Australian Government
Office of the Chief Scientist

Quantum Meets Resources Workshop Summary

A workshop led by Australia's Chief Scientist
in partnership with the CSIRO and Geoscience Australia

In partnership with:

CSIRO

Australian Government
Geoscience Australia

Acknowledgement of Country

The Office of the Chief Scientist acknowledges the traditional owners of the country throughout Australia and their continuing connection to land, sea and community. We pay our respect to them and their cultures and to their elders past and present.

Artwork: Connection to Country, 2021 by Shaenice Allan

Meeting Place icon by DISR employee Amy Huggins

Disclaimer

The purpose of this publication is to summarise the events and outcomes of the Quantum Meets Resources event which occurred in Adelaide on 14 February 2024.

The Commonwealth as represented by the Department of Industry, Science and Resources has exercised due care and skill in the preparation and compilation of the information in this publication.

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Microsoft Co-Pilot was used in developing this summary.

Workshop overview

Quantum Meets Resources was an in-person workshop led by Australia's Chief Scientist in partnership with the CSIRO and Geoscience Australia. It was held at the National Wine Centre in Adelaide on 14 February 2024. Approximately 70 people attended, including representatives from the resources sector, quantum businesses, universities, and government.

Scene setting

Australia's Chief Scientist, Dr Cathy Foley, described the workshop as an opportunity to identify potential applications of quantum technology in the resources sector. This event was part of a broader effort to realise the ambition embodied in Australia's National Quantum Strategy.

Dr Foley told the attendees that not all quantum technologies are futuristic; mining companies have used quantum sensors in mineral exploration for 25 years. Some new quantum technologies are developing quickly and being tested in the field. Other quantum technologies, such as large-scale, fault-tolerant quantum computers for geomodelling, will take longer to develop but will bring big benefits when they do. Industry should look at how to use quantum technologies now to get an early competitive advantage.

Even small percentage efficiency improvements could make a big difference for the resources sector. Quantum sensors in existence can provide some of these efficiencies. For example, quantum sensors can help navigate underground where GPS does not work and help exploration companies see the extent and nature of mineral deposits before mining.

Dr Foley concluded by saying that Australian businesses should act early to understand how quantum technologies will affect their sector. This will help Australia stay competitive and understand changes in the competitive landscape as mining companies in other parts of the world invest in quantum solutions.

Dr Steve Hill, Chief Scientist of Geoscience Australia, encouraged participants to embrace the opportunity to embark on a new frontier. He referred to the resource industry's long-term drive to work more efficiently and challenged the group to help find the balance between living with and respecting the planet while being bold and early adopters of new opportunities, such as quantum.

Geoscience Australia:

"Quantum technology will help grow Australia's resources wealth and accelerate positioning technology and applications, ensuring a future where geoscience is as nimble and efficient as the quantum phenomena we harness."

Image 1. Quantum Meets Resources event.

Tania Constable, CEO, Minerals Council Australia:
"*Innovate, experiment, and collaborate – 3 key words that really summed up this workshop. At the end of this great day – two things are clear: We are motivated, and we are energised to make a difference … Today is a remarkable opportunity to use our new contacts and turn them into new conversations, relationships, and partnerships. Quantum is not just needed; it is an imperative."*

Areas of industry impact

Ore and water detection

Quantum magnetometers, gravimeters and gradiometers are types of quantum sensing devices that can find ore bodies deeper and more accurately. Many are field-ready and provide advantages compared with traditional classical sensor systems.

Navigation

Quantum accelerometers can be used to navigate without the need for external sources like GPS. This is useful in areas where GPS cannot reach, such as underground or underwater and would improve navigation and safety in mines. Quantum gyroscopes can further help with the navigation, guiding and stabilising of machines.

Geochemistry analysis

Quantum spectrometers can be used for remote sensing, spectroscopy, and chemical analysis. This could help companies to improve identification of high-quality minerals and avoid using precious resources to extract and process low-grade material.

Logistics

Quantum annealing computers can optimise mining logistics, making mining operations much more efficient.

Modelling

Quantum computing can offer advanced modelling such as addressing the “inverse problem”, real-time asset monitoring and management, and the ability to handle and combine large datasets. It also has the potential to solve complex problems that classical computers struggle with.

