

CHAPTER 4. TYPE OF DEVELOPMENT

4.1 Mineral Deposits and Mining in the Bristol Bay Watershed

Significant mineral resources are located in Alaska, and the state has a long mining history. Russian explorers began searching for placer gold in the early 1800s, and substantial placer deposits have been found in many areas of the state. More recently, hard rock exploration has increased throughout the region. Alaska mines range in size from small, recreational suction dredging operations to large-scale commercial operations, for a variety of deposit types (Table 4-1).

Several known mineral deposits with potentially economically significant resources are located in the Nushagak and Kvichak River watersheds, and active exploration of deposits is occurring in a number of claim blocks (deposits other than Pebble are considered in greater detail in Chapter 13; see Table 13-1 and Figure 13-1 for the names and locations of these deposits). Of deposit types occurring or likely to occur in the region, porphyry copper, intrusion-related gold, and copper and iron skarn may indicate economically viable mining, thereby prompting large-scale development. Thus, the development of a number of mines, of varying sizes, is plausible in this region—and once the infrastructure for one mine is available, it would likely facilitate the development of additional mines (Chapter 13).

The potential for large-scale mining development within the Nushagak and Kvichak River watersheds is greatest for porphyry copper deposits, most notably the Pebble deposit. Significant exploration activity has been ongoing at this deposit for many years, and the information available provides the most complete description of potential mining in the region. Because the Pebble deposit is the most likely deposit to be developed in the near term, this assessment focuses exclusively on porphyry copper deposits. However, much of the discussion of mining methods (Section 4.2.3) applies to all types of disseminated ore deposits (i.e., ores with low concentrations of metal spread throughout the body of rock).

Table 4-1. Characteristics of past, existing, or potential large mines in Alaska.

Mine	Kennecott	Donlin	Fort Knox	Greens Creek	Kensington	Pogo	Red Dog	Pebble (78-yr)[a]
Location	Copper River basin, in Wrangell–St. Elias National Park	13 miles N of village of Crooked Creek and Kuskokwim River	26 miles NE of Fairbanks	18 miles SW of Juneau, in Admiralty Island National Monument	45 miles NW of Juneau, between Berners Bay and Lynn Canal	85 miles ESE of Fairbanks	Western Brooks Range, 82 miles N of Kotzebue and 46 miles from the Chukchi Sea	Headwaters of three streams running into the Nushagak and Kvichak Rivers
Target metals	Copper, silver	Gold	Gold	Zinc, lead, silver, gold	Gold	Gold	Zinc, lead	Copper, gold, molybdenum
Ore type	Massive sulfide	Gold-bearing quartz	Oxide ore body	Massive sulfide	Gold-bearing quartz	Gold-bearing quartz	Massive sulfide	Porphyry copper
Ore grade quality	Very high	Moderate	Low	High	Moderate	Moderate	High	Low
Operational life (years)	27 (1911–1938)	22	20	35–50	10	11	42 (1989–2031)	78
Extraction type	Underground stope mining	Open pits (2)	Open pit	Underground stope mining	Underground stope mining	Underground stope mining	Open pits (2)	Open pit
Total resource (million metric tons)	~ 4.5	491[b]	401	29	24	9.1	171	5,920
Ore processing rate (metric tons/day)	~ 91	48,524	33,000–45,000	1,524	1,134	2,267	7,500–8,300	208,000
Total waste rock (million metric tons)	<0.9	1900	338	~ 1.8	1.5	1.7	142	14,600
Tailings disposal	On Kennicott Glacier	Dams/ponds (2)	Dam/pond	Dry tailings	Lake disposal	Dry tailings	Dam/pond	Dams/ponds (multiple)
Tailings amount (million metric tons)	<0.9	426	181	~ 13.6	4.1	4.9	91	5,860
Tailings footprint (km^2)	NA	5.4	4.5	0.25	0.24	0.12	3	46
Dam height (m)	NA	143 (largest of multiple dams)	111	NA	27[b]	NA	63	209 (largest of multiple dams)
Acid mine drainage potential	No	Yes	No	Yes	No	No	Yes	Yes

Notes:
[a] Ghaffari et al. 2011.
[b] Novagold 2012.
NA = not applicable.
Source: Levit and Chambers 2012, except as noted.

4.2 Porphyry Copper Deposits and Mining Processes

4.2.1 Genesis of Porphyry Copper Deposits

Porphyry copper deposits are found around the world, often occurring in clusters (Lipman and Sawyer 1985, Singer et al. 2001, Anderson et al. 2009) in areas with active or ancient volcanism (Figure 4-1). They are formed when hydrothermal systems are induced by the intrusion of magma into shallow rock in the Earth's crust. Water carries dissolved sulfur-metallic minerals (sulfides) into crustal rock where they precipitate (John et al. 2010). Minerals containing sulfur and metals are disseminated and precipitate throughout the affected rock zone in concentrations typically less than 1% (Table 4-2) (Singer et al. 2008). Porphyry copper deposits range in size from millions to billions of tons (Table 4-2). The well-delineated Pebble deposit is at the upper end of the total size range; thus, any additional deposits found in the Nushagak and Kvichak River watersheds are likely to be much smaller than the Pebble deposit.

Table 4-2. Global grade and tonnage summary statistics for porphyry copper deposits.

Parameter	10th Percentile	50th Percentile	90th Percentile	Pebble Deposit[a]
Tonnage (Mt)	30	250	1,400	10,777
Copper grade (%)	0.26	0.44	0.73	0.34
Molybdenum grade (%)	0.0	0.004	0.023	0.023
Silver grade (g/t)	0.0	0.0	3.0	unknown
Gold grade (g/t)	0.0	0.0	0.20	0.31

Notes:

[a] Pebble deposit information is based on 0.3% copper cut-off grade, and includes measured, indicated, and inferred resources from Pebble Limited Partnership.

