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Analysing spatial data via geostatistical methods

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CHAPTER 2
GEOSTATISTICS AND THE MINING INDUSTRY

2.1 Introduction

Mining companies continuously sample† the ore deposits† that they mine. The locations of the samples† are recorded together with other measurements that may be of interest to the company (e.g. ore grade or ore thickness†). The mining company then uses these samples to, amongst other things, help estimate the quantity and quality of ore† at areas that are yet to be mined. The spatial nature of this type of mining data and the need for spatial estimation makes geostatistics ideally suited for use in the mining industry. In fact, many areas within a mining operation can benefit from the knowledgeable application of geostatistical techniques (see Section 2.3), and it is no surprise that the uses of geostatistics in this industry have been well documented.

Many geostatistical books are aimed primarily at mining engineers, geologists, and other individuals working in mineral extraction (even though most of the theory presented in these books is equally relevant to fields outside of mining). The geostatistical texts *Geostatistical Ore Reserve Estimation* (David, 1977), *Mining Geostatistics* (Journal & Huijbregts, 1978) and *Basic Linear Geostatistics* (Armstrong, 1998) are all examples of geostatistical books focusing on the mining industry. In addition, articles and case studies based on geostatistical research in the mining industry are numerous and are frequently published in mining related journals.

This association between geostatistics and the mining industry is not unexpected. After all, it was problems in the mining industry that led to the work of H. S. Sichel and D. G. Krige, and the subsequent development of geostatistics by G.

† Definition of term provided in Section 2.2.

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Matheron (see Chapter 1). Nowadays geostatistics is readily used in many industries, but the mining industry remains one of its most frequent users.

2.2 Mining Terminology

The mining industry contains has a number of terms that may be unfamiliar to people outside of the industry. Mining terms that have been used in this dissertation are listed below, together with their associated definitions.

(Definitions have been drawn from: Phillips (n.d.), Storrar (1977), Annels (1991), U.S. Bureau of Mines (1996), Armstrong (1998) and Wellmer (1998)).

accumulation: the product of ore thickness and ore grade. Units in which accumulation can be measured include centimeter grams per ton (cm g/t) and meter percentage (m %).

centimeter grams per ton (cm g/t): the measurement unit of accumulation when the ore thickness is measured in centimeters and the ore grade is measured in grams per ton.

cut-off grade: see *pay-limit*.

grade: a measure of the quality or relative quantity of mineral within the ore. Units in which grade can be measured include grams per ton (g/t) and kilograms per meter cubed (kg/m^3).

grams per ton (g/t): the amount of mineral (measured in grams) per metric ton of ore.

mineral: an inorganic substance (element or compound) occurring naturally in the earth and having a consistent and distinctive set of physical properties and a composition that can be expressed by a chemical formula. Minerals are classified as either common rock-forming minerals or minerals of economic value.

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mineral deposit: a mineral occurrence of sufficient size and grade that it *might*, under favorable circumstances, be considered to have economic potential.

mining: the process of extracting minerals of economic value from the earth's crust.

ore: a natural mineral-bearing substance that is of economic interest.

ore deposit: a mineral deposit that is found to be of sufficient size, grade and accessibility to be of economic interest.

ore reserve: the tonnage and specific mineral content of the payable ore adequately exposed by mining operations (i.e. ore that is mostly ready for mining) at the date of computation.

payable ore: ore that can be profitably extracted under current conditions. That is, ore with a grade equal to or greater than the current pay-limit.

pay-limit: the minimum grade of ore that can be extracted profitably.

sample: As a noun - a small, definable part of the overall mass of material (usually the ore deposit) that can be analyzed or otherwise examined (see Note 2.1). As a verb - the process of taking samples from a deposit.

selective mining: the practice of many mining operations whereby blocks of ore estimated to be above the cut-off grade are mined while blocks estimated to be below the cut-off grade are either left in place or dumped as waste.

support: see Section 2.4.1

Note 2.1 Crow & Shimizu (1988 : 358) state:

> When studying statistical applications in geology, one should be aware of the difference between the statistical definition of a sample and the corresponding geological definition. In statistics, a sample is a group of observations. In geology a sample is a

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representative fraction of a body of material, whose properties are analyzed to obtain a single value.

Samples provide information about the grade and other properties of the ore at the sampled locations. The samples are used to help estimate the grade and other properties of the ore at the unsampled locations within the ore deposit.

Figure 2.1, taken from Wellmer (1998 : 1), illustrates the difference between the statistical and geological concept of a sample. Figure 2.1 shows a statistical sample of ten spheres taken from a population of forty five spheres. It also shows eight drill core samples and eight larger block sized samples that have been taken from an ore deposit.

