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Issues and Challenges in the Application of Geostatistics and Spatial-Data Analysis to the Characterization of Sand-and-Gravel Resources

Chapter J of

Contributions to Industrial-Minerals Research

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By Daniel R. Hack

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Issues and Challenges in the Application of Geostatistics and Spatial-Data Analysis to the Characterization of Sand-and-Gravel Resources

By Daniel R. Hack[1]

Abstract

Sand-and-gravel (aggregate) resources are a critical component of the Nation's infrastructure, yet aggregate-mining technologies lag far behind those of metalliferous mining and other sectors. Deposit-evaluation and site-characterization methodologies are antiquated, and few serious studies of the potential applications of spatial-data analysis and geostatistics have been published. However, because of commodity usage and the necessary proximity of a mine to end use, aggregate-resource exploration and evaluation differ fundamentally from comparable activities for metalliferous ores. Acceptable practices, therefore, can reflect this cruder scale. The increasing use of computer technologies is colliding with the need for sand-and-gravel mines to modernize and improve their overall efficiency of exploration, mine planning, scheduling, automation, and other operations. The emergence of megaquarries in the 21st century will also be a contributing factor.

Preliminary research into the practical applications of exploratory-data analysis (EDA) have been promising. For example, EDA was used to develop a linear-regression equation to forecast freeze-thaw durability from absorption values for Lower Paleozoic carbonate rocks mined for crushed aggregate from quarries in Oklahoma. Applications of EDA within a spatial context, a method of spatial-data analysis, have also been promising, as with the investigation of undeveloped sand-and-gravel resources in the sedimentary deposits of Pleistocene Lake Bonneville, Utah.

Formal geostatistical investigations of sand-and-gravel deposits are quite rare, and the primary focus of those studies that have been completed is on the spatial characterization of deposit thickness and its subsequent effect on ore reserves. A thorough investigation of a gravel deposit in an active aggregate-mining area in central Essex, U.K., emphasized the problems inherent in the geostatistical characterization of particle-size-analysis data. Beyond such factors as common drilling methods jeopardizing the accuracy of the size-distribution curve, the application of formal geostatistical principles has other limitations. Many of the variables used in evaluating gravel deposits, including such sedimentologic parameters as sorting and such United Soil Classification System parameters as gradation coefficient, are nonadditive. Also, uniform sampling methods, such as drilling, are relatively uncommon, and sampling is generally accomplished by a combination of boreholes, water-well logs, test pits, trenches, stratigraphic columns from exposures, and, possibly, some geophysical cross sections. When evaluated in consideration of the fact that uniform mining blocks are also uncommon in practice, subsequent complexities in establishment of the volume/variance relation are inevitable.

Several approaches exist to confront the limitations of geostatistical methods in evaluating sand-and-gravel deposits. Initially, we must acknowledge the practical requirements of the aggregate industry, as well as the limitations of the data collected by that industry, as a function of what the industry requires at the practical level, and consider that broader acceptance of formal geostatistics may require modifications of typical exploration and sampling protocols.

Future investigations should utilize data from the full spectrum of sand-and-gravel deposits (flood plain, glacial, catastrophic flood, and marine), integrate such other disciplines as sedimentology and geophysics into the research, develop commodity-specific approaches to nonadditive variables, and include the results of comparative drilling.

Introduction

Sand-and-gravel mines, as sources for concrete aggregate, exert a tremendous influence on the Nation's infrastructure, yet few mining researchers or professionals have taken aggregate-mining technology seriously. Deposit-evaluation and site-characterization methodologies are at least 2 decades behind those in other mining sectors, and applications of geostatistics and spatial-data analysis have been little studied. This lack of commodity-specific engineering research consequently affects mine planning, scheduling, and other unit operations, compromising the overall efficiency of gravel-mining operations.

This chapter examines current approaches to aggregate-resource exploration and evaluation, describes the current status of research into applications of geostatistics and spatial-data analysis in the aggregate sector, reviews the methodologies developed and implemented (or

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attempted) by previous workers, suggests the limitations inherent in using geostatistics in gravel-deposit evaluation, and proposes how exploration methodologies, sampling protocols, and data evaluation may need to be modified to characterize gravel deposits within a spatial context.

In this chapter, I define the basic concepts of exploratory-data analysis (EDA), spatial-data analysis (SDA), and formal geostatistics with respect to applications to aggregate-resource characterization. I discuss the limitations of these applications, such as issues with the volume/variance relation, nonadditive variables, and the use of size-distribution curves. I propose potential solutions for practically confronting these limitations at the level of resource exploration and analysis, as well as concise suggestions for the design of sampling programs. I conclude by proposing measures to improve future results, such as comparative drilling exercises (that is, shell and auger versus reversed-circulation drilling) before beginning serious exploration, and assessing data from the full spectrum of sand-and-gravel deposits (flood plain, glacial, catastrophic flood, and marine) in order to better understand deposit-specific data-collection requirements.

Background

Arthur (1994), who presented the most comprehensive examination to date of the potential application of geostatistical principles in economic sand-and-gravel evaluation, remains the only serious such attempt, with a few minor exceptions. He proposed sampling methodologies that have never been implemented, or even taken seriously, by the aggregate sector. His summary comments were undeniably cynical (Arthur, 1994, p. 1):

> * * * the lack of research on inplace resource estimation in the sand-and-gravel industry is highlighted by the lack of papers on the subject in the scientific literature, especially when compared to the rest of the mining industry. * * * there appeared to be several reasons for the lack of interest, the main ones being the lack of in-house knowledge of the techniques involved, the high cost of installing computerized systems [in 1994], scepticism concerning the advantages over the cost and time involved in obtaining data, and a general lack of understanding of the problems that can occur. * * * very little work has been carried out in the past to assess the precision of data obtained from the drilling and sampling of natural aggregates.

In the subsequent decade, little has changed, and the stumbling blocks that Arthur encountered still remain. I discuss his methods and results in the section below entitled “Existing Geostatistical Investigations.”

The increasing saturation of computer technologies in every facet of daily life, however, will inevitably influence the acceptance of computerized methods in the aggregate sector, particularly when this trend is taken into account with the emergence of megaquarries. Sand-and-gravel mines are becoming large independent operations that must plan and operate similarly to open-pit metal mines as the realities of government regulation, automation, and economies of scale catch up with them. Computerization in the aggregate sector, however, is may be 2 decades behind that in the metal-mining industry—easily several generations of computer technology. Given imminent modernization, however, mine-planning-software companies eventually must seriously address the requirements of this sector (Hack, 2002b). The demands of 21st century infrastructure have compelled the emergence of megaquarries (Bliss and others, 2002), which are large mines accessible by rail or marine transport that produce more than 5 million tons of aggregate per year, with an expected lifetime of 50 years. Megaquarries are an inevitable result of two factors: the tremendous cost of permitting numerous small minesites, and an accelerating trend toward consolidation in the aggregate and concrete industry that began in earnest in the 1990s. This creation of aggregate companies with capacities for output scattered across the globe, and subsequent planning and operational requirements for these new economies of scale, ensure that the aggregate sector will require deposit evaluation (and the corresponding computer technologies) far advanced from what is presently in use. It is reasonable to propose that in the next decade, megaquarries identified as “type III” (consisting entirely of sand and gravel) will constitute most worldwide aggregate production (Bliss and others, 2002). The proximity of most type III megaquarries to maritime shipping lanes will broaden the scope of influence of these mines considerably. In addition, several large marine aggregate deposits are being developed to supplement onshore production, diminished because of environmental constraints.

Another development in the aggregate sector that will require deposit-evaluation methodologies comparable to those in other mining-industry sectors is the emergence of “type II” megaquarries. These mines produce rock not only for aggregate but also for various products suitable for such uses as chemicals, agricultural lime, filler, and cement. According to Bliss and others (2002, p. 306–307), “these quarries require considerable management to maximize return from the complex mixture of commodities they produce.” Aggregate miners, to date, have few (if any) industry-specific tools at their disposal to plan and manage such operations, whereas other mining-industry sectors have benefited from geostatistics and mine computing for decades. One of the first steps to the successful application of such techniques for sand-and-gravel mines is the evaluation of SDA methodologies, which will aid the evolution of aggregate-mine engineering from a haphazardly planned accessory to concrete production, ultimately to sophisticated three-dimensional planning, scheduling, and optimization routines.

