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Cradle-to-cradle mining: a future concept for inherently reconstructive mine systems?

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Abstract

Mining creates vast quantities of waste and is inherently damaging to land. These two issues have been among the most intractable in resolving sustainable mine closure. Here we propose a new ambitious concept for future mining practice, where land use and material waste are recognised as part of a mine's assets not its legacy. The challenge is firstly to build a closed-circuit mining system where all excavated materials are exploited as a resource. These uses may be quite disconnected from the primary mined ore where other industrial, agriculture or urban uses may be found, along with more conventional uses for the encapsulation of toxic wastes and the reconstructed and sustainable post-mining landscape. The 'cradle-to-cradle' concept should lead to a post-mining landscape that has equal or greater ecosystem services to the pre-mining landscape. This approach demands more detailed knowledge of the mineralised system from the earliest exploration stage, outlining the nature of the entire orebody and enclosing rock mass that will allow a more complete planning of mineral recovery and handling of discarded material, accommodating any plans for future secondary recovery operations. This knowledge also directly informs the planned reconstruction and remediation strategy. Post-mining landscapes will need to have reconstructed ecosystem services that are designed to be 'net-nature-positive' while delivering outcomes that are beneficial for all stakeholders. Consequently, closure planning needs the collaborative involvement of all stakeholders from the start (socially embedded rather than socially engaged) which can then help deliver an inherently reconstructive cradle-to-cradle approach to the operation transferring the site back from the mining company to government or a third party for its future use.

Keywords: *geological audit, life of mine, land rehabilitation, material characterisation, stakeholder engagement*

1 Introduction

Current best practice in mining has a clear focus on resource economics, and planned and optimised mining operations, leading to a phase of closure management. These phases are typically sequential in execution and, while commercially successful, can lead to a legacy of waste materials and a patchwork of repaired but, in the long-term, not self-sustaining, post-mining landscape structures.

An International Council on Mining and Metals (ICMM) study in 2018 suggested that in the next 25 years, 40% of the mining operations of reporting members were expected to close, with nearly half due to close before 2028 (Brock & Stevens 2021). ICMM guidelines (ICMM 2019) are that there should be a shared vision for post-mining use across all stakeholders; a robust and regularly updated costed mine closure plan; plans for the workforce and communities' post-closure; adequate financial provision to cover future issues arising from closure; and lastly a plan for the mining company to transfer ownership back to government or a third party for its future use. This is an incredible challenge given the observation that there are only a few examples globally of mines that have received full certification for rehabilitation that meets a standard acceptable for a transfer to either government or a third party (Brock & Stevens 2021). The scale of costs for closure is clearly acknowledged by the major mining companies, with BHP and Rio Tinto setting aside provisions of USD 12 and USD 14.5 billion respectively on their balance sheets for the costs involved in near term mine closures.

We propose there should be a new concept that will lead to a **net positive impact** for any mining venture across economics, and natural and human social ecosystems that will satisfy the declared ambition for any closure planning right from the start of the project. We propose a step-change in thinking about mining practice that will be net positive for the miner, the local communities, and the environment. We suggest that industry adopt a new best practice for mining ventures that will avoid any negative legacies through a concept of **cradle-to-cradle mining**, where the starting landscape and the agreed future post-mining landscape are of equal or greater function and value (including biodiversity and ecosystem services), where a use for all excavated material is assessed and agreed, with the concept of 'waste' being eliminated as all material will have a prescribed use either on or off the mine site.

2 The challenges for mine closure with a conventional cradle-to-grave project model

Mining projects have historically tended to form four distinctive sequential phases of work arranged in a linear fashion, historically describing an essentially **cradle-to-grave** model, that can be loosely subdivided into exploration, resource definition (project), operation and then closure stages (Figure 1). Such subdivision is reflected by four different project 'ownership' philosophies attached to the asset (either different company types or different business units in a multi-national organisation with changes in reporting emphasis). Hence, each stage shows a different project focus with respect to the three bounding definers of viability – technical, financial and licence to operate (ESG). As a result, projects at key stages early in the project stage may not fully incorporate considerations that will become critical for the post-mining closure stage.

