СОВРЕМЕННЫЙ ПРОГРЕСС ТЕХНОЛОГИЙ ВОССТАНОВЛЕНИЯ НА МЕСТЕ ЗАЛЕГАНИЯ (RECENT PROGRESS IN PLACE RECOVERY)

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Mineral processing has a long history well covered in a recent publication[1] who points out "the ancient Egyptians knew already that it would be easier to melt an earth rich in gold particles than another which is poor. As a result, all efforts were made to enrich the gold by washing away the light gangue minerals. Since the middle ages, striving for improved economics has driven a string of innovative developments in milling and separation. The reader is again referred to the informative and illustrative text by Habashi.

The point is that developments in mineral processing have, since ancient times, been driven by the availability and nature of the minerals. The ancient Egyptians did not have access to iron and steel and yet a dagger found in the tomb of the pharaoh Tutankhamen is made of an iron-nickel alloy[2]. The source is from a meteorite, again illustrating the point that mineral processing is very much a function of the source of the material to be processed.

Mineral processing and mining interact

When we turn to the primary sources of materials that are mined or recovered and sent for mineral processing, it is informative to analyze recent trends. The first we might consider is the incremental improvements to existing methods of mining. Overwhelmingly, the main trend has been one of increasing scale, ever since the breakthrough of open cut mining first practiced at Bingham Canyon in 1906[3]. Various mines have at times held the world record for size of excavation or daily capacity with Panguna and Freeport featuring, but eventually eclipsed by Escondida.

With the demand for increases in throughput has come corresponding increases in the size of equipment. Particularly, for example, as the head grade of ore diminishes, rougher flotation requires more capacity and this is the driver for using very large flotation machines[4].

While sensing, automation and control has markedly improved in recent years[5], there remain challenges with this incremental approach of ever increasing scale. First and foremost, the grades mined on a global basis are declining. As

[1] Habashi, F., 2006 A short history of mineral processing. https://works.bepress.com/fathi_habashi/45/. (Accessed 22 February 2018).

[2] Filser, H., 2018. Der kosmische Dolch des Pharao. http://www.sueddeutsche.de/wissen/archaeologie-der-kosmische-dolch-des-pharao-1.3819470. (Accessed 22 February 2018).

[3] Wikipedia, 2018. List of open-pit mines. https://en.wikipedia.org/wiki/List_of_open-pit_mines. (Accessed 22 February 2018).

[4] Boeree, C. R., 2014. Upscaling of froth flotation equipment. Master Degree in Resource Engineering, Delft University of Technology, The Netherlands. https://repository.tudelft.nl/islandora/object/uuid:660e58d7-a82d-46d9-a8ff-1bfba42b2b05/datastream/OBJ. (Accessed 22 February 2018).

[5] Shean, B. J., Cilliers J. J., 2011. A review of froth flotation control. International Journal of Mineral Processing, v100, Issues 3–4, pp 57 — 71.

such, to maintain (or increase) production, the amount of material to be treated by mineral processing is rapidly increasing and with it the corresponding energy and water demands and hence costs, and carbon footprint. This has led to a parallel massive increase in waste and tailings generation and storage costs and risks and occasional disasters (see for example Bingham Canyon landslide[1] and Bento Rodrigues tailings dam failure[2,3]. Taking copper as an example, the figures from Marsden[4] indicate clearly that no matter what processing route is chosen, all of the common steps in copper recovery involve increasing energy as grade falls. There are of course many improvements to circuits brought about by knowledge sharing with the activities of the CEEC being exemplary[5]. The CEEC also publicizes many examples of improvements in circuits[6]. Increasingly new types of equipment promise finer comminution and lower power consumption. Some of these developments are at the small tonnage scale[7] while others are still in development[8]. There is little however that promises to halve energy costs and water consumption, what some estimate as necessary within 20 years to maintain present consumption levels. A complication that operators are increasingly aware of, is the level of impurity in the ore. As grade drops the relative level of problematic impurities is often increasing. An exemplar of this would be arsenic in many copper sulfide ore bodies. High levels of impurities, such as arsenic, can be of health and safety, and economic concerns, with penalties being imposed in most off-take agreements.

To make the situation worse for most companies, the rate of discovery of new ore bodies, and particularly Tier 1, World Class or Giant Ore Bodies[14] has dropped significantly, with most metals like copper being found in a handful of known deposits. While investment into the development of exploration technologies continues, the success and consequently the appetite for investment into further exploration has been significantly curtailed.

