Appendix B—CHAPTER 6 CASE STUDIES

ANALYSIS OF VARIANCE (ANOVA)

Lower Kittanning Coal, Pennsylvania

The ANOVA example described below is from a reconnaissance sampling study of Lower Kittanning Coal samples from marine and freshwater paleoenvironments in Pennsylvania (Hornberger, 1985)* . This preliminary sampling study was conducted to determine if three channel samples of coal and/or overlying shale per surface mine would be sufficient to characterize any significant differences in sulfur content, pyrite morphology, and leachate quality between paleoenvironments. Three channel samples of the exposed Lower Kittanning coal and the first three feet of the immediately overlying shale were collected in four strip mines in Armstrong, Jefferson, Lawrence, and Somerset Counties. The Lawrence and Somerset County mines were characterized by a shale of freshwater paleoenvironment. The mines in Armstrong and Jefferson Counties were characterized by a marine shale overlying the Lower Kittanning coal.

The channel samples were collected at widely spaced intervals within the mine sites, and were obtained in accordance with the sample collection procedures outlined by Schopf (1960). The samples were subsequently crushed with a jaw crusher to a nominal quarter inch (6.35mm) size. After crushing, the samples were riffled and split to obtain representative samples for sulfur analyses, leaching studies, and the preparation of polished pellets for reflected light microscopy.

Variations in sulfur content data, framboidal pyrite count data, and leachate chemistry data were statistically examined with ANOVA techniques to determine the magnitude of and significance attributable to variations: between paleoenvironments, between mines of the same paleoenvironment, and within mines (i.e., between channel sample replicates plus error). The total sulfur contents of the Lower Kittanning coal samples are shown in Figure 6.1. The pyritic sulfur, sulfate sulfur, and organic sulfur fractions are also shown to illustrate variations within and among mines and paleoenvironments.

In the ANOVA procedure, the sum of squares (i.e. squared deviations for each source of variation) and mean squares, which are variance estimates computed by dividing the sum of squares by the appropriate degrees of freedom (generally, the number of variables minus 1), are calculated. Tables 6.7a-c show estimated percentages of the total variance attributable to each of the component sources of variation by the total sum of squares. The results for the sulfur forms data are shown in Table 6.7a, along with a one-way ANOVA for each of the sulfur variables. Considering the organic sulfur content, for example, approximately 58% of the variation in the data occurs at the paleoenvironmental level (i.e., between marine and freshwater settings), while approximately 29% occurs between mines, and approximately 14% of the variation remains within mines (i.e., between channel sample replicates plus error).

While division with the sums of squares provides a quick survey of the percentage of the variance

* References for Appendix B can be found at the end of Chapter 6, starting on page 165.

