CHAPTER 6: OVERBURDEN SAMPLING CONSIDERATIONS

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INTRODUCTION

This chapter provides guidelines and strategies to adequately assess the vertical and horizontal distribution of rock properties on a mine site as well as the variability in the overburden geochemistry with respect to the potential for acid mine drainage (AMD) formation. The accuracy of overburden analysis, upon which predictions of post-reclamation mine water quality commonly rely, is critically dependant on the sampling procedure used (Donovan and Renton, 1998). The failure of predictions of post-reclamation mine water quality is probably due at least as much to inadequate sampling strategy as it is to inappropriate analytical techniques.

A basic question for anyone attempting to predict AMD prior to mining is whether the sampling strategy representatively (with a predetermined degree of confidence) samples the overburden. Precise analyses performed on an unrepresentative sampling plan will, at best, accurately characterize that unrepresentative population. Another important question is how will that overburden material ultimately affect the chemistry of the mine discharges. The answers to these questions have obvious economic consequences due to the costs of drilling, sampling, and overburden analysis.

Overburden sampling strategies have spatial, vertical, horizontal (sampling density for given geologic units) and temporal (before mine permitting or over the entire life of the mining and reclamation operation) dimensions. The basis of developing a sampling plan varies considerably among sites, among regulatory agencies, and even among permit reviewers. Techniques for sampling overburden range from informal methods based on geological knowledge and rules of thumb to a number of more quantitative methods based on statistics. Among the latter are geostatistical techniques designed to analyze spatially distributed geologic variables, which are used in mineral exploration and reserve calculations. These sampling techniques will be described below and in more detail in Appendix B, where actual mine overburden analysis case studies can be found.

SAMPLING GEOLOGICAL POPULATIONS

The goal of sampling is to collect information about a population. In geological sampling, a sound understanding and knowledge of the geology of the area are key in understanding the nature of the spatial variation of the data being sought and in designing a sampling strategy. This initial discussion introduces broadly applicable principles that are the basis for more specific sampling procedures discussed later in this chapter and is largely based on the fundamental work of Griffiths (1967) and Griffiths and Ondrick (1968).

In the context of evaluating the potential for AMD, the population to be sampled can be defined as the total volume of overburden above the coal seam(s) to be mined. The objective of the sampling is to provide

statistically valid estimates of sulfur and carbonate content of the overburden population. The sulfur and carbonate contents represent measured variables. A variable is a quantity that can assume any of a set of values. Accordingly, we are interested in learning about the quantity, distribution and magnitude of the variability in the data collected for these or any other variables of interest within the population under study. The greater the degree of variability, the greater the number of samples that are generally needed to adequately characterize a site.

We are usually concerned with the total volume of overburden overlying the coal seam(s) to be mined; this is referred to as the *existent population*. However, usually only part of the existent population is actually available for sampling. The available population is that collection of elements that is readily accessible and usually sampled. If the available population represents the existent population and is sampled under the fairly stringent requirements that will provide random samples, we will expect to get results that will adequately describe the existent population. One must invest enough time and money into the sampling program to ensure that the data obtained are reliable and that the interpretations and conclusions based on the sampled available population will apply to the existent population. Obviously, any sampling plan that relies on a single random (drill hole) sample of coal overburden will yield only one mean value for each variable measured, which is unlikely to be representative of the entire overburden population. However, compromises in sampling are often made, resulting in data that are of limited value.

As noted above, a sampling procedure that yields random samples should be followed. Random sampling means that each item in the population has an equal chance of being selected. Random sampling is easy to define, but is usually difficult to achieve in practice. A continuous variable, such as the amount of pyrite or carbonate in overburden, which is randomly distributed, will have a frequency distribution that follows a normal probability distribution model. Random samples from such a population will provide best estimators of the properties being measured. Because of the possible existence of bias in sampling, testing is needed to see if random samples from a known distribution have been achieved. There are a variety of statistical parameters used to test whether the samples collected fit the expected model; these can typically be found in general books on statistical analysis (e.g. Griffiths, 1967).

For stratified geological populations, there are two basic sampling designs. One is to take individual samples across all layers, as in a channel sample. Sampling of an entire section of overburden via a drill hole is equivalent to a channel sample of the entire overburden. Two important parameters of any measured variable are (1) the mean or average and (2) the variance or deviation of the sample values around the mean. One can enhance the degree of precision of the mean and variance of AMD-related variables by simply increasing the number of samples, i.e. drill holes.

The other sampling design for stratified populations is stratified sampling, in which the mean and variance are obtained for each identified layer and the *within-layer* and the *between-layer* statistical estimators can be determined and compared. With appropriate weighting to allow for the thickness of the different layers, an adequate estimate can be obtained for the entire layered population. There are other kinds of variation that could be encountered, including a uniform or massive population and a *patchy* population. A patchy

arrangement can be considered as a special case of a layered arrangement by considering each patch or zone as a layer.

All the above supposes that the arrangement can be discerned at the outset. Sampling sedimentary rocks without knowing the arrangement beforehand has led to the development of a sampling model based on the relative degree of variation between and within samples. If you have a homogeneous or massive population, the relative degree of variation between samples will be small, but the variation within samples will be large. If you have a poorly developed stratified population, the variation between samples will be moderate, and the variation within samples will also be moderate. If you have a well-stratified population, the variation between samples will be large, but the variation within samples will be small.

RATIONAL STEPS IN SAMPLING DESIGN

Sampling in a geological context can be achieved through a number of generic sampling plans or sampling designs. These include multi-stage or hierarchical sampling, in which a large sample unit such as an outcrop or drill core is further subdivided into smaller sample specimens, and these in turn are reduced to the final sample for laboratory or other analysis. Others include: composite sampling, in which a number of individual samples are combined to yield an average value; channel samples (including drill core samples), in which an entire section of overburden is sampled at one time and then further subdivided into subsamples; and stratified [stratified random] samples, in which [random] samples are taken within and between stratigraphic units. There is also cluster sampling, in which sampling is restricted to one or a few particular areas of interest (Griffiths, 1967).

It is generally preferable to do the exploratory drilling first. This preliminary drilling enables the determination of the number of mineable coal seams, maximum and minimum overburden thicknesses (cover heights) and the lateral extent of the various lithologies. This information can then be used to better locate the number and depth of overburden holes to be used for overburden sampling and geochemical analysis. This should yield a valid representation of the lithologic and geochemical variation and the degree of weathering within the site. If this research and exploration is done prior to drilling, it is less likely that additional holes will have to be drilled later in the permitting process. Such a preliminary or reconnaissance sampling program helps to determine the final sampling scheme, both in terms of the number of samples and drill holes, and how they are to be collected. This two-stage process helps to ensure a reasonable degree of confidence that the final sampling will be representative of the geological population under study (Griffiths, 1967). It is as equally important to know and to document the quality of the data collected (see Appendix A).

Site-specific factors should be used to determine the spatial density of an overburden drilling program. The overburden holes must be located within the limits of the proposed mining area. Mine size and layout are also important. A long narrow site may require more drill holes for an accurate characterization than a more rounded site of similar acreage. Mining method and depth of cover will also impact the drilling density. If only shallow cover is to be affected, drill holes in high cover will not accurately reflect the overburden quality. Depth of the weathered zone, topography, stratigraphic variations, and geochemistry will also affect the number of drilling locations, as discussed in Chapter 2 and in Brady et al. (1988). Some holes must be

located at maximum highwall conditions, and the holes must represent all of the strata to be encountered by mining. Other holes should be located under low and average cover conditions to provide representative sampling of the overburden where zones may be missing or may have been altered due to surface weathering (Tarantino and Shaffer, 1998). Exploratory drill holes also may indicate significant facies changes across a site, which would need to be delineated by the overburden analysis holes.