Current Approaches to Aggregate-Resource Exploration and Evaluation

Aggregate-resource exploration and evaluation differ fundamentally from comparable activities for metalliferous ores. Barksdale (1991) noted that the goal of aggregate exploration is to supply a given market at a competitive price. Although the goal in metal exploration can be described in comparable terms (that is, locating an economic-mineral resource), aggregate exploration is much more directly linked to the end use of the mined commodity. At the most basic scale, a single basalt bench can be located and mined for a few weeks to supply a paving project immediately adjacent. The factors in selecting of such a site are simple: material suitability, proximity to end use, landowner approval, and any applicable municipal land-use issues.

Likewise, deposit exploration and evaluation methodologies reflect this cruder scale. The various common aggregate references and guidebooks describe exploration and evaluation methodologies, although experience has demonstrated that the exploration procedure can easily be backward: the deposit finds the miner, rather than the other way around. For example, large gravel companies search out old mines and prospects, such as State department of transportation (DOT) pits, or promoters ("bird doggers") call the sites to the companies' attention. Also, a large producer can consolidate several small gravel pits in the same deposit into a single operation. With this methodology, at least a preliminary indication exists that the material meets some level of quality; and in terms of land-use restrictions, the value of the site for aggregate-resource extraction has already been established. This final point implies an overwhelming factor in aggregate-resource development in the United States today: municipal land-use and zoning constraints. As a component of its Front Range Infrastructure Resources Project (FRIRP), the U.S. Geological Survey has developed geographic-information-system (GIS) techniques for the evaluation and protection of aggregate resources at the urban-planning stage, as well as for use as an exploration base (Melick and others, 1998). Lindsey (1997), in another report affiliated with FRIRP, provides an excellent introduction to the basic characteristics of deposit types, how models are developed, and the types of data used.

The "exploration guidance" of Barksdale (1991), which may be the most down to earth in terms of what is realistic for many companies, explains resource exploration in the most practical terms. His description of site selection begins with a discussion of the "principle of the weakest point" (and rightly so), pointing out the senselessness of spending money to develop a resource if one critical component in the exploration process (zoning, material quality, or cooperation of landowners) is missing. The importance of transportation routes is another factor that differentiates aggregate- from metalliferous-resource evaluation: aggregate must be mined near its end use, and haulage and handling costs compose a predominant percentage of final unit costs. Beyond these initial factors, Barksdale (1991) continues with further considerations, seemingly simplistic in opposition to something as sophisticated as the discovery and examination of porphyry copper deposits.

The exploration guidance provided by other workers, such as Smith and Collis (1993) and Primel and Tourenq (2000), is relevant, but the methodologies they outline are standard geologic procedures: literature review, reconnaissance-level field investigations, local sampling and mapping, data analysis, deposit modeling, and presentation of results. Both of these references, however, place particular emphasis on "inventories." Smith and Collis describe British Geological Survey geologic- and geophysical-resource appraisals for various areas in the United Kingdom (including offshore resources). Primel and Tourenq describe small (1:100,000)- and medium (1:25,000)-scale inventories produced by the French Geological Survey and regional laboratories of the Department of Roads and Bridges. As does Barksdale (1991), Smith and Collis suggest the "three-legged stool" of municipal land use, transportation networks, and end use of the commodity.

In general, suitable information has been published on the traditional geologic aspects of aggregate-deposit exploration and evaluation, with notably progressive discussions of satellite imagery, remote sensing, and airborne geophysics. Many of these concepts, however, would be far beyond the understanding (or interest) of most regionally based concrete companies. Smith and Collis (1993, p. 55–58) skillfully summarize the various aspects of common drilling methods, with their general applications and characteristics:

- Hand augers: "the strata must be self-supporting, soft, and with only very few pebbles."
- Power augers: "numerous disadvantages when precise sampling is required. Unconsolidated material, particularly beneath the level of the water table, tends to collapse into the borehole *** tends to churn the strata, leading to contamination of one layer with another *** can provide good guidance on the thickness of overburden can quickly penetrate unstable strata without the need for lining tubes."
- Hollow-stem augers: "can penetrate unstable strata without the need for lining tubes *** sampling quality is likely to be higher than that achieved by open-hole augering."
- Light-cable percussion boreholes: "an adaptation of standard well-boring methods *** a limitation on the depth of drilling is commonly imposed by the capacity of the rig to extract the lining tubes from the ground strongly preferred where sampling is the major objective because progress cannot be maintained unless casing is inserted, and this ensures samples remain uncontaminated."
- Reverse circulation drills: "sampling is unconsolidated and entirely representative *** the speed of the drilling operation is such that refined sampling and logging may not be achieved unless many hands are available."

Arthur (1994) discusses some of the limitations highlighted for these methods, particularly with respect to geostatistical and other SDA approaches, in the course of his investigations. At the level of "prospecting," the approach of Primel and Tourenq (2000) is not as firmly based on classical field geology as is that of Smith and Collis (1993). Primel and Tourenq particularly emphasize the use of topographic and isopach maps to properly evaluate and exploit variations in deposit and overburden thickness. They also astutely suggest that the most important data to extract from regional studies are mean grading within the zone, mean and extreme thicknesses of the overburden and gravel, mineralogic and petrographic compositions of various aggregate sizes, and principal heterogeneities.

Again, Barksdale (1991, p. 4.25)'s suggestions are generally candid and practical, most productive with respect to his target audience. Sampling methods are not confined only to drilling but also involve grab samples ("preliminary only and rarely can be considered typical of a deposit") and pit samples ("relatively inexpensive").

Principles of the sampling of particulate material must be regarded in tandem with these commodity- and industry-specific considerations. Resource data, as well as subsequent analysis and modeling, will be suspect unless workers have obtained representative samples in the field and retained their integrity throughout analytical procedures. Theories of the sampling of particulate solids were developed by Pierre Gy on the basis of seven types of sampling errors, along with concise techniques for their minimization. Examples of sampling errors include "increment-delimitation error" (error tied to inappropriate sampling design and the wrong choice of equipment) and "grouping and segregation error" (error due to nonrandom distribution of particles, usually by gravity). Gy's theories became popular in practice because useful sampling and subsampling methods can be derived that are applicable for little or no extra expense. Pitard (1993)'s book is a fundamental reference on these theories and methods.

By the nature of the commodities in question, a fundamental stumbling block exists in the application of metalliferous-resource exploration and evaluation methods and protocols to the aggregate sector. "Gradation," otherwise known as the characterization of particle-size distribution and also called granulometrics, is a key factor in identifying suitable aggregate prospects for a given market demand. In addition, the characterization within a spatial context of the gradation of a gravel deposit could enable gravel-mine planning to move closer to the level of planning expected at most other mines (metalliferous, coal, and most industrial minerals) in the present era. However, with a few exceptions that have met with mixed results, such investigations have never been taken seriously in the aggregate sector. The purpose of this chapter is to identify the analytical methods available, summarize the spatial-data investigations that have been completed, outline the limitations of these methods, and establish goals for further study.

Concepts of Exploratory-Data Analysis and Spatial-Data Analysis

The basic concepts of exploratory-data analysis (EDA) were summarized by Tukey (1977), in what remains the seminal EDA guidebook to this day, although many of these concepts had already been developed and used in Earth-science applications for some time (Krumbein and Graybill, 1965). EDA is not a concise set of techniques or unifying principles (as with geostatistics) but a general analytical approach that usually employs graphical methods to allow the data to reveal their own model. The intent of EDA is to maximize insight into a dataset by (among other goals) uncovering underlying data structures and detecting outliers and anomalies. Typical techniques, as described by Tukey, (1977), are "stem-and-leaf displays," "box-and-whisker plots," and "parallel-schematic plots." EDA has gained popularity in mining-operations research and simulations, because operating mines produce a tremendous amount of data that must be characterized if they are to be used efficiently. Kannan and others (1999) provided a good introductory demonstration of EDA applications in mine-operations research.