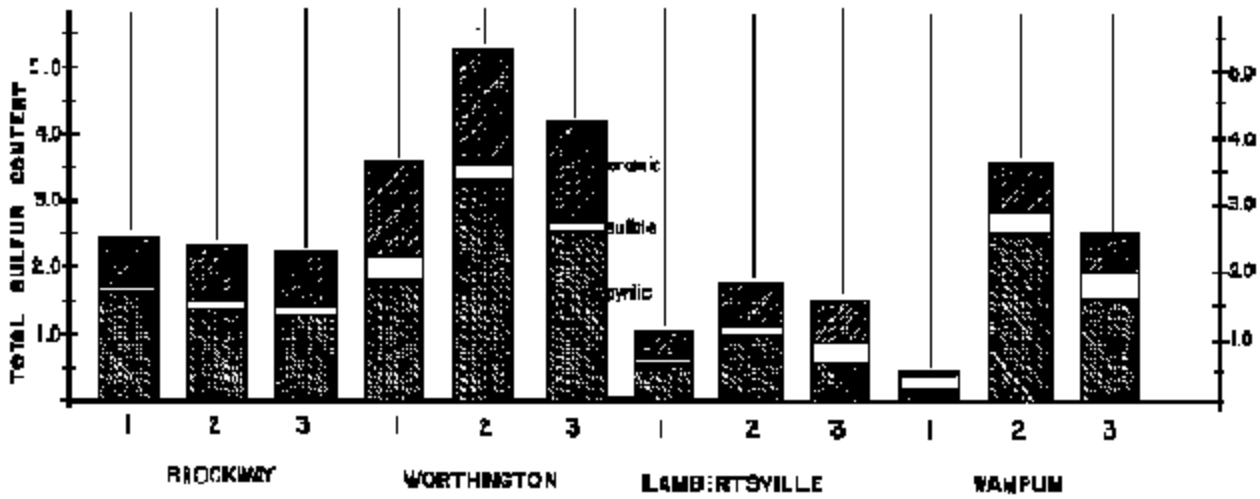

Figure 6.1. Sulfur content of Lower Kittanning Coal samples from marine and freshwater paleoenvironments.

explained at each level of the hierarchical experimental design, the F-test or variance ratio test is a formal test of significance. For example, it can be used to determine if the variance attributed to paleoenvironment is significantly different than the error. The value of the component with the greater expected mean square (i.e., paleoenvironment) is divided by the error mean square, and the quotient may be compared to values in a reference table such as in Arkin and Colton (1963).

The F-test and significance levels are shown for the sulfur data in Table 6.7a, where the F value of 33.351 for the organic sulfur data is sufficiently large that there is less than one chance in 10,000 that a value of that magnitude would occur purely by chance. As a result of ANOVA of total sulfur contents and the contents of pyritic, sulfate, and organic forms of sulfur, it was found that variations in organic sulfur content of the coal samples were highly significant between paleoenvironments while pyritic sulfur variations were not. The mean pyritic sulfur content of samples from a marine paleoenvironment is higher than that of the freshwater paleoenvironment, as was true for the organic sulfur content. However, in this study, the major portion of the variance in the pyritic sulfur data remains at the within-mine level of channel sample replicates plus error.

Previous studies have examined the association of the framboidal form of pyrite and other pyrite morphologies with various depositional environments (e.g., Reyes-Navarro and Davis, 1976), and the significance of framboidal pyrite in acid mine drainage production (e.g., Carruccio and Parizek, 1968; Carruccio et al., 1977). Polished pellets made from representative splits of the Lower Kittanning coal samples were examined by reflected light microscopy in order to test the significance of variations in framboidal pyrite occurrences in the array of coal samples. The pellet mounts of the samples were constructed and polished as described in Reyes-Navarro and Davis (1976, p. 52-54). The microscope was equipped with a point-count stage and had a 10-point grid inserted in the ocular. All pyrite occurrences within the field of view were examined during a continuous scan of a 10mm traverse; the pellet was then moved 1mm perpendicular to the completed traverse, and this procedure was repeated until ten traverses

of 10 mm had been scanned. Four classes were established for counting purposes. Two were for discrete classical framboids (less than or greater than 10 microns in diameter). The other two were for clusters of euhedral microcrysts and intergrowths of framboids in which individual framboids could not readily be discerned or counted (having a long dimension less than or greater than 10 microns (Carruccio et al., 1977; Love and Amstutz, 1966; Rickard, 1970).

TABLE 6.7a. Analysis of variance summary table of sulfur content data

Percent of Variance Estimated (from Sums of Squares) F-Test Mean

	P	M	R&E	P/E	Significance Level	Marine Mines	Freshwater Mines
Pyritic Sulfur	26.0	27.8	46.2	4.493	0.0669	2.027	1.133
Sulfate Sulfur	6.7	62.2	31.0	1.736	0.2242	0.162	0.218
Organic Sulfur	57.5	28.8	13.8	33.351	0.0000	1.160	0.505
Total Sulfur	33.2	33.3	33.4	7.960	0.0224	3.348	1.857