SAMPLING METHODS

Sampling of overburden material was outlined in great detail by Noll et al. (1988). Overburden material is generally sampled by drilling (mainly air rotary or core drilling) or channel sampling. Channel sampling (manual collection of rock samples without a drill rig) is conducted at fresh exposures of the overlying strata, generally along a highwall. The advantages and disadvantages of various sampling techniques along with remedies for problems associated with each sampling type are summarized in Table 6.1.

Air Rotary Rig: Normal Circulation

Air rotary drilling is probably the most common method of sampling overburden. Drilling in this manner breaks the rock into small fragments and uses air to blow the rock chips to the surface where they are collected. The rock chips are bagged and the depth interval sampled is determined. The most common pitfall with normal circulation air rotary drilling is that the individual samples of stratum can be contaminated by an overlying sample zone as the rock chips are blown up the annular space of the drill hole. There is a lag time between drilling a unit and when it is sampled at the surface, caused by the travel time of the rock chips. This becomes especially troublesome as the depth increases and/or when a relatively thin potentially acidic unit is encountered. However, periodically halting drilling and purging the rock chips from the hole can minimize such problems.

The rock chips traveling in the annular drill hole space can dislodge loose particles from an overlying source. Care should be taken to stop the downward progression of the drill stem after each interval has been sampled and to allow any loose particles to blow out prior to continuing downward. Contamination of the sample can also occur at the surface due to the pile of ejected material that forms near the drill hole. These piled materials, if not removed during drilling, can slough back into the open hole and the chip stream. This can be avoided by shoveling the materials away from the hole during the period when drilling is stopped to blow out the hole. Another option is to add a short length of casing to the top of the hole after the upper few feet have been collected. Samples are collected by placing a shovel under the chip stream. Care should be taken to clean the shovel of any accumulated materials from previous usage or sampling. This is particularly important in sampling of wet test holes where the ejecta consist primarily of mud. Before drilling the overburden hole, the driller should be instructed to also clean the dust collector hood to remove any accumulated materials that may dislodge and contaminate the samples being collected.

Air Rotary Rig: Reverse Circulation

This type of drill rig is less commonly used as a drilling platform for the collection of overburden samples than normal circulation rigs, primarily because of availability. A reverse circulation rig uses

Table 6.1. Comparison of Overburden Sampling Techniques

Sampling Type	***Advantages***	***Disadvantages***	***Remedy***
Air Rotary (Normal Circulation)	Very common; drill rigs readily available; fast and inexpensive; less sample processing (crushing) than core drilling.	Potential for cross contamination problems from intermixing; difficult drilling spoil, till or refuse; lack of data regarding fracture systems; and difficulty in determining exact elevation of specific lithologic units and perched water zones.	Halt drilling and purge rock chips from hole; use reverse circulation air rotary for drilling spoil, till or refuse.
Air Rotary (Reverse Circulation)	No cross contamination problems; cleaner and faster than normal circulation air rotary, does not need to be stopped to blow out hole; excellent for unconsolidated materials; less sample processing than core drilling.	Less common than normal circulation air rotary; drill rigs may not be available.	
Diamond Core	Provides a continuous record of the lithology not readily available from rock chips; little chance of cross-strata contamination of lithologic materials.	More expensive due to drilling time and sample recovery and preparation (crushing); problems with core loss.	Use as a secondary means of data collection to isolate previously identified problem zones, or as a primary sampling tool in the area of the coal, i.e. the interval 5 feet above and below the coal horizon.
Auger		Limited depth and great potential for cross contamination and intermixing.	Use for unconsolidated homogeneous strata only; i.e. glacial till or uniform spoil or refuse.
Channel Sampling (Highwall)		Limited to active or abandoned sites with exposures; not always representative; (lithology different from proposed mine area); getting fresh unweathered samples and a vertically continuous sample of the entire strata may require backhoe or excavator; dangers associated with highwalls; sampling and weighting problems due to breaking resistance.	Limit to supplement air rotary or diamond core data; get fresh samples only.

a double-walled drill stem through which water or air is forced down the outer section of the drill stem and the cuttings/chips are forced up the inner section of the drill stem. The cuttings and water or air are brought into a separator and dropped near the rig where the samples can be collected. The samples are isolated from contact with overlying strata, so this type of drilling offers a much cleaner and quicker means of obtaining overburden samples. The drilling does not need to be stopped to blow out the hole. If water is employed in the drilling process, the materials are also washed free of the fine dust coating that accumulates

on the chips during drilling with air. This allows for much easier identification and logging of rock type than is the case for Normal Circulation rotary rigs.

Diamond Core

Core drilling is also a common exploration technique and is an excellent method of sampling the overburden, provided that core recovery is essentially complete. As a rule, core drilling improves the validity and quality of rock samples compared to air rotary. Diamond core barrels can be used on both types of rotary drilling platforms. Coring provides a continuous record of the lithology present with little chance of cross-strata contamination of lithologic materials and can provide the geologist with more information than can be obtained by the collection of rock chips (cuttings). Cores provide a better overall view of the lithology underlying a proposed site by providing the geologist with the ability to judge rock color, gross mineralogy, grain size/texture, fossil content and relative hardness. Fracture zones and any associated mineralization can be evaluated in considerable detail. This type of information is not always readily available from rock chips. Although a core provides an uncontaminated and better source of reliable lithologic data than air rotary drilling does, coring is very time consuming and costly, especially if the entire overburden section is to be sampled by this means. Diamond cores can be used as a secondary means of data collection to isolate previously identified problem zones, or as a primary sampling tool in the area of the coal, i.e. the interval 5 feet above and below the coal horizon. The entire core section must be collected and processed for analysis to ensure representative sampling. Successful coring is mostly dependent upon the experience of the on-site geologist, project engineer, or driller.

A problem that can occur with coring is core loss. This normally occurs when encountering mine voids or solution channels, but is also a common problem in the first 10 feet (3 m) or so of unconsolidated soil and rocks and in the transition through weathered rock into competent rock. Core recovery on the order of only 50 to 60% or less is not unusual for such material. When drilling is done in the unweathered zone (sometimes indicated by an absence of iron staining), core recovery approaching 100% is the norm rather than the exception.

When coring the coal, it is advisable to use a core barrel long enough to core the entire thickness of the coal. It is preferable to have a nearly empty core barrel containing only 6 to 12 inches (15 to 30 cm) of overburden, and at most one that is not more than 20% full when first encountering the coal. The small amount of overburden aids in determining if the entire coal section has been sampled; i.e., knowing the starting and ending points of the coal. It also helps protect the coal from being crushed by the ram when extracting the coal from the core barrel (Personal Communication, Clifford Dodge, Richard Beam, William Marks).

Besides actual core loss encountered while drilling, drilling data can also be lost due to the improper handling of the cores. Common problems include placing cores in the core boxes in the wrong order or upside down, and damage caused to the core during handling and shipping.

Augering

Auger drilling is not recommended for general overburden sampling. It is typically used for unconsolidated or highly weathered materials. The auger lifts the materials on the auger screw. The potential for contamination is high in that the material being lifted is in constant contact with the overlying stratum, thus providing for intermixing. However, augering can be successfully used in homogeneous materials such as glacial till and/or old mine spoil.

Channel Sampling (Highwall)

Samples can be collected directly from an open source, such as a highwall within or near a proposed permit area, for overburden analysis provided several caveats are understood. First, samples might be weathered to such a degree that they do not represent the strata to be mined. Second, the availability and accessibility of highwalls limit highwall sampling. Therefore, care should be taken to collect only unweathered samples from the highwalls in close proximity to and representative of the proposed mining. It is recommended that open source (outcrop, highwall, etc.) samples be used primarily as a supplement to drilled samples.