Program schedule:

Setting the scene

- Dr Cathy Foley, Australia's Chief Scientist
- Dr Steve Hill, Chief Scientist of Geoscience Australia
- Tania Constable, CEO of Minerals Council Australia

Keynote 1 – Critical challenges for the resources sector

- Asmita Mahanta, Global Practice Lead Geophysics at BHP
- James Alderman, Regional Technology Partner at Rio Tinto

Keynote 2 – Meeting the challenge with quantum technologies

- Professor Andre Luiten, Co-founder and Managing Director of QuantX, Chair of Experimental Physics at the University of Adelaide
- Professor Chris Vale, Professor of Physics and Director of the Quantum Technologies Future Science platform at the CSIRO

Panel 1 – Sub-surface imaging: Seeing through the Earth

Chair: Professor John Close, Professor of Quantum Science and Technology at ANU

- Dr Anandaroop Ray, Geophysicist at Geoscience Australia
- Keith Leslie, Scientist/Engineer at the CSIRO
- Dr Andrew Fitzpatrick, Exploration Manager at IGO Limited
- Teo Hage, Managing Director at Xcalibur Multiphysics

Panel 2 – Where are you located: Geopositioning

Chair: Professor Andre Luiten, Co-founder and Managing Director of QuantX, Chair of Experimental Physics at the University of Adelaide

- Dr Jack McCubbine, Director of National Geodesy at Geoscience Australia
- Dr Silvana Palacios, Lead Quantum Physicist at Nomad Atomics
- Dr Michael Hush, Chief Scientific Officer at Q-CTRL
- Dr Mark Dransfield, Consultant at Mark Dransfield Consulting

Panel 3 – Responsible innovation in environment and risk management

Chair: Adrian Beer, CEO of METS Ignited

- Holly Bridgwater, Director at Unearthed Solutions
- Gabi Skoff, PhD Candidate: Responsible Innovation of Quantum Technologies at University of Sydney
- Dr Chris Vernon, Senior Principal Research Scientist at the CSIRO

Panel 4 – Dealing with big data

Chair: Professor Chris Vale, Professor of Physics and Director of the Quantum Technologies Future Science platform at the CSIRO

- Professor Peter Turner, CEO of Sydney Quantum Academy
- Professor Simon Lucey, Director of the Australian Institute for Machine Learning at University of Adelaide
- Karl Malitz, Manager Open Innovation at Rio Tinto
- Asmita Mahanta, Global Practice Lead Geophysics at BHP

Breakout sessions

Six breakout sessions focused on exploring specific issues for the resources sector that could be solved by quantum technologies.

Overview of government funding opportunities

Michele Graham, General Manager of the Quantum Branch, Department of Industry, Science and Resources

Next steps and closing statement

Tania Constable, CEO, Minerals Council of Australia

Dr Cathy Foley, Australia's Chief Scientist

Keynotes

Critical challenges for the resources sector

Asmita Mahanta, Global Practice Lead Geophysics at BHP, spoke about the big challenges for the resources sector. She said the sector needed to move from "drill to define" to "drill to verify". Quantum technologies could help by providing new ways to sense, image and compute subsurface information. This could give more accurate, consistent, and timely data, while reducing costs and risk.

James Alderman, Global Technology Theme Lead – Geophysics at Rio Tinto, discussed the opportunities for mining companies and mining equipment, technology and services companies to collaborate. He said greater investment should be made in research and development to make better decisions in the future.

Meeting the challenge with quantum

Professor Andre Luiten, Co-founder and Managing Director of QuantX, introduced “the art of the possible” – imagining a multitude of possible uses. Quantum companies aimed to make tools that would be helpful and valuable for users, such as quantum sensors for finding minerals and analysing their composition. He discussed opportunities to work with the resources sector while leveraging Australia’s quantum strengths.

Professor Chris Vale, Director of the Quantum Technologies Future Science platform at the CSIRO discussed quantum computing capabilities and the current limitations of quantum computing in relation to reliability and error rates.

Image 2. Asmita Mahanta presenting on resource sector challenges.

Image 3. Professor Andre Luiten presenting on quantum technology.

Panel composition and discussions

Panel 1 – Sub-surface imaging: Seeing through the Earth

Chair: Professor John Close, Professor of Quantum Science and Technology at ANU

- Dr Anandaroop Ray, Geophysicist at Geoscience Australia
- Keith Leslie, Scientist/Engineer at the CSIRO
- Dr Andrew Fitzpatrick, Exploration Manager at IGO Limited
- Teo Hage, Managing Director at Xcalibur Multiphysics

The panel discussed problems in discovering resources under cover and ways to improve mining efficiency. It identified that using quantum technologies such as superconducting magnetometers and quantum computing could reduce the amount of drilling needed to delineate an ore body. It also discussed industry regulations, the depth of 500 m to 1 km, or even 2 km, at which tools need to work to be effective and how quantum technologies could collect real-time drilling data.

