Mining

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Synonyms

Abstracting; Cutting; Digging; Dig-out; Excavating; Extracting; Hollowing; Quarrying; Removal; Scooping; Unearthing

Definition

Mining is the extraction or abstraction of mineral deposits from the surface or subsurface of the Earth.

Overview of Mining, Minerals, and Society

"If it can’t be grown, it has to be mined"...! Almost every item we use contains minerals. Society has and continues to be dependent on minerals produced by mining. It could be argued that every material item in society is produced from a mineral or derived from a mineral product. Mineral resources are therefore likely to remain a fundamental demand for society into the future.

Mining, like agriculture, represents one of the earliest activities of Homo sapiens. Evidence (stone tools) for mining extends back to Paleolithic times (ca. 450,000 yr. BP). Surface/underground mining in parts of Africa (e.g., Swaziland) dates back to 40,000 yr. BP. Fired clay pots in Czechoslovakia date back some 30,000 yr. BP, and gold and copper were being worked in some parts of the world as long ago as 18,000 yr. BP. Since then, mining has continued to expand and helped advance and develop human civilization, through the Bronze Age (4000–5000 yr. BP), Iron Age (1500–1780 yr. BP), Steel Age (1780 BP–1950 AD), and the Modern Age (1950–present) (Agricola 1556). Mining has taken place throughout the world for hundreds and in some localities thousands of years. In the UK, for example, evidence for mining dates back to the Neolithic where flint nodules contained in chalk were mined for tool making (e.g., Grimes’ Graves, Norfolk), and coal was mined by the Romans as long ago as 122 AD. Vast fortunes, economic wealth, prosperity, and growth have resulted from mining and the mineral commodities produced. The Industrial Revolution in Britain was founded upon coal and associated mineral resources, resulting in the establishment and expansion of industrial cities. Mineral commodities are the end product of mining. Modern society would not function as we know it, without mining and the raw materials and commodities associated with mining. Minerals are required for tools, utensils, building and construction, food, weapons, ornamental jewelry and cosmetics, currency, energy to produce heat and power, industrial machinery, electronics, and nuclear fission (Table 1).

Clearly, there are many benefits of mining as minerals contribute significantly to the economic development of countries, ease poverty, and directly or indirectly improve people’s lives around the world. Conversely, the collapse of mining driven by economic recession, falling commodity prices, or geological complexities has resulted in entire communities or towns becoming adversely affected causing economic and social deprivation or environmental hazards. As such, mining can be a “boom-and-bust” industry.

The Life Cycle of a Mine

Geological exploration and engineering geological and geo-technical investigations to locate, define, and characterize the deposit precede a mine. Next technological, financial, and social evaluations determine if the mine is economically viable. The mineral(s) is then extracted from the ground by mining engineers before mineral processing engineers (metallurgists) prepare the mineral into a higher-quality
### Minerals, commodities, and their common uses

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Commodity</th>
<th>Uses</th>
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</thead>
<tbody>
<tr>
<td>Bauxite</td>
<td>Aluminum</td>
<td>Vehicles, packaging, building construction, electrical, machinery</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Beryl</td>
<td>Light, strong alloys, aircraft industry, fluorescent lamps, X-ray tubes, gemstones (emerald and aquamarine), computers, telecommunication, aerospace, defense, medical equipment</td>
</tr>
<tr>
<td>Cobalite</td>
<td>Cobalt</td>
<td>Superalloys, aircraft gas turbine engines, cutting tools, wear-resistant applications, chemicals (paint dryers, catalysts, magnetic coatings), permanent magnets</td>
</tr>
<tr>
<td>Stibnite</td>
<td>Antimony</td>
<td>Lead batteries, cable sheaths, bearing metal, type metal, solder, collapsible tubes, foil, pipes, semiconductor, flame retardant, fireworks, rubber, chemicals, textiles, medicine, glassmaking</td>
</tr>
<tr>
<td>Feldspar</td>
<td>Feldspar</td>
<td>Glass, ceramics, enamels, soaps, abrasive wheels, enamel, insulating compositions, fertilizer, roofing materials, textiles and paper, pottery</td>
</tr>
<tr>
<td>Zinc and bauxite ore</td>
<td>Gallium</td>
<td>Circuits, light-emitting diodes (LEDs), photo detectors and solar cells, treatment of cancer, defense applications, computers, telecommunications</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Calcium</td>
<td>Prefabricated wallboard, building plaster, cement, agriculture</td>
</tr>
<tr>
<td>Zinc ores</td>
<td>Indium</td>
<td>Electrical conductivity, liquid crystal displays (LCDs), solders, alloys, compounds, electrical components, semiconductors, research</td>
</tr>
<tr>
<td>Galena</td>
<td>Lead</td>
<td>Batteries, tanks, solders, seals, electrical, TV tubes, glass, construction, communications, weights, ceramics, crystal glass, X-ray and gamma radiation shielding; soundproofing; ammunition</td>
</tr>
<tr>
<td>Pyrolusite</td>
<td>Manganese</td>
<td>Iron and steel, ferroalloys, construction, machinery transportation</td>
</tr>
<tr>
<td>Molybdenite</td>
<td>Molybdenum</td>
<td>Car parts, construction equipment, gas transmission pipes, stainless steels, tool steels, cast irons, superalloys, chemicals, lubricants, light bulbs</td>
</tr>
<tr>
<td>Polite</td>
<td>Silica</td>
<td>Building, construction, fillers, horticulture aggregate</td>
</tr>
<tr>
<td>Apaiente</td>
<td>Phosphate</td>
<td>Phosphoric acid, phosphate fertilizers, feed additives for livestock, phosphate chemicals for industrial and domestic uses</td>
</tr>
<tr>
<td>Quartz</td>
<td>Silica</td>
<td>Semiprecious gem stone (amethyst, citrine, rose quartz, smoky quartz, agate, jasper, onyx); piezoelectric properties (pressure gauges, oscillators, resonators, computer chips, glass, refractory materials); ceramics, abrasives, water filtration, hydraulic cements; cosmetics, pharmaceutical, paper, insecticides, foods, paints; thermal, photovoltaic cells. China is the leading producer</td>
</tr>
<tr>
<td>Argentinite</td>
<td>Silver</td>
<td>Coins; medals; electrical; electronic devices; jewelry; silverware; photography; electronics water distillation; catalyst; mirrors; silver plating; table cutlery; dental, medical, and scientific equipment; bearing metal; magnet windings; brazing alloys; solder; catalytic converters; cell phone covers; electronics; circuit boards; bandages; batteries</td>
</tr>
<tr>
<td>Columbite-Tantalite</td>
<td>Tantalum</td>
<td>Electronic component (capacitors, circuitry), auto electronics, pagers, personal computers, telephones, superconductors, high-speed tools, catalyst, sutures body implants, optical glass, electroplating devices</td>
</tr>
<tr>
<td>Scheelite</td>
<td>Tungsten</td>
<td>Cemented carbide; cutting; wear-resistant materials; construction; metalworking; mining; oil and gas drilling; high-density electrodes; filaments; wires; electrical, electronic, heating, lighting, welding applications; steels; superalloys</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Vanadium</td>
<td>Alloys, iron and steel, sulfuric acid</td>
</tr>
<tr>
<td>Zeolites</td>
<td>Zeolite</td>
<td>Animal feed, cat litter, cement, water softener, purification, odor control, radioactive ions from nuclear plant effluent</td>
</tr>
<tr>
<td>Coal</td>
<td>Carbon</td>
<td>Thermal power generation, steel making, chemical, household coal briquettes, cement manufacturing</td>
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<tr>
<td>Barges</td>
<td>Barium</td>
<td>Oil well drilling, paper, rubber, cloth, ink, plastics, radiography, deoxidizer for copper, sparkplugs in alloys, white pigments</td>
</tr>
<tr>
<td>Clay</td>
<td>Bentonite</td>
<td>Floor and wall tiles, absorbent, sanitation, mud drilling, foundry sand bond, iron pelletizing, bricks, aggregate, cement, drilling mud, pet waste absorbent</td>
</tr>
<tr>
<td>Chromite</td>
<td>Chromium</td>
<td>Chemicals, ferroalloys, stainless and heat resisting steel products</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>Copper</td>
<td>Construction, electronic products (cables and wires, switches, plumbing, heating), transportation equipment, roofing, chemical and pharmaceutical machinery, alloys (brass, bronze) castings, electroplated protective coatings</td>
</tr>
<tr>
<td>Fluorite</td>
<td>Fluorspar</td>
<td>Ceramics, optical, electroplating, plastics industries, smelting, carbon electrodes, emery wheels, electric arc welders, toothpaste, paint pigment</td>
</tr>
<tr>
<td>Gold</td>
<td>Gold</td>
<td>Jewelry, dentistry, medicine, coins, ingots, scientific and electronic instruments, electrolyte</td>
</tr>
<tr>
<td>Halite</td>
<td>Sodium</td>
<td>Human and animal diet, food seasoning and preservation, chemicals, ceramic glazes, metallurgy, curing of hides, mineral waters, soap manufacturing, water softeners, photography</td>
</tr>
<tr>
<td>Hematite</td>
<td>Iron oxide</td>
<td>Steels manufacture, vehicle auto parts, catalyst, medicine tracer element in biochemical and metallurgical research, paints, printing inks, plastics, cosmetics, paper dyeing, polishing</td>
</tr>
<tr>
<td>Spodumene</td>
<td>Lithium</td>
<td>Ceramics, glass, batteries, lubricating greases, rocket propellants, vitamin A synthesis, silver solder</td>
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<tr>
<td>Mica</td>
<td>Mica</td>
<td>Paints, cement, agent, well-drilling muds, plastics, roofing, rubber, welding</td>
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(continued)
product, concentrating and refining the minerals (or rock) for marketing and sale. Finally, all mines eventually close and are abandoned, and this can leave behind a legacy of hazards and liabilities that may detrimentally impact the economy, environment, and society. Geologists are likely to be involved in almost every stage of a mine’s life, although the majority of the engineering geological requirements will be during exploration, mine design, operation, and abandonment. A mine therefore has a “life cycle” as shown in Fig. 1 and outlined below.