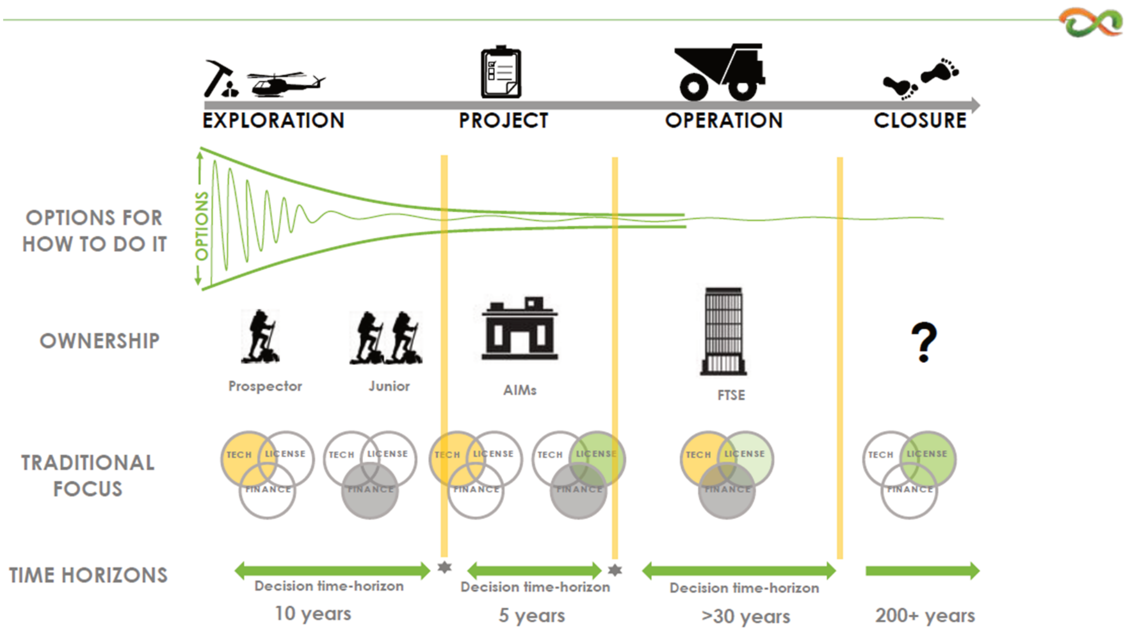

Figure 1 Schematic showing what is the conventional cradle-to-grave mining lifecycle, highlighting the changes in focus for projects through time with respect to technical, financial and licence to operate (ESG) (courtesy of Sarah Gordon, Satarla)

At the early exploration stage, where the ownership is in the hand of a prospector or junior company, key drivers are the technical and financial viabilities of the project and since exploration is an inherent loss-maker, the priority is to develop a well-performing stock based around technical discovery and focus is on the positive value of the resource. The nature of mine closure may be far from the explorer's mind. As exploration moves into the defined project (evaluation) stage, ESG considerations rapidly increase in focus and by the time a decision to start mining is made, the project is subject to close performance scrutiny across all three areas. Nevertheless, the operations part of the mining cycle is still very much geared to monitoring costs while optimising return, and mine closure may seem a distant problem and may not be foremost in the operator's mind. Waste rock and tailings may therefore not have been monitored or evaluated in sufficient detail.

The biggest issue that miners face on closure will be the legacy of wastes, tailings, and the generated wastewater runoffs. Optimal closure plans will need to ensure that any negative legacy from these materials is avoided, removed, or neutralised, yet evaluating the behaviour and potential value and utility of these materials is often hampered by the lack of adequate knowledge of their nature (e.g. Žibret et al. 2020). There is also evidence that mine waste and tailings facilities that are designed without considering the effects of ecological processes may evolve to deliver sub-optimal performance as the living ecosystem interacts with the geotechnical structure (DeJong et al. 2014). Another aspect is that in long-lived mining projects, changing economics and other factors may change what was initially considered as waste and disposed of as such, could become a new resource moving forward (Nwaila et al. 2021). Many elderly mines switch to reprocessing former wastes which may have only been defined in basic form so the future utilisation of any resource will need a full re-evaluation, similar in scope to what was performed for the initial mine planning. Lastly, the extractive sector has historically focused on stakeholder engagement that will simply satisfy the ESG standards of the day (Fraser 2018).

