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Mineral Inventory: An Overview

The life of a mine does not start the day that production begins, but many years before, when the company sets out to explore for a mineral deposit. A good deal of time and money is spent simply looking for, locating and quantifying a promising mineral occurrence. Not many will be found and not many of the ones found will have the potential to become mines. It is not unusual to spend five to ten years searching for a mineable deposit.
(Anonymous, Groupe de Reflexion, cf. Champigny and Armstrong, 1994)

Chapter 1 introduces the setting within which mineral inventories are estimated, explains concepts and terminology important to the general problem of resource/reserve estimation, and describes a range of empirical estimation methods that are widely used in industry. Important concepts include the systematic and sequential nature of gathering data, three-dimensional block models of a mineral deposit, errors of estimation, cutoff grade, geologic and value continuity, and the structured nature of a mineral inventory estimation. Computers are an essential tool for modern requirements of mineral inventory estimation.

1.1: INTRODUCTION

The investment necessary to start a mine is on the order of tens to hundreds of millions of dollars. In order for the investment to be profitable, the potential product in the ground must be present in adequate quantity and quality to justify a decision to invest. Mining and processing systems used to extract the products must then operate so as to produce revenue to offset the planned investment and provide an acceptable profit. Clearly, all technologic and financial decisions regarding planned production are built on an understanding of the mineral assets available. Thus, the estimation of grade and location of material in the ground (in situ resources) must be known with an acceptable degree of confidence. This is especially true of certain large, low-grade deposits for which grade is only slightly above minimum profitable levels and for some precious metal deposits where only a small percentage of mineralized ground can be mined at a profit. Mining profits are strongly leveraged to product price and realized grade of material mined. A small difference between planned (estimated) and realized production grade or a small change in metal price can have a large impact on mine profitability.

To remain competitive, mining companies must optimize productivity of each mining operation. There are several ways to accomplish this goal. Moving and processing more tons with the same or less equipment is a common first goal, followed by inventory/materials management and control, purchasing new and better equipment, and so on. Each of these courses of action has an associated cost and a potential return on investment. Another method of increasing productivity is to increase the product content in the material being mined and processed (i.e., improved grade control during mining). This can be accomplished by increasing the grade for the same tonnage, increasing the tonnage while maintaining the same average grade, or some combination that involves improved selection of ore versus waste. Improved grade control arguably offers the best return for the least investment because of the leverage that grade mined has on revenue.

The three undertakings – ore estimation, mine planning, and grade control – are complementary in an efficient mining operation and are natural progressions. The integration of these three endeavors is important because the grade control system must balance with the ore reserve as well as with the final products of the operating plant, and both estimation and grade control are influenced by planned operational procedures. If this balance is not achieved, the original investment may be in jeopardy. Reappraisals of mineral inventories may be necessary many times prior to and during the life of a mine.

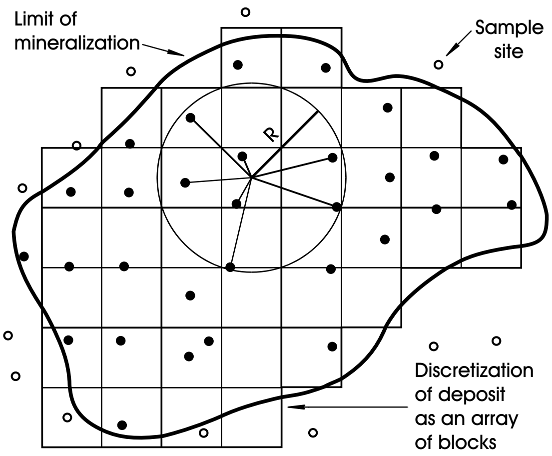

Figure 1.1: A two-dimensional representation of the general situation in mineral inventory estimation. A mineralized zone/deposit defined by geology is discretized by a number of blocks (commonly of uniform size, but not necessarily so). Each block is to be estimated using nearby data within a search area (volume), in this case defined by a circle centered on the block to be estimated. Small black dots are sample sites (for which there would be grade values) within the deposit; small open circles are samples outside the limits of the deposit.