"Spatial-data analysis" (SDA) is a general term that encompasses methods as simple as rudimentary plotting and contouring, and as complex as lattices and geostatistics. In this chapter, the term includes methodologies that evaluate data in consideration of their position in two- or three-dimensional space. Although this definition includes the geostatistical spectrum, SDA here refers to techniques up to, but not including, geostatistics in level of complexity and sophistication. Utilization of both EDA and SDA requires a practical knowledge of such classical-statistical concepts as the four moments (mean, variance, skewness, and kurtosis), confidence intervals, the common statistical tests (t, z, f, and χ^2), and calculation of correlation and covariance. Crow and others (1960), and Hammond and Householder (1962), and Krumbein and Graybill (1965) present a thorough introduction to background concepts.

EDA can be an approximate and simplistic method of data evaluation, and so it lends itself to gravel mining. Preliminary research on the practical applications of EDA in the aggregate sector has been promising. Bliss (1999) suggests that four types of model are used in regional aggregate assessment: descriptive models, distribution models, relational models, and spatial models. He derives a linear regression equation, by way of EDA, for forecasting freeze-thaw durability from the absorption values of Lower Paleozoic carbonate rocks mined for crushed aggregate from quarries in Oklahoma. He uses a "relational model," whereby such statistical relations as regression are established among geologic variables to other variables, but with no consideration of spatial distribution. The results, however, are impressive because the regression equation explains 95 percent of the observed variation.

Bliss and Bolm (2001) provide a critical link between the use of EDA methodologies for practical data correlation (that is, predicting freeze-thaw durability to save on laboratory costs) and SDA modeling of aggregate-quality parameters within a spatial context. The two objectives of their study were to demonstrate how statistical methods can be used to examine the relations between geologic classification of sand-and-gravel deposits and material characteristics (such as Los Angeles wear and fines content). Bliss and Bolm (2001, p. 196) note that "the nature of undeveloped sand and gravel resources" can be forecasted by models prepared from statistical analysis. Their research was on the sedimentary deposits of Pleistocene Lake Bonneville, an important source of sand and gravel suitable for aggregate and construction in Utah. Lake Bonneville, which was comparable in size to Lake Michigan, straddles the boundary between the Basin and Range Province and the Wasatch Domain.

The result of Bliss and Bolm (2001)'s study was an application of EDA within a spatial context. The subsequent methodologies could be practically implemented, particularly in consideration of the interconnectedness of deposit exploration and land-use planning. Two classes of results were obtained. First, several trends were apparent, such as that sand and gravel in younger shorelines are slightly more durable and the deposits considerably larger in volume, and that the northern part of the Bonneville Basin contains slightly more durable sand and gravel than the southern part. Second, according to Bliss and Bolm (2001, p. 195), some results could have "immediate economic significance," such as that the median sand-and-gravel deposit in the Wasatch Domain is 3 times larger than that in the Basin and Range Province.

As already mentioned, SDA encompasses a broad range of methodologies that evaluate data in consideration of their position in two- or three-dimensional space, such as trend-surface analysis (TSA), inverse-distance weighting, and geometric methods. Simply stated, TSA emphasizes the main features of a spatial distribution by smoothing over some of the local irregularities so that important trends can be isolated from the background more clearly. TSA mathematically separates spatial data into two components: regional and local (Davis, 1973).

Mineral-resource estimations performed manually on plan maps and cross sections typically belong to a class of "geometric methods" that are based on geometric weighting of assays (or other material properties). One of these methods is *polygonal estimation*, in which each assay grade for a given sampling unit is assigned its own polygon of influence (Noble, 1992). Polygons are drawn on maps on the basis of perpendicular bisectors of the line between each sample locality. Tonnage for each polygon is estimated by multiplying the area of each polygon by the thickness of the deposit, then dividing by the tonnage factor. "Nearest-neighbor estimation" is a computer approximation of polygonal estimation.

"Inverse-distance weighting" and "kriging" are methods of "moving-average estimation," in which the basic procedure involves dividing the ore body into a matrix of rectangular blocks (taking into account any geologic controls that may affect grade assignment) and estimating the grade of each block by computing a weighted average based on the grades of surrounding blocks (Noble, 1992). Practical considerations involve determination of block size, anisotropies, and sample-selection criteria. Inverse-distance weighting is based on the empirical observation that the weight of each sample from which the weighted-average equation is derived is proportional to an inverse power of the distance from the location of the estimate to the sample. Kriging is described in the next section.

Cressie (1991) provides a useful survey of SDA methodologies, with an emphasis on the theoretical background rather than on concise procedures for field practitioners. He discusses such less common SDA topics as "lattice models," "infill asymptotics," and "spectral representations," as well as the theoretical background behind such specialized geostatistical subjects as "Bayesian kriging" and "kriging-variance stability."

Basic Concepts of Geostatistics

The term "geostatistics" refers to a collection of statistical and probabilistic methods that were developed in the South African mining industry in the 1950s (Krige, 1951) from forestry analysis in Scandinavia, although comparable mathematical concepts were being formulated by the Soviets with respect to the study of meteorologic fields (Gandin, 1965). A theoretical framework for geostatistics was established by Matheron (1963) and his colleagues, termed by them "regionalized-variable theory." The practice of geostatistics has been standardized in the mining of metalliferous ores since at least the 1970s, and has gained acceptance in such fields as hydrology, landscape ecology, and forest biometrics. Simply stated, geostatistics is used to describe and utilize correlations among spatially distributed data and to build models that can be adapted to practical situations. A geostatistical evaluation can drastically change the approach to the development of sampling methodology because spatial characterization is the intent, counter to traditional sampling, where the intend is to eliminate spatial dependencies. I avoid detailed mathematical and statistical discussions here, and the reader is referred to several excellent references, such as the reports by David (1977), Journel and Huijbregts (1978), Rendu (1978), Clark (1979), and Isaaks and Srivastava (1989). At this point, I am content to introduce general concepts and terminology derived from these references.

A typical geostatistical analysis can be summarized in a few concise steps:

- Initial examination of the dataset, such as calculation of basic statistics, production of simple contour maps, and, most importantly, data validation
- Fitting of semivariogram models to the sample data, allowing spatial and directional characterization of variables
- On the basis of model fit, determination of such semivariogram parameters as range, sill, and nugget
- Estimation
- Simulation, if desired

I define a few necessary concepts and terms as follows. The term "semivariogram" is a fundamental expression of the spatiality in a dataset. Simply stated, a semivariogram aids in measuring or predicting how a given value (grain size, ore grade, and so on) will change in dependence on its location in two- or three-dimensional space. A semivariogram is a mathematical function that expresses the variation in a measured or predicted value among sample points separated by a distance h. Thus, a "directional" semivariogram is the function along a given azimuth in two or three dimensions, and an "omnidirectional" semivariogram does not take direction into account. If a dataset demonstrates different spatiality (expressed by the semivariogram parameters "sill" and "range") in different directions, then the dataset is "anisotropic." If no anisotropy is detected, then an omnidirectional semivariogram can be used. If the variable is nonadditive, then application of a suitable transformation before computing variograms, though not always possible, may be appropriate. Various transformations are available, of which the log transformation is the most commonly applied.

The term "nugget" (C_0, fig. 1), which appears in the semivariogram as an apparent discontinuity at the origin, is an expression of either pure random variation or sampling error, or, more likely, both. The term "range" (a) identifies the distance h at which the semivariogram in a spherical model reaches a constant value, known as the "sill." Intuitively, h is the maximum distance at which samples can be spatially correlated, beyond which no spatial correlation exists. The sill (C_0+C_1), which is the value of the semivariogram at a distance h beyond the range, represents the ordinary sample variance. These parameters are illustrated in figure 1.