3 The new model of cradle-to-cradle mining

The challenge therefore will be to embrace the concept of **cradle-to-cradle**, a concept first applied to manufacturing (Braungart & McDonough 2002), where consideration of the value of the end of life of a product needs to be incorporated into plans for its production. We suggest the same approach should be applied to mining. Mining is actually a temporary intervention that extracts the valuable sub-surface resource from the mine site. As a process, mining is an inherently unsustainable use of the site since the outlined resource will ultimately be exhausted. However, upon completion of the mining, the site can be repurposed and reconstructed to be a re-valued, 'net-nature-positive' landscape which then becomes the new **cradle** ready for its repurposed ongoing use. Development of this regenerated **cradle** will only be possible after a carefully agreed plan, initiated in the early stages of exploration and evaluation, involving industry, government, and any interested and affected communities.

The five key components to a successful **cradle-to-cradle** mining are:

1. Building a closed circuit within any mine operation that is geared towards generating net zero waste.
2. Developing an in-depth audit of the entire geological system during the evaluation process that will characterise all excavated material including ores, wastes and other redistributed material.
3. Developing material control systems for the entire lifecycle of the mine that will track the stocks and flows of mined components following their fate.
4. Using knowledge of the existing local biodiversity, including the microbiome, to design and help deliver an enhanced legacy ecosystem to the post-mining site.
5. Working with local communities including indigenous groups from the start in collaborative ways to develop an approved plan for site transfer back to either government or third party for future use.

4 What does the cradle-to-cradle approach need?

1. **Closed-circuit mine:** Building this demands that all mined/moved materials will be put to use, whether as a downstream product that leaves the mine site, resource sent to storage as a 'stock' for potential future recovery or material that will be repurposed in the reconstruction of a new landscape of greater or equal function to the pre-mining state. This closed-circuit mining should be harnessing novel technologies such as smart sorting, and appropriate new technologies such as

hydro- bio- and deep eutectic solvents into recovery systems for optimised recovery of contained components, using as much of the mined material as possible, with a target of zero waste. Utilising a full lifecycle assessment (LCA) of the mining cycle will drive systems towards reduced energy consumption and reduction of water use in the cycle (Pell et al. 2021). Optimising and potentially decarbonising existing and future mineral processing operations, will move us closer to **wasteless mining** where all extracted materials (ore, gangue, waste) are characterised and in future classed as a resource of some sort. Alongside this, projects need to investigate the recovery of useful materials from legacy 'stocks', including material formerly evaluated to be waste during the course of mining (Hudson-Edwards et al. 2011).

2. **Detailed geological audit:** An in-depth physical, mineral, and chemical audit of the entire portion of the deposit and its enclosing rocks that is to be excavated is an essential part of developing this approach and perhaps this should become mandatory (Gloaguen et al. 2022). Apart from ore minerals and immediate host rocks, all the material that will be moved and relocated as a function of development and mining needs to be audited, and this must include physical and chemical properties in bulk, as well as at mineral and even at the atomistic scale, well before the project moves to any production decision. There must be mechanisms for identifying and ascribing potential uses for all of the materials mined (including the over and interburdens), which will enable an assessment of the onsite or offsite uses for the entire excavated rock mass. Understanding the nature of the material that is not going to be removed from the mine gate is key, since this material will be used in the process of rehabilitation and ecosystem reconstruction. Many current mining operations routinely implement the combined use of geological and mineral processing (metallurgical) data in order to develop spatially based predictive models for mineral processing outcomes (Liebezeit et al. 2016). This is termed geometallurgy and is now routinely applied to processing and extraction, but usually only for understanding material that will be sent to the processing plant for beneficiation. The characteristics of waste rock and fractions reporting to tailings and other wastes are often currently poorly characterised and as a result predicting and controlling their fate in the mining cycle is more difficult. A detailed workflow that incorporates techniques like automated mineralogy and advanced characterisation for all resource types at the site (Figure 2) would better inform the project at the planning stage and allow better decisions to be made regarding the use of all mined material.