Overburden Sampling Practices

The ADTI Prediction Work Group surveyed various states to determine how overburden sampling is practiced in the eastern coal producing states. The results are given below. These practices have, in large measure, governed overburden sampling frequency. All of the states surveyed, except Virginia, have some minimum spatial distribution requirements for overburden analysis that must be supplemented upon request from the reviewing professional(s). Even though the states have stated minimum spatial requirements, few new permits are considered with data supplied by the applicant that only meets the minimum requirements. Table 6.2 gives minimum overburden sampling requirements by State.

In addition, all of the states have minimum requirements for vertical sampling intervals. The most commonly submitted sampling data is collected from rotary drill cuttings and core splits; however, all the states will accept fresh highwall samples to extend existing permits. Table 6.3 gives minimum overburden interval sampling requirements by State.

SAMPLING DESIGN CONSIDERATIONS AND GUIDELINES

Relevance to Acid Base Accounting

A critical factor in the use of Acid Base Accounting (ABA) methods (see Chapter 4) is the suitability of the overburden sampling scheme for extrapolation to mine scale. While generalized rules of thumb are being used, no consistent scheme based on either theory or empirical evidence exists for determining the number or spatial distribution of samples required to characterize a given site for ABA. Horizontal drillhole spacings that will provide reasonably accurate ABA estimates are still being debated. In current practice, estimates of NP/MPA are obtained from relatively sparse drillhole sample densities, with one sample representing every 2-5 vertical feet (Tarantino and Shaffer, 1998). Core and rotary samples are normally employed. For example, West Virginia requires that NP and MPA data be derived from core drilling samples, but does not

specify the minimum number of cores. Pennsylvania has found that the 6 to 7 holes it typically requires per 100 acres is generally sufficient to accurately predict whether a site will produce acidic or alkaline water (Brady et al., 1994).

As mentioned in Chapter 1, the collective experience of the ADTI Coal Sector is that Pennsylvania's experience can be generalized though site-specific criteria may require more intense or less intense sampling. Also, ABA should not be used alone for predictions; it is but one of several tools in the mine drainage prediction toolbox. For example, Pennsylvania recognizes that if sufficient information exists from adjoining sites, no overburden analysis at all may be necessary. Further discussion on this subject can be found later in this chapter in the section on Stratigraphic Considerations-Lateral Variation and Number and Distribution of Boreholes.

Table 6.2. Minimum Overburden Sampling Requirements

STATE	MINIMUM REQUIREMENT
AL	Two sample point locations on small permit properties (<10 acres). One sample point location per 160 acres, or one per property quarter on larger permits.
IL, IN	A minimum of one sample point required. Adjacent mine sampling points can be submitted to supplement site specific data. In general, accepts any information submitted by the applicant, considers the quantity, quality, and consistency of the overburden analysis for the permit area, and then makes a decision on whether a reasonable characterization of the site is possible based on the spatial distribution provided.
KY	Eastern KY—sample points should be distributed on a staggered, ¼ mile grid pattern. Western KY—sample points should be distributed on a staggered, ½ mile grid pattern.
MD	One sample point location per site regardless of size.
OH	One geologic test hole for each 25 acres, or fraction thereof, of coal stripped. At least one hole must be located at the point of highest elevation. Holes must be located as far apart as the size and shape of the area to be mined will allow and must be drilled to the bottom of the material underlying the lowest coal seam to be mined. Additional test holes may be required in order to verify the submitted data. Core drilling may be required if it is determined that site conditions warrant more precise information. The applicant may request a waiver for the number of test holes prior to application submittal if equivalent information is available.
PA	Two sample point locations per site regardless of size. However, a rule-of-thumb of 2 holes per site plus 1 hole per 100 acres is usually requested. On average, most applications contain 6-7 overburden analysis hole for every 100 permit acres. These requirements may be waived if it can be demonstrated that equivalent information is available to characterize the AMD potential of the site.
TN	One sample point location per 60-100 acres for permits to mine coal considered a high risk for AMD, based on past experience. One sample point location per mile in coal considered a low risk for AMD.
VA	In general, accepts any information submitted by the applicant, considers the quantity, quality, and consistency of the overburden analysis for the permit area, and then makes a decision on whether a reasonable characterization of the site is possible based on the spatial distribution provided.
WV	At least one hole in low cover and one in high cover. Otherwise, WV permits geologists to use their best professional judgement when determining the number of ABA boreholes required for a permit. In general, accepts any information submitted by the applicant, considers the quantity, quality, and consistency of the overburden analysis for the permit area, and then makes a decision on whether a reasonable characterization of the site is possible based on the spatial distribution provided.

Table 6.3. Minimum Overburden Interval Sampling Requirements

STATE	INTERVAL SAMPLING REQUIREMENTS
AL	One sample every 5 feet or at a significant lithologic change, whichever comes first. Sample compositing is not allowed. AL reserves the right to request core drilling in permit areas where there are known acid-forming lithologic units.
IL	One sample required for each lithologic unit. A composite sample is acceptable for thin, adjacent units. A composite or multiple samples are acceptable for units that exceed 5 feet.
IN	One sample required for lithologic units 0.5-5 feet thick, two samples recommended for strata 5-10 feet thick, and, for strata more than 10 feet thick, one sample every 5 feet or at a significant color or lithologic change, whichever comes first.
KY	One sample for suspected acid-producing strata and coal seams less than 1 foot thick; smaller strata and seams may be grouped with next lower unit. One sample within the lithologic unit for strata 1-5 feet thick. Two samples for strata ranging from 5-10 feet thick. One sample every 5 feet for strata more than 10 feet thick.
MD	For rotary drill cuttings, one sample every foot or at a significant lithologic change. For core samples, 3 foot composite samples or at a significant lithologic change.
OH	Each stratum and coal seam must be analyzed. In practice, sampling intervals greater than 20 feet are discouraged. Requests for waivers from overburden analysis must be submitted prior to application and must document that equivalent information is available.
PA	One sample per 3 vertical feet or at a lithologic change plus 1 foot above and below the coal bed. Rotary drill samples must be collected in 1 foot increments that then can be composited up to 3 feet. Core sample composites limited to 3 foot increments regardless of unit thickness; an equal portion of the entire core length must also be crushed and split for analysis.
TN	One sample every 3 feet or at a significant lithologic change, whichever comes first.
VA	Sobek, et. al. (1978) protocol: one sample every 5 feet for sandstone units; one sample every 3 feet for other lithologies.
WV	One sample every 5 feet or at a significant lithologic change, whichever comes first. Sample compositing is not allowed. Sobek et. al. (1978) followed as the official guide (one sample every 5 feet for sandstone units; one sample every 3 feet for other lithologies). Permit geologists also refer to NPDES, DMR discharge data, and other historical data from adjacent operations in the same seam.

Inherent spatial variation in NP and MPA can be caused by stratigraphy, lithology and/or the effects of weathering. The critical issue is, therefore, the sampling strategy and sampling density required to provide adequate ABA assessments. Also, within a mine setting, compositional variations exist not only between rock facies but also within individual facies, where spatial variations exist both in vertical sequence and in lateral extent (Renton et al., 1989).

As a result of spatial variations in geologic facies, the geochemistry of coal and coal overburden materials display some degree of order over large distances, and overburden samples from different drilling locations need not be treated as being statistically independent (Caruccio and Geidel, 1982; Tarantino and Shaffer, 1998). The development of acid production may be caused by either the distribution of high concentrations of pyrite or by the paucity of carbonate minerals capable of neutralization. The possibility that pyrite may display a *nugget effect* requiring very small sample densities has been raised based on the commonly asymmetric univariate sampling distribution of rock sulfur concentrations (Rymer and Stiller, 1989). Some

site-specific information on the spatial covariance of sulfur and carbonate is included in Appendix B (New Allegheny Mine, West Virginia Case Study); see also Donovan and Renton (1998).