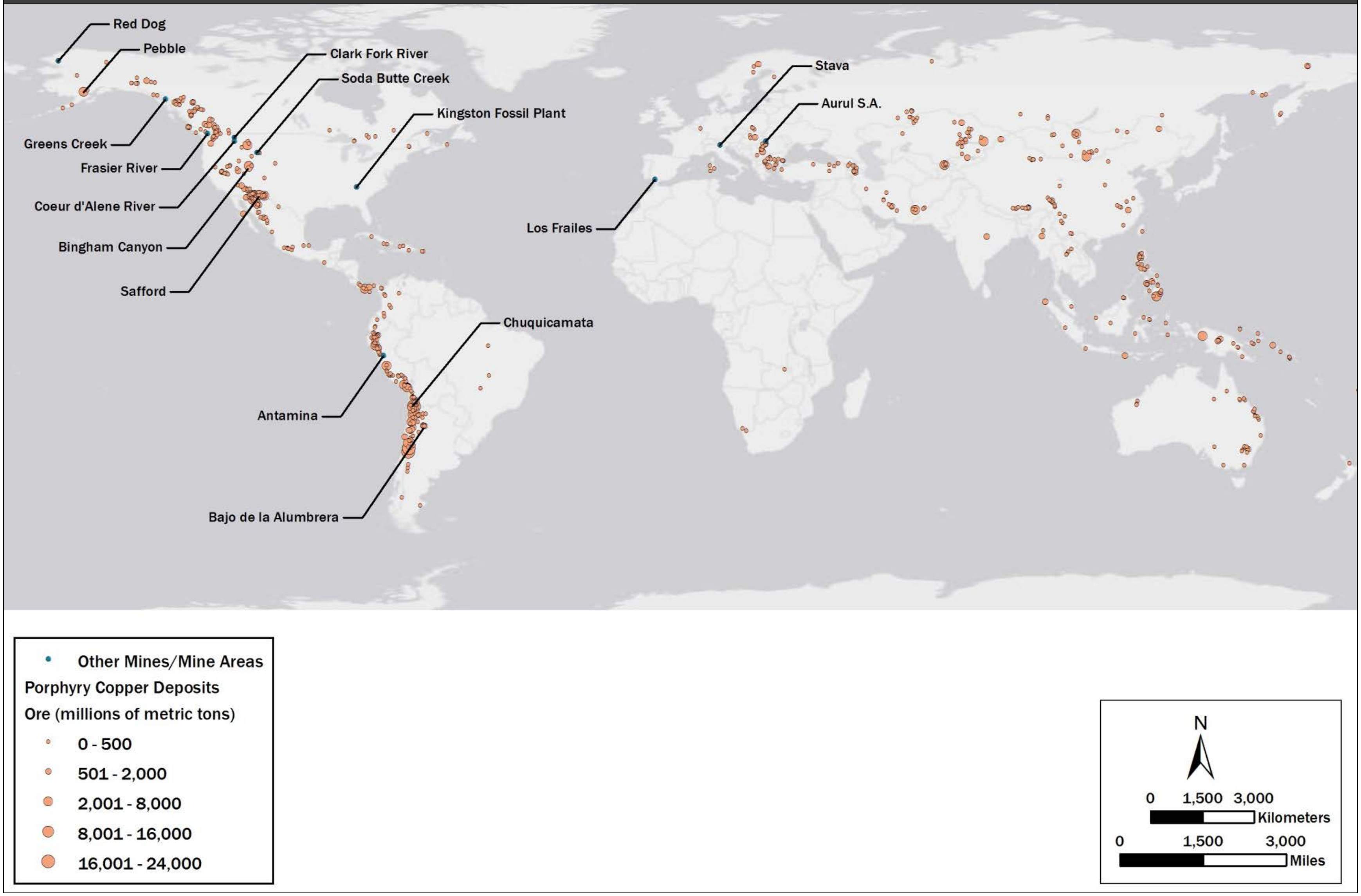
Mt = million tons; g/t = grams per ton.

Sources: Singer et al. 2008; Appendix H.

4.2.2 Chemistry and Associated Risks of Porphyry Copper Deposits

Exposure to hazards associated with mining porphyry copper deposits can pose risks to aquatic and terrestrial ecosystems and to human health. These risks can range from insignificant to extremely harmful depending on a variety of factors that control the hazards, including site geology (both local and regional), hydrologic setting, climate, and mining and ore processing methods. There are a variety of geochemical models and approaches to understand and predict the water quality of releases to the environment; however, our ability to make predictions is limited because of data insufficiency and the inherent complexity of natural materials and their environment.

Figure 4-1. Porphyry copper deposits around the world. Values are from the database compiled by and described in Singer et al. 2008. Other mines and mining regions mentioned in the text also are shown on the map.



Sources of hazards from porphyry copper mines can be grouped into four broad, interrelated categories: acid-generating potential, trace elements and their mobilities, mining and ore processing methods, and waste disposal practices. The relative importance of these categories will vary from deposit to deposit, but some generalization can be made for porphyry copper deposits as a whole. In this section we consider those categories related to environmental chemistry, acid-generating potential, and trace elements (categories related to mining processes are described in Section 4.2.3).

Mining processes expose rocks and their associated minerals to atmospheric conditions that cause weathering, which releases minerals (e.g., copper minerals) from the rock matrix. Grinding methods used in these processes create materials that have high specific surface areas, which accelerates the rate of weathering. Porphyry copper deposits are characterized by the presence of sulfide minerals, and oxidation of sulfide minerals creates acidity, sulfate, and free metal ions (e.g., iron in the case of pyrite); in addition, the acid produced can further accelerate weathering rates. Because most metals and other elements become more soluble as pH decreases, the acid-generating or acid-neutralizing potentials of waste rock, tailings, and mine walls are of prime importance in determining potential environmental risks associated with exposure to metals and certain elements in the aquatic environment.

One way to predict if acid generation has the potential to occur is to perform acid-base accounting tests. Acid-base accounting tests are rapid methods to determine the acid-generating potential (AP) and neutralizing potential (NP) of a rock or mining waste material, independent of reaction rates. These potentials are then compared to one another by either their differences or their ratios, with the net neutralizing potential (NNP) being NP-AP and the neutralizing potential ratio (NPR) being NP/AP. AP, NP, and NNP typically are expressed in units of kilograms of calcium carbonate per metric ton of waste material (kg $CaCO_3$/metric ton). Positive NNP values are net alkaline and negative values are net acidic.

Although methods used for acid-base accounting have known limitations, it is common industry practice to consider materials that have an NPR of 1 or less as potentially acid-generating (PAG) and materials that have an NPR greater than 4 as being non-acid-generating (NAG) (Brodie et al. 1991, Price and Errington 1998). Materials that have a ratio between 1 and 4 require further testing via kinetic tests and geochemical assessment for classification (Brodie et al. 1991, Price 2009, Price and Errington 1998). This further testing and assessment are necessary because if neutralizing minerals react before acid-generating minerals, the neutralizing effect may not be realized and acid might be generated at a later time—that is, pH of the system may decrease over time as neutralizing materials are used up, resulting in acid mine drainage. Additionally, some toxic elements (e.g., selenium and arsenic) may be released from mining materials under neutral or higher pH conditions, which would be observed during kinetic leaching tests conducted at variable pH values. Depending on the water chemistry of both a receiving water body and any mine drainage, released elements may either be transported downstream as dissolved ions or form precipitates that travel as suspended solids or settle to the streambed.

In general, the rocks associated with porphyry copper deposits tend to straddle the boundary between being net acidic and net alkaline, as illustrated by Borden (2003) for the Bingham Canyon porphyry copper deposit in Utah (Figure 4-2A). AP values for porphyry copper deposits typically correlate with the distribution of pyrite. The pyrite-poor, low-grade core corresponds to the central part of the Bingham Canyon deposit, where NNP values are greater than zero. Moving outward from the core to the ore shell and pyrite shell, pyrite abundance increases and NNP values become progressively more negative (Figure 4-2B).