Uncomfortable as it is, we might conclude that the ever increasing scale of mineral processing is not keeping up with the requirements to reduce water, energy and costs.

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[1] Utah Geological Survey, 2016. Bingham Canyon's Manefay landslides and the future of the mine. https://geology.utah.gov/map-pub/survey-notes/bingham-canyon-manefay-landslides/. (Accessed 22 February 2018).

[2] do Carmo, Flavio F., Kamino, L. H.Y., Junior, R. T., de Campos, I. C., do Carmo, Felipe F., Silvino, G., Mauro, M. L., Rodrigues, N. U.A., de Souza Miranda, M. P., Pinto, C. E.F., 2017. Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. Perspectives in Ecology and Conservation, Vol. 15, Iss. 2, 145 — 151.

[3] Wikipedia, 2015. Bento Rodrigues dam disaster. https://en.wikipedia.org/wiki/Bento_Rodrigues_dam_disaster. (Accessed 22 February 2018).

[4] Marsden, J. O., 2008. Energy Efficiency & Copper Hydrometallurgy. http://metallurgium.com/pdf/JOM%20Energy%20Hydromet%202008%20rev5.pdf. (Accessed 22 February 2018).

[5] CEEC, 2018. https://www.ceecthefuture.org. (Accessed 22 February 2018)

[6] Nkwanyana, S., Loveday, B. 2017. Addition of pebbles to a ball-mill to improve grinding efficiency. Minerals Engineering, vol. 103 — 104, pp72 — 77. https://www.ceecthefuture.org/papers-rss/1960-addition-of-pebbles-to-a-ball-mill-to-improve-grinding-efficiency. (Accessed 22 February 2018).

[7] Kelsey, C. G., Kelly, J. R., 2016. Super-fine crushing — Pivotal comminution technology from IMP Technologies Pty. Ltd. XXVIII International Mineral Processing Congress Proceedings, September 11 — 15, Quebec City, Canada. Published by the Canadian Institute of Mining, Metallurgy and Petroleum (CIM). https://www.ceecthefuture.org/resources/super-fine-crushing-pivotal-comminution-technology-from-imp-technologies-pty-ltd. (Accessed 22 February 2018).

[8] Shi, F., Zuo, W., Manlapig, E., 2015. Pre-concentration of copper ores by high voltage pulses. Part 2: opportunities and challenges. Minerals Engineering, 79, pp 315 — 323.

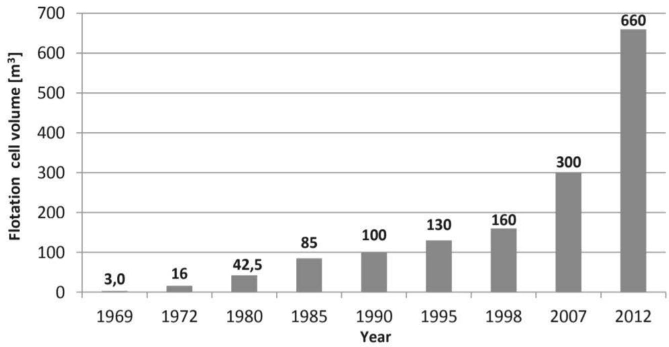

Fig. 1. Largest available mechanical float cells, from Govender[4]

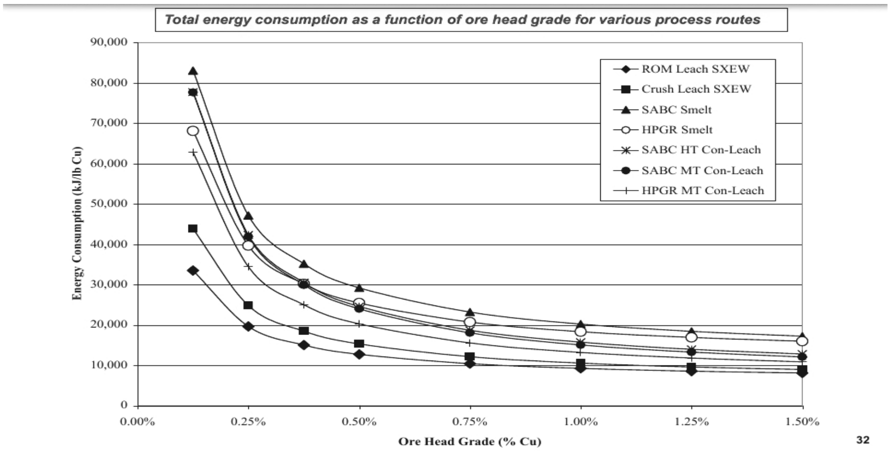

Fig. 2. As head grades continue to fall, so energy consumption continues to rise, no matter what processing route is chosen[9]