1.2: MINERAL INVENTORY ESTIMATES

Mineral inventories are a formal quantification of naturally occurring materials, estimated by a variety of empirically or theoretically based procedures. Inventories that are based on an *economic feasibility study* are commonly classed as *reserves*; inventories that are less well established are considered *resources*. These resource/reserve estimates, commonly determined from a two- or three-dimensional array of assayed samples, are applied to mineralized rock volumes that total many orders of magnitude larger than the total sample volume (Fig. 1.1). Thus, errors of estimation can be viewed as errors of extension (i.e., errors made in extending the grades of samples to a much larger volume [tonnage] of rock). For purposes of establishing a mineral inventory, a mineral deposit generally is discretized into an array of blocks, and the average value of each block is estimated in some manner from the nearby data. Thus, a mineral inventory can be viewed as a detailed breakdown of blocks whose individual sizes, locations, and grades are well established.

Quantification of a resource/reserve is to a level of confidence (subjective or statistical) appropriate to the available data and the stated needs of the estimate. Volumes, tonnages, grades, and quantities of metals or minerals are the common attributes that are quantified. Their estimation must be optimal in the sense that they must be unbiased and the random error must not exceed an acceptable quality criterion. Mineral inventory estimates are used to determine economic viability that is relatively assured in the case of reserves. Volume (or tonnage) of ground classed as *resources* generally has not been evaluated rigorously for economic viability or has been found to lack immediate economic potential. Estimation procedures can differ substantially for deposits to be mined underground compared with deposits to be mined by surface pits. Similarly, methodology can vary depending on whether the mineral inventory in question is for short-term or long-term production planning.

Mineral inventories are determined at various times in the exploration, evaluation, and production of

Table 1.1 Staged sequence of data gathering in mineral exploration and evaluation

Phase of exploration	*General description of work*
Discovery	May result from a staged exploration program, prospecting wildcat invesigation, or by accident. This stage includes initial ground control by staking, options, etc.
Preliminary surface evaluation	Limited surface examination, including conceptual geologic appraisal, limited geochemical or geophysical responses are measured, sampling for assay and mineralogic studies, limited test pits, and stripping. This is the rapid property appraisal, or "scouting," stage of many major companies.
Detailed surface evaluation	Generally begins with the laying out of a regular grid on areas of interest to serve as a base for detailed geochemical and geophysical surveys and geologic mapping. Limited stripping, trenching, drilling, and systematic sampling are common at this stage as a guide to development of geologic concepts.
Subsurface evaluation	Involves various types of drilling, generally in a more or less systematic manner and initially with a relatively wide spacing of holes. Other methods, such as sinking exploratory shafts or declines and driving adits and other workings are useful for many deposit types.
Feasibility	Begins when a conscious decision is made to mount a detailed program to examine the possibility of economically viable production. It includes reserve estimates, mine planning, mill design, and costing of necessary infrastructure and environmental considerations, including mine reclamation. Several stages of prefeasibility work can be involved, i.e., studies that are close approaches to a true feasibility study, but with uncertainties that are unacceptable in a final feasibility study.
Development	Normally represents a halt in exploration efforts while deposit is prepared for production.
Production	An ongoing exploration program is common during the productive life of a mineral property. Both surface and underground techniques are used as needs arise. Work can be focused on extending the limits of known mineral zones or searching for new and discrete zones.
Reclamation	Exploration has normally been completed when reclamation begins.

Source: Modified from Champigny et al. (1980).

a mineral deposit (Table 1.1). At the exploration stage, a mineral inventory is useful in providing information concerning a target whose quantities are imprecisely known. The geologic setting of the mineralization may define features that provide limits to such targets, indicate possible directions of continuity, or help in constraining the extent of a target – that is, localizing the target for more detailed evaluation. Estimation errors, available quantitatively from some estimation methods, can be used to develop an appreciation of the effects of additional information (e.g., drill-hole density) on the quality of mineral inventory estimation.

Global estimates concerned with the average grade and tonnage of very large volumes of a deposit can be used to quantify a reserve or resource that will form the basis of continuing production. Thus, global resources/reserves represent a justification for long-term production planning. Global resources commonly are referred to as *in situ* or *geologic* because normally only very general economic factors have been taken into account. Increasingly, efforts are being made early in the exploration of a deposit to estimate the proportion of in situ resources/reserves that are recoverable under certain mining conditions.

Local estimation, both at the feasibility stage and in operating mines, commonly is used for short- and medium-range production planning. In particular, local block estimates generally serve as the basis for classifying blocks as ore or waste (see Fig. 1.1). Recoverable reserves are determined from a subset of local estimates (reserves actually recoverable by the planned mining procedures) and serve as a basis for financial planning.