4.2.3 Overview of the Mining Process

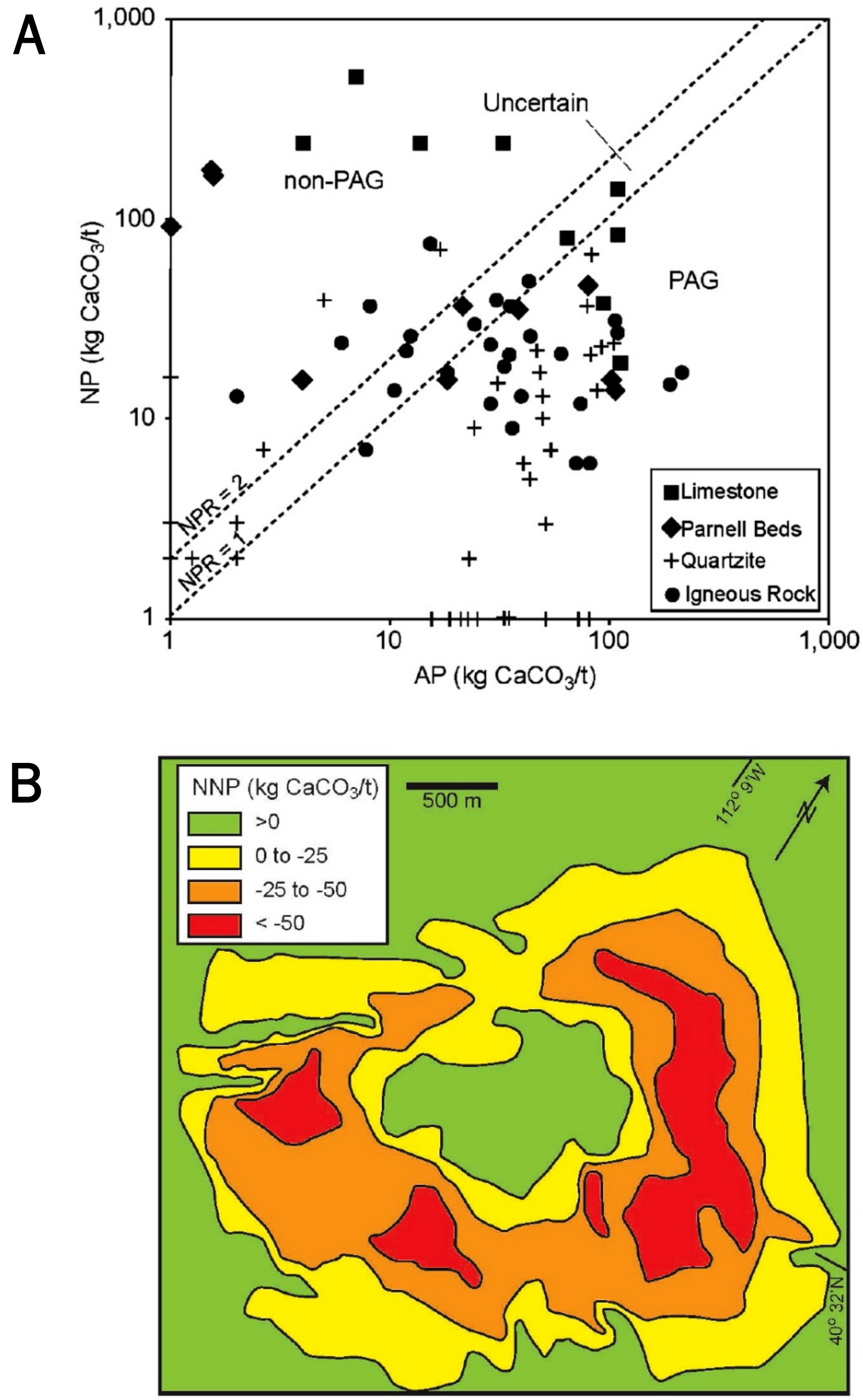
Developing a mine requires establishing surface or underground mine workings that allow access to the ore body. The scope and complexity of development-related activities vary depending on the characteristics of each project, but typically include the following components.

- **Site preparation (clearing, stripping, and grading).** Topsoil and overburden are removed and typically stockpiled for later use in mine reclamation.
- **Construction of mine site infrastructure.** Specific requirements depend on the size and type of mine operation, its location, and proposed mining, milling, and processing methods. Typical infrastructure includes facilities for ore crushing, grinding, and other mineral separation processes; ore stockpiling and waste rock disposal facilities; tailings storage facilities; water supply, treatment, and distribution facilities; transportation infrastructure such as roads or railways; pipelines; conveyers; and other infrastructure (e.g., offices, shops, housing).
- **Establishment of mine workings.** Once the site is prepared and infrastructure is constructed, mine workings are established: ore is extracted and processed, water at the site is managed and treated, and tailings and waste rock are stored and managed.

At each stage of mine development, potential impacts on the environment and human health can be reduced by ensuring effective implementation of proper design, construction, operation, and management techniques and protocols (Box 4-1).

Any mining company must comply with a number of federal, state, and local laws when developing and operating a mine. Compliance is facilitated through the regulatory permitting process and involves multiple state and federal agencies (see Box 4-2 for additional detail on these regulatory requirements). Regulations also serve to hold an operator accountable for potential future impacts, through establishment of financial assurance requirements and imposition of fines or compliance orders upon non-compliance with permit requirements (Box 4-3).

Figure 4-2. Neutralizing potential at the Bingham Canyon porphyry copper deposit in Utah. (A) Plot of neutralizing potential (NP) vs. acid-generating potential (AP) for mineralized rock types. PAG denotes potentially acid-generating. Note that the range of uncertainty is indicated as 1 to 2 in this figure; in the assessment, we use the more conservative range of 1 to 4. (B) Plan view of the distribution of net neutralizing potential (NNP) values. Plots modified from Borden (2003).



BOX 4-1. REDUCING MINING'S IMPACTS

Reducing mining's impacts on the environment and human health requires proper mine planning, design, construction, and operation; appropriate management and closure of waste and water containment and treatment facilities; and monitoring and maintenance over all mine-life phases, including post-closure. Some general methods for reducing adverse impacts of mining are provided here, along with information about how these concepts are incorporated into the assessment.

Best management practices refer to specific measures for managing non-point source runoff (40 CFR 130.2(m)). Measures for minimizing and controlling sources of pollution in other situations are often referred to as best practices, state of the practice, or simply mitigation measures. These are not the best possible or conceivable practices, but rather the current practices of the best operators. We assume that these types of measures would be applied throughout a mine as it is constructed, operated, closed, and post-closure. Although we describe some measures as they are relevant to a discussion, it is not necessary, for the purpose of this assessment, to describe them all.

Mitigation refers to all steps taken to avoid, minimize, treat, or compensate for potential adverse impacts on the environment from a given activity. One example of a mitigation measure for avoidance is to avoid mining a particularly reactive type of rock that might make future leachate management too difficult. Minimization of an impact is practiced when avoidance is not feasible, and includes measures taken to lessen the amount of contaminant released. An example of a mitigation measure to minimize an impact is to blend known acid-producing material with sufficient neutralizing material. Treatment is required when contaminants are released. An example is the diversion and collection of seepage from a waste rock pile for passage through a wastewater treatment plant to meet appropriate water quality criteria prior to release to the environment. Many elements of our mine scenarios include mitigation measures and all are assumed to meet minimum regulatory requirements. Appendix I contains further discussion of mitigation measures.

Compensatory mitigation refers to the restoration, establishment, enhancement, and/or preservation of wetlands, streams, or other aquatic resources to offset environmental losses resulting from unavoidable impacts on waters of the United States, as authorized by Clean Water Act Section 404 permits issued by the U.S. Army Corps of Engineers (40 CFR 230.93(a)(1)). This becomes an option only after all opportunities for aquatic resource impact avoidance and minimization have been exhausted. See Box 7-2 and Appendix J for a more complete discussion of compensatory mitigation.

