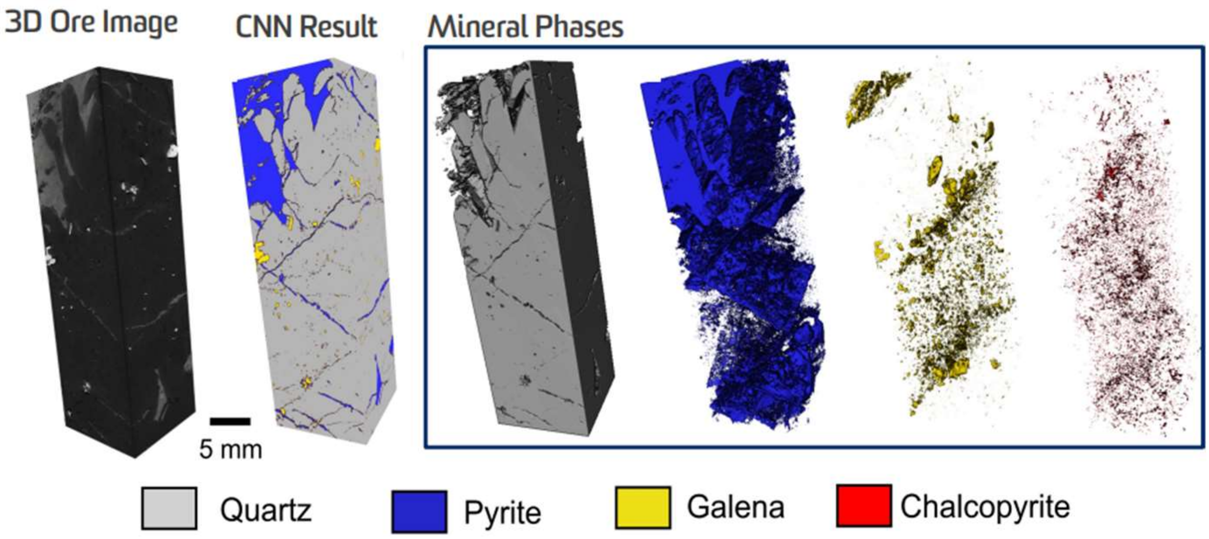
X-ray Computed Microtomography



Diameter: 2 mm
Length: 12 mm
Spatial resolution: 2 um

Diameter: 1 cm
Length: 3 cm
Spatial resolution: 5 micron

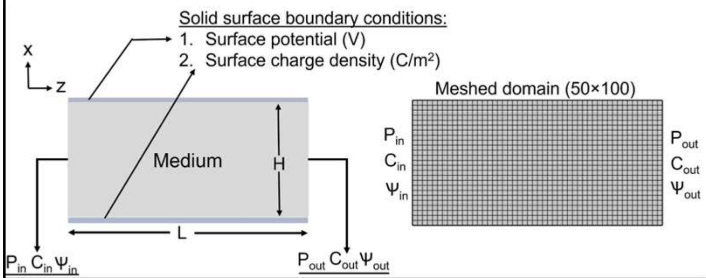
For accurately characterizing the mineral distribution and occurrence on the micro-CT image, we design a workflow that using the 2D mineral information (micro-XRF, QEMSCAN, SEM) and propagate into 3D with deep learning.

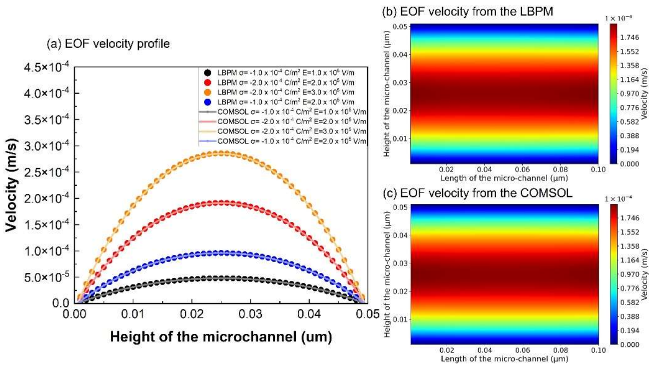


Fundamental understanding of fluid/ion flow in the ore for ISR

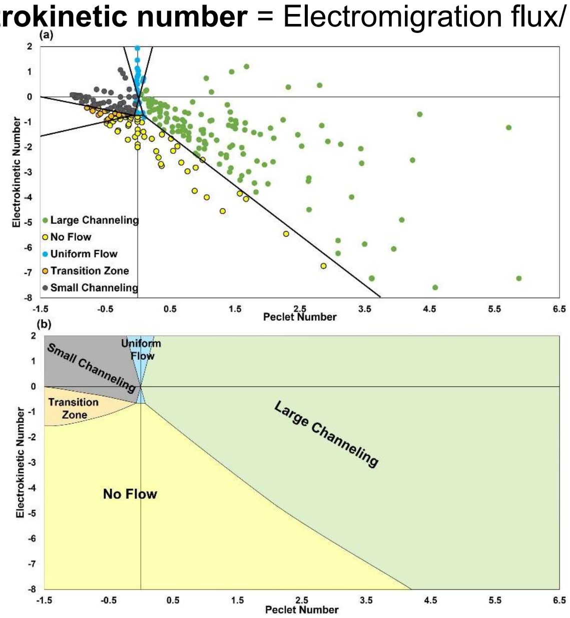
Mechanisms of lixiviant and ion flow for ISR or EK-ISR:

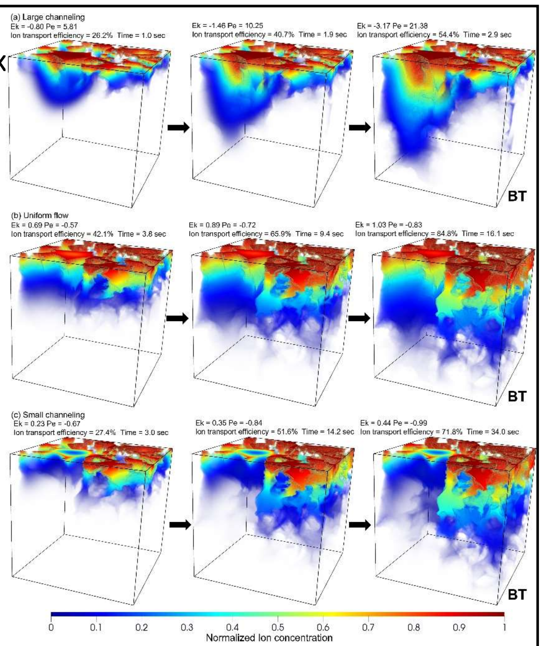
Lixiviant: Hydraulic pressure, Electroosmosis (EOF)
Ion: Hydraulic pressure, Electromigration, Diffusion (Concentration gradient)



