Mine Closure and Reclamation - Practical Examples of Options and Issues

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Abstract
This paper discusses a number of successful case histories of mine reclamation. It aims to highlight some of the issues for planning and implementation of mine closure. The paper covers pit backfilling, rapid flooding to form a pit lake, closure as an in-pit wetland, and dry closure using free-drainage by gravity. The paper also discusses chemical dosing of in-pit waters, the implications of pit slope instability on closure programs, and how to minimize the potential for acid generation and achieve acceptable post-mining water quality. A number of recent case studies are used to illustrate the wide-ranging closure issues.

Key words: mine closure, reclamation, rapid flooding, pit lake, chemical dosing, slope stability

Introduction
The options and issues associated with mine closure and reclamation are illustrated in this paper by practical examples from around the world, all based on successful projects carried out by Water Management Consultants. Case studies include several open pits in Nevada, USA, which have been reclaimed by rapid filling with water to minimize the release of mineral acidity from pit walls. Closure of multiple pits in South Carolina is also discussed to illustrate how backfilling with sulphide rock can be used to allow passive treatment systems to function effectively and eliminate the need for active long-term active water treatment. Recent reclamation of a large open pit on the Bolivian altiplano is used as an example of how rapid filling can be used to control high pore water pressures and help prevent slope failures from releasing reactive wall rocks into the juvenile lake waters. Examples of post-mining covers for pit slopes are provided from New Zealand, together with maximizing the submergence of underground workings. Before considering the case studies, mine closure constraints and a general approach to mine closure will be discussed briefly.

Closure constraints and general approach to mine closure
At sites where sulphide-bearing minerals are exposed to oxidation during mine operation (in pit slopes, underground workings, heap leach facilities or waste rock storage facilities), the management of Acid Mine Drainage (AMD) becomes a primary constraint for closure. In these cases, the key to successful closure is isolation of potentially acid-generating material and minimising down-gradient flows. Ongoing chemical reactions have less influence on the overall closure conditions if the degree of contact with the active flow system can be reduced. The potential for successful installation of down-gradient passive treatment or attenuation systems is greatly increased if outflows from the site can be minimised. Methods that have been successfully applied to achieve physical isolation include:

- Evaporation and creation of a hydraulic sink in arid environments.
- Permanent diversion of up-gradient water.
- Creation of preferential flowpaths through workings.
- Application of backfill or covers.

The most suitable approach is strongly influenced by the physiographic conditions at the site. In general, the following observations on constraints can be made, based on experience in implementing closure plans at a large number of operations:

- *Open pits in arid environments:* AMD remains local to site. It is physically possible to create hydraulic sinks. Evapo-concentration is a key constraint for closure.

- *Open pits in temperate/humid environments:* AMD becomes flushed out and transported. Wall rocks potentially require cover and isolation or submergence. Mixing, hydrochemical adsorption, hydrochemical precipitation may act to minimise changes in the down-gradient environment.
- *Underground mines in elevated terrain:* Difficult to permanently submerge workings. Often permanent discharges occur through adits and tunnels. Site is typically more difficult to isolate.
- *Underground mines in lowland terrain:* Workings can often be permanently submerged below the water table. Down-gradient groundwater chemistry is typically the primary concern. Often present the most straightforward closure implementation.

In response to these constraints, the general approach to mine closure planning should be as follows:

- Understand the prevailing meteorological conditions.
- Characterise the groundwater and surface water flow systems and any changes resulting from mining.
- Identify the potential leaching behaviour of all rock types present.
- Determine the exposure of each rock type in all facilities at closure, including pit wall lithology.
- Predict potential long term behaviour of a pit lake (hydraulic source or sink, development of pit lake water quality with time).
- Outline an initial flexible closure plan taking account of costs.
- Implement closure operations with detailed monitoring.
- Refine overall closure plan in response to monitoring data.