**Prospecting and Exploration**

All mining operations start with prospecting and exploration. The content, scale, and costs of duration of exploration programs vary considerably. Exploration is carried out and funded by geological surveys, minerals agencies, mining companies, consultants, or contractors. The design of an exploration program is influenced by the political and security regime within a particular country, remoteness of location, available infrastructure, land ownership, world commodity markets, and weather. Generally, exploration aims to locate, define, and characterize an economically viable mineral, within a prospect (also known as a lease, tenure, or tenant). Raising finance and securing a mineral prospect are the first stage of exploration, known as prospecting (i.e., exploration limited in scope), which might lead to a discovery. Securing the legal rights to prospect and explore often requires collaboration with a geological or resources ministry and the award of an exploration license. This will define the area where exploration can be legally conducted, by who, the permissible techniques, duration, and terms of the tenure. The distinction between prospecting and exploration is ill-defined, this is normally transitional with exploration referring to an increase in the scale of exploration operations.

Exploration may take place in an entirely new geographical location (grassroots exploration) to define the type, size, geometry, quality, quantity, and grade of the mineral(s) or to extend an existing mine or known deposit (mine-based exploration). It is time consuming and expensive, and the costs for exploration can be in the order of several millions of dollars. Exploration budgets are generally reviewed by the investors on a regular basis. Returns on exploration investment may take years, if and when the mine goes into operation. Exploration is a high-risk business, and not all exploration targets develop into a mine. Exploration surveys may be halted when it can be shown they are not economically viable, although they may reopen in the future if the controlling factors (economic, technical, security, or political) change.

**Desk Study and Target Evaluation**

Exploration begins with planning, the commissioning of a desk study, and development of an exploration strategy (Marjoribanks 2010; Moon et al. 2006). The relevance and veracity of any existing data and information must be diligently assessed. For example, if there are airborne geophysical data with obvious anomalies, those with an increased likelihood of containing economic minerals are selected for further consideration and targeted exploration. Evaluation may begin with a review of the following (if available):

<table>
<thead>
<tr>
<th>Mining, Table 1 (continued)</th>
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<tbody>
<tr>
<td>Mineral</td>
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<tr>
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</tr>
<tr>
<td>Pentlandite</td>
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<tr>
<td>Platinum Group Metals</td>
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<tr>
<td>Pyrite</td>
</tr>
<tr>
<td>Rare Earth Elements:</td>
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<tr>
<td>Trona and Nahcolite</td>
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<tr>
<td>Palladium</td>
</tr>
<tr>
<td>Uraninite or Pitchblende</td>
</tr>
<tr>
<td>Sphalerite</td>
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<tr>
<td>Limestone</td>
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<tr>
<td>Oil and Gas</td>
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</tbody>
</table>
Geological and geomorphological maps, reports, and analytical data from a geological survey

Satellite imagery and air photographs (including stereo-graphics pairs)

Airborne geophysical data

Geochemical data

Reporting of past exploration results

Technical and assay reports for soil and rock sampling from exposures, trenches, and drill core and preliminary drilling

Ultimately, a conceptual geological model should be developed to characterize and categorize the type and style of mineralization and identify data deficiencies and gaps in knowledge about the deposit.

Geological Mapping

Geological mapping, often initiated during prospecting, involves the detailed assessment of the mineral deposit including the mineralization, alteration, geomorphology, and the collection of soil and rock samples for further laboratory analysis. Geological maps provide the basis for the location of future drilling campaigns. Due consideration must be given to the scale of mapping and the appropriate use of software for the production and interrogation of the maps produced. These may be large-scale (1:1,000, 1:2,500, or 1:5,000) or small-scale (1:100,000 or 1:250,000). Mapping techniques may vary from basic field observations combined with the use of a compass-clinometer and tape measure to the deployment of highly sophisticated mapping techniques such as LiDAR, InSAR, and GPS combined with GIS. The mapping coordinate system should be carefully considered as this varies across the world (e.g., Geographic, Cartesian, or Universal Traverse Mercator (UTM)). Geological mapping may also take place in exploratory trenches, open-pit mines, and underground mineworkings, often at mapping scales of 1:100 or 1:10.

Geochemistry

Systematic geochemical sampling of soils is undertaken to identify the relationship between mineralized rock and residual soil deposits. These surveys normally take place over large areas of many square kilometers, along streams and small rivers or in trenches to obtain bulk samples or chip samples. The sample numbers, locations, frequency, and time available will depend on the exploration budget and mineralization type. The geostatistical analysis of the soil chemistry and the resultant anomalies provide an indication of where the mineralization occurs, by comparison to the background values in unmineralized areas. Further and denser sampling may then need to be undertaken.

Geophysics

Geophysical surveys detect the differences in physical properties of the mineral deposit and the host rock. These may be
deployed remotely, from the air or from the ground. The most suitable suite of geophysical techniques must be chosen to increase the probability of geophysical anomalies being detected. Geophysical surveys may occur at a single point, along as a series of traverses along the ground surface or covering a designated area. Computer software and GIS can assist in processing and producing a 2D or 3D geophysical interpretation of the geology. The depth of the surveys can vary from less than 1 m to thousands of meters depending on the instrument and technique used. The choice of geophysical methods must be designed on the basis of an understanding of the geology. Ideally, geophysical surveys are deployed in a phased manner with successive focus on relatively smaller areas to more accurately delineate the mineral deposit. The appropriate choice in instruments will also depend on environmental considerations and in particular any geophysical “noise.” All geophysical anomalies require validation by drilling and the use of borehole geophysical methods. Typical geophysical methods used in mineral exploration are examined in (Kearey et al. 2005).

Rotary Core Drilling

Rotary core drilling is required to delineate the mineral deposits and determine the size, geometry, grade, tonnage, and engineering characteristics. A preliminary and wider-spaced drilling grid is followed by a secondary and much denser array of boreholes. If required, advanced stages of drilling may take place (at the feasibility stage). Drilling provides an exploration and resource geologist with the opportunity to quantify the mineralization and the engineering geologist with the opportunity to evaluate the engineering characteristics of the minerals, host rock, and overburden rock mass (Fig. 2).