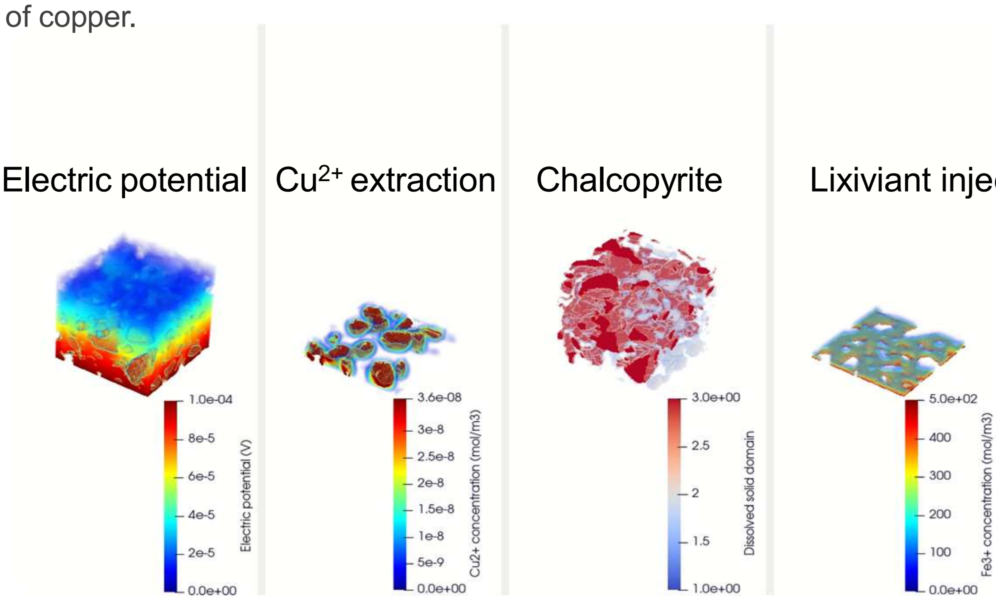


Peclet number = Advection flux / Diffusion flux
Electrokinetic number = Electromigration flux/ Diffusion flux





Fully coupled simulation of electrokinetic transport of Lixiviant, reaction with chalcopyrite, and recovery of copper.



A little bit details about the governing equations we used:

The flow of the electrolyte solution is governed by the incompressible conservation of mass and Navier–Stokes equation:

$$\nabla \cdot \boldsymbol{u} = 0,$$
$$\rho_0 \frac{\partial \boldsymbol{u}}{\partial t} + \rho_0 \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{F}, \quad (1)$$

The electric potential of the distribution of ions was solved by the Poisson equation:

$$\nabla^2 \psi = -\frac{\rho_e}{\varepsilon_r \varepsilon_0}, \qquad \boldsymbol{u} = -\frac{\epsilon \zeta}{\mu} \nabla_T \psi, \quad \text{for } \boldsymbol{x} \in \partial\Omega,$$

Ion transport is governed by the Nernst–Planck equation, which incorporates electrochemical migration as an extra drift term into the mass flux:

$$\frac{\partial C_i}{\partial t} + \nabla \cdot \left[\left(\boldsymbol{u} - \frac{z_i D_i}{V_T} \nabla \psi \right) C_i \right] = D_i \nabla^2 C_i, \quad (3)$$

The LBPM flow solver is coupled with Phreeqc where geochemical reaction is simulated for simulating the reactive transport in the real 3D micro-CT image of the ore.

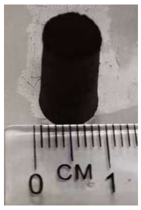
Considering the effects of: Zeta potential, pH, Ionic concentration, Tortuosity, Heterogeneity , Porosity, Permeability, Columbic interaction, Mineral occurrence, etc.

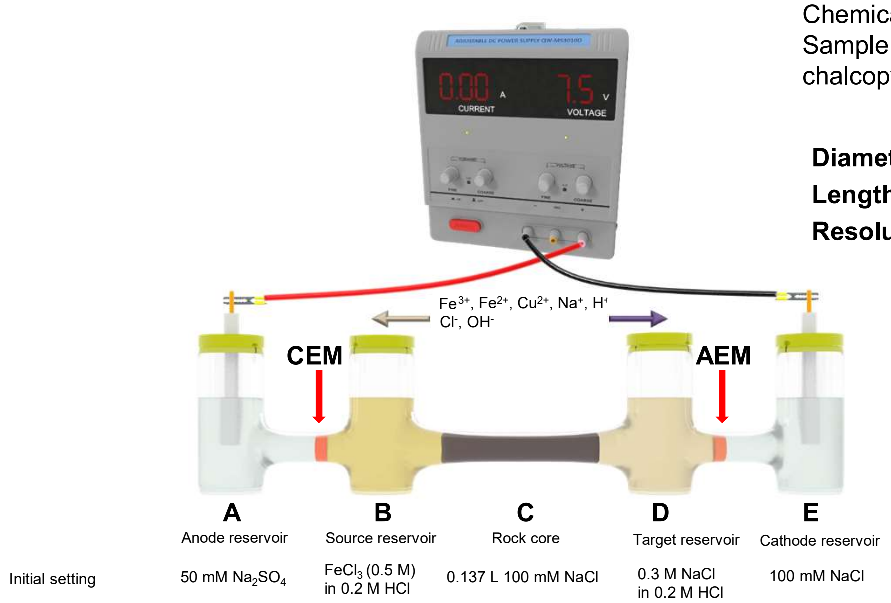
Solver: https://github.com/OPM/LBPM
Related paper: https://arxiv.org/abs/2303.17150

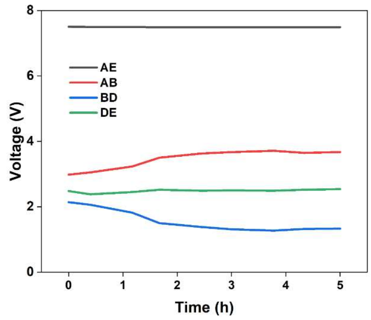
3. Experimental setup for EK-based chalcopyrite leaching (Uniform flow)

Chemical: $FeCl_3$ lixiviant
Sample: Synthetic sample (Consolidate chalcopyrite-glass bead sample)

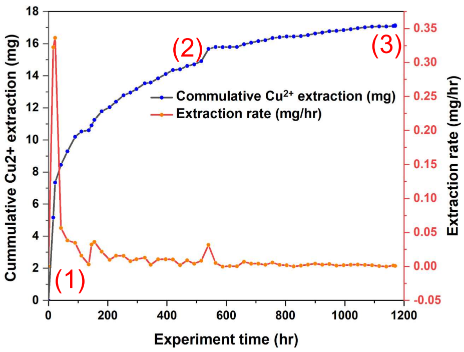
Diameter: 1 cm
Length: 3 cm
Resolution: 5 micron