Table 6.7b. Analysis of Variance Summary Table of Framboidal Pyrite Occurrence

Percent of Variance (Estimated from Sums of Squares) F-Test Mean

	P	M	R&E	P/E	Significance Level	Marine Mines	Freshwater Mines
Raw Count Data							
Discrete, less than 10 microns	77.3	0.1	22.6	27.331	0.0000	50.833	0.833
Discrete, greater than 10 microns	23.8	12.1	64.1	2.970	0.1231	2.50	0.167
Clusters, greater than 10 microns	76.4	7.7	15.9	38.404	0.0000	16.50	0.667
Clusters, less than 10 microns	94.4	2.4	3.2	234.472	0.0000	113.33	7.000
Total Framboids	91.2	1.1	7.7	95.306	0.0000	183.17	8.667
Square Root Transformed Data							
Discrete, less than 10 microns	89.5	1.1	9.4	76.318	0.0000	6.996	0.50
Discrete, greater than 10 microns	53.2	6.8	40.0	10.629	0.0115	1.402	0.167
Clusters, greater than 10 microns	86.7	5.3	8.0	86.795	0.0000	4.000	0.455
Clusters, less than 10 microns	94.5	0.9	4.6	163.621	0.0000	10.616	2.381
Total Framboids	94.4	0.4	5.2	145.932	0.0000	13.466	2.653

Table 6.7c. Analysis of Variance Summary Table for Leachate Data
Percent of Variance Estimated (from Sums of Squares) F-Test Mean

	P	M	R&E	P/E	Significance Level	Marine Mines	Freshwater Mines
pH	26.9	0.9	72.2	2.611	0.1502	2.559	3.003
Net Acidity	11.7	14.8	73.5	1.114	0.3262	3.216	2.894
Conductivity	5.0	30.8	64.2	0.549	0.4827	3.623	3.544
Sulfate	23.0	4.3	72.7	2.216	0.1802	3.417	2.043

P = Paleoenvironments; M = Mines (within paleoenvironments); R & E = Replicates plus Error

This data is shown in Table 6.8. The results of the ANOVA of the untransformed (raw) and transformed data of the framboidal pyrite point counts are shown in Table 6.7b. Count data are on a discontinuous scale (i.e., as compared to measurement data on a continuous scale) and as such, are typically related to a binomial, a Poisson, or another discrete frequency distribution. A square root transformation of such data is often appropriate (Griffiths, 1967; Krumbein and Graybill, 1965; Tukey, 1977).

A one-way ANOVA was computed on the untransformed and square-root transformed counts of framboidal pyrite in the Lower Kittanning coal samples according to the hierarchical sampling plan of marine and freshwater paleoenvironments, mines within paleoenvironments, and channel sample replicates within the mines. The results of these analyses are shown in Table 6.7b in the same format as the sulfur analyses. As most of the variance explained occurs at the paleoenvironment level, it is obvious that significant differences exist in the abundance of framboidal pyrite in the sampled marine and freshwater paleoenvironmental settings. On the basis of the assembled data on Lower Kittanning coal samples shown in Tables 6.7b and 6.8, there is little doubt that framboidal pyrite is preferentially deposited in marine paleoenvironments and somewhat rare in freshwater paleoenvironmental settings.

The leachate chemistry data used in the ANOVA in Table 6.7c were obtained from simple leaching columns that were used and described in a series of studies (Hornberger, 1985; Hornberger et al., 1981; Morrison, 1988; Rose et al., 1985; Waters, 1981; Williams et al., 1982, 1985). These test procedures include elements of leaching column tests and humidity cell tests that are discussed in detail in Chapter 4 of this volume. The leachate chemistry data in Hornberger et al. (1981, 1985) were expressed as either fast drained (i.e. one-hour contact) or one-week-contact values. This was based on how long the influent water was in contact with the coal sample before the effluent was removed for chemical analyses during each of several weeks of testing.