Image 4. Panel 1 discussion.

Panel 2 – Where are you located: Geopositioning

Chair: Professor Andre Luiten, Co-founder and Managing Director of QuantX,
Chair of Experimental Physics at the University of Adelaide

- Dr Jack McCubbine, Director of National Geodesy at Geoscience Australia
- Dr Silvana Palacios, Lead Quantum Physicist at Nomad Atomics
- Dr Michael Hush, Chief Scientific Officer at Q-CTRL
- Dr Mark Dransfield, consultant at Mark Dransfield Consulting

The panel discussed the need for more accurate and reliable geopositioning in the resources sector, due to the reliability and accuracy issues associated with GPS. Quantum technologies could offer an advantage over current tools because they were more sensitive, more precise and provided better noise rejection. It also discussed funding opportunities to support the development and use of quantum technologies. Panellists mentioned existing and potential collaborations, such as the Cooperative Research Centre project grant given to Q-CTRL.

Image 5. Panel 2 discussion

Panel 3 – Responsible innovation in environment and risk management

Chair: Adrian Beer, CEO of METS Ignited

- Holly Bridgwater, Director at Unearthed Solutions
- Gabi Skoff, PhD Candidate: Responsible Innovation of Quantum Technologies at the University of Sydney
- Dr Chris Vernon, Senior Principal Research Scientist at the CSIRO

The panel discussed working together to mine in a responsible and respectful way. It discussed the ethical, social, and environmental impacts of quantum technologies and how these technologies could help create a more sustainable and circular economy. Panellists talked about solving legacy mining problems, such as tailings dams, mine closures and ore quality, and how to track resources from waste rock and closed mines throughout the value chain.

Image 6. Panel 3 discussion.

Panel 4 – Dealing with big data

Chair: Professor Chris Vale, Professor of Physics and Director of the Quantum Technologies Future Science platform, at the CSIRO

- Professor Peter Turner, CEO of Sydney Quantum Academy
- Professor Simon Lucey, Director of the Australian Institute for Machine Learning at the University of Adelaide
- Karl Malitz, Manager Open Innovation at Rio Tinto
- Asmita Mahanta, Global Practice Lead Geophysics at BHP

The panel discussed the need for big data analytics and optimisation in the resources sector, given the volume of data and the variation in the data sources. Quantum computing had the potential to solve some intractable problems with this data, such as optimising the whole system, modelling ore bodies, and use of multi-modal AI, noting that it is a challenge to maintain data accuracy. It also discussed the feasibility, readiness and applicability of quantum computing for the resources sector.

Image 7. Panel 4 discussion.

Breakout sessions

During smaller group discussions, attendees explored new ideas, including:

- Responsible innovation, such as the establishment of an organisation to develop quantum technology in mining, while considering environmental, social and governance factors.
- Ideas for targeted extraction.
- Using quantum sensors to monitor carbon emissions.
- Developing quantum sensors that can fit down boreholes.
- Developing a joint project to optimise mining in the Pilbara.
- Balancing new innovations with reducing waste and environmental impact.

Where available, raw notes of these breakout sessions are summarised in the Appendix.

Overall, some key challenges identified included:

- The current depletion of most mines combined with the fact that many discovered ore bodies are not economical to extract.
- The need for mines to be deeper underground or have deeper pits.
- The need for water management and water tables to be designed and monitored more effectively.

Suggested areas to focus efforts to address these challenges included:

- Measuring rock mass earlier in the discovery process, which could help mines be more economical and start working sooner.
- Delineating and verifying an ore body without drilling, which would improve economics and environmental impact.
- Producing higher quality data and handling new types of data at a faster rate, which would support better mine management.
- Overcoming the limitations of current computer capability, which would generate geological models and do so faster.
- Focusing on the economics saved through small improvements. For example, a 1% steeper pit difference could save money.

Further questions raised included:

- How can resource companies reduce the environmental impact of exploration?
- How can we improve discovery rates, find more ore bodies, and make the best use of what we have?
- Can we find resources faster and more efficiently?
- Some ore bodies, such as critical minerals, have physical properties that are similar to their surroundings and are hard to find with traditional methods. Is there a sensor that can tell the geochemistry from the drill core using x-ray fluorescence?
- Can we drill half the number of holes and use sensor data and computer modelling to fill in the gaps?