The engineering logging of the drill core takes place simultaneously with lithological, stratigraphic, and mineralogical logging. A degree of collaboration and coordination is required to ensure optimum data and observations are obtained from the drill core. Whereas the exploration geologist may be primarily interested in the drill core obtained from the mineralized areas, the engineering geologist will be interested in both the mineralized and barren areas. These observations will be important to assist with the acquisition of geotechnical parameters for the design of the open-pit or underground mine. Alternatively, a designated number of targeted engineering geological (geotechnical) and hydrogeological boreholes may be required. It is important to note that the drilling of boreholes to obtain engineering geological parameters must include the orientation of the drill core to ensure the rock mass discontinuities are correctly aligned to represent in situ rock mass. Typical engineering geological investigations may include consideration of the following:

- Drilling parameters (e.g., type, layout, flush, setup, contractors, time of drilling, depth from, depth to, meters drilled, run length, core recovery, rock types drilled, length of drill, bit diameter, and internal barrel diameter).
- Core handing procedure including washing and transportation to the logging facility.
- Core logging facility and samples security.
- Engineering description and classification of lithologies.
- Core orientation (e.g., ACT II® Electronic Core Orienter).
- Rock quality designation (RQD).
- Fracture index (FI).
- Solid core recovery (SCR).
- Fracture frequency (FF) (0–30°, 30–60°, 60–90°).
- Intact rock strength (hardness).
- Geological strength index (GSI).
- Rock mass quality (Q-value).
- Discontinuities (type (i.e., joints, bedding, faults), classification, infilling mineralization, roughness, joint wall strength, veinlets, drilling-induced fractures, macro- and micro-roughness, orientation, length, and azimuth).
- Degree and intensity of weathering and alteration.
- Determination of tectonic structure, rock mass structures, microfracturing, and fabric.
- In situ testing and monitoring boreholes may include the use of a high-pressure dilatometer (stiffness).
- In situ hydraulic fracturing (rock stress).
- Lugeon, slug, and pulse tests and the installation stand pipes and piezometers to monitor the groundwater regime.
- Cone penetrometer testing (CPT).
- Downhole surveying (diameter, trajectory, azimuth, and inclination).
- Geophysical borehole surveys might also be deployed to investigate faults (e.g., acoustic or optical televiewer, verticality, caliper, sonic, P-S suspension, natural gamma, gamma-gamma (density), neutron, fluid flow, and temperature logging).
- Core photography (with appropriate lining, color chart, and scale).
- Core logging (including a check that the markers in the core box correspond to the drillers’ logs, date of logging; shift, drill runs “from” and “to,” core recovery, lithological descriptions, rock types, rock descriptions including color, texture, structures, weathering, alteration, fractures and contacts, and mineralization type and percentage) and comparison to the drillers’ logs.
- Lithological reference samples.
- Core logging databases and database management.
- Core splitting, sampling procedure, labeling, sample preparation for assays, or mineral/rock quality/grade.
- Long-term core and sample storage, chain of custody of samples, and security.
- Metallurgical and chemical laboratory test work schedule, controls, duplicate, and repeated samples.
- Geotechnical laboratory test work schedule (e.g., uniaxial compressive strength, triaxial strength, or shear strength).
Quality Assurance and Quality Control (QAQC)

Quality assurance and quality control (QAQC) peer review audits of mineral exploration are good practice. This enables the exploration and engineering geologists, client, and investors to have a high degree of confidence in the results. The purpose of the QAQC audit is to ensure that all procedures and assays are reliable, accurate (i.e., how close are the assays to the true metal content in the samples), precise (i.e., how repeatable are the values from the samples), and relevant to the exploration programs and mineral type.

Databases

Exploration, resource and geotechnical databases, and geographical information systems (GIS) are an important part of modern mineral exploration programs. They may include commercial or proprietary in-house exploration software. Databases enable efficient manipulation of huge volumes of data. Furthermore, databases facilitate geological interpolation and extrapolation, the interrogation of geospatially referenced different data sets, statistical analyses, calculation of resources and reserves, and the production of 2D and 3D geological cross and longitudinal sections through the mineral deposit. Validation of digital databases is important to reduce the risk for errors and to ensure the data are properly managed and suitably backed up and secured.

Geological Model

A geological model may be a fundamental requirement for the reporting of mineral resource and reserve. Modelling begins with the collation and review of historical and newly obtained exploration and engineering geological data. A database should then be constructed and validated to identify errors. Geological modelling provides the following:

- The cost-effective management of large volumes of data.
- The 2D or 3D spatial assessment and characterization of the mineral deposits.
- The interpolation of geological data between boreholes and Points of Observation (PoO).
- Stratigraphic modelling identifies the geometry and thickness of the mineral deposits or the top and bottom of each coal seam and each geological unit.
- Classification of resources into measured, indicated, and inferred (see below).
- Facilitation of audits and due diligence.
- Provision of the understanding of mineral properties for beneficiation and processing.
- Provision of information for mining engineers to assist with the design, planning, and scheduling of a mining operation.

Reporting of Exploration Results, Resources, and Reserves

In 1995, Bre-X Minerals Ltd., a major Canadian-based gold mining company reported a huge gold deposit at Busang, in Borneo, Indonesia. This announcement increased significantly the share stock price on the Toronto Stock Exchange (TSE). However, in 1997 the gold samples were investigated by an independent consulting company, and previously tested samples were found to be fraudulent. Alluvial placer gold grains that had been introduced were not consistent with the gold found in the host rock. This caused the collapse of the Bre-X share price and significantly upset the TSE.

Fraudulent claims, mining scandals, and corruption helped provide the basis for the development of international reporting
standards to ensure consistency in the reporting of mineral resources and reserves, in a common style and language, across borders, and in a manner that is understandable by investors and other nontechnical persons. Commonly used commercial, international reporting codes and standards have therefore been produced by professional organizations and/or government agencies. “Codes” must be followed, whereas “guidance” documents provide advice and information on best practice. Each standard generally defines resources and reserves (Fig. 3).

The first mining code was the “Code and Guidelines for defining and Classifying Mineral Reserves, Mineral Resources and Exploration Results,” known as the “JORC Code”. The JORC Code was originally published in 1989 and updated in 1992, 1993, 1996, 1999, 2004, and 2012 (JORC 2012). The JORC Code can be applied to all mineral deposits, and there is a separate JORC guideline document for coal. These guidelines contain definitions of various categories of resources and reserves, Points of Observations (PoOs) (e.g., boreholes, underground exposures, surface exposures, geochemical data), and recommendations for minimum spacings of PoOs for various categories of geological confidence (e.g., measured, indicated, and inferred). Generally, the lower the quantity and quality of data, the lower the classification. Fundamentally, JORC and other standards and codes and assessments must be carried out by an appropriately qualified and suitably skilled Competent Person (JORC Code) or “Qualified Person” (NI43-101) with a minimum of 5 years experience relevant to the style of mineralization and deposits type being considered and a member of a professional body that has an enforceable code of conduct. The principles governing the operation and application of the JORC Code are as follows:

- “Transparency”: The provision of clear and ambiguous data and information.
- “Materiality”: All relevant and reasonable data information are presented to allow informed judgments to be made.
- “Competence”: Member of a professional organization and at least 5 years relevant experience.

JORC was followed by the publication of other international reporting standards including the following:

- South African Minerals Code (SAMREC) (South Africa).
- National Instruments NI 43-101 (Canada).
- AusIMM (Australia).
- Australian Institute of Geoscientists (Australia).
- The Pan-European Reserves and Resources Reporting Committee (PERC) (Europe).
- The Chilean Mining Code (Chile).
- Canadian Institute of Mining, Metallurgy and Petroleum (CIM) (Canada).
- The Institute of Materials, Minerals and Mining (IOM3) Code (UK).
- The Peruvian Mining Code (Peru).
- The Philippines Mining Code (Philippines).
- The South African Institute of Mining and Metallurgy (SAIMM) (South Africa).
- The Society for Mining, Metallurgy & Exploration (SME) (USA).
- GKZ State Commission on Mineral Reserves (Russia and CIS).
- The Polish Mining Code (Poland).
- The Ukrainian Mining (Ukraine).
- Chinese Resource and Reserve Classification (China).
The results from mineral exploration do not define a Resource or Reserve. This may be due to insufficient or noncompliant Points of Observation (PoO) and insufficient data to enable the tonnage, grade, or volume of mineralization to be determined.