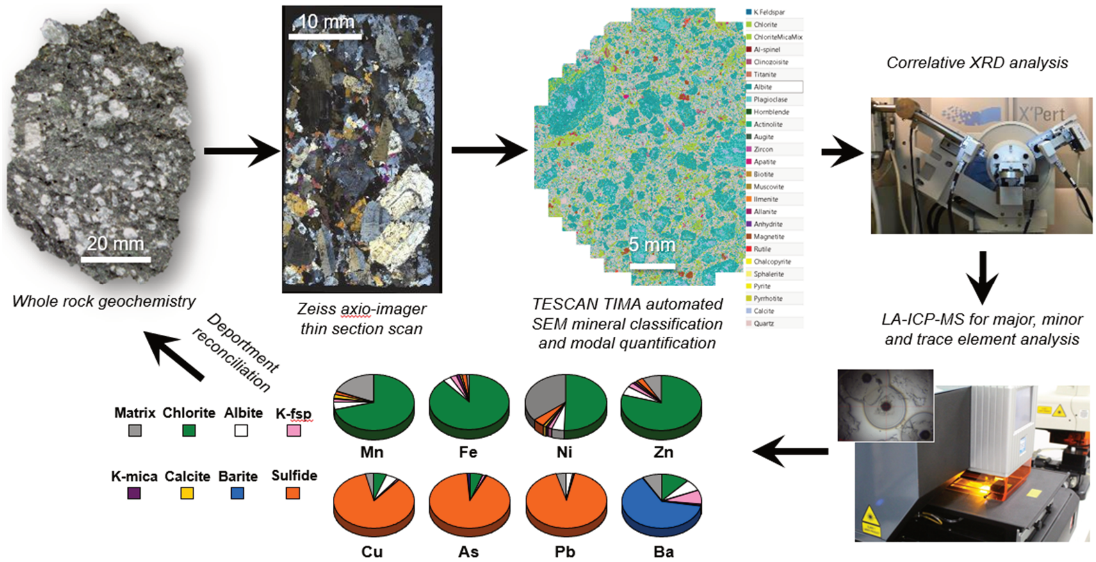

Figure 2 Flow chart showing the type of analytical workstream needed to yield the total mineral-chemical-petrological data needed to make a more complete analysis of the entire mineralised body (Natural History Museum unpublished data)

The benefits of extending the geometallurgical understanding to potential waste streams are obvious. Some recent projects have incorporated the evaluation of potential waste material and with that data and careful planning, projects are able to develop a closed system of waste capture that mitigates any impact on its surroundings (Grohs & Pearce 2019). Understanding mine wastes may point to other new opportunities for discarded material, like the proposed use for ultramafic rock waste from the Mt Keith mine as a sink for CO_2 capture and storage (Wilson et al. 2014), something not evaluated when the mine initially opened.

3. **Mined material control system:** Strict monitoring of the nature and the fate of all excavated material needs to be integrated into the mining plan for the tracking of all excavated and onwardly processed material. Since the entire rock mass will have been characterised, such a control system can monitor i) useful materials that can be currently recovered; ii) materials that can be set aside for potential future usage and recovery; iii) problematic waste that needs a designed mitigation strategy to be stored safely; and iv) benign 'waste' materials that may be used for post-mining landscape and thereby form the base for ecosystem reconstruction. Mining should endeavour to eradicate the binary terms of 'ore' and 'waste' that focus only on grade and recovery of primary metals. Closer attention to neglected potential by-products, potential deleterious components and useful bulk materials could reclassify much of what has previously been called waste and lead to potential future resource being carefully stored and managed. There are many current examples of waste streams in problematic mine tailing storage sites that could be re-evaluated for the significant contained metal budgets hampered by poor knowledge of the nature of the material (e.g. Mathieux et al. 2017; Žibret et al. 2020).