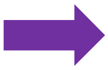


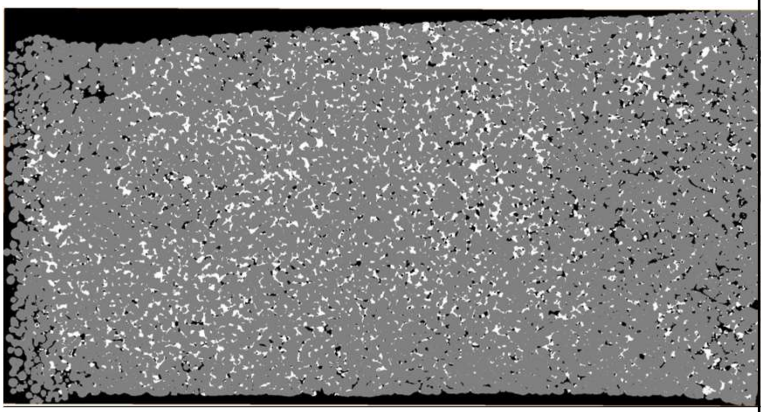


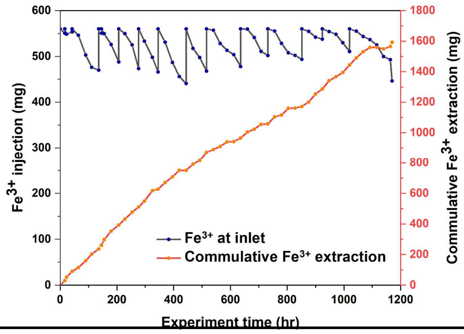


Three timesteps are scanned during experiments



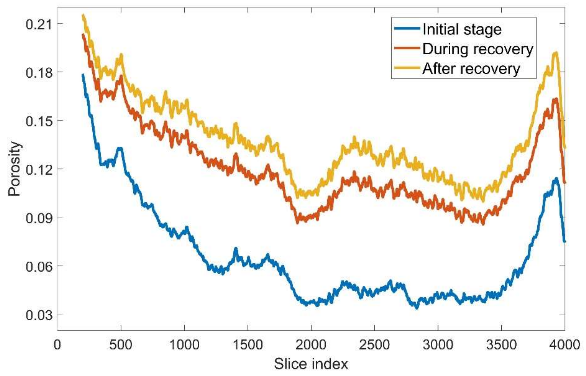




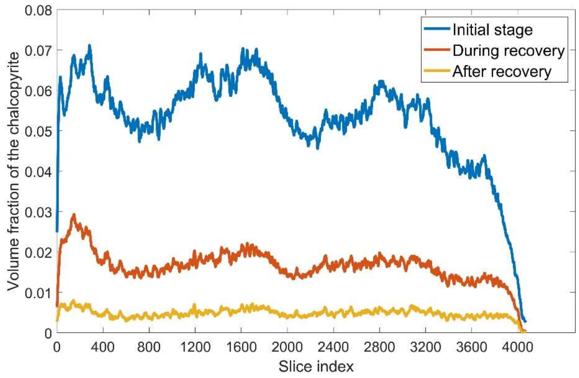


Chalcopyrite Glass bead Pore

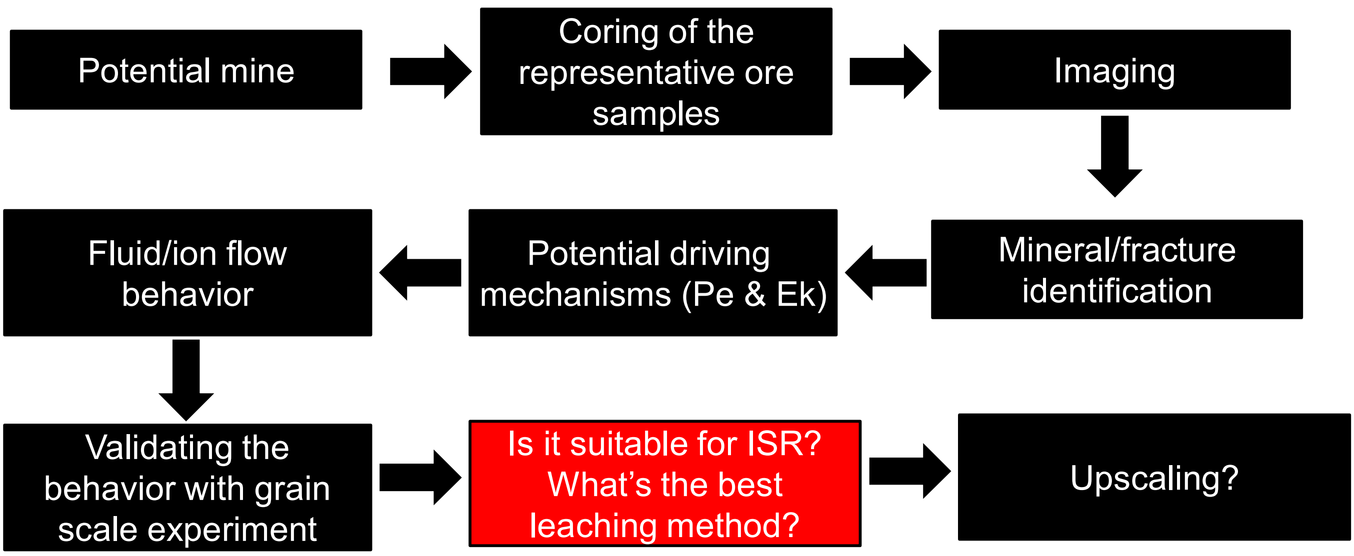
Porosity



Chalcopyrite volume frac

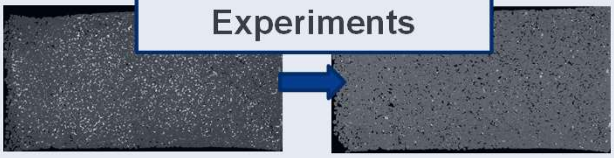


Screening criteria:
Is this mine suitable for in-situ recovery from a pore-scale perspective?



Extention

Grain Scale Experiments

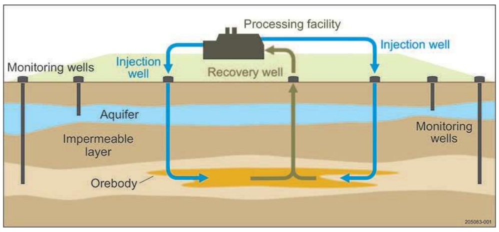


Before After

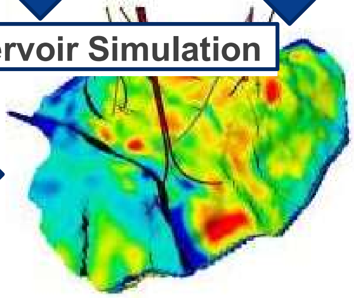
Grain Scale Simulations

Pilot Scale

Pilot Study



Reservoir Simulation



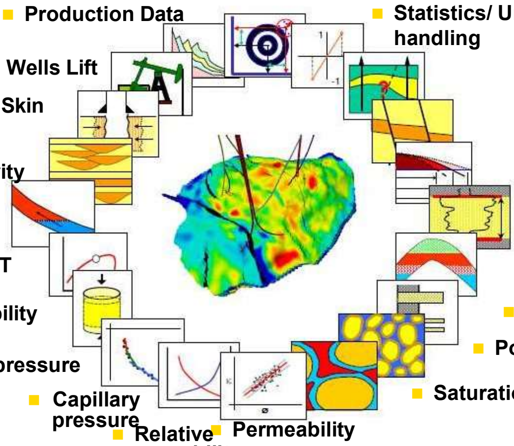
Multiscale Transport in Porous Systems

MUTRIS

UNSW SYDNEY Australia's Global University

Collaborators:

Professor Ryan T. Armstrong
Dr Zhe Li
Dr Ying Da Wang
Dr Zhengkai Bo
Associate Professor James E. McClure
Professor Peyman Mostaghimi