Mineral resources are an in situ estimate of the grade and tonnes of mineralization with a realistic prospect of eventual economic extraction. Mineral resources can be demonstrated by technical evaluation and economic analysis to be likely mineable, treatable, and saleable.

Mineral reserves are derived by the application of “modifying factors.” Whereby, the classification of a resource on a geological basis is converted to a reserve by prefeasibility and feasibility study that evaluates the “modifying factors” to demonstrate that mining could reasonably and economically take place at the time of reporting.

Some codes have different terms to describe “Resources” and “Reserves.” For instance, the Ukrainian standard was inherited from the Soviet centrally planned economies where assessments were made by state-owned geological institutes. These methods were rule-based and prescriptive and different from many of the international reporting codes noted above. The Russian GKZ system reports Prognostic Resources (P1, P2, P3) from exploration results and deposit definition and Off-Balance Reserves and Balanced Reserve (C2, C1, B, A) which have increasing levels of geological knowledge and confidence. Industrial Reserves were considered available for mining, whereas Operational Reserves are minerals recoverable from the mining layouts. Note that these codes do not assess the different categories of Reserves depending on economic viability and the international term Resource is not recognized. The alignment between different codes may be complex, and it is not accurate to simply transfer a category of reserve from one of these systems into the resource and reserve classification of the JORC code.

There is no single international code for the global mining industry. In 1999, the Council of Mining and Metallurgical Institutions (CMMI) and United Nations Economic Commission for Europe (UNECE) agreed on the same definitions and the application of the United Nations Framework Classification for Solid Fuels and Mineral Commodities (UNFC). In 2006, the Committee for Mineral Resources International Reporting Standards (CRISCO) became the successor to CMMI and published a template for the International Reporting Template for Exploration Results, Mineral Resources and Mineral Reserves. This is not mandatory, and it does not replace existing codes and standards but provides a basis for resource and reserves classification for countries that do not have existing codes or standards. It provides a generic international standard without the legal and regulatory requirements unique to each country. This is aimed at investors to help decide the viability of a future prospect and to assist with decision making for mergers and acquisitions (CRISCO 2013).

Scoping Study

A scoping study is carried out at an early stage to identify if a mining project may be technically feasible and economically viable. This may be used as a basis to attract some funding and investment or for the purposes of obtaining an exploration license. The geology of the deposits and deposit type are characterized, and mining options are evaluated. In addition, hazards, constraints, and fatal flaws are identified as part of a risk assessment. A scoping study aims to have an accuracy of approximately +/- 30%, and the results determine if a prefeasibility should be carried out.

Prefeasibility Study

A prefeasibility study is carried out to assess the technical aspects of a mining project and to help investors or the mining company decide if a project is potentially profitable. Typically, a prefeasibility study evaluates the geology, mine design, mine planning, mineral processing, economic viability, risks and uncertainties, and whether the project can justify additional expenditure on mineral exploration, mineral processing, experimental test work, mine planning, and ultimately a feasibility study. A detailed geological assessment and resource estimate determine the quality and quantity of the mineral deposit. A recognized international resource reporting code or standard will be required. A 3D geological model, combined with geostatistical modelling, helps to define the resources. Other items that may be required to be assessed include the mining method options, mining scale, mineral processing, metallurgical and beneficiation requirements, preliminary civil engineering, geotechnical and infrastructure requirements, mining waste management, environmental impact assessments (EIA), social impact assessments (SIA), groundwater and hydrogeology, and financial and cost estimates. A Prefeasibility study aims to have an accuracy of approximately +/- 20% to 25%, and the results determine if a feasibility study should be carried out.

Feasibility Study

The Feasibility Study is sometimes also known as a Bankable Feasibility Study (BFS) (although this can be misleading as it does not actually mean the report is “bankable”) or Definitive Feasibility Study (DFS). The objective of a feasibility study is to evaluate and assess the technical, economic, and environmental feasibility of a mine and to identify any fatal laws and constraints as part of a risk assessment. Essentially, a feasibility study should determine a project design and economic viability. The results of a feasibility study can also be used to provide confidence to investors and may have a role in equity...
raising and securing debt finance. The feasibility study can also be used to assess other projects on an equal basis. This focuses on the most technically and economically favorable option; it assesses all risks to the mining project, removes or reduces uncertainty, increases confidence for the investors and/or shareholder/stakeholders, and presents the data and information that can be audited as part of a due diligence. Ultimately, the feasibility study is aimed at demonstrating with a high degree of confidence that the mining project can be constructed in an economically viable and technically feasible way. The data and information contained in the feasibility study provide the basis for detailed civil engineering design of mine buildings and associated infrastructure. Finance may also be based on the findings of a feasibility study and can provide the basis for any permitting approvals or regulatory requirements. A feasibility study has an accuracy of +/− 10% to 15%. Engineering geologists are likely to be involved in the analysis and design of the following:

- Engineering characterization of drill core.
- Mine infrastructure, processing plant, and foundations.
- Pipeline and utilities routes.
- Haul roads, access roads, cutting, embankments, and retaining walls.
- Diggability and trafficability of large plant.
- Drilling and blasting requirements.
- Underground rock mechanics (roadways, shafts, adits, inclines, stopes) and strata control.
- Open-pit optimization, rock mechanics, soil mechanics, and slope stability.
- Tailings dams, sediment ponds, water supply reservoirs, and impoundments.
- Waste rock or colliery spoil tips.
- Heap leach pads.
- Evaluation of mining hazards.

**Surface Mining and Quarrying**

Minerals can be mined by underground or open-pit methods (Fig. 4) depending on the following (Fig. 5):

- Geological and resource factors: deposit type, depth, geometry, structure (faults, dykes, folds, and discontinuities), grade variations, surface constraints, in situ stress orientation, hydrogeology, and environmental impacts
- Mine factors: ventilation, geological hazards, geotechnical parameters, and engineering behavior of the rock mass or soil
- Other factors: development and capital costs, production costs, reserve recovery, assessment, socioeconomic or political issues

**Open-Pit Mining and Quarrying**

Surface mining (also known as open-pit or open-cast mining) and quarrying are used to extract stratified mineral resources that are close to the ground surface, for example, lignite, coal, metalliferous minerals, industrial minerals, and aggregates (Read and Stacey 2001; Smith and Collis 2001). A principal limiting factor is the stripping ratio (the amount of overburden to be removed) and the hydrogeology. If groundwater is present, dewatering will be necessary. The impact of dewatering on neighboring properties and the potential for the groundwater to be polluted should be assessed. Groundwater monitoring is required in boreholes during exploration to identify if the surface mine will extend below the water table. The stability of the open-pit walls, slopes, and benches require engineering geological evaluation with particular emphasis on the strength of the rock mass and the characterization of the rock mass discontinuities. The direction of dip and strike of strata in relation to the geometry and orientation of quarry and open-pit faces will also influence rock stability. These may also be investigated by the engineering geological logging of drill core during the exploration phase combined with slope stability analysis. If the strata daylight (dip into) the open pit/quarry, sliding failure may occur. Where the strata dip steeply and cannot be worked against the dip, the face should be parallel to the bedding. The relationship between the angles of shearing resistance along a joint when sliding occurs under gravity and the dip of the joint will be relevant. Strong rock may fail suddenly and violently if the peak strength is exceeded on a high or steep rock face slope. Weaker rock, with marginal differences between the peak and residual strengths, fails gradually. The length and inclination of joints, friction and shear strength (frictional resistance), joint roughness, and moisture (effective stress) are relevant rock mass parameters for medium and high slopes, whereas unit weight parameter is important for small slopes. Where rock slopes become higher, the water pressure is relevant, and cohesion is less important. Some quarries may have a short-term and higher-working face and a shorter, longer abandoned face. Thin, intercalated beds of mudrock or shale and the rock mass discontinuities may also promote rock falls (e.g., ravelling, toppling, wedge, sliding, or planar failure). Loose overburden may fail by slipping or flowing into open pits/quarry by retrogressive rotational slip (Matheson and Reeves 2011). Active and abandoned quarries, including rock faces and tips, will be subjected to weathering, erosion, and failure and should be subjected to regular appraisals and assessments (Anon 1987, 2013).