Next steps and closing

Tania Constable, CEO of the Mining Council of Australia, wrapped up the event. An edited extract of her speech is below.

We set out to explore the value that quantum can bring to resources. I must say it has been a spectacular success. Innovate, experiment, and collaborate. Three key words that really summed up this workshop. It has been about finding the possibilities in each other and to talk across sectors.

We take great pride in our resources industry and celebrate its unrivalled success, which has relied on technology and innovation to improve safety, drive productivity, and deliver better sustainability.

We heard that bold, early adopters drive the cutting edge for venturing into new frontiers and the frontier opportunity that quantum offers to resources. It applies to exploration, geospatial information and throughout the industry, particularly for the transition to net zero. The minerals industry is essential to modern life. More metals and materials are required to help the global economy to transition to net zero.

EVs require 6 times more minerals than conventional vehicles – the world will need almost 1.4 billion passenger and light EVs. Wind generation requires 9 times more minerals per megawatt of generation than a gas-fired power plant – we need 1.5 million onshore turbines and about 650,000 offshore turbines. We will also need 28.6 billion solar panels.

It's the university sector that supports resources to continuously innovate and educate the next generation of resources professionals and scientists, as well as to deliver the tools, techniques, data, and research to address the challenges we have talked about today.

Resources has intractable problems. Undercover exploration is costly, our industry needs to continuously innovate and be more efficient. To be victorious, the innovators in this room need to talk to each other, collaborate, and combine their expertise. Industry explained this morning that the residual near-surface search space is depleting, it is getting deeper and we cannot see beneath the cover. It's not unique to Australia. It is a global phenomenon. Ground access is vital and social licence to operate is increasingly challenging and expensive. Most exploration projects don't make a discovery – for every 500–1000 exploration projects, you might get one profitable mine. That means we can't keep doing the same things as we have done before and hope to find the next big deposit.

We have an increasingly data-rich environment – but our ability to integrate, interpret and turn this data into real business decisions, presents a huge challenge. Resources has a saying – there is a need to have minimum appropriate data to move the project to the next level. We need to step it up a notch through collaboration, partnerships and acting more quickly.

We need to ensure we focus our people, time, and money to be used as efficiently as possible. Our current exploration technology package is optimised for near-surface exploration. Industry needs to develop a different type of technology package to enable discoveries under cover. Making surveys cheaper, faster and with lower impact aids in bringing opportunities forward.

The world is speeding up, it's volatile and uncertain. Quantum is helping create a competitive edge and it was a relief to hear it is being applied in our national defence. We need to get onto a war-like footing through new partnerships and collaborations with entities such as Defence. It is these partnerships with other industries like Defence that are crucial to help all industries. Government investment is needed and defence offers a significant opportunity for resources to partner in navigational sensor capability.

Clearly, resources still has a long way to go to improve our environmental and cultural reputation across communities. Mining is good at moving rock, but making quantum the hero or heroine in applying in-situ recovery and other extraction methods is mind-blowing and would add positively to our social licence to operate. There are huge opportunities. So why don't we adopt quantum?

It is because too much risk presents danger. Boards don't like too much risk. They will dutifully have a great discussion, ask management to look for solutions and then actively vote to only do incremental change. So, we need to make sure there is understanding of markets and how to incentivise the business case to manage this risk and to build resilience into our systems.

We also heard that in the next 27 years we will double the copper we use to more than we have used in human history. Here is another set of stats and a huge opportunity – to deliver global electricity storage required by just 2030, 50 new lithium mines, 60 new nickel mines, and 17 new cobalt mines are needed. That is a lot of rock!

Quantum is not just needed – it is an imperative.

We know that quantum is the game changer – it's revolutionary. But we have only so much capability in Australia. There is a question on how we take the amazing academic community sitting in this room and beyond and turn you into the hub of the country. I hope that every industry person here has picked someone to buddy up with and progress a conversation.

We can seize on these emerging opportunities by listening carefully and really hearing each other. We are motivated and we are energised to make a difference.

Thank you all for your participation. Today is a remarkable opportunity to use our new contacts and turn them into new conversations, relationships, and partnerships.

Appendix: Case studies

Downhole/bore sensing

Case study provided by IGO Ltd

Big picture problem

Current exploration technology is designed for near-surface exploration. The mining industry needs to develop new technology to find resources under cover.

Breaking the problem down

Most exploration data is collected using surface measurements such as gravity and magnetics. However, borehole measurements are not common because most sensors only collect data close to the borehole. There are no sensors designed to see further away from the borehole, except for downhole electromagnetics.