POTENTIAL APPLICATIONS OF BIOMINING FOR IN SITU RECOVERY

By

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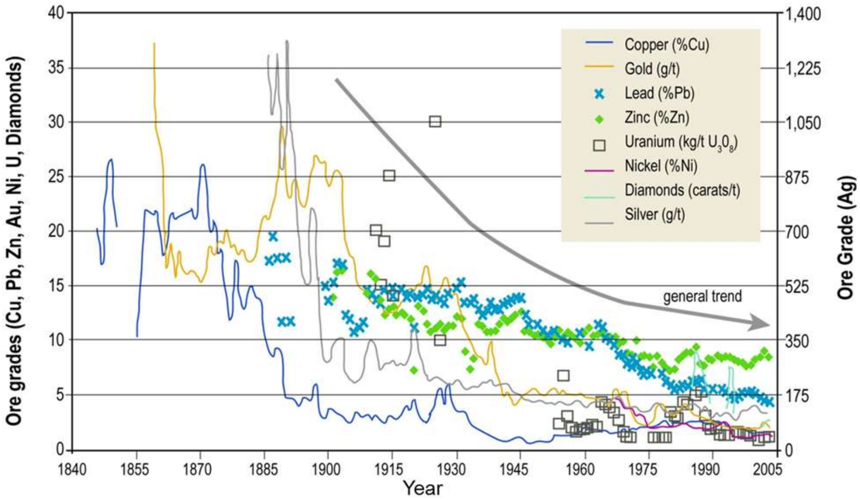
ABSTRACT

Biomining utilises the activity of microorganisms to extract and recover elements of interest from ores and wastes. It has been applied on a commercial scale for the bioleaching of base metals such as copper, nickel, zinc and cobalt from sulfide ores, for the biooxidation of refractory sulfidic gold minerals before cyanide leaching, and for metal recovery from solution through bioprecipitation. Bioleaching has been most commonly implemented in engineered heaps, whereas bioreactors are typically used for the biooxidation of refractory gold-containing sulfide concentrates. *In situ* bioleaching has been explored at some mine sites for the extraction of uranium and base metals. With the depletion of easily accessible shallow ore deposits, the interest to explore the potential of biomining to facilitate *in situ* recovery (ISR) from deep ore deposits has been increasing as an approach to reduce the consumption of chemicals and reduce mineral passivation as compared to chemical leaching. Depending on the mineralogy and commodities of interest, the microbial catalysts may include ferrous iron-, sulfur- and iodide-oxidising, ferric iron-reducing, organic acid-producing, and phosphate-solubilising microbes. Biogenic leaching agents may be generated in above-ground bioreactors and delivered underground for leaching under saturated conditions or regenerated in the subsurface ore body for leaching processes operated under unsaturated conditions. Pre-leaching with water or acid may be required if the ore body is very saline or contains large quantities of acid-consuming minerals. Other considerations for the application of biomining for ISR include the availability of essential nutrients for microbes, and understanding the characteristics of the ore body that may impact microbial growth (particularly temperature and pressure). This presentation will give an overview of biomining mechanisms and microbes that can be utilised for ISR, engineering approaches and examples of some ISR trials that explored biomining.

Keywords: Biohydrometallurgy; Bioleaching; Biomining; Biooxidation; In situ recovery.

Declining ore grades



→ Motivation for biomining and *in situ* recovery

Mudd GM. 2009. The sustainability of mining in Australia: Key production trends and their environmental implications for the future. Research Report No RR5. Monash University and Mineral Policy Institute.

Principles of biomining and bioleaching

- **Biomining:** the use of microorganisms for extraction of metals from minerals and wastes and recovery of metals from leach liquors
  - **Bioleaching:** the use of microorganisms for the extraction of metals from minerals and wastes through redoxolysis, acidolysis and/or complexolysis
  - **Biorecovery:** the use of microorganisms for the recovering metals from leach liquors through bioprecipitation and/or biosorption

Bioleaching through redoxolysis

Biological process	Description	Electron donors and acceptors
Oxidative bioleaching	Fe^{2+} biooxidation for oxidative ferric leaching of sulfide minerals	Electron donor: Fe^{2+} Electron acceptors: O_2, NO_3^-
	Mn^{2+} oxidation to Mn^{4+} for use of MnO_2 as an oxidant for bioleaching sulfide minerals	Electron donor: Mn^{2+} Electron acceptor: O_2
Reductive bioleaching	Fe^{3+} bioreduction for reductive bioleaching of oxide minerals	Electron donors: organic compounds, H_2, reduced sulfur compounds Electron acceptor: Fe^{3+}
	Mn^{4+} bioreduction for reductive bioleaching of Mn ores	Electron donors: organic compounds Electron acceptor: Mn^{4+}

Adapted from: Gumulya Y, Zea L, Kaksonen AH. 2022. *In situ* resource utilisation: the case for space biomining. Minerals Engineering 176: 107288.

Bioleaching through acidolysis

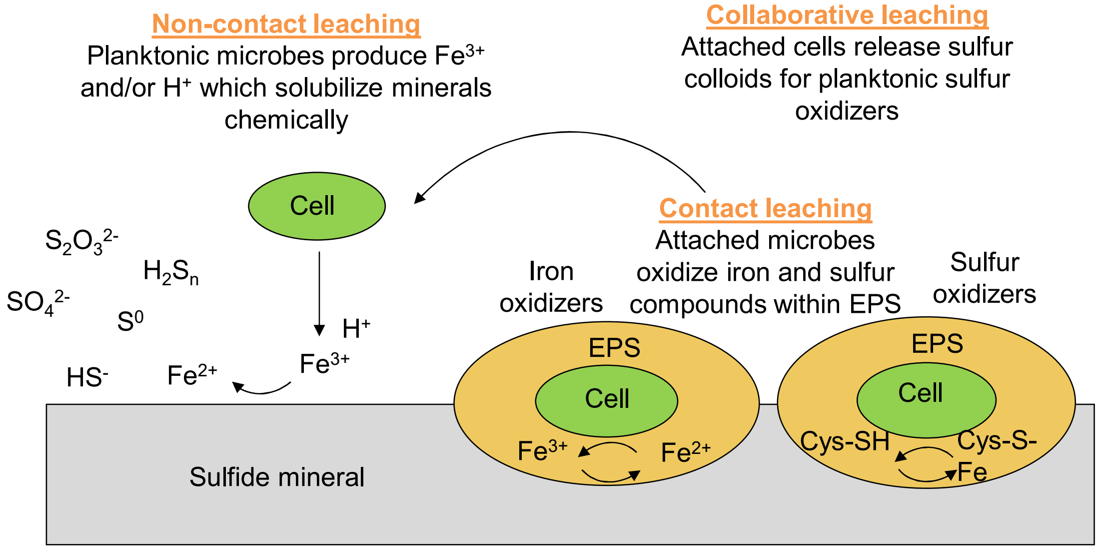
Biological process	Description	Electron donors and acceptors
Acidolysis with inorganic acid	Sulfur biooxidation to sulfuric acid for leaching acid-soluble minerals and wastes	Electron donors: reduced sulfur compounds Electron acceptors: O_2, Fe^{3+}
Acidolysis with organic acids	Biogenic organic acids production for leaching acid-soluble minerals and wastes	Electron donor: organic compounds Electron acceptor: O_2, none (fermentation)

Adapted from: Gumulya Y, Zea L, Kaksonen AH. 2022. *In situ* resource utilisation: the case for space biomining. Minerals Engineering 176: 107288.