Rather than trying to fit an equation to every possible form of semivariogram curve, several different mathematical models are used, most commonly "linear," "spherical," "exponential," and "Gaussian." (See the above-cited references for details.) The basic forms of these model types are illustrated in figure 2.

According to Clark (1979, p. 120), anisotropy is "perhaps the easiest 'problem' to tackle." Basically, anisotropy represents variations in behavior or characteristics in different directions in two or three dimensions. In geostatistical investigations, the most common manifestation of anisotropy is a variation in the distance h in different directions with no change in the sill, which is a "geometric" anisotropy (fig. 3). A "zonal" anisotropy is one in which the sill changes but the variation in the distance h remains constant. Anisotropies are "corrected" in computations by means of various transforms, as discussed in detail throughout the above-cited references. In alluvial deposits, anisotropic characteristics of granulometric indices can suggest variations in depositional mechanics. For example, such indices as gradation coefficient evaluated for different strata (representing different flood events) in a catastrophic-flood deposit may exhibit varying degrees of anisotropy.

The issue concerning "stationarity" is another important consideration in variography and kriging. Without going into mathematical detail, if data are stationary, they have no definable trend. In the simplest terms, a sloping surface is not stationary. "Drift," a simple polynomial function, is used to temporarily impose stationarity on data for the purposes of kriging. Even if data are nonstationary, they may be considered locally stationary (that is, to exhibit no definable trend) over a shorter distance, called the limit of quasi-stationarity (fig. 3). Kriging can be performed over this limit, rather than relying on a drift function.

The concept of "nonadditive variables" is an important consideration in the application of geostatistics to granulometric data and, potentially, with other aggregate parameters. An "additive model" is one in which the input variables have

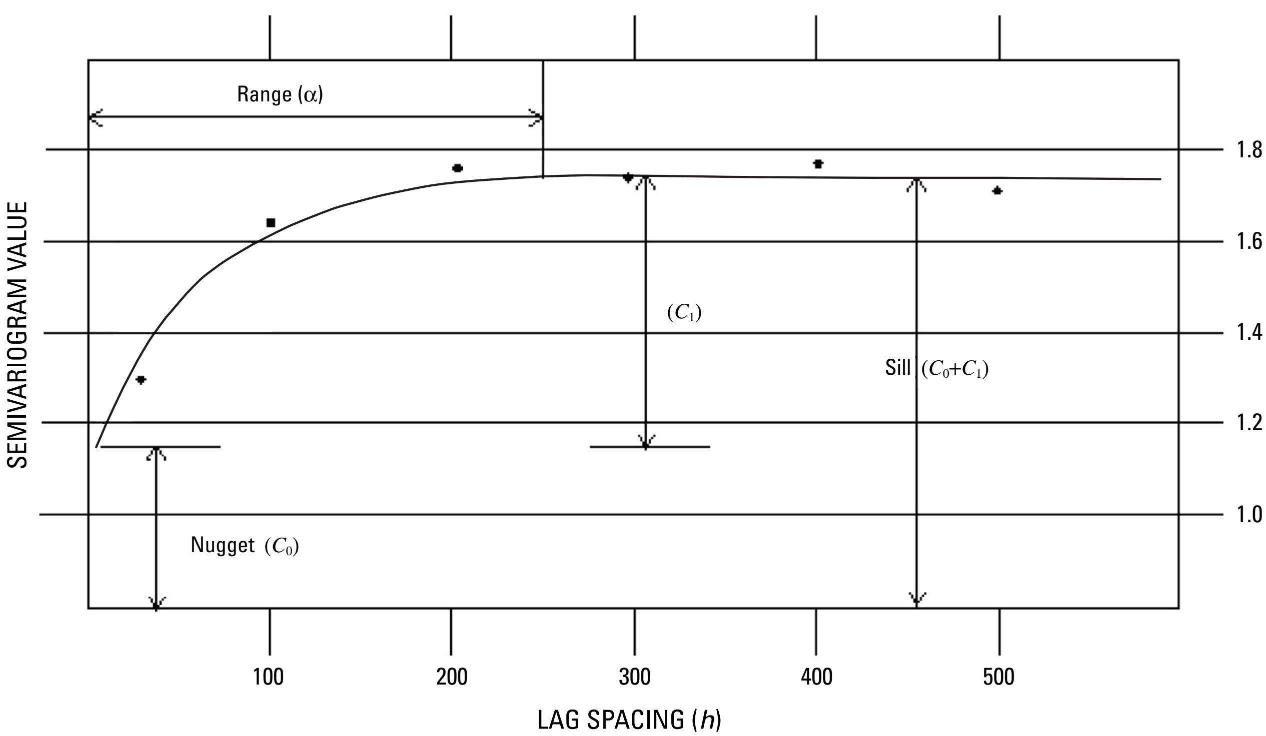

Figure 1. Basic features of the semivariogram.

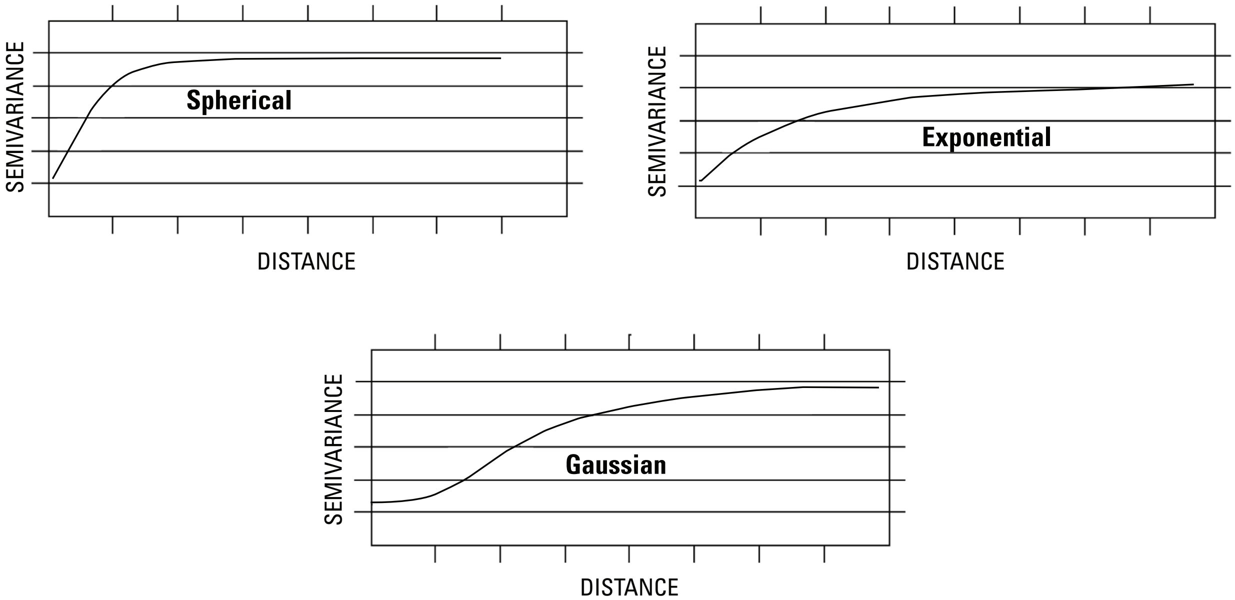

Figure 2. Spherical, exponential, and Gaussian semivariogram model forms.

an additive effect on the output variables. As a simple example, if the input variable A has an effect of magnitude a on the output, and the variable B has an effect of magnitude b on the same output, then the combined effect of A and B would be $a+b$–a linear relation. Otherwise stated, the equation is additive because the contributions to the result are added together. This relation is not true, however, in a "nonadditive model," where the combined effect of A and B cannot be expressed linearly, such as would be the case with, for example, $4A^2+2B^3$. Many variables used in the evaluation of metalliferous ores, such as troy ounces of Au per ton or weight percent Cu, are additive, whereas most granulometric indices, such as sorting or gradation coefficient, are nonadditive. (See section below entitled "Limitations of Geostatistics.")