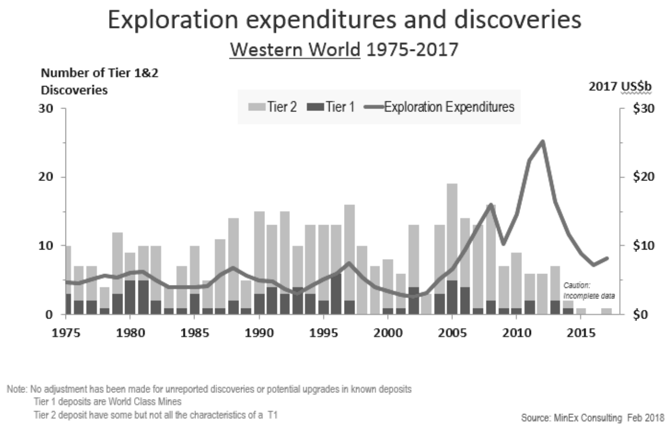

Fig. 3. Discoveries of Tier 1 and 2 ore bodies between 1975–2017[1]

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[1] Schodde, R. C., 2018. MinEx Consulting. Private communication.

Finally, we might consider whether the trend to "geometallurgical processing" will deliver the needed reductions in energy and water consumed in mining and mineral processing. This approach to mineral processing goes beyond the "mine to mill" stage and takes a form of selective mining to its ultimate conclusion where much finer parcels of mineralised material are mined and appropriately sorted and then sent for finely tuned mineral processing. The benefits are quite significant and some mineralisations that were uneconomic using conventional mine planning and mineral processing are now considered economic. Further, by introducing bulk sorting of some parts of an ore body, quite significant improvements in operating costs have been demonstrated, see for example Carrasco et al[1]. The goal, to remove gangue earlier and not to send as much gangue for milling in the first place, has been captured in the concept of Grade Engineering and is being developed collaboratively through CRC Ore[2]. There are also good indications from the CRCORE and its partners that a more open approach to innovation can help bring down the energy and water demands as well as the costs. The paper by King and Adair (2017) notes[3] a string of improvements that have resulted in the MSC mine in Bolivia achieving a first quartile position, despite having some of the lowest head grades in the world.

[1] Carrasco, C., Keeney, L., Napier-Munn, T. J., Bode, P., 2017. Unlocking additional value by optimising comminution strategies to process Grade Engineering® streams. Minerals Engineering 103—104, 2—10.

[2] CRC Ore. Application of Innovative Grade Engineering® Technologies. Grade Engineering White Paper. https://www.crcore.org.au/grade-engineering. (Accessed 22 February 2018).

[3] King, D., Adair, B., 2017. Innovation in action. A step change in the energy, production and water signatures at the MSC site in Bolivia. IMARC 2017, International Mining and Resources Conference.

It is relatively early days for this approach and Grade Engineering with more open innovation will help but we conclude that in place mining will be necessary to cater for the lower grades of 2028.

The social license to operate

Mineral processing as a key part of mining has always been subject to a social license to operate. The revolution that closed the Panguna mine is but one reminder that the license to operate can be abruptly withdrawn[4]. Many argue, and indeed demonstrate that understanding and engaging stakeholders is the key to obtaining and maintain the license to operate, eg Reggio and Lane[5]. There is excellent recent work on testing just how much and what form of engagement is the most effective in obtaining and holding the social license to operate[6]. This work from CSIRO[7] used engagement for a hypothetical mine and observed that the most effective route in winning trust was not just provision of an overview of the project, but also a commitment to engage, a demonstration of adherence to prevailing regulations and requirements and, importantly, also

[4] Mineral Policy Institute. 2013. Mining Legacies in PNG. http://www.mpi.org.au/our-work/mining-legacies-in-png/. (Accessed 22 February 2018).