Bioleaching through complexolysis

Biological process	Description	Electron donors and acceptors
Complexo-lysis	Biogenic organic acids production for rare earth element leaching	Electron donors: organic compounds Electron acceptors: Fe^{3+}, O_2, none (fermentation)
	Biogenic cyanide production for gold leaching	Electron donors: organic compounds Electron acceptor: O_2
	Iodide (I^-) biooxidation to iodine (I_2) for gold leaching	Electron donor: I^- Electron acceptor: O_2

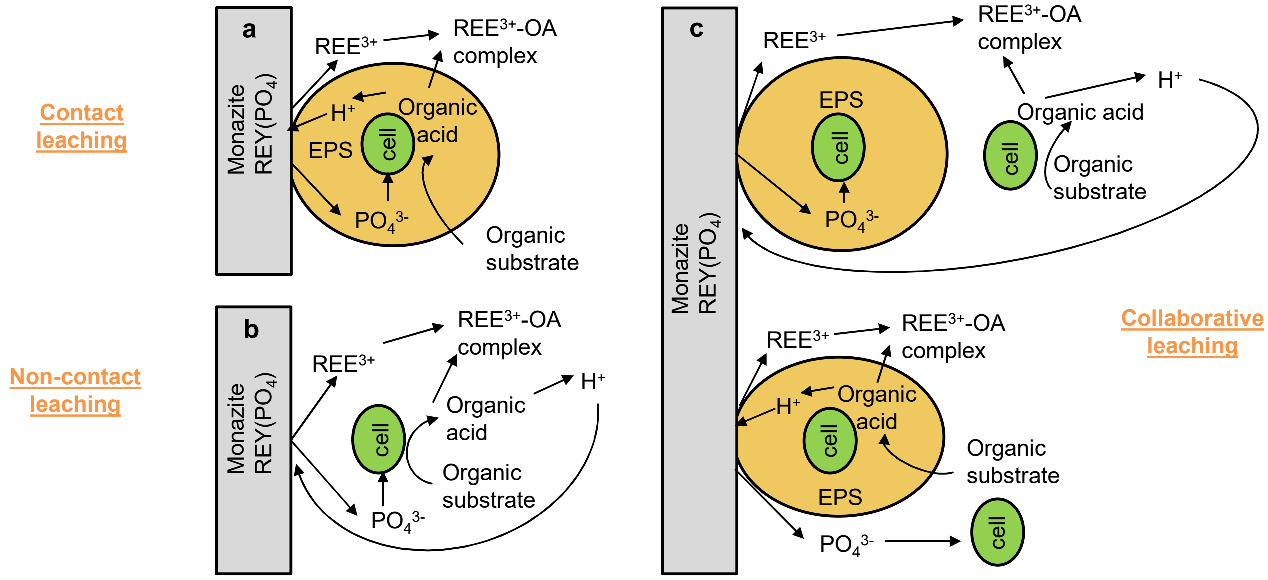
Contact, non-contact and collaborative bioleaching of sulfide minerals



EPS = exopolysaccharides

Rawlings DE. 2002. Heavy metal mining using microbes. Annual Reviews of Microbiology 56:65–91.

Contact, non-contact and collaborative bioleaching of rare earths from monazite

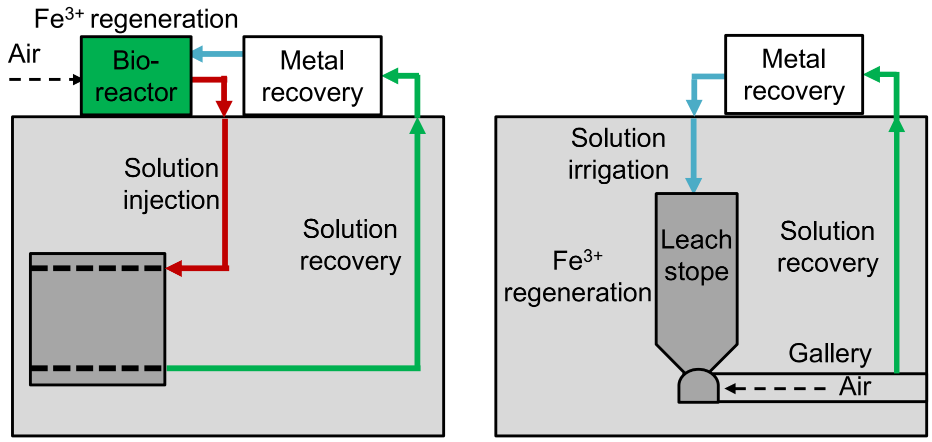


Adapted from: Fathollahzadeh H, Eksteen JJ, Kaksonen AH, Becker T, Watkin ELJ. 2018. Microbial contact enhances bioleaching of rare earth elements. Bioresource Technology Reports 3: 102-108.

In situ biomining of under saturated and unsaturated conditions

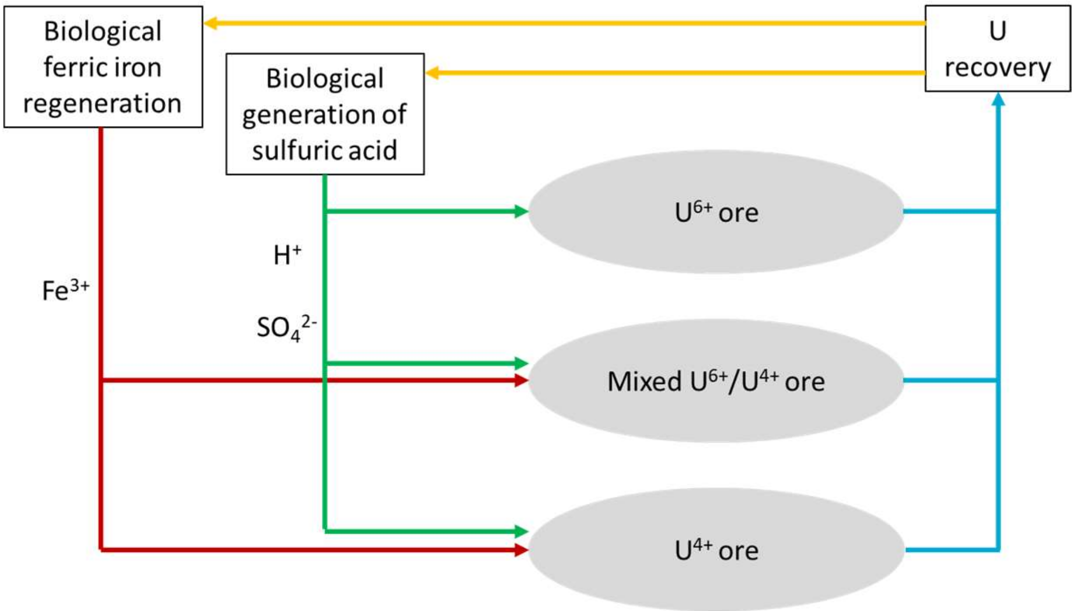
Saturated *in situ* biomining (biogenic lixiviant generation and leaching in separate unit processes)

Unsaturated *in situ* biomining (biogenic lixiviant generation and leaching in a single unit process)



Adapted from: Kaksonen and Pedersen 2023. Chapter 17: The Future of Biomining: Towards Sustainability in a Metal-demanding World. In: Bryan, Johnson, Roberto and Schlömann (eds.) *Biomining Technologies:* Bioprocessing Options for Extracting and Recovering Metals from Ores and Wastes. Springer-Verlag (Heidelberg, Germany). Pp. 295-314.