4. **Site specific detailed biodiversity audit:** This work needs to be carried out in order that the project has the information needed to deliver enhanced legacy ecosystem services post-mining. Achieving this this demands an early assessment of both the microbiome (at surface and sub-surface) as well as broader macro ecosystem components (e.g. plants, soils, pollinators) and their associated ecosystem services at the site. Understanding ecosystem services prior to any major disturbance will serve to benchmark any later interventions. The planned reconstruction post-mining should design a trajectory for ecosystem development that allows for biodiversity enhancement, ways of providing new ecosystems with greater resistance and resilience to future land uses and their environmental perturbations, achieving 'no net loss' (Sonter et al. 2014) or preferably 'net positive impact' (Teck 2017). During exploration, environmental baseline studies (EBS) are initiated to analyse and quantify the relevant environmental parameters for the area containing the footprint of the future mine as a record of the environmental conditions before any project activities have taken place and have traditionally included: compiling local geological, topography and climatic data; surface water studies; representative soil and stream sediment sampling over the site; wildlife and vegetation identification; and socio-economic information from the area including initial engagement with local communities and any aboriginal groups. Such studies should be extended to investigating the microbiome of the surface and sub-surface since this may include important organisms that have a functional role in stabilising natural mineral-soil systems (DeJong et al. 2014). Any onsite reconstruction will benefit from understanding the initial natural interactions and the range of functional microorganisms in the system. In addition to integrating genomic sequencing technology into the EBS ecological and biodiversity assessment approaches, the same techniques can be used through the mining cycle to monitor the impact of the operations and their legacy sites on agroecosystems, forests, and freshwater habitats, thereby informing any future restoration processes (e.g. Liddicoat et al 2022; Peddle et al. 2022). In sites that are seriously degraded prior to mining, the post-mining landscape could actually have a trajectory towards a strongly net-nature-positive outcome and there are good examples where post-mining or quarrying landscapes have been engineered to be beneficial to the environment (Mineral Products Association 2021).

5. **Stakeholder plan:** Any post-mining landscape needs to be planned together with local interested parties for this to achieve appropriate sign-off for transfer back to government of a third party. Work to scope any future ideas for what the mine will look like needs to be started very early in the exploration program and projects need to be 'socially embedded' rather than simply 'socially engaged' (Gloaguen et al. 2022) with a collaborative approach to design which evolves as the mine progresses. This type of approach has been missing from a number of past and active mine sites and any new project must engage early on with interested parties since local parties are likely to be a part of the post-mining future for the site.

5 Implementing the cradle-to-cradle approach

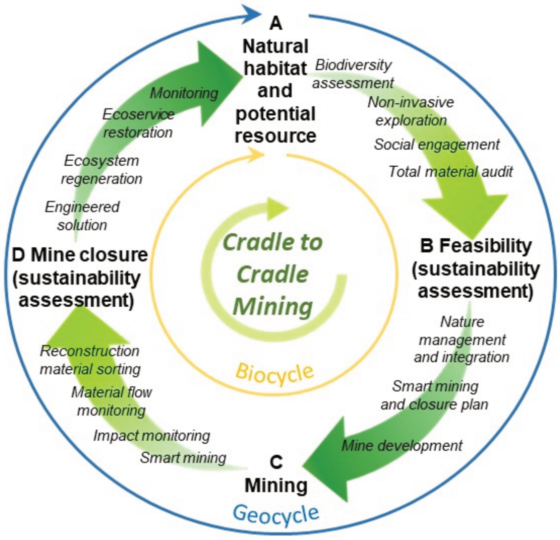

Figure 3 Graphic representation of the cradle-to-cradle mining approach including four sequential stages, cycling the landscape back to a clean, stable and functional state

Figure 3 encapsulates the thinking behind our **cradle-to-cradle** model. The process starts at **A** where the initial site has an existing natural habitat value and a to-be-defined resource value. Moving the process clockwise towards **B**, exploration needs to establish a thorough biodiversity assessment (both macro and micro) as part of the remit to establish the site's natural value (Constanza et al. 1997). This will include important data that can inform post-mining reconstruction plans as well as forming a benchmark to monitor any future project impact on biodiversity. Minimising the exploration footprint during evaluation is a given, whilst developing an early collaborative plan with all interested stakeholders. Once this dialogue starts, a strategy for mine closure needs to be worked on since for many stakeholders the mine closure will be as important an event as any mine opening. A full material audit of the mass likely to be mined forms an essential part of the evaluation since data about all the material that is to be used for onsite post-mining reconstruction is needed. Exploration will be using new, less invasive geological tools for ground selection in order to reduce the environmental footprint to a minimum at this stage.