Dimension stone may be worked by the drilling of closely spaced boreholes or the use of a mechanized diamond and tungsten carbide-impregnated chain saws, wire saw, or wedges to split the rock. Rotary percussion drilling and blasting are a common method for the extraction of metalliferous and industrial minerals and the removal of overburden.
Usually, the open pit is operated from a series of benches that enable extraction and drilling and blasting to take place simultaneously. The fracture index and engineering properties of the rock help to determine the blasting fragmentation.

**Contour Mining**

Contour mining (also known as “mountain removal mining” or “mountaintop mining”) is a coal mining method that involves the topographic removal or alteration of a ridge or summit. The entire coal seam is excavated by the removal of the overlying overburden. First, the overburden is removed by draglines or truck and shovel. Secondly, the uppermost coal seams are removed, and transported to the processing plant. The mining waste often may be used to infill adjacent valley floors (known as “holler fills” or “valleys fills”. Thirdly, draglines excavate the lower coal seams and intervening overburden, and these are placed into stock piles and valley fill, respectively. Finally, rehabilitation and vegetation take place. Due to deforestation and huge environmental impacts, this is a controversial mining method that takes place in Kentucky, West Virginia, Virginia, and Tennessee, in the Appalachian Mountains, USA.
Strip Mining
Strip mining is a type of open-pit coal and lignite mining, which starts by the cutting of an initial box-cut using face shovels. A dragline or bucket wheel excavator is then used to remove the overburden, which is subsequently stockpiled. In strip mining the waste overburden is placed by a dragline in parallel rows. Face shovels, dump trucks, and scrapers then work the exposed rock and associated minerals. The removed waste may be used as back fill, for rehabilitation, restoration, and landscaping as the highwall face advances. Mining waste may be stored at their angle of repose if they are temporary slopes but may need profiling for longer-term stability. The failure of mining waste in 1996, at Aberfan, in South Wales, destroyed a school killing 116 children and 28 adults. The maximum depth for open-pit coal mining depends on several economic and geological factors, but it is in the order of approximately 100 m (although some mines exist that are deeper) and striping rations up to 25:1. Open-pit mines can be large with faces 3–5 km long. The reach of a dragline can be as much as 45 m and highwall faces may be 100 m high. The diggability of rock and method of excavation (e.g., digging, ripping, or blasting) can be determined by evaluating the unconfined compressive rock strength, rock mass discontinuities, block size (joint spacing and bed separation), and weathering (Scoble and Mutfuoglu 1984), although other methods are also available using seismic velocities of the rock mass to determine diggability.

Auger Mining
Auger mining is a method for the extraction of coal by the boring of an auger into a coal seam. This is usually associated with open-pit or strip mining when it becomes uneconomic to recover coal due to excessive depth and overburden removal. The use of an auger is controlled by the dip of a seam and the engineering properties of the coal. Auguring requires a coal seam to be horizontal or slightly dipping and to have reasonable strength.

Highwall Mining
Highwall mining, like auger mining, is associated with open-pit coal mining, whereby a seam of coal is excavated at outcrop. This method uses a continuous miner operated by a hydraulic boom with a shearer and cutter-head boom that can be extended for approximately 300 m into a coalface.

Alluvial Mining
Placer minerals, such as gold, platinum, tin, diamonds, gemstones, ilmenite, zircon, and monazite, are concentrations of minerals that have been eroded from source and then deposited elsewhere by gravity. These are common in alluvial, fluvial, lacustrine, glacial, glacio-lacustrine, aeolian, eluvial, and residual sedimentary settings. Alluvial mining of placer deposits involves the surface excavation of loose sediments from stream, river, lake, estuary, or beach deposits. This can include small-scale panning or the use of a sluice box to trap heavy minerals. Alluvial mining can have severe environmental consequences since large volume of silt, sand, or gravel often may be processed to recover the economic minerals (Fig. 6).

Dredging
Dredging is used to recover relatively dense minerals such as cassiterite, rutile, ilmenite chromite, and scheeleite that are under a natural or artificial body of water by the use of a floating vessel, with associated processing equipment, sumps, waste disposal, and storage facilities. Alternatively, the excavated sediments can be processed onshore.

Sand, Gravel, and Clay Pits
Sand, gravel, and mudrocks are excavated from surface workings for the production of building and civil engineering raw materials (e.g., aggregates, tiles, sewer drains, bricks, mortars, cement, plaster, and renderings). The deposit commonly occurs as river, beach, marine, glacifluvial, and aeolian deposits. The degree of sorting, composition, and characteristics can be variable depending on the depositional environment. Bimodal, glacifluvial deposits contain gravel and sand grade materials. Some alluvial gravel may contain detrital carbon (coal), shale, shell fragments, or deleterious salts that could be detrimental to the desired products, whereas aeolian deposits tend to be well sorted.

Clay used for brickmaking must have suitable chemical and physical properties including moderate plasticity, suitable workability, high strength when dry, low shrinkage, long vitrification, and low sulfide minerals. The environmental impacts of working sand and gravel must be carefully considered, for instance, to ensure the removal of the deposit doesn’t cause or exacerbate flooding or coastal erosion. The intact strength, bulking factor, and natural moisture contents will influence diggability and the types of mining equipment. These factors may be determined during exploration by engineering geological evaluation and geophysics. The stability of these deposits needs to be estimated to assist with the design of the pit walls. Displacement takes place when the shear stresses exceed the shear strength of the deposits. Generally, slope angles of between 35° to 45° tend to be used in sand and gravel pits and 30° and 45° in clay soils, but this depends on the deposits’ (soil) engineering characteristics and mechanical behavior. Mining may take place by the use of a dragline or mechanical excavator that loads the materials onto trucks or a conveyor for sorting, washing, and grading to produce finer and coarse grades. Flooding is often required to be controlled, and upon abandonment sand and gravel pits may be rehabilitated to form artificial lakes and wetlands.
Underground Mining

Underground mining methods may be classified depending on whether supports are required. Where supports are used, these are further categorized if rock or artificial support is installed. Some of the main underground mining methods are described below (Hustrulid and Bullock 2001).

Artisanal and Small-Scale Mining

Artisanal mining includes both surface and underground operations. Typically, this takes place in some less developed countries (Fig. 7). There are an estimated 13 million people involved in artisanal and small-scale mining (ASM), in approximately 30 countries, and up to 100 million people are dependent on ASM (Hentschel et al. 2003). Minerals that are extracted by ASM include gold, silver, zinc, tin, copper, precious and semiprecious gemstones, coal, bauxite, limestone, and other industrial minerals. ASM often takes place with the following characteristics:

- No or little appreciation of the geology.
- No or poor prospecting and exploration strategies.
- No or low mechanization.
- Labor intensive.
- Insufficient regulations and policies.
- Low levels of health and safety.
- Unskilled and inexperienced work force.
- Rudimentary mining and mineral processing techniques.
- Low productivity and low salaries.
- Noncontinuous mining controlled by seasons, weather, and climate or market conditions.
- Poor capital investments.
- Little regard for the environment and future sustainability of the mineral resource.

ASM may involve vulnerable members of society, including children, women, and the elderly. What is more, ASM may operate outside the law and may be associated with fraud, corruption, criminal gangs, land and mineral right conflicts, and the displacement of local tribes and indigenous people. ASM can lead to adverse environmental damage including pollution of surface water courses and aquifers, contamination, unstable waste, subsidence, fires and spontaneous combustion, and dereliction. ASM can result in mineral resources depletion or lead to the sterilization of some deposits since it is not possible to accurately quantify resources.