The concepts of "support" and the "volume/variance relation" are important in geostatistical analyses because the size (or support) of the dataset and the distribution of sample values are related. Intuitively, to use an example

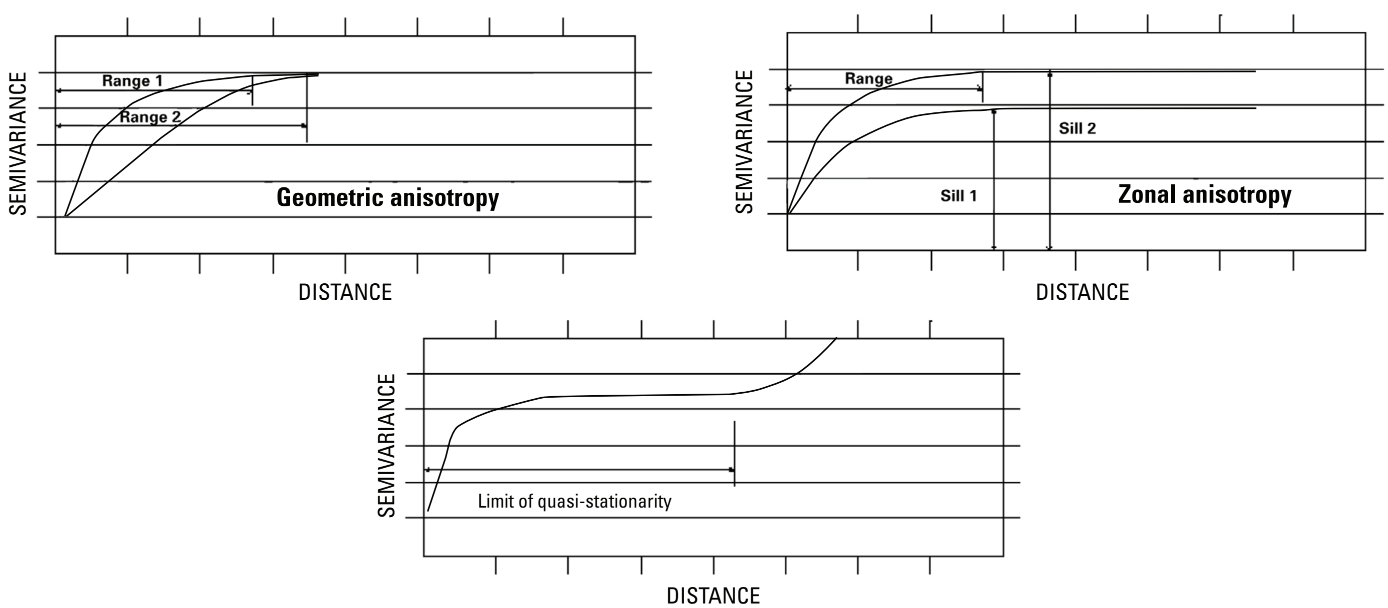

Figure 3. Semivariogram models demonstrating anisotropy and quasi-stationarity.

from Isaaks and Srivastava (1989), very small sample sizes, such as rock chips, would vary considerably if one nugget were pure gold and another were barren, whereas truckload-size samples from the same deposit would vary much less. This concept is known as the volume/variance relation.

Evaluation and modeling of data under the assumption that the sample values are located at discrete points, rather than being part of a volume, such as a drill core, is termed a "point support." On a point support, the sill ideally equals the variance. If the samples are not points, however, but drill cores of a given length, some of the point variation will be "smoothed out," as in the previous example, where numerous individual values are effectively replaced with one average. Changing the semivariogram parameters in consideration of different support is termed "regularization" (Clark, 1979). During kriging, support volume is a consideration during estimation and "block modeling."

The geostatistical procedure of estimating points or blocks (local versus global) is termed "kriging," the designation of a set of linear-regression routines that minimize estimation of variance from a predefined covariance model (such as that represented by the semivariogram). "Kriging variance," the variation in estimation error, is not data dependent but is determined by the semivariogram, the original sampling pattern, and the location of the point to be estimated relative to the sample locality. Estimates derived from kriging depend on the support of the estimated block, as well as on the sampling data.

The basic procedure of "ordinary kriging" in terms of "block modeling" can be summarized as follows:

- A search is made around the block to be estimated. Samples located within the search window are used for estimation of the block, and samples outside this window are omitted.
- Samples within the search window are assigned weights that reflect spatial characteristics, as manifested in the semivariograms. In ordinary kriging, these weights sum to unity.
- A weighted average is calculated to yield the block estimate.

Numerous kriging techniques have been developed, depending on such factors as degree of stationarity, data density, and ultimate use of the estimates; common types are "ordinary kriging," "simple kriging," "universal kriging," and "indicator kriging." Simple kriging differs from ordinary kriging in that the sample weights do not sum to unity, using the average of the entire dataset rather than a local average and resulting in a less accurate but "smoother"-looking result. Both ordinary and simple kriging require stationarity or, at least, a practical limit of quasi-stationarity. Universal kriging can be used for nonstationary datasets by using the residuals (difference between the drift and the actual values of scatterpoints). Indicator kriging, which deals with threshold values, is basically a nonparametric counterpart to ordinary kriging. "Disjunctive kriging," also known as full-indicator cokriging, is the cokriging of multiple indicators, beneficial over standard indicator kriging because an optimal estimation can be reached whereby each indicator profile is consistent with every other. "Multi-Gaussian kriging," a generalization of lognormal kriging, is the application of kriging to the normal-score transformations of the input sample points. Thorough discussions of the numerous approaches to kriging are presented in the above-cited references.

Local and global estimates by way of kriging, which can be insufficient at the planning stage, can be beneficial to predict the variations in characteristics during mining and stockpiling. This estimation is the purpose of simulations, a field that has rapidly gained importance along with comparable increases in computing power. Simply stated, simulated deposits have the same values as those at the experimental locations and the same dispersion characteristics (up to order 2) of the real deposit. The difference is that the objective of estimation is to provide, at each point, an estimate that is as close as possible to the true unknown grade. The simulation (or, better yet, "conditional simulation") has the same two experimental moments (mean and covariance or variogram), as well as the same histogram, as the real grades—that is, it identifies the main dispersion characteristics of these true grades. In any single realization at each point, however, the simulated value is not the best possible estimate. "Conditioning" occurs when the simulations that are chosen are those that match the values at the experimental locations. (See Journel and Huijbregts, 1978, for additional details.)

Existing Geostatistical Investigations

Formal geostatistical investigations of sand-and-gravel deposits are quite rare, and the primary focus of completed studies has been on the spatial characterization of deposit thickness and its subsequent effect on ore reserves. Royle and Hosgit (1974) present a thorough treatment of the geostatistical evaluation of deposit thickness; their report generated some important preliminary results—in particular, that anisotropy and considerable nonstationarity should be expected in a deposit formed from multiple flood events.

Arthur (1994) investigated aggregate exploration by RMC Ltd. in an area of central Essex, U.K., that had been extensively worked for gravel. Objectives of his study included exploration and characterization of sand-and-gravel resources, covering such topics as optimum sampling pattern and density, errors inherent in different drilling and sampling techniques, geologic variation and its subsequent effect on plant feed, and the feasibility of formal geostatistical investigations. As stated above, such concepts are rudimentary in the evaluation of metalliferous resources, but their adoption in the aggregate sector has been slow to nonexistent.

Like Royle and Hosgit (1974), Arthur (1994) also examines the geostatistical characterization of deposit thickness, with applications toward computer-based extraction-volume calculation. A convincing example of infill drilling, using a 25- versus a 100-m grid, is an important component of his examination. Arthur's study also was somewhat successful in geostatistically analyzing the continuity of a deposit in the horizontal and vertical directions, to influence borehole spacing for the next round of drilling.