Reclamation refers to restoration of a disturbed area to an acceptable form and planned use following closure of a mining operation. Our mine scenarios assume that the site would be reclaimed according to statutory requirements and present some options that are feasible and common, but it is outside the scope of this assessment to evaluate a specific post-closure plan.

Remediation refers to fixing a problem that has become evident, such as an accidental release or spill of product or waste material. For example, a tailings slurry spill would require remediation. The dam may have been designed and constructed to properly mitigate (i.e., avoid or minimize) the potential for a spill, but an accident or failure could cause contaminant release, thereby creating the need for remediation.

BOX 4-2. PERMITTING LARGE MINE PROJECTS IN ALASKA

Large mine projects in Alaska must comply with federal and state environmental laws, and many federal, state, and local government permits and approvals are required before construction and operation of a large hard rock mine can begin. The specific permits and approvals vary from project to project, depending on the unique challenges posed by each mine.

Federal laws and agencies. The involvement of federal agencies varies for each mine, but most projects at least require authorizations from the U.S. Army Corp of Engineers. Other agencies that may be involved include (but are not limited to) the U.S. Environmental Protection Agency, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, the U.S. Coast Guard, and the U.S. Department of Transportation.

Federal agency authorizations ensure that projects comply with the following applicable federal laws.

- Clean Water Act
- Clean Air Act
- National Environmental Policy Act
- National Historic Preservation Act
- Resource Conservation and Recovery Act
- Rivers and Harbors Act
- Endangered Species Act
- Bald Eagle Protection Act
- Migratory Bird Act
- Magnuson-Stevens Act
- Mine Safety and Health Act

Alaska Department of Natural Resources permits and approvals. The Alaska Department of Natural Resources (ADNR) Office of Project Management and Permitting coordinates the permitting of large mine projects via the establishment of a large mine project team for each project. This project team is an interagency group, coordinated by ADNR, that works cooperatively with large mine permit applicants and operators, federal resource agencies, and the Alaskan public to ensure that projects are designed, operated, and reclaimed in a manner consistent with the public interest.

ADNR may require the following permits and approvals.

- Plan of operations approval
- Reclamation plan and bond approval
- Right-of-way for access and utilities (roads, power lines, pipelines)
- Millsite lease
- Permit to appropriate water
- Dam safety certification (certificates of approval to construct and operate a dam)
- Upland or tideland leases
- Material sale
- Winter travel permits
- Cultural resource authorization
- Mining license

Alaska Department of Environmental Conservation permits and approvals. The Alaska Department of Environmental Conservation may require the following permits related to wastewater management and water and air quality.

- Waste management permit
- Alaska pollutant discharge elimination permit
- Domestic and non-domestic wastewater disposal permits
- Certificate of reasonable assurance for 404 permits
- Stormwater discharge pollution prevention plan
- Air quality permits
- Approval to construct and operate in a public water supply system
- Plan review for non-domestic wastewater treatment system
- Plan review and construction approval for domestic sewage system
- Oil discharge prevention and contingency plan

Other state permits and approvals. The state may require the following permits and approvals.

- Fish passage permit
- Fish habitat permit
- Utility permit on right of way
- Driveway permit
- Approval to transport hazardous materials
- Life and fire safety plan check
- State fire marshal plan review certificate
- Certificate of inspection for fired and unfired pressure vessel
- Employer identification number

BOX 4-3. FINANCIAL ASSURANCE

Many of the regulatory checks listed in Box 4-2 help to reduce potential impacts of mining on the environment, but they do not ensure that a permitted mine will have negligible effects on the environment. Even with the most stringent requirements, accidents and human error may cause mine systems to fail—and the most unpredictable accidents and errors often result in the most economically and environmentally costly failures. Thus, regulations also serve to hold an operator accountable during mine operations via both the imposition of fines for non-compliance with permit regulations and the establishment of financial assurance requirements for closure and reclamation of the mine. Financial assurance basically means that operators must ensure that sufficient funds are available for future remediation, closure, and reclamation of a mine.

Operators of Alaska's hard rock mining facilities, including copper and gold facilities, are required by the state to demonstrate financial assurance for reclamation, waste management, and dam safety costs.

- Prior to the start of hard rock mining operations on state-owned, federal, municipal, or private land, the Alaska Department of Natural Resources (ADNR) must approve a reclamation plan and financial assurance must be demonstrated in an amount necessary to ensure performance of the plan (Alaska Statute 27.19).
- The Alaska Department of Environmental Conservation may require hard rock mining operations that dispose of solid or liquid waste material or heated process or cooling water under a waste management and disposal permit to demonstrate financial assurance in an amount based on the estimated costs of required closure activities and post-closure monitoring for the waste management area (Alaska Statute 46.03.100(f)).
- Operators of hard rock mines on state-owned or privately owned land seeking ADNR approval to construct mine tailings dams must demonstrate financial assurance to cover the cost of reclamation and post-closure monitoring and maintenance of the dam (Alaska Statute 46.17).
- Operators of hard rock mining facilities on land managed by the Bureau of Land Management or U.S. Forest Service can be required by these agencies to demonstrate additional financial assurance for reclamation (43 CFR 3809 and 36 CFR 228 Subpart A, respectively).
- In addition to State of Alaska and Bureau of Land Management financial assurance requirements, facilities operating under leases, permits, or other agreements for the development of hard rock minerals on tribal lands can be required by the Bureau of Indian Affairs to demonstrate financial assurance to ensure compliance with the terms and conditions of the mineral agreement and applicable statutes and regulations (25 CFR 211.24 and 225.30).

Financial assurance calculations assume that a government entity would have to enter the site and commence reclamation activities without the benefit of any equipment or labor that may be at the site. The process determining the cost of every shovel, loader, gallon of fuel, and hour of labor is revisited and adjusted as necessary every 5 years. The State of Alaska allows several types of assurance (e.g., cash, gold bullion, surety bonds, reclamation trust funds, irrevocable letters of credit).

Example Financial Assurance Amounts for Alaska Mines

Mine	Amount
Fort Knox	$68,852,293
Kensington	$28,727,011
Pogo	$44,430,000
Red Dog	$305,150,000

It is important to note that effective financial assurance depends on accurate estimates of costs, which poses challenges when dealing with the potentially long-term, unpredictable, and costly events that a hard rock mining operation must consider. For example, current financial assurance requirements do not address chemical or tailings spills because of the greater degree of uncertainty related to these accidents; whereas the costs associated with reclamation and closure can be estimated, the cost of cleaning up a spill is unpredictable. However, financial assurance calculations increasingly include long-term water treatment.

4.2.3.1 Extraction Methods

The low concentrations of disseminated metals in porphyry copper deposits require large amounts of ore to enable a return on investment. Bulk or large-scale mining methods have been developed for this purpose, and specific mining methods depend on ore quality and depth. A long-range mining plan is usually developed first to match the final mine design with the available ore reserves, weighing economics against engineering restrictions. This plan is re-evaluated throughout the life of the mine to reflect changes in the economy, increased knowledge of the ore body, and potential changes in mining technology.