Outcrop Workings

It is likely that minerals were originally mined where they cropped out. This was almost certainly the case in historical times when the target mineral was observed at or near the ground surface. Early surface workings were probably rudimentary with little or no understanding of the geology, groundwater, roof support, and ventilation.

Drifts

When mineral extraction becomes too deep, adits are driven into hillsides until rock failure or lack of ventilation prevents further advancement. By comparison, modern drift mining may be highly mechanized and may be horizontal, inclined up to approximately 45°, or helical.

Soughs

Soughs are horizontal tunnels excavated to drain groundwater to enable mineral resources to become mined. In the UK, soughs date back to the fifteenth century where rudimentary pumping methods were developed using, for example, horses and simple winding mechanisms.
Bell Pits
Bell pits, although still used in some less developed countries, were a historical mining method that started in parts of Europe in the thirteenth or fourteenth century (possibly earlier) to extract mineral deposits that were located no deeper than approximately 7 m below the ground surface. Coal and chalk were commonly mined using bell pits, the former known as “deneholes.” Fires were used for ventilation circuits, although this caused explosions in some coal mines. Bell pits were commonly used to extract coal, sandstone, flint, clay, and semiprecious and precious gemstones. A vertical shaft was excavated, and then the bottom of the shaft was extended once the mineral had been intersected. An adjacent bell pit was sunk, at a distance of up to about 10 m, once the mineral had been exhausted and within the limitations of the roof support and ventilation. Bell pits may be exposed in modern-day open-pit workings.

Partial Extraction: Room and Pillar Workings
Stratified mineral deposits can be mined by partial extraction methods where part of the mineral is sacrificed and left in the mine to support the roof. Room and pillar workings (also known as pillar and stall, post and stall, stoop and room, and bord and pillar) replaced bell pits and comprised a series of radiating rooms, supported by in situ pillars. Historical room and pillar workings were unplanned. Often, mine abandonment plans do not exist and the location, depth, and geometry of old mine may not be known. Support pillars may vary considerably in size and extraction ratios vary from 30 to 70%. Unmined minerals may also have been left in the roof and floor to promote stability of the voids. Groundwater is managed by pumping or natural drainage. Two or more shafts were constructed to facilitate ventilation along with underground fan pit installations and to provide alternative means of access and egress. Waste rock may have been stored in the mine workings (stowing) to reduce the labor time and costs of surface disposal and to prevent subsidence. Stress concentrations on old pillars may cause these to fail, which can trigger collapses of adjacent pillars. In other situations pillars may have been “robbed” at the closing stages of mining which can influence the stability of mine roof and increase the possibility for future subsidence. Pillars may also become destabilized by mine water ingress. Where the floor strata are weak, pillars can punch into a weaker floor, causing ground subsidence. This may generate collapses that can chimney to the ground surface to generate a collapse or
crown hole (Piggott and Eynon 1978). Collapse of these mine workings and void migration will be determined by the unsupported span width, extraction height, and engineering properties including shear strength and discontinuities in the cover overlying strata, dip, depth of superficial deposits, and groundwater regime. Modern room and pillar mines for halite, gypsum, limestone, chalk, and sandstone may be of considerable size, systematic, and mechanized.

**Early Longwall Mining**

An adaptation of longwall mining developed in the Midlands coalfields in the UK during the 1600s (Shropshire Longwall) consists of two parallel roadways (gates) driven about 10 m apart to excavate a coal seam. The gates advanced as the coalface was mined, and these also permitted labor, equipment, and a ventilation circuit to be established. Firstly, the bottom of the coal seam was undercut using hand-held tools and using timber support. This was followed by a vertical cut. Iron wedges inserted into the top (later replaced by explosives) of the exposed seam allowed several meters of the seam to drop, where it could be manually loaded into wagons for transportation along the gates to the surface. This method of working generated subsidence and influenced groundwater in overlying aquifers.

**Modern Longwall Mining**

Mechanized longwall mining developed in the deep coal mines of Europe from around the early to middle part of the twentieth century. Two parallel roadways, some 200–300 m apart, were excavated for a distance of up to several kilometers. These were joined at right angles to form a working face and to provide ventilation. The coal extraction was automated using a rotating armored platted coalface shear or plow where the seams were thin (less than ca. 1 m) and which cut the entire length of the face in a single run. The roof was supported by hydraulic props which advanced causing the roof behind to collapse into the goaf, reducing the compressive stress on the operating face. The excavated coal fell onto a conveyor belts that transported the coal to the surface for processing. In retreat longwall mining, the two roadways were driven along the full extent of the seam being extracted, which ensured there was geological continuity, before the shearer then extracted the intervening coal. Longwall mining generates subsidence, influences aquifer permeability, and produces large volumes of waste that were disposed as spoil heaps. Longwall mining was not permitted beneath some water bodies unless there was at least 105 m of rock cover between the roof of the mine and the sea bed (Whittaker and Reddish 1989).

**Shortwall Mining**

Shortwall mining uses narrow panels, up to approximately 45 m long, and a single roadway in an attempt to control subsidence. Modern shortwall mines have fully automated face equipment, ventilation systems, and gas monitoring devices. Due to the short faces, the goaf and any support pillars may not completely converge with the floor leaving voids.

**Wongawilli Mining**

The Wongawilli mining method was developed in Australia for the extraction of coal. This comprises two or three headings that divide the coal panel into smaller panels. The panel may be up to 1 km long and up to 200 m wide and are excavated using mechanized coal cutting, support, and transportation systems.

**Sublevel Stoping**

Sublevel stoping is a method of mining for metalliferous deposits. Various levels are driven into the zone of mineralization, and then the rock is removed between these levels by blasting and gravity, before being removed to a haulage level. In cut-and-fill stoping, horizontal slices of the ore body are excavated in the stope and waste rock is used to backfill the void. Each slice is driven into the footwall, with crosscuts, and the rock is systematically removed and transported to the ground surface for processing. Hydraulic backfilling may take place as the mining advances, controlled by dams and barriers. This type of mining must consider the engineering properties of the host rock and the groundwater to ensure failure and folding do not occur.

**Shrinkage Stoping**

Shrinkage stoping shares similarities with the cut-and-fill mining method, but the broken rock is not extracted and remains in place to support the walls and to provide a working floor to enable the upward progression of the roof.

**Sublevel Caving**

Sublevel caving methods allow the ore body and host rock to cave into the space generated by the extracted mineral. This caving takes place in a controlled manner and cannot be used in areas where subsidence is prohibited or there are aquifers. A network of shafts, development drifts, crosscuts, and haulage levels develop a mine complex. This mining method takes place in steeply dipping or vertical mineral deposits.

**Block Caving**

Block caving is used to mine massive, steeply dipping or tabular dipping mineralized rock. A large rectangular block is drilled, blasted, and undercut to cause the block to fail. The mineralized rock and waste collapse before being removed via chutes, drawpoints, and crosscuts to a haulage level. The subsided ground may contain scarps, fissures, and broken and loose material.

**Solution Mining**

Soluble rocks, such as halite, can be mined with injection of water and solvents in lined and cased boreholes to dissolve
the salt. Brine returns to the surface and the salt is extracted. The size and geometry of the voids created are controlled to prevent collapse and subsidence.

**Unconventional Mining**
Some mining methods require the development of new and innovative methods of mineral extraction. This includes for example:

- **Shale gas**: The extraction of natural gas found in shale. To extract the gas, deep and horizontal boreholes are hydraulically fractured to enhance the permeability of the shale enabling the gas to flow for extraction.
- **Coal mine methane (CMM)**: The abstraction of methane gas, via boreholes, that has accumulated in voids associated with past and abandoned coal mines.
- **Coal bed methane (CBM)**: The abstraction of methane gas, via boreholes, in areas of unworked coal.
- **Underground coal gasification (UCG)**: The extraction of syngas from coal seams by the underground controlled ignition of the seam via boreholes.
- **Heat pump technology**: The use of mine water in shallow, abandoned, flooded mine workings to heat or cool buildings.