Sleeper gold mine, Nevada, USA

The Sleeper gold mine is located in the Basin and Range province of Nevada, in the western USA. The ore body was hosted in Tertiary intermediate volcanic rocks with high pyrite content. The volcanics were unconformably overlain by Pliocene to Quaternary basin-fill alluvial sediments, and the western pit wall encountered about 30 m of saturated alluvium. Open pit mining at Sleeper commenced in 1985, initially as two separate open pits until mining resulted in the pits merging in 1989. Mining of the open pit was staged, so that 30 million tonnes of the waste rock removed from active sections of the pit was placed in mined-out sections of the pit, to buttress unstable sections of the pit slopes. Open pit mining ceased in March 1996, and the final pit was about 1,800 m long, 900 m wide and 200 m deep. Prior to mining, the depth to groundwater in the alluvial sequence overlying the pit was 10 to 15 m. Dewatering during the mining phase was focussed on intercepting groundwater flow in the alluvial sequence, and the maximum dewatering rate required to control inflows was 1,300 l/s.

As a result of the close connection between the alluvial groundwater system and the Sleeper Pit, a pit lake was an essential component of the closure approach. Detailed water balance studies demonstrated that due to the low precipitation conditions at the site and the large surface area of the lake for evaporation, the pit lake would act permanently as a hydraulic sink, with local groundwater flow being towards the pit lake. The primary constraint for the closure program was therefore the hydrochemistry of the pit lake, during filling and in the long term, and detailed hydrochemical characterisation and modelling were carried out. Based on the hydrochemical studies, the adopted closure approach was:

- Minimise the influence of potentially acid-generating backfill within the open pit by the placement of oxide covers prior to lake filling.
- Accelerate filling of the pit lake by operating alluvial dewatering wells at around 1000 l/s and discharging to the pit. This served to: minimise the exposure and oxidation period for the pit slopes and backfill material; improve the quality of the pit lake and mixing of the lake water during the filling phase; and provide an opportunity for active treatment of the lake waters.

- Apply lime dosing of the lake waters during filling. 12,000 tonnes of lime was introduced to the lake via flow from the alluvial wells and a lime slaker operated from 1996 to 1998. This acted to neutralise acidity and precipitate metal hydroxides being liberated from the pit slopes and backfill during the filling process.
- Introduce nutrients during filling. Around 800 tonnes of manure was added to the lake to stimulate growth of algae and accelerate the establishment of aquatic biota.
- Re-grade the upper alluvial slopes above the permanent pit lake, with alluvial material being pushed onto the lower pit slopes. Benefits to the pit lake were: providing a more stable landform for the establishment of vegetation above the permanent lake; liberating additional alkalinity within the pit lake, resulting from carbonate rich sediment horizons; introducing additional dissolved and solid phase iron to the pit lake to maximise precipitation and adsorption of dissolved metals; and forming a blanket over the potentially acid generating material in the lower pit slopes.

Haile gold mine, South Carolina, USA

Haile gold mine in South Carolina, USA, has been mined since 1827 with a combination of underground and open pit mining, with modern open pit mining commencing in 1985 and lasting until 1991. Before reclamation, the site consisted of the usual features of historic pits filled with tailings, open pits, waste dumps, heap leach pads and other associated mine facilities. Issues that had to be taken into account during closure planning included: low background pH (3.2 to 5.6 in surface waters); water quality impacts from historic features (tailing, waste rock, pits); the local stream, Haile Gold Mine Creek, being on the US Government's impaired stream list; high sulphide content in pit walls and waste rock (up to 17% sulphide); and precipitation exceeding evapotranspiration. The adopted closure approach for both Haile and Red Hill pits was as follows:

- The risk and performance of the proposed closure design was evaluated thoroughly prior to finalising the plan, taking into account water quality, regulatory acceptance, cost, and what could go wrong.
- The closure system was designed to be compatible with site conditions and climate. By careful contouring of the site, most runoff from precipitation is released as non-contact stormwater.
- Extensive consultation with stakeholders, especially the regulatory authorities, obtained regulatory buy-in to the closure plan.
- The closure design makes widespread use of carefully designed passive treatment systems so that no active treatment is required, and there are minimal maintenance requirements.