The challenge with downhole probes is making the sensors small enough to fit in exploration holes, which are typically 75.7 mm in diameter. Most borehole sensors are less than 50 mm in diameter.

It would be helpful to have a device that can collect multiple types of measurements at once. These include measurements of nuclear magnetic resonance, gravity, magnetic susceptibility, magnetic fields, density, piezoelectric and acoustic imaging.

The device needs to be small, be lightweight, be low power, be low cost, have no moving parts, be modular, communicate with the surface, go down 500 m to 1 km (and up to 2 km in some cases), handle the pressure at that depth (200 psi currently) and operate at temperatures between 60 and 80 degrees Celsius.

The device should take static measurements every 10–20 m and potentially continuously, depending on what is being measured. If not powered from the surface, it should run for 10–12 hours to cover a standard operating shift.

A secondary goal is to apply real-time data analysis to the collected data to determine rock properties, especially in holes that use reverse circulation drilling.

How could quantum technology help?

Quantum technology might not apply to measuring all the proposed properties, but it can help in the following ways:

Gravity gradiometry: This method uses sensors to measure gravity differences and provide stable, sensitive data. These sensors can also give information about position, navigation, and timing. Currently, only one borehole gravity tool (the Gravilog slim-hole gravity tool[1]) has been developed using traditional methods, but it is not widely used.

Quantum sensors: These are used in surface time-domain electromagnetics and could be adapted for use in downhole environments. This would make them more sensitive and able to identify targets further away from the drill hole. They might also be used for nuclear magnetic resonance (NMR) applications.

[1] https://scintrexltd.com/product/gravilog-slim-hole-gravity-probe/

Density measurements: Some current methods use radioactive sources, which can be dangerous. Using quantum technology could eliminate these sources, making measurement technologies safer and easier to operate.

Next steps

Ideal quantum sensors must have the following properties:

- low drift
- robust
- accurate
- wide bandwidth and long slew rate
- large dynamic range
- safe work operating procedure.

The first step in using quantum sensors in boreholes is to assess their physical size limitations and whether they can handle very high pressure (200 atm) in the borehole setting.

Raw notes on the downhole bore sensing breakout session

Sensors down boreholes – how can you get data in a drill hole? Ideal specifications are:

- Petrophysical data
- Down boreholes
- Low SWOP
- No moving parts
- One device to do all the measurements
- Can you get SQUID quality with RT sensors? RT sensor that operates at 80 m?
- Exploration needs sensitivity and wavelength, lightweight systems for airborne use that are cheaper, faster and robust
- Problem is the hole diameter is only 2 inches (63.25 mm – length is ok)
- Desired measurements from down a borehole are:
  - Downhole EM – conducting ore body
  - NMR
  - Gravity
  - Magnetic susceptibility
  - Density
  - Piezoelectric
  - Acoustic imaging
- Need to be able to go down 500 m to 1 km (in some cases 2 km) and handle the pressure at that depth
- Measurement on the way down every 20 m
- Operating temperature is in the range of 60-80^{o}C
- Would like to achieve real-time inverse data analysis
- Probes can be 2–3 m length
- Housing important – modular construction -screw together
- Ability to communicate with the surface

Characterising rock mass to determine the boundaries and delineation:

- Density is the most important parameter
- Can you achieve cross hole neutron decay measurements?
- Physical contrast – a main aim is to determine the sensitivity
- Greenfield exploration
- Surface maps
- Petrophysical data needed

Comments on different sensors:

- Magnetics – has been available for a long time; vector and tensors provide more information about the rocks than scalar measurements.

- Magnetic sensing needs for shallow detection – HF 100 kHz and deep detection needs low frequency Hz.
- Different magnetometers have a wide range of frequencies and quantum measurements over a wide range of depths with one sensor would be an advantage.
- Rejection of background noise accurately is important; aim is for 0.5% cut-off
- Quantum sensors – would it be possible to have one sensor from exploration to conveyer belt and truck?
- Motion sensors to remove background
- In-situ rock mass – get the information on the ore body extracted as early as possible
- NV diamond for NMR?
- Grade determination on a conveyer belt and remove the low-grade ore as early in the process as possible?

Responsible innovation

Case study provided by the CSIRO.

Big picture problem

Mining needs to improve its social and environmental impacts. Responsible innovation is an approach that:

- Anticipates and mitigates social and environmental harms.
- Involves a wider and more diverse range of people in finding solutions.
- Develops new technologies in high-impact areas, which benefit society and the environment.