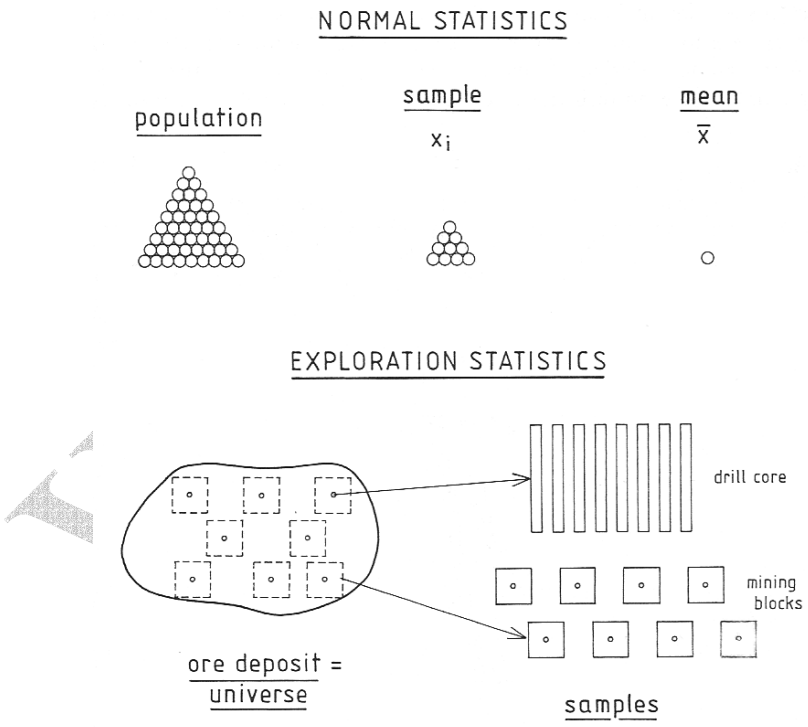


Figure 2.1 An illustration of the difference between the statistical and geological concept of a sample, taken from Wellmer (1998 : 1).

Note 2.2 Whenever the term sample is used in this dissertation, it will hopefully be obvious which definition of sample is implied. However, to make sure that the reader knows exactly which definition is implied, whenever the term sample is used in the statistical sense, a footnote will be assigned to the term and will read, 'Statistical definition'.

2.3 The Application of Geostatistics in the Mining Industry

(Much of Section 2.3 has been taken from Armstrong, 1998 : 2-3)

The use of geostatistical methods can prove beneficial in many areas of a mining operation and provide estimates[†] that will assist with decision making and help maintain the profitable continuation of the mine. A particular benefit of geostatistical estimation as opposed to traditional estimation techniques used in mining (such as inverse distance weighting and polygonal estimation, see Sections 4.4.1 and 4.4.3) is that geostatistics provides a measure of the accuracy of all its estimates (see Section 7.7).

Geostatistics can be effectively used to determine the optimal sampling pattern that will ensure a required accuracy of estimation[‡], and can provide estimated contour maps of the deposit. Ore is generally mined as blocks (see Section 2.4.1), and geostatistics can provide estimates of the average value of these mining blocks based on nearby sample values. Thus, geostatistics can assist in selective mining procedures and estimation of ore reserves. Furthermore, geostatistical simulations[§] can be performed to assist in mine planning and decision making. As an example, simulations can be used to test the consequences of using various types of machinery on the output of the mine (Journel & Huijbregt, 1978 : 10).

[†] In the mining industry, geostatistics is most commonly used to estimate the ore grade, the ore thickness and the ore accumulation.

[‡] The kriging variance depends on the semi-variogram or covariance model (see Chapters 4 and 5) and the location of the samples, but not on the actual sample values. Thus, once the semi-variogram or covariance model has been defined, potential sample locations can be tested to determine which of these sampling patterns will minimize the kriging variance, see Section 7.7 (Armstrong, 1998 : 2).

[§] The theory of geostatistical simulation is not covered in this dissertation. For a detailed discussion, see Journel & Huijbregts (1978 : 491-554).

These are but some of the many areas in which geostatistics can be applied in mining. Provided that geostatistics is used with understanding, it can prove a valuable tool in the success of any mining operation.