Arthur (1994) proceeds to examine the potential use of geos`Because aggregate-mining companies tend to report size-grading data in terms of cumulative percent passing (owing to easier correlation to commercial screen sizes), most of the granulometric data used by Arthur (1994) were generally expressed in this format; however, the basic statistics of individual size fractions were calculated for percent-retained and percent-passing data. When percent-passing data were evaluated, the coarse fraction (20–75 mm) exhibited an inverse lognormal distribution, and only the medium (10, 14, and 20 mm) fractions exhibited a normal population distribution, whereas when percent-retained data were evaluated, coarse- and fine-fraction end members (28–75 mm and <75–300 µm, respectively) exhibited lognormal distributions, and size fractions in the midrange (0.6–20 mm) exhibited normal distributions.

The most notable result of this analysis, in terms of further statistical and probabilistic examination, is the difference between the use of percent-passing and percent-retained data. For example, *f* and *t* tests comparing drilling data from the 25-m grid with those data from the 100-m grid showed a significant similarity for most size fractions when percent-retained data were used; however, the same tests conducted by using percent-passing data showed that only the midrange size fraction <1.18 mm exhibited a significant similarity. Furthermore, correlations between individual size fractions can be derived only from percent-retained data. For example, significant negative correlations were measured between fractions in the gravel range (5, 10, 14, and 20 mm) and in the fine-sand range (75, 150, 212, and 300 µm), suggesting a subdivision of the study area into zones characterized by coarser and finer material and reinforcing results suggested by contouring.

Geostatistical analysis consisted of producing semivariograms on varying sample supports, borehole spacing, and locations within the study area. Drilling data from both the 25- and 100-m grids were used. Notable results are summarized as follows:

- Bench composites of 1 m produced from raw data did not lead to a significant increase in the quality of semivariograms.
- Most semivariograms exhibited either a pure-nugget effect or so much random behavior that no sill was definable. Directional plots were mostly noise, owing to the absence of usable sample pairs.
- Ranges modeled on the 100-m grid were from 400 to 800 m, whereas those modeled on the 25-m grid averaged about 125 m.
- Semivariograms for size fractions above 14 mm exhibited the pure-nugget effect for both datasets, and those for size fractions between 75 and 300 µm required logarithmic transformation before modeling.

The overall average correlation from a crossvalidation exercise performed on normally distributed midrange size fractions was only 0.52, suggesting that the model parameters do not accurately represent the original data.

Arthur (1994, p. 7–12) concludes that “it is pointless to carry on using this data to produce a geostatistical reserve estimate.” He emphasizes several considerations specific to the evaluation of sand-and-gravel deposits:

- Owing to the nature of deposition, most sand-and-gravel bodies will exhibit a proliferatio of small-scale structures that coarse drilling grids may fail to detect, including small channels, clay and silt pockets, and organic inclusions. Changes in grain size from fine sand to coarse gravel can occur over distances as small as 0.3 m.
- A considerable drop in accuracy occurs for the estimation of end-member (coarsand fine) fractions from the shell-and-auger drilling method. In particular, loss of fines can lead to underestimation by as much as 75 percent. Therefore, grain-size distribution could not be accurately modeled because actual cutpoints are unknown. The shell-and-auger drilling method, however, produced good depth estimates necessary for geostatisti cal evaluation of horizon thickness.

Additional datasets based on reverse-circulation drilling were also suitable for quantifying vertical variations in the deposit, but much coarse material was lost.

Further Research Based on Existing Geostatistical Investigations

From the above discussions, it may be obvious that Arthur (1994) attempted several investigations on topics necessary needed for the further study of spatial-data applications in the aggregate sector, implying a twofold significance for his study: (1) although not all of his investigations were notably successful, the limitations of the methodology suggested, sometimes clearly, that common drilling methods jeopardize the accuracy of the size-distribution curve; and (2) no other researcher has seriously attempted that subject matter, at least in such detail.

A few more recent studies have investigated specific aspects of geostatistical analysis, with applications toward production accounting and land-use planning. Hack (2001) developed a correlation between δ⅜″ (cumulative percent passing through a ⅜-in. mesh) and inplace density. His intent was to utilize changes in δ⅜″ (an index measure routinely measured by quality-control staff) to track changes within inplace density, necessary for proper accounting and verification of royalty payments. The logarithmically transformed semivariogram for density fitted a Gaussian model and was generally isotropic, except for a significant zonal anisotropy in the northwest/southeast (azm 135°±030°) direction. The semivariogram for δ⅜″ exhibited significant zonal and geometric anisotropies on azimuth 115°±030°. Following variography, ordinary kriging on a point support was used to estimate point values of δ⅜″ in several places where density samples had been taken. Kriging variance was approximately

1.2 percent squared, on a mean δ⅜″ of 36 percent. A regression equation of density on δ⅜″ was then derived, with the regression on δ⅜″ accounting for 80 percent of the observed variation in density (fig. 4). At the practical level, however, this relation should be applied with some degree of caution because of the small size of the datasets. Uncertainty in the final extracted quantity, however, is subject to other factors, such as vertical tolerances in topographic surveying.

SDA of aggregate-resource characteristics within the context of mine and development planning is the subject of Hack's (2002a) report. This component of ongoing research involved Tenmile Terrace, the oldest major Pleistocene terrace in the lower Boise River Valley, Idaho. Data were collected by various parties, usually the Idaho Transportation Department, from 1953 to 1999. The terrace, whose largest outcrop is 19 km long by 5 km wide and generally about 10 m thick, is divided into two components: the main body designated as the "upper" terrace and the scattered remnants designated as the "lower" terrace. A total of 10 composite samples from the upper terrace, each representing an individual gravel pit or prospect, were derived from 46 individual samples, and a total of 13 composite samples for the lower terrace were derived from 39 individual samples. The composite samples were created to assess spatial variations across the entire Tenmile Terrace. Cumulative percent-passing data were entered from laboratory sheets into the software program SGMatrix, and then various sedimentologic, engineering, and concrete-industry factors, such as uniformity coefficient, gradation coefficient, sorting, and dust ratio, were calculated from cutpoints (D_{10}, D_{25}, and so forth). All the various factors were correlated with each other, as well as with (x, y) sample locations, to create a "matrix" of correlation coefficients (table 1).

The results were used in the preliminary identification of spatial structures. Long-range resource evaluation in the lower terrace indicated a strong negative correlation of easting and northing with cutpoints D_{50} and D_{75}. Otherwise stated, the median and 75th percentile decrease as sampling progresses northeastward, reinforcing the previous geologic interpretation that deposition was from southwestward-flowing streams, because coarser material would have been deposited at the headwaters, with finer sediment settling out downstream. The intent of short-range resource evaluation was to appraise the spatiality of the individual sites (active pits, dormant pits, or prospects), with potential applications toward mine planning, as with Arthur (1994). Analysis at this scale suggested results of sedimentologic interest that were beyond the scope of Hack's (2002a) study, such as consistent indications that sorting characteristics are related to the proportion of sand. Within a spatial context, cutpoints in the range D_{60}–D_{75} exhibited strong correlations to northing and easting. Limited attempts at exploratory variography had mixed results, although midrange cutpoints generally exhibited linearity. Semivariograms for cutpoints D_{50} and D_{75} were spherical in form, with ranges typically 3 to 5 times those of sorting and gradation parameters.

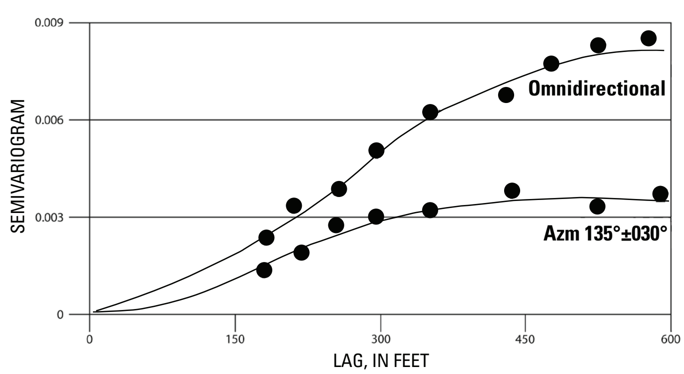

Figure 4. Log-transformed semivariogram of density (from Hack, 2001).