In situ bioleaching of uranium

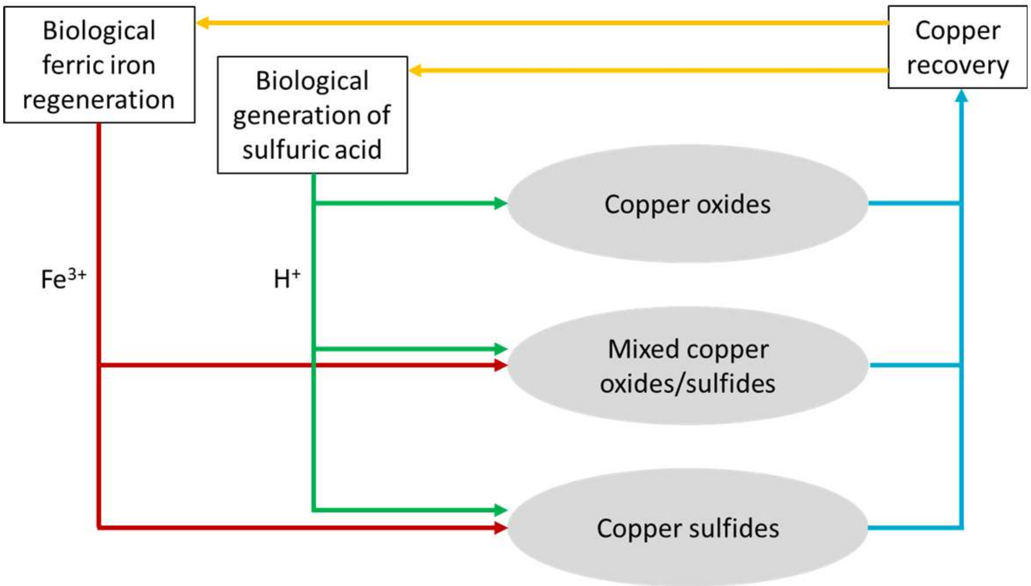


In situ stope bioleaching of uranium (Ontario, Canada)

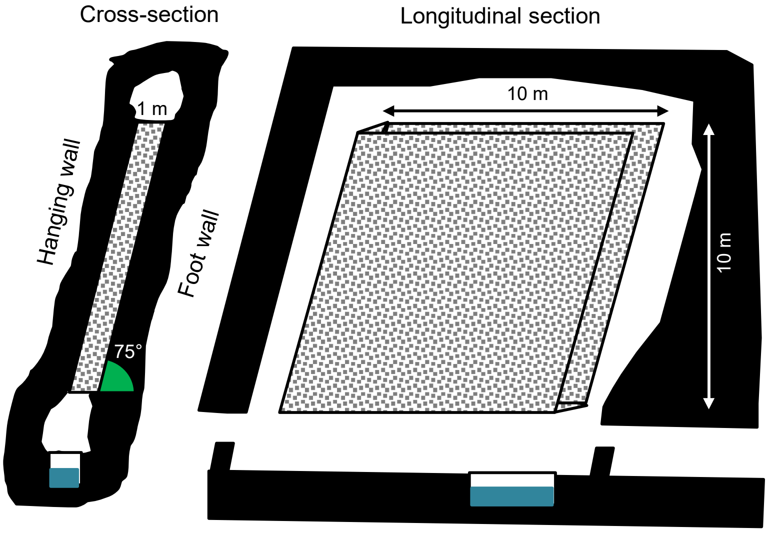
- **Stanrock Mine (1960s)**
  - Nutrient addition did not improve leaching
- **Agnew Lake Mine (late 1970s)**
  - Challenges with ore fracturing, and enabling sufficient contact between solution and minerals while containing the leach solution
- **Denison Mine (1980s and early 1990s)**
  - Ore was fractured and concrete bulkhead constructed across the opening of a horizontal shaft
  - Ore behind bulkhead was flooded with leach liquor in cycles and pregnant leach liquor drained after 3 weeks for U recovery
  - Bacteria and acidic ferric sulfate leaching improved yields compared to chemical acid leaching

Kaksonen AH, Lakaniemi A-M, Tuovinen OH. 2020. Journal of Cleaner Production 264: 121586

In situ bioleaching of copper



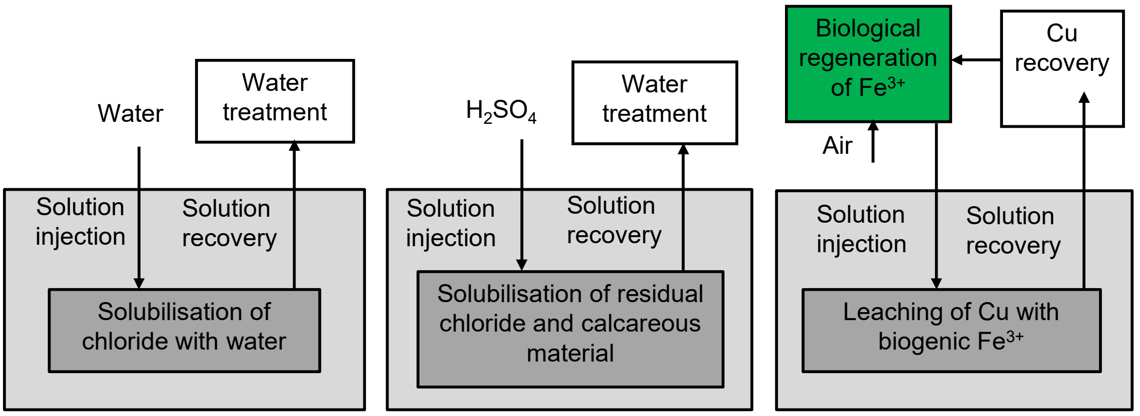
In situ stope bioleaching of Cu and Zn at Ilba Mine (Romania)



- Sulfidic ore: pyrite (FeS_2), chalcopyrite ($CuFeS_2$), covellite (CuS), bornite (Cu_5FeS_4), sphalerite (Zn,Fe)S, galena (PbS), marcasite (FeS_2)
- Ore blasted to <30 cm rocks
- 30% of ore removed → 70 m^3 ore leached in 10 m x 10 m x 1 m stope
- Inoculation with acidophilic Fe- and S-oxidisers
- Leach liquor aerated and circulated intermittently
- 10% Cu and 78% Zn leaching after 18 months
- Challenges with ore humidification and in winter access to energy for aeration and liquor circulation

Sand W, Hallmann R, Rohde K, Sobotke B, Wentzien S. 1993. Applied Microbiology and Biotechnology 40:421-426