Breaking the problem down

The energy transition requires the mining of more critical minerals such as copper, lithium, cobalt, and rare-earth elements. These minerals need to come from new mines and deposits that have not yet been discovered and which may have lower ore grades. Most of the easy mining in accessible sites has already been done. The future of mining needs to be more precise and targeted. Mining in tougher and more extreme conditions presents increased safety issues. With changing societal expectations, there is more scrutiny on the sector's performance and environmental impact. While optimising operating efficiencies is a known way to reduce costs in mining, using quantum technologies presents new opportunities for delivering transformative social and environmental benefits.

How could quantum technology help?

Quantum sensing to detect the magnetic fields of highly conductive commodities such as copper, silver and nickel is already established. New applications of quantum sensing could include:

Quantum sensing for transforming discovery and recovery: Quantum sensing techniques may change the way we identify, verify and mine in relation to ore grades. By integrating quantum sensors with drill technology, it may be possible to:

- Verify higher value targets prior to mining.
- Avoid targeting lower value deposits during mining.

More accurately targeting desirable material reduces waste, surface disturbance and energy usage.

Quantum sensing for mine site safety and performance: Quantum sensors can be used to monitor changes in environmental conditions, maintain the site and detect critical threats. For example, they can detect early fractures or low-level emissions of harmful contaminants and chemical leaks.

But what about quantum computing? Advances in quantum computing might help with challenges, such as, analysing well log data or simulating reservoirs for oil exploration. Efforts to optimise transport logistics in other sectors are ongoing, but challenges persist. Potential future applications of quantum computing might include:

Quantum computing for optimising processing and logistics: Given the range of ore processing that occurs on site, improved processing optimisation could further improve energy efficiency. Optimising above-ground activities, such as onsite and offsite transport of commodities, could reduce the overall environmental footprint of mines.

Quantum computing for optimising traceability: Quantum computing may create new forms of social and environmental value, such as transparent and ethical mineral supply chains. By bringing significantly enhanced computing power to the processing of secure, decentralised blockchain networks, quantum computers could allow 'quantum tagging' of products to ensure traceability from deposit to end use. This could also track environmental performance (CO_2 emissions in supply chains) and inform verifiable environmental disclosure reporting.

Next steps

Finding out how quantum technologies can solve problems in the resources sector, change traditional practices, and create high-impact applications that benefit society and the environment. This includes figuring out how advances in quantum computing can best tackle optimisation challenges.

The next step is connecting quantum researchers with companies and peak bodies in the resources sector. Targeted cross-sector collaboration will help identify and prioritise the most transformative Australian solutions, using our expertise to improve industry performance and advance quantum technology development.

Raw notes on the responsible innovation breakout session

How do you close a mine to reduce environmental impact? Need to consider this even at the exploration stage. How can you do in-situ recovery especially of low-grade ores?

Issues are:

- Decarbonising
- Reducing waste
- 11% of the world's energy is used to crush rocks
- Less rock less energy needed
- Questions of how quantum will help to do exploration and mining differently
- Sensors for mine closures
- Characterisation of tailings dams – how much metal?
- Ore tracking as it moves around when blasting
- Improving the recovery percentage

Quantum optimisation for operations

Case study provided by Q-Ctrl

Big picture problem

The resources sector will face many challenges in the coming decades. These include running operations efficiently and resiliently, meeting the goal of net zero emissions by 2050, and reducing the environmental and social impact of mining. To tackle these big challenges, different operational processes can be optimised to improve productivity, make supply chains stronger and use available resources more effectively.

Breaking the problem down

Challenging operational tasks include managing supply chains, such as planning routes and schedules for processes and workers, allocating equipment, and mixing raw materials. Because these operations are large and valuable, the potential savings could be significant enough to make previously unprofitable mining sites viable. This increased flexibility in site selection could greatly reduce environmental and societal impacts. For example, Deloitte reports that optimising the drill-and-blast operation by PETRA Data Science in a Western Australian iron-ore operation led to a 5.5% improvement in plant throughput. This resulted in an estimated annual financial benefit of more than $450 million.[2]

According to Deloitte, resource companies are encouraged to "step up their quest for operational optimisation" and use available software solutions for high-priority tasks. This can lead to much better solutions through expert use of existing tools, but the highlighted tasks are usually too complex for exact solutions and hard to approximate. Therefore, suboptimal solutions are used in practice.

How could quantum technology help?