Again using Tenmile Terrace as a test case, D.R. Hack (unpub. data, 2003) broadens the scope of long-range resource evaluations, emphasizing regional trends relevant to municipal land use and resource planning. The project area straddled two counties, Ada County and Canyon County, in southeastern Idaho. The terraces were generally split along county lines, with most of the lower terrace in Canyon County and most of the upper terrace in Ada County. In both counties (terraces), sampling tended to cluster in two general areas, about 20 km apart. Before the calculation of spatial correlations, sampling localities that potentially represented "anomalies" could be identified.

This approach highlighted significant differences between the two general areas. The samples from Canyon County (lower terrace) exhibited spatial correlations that could aid in deposit characterization. The above-noted correlation of cutpoint D_{75} with the southwest direction ($\rho\approx0.70$) decreased with a virtually linear trend through cutpoints down to D_{10}, where the correlation was $\rho\approx0.20$. Size fractions in the mesh-size range #10 (2,000 µm) to #30 (600 µm), as well as skewness and kurtosis, exhibited moderate correlations ($\rho\approx0.60$) with the northeast direction (180° from previously noted correlation). Therefore, skewness and kurtosis exhibit strong correlations with mesh sizes #10 and #30 (ρ=0.60–0.80), possibly providing insight into the sedimentologic environment. Also of potential sedimentologic interest, correlations of uniformity coefficient with mesh sizes #100 (150 µm) and #200 (75 µm) were ρ=0.68 and ρ=0.85, respectively, and correlations of dust ratio with mesh sizes #50 (300 µm) and #100 were $\rho\approx-0.70$.

The samples from Ada County (upper terrace) samples, evaluated as a whole, exhibited no notable spatial correlations (at least of ρ>0.50): however, similarities in sedimentologic environment were noted between the two terraces. Correlations of uniformity coefficient with mesh sizes #100 and #200 were even stronger than in Canyon County. Dust ratio was also negatively correlated with mesh sizes #50 and #100, but not to so high a degree. In Ada County, however, sorting exhibited strong correlations with mesh sizes #10 and #30 (ρ=0.88 and ρ=0.70, respectively).

Resource exploration or planning can benefit from such interpretations if granulometric data are available from prospects or operating pits in the area of interest. Using this result from Ada County, Idaho, an example, prospects that exhibit higher proportions of mesh sizes #10 and #30 material will

Table 1. Correlation coefficients for the lower Tenmile Terrace, Idaho.

[Bold numbers are diagonal elements. From Hack (2002a)].

	East	North	Fines	D_{10}	D_{25}	D_{50}	D_{75}	D_{90}	Sort
East -------	1.0	**0.806**	0.230	−0.411	−0.089	**−0.687**	**−0.804**	−0.453	−0.250
North------	**.806**	1.0	.037	−.205	−.364	**−.615**	**−.729**	−.504	.044
Fines ------	.230	.037	1.0	**−.663**	.086	−.072	−.146	.288	−.292
D_{10}---------	−.411	−.205	**−.663**	1.0	−.005	.212	.283	−.045	.148
D_{25}---------	−.089	−.364	.086	−.005	1.0	.418	.330	.378	**−.891**
D_{50}---------	**−.687**	**−.615**	−.072	.212	.418	1.0	**.961**	**.759**	−.107
D_{75}---------	**−.804**	**−.729**	−.146	.283	.330	**.961**	1.0	**.761**	.029
D_{90}---------	−.453	−.504	.288	−.045	.378	**.759**	**.761**	1.0	−.133
Sort--------	−.250	.044	−.292	.148	**−.891**	−.107	.029	−.133	1.0

statistically exhibit a higher level of sorting, a potentially important consideration when evaluating sites for concrete aggregate. Likewise, when evaluating the Canyon County sites within a spatial context, higher cutpoints (such as D_{75}) are significantly correlated with the southwest direction, suggesting to a prospector that sites toward the southwest may be more likely to exhibit larger gravel (cobbles) at the coarse tail of the particle-size distribution.

Limitations of Geostatistics

A major obstacle in the adaptation of formal geostatistical principles to practical applications in aggregate exploration, evaluation, and mining is the rigorous theoretical standards to which the term "geostatistics" is normally applied. As noted above, however, data can be evaluated within a spatial context in the SDA spectrum, allowing acknowledgment of spatial-data structure without violating the academic constraints under which geostatistics operates, possibly providing the most practical route for workers in the aggregate sector. Nonetheless, geostatistical evaluation remains a reasonable goal to strive for, although its limitations must be confronted at the outset.

The most productive route to quantifying the role of geostatistical principles in aggregate-resource evaluation is to identify those aspects of geostatistical analysis that are taken for granted in the evaluation of metalliferous ores but would be challenging to apply to the sampling and modeling of a gravel pit. Most notable among these aspects are the additivity of the variables involved, the use of a uniform sample size (such as a drill-core barrel) in exploration, and the clear definition of a "selective mining unit." Each of these terms is discussed below.

Nonadditive Variables

As suggested above, nonadditive variables are an important consideration in applications of geostatistics to granulometric data and other parameters used in the aggregate sector. Some of these variables are explicitly nonadditive, by function of their mathematical form—for example, the sedimentologic statistical moment identified as "skewness," expressed as $\sqrt{[(D_{25}\times D_{75})/(D_{50})^2]}$, or the United Soil Classification System soils-engineering parameter "gradation coefficient," expressed as $C_g=(D_{30})^2/(D_{60}\times D_{10})$. Other variables are not obviously nonadditive by their mathematical form but would be within the context of geostatistical evaluation and a subsequent block model or simulation—for example, such quality measures as Los Angeles wear and freeze-thaw durability. Not only could creation of suitable mathematical transforms be challenging, but also ensuring that the applications of these transforms are suitable with respect to other mathematical limitations.

Peroni and others (1999) provide a clever treatment of the geostatistical evaluation of nonadditive variables in a kaolinite deposit. Specifically, they use the Kubelka-Munk function to create a nonlinear transformation of the parameter brightness, a primary quality-control parameter in the evaluation of kaolin deposits. Its use avoids bias in block modeling and reserve estimation, and crossvalidation results are excellent.

Uniform Sample Size

Most practitioners of geostatistics in the metalliferous- or coal-mining industries take for granted the use of a uniform sample size, such as a drill-core barrel, during exploration and deposit evaluation. Likewise, most geostatistics textbooks, software, and ensuing methodologies are written with this aspect of geostatistical analysis in mind, because it applies to most conditions. In a gravel deposit, however, a uniform drill-core barrel is not practicable because the material is unconsolidated. Furthermore, borings are not the fundamental deposit-evaluation tool, for obvious reasons (see discussion above pertaining to Arthur, 1994). For many mine sites (if adequate sampling even exists), deposit evaluation will be a combination of boreholes, water-well logs, test pits, trenches, stratigraphic columns from exposures, and, possibly, some geophysical cross sections. A two-sided approach is needed to reconcile this issue: developing academically suitable methods to use such varied data (in widely varying three-dimensional geometric forms) in a proper geostatistical evaluation, and convincing those who prepare and utilize the end result that this diminished consistency in data types and methodology is acceptable, and that the results are still usable at a practical scale.

Support and Selective-Mining-Unit Issues

As implied by the preceding discussion, a nonuniform sample size (or, as in a trench or stratigraphic column, any definable sample size at all) will create subsequent complexities in establishing the volume/variance relation. This problem is not one sided, and it is complicated by the mode of operation in most aggregate mines. A uniform mining block, such as is known in the mining of metalliferous ores, is unheard of in a sand-and-gravel pit. The closest comparison would be to a standard bench height, based on equipment selection or regulatory requirements. Mine planning, at best, will be at the level of benches. However, the goal of geostatistical applications, or even SDA, is not necessarily the generation of a "block model" for a gravel pit that will not be mined in uniform blocks. Instead, the goal may to identify general trends, zones, or the sedimentologic environment at the inpit level, or to identify overall trends and environments at the level of exploration or resource-management plans.