**Mine Ventilation**
The manager of an underground mine must ensure that all parts of a mine are adequately ventilated. A Mine Ventilation Officer may be appointed by the Mine Manager, although this does not relieve the manager of any statutory duty. Ventilation must dilute or remove flammable and noxious gases so that they are harmless and do not exceed safe operational limits. These include, for example, methane (CH₄), radon (Rn), carbon dioxide (CO₂), carbon monoxide (CO), hydrogen sulfide (H₂S), oxygen (O₂), and stythe gas (air enriched in nitrogen and depleted in oxygen). Air entraining a mine is subsequently distributed within the mine complex via a network of internal raises, ramps, steel ducting, and regulators to generate auxiliary ventilation systems. Exhaust systems draw out the contaminated air from the mine. Ventilation cells in the mine must provide no less than 19% oxygen (by volume) in the general body of the air. The mine ventilation system must also ensure that the mine atmosphere is reasonable in terms of the temperature, humidity, and dust. Miners may be evacuated if methane levels exceed 2%, shot firing may not proceed, and electricity supplies might be closed down. Methane levels become explosive if there is a source for ignition in concentrations of 5–15% by volume. In the UK, ventilation in mines may be provided by exhaust systems as this maintains the pressure inside a mine at a lower level than outside. Therefore, if the fans ceased operating, fresh air would be sucked into the mine. In coal mines, coal is usually wound up the downcast shaft to prevent a plug of methane following coal travelling along a conveyor, although this differs around the world. Drill holes may be drilled into the roof of some mines to control hazardous gas accumulations. Automated gas monitoring systems are also used to replace conventional methods of gas detection such as the yellow canary or Davy lamp.

**Open-Pit Stability, Tip Stability, and Strata Control**
Strata control considers how the strata may be controlled in the direct vicinity of the mine opening, including mine shafts, roadways, stopes, and operational faces. However, mining subsidence is generally not considered (see section on “Mining Hazards”). Engineering geologists, geotechnical engineers, and mining engineers will be involved in the evaluation of how the rock mass may behave during and following underground excavation and what methods and techniques may be available to cost-effectively prevent and control strata failure around the mine openings. Parts of the mine may require stabilization for a specified and limited time period, such as the roof and goaf in a longwall coal mine, whereas roadways and shafts bases may require longer-term stability. Generally, the engineering properties of the strata will require assessment, including the rock mass characteristics, density, tensile and compressive strength, Poisson’s ratio, Young’s modulus of elasticity, geological structure, and in particular the rock mass discontinuities, the three-dimensional stress field, and groundwater. Where these parameters cannot be measured in laboratory, by in situ tests or by monitoring or modelling it may be necessary for these to be conservatively estimated.

Rock mass classification methods may be used to assist with stability analysis in mining and tunnelling. Since 1946, these have been used to evaluate the empirical relationships between rock mass parameters and the engineering design. Several different rock mass rating systems are available including rock mass rating (RMR), Q-system, mining rock mass rating (MRMR), and New Austrian Tunnelling Methods (NATM), and others exist for rock slopes (Bieniawski 1989; Fig. 8).

Conventional support methods include in situ pillars or timber props and insets. Steel arches with metal lagging may be used in roadways, which may be semicircular, combined radius arch, or Gothic arch. Hydraulic face supports move forward as a longwall face advances. Steel or fiber glass roof bolts are increasingly used in mines as a cost-effective and efficient method of strata control.

**Mine Closure and Abandonment**
Mines can close due to a variety of reasons. These include geological constraints, mineral(s) becoming exhausted or uneconomic, reduced demand for the mineral product, and political or environmental reasons. Some mines close and
then reopen at some future stage perhaps under more favorable economic climates. Interestingly, some mines remained open in the former Soviet Union even though there was no or little demand for their products and they were working at an economic loss. This was driven by the fact they sustained the lives of several thousands of people who lived in the mining towns in remote and challenging geographical locations. Mine closure can have an inevitable destructive and detrimental impact on the local or national economy and the society which was dependent on the mine, sometimes leading to a “ghost town.” Some old mining sites have historical and archaeological value or contain protected flora and fauna (e.g., kestrels nesting on quarry faces, bats in mine entries, or unique plants on mineral waste tips).

Serious environmental consequences can also be caused by mine closure. The extent of the impact will depend on the mineral worked, the number of years over which mining took place, processing and beneficiation, the management of mining waste, and so on. Today, mining projects consider the environmental and social impact of mining well in advance of any mine closure proposals; this can be undertaken as part of an Environmental Impact Assessment (EIA) and Social Impact Assessment (SIA) usually at the prefeasibility and feasibility stages of the project.

The planned and phased closure of a mine may assist to ensure the mine is left in a secure state and the associated hazards, constraints, and social and environmental impacts are properly addressed, managed, and mitigated. If mine closures are appropriately implemented, the maximum value of the land and future redevelopment options can be evaluated. The planning for mine closure will require due consideration of several multidisciplinary issues such as geological, technical, environment, financial, legal, and socio-economic. The mine closure plan should commence well in advance of the actual closure of the mine taking place and to ensure there are sufficient financial resources to enable the liabilities, hazards, and associated geotechnical risks to be evaluated.

Engineering geological investigations determine the treatment and long-term stabilization of mine entries (shafts and adits), support pillars, roadways, subsidence prevention, and the stability of rock slopes in open-pit mines and on spoil tips.
A hydrogeological evaluation of mine water, mine water rebound and mine effluent discharges may also be required.

In some countries there exist environmental legislation and regulations to identify the responsibilities of the mine owners, operators, investors, and stakeholders. An environmental audit is recommended before mine closure is finalized. This should include a review of the mine infrastructure, buildings, mine roadways, shafts, utilities, spoil, dams, lagoon, and hazardous substances (e.g., explosives, polychlorinated biphenyls (PCBs), fuel, asbestos, and grease). Monitoring could be required for surface effluent, mine water, sewage, mineral processing sites, noise and dust, etc. A mine closure plan should also consider the salvage, reuse, or sale of mining equipment and machinery and considerations of a potential buyer for the abandoned mine. If the decision to close a mine has not been finalized, it may be possible that the mine goes into a period of “care and maintenance” before the cessation of mining operations.

New mines can be controversial, with debates often focusing on the need to generate income, provide resources, and maintain people’s livelihoods and the environmental impact of the proposed mine. Mining is often not permitted or strictly regulated and monitored in some locations, such as national parks and areas of outstanding national beauty.

Old mine workings are normally considered to be a liability, but many are protected sites of heritage, archaeological, or geological value. The alternative use of old mines could make them a commercially viable asset. This will depend on the geology, hydrogeology, mine geometry and characteristics, and desired end use. Examples of the possible uses of old mine workings are as follows:

- Old, large, dry, room and pillar mines can be used for storage (e.g., oil, gas and chemicals, data centers, and document) (e.g., Cheshire salt mines, UK and Argentine limestone mine, Kansas City, USA).
- Secure military facilities (e.g., Corsham, UK, now decommissioned, West Poland mines, and Iron Mountain, Pittsburgh, USA).
- Low-level radioactive waste (e.g., salt mines, Hannover, Germany).
- Munitions storage (e.g., Burton, UK).
- Storage of mining waste from coal-fired power plants and mine workings (e.g., Romania, Hungary, and Czech Republic).
- Storm water channels in major cities (e.g., parts of Glasgow, Scotland).
- Storage of foodstuffs (e.g., Carrickfergus, Northern Ireland).
- Scientific research in a controlled atmospheric environment (e.g., abandoned gypsum and anhydrite mines (Midlands, UK).
- Tourism and museum (e.g., National Coal Mining Museum and Sygun Copper mine, UK).
- Heat pump technology from shallow, abandoned, flooded coal mine workings (e.g., parts of the UK).
- Unconventional and alternative energy (e.g., abandoned mine methane).
- Landfill and domestic waste storage (e.g., waste management in Europe).
- Aquatic and wildlife centers (e.g., flooded sand and gravel pits and quarries in Europe).
- Theme parks and leisure facilities (e.g., Alton Towers, Midlands, UK).
- World-class floral garden facility (e.g., Butchart Gardens, British Columbia, Canada).