Porphyry copper deposits are most commonly mined using open pit and, less commonly, underground mining methods (John et al. 2010). Open pit mining is typically used to extract ore where the top of a deposit is within 100 m of the surface (Blight 2010). Excavation of a pit begins at the surface, with drilling and blasting to strip overburden from the ore body surface. The equipment and materials used will fit the economies of scale for the project (e.g., mine life, daily production). The ore is drilled and blasted according to a blasting pattern. The size and spacing of the drill holes and the amount of explosives used determine the size of the material that is loaded and hauled to the crushing plant. The pit is successively enlarged until the pit limits are established by the extent of ore that can be profitably mined.

Pit design depends on the material characteristics of the ore and waste rock. The moisture content, strength, and load-bearing capacity of the ore and waste rock help determine the angle of the pit slopes, which generally are designed to be as steep as possible while still maintaining stability. A properly designed pit reduces the stripping ratio, or the volume of waste rock to ore, thereby increasing efficiency, potentially decreasing costs, and optimizing the amount of ore that can be mined economically.

Block caving is an underground mining method used for large deposits with rock mass properties amenable to sustainable caving action (Singer et al. 2008, Lusty and Hannis 2009, Blight 2010). Such deposits typically have mineralization throughout the rock (e.g., porphyry copper deposits) and are too deep to be mined economically by open pit methods. Block caving uses gravity to reduce the amount of drilling and blasting required to extract ore. It involves tunneling to the bottom of the ore and undercutting it, so that the deposit caves under its own unsupported weight. As ore is removed from below, fractures spread throughout the block, which breaks into fragments and is removed from the bottom of the enlarging void (Box 4-4).

Underground mining via block caving has a different set of costs than open pit mining, because of the extensive drilling of tunnels and shafts through non-ore-bearing rocks needed to gain access to the ore. Once begun, block caving generally requires less drilling and blasting, allows for less ore selectivity in the mining process, and may require less labor relative to open pit mining. As with other types of mining, the economics of block caving are determined by the prices of the metals being extracted, operational costs, and a number of other factors. If block caving allows the mining of additional ore that could not be mined using open pit mining methods, it creates the need for additional tailings storage capacity, increased capacity at the mill, increased consumption of utilities such as water and power, increased production of metal concentrates, and possible extension of the mine life.

BOX 4-4. BLOCK CAVING AND SUBSIDENCE

Subsidence at the ground surface is an inevitable result of the extraction of any underground resource (SME 2011). Block caving causes the surface above the worked-out mine to collapse into the void created by the removed ore. The area of subsidence on the ground's surface generally is larger than the area actually block-caved underground (Whittaker and Reddish 1989, USDA 1995). The extent and rate at which subsidence occurs depend on a number of factors, including the strength and thickness of the overburden, the extent of faulting and fracturing, and the depth of the mine workings (Whittaker and Reddish 1989).

In addition to altering surface topography, subsidence can affect both the quantity and quality of surface-water and groundwater systems, either directly or indirectly. For example, Slaughter et al. (1995) observed both increases and decreases in groundwater levels and changes in groundwater total dissolved solids concentrations due to subsidence at a coal mine in Utah. The authors attributed the rise in the water table to stream water seeping through fractures in the streambed, the subsequent decrease in the water table to connectivity between streambed fractures and the mine workings, and the total dissolved solids changes to exposure of the water to mine workings (Slaughter et al. 1995).

Backfilling a mining void is known to reduce subsidence. However, this requires a sufficient amount of suitable material, which may need to be imported in areas mined with methods that generate little waste material (SME 2011). Void-filling grout also may be used to mitigate subsidence, as well as to minimize oxidation of mined surfaces to reduce the potential for production of acid mine drainage.

4.2.3.2 Water Treatment and Management

Because mine workings must be kept dry for the duration of mining activities, dewatering is required for both open pit mines and block caving operations. Dewatering is accomplished by pumping water either directly from the pit or underground workings or from wells surrounding these areas. This pumping of water may create a cone of depression, which is a cone-shaped reduction in water level extending outward from the point of water withdrawal, where water levels are lowest. Water extracted during dewatering typically is pumped to lined process water ponds for use in the milling process. Excess water typically is tested and, if necessary, treated before discharge.

In hard rock metal mining, most water use occurs during milling and separation operations. This water is obtained from the mine site area and then held in storage facilities until its use. However, much of the water used in the mining process is recycled and reused. For example, the water used to pump tailings slurry from the mill to the tailings storage facility (TSF) becomes available when the tailings solids settle and excess overlying water is recycled back to the mill. Other water use needs include power plant cooling and transport of metal concentrate slurry (where transport occurs via pipeline).

In general, stormwater runoff is diverted around mine components (e.g., the open pit or waste rock piles) to keep it from becoming contaminated, and then collected in sedimentation ponds to settle out suspended solids prior to use or discharge to a stream. Stormwater runoff that contacts mine components may be contaminated with pollutants. Such water is directed to collection ponds and treated before being used in mine processes or released. Seepage and leachate are directed to storage ponds for containment, treated, and released to the environment. Tailings may be dewatered, and reclaimed water directed to process water holding ponds for reuse. Surface water and groundwater are monitored for contamination throughout mine operations, and are routed to a treatment facility if significant contamination is detected.

Water treatment options include physical or chemical methods—for example, reverse osmosis (physical) and formation of precipitated solids (chemical)—used together or independently. The choice of treatment methods and the chemicals used for treatment depends on the site's specific water chemistry and the water's end use.

Once mining ceases, an open pit is typically allowed to fill with water. Acid-generating waste rock and other potentially acid-generating (PAG) materials (e.g., pyrite-rich tailings) may be placed at the bottom of the pit to submerge these materials and reduce the potential for acid mine drainage once the pit fills. In block caving, ore is removed from the ground and the resulting void is filled by overlying materials (Box 4-4). After mining operations cease, groundwater fills in the remaining pore spaces in the void.