In some cases, mineral inventories are approximated by numeric simulations. Conditional simulations (i.e., simulations that honor the available data) can be used to provide insight regarding grade continuity, mine planning, mill planning, and overall financial planning. Simulations are not used as widely as warranted.

Many governmental jurisdictions require that resource/reserve estimates be classified according to an accepted legal or professionally recognized system for purposes of formal publication, use by financial institutions, use in public fund-raising, and so on. In this respect, the resources/reserves represent an asset with an attendant level of risk related to the specifications (commonly poorly documented) for the corresponding classes of the classification system. In Canada, for example, reserves were classed historically in the following categories of decreasing reliability: proven, probable, or possible.

The process of mineral inventory estimation can be seen above to be an ongoing endeavor subject to continual refinement. King et al. (1982) note that "an Arizona porphyry copper mine achieved satisfactory ore reserve prediction only after 20 years of study and trial" (p. 18) and "it took a large Australian nickel mine six years to develop their computerized polygonal procedures to the point of yielding a 'planned mining reserve' " (p. 18). Optimal procedures for resource/reserve estimation are not cut and dried; rather, they contain an element of "art" based on experience that supplements technical routine and scientific theory.

In addition to preparing comprehensive mineral inventory estimations, geologic and mining professionals commonly are required to conduct a "reserve audit" or evaluation of a mineral inventory estimation done previously by others (cf. Parrish, 1990). A *reserve audit* is a comprehensive evaluation based on access to all geologic data, assays, and other pertinent information. An auditor does not repeat the entire study, but normally might take about one-tenth the time of the original study. The purpose is to provide confidence as to the quality of data and methodologies used and the general reliability of the reported estimates. An auditor's aim is to provide assurance that high professional standards have been maintained in decision making and that acceptable industrial practice has been followed in arriving at a resource/reserve estimate. Parrish (1990) provides a concise summary of the structure of a resource/reserve audit.

Exploration geologists are called on routinely to provide rough estimates of tonnages and grades of large volumes of rock based on a very limited amount of exploration data. Such "guesstimates" are not comparable to a mineral inventory study; rather, they are rough professional estimates as to the size of a likely target, based on limited geologic and assay information and/or a nonrigorous approach to estimation. These guesstimates should be viewed as attempts to define exploration targets that require verification. Such crude attempts should not be confused with more rigorous estimates of resources or reserves, unless the information is sufficient to satisfy the criteria of a formal classification (see Section 1.3.4).

1.3: SOME ESSENTIAL CONCEPTS IN MINERAL INVENTORY

As with so many professional undertakings, mineral inventory reports are filled with professional jargon and a range of usage not standardized everywhere. In some cases, the common use of terminology is lax relative to widely accepted technical definitions. In other cases, certain technical terms have specific meanings that are not widely appreciated either within or outside the industry because they have entered the mineral inventory literature from elsewhere; such is the case, for example, with a number of terms originating from the field of geostatistics. For the forgoing reasons, it is useful to define a number of terms and concepts that are now widely integrated into mineral inventory work.

1.3.1: Ore

The wide range of published definitions of the term *ore* has prompted Taylor (1986, p. 33) to propose the following definition: "the valuable solid mineral that is sought and later extracted from the workings of a mine; for the hoped or expected (though not always achieved) advantage of the mine operator or for the greater good of the community." The generality of this definition obscures the range of common usage.

The term *ore* is applied to mineralized rock in three senses: (1) a geologic and scientific sense; (2) quality control in ore reserves; and (3) for broken, mineralized ground in a mine, regardless of grade. In mineral inventory work, the second definition is of importance and implies the distinction of *ore* (mined at a profit) and *waste* (containing insufficient value to earn a profit). The recognition of such ore involves the consideration of three different categories of profit: (1) that relating to small increments of ore; (2) that referring to annual or other periodic outputs of ore; and (3) that expected from entire ore bodies. Note that for each of these types of profit, there is a different corresponding threshold (cutoff grade) that separates ore from waste. As indicated by Wober and Morgan (1993), the definition of the ore component of a particular mineral deposit is a function of time factors (metal price, technology, tax regime, etc.), place factors (relation to infrastructure), legal factors (safety, environmental, labor, etc.), profit, and discount rates.