Abandoned mines can be rehabilitated or restored. Landscaping reduces the visual impact of former mine sites including the profiling of waste tips and landform replication. Embankments and bunds can be constructed and vegetation reestablished, often using the mine waste. Where mine workings exist beneath urban area or sites where new infrastructure or housing is proposed to be developed, it is important for the hazards and risks to be assessed. When required, voids and shallow mine workings may need to be stabilized by grouting or capping of any mine entries. The potential impact of mining includes the following (see chapter on “Mining Hazards”) (Bell and Donnelly 2006).

- Disruption to land.
- Alteration of the topography.
- Adverse effects on groundwater.
- Mine water rebound.
- Effluent discharge from mines and acid mine drainage.
- Explosive, toxic, or asphyxiating gas emissions.
- Surface water pollution.
- Derelict land and contamination.
- Mining waste and spoil heaps blighting the landscape.
- Damage to vegetation.
- Spontaneous combustion and fires (coal).
- Abandoned mine entries (shafts, adits, and inclines).
- Mining subsidence and fault reactivation.
- Induced seismicity.
- Noise.
- Dust.

**Mine Entries: Shafts, Inclines, and Adits**

Modern mines must have two means of access and egress. It could be two drifts, a drift and a vertical shaft, or two vertical shafts. Vertical shafts or horizontal entry adits and inclines are required to provide access to mine workings, provide ventilation, connect mining levels, for mining infrastructure (e.g., fan house, shaft balance weights, windings engines and
pumps to remove mine water), enable the supply of labor and equipment, and remove waste and minerals. The age, width, shape, depth, and lining of shafts may vary considerably. Old shafts may be unlined or lined with wood (tubing), brick, or masonry. In the seventeenth and eighteenth century, cast iron rings and rivets permitted shaft construction through water-bearing strata. Since the start of the twentieth century, shafts became lined with reinforced cylindrical concrete rings, pre-cast concrete or steel segments, and/or shotcrete to provide stability and control groundwater ingress where there was a high hydrostatic pressure or high lateral pressures. The geological factors influencing shaft construction includes the engineering properties of the rock mass, groundwater, in situ stress, and ventilation. The demand for coal during the European Industrial Revolution and the invention of water pumping methods in the eighteenth century (e.g., the Newcomen atmospheric engine in 1712) enabled mineshafts to be constructed to greater depths. In the twentieth century, the development of ground freezing techniques enabled deep shafts to be constructed through aquifers. The shape of mine shafts can be round, oval, square, and rectangular, and their depths vary from less than 10 meters to thousands of meters deep.

Upon abandonment mine shafts may have been backfilled but this was not always the case. The engineering characteristics of backfill materials may be unknown and could be hazardous (e.g., agricultural, industrial, chemical, animal, military, or domestic waste or old mining equipment), explosive, or radioactive. Backfilled materials may move into radiating mine roadways or consolidate under their weight; however, this will be influenced by the density of the material, friction against the shaft lining, and large obstacles in the shaft that cause blockages or arching. Some shafts may have a wooden staging or plug comprising a tree, timber, reinforced concrete, or old mining equipment. These often deteriorate over time also leading to collapse and subsidence. Shafts may contain spoils where they have subsided leading to a depression, and this can provide evidence for their existence. Shaft caps include railway sleepers, concrete slabs, brick, or “beehive” masonry domes, or they may be fenced with signage to prevent accidental access (Fig. 9). Metal grills may also be laced over mine entries for ecological reasons (e.g., if they contain bats). Some mine shafts may require to be ventilated to prevent gas accumulations. Where a shaft has been levelled, there may be no visible topographic expression, and their locations often may be unknown.

Hazards associated with abandoned mine entries include subsidence or collapse, gas emissions, and mine water discharges. In areas where shafts and mine entries are suspected, these must be located (e.g., by geological mapping, geophysics, trenching, or drilling) and treated (e.g., by grouting, backfilling, and capping). Industry best practice guidance is available for the assessment and mitigation of mining hazards including the backfilling and capping of mine entries (CIRIA 2018).

Mining Records

Mining plans and reports might be available in some countries and held by a government, state, or federal mining organization, geological survey, ministry, or chamber. For example, in the UK, it became a statutory obligation for mine plans to be produced and submitted on abandonment of a coal mine, but this was not compulsory until 1872. In 1911, the legislation required coal mine owners to maintain accurate plans of a specified scale and revise them every 3 months. However, this was not the case for owners of metalliferous mines. Mine abandonment plans and mining records cannot always be relied on for accuracy, and many mines are unrecorded.

Summary

Mining has taken place throughout the world for thousands of years. The minerals and commodities produced by mining have influenced past civilizations and are likely to continue to remain vital to sustain future generations in both developed and less developed countries. Globally, modern society, economies, and industries are reliant on minerals produced by mining. Mining takes place by underground or surface operations. Mining is highly variable ranging from low investment, poorly planned, small-scale artisanal mines with rudimentary mining methods to highly mechanized, sophisticated, and complex mining operations. Engineering geologists may be involved in most stages of mining and tend to be more involved in exploration and the logging of geotechnical boreholes, mine design (open-pit stability and the construction of tailings dams and lagoons, stopes, roadways, and portals), infrastructure development (utilities, haul roads, embankments, settings, bridges, tunnels, mine buildings, reservoirs, sewers, processing plant, airports, etc.), mine abandonment, and mining hazards assessments.

Engineering geologists should have a good appreciation of the mining cycle and how these interrelate. The life cycle of a new mine may follow a phased process including, for example, a desk study, scoping study, exploration program, due diligence audits, resource and reserve reporting, prefeasibility and feasibility study, mining operation, mine closure, and abandonment. Often significant financial investments are required to develop or extend a mine over periods from a few years to several decades. Each stage increases geological and geotechnical knowledge and stakeholder confidence and reduces technical, financial, and environmental risks to determine whether there is a realistic and reasonable prospect for eventual economic mining.

Firstly, licenses and rights to explore minerals have to be secured and agreed with the appropriate land and mineral
owner or government organization/agency. This is followed by the design, management, and implementation of an exploration and geotechnical program to locate and accurately determine the geometry, size, depth, quantity, quality, and tonnage of the mineralization and to characterize the engineering properties and hydrogeology of the deposits and associated unmineralized rock mass. Geological modelling techniques with integrated geostatistical analysis and geographical information systems facilitate the analysis of historical and newly acquired data. The resultant geological models and mineral resources and reserves may have to be produced compliant with an international reporting standards.

Minerals are mined by underground and/or surface methods. This depends on several interrelated factors such as the geology, depth, and geometry of the mineral deposit and engineering behavior of the mineralized and unmineralized host rock and the groundwater regime. Surface methods include quarries for industrial minerals; pits for clay, sand, and gravel; and open-pit (open-cast) operations for coal. Underground mining methods historically began from shallow adits and bell pits, later advancing to rudimentary room and pillar workings. Modern underground mines include mechanized room and pillar workings, longwall mining (mainly for coal), and variety of cut-and-fill or stoping methods (mainly for metalliferous minerals). Once extracted, minerals are processed and beneficiated to remove the waste or provide the concentrate for advanced refinement or mineral commodity (this extends beyond the scope of this chapter).

Engineering geologist may be required to evaluate the impact of mine closure or abandonments. This includes the identification, management, investigation and mitigation of any liabilities and mining hazards, and assessment of their consequences and associated geotechnical and environmental risks (see chapter on “Mining Hazards”).

Cross-References
▶ Acid Mine Drainage
▶ Angle/Area of Influence
▶ Backfill
▶ Blasting
▶ Borehole
▶ Borehole Investigations
▶ Classification of Rocks
▶ Classification of Soils
▶ Cut-and-Fill
▶ Dewatering
References

Bell FG, Donnelly LJ (2006) Mining and its impact on the environment. Taylor/Francis (Spon), Hoboken
Joint Ore Reserves Committee (JORC) (2012) Australasian code for reporting of exploration results, mineral resources, and ore reserves (The JORC Code)