Point **B** is a key step where a **sustainability assessment,** the key part of which will be a bankable feasibility study, will consider the full technical, financial, social and environmental aspects of the likely mine project, which has to incorporate the post-closure plans for the site. At this point, valuing the financial and strategic value of the defined resource should evaluate the likely effect of the mining process on the value of the current ecosystem services. Given a positive decision at this point, moving clockwise to mine development will, of course, incorporate the best practice with the aims of maximising recoveries of useful components, with identification of both potential by-products and deleterious components, as well as screening for useful bulk materials that could be used for other purposes including post-mine rehabilitation. Considerations of integrating 'nature' into the mine plan are relevant here as early interventions during mining can mitigate impacts and form the basis for the post-mining landscape. There are increasing opportunities to consider technologies like smart sorting, hydrometallurgy, bio processing and deep eutectic solvents in the mining flow sheet that can be assessed with detailed LCA to seek both decarbonising and water reduction strategies in the processing flow sheet (Pell et al. 2021).

From point **C**, the operating mine will implement the plan whilst monitoring the material flows and stocks during processing, paying attention to optimise recovery of useful products and by-products whilst minimising wastes (Pell et al. 2021). It is critical to understand the nature of the residual material that will form the basis for a reconstructed post-mine landscape, with an opportunity to start to incorporate nature-based legacy solutions that will mitigate the environmental footprint of the mining process. Progressive rehabilitation is recognised to be a key strategy to minimise closure costs and ongoing environmental risks (Pearce et al. 2016).

The next key decision point is point **D**, mine closure, another **sustainability assessment**. At this point there needs to be a signed off plan of landscape and ecosystem reconstruction that should be future-proofed with a system of meaningful monitoring to ensure continued success. Any stocks of future potential resources left at the mine site need to be logged with relevant information about their nature and properties recorded to simplify any future utilisation. Reconstructions of the post-mining landscape do not necessarily replicate pre-mine topography but attempts to emulate natural landforms after mining operations are more likely to restore functionality and diversity of ecosystems at degraded sites (Martin Duque et al. 2020). Restoring ecosystem services is both desirable from the biodiversity impact point of view but also increasingly recognised for the value that such ecosystems provide (Bullock et al. 2011). Any geotechnical design will evolve as a result of ecological processes so soil scientists and restoration ecologists must be involved in any project design that is likely to have long-term viability (DeJong et al. 2014), ensuring that the ecosystems' service value is maintained or preferably increased (Masarei et al. 2021). A system of long-term site monitoring should be implemented which should have a focus on the microbiome of the restored site and water courses since this will give key insights into the behaviour of the restored site below ground. The site thus then returns to point **A** in Figure 3, with a reconstructed site and restored ecosystem of equal or greater value than the pre-mining situation returned for future use.

6 Summary

Designing a mining system that avoids the outdated linear path of a cradle-to-grave fate for the project, where the post-mining landscape delivers a negative legacy is essential for any project.

A model of cradle-to-cradle mining changes the linear model into a virtuous circle where the development of the post-mining landscape demands improvements to the exploration and mining processes, that will inform the design of viable and future-proofed post-mining reconstruction and monitoring options for the site.

This approach needs:

- Better characterisation of the biodiversity of the chosen site at the earliest stage, including the sub-surface microbiome, to establish the ecosystems' service value of the site and identify organisms useful for reconstructing the site post-mining.
- More detailed knowledge (audit) of all the material that will be excavated during mining since this will i) drive better and more efficient recovery methods during mining, ii) identify any future resources that may be recovered in later operations and iii) materials that will be useful for the reconstruction of the site after mining.
- Design of the post-mine landscape with its functional and sustainable ecosystems that needs to be completed in collaboration with all stakeholder groups, designed to provide 'net-nature-positive' food webs and ecosystem functions for the post-mining stable landscapes, waters, and communities.

The strategy of this approach will also drive mining farther away from the flawed single financial bottom line mining model to the more equitable concept of a positive triple top line (Braungart & McDonough 2002) for all mining activities that serves planet, people, and profit.

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