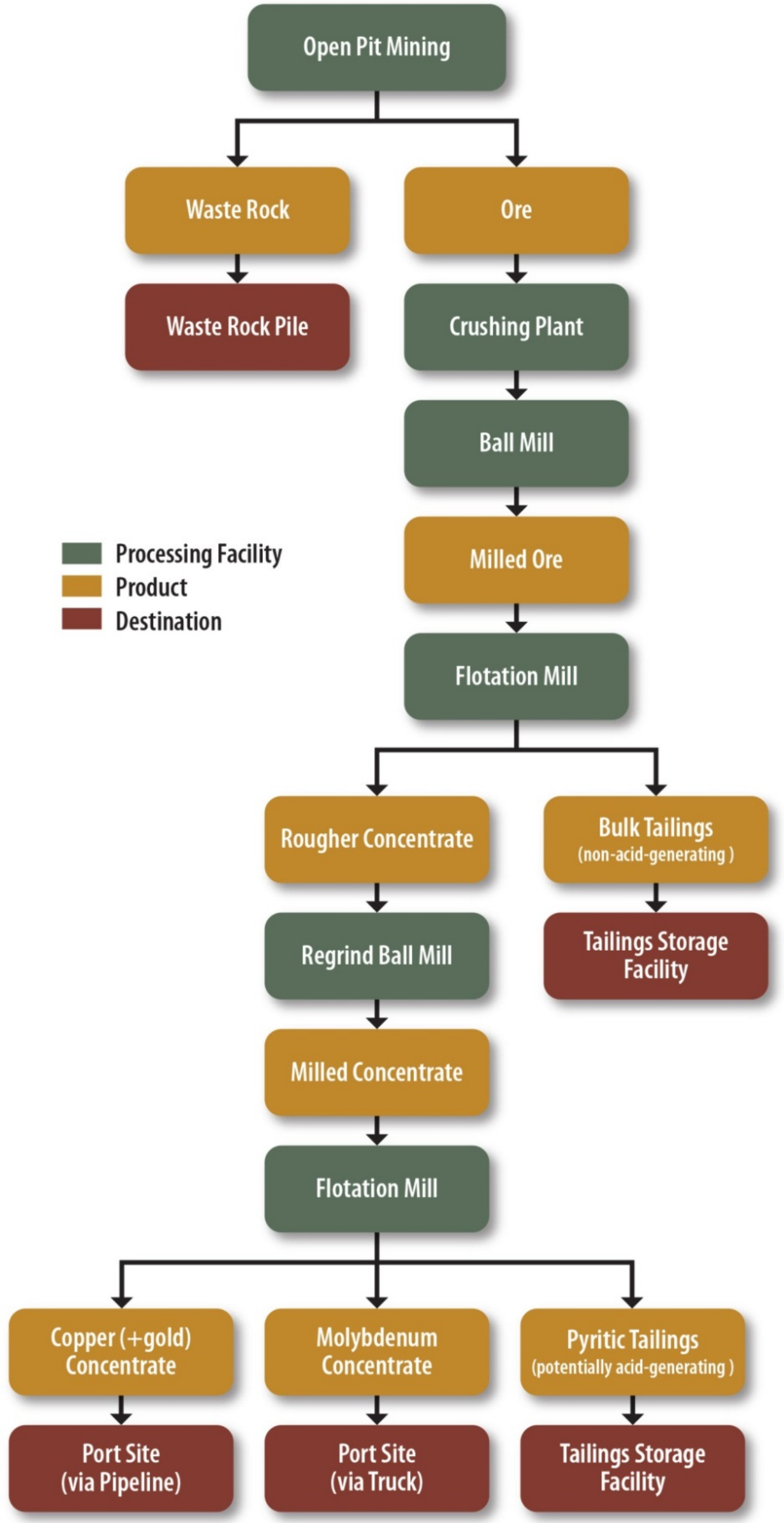
4.2.3.3 Ore Processing

Generally, two streams of materials come from a mine: ore and waste rock (Figure 4-3). Ore is rock with sufficient amounts of metals to be economically processed. Waste rock is material that has little or no economic value at the time of disturbance, although it may have recoverable value at a future time (i.e., under different technological or economic conditions).

Ore blasted from a porphyry copper mine typically is hauled to a crushing plant near or in the mine pit (Figure 4-3). The crushing plant reduces ore to particle sizes manageable in the processing mill (e.g., less than 15 cm; Ghaffari et al. 2011). Crushed ore is carried by truck or conveyer to a ball mill, where particle size is further reduced (e.g., 80% to less than 200 μm; Ghaffari et al. 2011) to maximize the recovery of metals. The milled ore is subjected to a flotation process with an aqueous mixture of chemical reagents (Box 4-5) to collect valuable copper, molybdenum, and gold minerals in a copper-molybdenum concentrate, which also contains gold. Bulk tailings are the material remaining after the first flotation circuit, which are directed to a TSF (Figure 4-3). Figure 4-3 assumes NAG bulk tailings; however, if prior testing has indicated the potential for acid production, they can be treated further to minimize this potential prior to their disposal. The copper-molybdenum (+gold) concentrate may be fed through a second ball mill to regrind the particles (e.g., 80% to less than 25 μm; Ghaffari et al. 2011). Once sufficiently sized, the regrind concentrate is directed into a second flotation process and then to a copper-molybdenum separation process. Final products are a copper concentrate that includes gold, a molybdenum concentrate, and pyritic tailings (Figure 4-3).

The most profound influence that ore processing can have on long-term management of a mine site centers on the fate of pyrite (Fuerstenau et al. 2007). Traditionally, PAG and NAG tailings were discharged together, thereby contributing to the acid-generating potential of the TSF. It is possible to use a technique called selective flotation to separate most of the pyrite into the cleaner circuit tailings (PAG) with the rougher tailings (bulk tailings in Figure 4-3) comprising predominantly NAG minerals. The PAG tailings would need to be stored separately and kept isolated from oxygen.

Figure 4-3. Simplified schematic of mined material processing.



BOX 4-5. CHEMICALS USED IN ORE PROCESSING AND HANDLING

After dry grinding and milling, water is added to the fine ore particles to create a slurry. This slurry undergoes further beneficiation using chemical reagents to separate minerals from gangue (rock barren of target minerals) and to separate one mineral from another. Reagents are added to the slurry at different points in the process to chemically or physically modify the surface of particles and facilitate separation. The amounts and types of reagents used are site-specific and depend on many factors such as particle size variation, particle density, ore grade, and host rock character. The volume of reagents used per metric ton of ore is closely monitored to optimize the mineral concentration process and minimize the unnecessary use of reagents. Although highly site-specific, most reagents are used at a rate of 0.01 to 0.3 kg of reagent per metric ton of ore (USEPA 1994a, Khoshdast and Sam 2011). To ensure the flotation system is optimized, the incoming ore composition is monitored and the reagent mix is modified as changes occur due to variations in the ore.

The reagents used in flotation generally fall into five categories.

- **Collectors** (e.g., xanthates, dithiophosphates) increase the ability of air bubbles to stick to a particle. Toxicity of collectors varies widely within the group, but some commonly used collectors, such as sodium ethyl xanthate, are toxic to freshwater organisms (Alto et al. 1977, Vigneault et al. 2009).
- **pH regulators** (e.g., lime, caustic soda, sulfuric acid) are added to maintain the proper pH level in the slurry. If released, these reagents could affect pH in natural waters.
- **Frothers** (e.g., aliphatic alcohol, methylisobutyl carbinol, propylene glycol) increase the stability of air bubbles so they do not burst before bringing a particle to the surface. These reagents are generally considered to have low toxicity (Fuerstenau 2003).
- **Flocculants and dispersants** (e.g., polyacrylamides, aluminum salts, polyphosphate) promote settling of fine materials and separation of fine gangue materials. They are generally considered to have low toxicity (Vigneault et al. 2009).
- **Modifiers** (e.g., cyanide salts, carboxymethylcellulose) make collectors more effective by either activating or depressing certain reactions. Toxicity of these reagents varies widely.

Although some of these reagents can be transported to a mine site as powder or pellets, most material arrives in liquid form.

The gold in porphyry copper deposits is partitioned among the copper-sulfide minerals (chalcopyrite, bornite, chalcocite, digenite, and covellite), pyrite, and free gold (Kesler et al. 2002). Gold associated with the copper minerals would stay with the copper (+gold) concentrate and be recovered at an off-site smelter. Gold associated with pyrite would end up in the TSF unless a separate pyrite concentrate were produced, and gold could be recovered from this concentrate by a vat leaching cyanidation process (Logsdon et al. 1999, Marsden and House 2006) (Box 4-6).

Porphyry copper deposits (and other metal deposits) often have marketable quantities of metals other than the primary target metals. These metals are carried through the flotation process and might be removed at some later point. As an example, the Pebble deposit is reported to have marketable quantities of silver, tellurium, rhenium, and palladium (Ghaffari et al. 2011), which are not sufficiently concentrated in the ore to warrant separation and production of an additional metal concentrate.