Optimisation problems affect how efficiently the resources industry operates. Better solutions can improve both economic and environmental outcomes. Today, the quantum computing industry is testing and comparing the performance of quantum optimisation on complex problems, both in the near-term and for future fault-tolerant quantum computers. When they are available, error-corrected quantum computers will provably solve large-scale problems faster than standard computers. However, today's quantum computers have errors that affect their performance. In the near term, there is more focus on quantum ‘heuristic’ methods, which aim to provide better or faster solutions than existing methods, but without guarantees.

[2] https://www.deloitte.com/au/en/Industries/mining-metals/about/tracking-the-trends.html

Rapid progress in quantum hardware and software has led to promising steps towards practical optimisation, as shown in Q-CTRL's recent work using more than 120 qubits. We expect the performance of quantum optimisation on hardware to steadily improve over the coming years, rather than expecting a sudden big leap to clear advantage. This means that use cases in the resources industry are an ideal early opportunity for quantum computing impact, where small improvements to existing methods can have significant benefits.

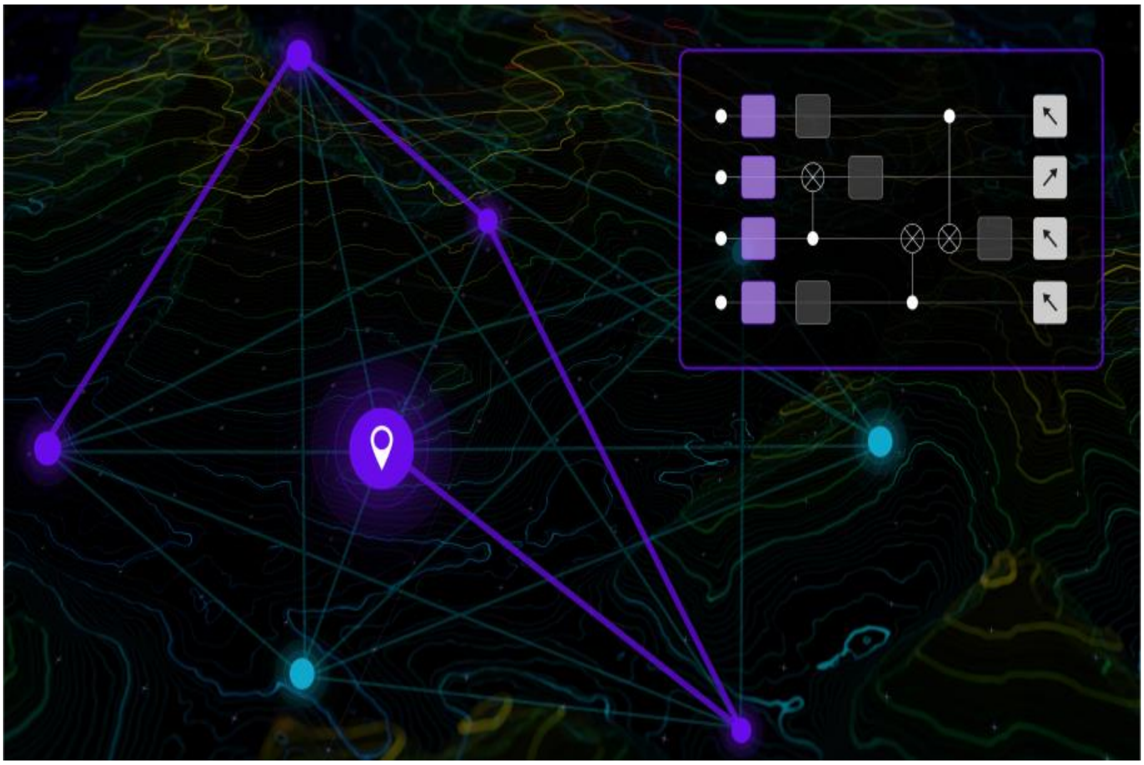

Image 8. Challenging operational use cases such as supply chain management, routing and scheduling and processing of materials could be optimised by quantum computers to improve throughput and site viability. This higher freedom in site selection could vastly reduce environmental and societal impacts. Image credit Q-Ctrl.

Next steps

- Creating specific examples and using the latest technology to solve problems in the resources sector, such as managing mine-site logistics, choosing and planning mines, allocating equipment, and blending stockpiles.
- Checking how well current quantum solutions work on available hardware and what quantum resources are needed to use quantum optimisation for solving difficult problems now and in the future.
- Creating a plan for the industry to start using quantum solutions with real quantum hardware and aiming to improve operational efficiency, improve resilience and reduce environmental impact.