In general, mines are put into production with the understanding that there will be an acceptable return on the necessary investment. Circumstances may dictate significant changes to the foregoing philosophy, or the concept of profit might change over time. A mine might operate at a loss for reasons of tax advantage, long-term planning, anticipation of short-term changes in metal prices or product sales, and so on. Moreover, government may impose regulations or incentives that affect operations normally expected to create losses. For example, historically, in the case of South African gold mines and the Alberta tar sands, some material was mined at a loss because it would otherwise not be recoverable and perhaps would be lost forever.

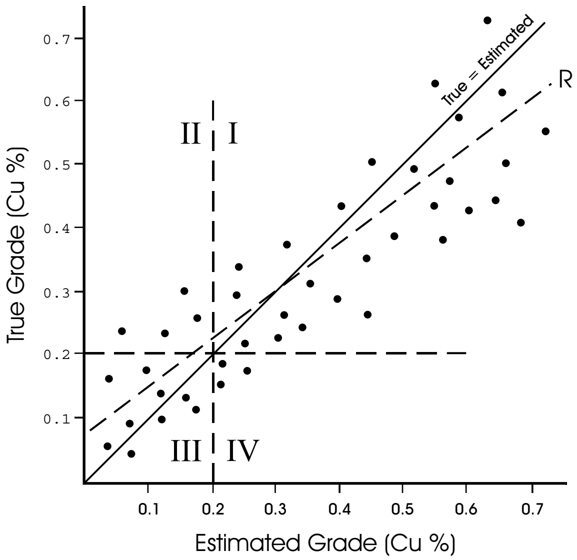

Figure 1.2: A plot of estimated grades versus true grades for many blocks (selective mining units) of mineralized ground (ore). A cutoff grade (x_c) applied to both axes divides the individual estimates into four quadrants that classify the estimates as follows: quadrant I = ore blocks correctly classed as ore; quadrant II = ore blocks incorrectly classed as waste; quadrant III = waste blocks correctly classed as waste; and quadrant IV = waste blocks incorrectly classed as ore. The fundamental concept inherent in this diagram is that random estimation errors necessarily require that an estimate can never be met by production (unless additional ore is encountered) because some ore is lost (i.e., incorrectly recognized as waste), and the remaining ore that is recognized is diluted by waste incorrectly classed as ore. A regression line (R) through the data indicates the common result for polygonal estimates (i.e., on average, estimates of high values overestimate the true grade, whereas estimates of low values underestimate the true grade). The alternate situation, in which high grades are underestimated and low grades overestimated, is common in situations in which groups of data are averaged to produce estimates.

1.3.2: Cutoff Grade

The concept of *cutoff grade and its practical applications* have invoked wide discussion in the technical literature (e.g., Lane, 1988; Taylor, 1972, 1985). For practical purposes, a *cutoff grade* is a grade below which the value of contained metal/mineral in a volume of rock does not meet certain specified economic requirements. The term has been qualified in many ways, particularly by accountants, and some ambiguity in its use has resulted (Pasieka and Sotirow, 1985). Cutoff grades are used to distinguish (select) blocks of ore from waste (Fig. 1.2) at various stages in the evolution of mineral inventory estimates for a deposit (i.e., during exploration, development, and production stages). Ore/waste selection is based on estimates (containing some error) rather than on true grades (which are unknown). Hence, in the case of block estimation it is evident that some ore blocks will be inadvertently classed as waste (quadrant II in Fig. 1.2) and that some waste blocks will be classed erroneously as ore (quadrant IV in Fig. 1.2). The volume of a predefined mining unit, on which mining selectivity is based and to which a cutoff grade is applied, can change during this evolution, as can the cutoff grade itself. As the cutoff grade increases, the tonnage of ore decreases and the average grade of that tonnage increases. As a rule, strip ratio (the units of waste that must be removed for each unit of ore) also increases with increasing cutoff grade. Generally, a fairly narrow range of cutoff grades must be considered in the process of optimizing the selection of a cutoff grade for a particular mining scenario.