Geologic Considerations Involved in Sampling Design

Numerous geologic factors affecting mine drainage prediction were discussed in Chapter 2 of this volume. Several of these geologic factors affect sampling design, including surface weathering and facies variations. In addition, proper correlation of stratigraphic units is an essential consideration in sampling, because there are a number of legitimate geologic reasons why there can be significant variations in sulfur content, NP, or other parameters in samples of the same stratigraphic interval from different drill holes. Without proper correlation, one cannot be certain of the lateral distribution of rock types, cannot design special handling plans, cannot accurately design a mining plan, and cannot accurately determine alkaline addition rates. Miscorrelation of coal seams or other stratigraphic units introduces an unnecessary source of variation and increases confusion and complexity in making accurate predictions of mine drainage quality.

The geologic considerations in sampling design affect both lateral variations (i.e. how many drill holes at what spacing) and vertical variations (i.e. how deep must the drill holes be; sampling interval within lithologic units) in obtaining representative samples of the overburden strata at a mine site. A description of these geologic considerations in sampling design, with examples from drill holes, is presented below. Additional information is contained in Chapter 2.

Surface Weathering Effects

Weathering results in the near-surface removal of carbonates and sulfide minerals; carbonates by dissolution and sulfides by oxidation. This zone is usually recognizable by the yellow-red hues (indicative of oxidized iron) of the rocks. Generally, in the unglaciated portions of the Appalachian Plateau, the intensely weathered zone extends to 20-60 feet (6-20 m) below the surface. Chemical weathering of bedrock is enhanced by physical factors such as stress-relief fracturing on hill slopes and bedding-plane separations due to unloading. Clark and Ciolkosz (1988) have suggested that periglacial conditions during the Pleistocene contributed to the shattering of near-surface rock. Shattering of rock increases surface area and thus accelerates weathering. These processes acting together also increase the permeability of the weathered zone. The ground water associated with the weathered zone is dilute, in terms of dissolved solids, because readily soluble products have been removed by chemical weathering (Brady, 1998).

Chemical weathering is also influenced by lithology. Coarser, more permeable lithologies may allow oxidation to extend to a greater depth. Kirkaldie (1991) measured the depth of the highly weathered zone. He noted that the maximum thickness of highly weathered rock was 28.9 feet (8.8 m) in sandstone, and only 11 feet (3.3 m) in shale. His observations were based on the physical appearances during drilling and may not directly correlate with chemical weathering.

This weathered-rock zone exists throughout the Appalachian Plateau. It is difficult to determine precise rules of thumb for the depth of leaching of carbonates and oxidation of pyrite because these minerals can only occur where they were originally present (before weathering). If no pyrite was ever present within a

stratigraphic horizon, its absence is not due to weathering, but to the fact that it was never there in the first place. The same is true for calcareous strata. Smith et al. (1974) investigated the effects of weathering on the Mahoning sandstone in northern West Virginia, and noted a "pyrite-free weathered zone approximating 20 feet (6 m) of depth below the land surface." Singh et al. (1982), in addition to noting the pyrite-free zone, also noted a loss of alkaline earth elements within 20 feet (6 m). Brady et al. (1988; 1998) in a study of the upper Kittanning and lower Freeport overburden in Fayette County, PA noted a similar loss of calcareous rocks in the near-surface weathered zone to about 6 m (20 feet) depth. Hawkins et al. (1996) noted weathering to depths of 30-60 feet (10-20 m). Brady et al. (1998) concluded that rarely do NPs greater than 30 tons of $CaCO_3$ per thousand tons or sulfur greater than 0.5% occur within 20 feet (6 m) of the surface in Pennsylvania. This conclusion can probably be generalized for the entire region, based on the fact that shallow groundwater chemistry, which represents water associated with the shallow weathered zone, had low concentrations of ions regardless of geographic location (Brady, 1998).

An accurate knowledge of the extent (depth) of the weathered zone is important from an overburden sampling standpoint. Overburden sampling must adequately represent both the weathered zone and unweathered bedrock. This will entail drilling overburden test holes at maximum cover to be mined and at lesser cover. Drilling only maximum cover or only lower cover overburden holes will probably not adequately define the overburden chemistry of the entire mine.

An understanding of the effects of weathering on the distribution of pyrite and carbonates is important in: (1) accurately defining their stratigraphic distribution within unmined overburden, (2) designing mine plans to prevent post-mining problems, and (3) accurately predicting post-mining water quality. An understanding of the weathering profile is just as important as understanding the lateral and vertical distribution of strata and their pyrite (sulfur) and carbonate content. Adequate characterization of the site is necessary to predict post-mining water quality. It is also necessary for designing pollution prevention measures such as calculating alkaline addition rates and designing special handling plans.

Facies Changes and Other Paleodepositional / Paleoenvironmental Considerations

Rather abrupt changes in overburden lithology can occur due to facies changes, where lateral variations in depositional environments result in contemporaneous deposition of an array of different sediments. For example, in modern coastal zone, barrier-island settings, a transition from beach and dune sands to back-bay brackish black muds to alluvial channel sands may be seen in a lateral distance of a mile to several miles inland from the ocean. A similar array of lithologic units occurs in Pennsylvanian Age coal-measure sedimentary rocks where the overburden above a coal seam may vary from sandstone to shale within a similar lateral distance. This becomes a significant sampling design problem. Generally, a sufficient number of initial exploration and overburden analysis holes must be drilled in order to delineate the facies changes and obtain representative samples of the different lithologic units.

Paleodepositional factors may also affect the vertical distribution of sulfur within a lithologic unit, and consequently have an effect on representative sampling within a drill hole. Numerous studies on the vertical distribution of sulfur and coal have been done for coals around the world, encompassing various geologic periods and ranges of coal rank. Increased sulfur at the top and bottom of coal seams appears to be the

rule rather than the exception, according to Brady et al. (1998) who cite numerous references for coals of the Appalachian Basin. Reidenour (1966) has shown that distribution of sulfur in the Lower Kittanning coal of western Pennsylvania may be significantly affected by local paleotopographic variations, hypothetically attributable to preferential deposition of pyrite in channels whose location in the paleotopograhic lows was controlled by differential deposition and compaction of peat. How to address such vertical variations in sulfur in sampling design is addressed later in this chapter.

Large-scale paleoenvironmental factors influence the distribution of pyrite and carbonate minerals within overburden strata and consequent mine drainage quality, as described in Chapter 2. The array of marine, brackish, and freshwater paleoenvironments of overburden strata for specific coal seams is typically mapped at the regional scale from fossil assemblages (e.g. Williams, 1960), and thus may not be particularly relevant to sampling designs for a single coal mine site. However, information about lateral variations in sulfur content gained from studies concerning these paleoenvironments may be useful in determining how many drill holes are necessary to obtain representative samples and characterize variations in overburden geochemistry at a mine site. For example, Williams and Keith (1963) found regional variations in total sulfur content of the Lower Kittanning Coal in western Pennsylvania, where areas with marine overburden were higher in sulfur than freshwater paleoenvironments. Hornberger (1985) conducted a preliminary sampling study of channel samples of the Lower Kittanning coal and overlying shale in western Pennsylvania in order to test the hypothesis that variations in coal mine drainage production could be attributed to systematic variations in pyritic sulfur content and the abundance of the framboidal form of pyrite between paleoenvironments. Three widely spaced channel samples were collected from the active highwall in each of four surface mines, two from a marine paleoenvironment and two from a freshwater paleoenvironment. While the mean total sulfur and pyritic sulfur content of the freshwater mines was somewhat less than that of the marine mines, an Analysis of Variance (ANOVA) showed that the largest percent of the variance in pyritic sulfur was due to the high variability between channel samples within the mines. (Additional data from that ANOVA study is included in a case study in Appendix B). Another example of high within-mine variability was found by Rooney (1997, personal communication), who used the Pennsylvania Department of Environmental Protection (PA DEP) overburden analysis database to compare NP/MPA ratios for three drill holes from each of three mines in freshwater, brackish, and marine paleoenvironment (nine mines total). The brackish mines generally had lower NP/MPA ratios than the freshwater and marine mines, indicating a greater potential for AMD production, but the variability between drill holes within the same mine is very large for some of these mines. These examples indicate that it may take much more than three drill holes or channel samples per mine in order to characterize patterns of sulfur content variations.