Other Considerations

Beyond these obvious complexities in the use of "classical" geostatistics for aggregate-resource evaluation, the fundamental expression of data must be confronted. For example, will the use of granulometric data, expressed by way of a size-distribution curve, be theoretically sound in terms of its use in a geostatistical framework? Part of this problem has been dealt with previously, such as by the transformation of nonadditive variables. However, the basis of a size-distribution curve—finite points on a graph—presents a spectrum of academic questions beyond the obvious problems within common geostatistical practice. Initially, size fractions (expressed here as mesh sizes #4, #200, and so on) are only finite points on a distribution curve, and when they are evaluated as cumulative percent passing, they are seen to be interdependent—if one size fraction is removed, all the numbers change—and so they cannot be evaluated as independent variates. Cutpoints (expressed here as D_{25}, D_{75}, and so on) and the numerous service variables derived from them) are the converse side of this relation. The complexities inherent in the use of cutpoints are well examined by Arthur (1994). In the broader sense, the academic implications of SDA of particle-size data have been little studied, and skepticism could be considerable.

As suggested above, Arthur (1994) concludes that it is good to use percent retained when attempting to quantify the spatial distribution of individual size fractions, but it is better to use percent passing because it can provide information on the requirements of processing screens or classifiers. From a geostatistical point of view, percent-retained data can be more suitable because they generally conform to either a normal or lognormal distribution, whereas percent-passing data commonly exhibit an inverse lognormal distribution, particularly for the coarser size fractions.

How to Practically Confront These Limitations

General Concepts

Once the theoretical limitations of geostatistical methods in evaluating sand-and-gravel deposits have been identified, the next step is to clearly state how geostatistics in practical terms can be performed. With respect to the preceding discussion, the following three points must be acknowledged.

The practical requirements of the aggregate industry.—Aggregate operators could benefit from deposit modeling, resource and mine planning, and computer-based scheduling. Expensive solutions at a level more complex than their operations will do them no good and will be met with immediate opposition.

The limitations of the data collected by the aggregate sector, as a function of what the mining industry requires at the practical level.—Aggregate operators do not mine their gravel pits on the basis of uniform mining blocks, and so they do not require intensive (and expensive) drilling campaigns that will result in block models which are irrelevant to their operating standards and likely unnecessary. However, aggregate operators have recently tended to collect more deposit data for requirements beyond deposit characterization, and useful data can be extracted from those examinations. For example, particle-size data obtained from a borehole drilled primarily to investigate aquifers, or from a test pit excavated to quantify overburden and topsoil thickness, can be used to aid in deposit characterization.

The possible requirement of modifications to the typical exploration and sampling protocol.—For formal geostatistics to be useful in aggregate-mining operations, sampling standards and protocols will need to be adapted toward this goal. Conversely, if geostatistical applications in aggregate are to be accepted by outside observers (skeptics), then sampling standards and protocols will need to be taken seriously.

If these requirements cannot be met—if the application of geostatistics to evaluating sand-and-gravel deposits is impractical—then one academic step backward in the SDA spectrum may need to be taken, such as earlier successful applications of EDA methodologies within a spatial context (for example, Bliss and Bolm, 2001). Indicator kriging is worth examining because the method is based on thresholds enabling evaluation of cutpoints. However, the successful demonstration of this methodology, as well as its ultimate application in the field, will require various robust datasets on which suitable crossvalidation examinations can be performed. Quantification of the variations of modeling requirements will require the compilation and analysis of data from the full spectrum of sand-and-gravel deposits (flood plain, glacial, catastrophic flood, and marine). If the chosen spatial methodology is initially successful, continues to validate the data, and yields beneficial results when implemented in the field, the concerns of skeptics can be reevaluated if shown to be irrelevant to actual field conditions.

Drilling Programs

With respect to drilling, Arthur (1994) proposes several approaches to improving the success of deposit exploration and characterization programs when geostatistical methods are being considered. Regarding phase I drilling:

- Phase I drilling on a regular, wide-spaced coarse grid of about 100 m will probably not define important characteristics because gravel deposits are naturally highly diverse.
- Shell-and-auger drilling should be used in coarser, gravelly deposits, and reverse-circulation drilling in finer, sandy deposits.
- Drillholes should be sampled at 1-m intervals (or smaller if suggested by lithology or type of sedimentary facies, or both), and each sample analyzed for grading and petrography.
- If the deposit is shallow, test pits should be used to directly assess the characteristics of the deposit, especially the >75-mm size fraction. Additionally, a direct comparison between drillhole samples and face samples could indicate the type and extent of any sampling errors, such as loss of fines by drilling. For example, holes could be drilled behind the advancing face, and then adjacent samples collected when the face advances. This method, however, could be prohibitively expensive.
- If the deposit is coarser, but the characteristics of the fines are important to the final product, shell-and-auger drilling should be supplemented with reverse-circulation drilling. The opposite approach applies for sandier deposits containing coarse material of interest.

  If these measures yield suitable geostatistical results for phase I drilling, the following approaches should influence phase II drilling:
- Geostatistical ranges should influence drillhole spacing, which would consist of at least three holes within the range in each direction of the drilling grid. Small-scale deposit-specific structures should be taken into account.
- Downhole semivariograms can aid in the identification of horizontal structures, if used in conjunction with vertical-grading profiles.
- Zones with different granulometric properties, as quantified by SDA, can provide information on the final products that can be obtained from the deposit. This approach is a first step toward mine planning and "block modeling" of a sand-and-gravel operation.

Proposals for Further Work

To proceed beyond, and take best advantage of, the examinations that have been performed to date, I suggest the following steps:

1. Data from the full spectrum of sand-and-gravel deposits (flood plain, glacial, catastrophic flood, and marine) must be evaluated. Potentially, these data will present varying model types because they represent different depositional environments and mechanics.
2. Such scientists as sedimentologists must be integrated into this research. The geology and mechanics of gravel deposition differ from those of, for example, a porphyry copper ore body. Therefore, geostatistical evaluation of alluvial material will require far different academic considerations from those of metalliferous ore bodies. Pursuing rigorous SDA without understanding the science of orogenesis could lead to improper assumptions and ultimate failure.
3. Other professionals or scientists can assist mining engineers and geologists with insight into such conundrums as the question, because dense drilling grids are required to detect small-scale structures, how do we know where to expend more resources in looking for small-scale structures? From geophysics? From extrapolation of stratigraphic columns in available exposures?
4. With hindsight, Arthur (1994) proposed that serious exploration should have started with a comparative drilling exercise between shell-and-auger, reverse-circulation, and continuous-flight-auger methods. He then suggested that all 1-m-interval samples should be sent for size-grading analysis, coupled with face sampling, to provide information on the precision and accuracy of each method and on the quality of size-grading data expectable from each method.
5. Evaluating data on a point-support basis can be suitable when the goal is to identify general spatial tendencies, trends, or basic zonation in terms of deposit characterization and reconnaissance-level resource planning. Beyond that goal, however, complexities with respect to the volume/variance relation will arise. Considerable theoretical and practical examinations will be needed to overcome this dilemma, and a mixture of theoretical and practical approaches is essential. A routine academic approach could be a formidable encounter. Suppose that the input data are from a few boreholes, test pits, and trenches; the output "spatial model" is, on the x, y plane, pit zones (sectors) and, in the z-direction, a bench height. The best approach may be to derive empirical methods and adapt them on the basis of validation results.
6. Even if support and volume/variance issues are reconciled, complexities from nonadditive variables may still arise. If the variables are explicitly nonadditive (such as skewness or gradation coefficient), mathematical transforms should suffice if given proper treatment. However, if the variables are quality based, such as Los Angeles wear, then such transforms as those used by Peroni and others (1999) will need to be created.
7. Additional sampling requires additional expenditure, which is likely the biggest stumbling block at present.

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