The concept of cutoff grade is closely linked to the practical connectivity of blocks of ore at the production stage (Allard et al., 1993; Journel and Alabert, 1988). As the cutoff grade rises, the volume of ore decreases and becomes compartmentalized into increasing numbers of smaller, separated volumes (i.e., decreased "connectivity" with increasing cutoff grade) as illustrated in Fig. 1.3. Cutoff grades represent economic thresholds used to delineate zones of mineral/metal concentration for potential mining. This delimitation of ore/waste can be a *cutoff grade contour* or a series of straight line segments (steplike) separating blocks estimated to be above cutoff grade from those below cutoff grade. Consequently, the quality of block estimates to be contoured or otherwise grouped must be understood vis-á-vis grade continuity (Section 1.3.3) in order to appreciate the possible magnitude of errors in cutoff-grade contours or block estimates.

Estimation of cutoff grade, although a complex economic problem beyond the scope of this book, is tied to the concept of operating costs (per ton) and can be viewed simplistically as outlined by John (1985). Operating cost per ton milled, OC, is given by

$$OC = FC + (SR + 1) \times MC$$

where

FC = fixed costs/ton milled
SR = strip ratio
MC = mining costs/ton mined.

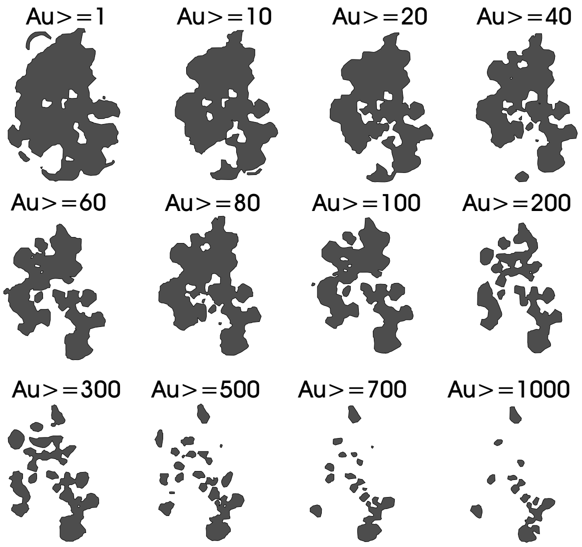

Figure 1.3: The concept of *connectivity* of ore as a function of cutoff grade. Data are 1,033 rock samples from the Mitchell–Sulphurets mineral district (Cheng, 1995), northern British Columbia, for which Au analyses (*g/mt*) have been contoured using different threshold values (cutoff grades). As the cutoff value increases, the high connectivity of Au deteriorates to increasing numbers of unconnected, isolated highs. Of course, where the cutoff value approaches the tail of the distribution, the number of high-grade patches decreases.

Cutoff grade, useful at the operational level in distinguishing ore from waste, is expressed in terms of metal grade; for a single metal, cutoff grade can be determined from operating cost as follows:

$$g_c = OC/p$$

where g_c is the operational cutoff grade (e.g., percent metal) and p is the realized metal price per unit of grade (e.g., the realized value from the smelter of 10 kg of metal in dollars, where metal grade is in percent). More exhaustive treatments of cutoff grade are provided by Taylor (1972, 1985) and Lane (1988).

Optimizing cutoff grade (selecting the cutoff grade that maximizes cash flow) is based on a confident mineral inventory estimate (e.g., as summarized in Table 1.2), where cash flow (CF) is given by

$$\begin{aligned} CF &= \text{Revenue} - \text{Operating Costs} \\ &= (g \times F \times P - OC)T \end{aligned}$$

Table 1.2 Grade–tonnage relations that simulate a typical porphyry copper deposit

Cutoff grade	*Tons of ore (millions)*	*Average grade ore*	*Strip ratio*
0.18	50.0	0.370	1.00:1
0.20	47.4	0.381	1.11:1
0.22	44.6	0.391	1.24:1
0.24	41.8	0.403	1.39:1
0.26	38.9	0.414	1.57:1
0.28	35.9	0.427	1.78:1
0.30	33.0	0.439	2.03:1
0.32	30.0	0.453	2.33:1
0.34	27.2	0.466	2.68:1

Source: After John (1985).

where

g = average grade of ore mined
F = recovery proportion per ton milled
P = realizable value of metal per ton milled
T = tons milled.