The process for removing metals from ore is not 100% efficient. At some point the cost of recovering more metals exceeds their value, so the amount of metals left in the tailings represents a tradeoff between revenues from more complete ore processing and extraction costs. The process proposed by Ghaffari et al. (2011) would recover 86.1% of the copper, 83.6 % of the molybdenum and 71.2% of the gold from the Pebble deposit ore. The residual metals remaining with the tailings would be discharged to a TSF along with the residue of blasting agents, flotation reagents, and inert portions of the ore.

BOX 4-6. USE OF CYANIDE IN GOLD RECOVERY

At mines producing both copper and gold, copper concentrate and gold doré (unrefined gold produced at the mine site) are extracted using standard processes such as gravity separation and froth flotation. If enhanced gold recovery is undertaken at the mine site, cyanide is universally used for such gold extraction (Marsden and House 2006).

The gold recovery process involves a cyanide leach step. The solution that remains after the cyanidation process is commonly passed through either a cyanide recovery unit or a cyanide destruction unit. Cyanide recovery allows the recycling of cyanide for reuse in the cyanidation process. Cyanide destruction converts the cyanide ion to less toxic cyanate, which is then treated in a wastewater treatment plant for discharge or transferred to a tailings storage facility (TSF). Because the tailings from this process have high concentrations of acid-generating sulfides, they are typically directed to the TSF, encapsulated in non-acid-generating tailings, and kept saturated to minimize oxidation. If water is recycled from the TSF into the copper process water system, cyanide can interfere with the flotation process; to prevent this interference, some mines isolate cyanidation tailings in a separate TSF (Scott Wilson Mining 2005).

Once in the TSF, cyanide concentrations may decrease through natural attenuation (e.g., volatilization, photodegradation, biological oxidation, precipitation) (Logsdon et al. 1999). Cyanide may escape the TSF through seepage or as dust from tailings beaches. Because cyanide dissolves other metals such as copper, fauna also may be exposed to high metal concentrations and toxic copper-cyanide complexes.

Reported rates of cyanide use at gold mines average about 0.15 to 0.50 kg of cyanide (as sodium cyanate) per metric ton of concentrate after cyanide recovery (Stange 1999).

4.2.3.4 Tailings Storage

Tailings are a mixture of fine-grained particles, water, and residues of reagents remaining from the milling process. The most common method of tailings storage is disposal in an impoundment (i.e., a TSF) (Porter and Bleiwas 2003). Tailings are transported from the mill to a TSF as a slurry, of which solids—silt to fine sand particles (0.001 to 0.6 mm) with concentrations of metals too low to interact with flotation reagents—typically make up 30 to 50% by weight. Tailings may be thickened (dewatered) prior to disposal. Thickening reduces evaporation and seepage losses and allows recycling of more process water back to the processing plant, thereby reducing operational water demand. It also minimizes the amount of water stored in the TSF.

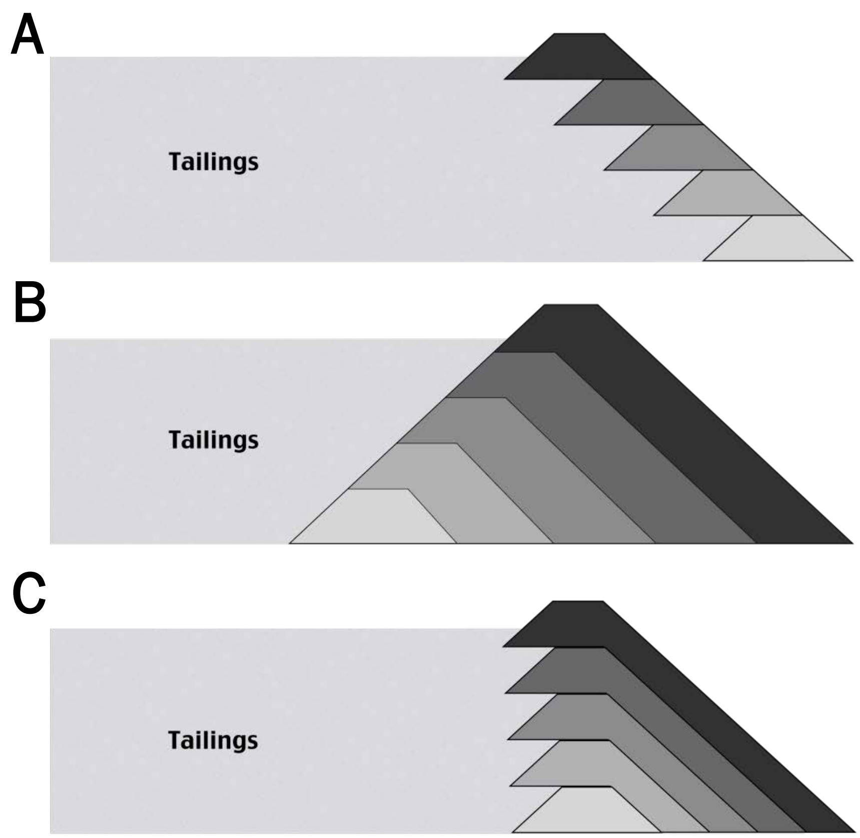
Tailings impoundments are water-holding structures typically built by creating a dam in a valley. Tailings dams are generally earthen or rockfill dams constructed from waste rock or the coarse fraction of the tailings themselves. The majority of existing tailings dams are less than 30 m in height, but the largest exceed 150 m (McLeod and Murray 2003, National Inventory of Dams 2005, Rico et al. 2008).

The engineering principles governing the design and stability of tailings dams are similar to the geotechnical principles for earthen and rockfill dams used for water retention. They are typically built in sections, called lifts, over the lifetime of the mine, such that dam height increases ahead of reservoir level, using upstream, downstream, or centerline methods (Figure 4-4). Tailings dams built by the upstream method are less stable against seismic events than dams built by either the downstream or the centerline method (ICOLD 2001). This is because part of the dam rests on the tailings, which have a lower density and a higher water saturation than the dam materials (USEPA 1994b). Although upstream construction is considered unsuitable for impoundments intended to be very high or to contain large volumes of water or solids (State of Idaho 1992), this method is still employed (Davies 2002). For example, an upstream dam lift was recently designed and constructed on the Fort Knox Mine tailings impoundment dam near Fairbanks, Alaska (USACE 2011). The downstream method is considered more stable from a seismic standpoint, but it is more expensive to implement than the upstream method. Centerline construction has characteristics of both upstream and downstream types (USEPA 1994b, Martin et al. 2002).

As they fill with tailings, TSFs must store immense quantities of water (Davies 2011). Water level is controlled by removing excess water either for use in the mining process or for treatment and subsequent discharge to local surface waters. Tailings are deposited against the embankment through spigots or cyclones. Coarser-grained sands are directed at the embankment to create a beach, causing water and fines to drain away from the dam to form a tailings pond. Care must be taken to prevent the formation of low-permeability lenses or layers on tailings beaches, as these layers may perch water in the TSF such that saturation of or flow through the dam may occur, leading to erosion or failure.

Although most of the tailings dam mass consists of fairly coarse and permeable material, the dams often have a low permeability core to limit seepage, as well as internal drainage structures to collect seepage water and to control pore pressures. Mitigation measures for seepage through or beneath a tailings dam may include any combination of liners, seepage cutoff walls, under-drains, or decant systems.