Stratigraphic Considerations-Lateral Variation and Number and Distribution of Boreholes

It is important to adequately represent any spatial lithologic variation by drilling enough boreholes. On an areal basis, a four and one-half inch diameter core is only sampling approximately one four hundred thousandth of an acre. The WV Surface Mine Drainage Task Force's Suggested Guidelines for Surface Mining in Potentially Acid-Producing Areas (1979) recommends that all surface mining in potentially acid-producing areas be within 1 km (approximately 3300 feet) of a sampled overburden analysis hole or highwall. Donaldson and Renton (1984) and Donaldson and Eble (1991) indicated that although cores

spaced up to 2 miles (3 km) apart in the Pittsburgh coal were adequate to reflect major thickness and sulfur trends, this spacing was not adequate for mine design. They felt that lateral Pittsburgh sampling at intervals on the order of 1200 to 1400 feet (365 to 427 m), or less than 500 feet (152 m) for the Waynesburg coal, along with geostatistics, are necessary to determine small-scale sulfur content trends.

Predictions based on overburden analysis require that the drill holes analyzed be representative of the strata present at a site. The more variability that exists in the overburden strata, the more likely it is that, for a fixed drilling density, the samples will not accurately represent the entire mine site. Increasing sampling density is one option to compensate for such variability, but this also increases drilling and analytical costs. While overburden sampling density is a critical component of the prediction process, there are no generally accepted methods currently in use for determining the number or spatial distribution of drill holes required to representatively characterize mine sites.

The geologic systems responsible for the deposition and alteration of the sediments and their chemical quality do not operate in a completely random fashion at the cubic centimeter level and, thus, do not produce overburden samples that are statistically independent (Tarantino and Shaffer, 1998). Although there are exceptions, most of the geologic systems, especially those that produce calcareous material, operate over large areas with some degree of order, and deposit laterally pervasive units (Caruccio and Geidel, 1982). Lateral continuity has also been observed in high sulfur strata. Facies changes can provide variations in lithology and the degree of surface weathering can cause changes to the percent total sulfur and NP over short distances. Therefore, it is imperative to know the areal extent of any alkaline or acidic material, high energy paleodepositional environments (for example, channel sandstones), and the degree or depth of weathering. Adequate exploratory drilling is essential to the development of a representative overburden sampling plan.

A recent study suggested that sulfur is not uniformly distributed in a homogeneous fashion, but is distributed in clusters of hot spots similar to large chips of chocolate in a cake. If this is true, accurately determining the mean percent total sulfur of a particular stratum would be difficult, which could in turn lead to under-predicting the potential to produce AMD (Rymer and Stiller, 1989). However, concern over the clustering effect neglects certain factors, one of which is that the concentration of total sulfur at a mine site may not be the critical factor of whether or not AMD will be produced. Acidity produced in laboratory experiments appears only to be strongly related to percent total sulfur for sulfur values above 1.0 part per thousand with acidity production being negligible for sulfur of lesser value unless there is a paucity of NP (Rose et al., 1983). However, experience has shown that in the field, sulfur as low as 0.5% (and possibly somewhat less) can be a problem. As discussed elsewhere in this volume, the presence of significant NP appears to be the more critical factor.

Another factor to consider is that the tendency for the mean percent total sulfur at a site to be skewed to the right is probably just a natural distribution of data involving the plotting of a quantity where the left boundary or minimum abscissa is zero, and there is essentially no right boundary. For example, most sulfur values in coal overburden are less than 0.5%; a rare few are as high as 10 to 20%. Pure pyrite has a

percent sulfur of 53.4% (the maximum right-hand value). Thus, a few high values will skew data to the right. This is a commonly observed distribution in geologic data (Koch and Link, 1980).

Current West Virginia Division of Environmental Protection (WV DEP) regulations require that a company submit NP and MPA data collected from samples acquired from core drilling; however, no regulations exist as to the minimum number of cores. In some cases, pre-mining environmental assessments have been made based on data from a single core.

Pennsylvania has grappled with overburden drill hole distribution since the advent of overburden sampling. The PA DEP bases its requirements on the mine-site specifics, if it is deemed necessary that the overburden be drilled. A minimum of 2 to as many as 15 holes per 100 acres might be required per mine site (Brady et al., 1994; Tarantino and Shaffer, 1998). The average number of holes for a typical site is 6 to 7 holes per 100 acres, with a high of 43 holes per 100 acres and a low of 2 holes per 100 acres.

A rule of thumb developed in Pennsylvania in the 1980s to determine a suggested minimum number of overburden holes was:

Number of Overburden Holes = (Number of acres to be mined/100) + 2

If this calculation resulted in a fraction, it was rounded to the closest whole number. For example, 3 holes were required for 143 acres, 2 holes per 49.9 acres, and 4 holes per 179 acres. The division factor for hectares (ha) is 40.47 rather than 100. This method assumed that for mines where overburden analysis was requested, at least 2 holes were needed to determine whether the drilling was representative. More recent data from Pennsylvania show that the actual sampling density for ABA drill holes is greater than the rule of thumb. A recent survey revealed that on average, there was one hole for each 15.5 acres (6.3 ha) of coal removal for 38 sites (Table 6.4). A similar survey of 31 Small Operator Assistance Program applications received in the 1993 calendar year revealed that on average there was one hole for each 18.8 acres (7.6 ha) of coal removed, as shown in Table 6.5.

Table 6.4 Number of acres per overburden analysis (OBA) hole (Brady et al., 1994).

Number of Applications =38	Coal Area acres (ha)	Area per OBA hole acres (ha)	Number of holes per 100 acres (40.47 ha) (rounded to next whole number)
Mean	43.5 (17.6)	15.5 (6.3)	7
Median	30.3 (12.3)	11.9 (4.8)	
Minimum	5.0 (2.0)	2.3 (0.9)	
Maximum	172.5 (69.8)	44.9 (18.2)	
Standard Deviation	38.0 (15.4)	10.6 (4.3)	

Table 6.5 Number of acres per overburden analysis (OBA) hole based on SOAP applications received in 1993 (Tarantino and Shaffer, 1998).

Number of Applications: 31	Coal Area acres (ha)	Area per OBA hole acres (ha)	Number of holes per 100 acres (40.47 ha) (rounded to next whole number)
Mean	72.6 (29.4)	18.8 (7.6)	6
Median	55.0 (22.3)	15.7 (6.4)	
Minimum	6.0 (2.4)	3.0 (1.2)	
Maximum	220 (89.0)	53.5 (21.7)	

Standard Deviation	54.6 (22.1)	12.3 (5.0)	

The ranges in the data are due to a multitude of factors, such as stratigraphic complexity and shape of the site and availability of other prediction tools. The data apply only to permit applications that had overburden analysis data. Approximately 30 to 40% of Pennsylvania's applications do not require submittal of overburden analysis because of the availability of equivalent prediction data, including data from adjacent mine sites. A variety of geological/geochemical clues can provide insight into the presence of acidity- or alkalinity-producing materials. Such clues might include:

- Exploratory drill hole data, to determine the lateral and vertical extent of rock types.
- Premining water chemistry in springs, drill holes and monitoring or water supply wells completed in or hydrologically related to the coal seams being mined. Both shallow and deep aquifers should be examined, but water from zones much deeper than the coal will probably not be useful. As a rule of thumb, if alkaline water is present, alkaline rocks are probably present.
- Water quality from adjacent mining sites within the same coal seam
- Maps and studies of paleodepositional environments
- The extent of glaciation and the carbonate content of glacial drift or till, where present
- The presence of burned out vegetation areas on adjacent mining areas
- Soil surveys can provide information on the variability of the host rock the soil was derived from. They also provide some information on depth of weathering and carbonate content.