The hypothetical mineral inventory data of Table 1.2 (John, 1985) simulate a porphyry copper deposit and are used to make the cash flow estimates shown in Table 1.3 for various potential cutoff grades. Clearly, for the situation assumed, cash flow is maximized for a cutoff grade of 0.28 percent metal. Changes in strip ratio, metal prices, percent recovery, and so on change the optimal cutoff grade. One useful concept emphasized by John (1985) is that the formulas presented here can be used to evaluate the effect that various alternatives (e.g., changing metal prices, different metal recovery) have on the selection of a cutoff grade; that is, a "sensitivity analysis" can be conducted for various parameters in which each parameter is varied independently in order to evaluate its impact on cutoff grade estimation. One such analysis (Fig. 1.4) shows variations in optimum cutoff grade with variation in metal price for the example used in Tables 1.2 and 1.3.

Parrish (1995) introduces the concept of *incremental ore* as

> that material that in the course of mining "bona fide ore" must be drilled, blasted and moved but contains sufficient value to pay the incremental costs of realizing that value and provide some profit as well. Incremental costs include the difference between delivery to the waste area and delivery to the feed bin, stockpile pad or crusher and the costs of crushing, processing, royalties, etc. (p. 986)

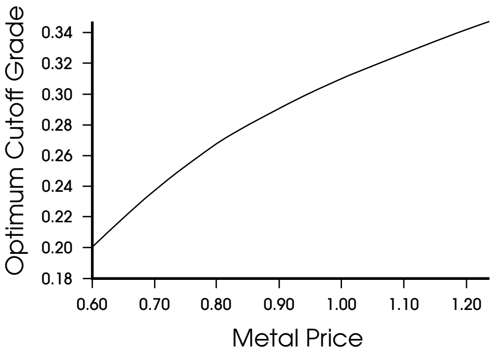

Figure 1.4: Optimum cutoff grade as a function of changing metal price for an information base used by John (1985) to illustrate the concept of cutoff grades. This diagram is based on the data presented in Tables 1.2 and 1.3.

It is evident from this definition that mining costs are not included in incremental ore; hence, the cutoff grade used for its definition is less than the cutoff grade based on all costs and is consistent with the term *internal cutoff grade* (e.g., Marek and Welhener, 1985). The paradox of incremental ore is that in theory it cannot be classed as reserves (because all costs are not recovered), but in practice it makes sense to mine and process it. Owens and Armstrong (1994, p. 53) also recognize the paradox when they state, "The grade cut-off concept has a role for selection of stope or ore zone size units, but not for isolated blocks of low grade within ore zones intended for underground mining."

1.3.3: Continuity

Continuity is "the state of being connected" or "unbroken in space." (*Oxford English Dictionary*, 1985, p.186). In mineral deposit appraisals, this spatial definition commonly is used in an ambiguous way to describe both the physical occurrence of geologic features that control mineralization and grade values. Such dual use of the term *continuity* leads to

Table 1.3 Calculation of cash flow (dollars per ton milled) for example in Table 1.1[a]

Cutoff grade	*Average ore grade*	*Strip ratio*	*Operating cost ($/t)*	*Total revenue*	*Operating cash flow*
0.18	0.370	1.00:1	3.50	5.24	1.74
0.20	0.381	1.11:1	3.58	5.38	1.80
0.22	0.391	1.24:1	3.68	5.54	1.86
0.24	0.403	1.39:1	3.80	5.70	1.90
0.26	0.414	1.57:1	3.93	5.86	1.93
0.28	0.427	1.78:1	4.09	6.04	1.95
0.30	0.439	2.03:1	4.28	6.22	1.94
0.32	0.453	2.33:1	4.50	6.40	1.90
0.34	0.466	2.68:1	4.76	6.59	1.83

[a] Results in Table 1.3 can be obtained from information in Table 1.2 with $MC = 0.76$, $FC = 1.98$, recovery = 0.83, and a metal price of $0.85/lb in formulas 1.1 and 1.3.
Source: After John (1985).

ambiguity. To clarify this ambiguity, Sinclair and Vallée (1993) define two types of continuity that bear on the estimation of mineral inventories as defined in Table 1.4.

Distinction between the two types of continuity can be appreciated by the particularly simple example of a vein (a continuous geologic feature), only part of which (ore shoot) is mineralized with economically important minerals. Value continuity can be defined within the ore shoot. These two types of continuity are partly coincident in space, perhaps accounting for the ambiguity in past use of the unqualified term *continuity*. Understanding both types of continuity is essential in appreciating the implications of each to the estimation process. An example of the impact that an error in interpreting geologic continuity can have on mineral inventory estimation is shown in Fig. 1.5. Chapter 3 contains a detailed discussion of geologic continuity; Chapter 8 is concerned with a quantitative description of value continuity.