Figure 4-4. Cross-sections illustrating (A) upstream, (B) downstream, and (C) centerline tailings dam construction. In each case, the initial dike is illustrated in light gray, with subsequent dike raises shown in darker shades (modified from Vick 1983). Tailings dams in our mine scenarios are assumed to use the downstream construction method initially and at some point change to centerline construction.



Liners may cover the entire impoundment area (e.g., as proposed for the Donlin Creek Mine TSF in Alaska) or only the pervious bedrock or porous soils. Full liners beneath TSFs are not always used; however, at least in Australia, mining companies are required to justify why a liner would not be necessary (e.g., the foundation has a sufficiently low saturated hydraulic conductivity or the groundwater has no beneficial use) (Commonwealth of Australia 2007). Full liners may not be economically practicable, in which case partial liners may be used to cover areas of pervious bedrock or porous soils.

Liners can include a high-density polyethylene, bituminous, or other type of geosynthetic material (geomembrane) and/or a clay cover over an area of higher hydraulic conductivity. A clay liner may have a saturated hydraulic conductivity of 10^{-8} m/s, whereas a geomembrane may have a hydraulic conductivity of approximately 10^{-10} m/s (Commonwealth of Australia 2007). However, geomembrane technology has not been available long enough to know the service life of these liners. Laboratory tests and data from landfills suggest that high-density polyethylene liner lifespans range from 69 to 600 years, depending on whether it is the primary (upper) or secondary (lower or backup) liner (Rowe

2005, Koerner et al. 2011). In general, longer lifespans are expected at lower temperatures and exposures to light (Rowe 2005, Koerner et al. 2011). Breakdown of the liner material and punctures by equipment or rocks may limit the effective life of liners (Rowe 2005). Overly steep slopes also may put stresses on geomembranes and cause them to fail. Service life data for other types of geomembranes are anecdotal and based on field performance, since no laboratory studies have been conducted (Koerner et al. 2011).

If seepage is expected or observed, mitigation or remedial measures such as interception trenches or seepage recovery wells can be installed around the perimeter and downstream of the TSF to capture water and redirect it to a treatment facility. Precipitation runoff from catchment areas up-gradient of the TSF is typically diverted away from the impoundment to reduce the volume of stored liquid.

Dry stack tailings management, in which tailings are filtered and “stacked” for long-term storage, is a newer, less commonly used tailings disposal method. Dry stacked tailings require a smaller footprint, are easier to reclaim, and have lower potential for structural failure and environmental impacts (Martin et al. 2002) (Box 4-7). Dry stack technology has found greatest acceptance in arid regions where water is scarce or expensive, although dry stacks are also used in wet climates or in cold regions where water handling is difficult (Martin et al. 2002). Currently, the only mines in Alaska that use dry stack tailings disposal are underground mines with high-grade ore and relatively low quantities of tailings (e.g., Greens Creek, a lead, silver, zinc mine in southeast Alaska; Pogo, a gold mine in eastern interior Alaska; and Nixon Fork, a gold mine in west-central Alaska).

BOX 4-7. DRY STACK TAILINGS MANAGEMENT

In a dry stacking operation, tailings are dried using filter presses or vacuum technologies such that water content typically falls below 20%. The dewatered tailings are either loaded into trucks or transported by conveyer to the tailings storage facility (TSF), where they are spread in lifts and compacted, similar to a traditional earth-moving operation.

The compacted tailings have a higher in-place bulk density than tailings placed using more conventional slurry methods. We estimate that dry stacking would reduce the required volume for tailings storage by approximately 15%. The lower water content of dry stack tailings means that less water is captured in the void spaces between solid tailings particles, reducing the amount of water “lost” to the TSF by approximately one-third. The additional water that is not captured in the TSF is available for treatment and release, potentially reducing streamflow losses in local streams. The higher density and lower water content of the tailings also increase their stability. In many cases, the need for a confining embankment and the risk of a tailings dam failure and tailings liquefaction can be eliminated with dry stack management.

The additional capital costs for dewatering equipment and the high energy cost of dewatering have often been barriers to adopting dry stack tailings management for low-grade ores such as porphyry copper. However, higher production costs may be at least partially offset by cost savings in other areas. For example, the increased stability of a dry stacked TSF may reduce closure costs, post-closure monitoring costs, and post-closure financial assurance requirements.

Dry stacked tailings are typically placed in unsaturated conditions, which can increase the exposure of tailings to oxygen. Thus, this type of storage may be less appropriate for potentially acid-generating tailings or may require additional engineering controls to limit, collect, or treat acid drainage. Where TSFs are typically used to store water as well as tailings, the use of dry stack tailings may not eliminate the need for construction and operation of a separate water impoundment facility.

4.2.3.5 Waste Rock

Waste rock is rock overlying or removed with the ore body that contains uneconomic quantities of metals. A waste-to-ore ratio of 2:1—that is, the removal of 2 metric tons of waste rock for each metric ton of ore—is not uncommon for porphyry copper deposits (Porter and Bleiwas 2003). Waste rock is stored separately from tailings (Blight 2010), typically in large, terraced stockpiles. Some waste rock that contains marketable minerals may be stored such that it can be milled if commodity prices increase sufficiently or if higher than usual metal concentrations in ore require dilution to optimize mill operation. However, the potential for environmental impacts must be managed if the waste rock is PAG, via selective handling, drains, diversion systems, or other means. PAG waste rock also may be blended with ore in the mill to maintain a steady and predictable composition of feed material for the flotation process over time. NAG waste rock may be placed in piles near the open pit, with ditches to divert stormwater around the piles and drains (or other systems) to capture leachate or direct it toward the open pit. At closure, a dry cover (e.g., encapsulation) can be placed over the waste rock pile to isolate it from water and oxygen, or the pile could be placed into the completed open pit and kept below the water line if it contains PAG material, depending on site-specific characteristics (O'Kane and Wels 2003). With small pits and in some settings, it is beneficial to fill the pit with waste rock and other waste material and then construct a dry cover over the filled pit area.

4.2.4 Timeframes

The mining process described above can be thought of in terms of three distinct periods.

- **Operation** refers to the period during which the mine is active—that is, the period when mine infrastructure is being built and ore is being extracted and processed.
- **Closure** refers to the period following completion of mining operations (either as planned or prematurely) when mining has ceased and activities related to reclamation and preparation of the site for future stability continue. During this period, waste areas are reclaimed and facilities needed to support ongoing monitoring and maintenance activities—such as stormwater management ditches, monitoring wells, engineered covers on waste materials (if required), wastewater treatment plants, and roads—are created, retained from the operational period, or replaced or remediated if they had become compromised.
- **Post-closure** refers to the extended period following closure activities when monitoring and maintenance activities continue. During this time, water leaving the site is monitored and treated for as long as contaminants are present at levels exceeding regulatory standards. The post-closure phase may last decades, centuries, or longer, until only minimal oversight is required. Such minimal oversight is necessary, perhaps in perpetuity, to ensure the remaining infrastructure's structural integrity and to minimize environmental impacts. Given the limited lifetime of human institutions, continued monitoring and maintenance of the site might become increasingly unlikely as the time from mine closure increases.