These clues can help define the extent and degree of variability of the overburden and in some cases may preclude the need for overburden analysis. Alternatively, where overburden analysis is indicated, these same data also provide information necessary to locate overburden holes to adequately represent the entire site (Tarantino and Shaffer, 1998).

Vertical Sampling Intervals

All distinct discrete lithologic units should be sampled separately. In the northern Appalachian basin, the common lithologic units include: sandstone, limestone, shale (including siltstone and claystone) and coal. The composition of these units can range widely. For example, sandstones can have a calcareous cement and shales can be calcareous or carbonaceous. Noll et al. (1988) use a somewhat different terminology for these rock units. They divided overburden rock units into sandstone, mudrock, limestone, coal, carbolith, intercalate, glacial till, and glacial outwash. The difference in the glacial units is that glacial outwash is stratified and glacial till is not. Sandstone must have over 50% sand-sized (less than 2 mm diameter) quartz particles. The term mudrock is broad and includes mudstone, siltstone, claystone, and shale. Limestones are composed of at least 50% calcium carbonate and should fizz aggressively with 10% HCl. Carbolith is any black or dark colored unit that contains 25-50% by weight carbonaceous matter (coal contains greater than 50% carbonaceous matter by weight). This term includes bone and waste coal, as well as carbonaceous mudrock. Intercalate is a unit which is composed of two or more rock types that are finely interbedded. Because of the high degree of interbedding, individual units cannot be sampled separately. In

other parts of the Appalachian Basin, this definition of lithologic units may have to be modified to allow for different units or conditions peculiar to a given geology.

The sampling interval for indurated strata should not exceed 3 feet within lithologically consistent units, according to Noll et al. (1988). Sobek et al. (1978) suggested that a sampling interval of 5 feet for sandstones and 3 feet for other rock types was adequate, although larger intervals may be considered adequate in various jurisdictions. Determining breaks in the sampling interval within monolithic units can be somewhat subjective, depending on the experience of the geological professional. However, within monolithic units, sampling breaks should occur where significant color, mineralogical, or grain size changes occur. Skousen et al. (1987) suggest sampling intervals as thin as 12 cm, especially if they exhibit a darker color (dark gray or black), which may be indicative of a high carbonaceous content. Sampling breaks should also occur at changes in sedimentary structure (e.g., a change from a cross-bedded to a massive sandstone) and at zones of significant fracturing or jointing. Location within the stratigraphic column can also determine the thickness of the sampling interval (e.g., intensive sampling of the strata directly overlying and underlying the coal). Some units commonly exhibit significant differences in terms of sulfur values compared to adjacent lithologically similar strata. For example, when a sandstone unit rests directly on top of a coal bed, the bottom few feet of that unit commonly exhibit much higher sulfur concentrations than the rest of the unit (diPretoro and Rauch, 1988; Donaldson et al., 1979). Mineralogical changes, inclusions (e.g., coal spars, clay or siderite nodules, clay veins, etc.), secondary mineral deposits (e.g., fracture filling by calcite ($CaCO_3$), and weathered zones should all influence the sampling interval.

There are several criteria for determining the sampling intervals of overburden. The required sampling interval for unconsolidated material (i.e., mine spoil, coal refuse, glacial deposits, and alluvium) should not exceed 5 feet in some jurisdictions, while it can in others (such as up to 10 feet in Texas). Additional sampling breaks within these units are subject to the variability of the material and the experience of the geologic professional. However, at the very least, unaltered portions should be separated from weathered or leached portions. It should be noted that it is neither pragmatic nor economically feasible to break samples out at each minor change. The sampling and compositing of the overburden should be conducted so as to minimize the number of samples to be tested, without significantly decreasing the quality of the overburden characterization. As an example, the mixing of thin high sulfur content strata with adjacent strata can lead to a conclusion that a much larger volume of material must be specially handled than if the sampling intervals were fine enough to resolve the smaller volumes of problematic strata.

The opposite effect can be observed in Table 6.6. In that example, if one assumes (for the sake of argument) that 0.5% sulfur is the threshold above which a unit is considered acid producing, a stratum with greater than 0.5% sulfur would be diluted to less than this value if it was combined with an adjacent low sulfur stratum. Dilution would cause one to under-predict the acid producing potential. For example, if the bottom-most unit on Table 6.6, a 1 foot thick black shale with a 2.34% sulfur content, was combined with the overlying rock, a sandstone with 0.01% sulfur content, a composite sample with a misleading average of 0.48% would be produced. This fine balance lies at the center of controversy between regulatory agencies and mining companies. While there are a number of statistically-based schemes of sampling, in the

final analysis, the development of representative sampling is dependent on the professional skill of the geologist who obtains the samples in the field.

Therefore, sampling intervals should not be increased to the point that there is no clear visual resolution of the individual stratigraphic units. A worst case scenario would be to simply collect one composite sample for an entire drill hole. In most cases, the percentage of sulfur and NP would be very low, but this would not mean that there were no strata within the drill log that have significant amounts of sulfur and NP.

Table 6.6. Compositing of too many 1-foot (0.3 m) intervals can under-predict acid producing potential (Tarantino and Shaffer, 1998).

Thickness (ft.)	Total %S	Lithology	Avg. %S of Interval			
1	**0.01**	**sandstone**				**0.48**
1	**0.01**	**sandstone**			**0.59**	
1	**0.01**	**sandstone**		**0.79**		
1	**0.01**	**sandstone**	**1.18**			
1	**2.34**	**black shale**				

Representative Interval Samples

Noll et al. (1988) do not discuss the subtle complexity of ensuring accurate, non-biased, representative samples. They do stress that it is critical that 100% of the sample volume be included for a sample interval for compositing purposes, because of possible geochemical variations within the three-foot (0.9 m) interval. The ultimate sample size used in ABA assessments is 1 g for total percent sulfur and 2 g for the NP test. Therefore, assuming no loss or contamination of the zone being sampled, only 1 to 2 g are tested out of a 25,550 g sample (based upon a 4.5 inch (11.4 cm) diameter drill bit and using an average rock density of 170 lbs/ft^3 (2,723 kg/m^3)). This means that only one out of every 10 billion g contained in a 3-foot interval over an acre is being tested for percent sulfur. Fortunately, sample preparation procedures have been developed to obtain representative small sample aliquots.

Sobek et al. (1978) suggested that a 5 inch (12.7cm) section out of the middle of a 1 foot interval of core can be assumed to be representative of that interval. The best way to ensure representativeness is to sample the entire interval. To avoid bias, one of the following two methods is recommended:

- The entire core interval having the same log description as described above, whether it be a 1, 2, or 3 foot (0.3, 0.6, or 0.9 m) interval, must be entirely crushed and reduced in size via a riffle or rotating splitter until a suitable size fraction remains for analysis.

- The entire core length should be bisected longitudinally using a core-splitter or saw. One-half of the core is retained for historical records and possible additional testing. The other half of the core is crushed for

the entire sampling interval. After crushing, the entire sample is divided and reduced in size via a riffle or rotating splitter until a suitable size fraction remains for chemical analysis.

There are three reasons for splitting and crushing samples:

1. To reduce the bulk (amount) of a geological sample.
2. To provide an unbiased statistically representative sample of small quantity, which can be used in a laboratory for ABA or leaching tests
3. To reduce samples to a small size fraction that maximizes surface area and minimizes the analytical time.

Guidelines for Drilling and Sampling Overburden and Coal at Surface Mine Sites

The following are general guidelines for incorporating geologic considerations in sampling design to account for lateral and vertical variations in geochemical parameters in an attempt to collect representative samples of the strata. The first four guidelines for determining the number and spacing of overburden analysis drill holes on a mine site are largely based upon the common sense application of geologic principles. The last spatial consideration is more difficult to describe or quantify because it attempts to answer the question of how variable is the mineralogy of samples from the same strata within the mine site or from the same stratigraphic interval and resultant mine drainage quality at nearby mine sites. Usually, this question cannot be answered until some overburden analysis holes have been drilled and the sample results have been evaluated, and that evaluation may require the use of geostatistical tools.