1.3.4: Reserves and Resources

Mineral inventory is commonly considered in terms of resources and reserves. Definitions currently vary from one jurisdiction to another, although there are increasing efforts being directed toward internationally acceptable definitions. In the absence of such international agreement, there is an increasing tendency in both industry and technical literature for an ad hoc agreement centering on definitions incorporated in the "Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves" (Anonymous, 1989, 1999). Thus, the Australasian terminology is summarized in Fig. 1.6.

A *resource* is an in situ (i.e., on surface or underground) mineral occurrence quantified on the basis of geologic data and a geologic cutoff grade only. The term *ore reserve* is used only if a study of technical

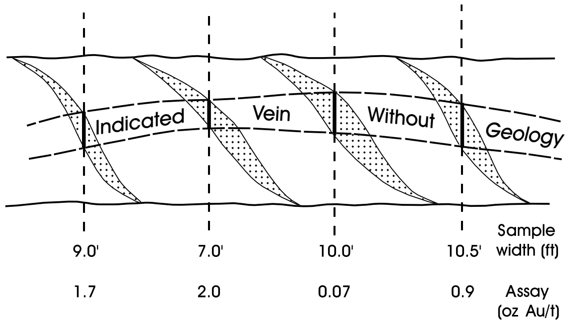

Figure 1.5: A simplistic illustration of the importance of geologic continuity (modified from Rostad, 1986). Interpretations concerning continuity clearly control the volume of ore (and therefore the tonnage) as well as the way in which sample grades will be extended. Detailed study of the geologic form and controls of mineralization constrain the geometric model of a deposit, which in turn has an impact on mine planning. In this case, vein intersections in a shear zone are shown misinterpreted as a simple vein rather than correctly as a series of sygmoidal veins.

Table 1.4 Two categories of continuity in mineral inventory estimation

Geologic continuity	Spatial form of a geometric (physical) feature such as a mineral deposit or mineral domain. Primary: veins, mineralized shear, mineralized stratum Secondary: postmineral faults, metamorphism, folding or shearing of deposits
Value continuity	Spatial distribution features of a quality measure such as grade or thickness within a zone of geologic continuity. Nugget effect and range of influence are quantified. Examine on-grade profiles (e.g., along drill holes) qualitatively in various directions. Quantify for each geologic domain using an autocorrelation function (e.g., semivariogram)

Source: After Sinclair and Vallée (1994).

and economic criteria and data relating to the resource has been carried out, and is stated in terms of mineable tons or volume and grade. The public release of information concerning mineral resources and ore reserves and related estimates must derive from reports prepared by appropriately qualified persons (i.e., a "competent person").

Prior to mineral inventory estimation, a variety of exploration information is available. As exploration continues, the information base increases and the level of detailed knowledge of a deposit improves. The estimation of reserves or resources depends on this constantly changing data and the continually improving geologic interpretations that derive from the data. Thus, the continuous progression of exploration information first permits the estimation of resources and, eventually, the estimation of reserves of different categories. Reserve estimation is thus seen as continually changing in response to a continually improving database. An indication of the wide range of data affecting mineral inventory estimation and classification is presented in Table 1.5.

On the international scene, it is becoming increasingly common to progress from resources to reserves by conducting a *feasibility study*. A feasibility study of a mineral deposit is "an evaluation to determine if the profitable mining of a mineral deposit is . . . plausible" (Kennedy and Wade, 1972, p. 70).

The term covers a broad range of project evaluation procedures yielding detailed insight into the geologic and quantitative database, resource/reserve estimation procedures, production planning, mining and milling technology, operations management, financing, and environmental and legal concerns. An exhaustive discussion of the classification of resources and reserves is provided in Chapter 18.

1.3.5: Dilution

Dilution is the result of mixing non-ore-grade material with ore-grade material during production, generally leading to an increase in tonnage and a decrease in mean grade relative to original expectations. A conceptual discussion of dilution during various mining operations is provided in Fig. 1.7 after Elbrond (1994). It is convenient to consider dilution in two categories: *internal* (low-grade material surrounded by high-grade material) and *external* (low-grade material marginal to high-grade material). Internal dilution can be subdivided into (1) sharply defined geometric bodies and (2) inherent dilution. *Geometric internal dilution* results from the presence of well-defined waste bodies within an ore zone (e.g., barren dykes cutting an ore zone, "horses"). *Inherent internal dilution* results from the decrease in selectivity that accompanies an increase in the block size (e.g., resulting from loss of equipment digging selectivity) used as the basis for discriminating ore from waste, even where no entirely barren material is present.