2.4 Statistical Considerations when Applying Geostatistics in the Mining Industry

2.4.1 Support and the support effect

In the mining industry, the term support is used to describe the volume, the mass, the size and/or the shape of an ore sample or block of ore (Armstrong, 1998 : 8 and Wellmer, 1998 : 361). Ore is generally extracted in mines as blocks of ore called mining blocks, and consequently it is often the case that ore samples and mining blocks are of a different support. Samples tend to consist of a small amount of material that measures an attribute value (such as grade or thickness) of an ore deposit at one particular point. Thus, samples are commonly said to have a point support. Mining blocks, on the other hand, consist of much larger amounts of ore extracted over large areas, each block being assigned a value equivalent to the average attribute value of all the points within that block (see Proof 2.1). Thus, mining blocks are commonly said to be of block support.

Consider an ore deposit and a particular ore attribute (such as the ore grade or thickness) that can be measured at any location within the deposit. It follows from basic statistical theory that the value distribution of the attribute based on a point support and based on a block support will have the same average value, but will differ in variability. Remember, blocks are valued by averaging all point values within the block. Therefore, it follows that the variability of mining blocks values will naturally be smaller than the variability of point support sample values (see Figure 2.2). This difference in value distribution of an attribute for different support sizes is termed the *support effect*.

It is of the utmost importance that the correct value distribution is used when considering a particular support. Performing calculations on the incorrect

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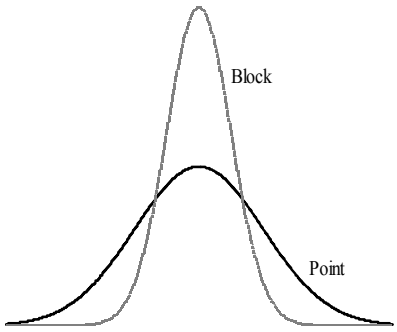


Figure 2.2 A comparison of the distributions of values based on point and block supports, taken from Wackernagel (1995 : 55). Notice that the two distributions have the same overall average value, but due to averaging, the variability of the block distribution is smaller than that of the point distribution.

distribution can prove detrimental to the continued life of the mine. As an illustration (taken from Wackernagel, 1995 : 55), the proportion of a grade distribution above an established cut-off grade represents the proportion of the ore deposit that is of economic interest and that can be mined profitably. If a point support grade distribution (say, the sample distribution) is used to describe that of a block support (say, the mining block distribution), a cut-off grade above the mean grade will over-estimate this proportion, with potential economic repercussions (see Figure. 2.3). Thus, it is important to always take into account the support effect.

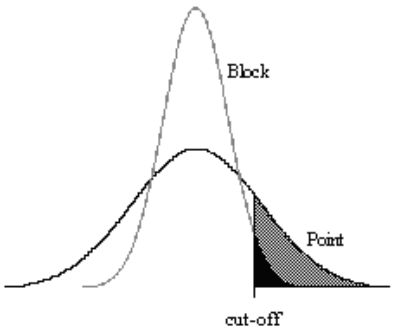


Figure 2.3 The proportion above cut-off for point and block support, taken from Wackernagel (1995 :56). Because the point support distribution has a larger variability and because cut-off is above the mean, a larger proportion of point support observations than block support observations will exist above the cut-off value.

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Proof 2.1

Without loss of generality, consider the grade of a block of ore A. Suppose that block A weighs x tons and has a mineral grade of y grams per ton.

The grade of the block of ore is calculated by the relationship

$$\text{grade of block (g/t)} = \frac{\text{weight of mineral in block (grams)}}{\text{weight of ore in block (tons)}},$$

and this relationship implies that block A therefore contains xy grams of mineral.

Now suppose that block A is divided into n smaller blocks, all of which are of the same support. Thus, each smaller block will have a weight of x/n tons and will have associated with it a specific mineral grade (not necessarily equal to y grams per ton). Let the mineral grade of each smaller block be equal to y_i grams per ton for $i = 1, 2,\ldots, n$ and let the weight of mineral within each smaller block be equal to w_i grams for $i = 1, 2,..., n$.

The average mineral grade of the n smaller blocks is then calculated as:

$$\begin{aligned} \frac{1}{n}\sum_{i=1}^{n} y_i &= \frac{1}{n}\sum_{i=1}^{n} \frac{w_i}{x/n} \\ &= \frac{1}{x}\sum_{i=1}^{n} w_i \,. \end{aligned} \tag{2.1}$$

Now since the total weight of mineral in the original block A is xy grams, i.e.

$$\sum_{i=1}^{n} w_i = xy,$$

where x is the weight of the block and y is the grade of the block,

it follows that, considering Equation 2.1,

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$$\frac{1}{x}\sum_{i=1}^{n} w_i = y\,.$$

This shows that the average mineral grade of the *n* smaller blocks is equivalent to the mineral grade of the original ore block *A*. By letting *n* tend to infinity, this relationship still holds. Therefore, the mineral grade of a block of ore is mathematically equivalent to the average grade of all points within that block.