- A sufficient number of exploratory drill holes should be drilled throughout a proposed mine site, prior to determining the number, locations and depth of overburden analysis drill holes. These exploration drill holes are routinely used on most mine sites to determine the number and thickness of mineable coal on site (i.e. coal reserves), and the maximum overburden thickness that is economically practical (i.e. stripping ratio). It is very important to perform a geologic evaluation of these exploratory drill holes (i.e. drill cores and/or rock chips) to correlate coal seams and other stratigraphic units throughout the site, and to determine if there are significant variations in lithologic characteristics or thickness of stratigraphic units within the site.
- The first consideration is determining the number and spacing of overburden analysis drill holes on a proposed mine site is related to mining engineering and geology. Most surface mining sites are designed, operated and reclaimed in a series of mining phases. At least one overburden analysis drill holes should be located within the initial mining phase. The placement of the other holes should consider the spatial configuration of the mine site and significant variations in stratigraphy and lithology that will be encountered in the progression of mining phases.
- At least one of the overburden analysis drill holes should be located at the maximum highwall height (maximum cover) and at least one of the overburden analysis drill holes should be located at much lesser cover, in order to evaluate surface weathering effects. (This is not intended to imply that two drill holes will be sufficient to characterize geochemical variability of any mine site.) In the areas of the mine site with low cover, the weathered-rock zone may be more than half of the overburden. For example, a thick shale within this weathered zone may have the top 25 feet fortuitously leached of most of the pyritic sulfur content, but also be leached of most of the carbonate minerals.

- If facies changes occur within the mine site, a sufficient number of exploratory or overburden analysis drill holes are needed to delineate the pattern of facies changes (i.e. paleoenvironmental map) throughout the site. Within each of the major stratigraphic sequences relating to the facies changes (eg. freshwater calcareous shale replaced by thick channel sandstone overburden), a sufficient number of overburden analysis drill holes should be located to obtain representative samples of the lithologic differences.
- A single overburden analysis drill hole is almost never sufficient to characterize the overburden quality of even the smallest of proposed mine sites, because it tells nothing about variability within the mine site and whether that single sample is representative.

The case studies of geostatistical techniques that follow provide examples of how variability of geochemical parameters can be quantified within and between mine sites. In areas of high lateral variability of total sulfur contents or other parameters of interest, it may be necessary to drill many more holes than implied from the preceding four guidelines, in order to adequately characterize these patterns of variation and obtain representative samples.

GEOSTATISTICAL APPROACHES

A large variety of statistical and quantitative techniques are available to evaluate data obtained from overburden sampling and to extrapolate the resulting information to the population represented by the samples. Basic statistical measures include the average or mean value of a measured variable or variables and the variance or the degree of variation around the mean. Statistical procedures in use in geological studies include frequency distribution analysis and analysis of variance procedures. More sophisticated techniques specifically designed to evaluate spatially distributed variables, such as variography, kriging, and three-dimensional modeling, are also being used. The following discussion is provided to illustrate the usefulness of these techniques in overburden sampling for AMD prediction. Some case studies giving more detail on the particular methods are provided in Appendix B. Readers are referred to the many basic works on statistical evaluations in geological studies, such as Koch and Link (1980), Griffiths (1967), and Krumbein and Graybill (1965). Recent works on geostatistics include ASTM Technical Publication 1238, Geostatistics for Environmental and Geotechnical Appications (ASTM, 1996), Practical Geostatistics 2000 (Clark and Harper, 2000), and Introduction to Geostatistics, Applications in Hydrogeology (Kitanidis, 1997). See also the many references noted in the discussion below and in the accompanying case studies.

Analysis of Variance

The analysis of variance (ANOVA) statistical method is commonly used in geological studies. Numerous examples of one-way and two-way classifications and more complex ANOVA models are described in early works by Griffiths (1967), Krumbein and Graybill (1965), Miller and Kahn (1962), Chayes and Fairbain (1951) in petrology, Griffiths et al. (1953) in petrography, Krumbein and Tukey (1956), and many more recent studies.

ANOVA techniques depend on the important property that the variance of a sum of random variables is equal to the sum of the variances of these random variables, provided that these variables are uncorrelated.

If, under these conditions, two or more uncorrelated factors introduce variability into a set of data, the total variability can be divided into individual portions that add up to the total. Each source of variation can then be evaluated to assess its relative contributions to the total variability in the observations (Krumbein and Graybill, 1965).

In the context of sampling geological populations, ANOVA techniques have at least two important uses. The first is to evaluate the results of reconnaissance sampling studies in order to determine if the number of samples collected per site is adequate to solve the geological problem, and if other aspects of the sampling plan are sufficient to implement a full scale sampling of the population. The second is to provide statistical tools to make meaningful interpretations and inferences about the variability of properties or portions of the geological populations under study.

A case study illustrating the use of analysis of variance techniques is provided in Appendix B. This example is based on a sampling study by Hornberger (1985), who examined variations in sulfur content, framboidal pyrite occurrence, and leachate chemistry of the Lower Kittanning coal and overlying shale at surface mines in western Pennsylvania. This case study shows how analysis of variance can provide meaningful information about the variability in sampling data and the sampling design.

Variography and Kriging

In addition to traditional univariate statistics, extensive geostatistical literature exists on determining optimal sampling patterns for estimating mean values of spatially distributed variables (Tarantino and Shaffer, 1998). Nearly all geological properties exhibit heterogeneity, either of a random type or displaying some degree of scale-dependent spatial covariation. Covariance is the tendency for samples close to each other to be similar in some property (e.g., sulfur concentration averaged for two nearby vertical boreholes). The identification of spatial covariance structure is called *variography*, and is performed by sampling at a very detailed scale and calculating covariance empirically at a variety of separation intervals, i.e. groupings of sample pairs (Armstrong, 1984; Journel and Huijbregts, 1978). The results of such an analysis (termed variograms, semivariograms, or correlograms, depending on the variance scaling employed) contain useful information on the covariance of spatially-distributed (or regionalized) variables (Isaaks and Srivastava, 1988). This information on the spatial covariance structure may be applied to estimate sampling needs or to interpolate values between points where information is available, i.e. to contour the data. Successful interpolation schemes obey the covariance structure indicated by the measured data, and minimize or eliminate error between observed data and interpolated values, called *residuals*.

One technique commonly applied to interpolation is *kriging*. Linear kriging, the most commonly applied, produces the best linear unbiased estimate of a variable within a given area based on values at known locations and weighting factors, estimated from variography to minimize residuals (Journel and Huijbregts, 1978). Application of linear kriging assumes that the sampled property is at least weakly *stationary* (spatially uniform with respect to mean and variance), i.e. there is no large-scale spatial trend within the area of study. Kriging across a field with a pronounced trend may require de-trending of the data set prior to analysis. However, kriged estimates employing a trend or *drift* (also known as *universal kriging*) may also be performed, by incorporating the drift into the weighting functions.

Both kriging and variography imply that both local scale variance (*noise*) and large-scale variance (*trend*) are present in observed datasets and, in principle, may be distinguished from, and perhaps separated from, each other. In practice, distinction of noise from trend may be subject to considerable error in estimation, and frequently requires large samples. The application to mine-overburden sampling is to allow estimation of sample number and frequency to distinguish trends in the presence of noise.