[5] Reggio, R., Lane A., 2012. Monitor Deloitte: Mining in Africa: How inclusive solutions can mitigate risk. p12. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/strategy/us-consulting-mining-in-africa.pdf. (Accessed 22 February 2018).

[6] Zhang, A., Measham, T. G., Moffat, K., 2018. Preconditions for social licence: The importance of information in initial engagement. J Cleaner Production 172, 1559—1566 accessed through www.sciencedirect.com/science/article/pii/S0959652617326252.

[7] CSIRO, 2015. Producing more from less. https://www.csiro.au/en/Research/MRF/Areas/Resourceful-magazine/Issue-07/Producing-more-from-less. (Accessed 22 February 2018).

allowing the community an opportunity to contribute. This suggests that the more novel practices of in place recovery have a reasonable chance of gaining acceptance provided best practice of engagement is followed.

Although not discussed in this paper, there is a similar challenge for regulators to better understand future novel approaches to value extraction (such as being pursued by Mining3) and develop appropriate regulations and approaches to their permitting. While it is uncomfortable for many associated with mining and mineral processing, there has been considerable activity suggesting that mining as we know it is dead and that a new approach is needed[1,2,3]. In terms of the social licence to operate, there has been particular attention in recent years to the problems associated with tailings and their safe disposal. The consequence of rising demand for metals and falling head grades referred to above means that there is an ever increasing amount of tailings to be safely disposed of. The performance of the industry here at a global level is very poor. Not only have there been several major disasters killing some hundreds of people, the number of major tailings dam accidents has increased significantly in recent years.

It can reasonably be predicted that the production of tailings to be sent to a storage facility will not be permitted in most countries in the near future. While dewatering is technically possible and will no doubt be practiced, it is expensive, and this gives impetus to develop techniques that totally eliminate tailings such as in place recovery.

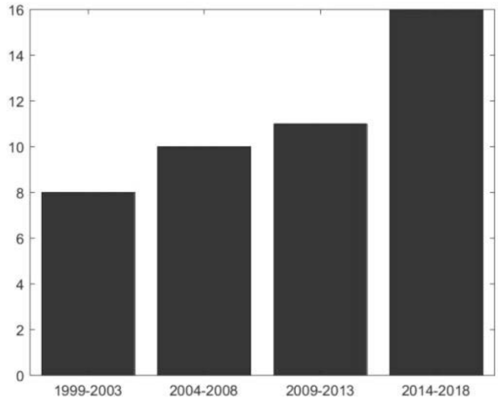

Fig. 4. Number of significant tailings dam failures per 5 years[4]

In-place mining as the next generation

In terms of in-place extraction of components, nature has been demonstrating this for a long time. The original "Rio Tinto" is of course a river in southwestern Spain where the red colour of the water is from acidic dissolution of iron minerals. The green blue colour of the stream that runs to the ocean from the abandoned Panguna mine on Bougainville Island is another example of in-place dissolution of metals, in this case from waste dumps, rainfall and exposed sulphides — a classic example of acid mine drainage.

Noting the leaching that occurs in nature, there have been many efforts to directly leach valuable minerals: copper as a prime example. The early efforts at Bingham Canyon were not successful as

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[1] Kellogg Innovation Network. 2012. Mining is broken. https://static1.squarespace.com/static/55ef2e62e4b03c55493aa901/t/561d825ce4b00071739bad0c/1444774492014/KIN-Catalyst-Mining-Company-of-the-Future-Infographic.pdf. (Accessed 22 February 2018).

[2] World Economic Forum. 2014. Scoping Paper: Mining and Metals in a Sustainable World. Geneva. http://www3.weforum.org/docs/WEF_MM_MiningMetalSustainableWorld_ScopingPaper_2014.pdf. (Accessed 22 February 2018).

[3] Hitch, M., Geo, P., Dunbar, W. S., 2015. Paths of innovation in the mining industry. Norman B Keevil School of Mining Engineering. Pp 61.