External dilution is the result of sloughing of walls, difficulty of sorting in open pits, or the inadvertent or purposeful mining of barren or low-grade material at the margin of an ore zone. Such dilution is generally significant in cases in which stope walls are physically difficult to maintain because of rock properties or where ore widths are less than the minimum mining width. External dilution can be of somewhat less significance in large deposits with gradational boundaries in comparison with small deposits because

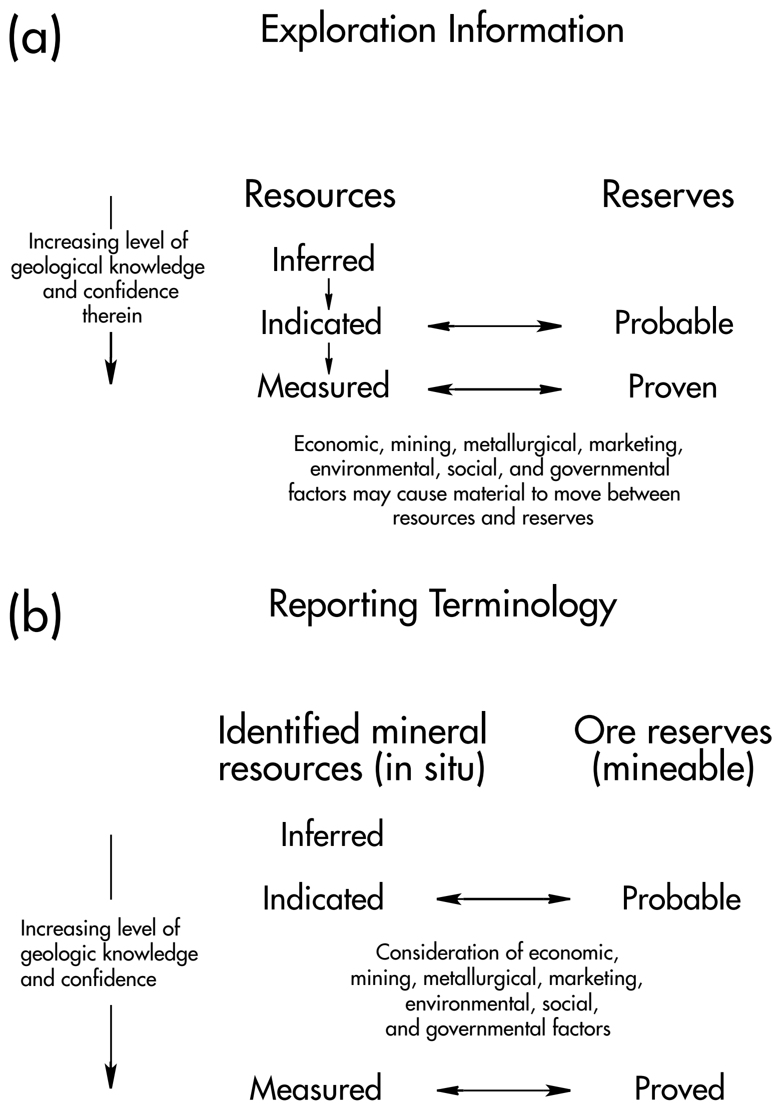

Figure 1.6: Examples of two published classification schemes for resources/reserves. (a) A proposed classification of the Society of Mining Engineers (U.S.). (b) Classification of the Australasian Institute of Mining and Metallurgy, in use in Australia since about 1980.

the diluting material (1) can be a small proportion of the mined tonnage and (2) contains some metal, possibly near the cutoff grade. In general, some uncertain proportion of waste must be taken along with ore during the mining operation. This form of dilution can be impossible to estimate with confidence in advance of mining; experience is probably the best judge. Accepted procedures for estimating dilution in underground mining operations are summarized by Pakalnis et al. (1995).

1.3.6: Regionalized Variable

A *regionalized variable* is a variable distributed in space in a partly structured manner such that some degree of spatial autocorrelation exists. The structured