In situ biomining of copper from a saline calcareous copper sulfide ore



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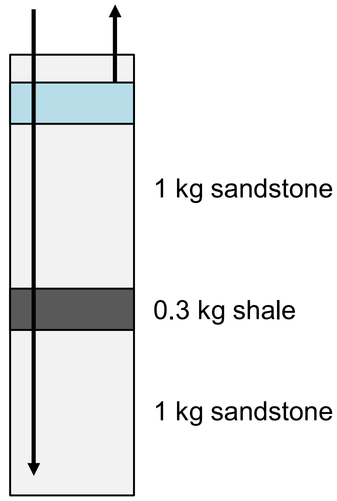
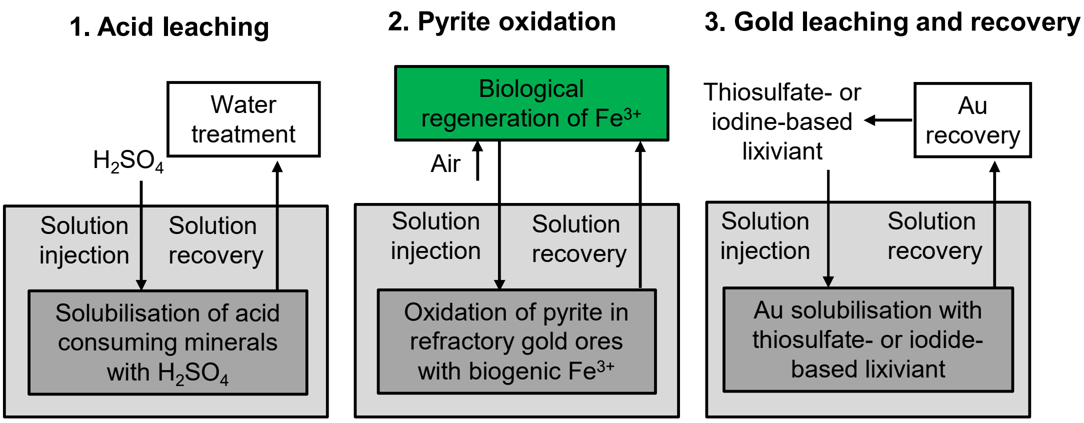
Lab-scale column study for evaluating *in situ* biomining of copper from a saline calcareous copper sulfide ore

- Kupferschiefer comprised of sandstone (2.98% Cu) and black shale (3.61% Cu), with Cu mainly in chalcocite (Cu_2S), bornite (Cu_5FeS_4),chalcopyrite ($CuFeS_2$),
- Lab-scale experiment with upflow columns and acidophilic iron- and sulfur-oxidisers
- Three steps:
  - 19 d water leaching
  - 3 d acid leaching (0.9 M sulfuric acid)
  - 40 d bioleaching (Cu removed with sulfide precipitation 7 time from bleed stream)
- Leaching yield: 59% Cu



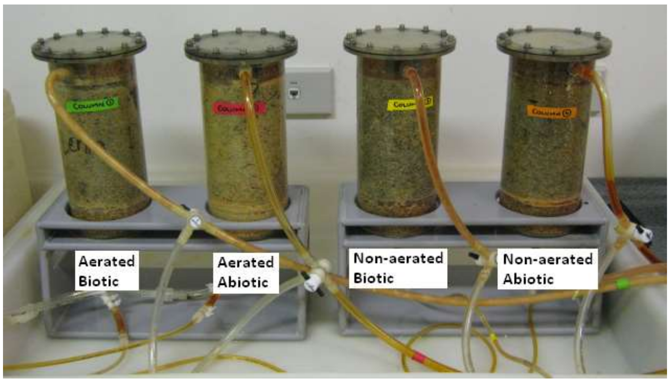
Pakostova E, Grail BM, Johnson DB. 2018. Bio-processing of a saline, calcareous copper sulfide ore by sequential leaching. Hydrometallurgy 179: 36-43.

In situ leaching of gold from refractory sulfidic deposit after biological pre-treatment



Adapted from: Kaksonen and Pedersen 2023. Chapter 17: The Future of Biomining: Towards Sustainability in a Metal-demanding World. In: Bryan, Johnson, Roberto and Schlömann (eds.) *Biomining Technologies:* Bioprocessing Options for Extracting and Recovering Metals from Ores and Wastes. Springer-Verlag (Heidelberg, Germany). Pp. 295-314.

Column study to evaluate *in situ* biooxidation of Au-bearing pyritic ores before gold leaching

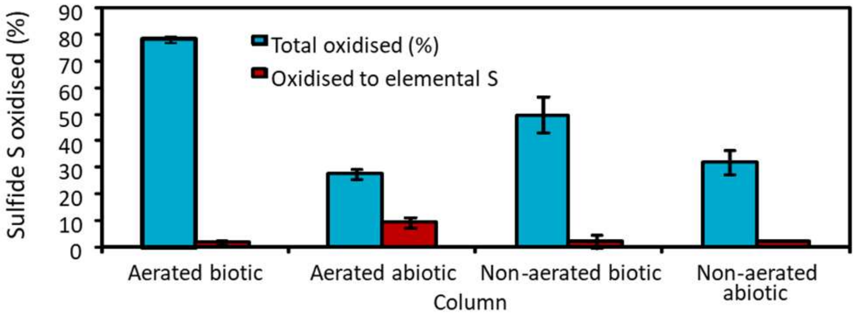


Upflow columns:
- 1.6 kg ore
- Particle size 1-4 mm
- S content 0.93%

- Ore washed with pH 1.5 distilled H_2O to decrease acid consumption
- Biologically generated ferric sulfate (26 g Fe^{2+} L^{-1} pH 1.7) pumped through 158 d
- Columns 1 and 2 aerated from the bottom at 0.6-0.8 L min^{-1}
- Thymol (0.4 g/L) added to abiotic (chemical control) column influents (2 and 4)

Kaksonen AH, Perrot F, Morris C, Rea S, Benvie B, Austin P, Hackl R. 2014. Evaluation of submerged bio-oxidation concept for refractory gold ores. Hydrometallurgy 141: 117-125.

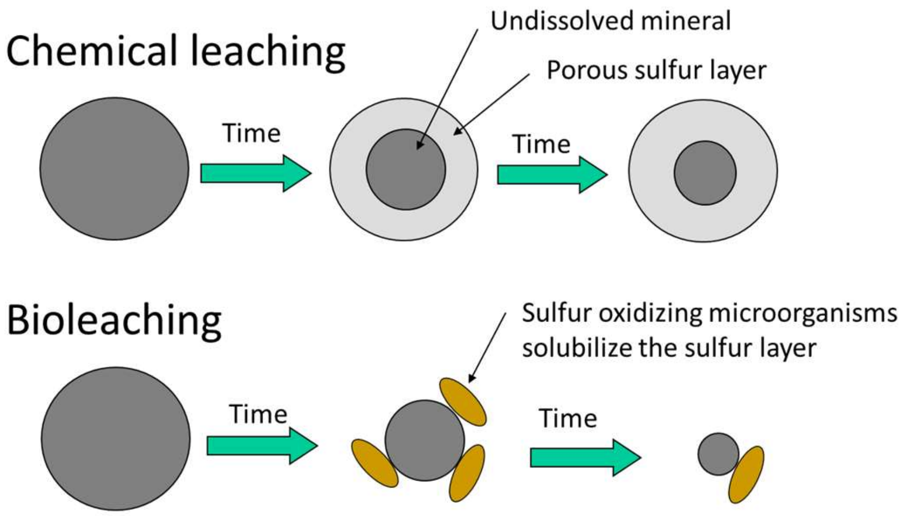
Key findings from the upflow column study



- Pyrite was oxidised under aerobic and anaerobic conditions using biologically generated ferric iron
- The simulated underground aeration and the presence of bioleaching microorganisms enhanced pyrite oxidation
- Microorganisms decreased the accumulation of S^0, the presence of which may decrease subsequent gold recovery

Kaksonen AH, Perrot F, Morris C, Rea S, Benvie B, Austin P, Hackl R. 2014. Evaluation of submerged bio-oxidation concept for refractory gold ores. Hydrometallurgy 141: 117-125.