Kori Kollo gold mine, Bolivia

The Kori Kollo gold mine is located in the mining district of La Joya in Bolivia. The gold deposit was mined from a single open pit in the period 1991 to 2003. The mine is situated at 3,700 masl (metres above sea level) on the Bolivian altiplano, and the pit walls are within 100 m of the Rio Desaguadero, which drains Lake Titicaca. Total pit depth at the end of mining was 260 m. The upper slopes of the Kori Kollo pit intersect saturated alluvium, which is recharged by infiltration from the Rio Desaguadero. During mining, an extensive dewatering system incorporating both alluvial and bedrock interceptor wells was operated. The peak dewatering flow from the system was around 1,000 l/s, and flow was recharged to the alluvial system using infiltration basins located 3 km from the open pit. High pore-water pressures in the pit walls were controlled by the dewatering system during mining, but a major concern for mine closure was that once active dewatering ceased, slope failures would release reactive wall rocks (with up to 15% total sulphur content) into the juvenile lake waters. The closure approach adopted was to achieve rapid filling of the pit by temporarily diverting water from the Rio Desaguadero. A 30-m wide off-take structure, with control gates, was constructed, leading into a lined channel as far as the edge of the pit. A 35-m wide drop structure controlled the entry of the water into the pit, at a point chosen especially for the geotechnical stability of the wall rocks. The pit was flooded in three months, using water diverted from the Rio Desaguadero at a rate of around 15,000 l/s.

Golden Cross gold/silver mine, New Zealand

The Golden Cross mine is located at the base of the Coromandel Peninsular in the North Island of New Zealand. The site is on the margin of a conservation area and within the headwaters of the Waitekauri River. Underground mining was undertaken from 1892 to 1917, with modern underground and open workings constructed in 1988. Closure investigations for the modern workings were initiated in 1997 and included extensive stakeholder and community consultation. The site is now fully rehabilitated. The gold and silver ore body at Golden Cross was hosted in volcaniclastic andesite flows, which were defined to be highly acid generating. The ore body was overlain by intensely argillic altered breccia which formed a hydraulic barrier to vertical groundwater movement and by intensely leached andesite flows which had a soil-like texture as a result of alteration.

During mining, the open pit was never actively dewatered, and surface water runoff pooling after significant precipitation events was observed to seep through the base of the pit to the underground workings, resulting in increased pumping demand from those workings. Rates of recharge to the underground system were much greater than observed prior to mining, due to the open pit penetrating the argillic altered material which previously acted as a barrier to infiltration. Geotechnical investigations identified that it would not be possible to reinstate this hydraulic barrier. In addition, hydrochemical modelling confirmed that discharge from the underground workings would require treatment for an extended period. The closure approach for the underground workings therefore focussed on minimising inflow to the workings, and the resulting demand on a treatment system. The approach comprised:

- Installing a clay seal across the base and walls of the open pit. This incorporated a rigorous testing program to ensure that the main source of recharge to the underground workings was removed.
- Partially backfilling the open pit using locally stockpiled waste rock. The backfill surface was given a dished geometry, resulting in cover being placed over 90% of the pit wall rocks mapped as being acid generating.
- Excavating a notch cut in the pit wall to allow the pit surface to discharge to the Waitekauri River without pooling.
- Establishing wetland vegetation at the base of the pit backfill surface.
- Routing up-gradient runoff channels into the pit and through the notch cut, including the overflow from the tailings facility which was closed as a permanent lake.
- Installing limestone lining in clean water up-gradient channels, which resulted in reductions of between 5% and 50% in concentrations of copper, iron, manganese, nickel and zinc.
- Rapidly flooding the underground workings by diverting surface water drainage into a vent raise.
- Installing discharge containment and flow alarms at all historical adits.
- Routing underground discharge to the water treatment plant, until an anaerobic upflow wetland was established to treat the flows.