2.4.2 Statistical distributions

Statistical distributions are extremely useful when it comes to the study of geological attributes. By fitting a distribution to the histogram constructed from the observed values of a geological attribute (such as the histogram of ore sample values), it becomes possible to estimate probabilities and statistics that describe the true behaviour and properties of this attribute. Furthermore, the fitted distribution is also of importance in geostatistics, especially in the estimation of the semi-variogram or covariance function (see Sections 5.6, 5.7 and 5.8). Of the many statistical distributions that exist in theory, a number are widely and successfully applied in the earth sciences.

According to Crow & Shimizu (1988 : 357), the lognormal distribution is commonly used to model geological attributes that have skew value distributions. Sichel (1947) initially demonstrated that the frequency distribution of gold-ore sample values obtained from the Rand Leases gold mine in South Africa were closely approximated by the two-parameter lognormal distribution (cited from Sichel, 1966 :106). This was found to also be the case for many of the other gold deposits within South Africa. Later, Krige (1960) introduced the use of the three-parameter lognormal distribution to the gold mining industry (cited from Crow & Shimizu, 1988 : 358). The importance of the lognormal distribution in gold mining is captured by the remark of Sichel (1966 : 106),

> Numerous studies after 1947, carried out all over the world, have shown that the lognormal model (either with two or three

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parameters) represents observed ore values adequately in the vast majority of investigations.

Over time, investigations and experience revealed instances where further refinements of the lognormal approach were required, and the use of, for example, the compound lognormal and lognormal generalized inverse Gaussian distributions (see, for example, Sichel, Dohm & Kleingeld, 1997).

The normal distribution is also frequently used to model geological attributes that display a symmetric value distribution. The normal distribution is a desirable model as it possesses many useful and well-known mathematical properties (Clark & Harper, 2000 : 31). Discrete distributions have also been effectively used in geological studies. According to David (1977 : 22), the binomial distribution was used by Cons (1964) to describe transformed magnetite grade data, while Clark & Harper (2000 : 112) mentions that the "…Poisson distribution and generalizations of it have been used to model the number of diamonds in a sample…."

2.5 The Mining Industry in South Africa

For decades, the South African mining industry has thrived and played a vital role in the growth of the South African economy. In 2001 alone,

- "…mining contributed R66.8 billion to [the South African] gross domestic product …" (Burger, c.2003 : 415)

- "mining contributed 10% to South Africa's gross fixed capital formation." (Burger, c.2003 : 417)

- "…sales of primary mineral products accounted for 29.3% of [South Africa's] total exports." (Burger, c.2003 : 417)

- "…the [South African] mining industry employed 408,894 people" and paid out "more than R24 billion … in wages." (Burger, c.2003 : 418)

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These figures emphasize the importance of the mining industry to South Africa and its economy. Yet, as Burger (c.2003 : 415) correctly points out, there still exists a great potential for growth in the industry, considering that South Africa possesses a vast amount of important mineral reserves. Some of South Africa's available mineral resources as measured in 2001 are shown in Table 2.1, which has been taken from Burger (c.2003 : 421). With mining geostatistics these days playing a significant role in many mining operations, the geostatistician clearly has a very important and highly specialized responsibility to fulfill in the continued growth of the South African mining industry.

Table 2.1: South Africa's mineral reserves, 2001 (from Burger, c.2003).

Commodity	Reserves	As a percentage of the World Reserves	World Ranking
Alumino – silicates	50.8 Mt	37.4	1
Antimony	250 kt	7.8	4
Chrome – ore	3 100 Mt	76.1	1
Coal	55 333 Mt	10.9	5
Copper	13 Mt	2.0	13
Fluospar	36 Mt	9.5	3
Gold	36 000 t	51.9	1
Iron ore	1 500 Mt	0.9	9
Lead	3 Mt	2.3	5
Manganese ore	4 000 Mt	80.0	1
Phosphate rock	2 500 Mt	7.0	3
Platinum – group metals	63 000 t	55.7	1
Titanium minerals	146 Mt	19.8	2
Uranium	284.4 kt	9.1	4
Vanadium	12 000 kt	44.4	1
Vermiculite	80 Mt	40.0	2
Zinc	15 Mt	3.5	5
Zirconium minerals	14.3 Mt	22.1	2

Mt = megaton, kt = kiloton, t = ton