Microbiological removal of passivating sulfur layers



Adapted from Crundwell FK. 2003. How do bacteria interact with minerals. Hydrometallurgy 71: 75-81.

Factors affecting bioleaching

Bioleaching

Mineralogical factors:
- Mineral composition
- Liberation
- Porosity/permeability

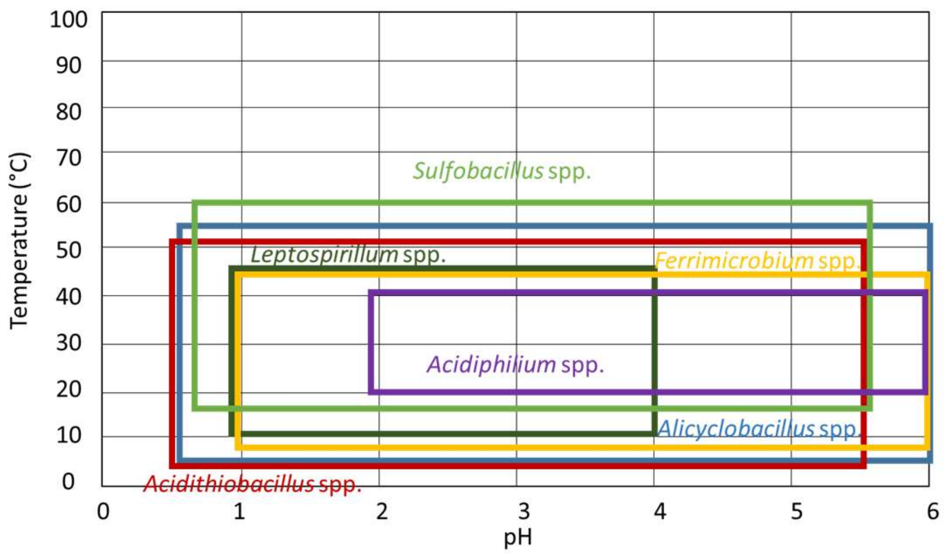
Physical-chemical factors:
- Temperature
- Pressure
- Solubility of gases (O_2, CO_2)
- pH
- Redox
- Fe^{2+}, Fe^{3+}
- Other metals

Process factors:
- Solid/liquid ratio
- Retention time

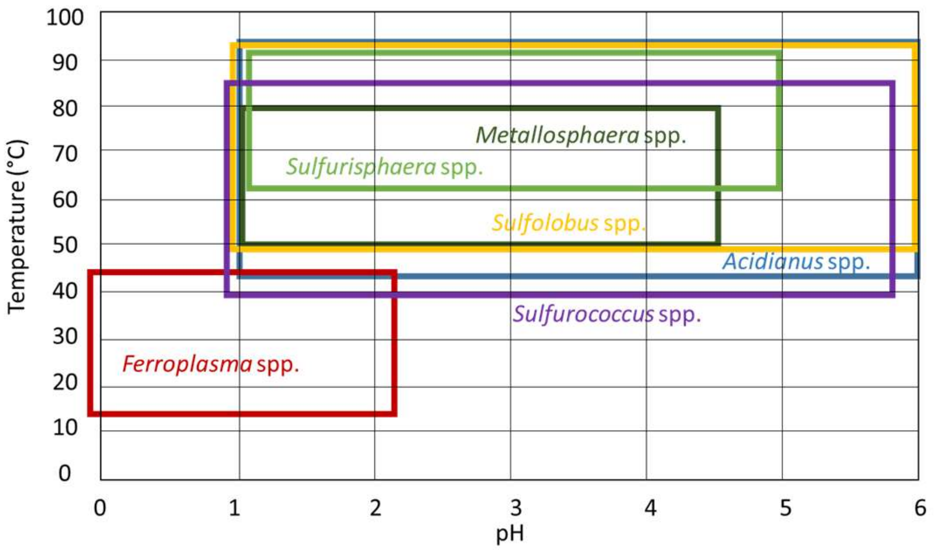
Microbiological factors:
- Strains
- Diversity
- Density
- Activity
- Distribution
- Substrate availability
- Tolerance

Kaksonen AH, Lakaniemi A-M, Tuovinen OH. 2020. Journal of Cleaner Production 264: 121586

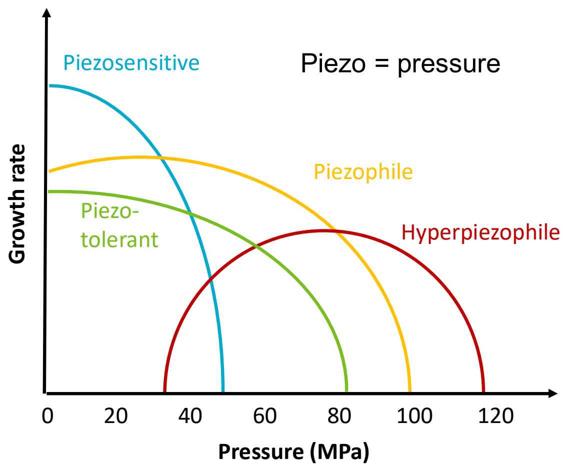
Temperature and pH ranges of bioleaching bacteria



Temperature and pH ranges of bioleaching archaea



Pressure requirements for microorganisms



Adapted from:

Abe F, Horikoshi K. 2001. The biotechnological potential of piezophiles. Trends in Biotechnology 19(3): 102-8.
Fang J, Zhang L, Bazylinski DA. 2010. Deep-sea piezosphere and piezophiles: geomicrobiology and biogeochemistry. Trends in Microbiology 18: 413-422.

- Pressure increases in with increasing depth approximately 27.4 kPa km^{-1} in continental crust (Jones and Lineweaver, 2010b).
- Limit of liquid water on Earth at a depth of ~75 km (p = 3,000 MPa and T = 431 °C) → depth limit for hydrometallurgical ISR (Jones and Lineweaver, 2010a).
- *Acidithiobacillus ferrooxidans* is tolerant to hydrostatic pressure of 15.2 MPa (Hiskey 1994; Torma 1975)
- Active and viable *Escherichia coli* and *Shewanella odeinensis* detected at pressures of up to 1,060 MPa and 1,680 MPa, respectively, equivalent to depths of ~35 km and ~50 km below Earth's crust (Sharma et al., 2012)

Conclusions

- Bioleaching utilises acidolysis, redoxolysis, complexolysis
- Bioleaching mechanisms include contact, non-contact and collaborative bioleaching
- *In situ* bioleaching can be conducted under saturated or unsaturated conditions for a range of minerals and commodities
- Multiple factors impact biomining efficiency and can be optimised to improve leaching yields
- The application of biomining to ISR can enable resource extraction from low grade, complex and deep ore deposits, reduce passivation of mineral surfaces and environmental impacts of mining