[4] Armstrong, M., Petter, R., Petter, C. 2019 Why have so many tailings dams failed in recent years? Resources Policy, Oct 1, 63:101412

many of the minerals in the waste dumps are not amenable to simple acid leaching. Indeed, the track record for in-place leaching (or in situ recovery) of copper has had many attempts but until relatively recently, few successes[1]. Most of the abundant copper minerals (particularly sulfides) are simply too slow to leach at reasonable temperatures. The more readily leachable minerals have been mined and heap leached so that the chemistry and kinetics are well known. Indeed, heap leaching operations can be very large. What is now apparent is that oxide copper deposits are now being targeted for leaching in situ and with good environmental performance and with the necessary social license to operate. In Arizona two copper ISR projects, the Excelsior company's Gunnison project[2] and the Florence Copper project[3], are both progressing well through approvals and into demonstration. While in Russia, Uralgidromed OAO, built by the Russian Copper Company in 2005, operate an in-situ recovery facility from the Gumeshevskoye deposit and appears to be in commercial production[4].

To some extent, the spate of interest in in-place recovery of copper should come as no surprise. References to in-situ recovery date back to 177 BC and the Chinese are known to have won copper by in-situ recovery in 907 AD. While applications in deep hard rock are still to become common place, porous soft rock deposits have been routinely mined by in-situ recovery for soluble salts (e.g. potash), uranium, gold and lithium.

Indeed, the low cost and environmentally sound nature of an ISR approach to the process of extracting values is illustrated well in the world of uranium mining where around 50% of the world's uranium is extracted using an ISR approach and the all of the lowest 1/3 cost uranium producers are all using and ISR approach[5].

Next steps for in place recovery

There have been many visionary projections for the mine of the future, including one of the present authors at the IMPC in 2003[6] and a recent update[7]. One notes that there are two pathways to in-situ recovery of values from hard rock minerals located deep underground. Both are evolutionary on existing practices.

The first will see the rapid development of enabling technologies that allow solution mining practices to extend deeper and into a broader range of ore bodies[8,9,10].

1 Sinclair, L., Thompson, J., 2015. In situ leaching of copper: Challenges and future prospects. Hydrometallurgy, 157, pp.306 — 324.

2 Excelsior Mining. 2018. Excelsior Mining Provides Draft Federal EPA Permit Update. http://www.excelsiormining.com/index.php/news/news-2018/538-excelsior-mining-provides-draft-federal-epa-permit-update. (Accessed 22 February 2018).

3 Florence Copper. 2018. A Rare Opportunity. https://www.florencecopper.com/. (Accessed 22 February 2018).

4 Springer Science +Business Media Inc. 2005. Introduction of an innovative technology for the underground beneficiation of copper ore and its subsequent extraction and electrowinning. Metallurgist vol. 49, Nos 9 — 10, pp9 — 10.

5 Heili, W., 2018. Key lessons learned from the application of ISR to uranium. ALTA 2018 https://www.linkedin.com/feed/update/urn:li:activity:6359628274930450432. (Accessed 22 February 2018).

6 Batterham, R. J., 2003. The mine of the future — will it be visible? XXII IMPC, Plenary 5, Cape Town.

7 Batterham, R. J., 2017. The mine of the future — even more sustainable. Minerals Engineering 107, pp2 — 7.

8 Kuhar, L. L., Breuer, P., Robinson, D. J., 2016. Factors affecting the ranking of deposits for potential in-situ processing. ALTA 2016 Nickel-Cobalt-Copper Conference, Perth, WA.

9 Robinson, D. J., Kuhar, L. L., Breuer, P., 2016. Opportunities, challenges and targets for hard-rock in-situ recovery. Hydroprocess 2016 Conference.

10 Kuhar, L. L., Shiers, D. W., McDonald R. G., Robinson, D. J., 2016. Copper deposit solution chemistry and its importance in in-situ recovery applications, TiGeR Conference, Perth.

The challenges are numerous but include; advanced in situ ore body characterisation tools, robust self-sufficient and wireless metal specific sensors for environmental and production monitoring, controllable fracturing technologies and improved in situ target mineral liberation, advanced lixiviants (more robust but environmentally benign and target metal selectivity). In parallel greater understanding of and the ability to measure and model fracture networks and ore body porosity, lixiviant flow and soluble metal pathways, economic outcomes (costs and production) will occur and improved confidence in ISR will grow[1]. This will likely depend on some early successes that demonstrate the progress. In particular brownfield use of an ISR method for mine life extension and increased value recovery e.g. around or in open pits and underground mines (operating or abandoned) will give operators confidence to move into green field projects[2].

Just as hydraulic fraccing has revolutionized the production of natural gas and changed the world order in terms of oil and gas production, so application of the same fraccing processes to solution mining practices will be a key step in enabling the mine of the future.