Raw notes on logistics optimisation breakout session

It costs $2 million/day to operate a mine. Real-time optimisation would have great benefits. For example, reducing the number of trucks would reduce emissions and costs. Improved logistics would be a game changer. Logistics optimisation depends on the problem definition. A full stack quantum computer is hardware agnostic and lowers the barriers for quantum application developers. Quantum with machine learning is being developed by the CSIRO and the University of Melbourne. QCTRL works on optimisation of logistics and optimisation problems in general.

Industry issues:

- Miners are spending very little on research
- Could the big miners collaborate more?
- Need to make sure quantum builds value for the customer
- Need to use a "systems" engineering approach
- What is the art of the possible?
- Quantum researchers need to realise what is the important measurement – not what is the easy measurement; what are the quantum tools needed to meet the requirements of the industry?
- What is the right business model? For example, Photoassay TM use a business model that is not focused on the equipment
- Problems we don't know about include the use of underground EVs and need to reduce emissions
- Regulations – drone restrictions, how to manage risk; need to look at economies of scale

Other issues:

- EV charging stations
- Less energy to transport
- Building capability
- Gap in performance

Raw notes on the inverse problems breakout session

- Quantum computing will enable quantum data and quantum algorithms – can they help?
- Subsurface imaging is a hard problem
- How do you solve the inverse problem? (The problem of taking distribution of measurements of a signal and to do an inversion mathematically to determine where the source of the signal came from.)
- Can’t surround the ore body to get mass density.
- Need to use parameters that are vectors which can be related to Maxwell equations with boundary conditions – how can we optimise them?
- Vectors with 106–109 parameters that cannot be resolved – quantum computing could help? HPCs are struggling to deal with this – note, AI/ML would also be able to help
- Big data and modelling
- Issue is how to determine you have quality data and how to combine different datasets
- How to use the data? Need to increase data-rich future; collecting data at a faster rate at higher volume and maintaining quality of data and rapid influx of new types of data – leads to the need to generate models faster

Raw notes on the general sensing breakout session

Sensing – magnetic, position, down borehole

Ideal quantum sensors would have the following properties:

- Low drift
- Robust
- SWOP
- Accuracy with high spatial resolution
- Wide bandwidth and long slew rate
- Large dynamic range

These sensors would need have their data integrated with:

- AUSAEM line 20 km spacing
- Gravity 2 km spacing
- Airborne magnetics 100 m spacing
- Best resolution is by drones at 10 m spacing

Ideally, sensors would have inexpensive multiphysics data from airborne systems (aircraft or drones) that fly as high as possible to avoid turbulence to discriminate targets under cover; a cost of $3/km is needed to be economical – challenges are:

- Design of only 2 sensors
- Need more sensors but the environment is hard to deploy in
- Performing LIDAR at 80 m
- Hyperspectral imaging
- How do we get resolution, bandwidth and flying height? Ideally 1.5 cm resolution for Ni and Cu
- At this stage – no single platform can provide the multiphysics needed
- Need to separate signals; gravimeter measures acceleration
- How do you pull this out from GMS data?
- EM needs to remove the Earth's magnetic field – can do this via algorithms e.g. at low frequency
  - Magnetics with good bandwidth is useful
  - Superconducting sensors have developed a lot, especially with the new compact cryocoolers that mean they can operate as a black box

Summary of exploration issues

- Down borehole positioning needed
- Gravity gradiometry – differential sensors and sensitivity and good stability; need to know where the bird is as it moves around with respect to the ground
- Displacement vector from mm to km would be a big step change if achieved
- Know acceleration of the aircraft with respect to the earth – and remove background with gravimetry
- Aircraft data analysed in real time
- Quantum assured PNT – use gravimeter to locate your sensors
- Attitude rotation – 10^9 31 bits
- Fibre gyroscope
- Horizontal drilling – logging when drilling and avoid the able

- Quality of gravity maps not sufficient – full tensor gravimeter, magnetometer and gradiometer maps are needed
    - Sub Eotvos sensitivities ideally needed

Navigation and geopositioning

- Positioning in GPS-denied environment is an issue; need to navigate underground quantum sensors have PNT solutions that provide location without GPS
- Nomad Atomics has a gravimeter that is light, sensitive enough to monitor underground water
- Can you achieve a transparent earth with a gravimeter plus LIDAR?
- Gravity survey costs – onsite opportunity
- Downhole sensing needs PNT