Case studies on the application of variography to overburden sampling and characterization are provided in Appendix B. The first one is a study on the application of variography to NP, MPA, NNP, and mineralogy in coal measures at working mines in West Virginia, based on work done by Donovan and Renton (1998). The second describes the use of variography to evaluate the AMD potential of overburden associated with mining operations in South Central Tennessee, based on work done by the Office of Surface Mining's Knoxville Tennessee Field Office (Office of Surface Mining, 1997, 1998). These studies show how variography can be used to detect primary spatial trends in overburden data and to estimate optimal sample spacing.

Visualization and Three-Dimensional Modeling

Visualization and three-dimensional modeling software can be used to portray the three-dimensional characteristics of subsurface overburden units and to produce three-dimensional models. The three-dimensional models can be used to accurately estimate the volumes of overburden materials that are potentially acid-forming. ***earthVision,*** by Dynamic Graphics, Inc. of Alameda, CA, is one of a number of such software packages that have been applied to AMD assessments of mining operations. ***earthVision*** software is included in the set of engineering and scientific software tools known as the Technical Information Processing System (TIPS) of the Office of Surface Mining. The TIPS system is available to permit reviewers and reclamation specialists on UNIX workstations in Federal, State and Tribal regulatory agency offices in all coal producing states to assist in the regulation and reclamation of coal mines. In 2000, TIPS plans to distribute a windows NT version of ***earthVision*** that will enable permit reviewers to utilize the software from their desktops.

Such software can be used to interpret, analyze, interpolate, and present spatially-distributed two-dimensional or three-dimensional data. Data may be analyzed statistically by exploratory data analysis (EDA) techniques including B clustering, three-dimensional viewing, histograms, probability and distribution analysis, regression, and declustering. The spatial covariance may be analyzed by conventional variography, using spherical, exponential, gaussian, or power-law models. Kriging may be accomplished using linear, ordinary, universal, or co-kriging algorithms. The kriged spatial distributions may be integrated to yield volumetric statistics, such as estimation of average or total property values. Volumetric analysis is enhanced using sub-cell sampling, allowing relatively high precision in the volumetric estimates. For overburden analysis, it may be used to estimate ABA from vertical samples over three-dimensional volumes or two-dimensional areas of interest.

A case study illustrating the application of ***earthVision*** to coal overburden data is provided in Appendix B. This case study, which evaluated overburden characteristics of a large surface mine in Eastern Texas, is based on work done by Behum and Joseph (1997). Three-dimensional models of overburden

characteristics and volumetric calculations of selected overburden zones were produced. This study shows how visualization and three-dimensional modeling software can be useful in AMD prediction and mine planning.

FINDINGS AND RECOMMENDATIONS

The following are our general findings and recommendations on overburden sampling based on the material presented in this chapter:

- Proper overburden sampling and analysis can result in accurate predictions of the potential for AMD prior to mining. However, there is no single way to sample overburden that fits all cases. Instead, there are a variety of tools that can be used to sample overburden. Methods need to be chosen based on site-specific conditions to fulfill the goal of collecting representative overburden samples.
- Accurate water quality predictions and design of pollution prevention techniques can only occur if the sampling strategy and density adequately represents the site variability. The greater the variability in the overburden, the greater the number of samples that are generally needed to adequately characterize a site.
- Predictions based on overburden analysis require that the drill hole or other samples analyzed be representative of the strata present at a site. Increasing sampling density is one option to compensate for such variability, but this also increases drilling and analytical costs. Any sampling plan that relies on a single random (drill hole) sample of coal overburden will yield only one mean value for each variable measured, which may not be representative of the entire overburden population.
- It is necessary to invest the time and money necessary to conduct appropriate sampling to ensure that the data obtained are reliable. Precise analyses performed on an unrepresentative sampling plan will, at best, accurately characterize that unrepresentative portion of the population.
- Sampling should be a two-step process, a preliminary reconnaissance sampling followed by a final sampling plan. While there are a number of statistically based schemes of sampling, in the final analysis, the development of representative sampling is dependent on the professional skills of the geologist who obtains the samples in the field.
- A sound understanding and knowledge of the geology of the area to be sampled are essential in designing a representative sampling strategy. Overburden sampling strategies need to consider both *spatial* and *temporal* factors; i.e., lateral and vertical sampling density of the geological units being sampled and whether sampling should continue over the entire life of the mining and reclamation operation.
- The geologic systems responsible for the deposition and alteration of the sediments and their chemical quality do not operate in a completely random fashion at the cubic centimeter level and, thus, do not produce overburden samples that are statistically independent.
- Near-surface weathering can alter overburden chemistry by decreasing pyrite and carbonate concentrations (by oxidation and dissolution respectively). The effects of weathering can influence the distribution of overburden mineralogy just as dramatically as other geologic processes, such as paleoenvironmental factors. For a site with variable overburden thickness, a sufficient number of high

and low cover overburden holes must be drilled to assure adequate and representative sampling.

- Local overburden sections can include a variety of facies and paleoenvironments. These, in turn, result in compositional variations between rock facies and within individual facies. Spatial variations exist vertically and laterally. Paleodepositional environments influence relative abundances of pyrite and carbonate. If facies changes occur within the mine site, a sufficient number of exploratory or overburden analysis drill holes are needed to delineate the pattern of facies changes (i.e. paleoenvironmental map) throughout the site. Within each of the major stratigraphic sequences relating to the facies changes (e.g. freshwater calcareous shale replaced by thick channel sandstone overburden), a sufficient number of overburden analysis drill holes should be located to obtain representative samples of the different lithologies.
- In order to identify areas of the proposed mine site that may differ from the general stratigraphic conditions, it is helpful to look at, among other things, exploratory drilling logs and groundwater quality. These can provide insight into the presence of acidity- or alkalinity-producing materials and can help define the extent and degree of variability of the overburden so that overburden holes can be located to adequately represent the entire site.
- Conventional air rotary drilling is probably the most common method of sampling overburden; however, air rotary-reverse circulation drilling, although less commonly used, offers a much cleaner and quicker means of obtaining overburden samples. Although core drilling provides a better overall source of reliable lithologic data than air rotary drilling, it is very time consuming and costly. At a minimum, diamond cores should be used as a secondary means of data collection to isolate and zoom in on previously identified problem zones.
- Most surface mining sites are designed, operated and reclaimed in a series of mining phases. One of the overburden analysis drill holes should be located within the initial mining phase; the location of other overburden analysis drill holes should consider the spatial configuration of the mine site and significant variations in stratigraphy and lithology that will be encountered in the progression of mining phases.
- At least one of the overburden analysis drill holes should be located at the maximum highwall height (maximum cover) and at least one of the overburden analysis drill holes should be located at much lesser cover, in order to evaluate surface weathering effects.
- Experience has shown that a minimum of three and more typically six or seven holes per 100 acres are necessary to capture the geologic variability of a site. However, the number of holes needed may vary up or down depending on local site conditions.
- Overburden analysis may not be necessary, if equivalent information is available from adjacent mining, pre-mining water quality, and other site characterization data.
- Analysis of Variance (ANOVA) techniques have at least two important uses: (1) to evaluate the results of reconnaissance sampling studies in order to determine if the number of samples collected per site is adequate to represent the area of study, and (2) to serve as a statistical tool to interpret and infer the degree of variability of the geological populations under study.
- The geostatistical methods of variography and kriging are valuable for determining optimal sampling patterns for estimating mean values of spatially distributed variables and to interpolate values between

points where information is available, i.e. to contour the data.

- Software is available that can perform interpretation, analysis, interpolation, and presentation of spatially-distributed distributed two-dimensional or three-dimensional data. The software may be used to estimate, among other things, ABA from overburden analysis data over three-dimensional volumes or two-dimensional areas of interest. Data may be analyzed using ordinary statistics and by variography and kriging. Kriged distributions may be integrated with a volumetric analysis to yield relatively high precision volumetric statistics of overburden property values. It should be noted that if mine permit data is submitted electronically, time-consuming data entry can be eliminated. Also, coal seams that are to be mined should be modeled separately to ensure these zones can be eliminated in the volumetrics.

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