The second and parallel path to the mine of the future involves deep mineralisations. While deep rock mining is never easy, one notes that there are many developments in sampling, analysing and understanding the nature of rock masses. There are good reviews on this in the set of articles in the August 2017 edition of "Engineering" with its focus on efficient exploitation of deep mineral resources[3]. So, we conclude that it is only a matter of time before in-situ recovery becomes standard, thus changing the whole nature of mineral processing.

Recent initiatives that suggest in-situ recovery will be commonplace within 20 years

The development of knowledge and enabling technologies that would create the opportunities for broader application of an in-situ recovery (ISR) approach are being promoted and pursued by Mining3, a partnership formed in July 2016 that brings together researchers, technology developers and operating companies in a collaborative manner (https://www.mining3.com/about-us/what-we-do/).

Within Mining3, ISR is seen as the end member of new approaches to the extraction of value in a transformational research pillar called "In Place Mining", which also considers "In Line Recovery" and "In Mine Recovery" along the evolution[4]. This continuum of development focusses on technologies and approaches that reduce material movement, increases processing in place (or at the rock face) and reduces surface impact, consequentially reduce costs and improve the safety and sustainability of our extraction industry. Such approaches would enable the profitable extraction of currently uneconomic ores, both greenfield and at existing operations (open pit or underground) where increased value recovery, mine life and longer lasting jobs would result.

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[1] Kuhar, L. L., Breuer, P., Robinson, D. J., McFarlane A. 2015. Making Hard Rock In-Situ Recovery a Reality, AusIMM Future Mining 2015.

[2] Robinson, D. J., Kuhar, L. L., Breuer, P., Haque, N., 2016. Considerations and potential economic advantages for the in-situ recovery of gold from deep, hard-rock deposits. SAIMM Hydrometallurgy Conference 2016: Sustainable Hydrometallurgical Extraction of Metals, August 2016.

[3] Various authors. 2017. Special issue of Engineering: Efficient exploitation of deep mineral resources. Engineering, 3(4), pp 527 – 566.

[4] Mining3. 2018. https://www.mining3.com/place-mining-transformational-shift-metal-extraction/. (Accessed 22 February 2018).

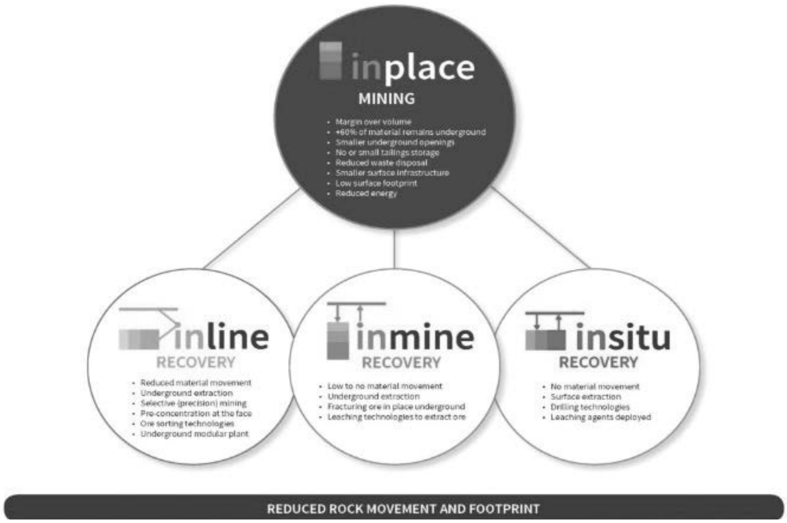

Fig. 5. In place mining methodology[1]

[1] Mining3. 2018. https://www.mining3.com/place-mining-transformational-shift-metal-extraction/. (Accessed 22 February 2018).

With falling grades, ever more costs for energy and water and a much more focused requirement for the public licence to operate, especially in terms of avoiding the production of wet tailings, mining must achieve the extraction of metal values with less than half the energy and water requirements seen today. Such a drastic change is unlikely to be met just by incremental improvements in mining and mineral processing. The most likely 20-year scenario is that there will be significant adoption of in-situ recovery of values from deep, hard rock deposits with very little surface footprint or impact. The Mining3 initiative described in this paper is a good step in expediting the process of change. This will be complemented by more and more examples of solution mining of shallow deposits.

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