Using the same procedures as described for analysis of the sulfur data, an analysis of variance was performed on the pH, net acidity, conductivity and sulfate data. These analyses of the leachate data are summarized in Table 6.7c, wherein it is evident that a large portion of the variation (e.g., 64 to 74%) in the leachate data (i.e., pH, net acidity, conductivity, and sulfates) was attributable to variations within mines (i.e., replicates plus error). Differences in leachate quality between paleoenvironments were not significant.

The portion of the total variance of the channel sample replicates plus error level was much greater than the portions of the variance at the mines and paleoenvironments levels for pyritic sulfur and the leachate chemistry variables. This preliminary or reconnaissance sampling study demonstrated that the sampling design must be modified in order to obtain more stable estimates of the means and variances for these variables. Stated another way, there is so much variation between the three channel samples per mine for the variables that these samples cannot be used to detect meaningful differences between marine and freshwater paleoenvironments, even if significant differences actually exist within these populations.

Table 6.8. Abundance of Framboidal Pyrite in Lower Kittanning Coal Samples

Location	Framboids Less than 10 microns	Framboids Greater than 10 microns	Framboidal Clusters Greater than 10 microns	Framboidal Clusters Less than 10 microns	Total Framboids
Brockway No. 1	69	9	12	106	196
Brockway No. 2	50	1	10	101	162
Brockway No. 3	36	1	17	97	151
Worthington No. 1	23	1	14	101	139
Worthington No. 2	80	2	29	139	250
Worthington No. 3	47	1	17	136	201
Lambertsville No. 1	1	0	1	1	3
Lambertsville No. 2	0	0	0	4	4
Lambertsville No. 3	4	1	3	16	24
Wampum No. 1	0	0	0	2	2
Wampum No. 2	0	0	0	4	4
Wampum No. 3	0	0	0	15	15

There are several options to consider in revising the sampling design to address this type of large within-mine variance. For example, one could collect a much larger number of channel samples within each mine (e.g., three closely spaced channel sample replicates at each of three widely spaced sample sites within each mine = nine samples per mine). Alternatively, one could use the means of the three channel sample replicates in the example above rather than the individual measurements. One could also make composite samples by combining representative splits of the three channel sample replicates in the example above to reduce the laboratory analytical costs from nine samples to three samples per mine. In discussing how to determine the number of samples (n) to be collected, Griffiths (1967) depicts the relationship between the standard error of the mean, $\sigma_{\bar{x}}$ (where σ is the sample standard deviation and $\bar{x}$ is the sample mean), and sample size (n) in simple random sampling, and states:

> It may be demonstrated under very general conditions that with a small number of specimens each composed of a few measurements, the means of the samples show less variability than the individual measurements (p. 21). Now let us suppose we have a good estimate of σ ; we can then reduce $\sigma_{\bar{x}}$ by increasing *n*.... Increasing *n* from one to four reduces $\sigma_{\bar{x}}$ to half its value, and increasing *n* to 16 reduces the value of $\sigma_{\bar{x}}$ to a quarter of its original value. This becomes an expensive way of increasing precision in many experiments because of the rapid increase in *n*.... The larger the number of measurements, the greater the precision; or, written in another way, the numbers of samples chosen should be proportional to the magnitude of the variability. If one material varies twice as much as another in some property under investigation, then, for equal precision in mean values, there should be four times the number of measurements in the more variable material than in the less variable.

The results of this ANOVA case study have also been applied to evaluating overburden analysis data in the Pennsylvania DEP data base using data on the Lower Kittanning overburden geochemistry described in Brady et al. (1998). A preliminary study with an experimental design similar to the above case study was completed by DEP personnel (Rooney, 1998, personal communication), wherein three mines in each of three paleoenvironments (i.e. marine, brackish, and freshwater) were selected, and the available overburden drill holes were the sample replicates. This preliminary study indicated that some differences in the total sulfur content and neutralization potential values of the Lower Kittanning overburden strata existed between paleoenvironments, but that more samples were needed (i.e., more mines and drill holes) to determine if these inferred differences were actually statistically significant. A much more extensive study is planned to commence when ongoing upgrades to the DEP overburden data base have been completed. That proposed study will include all relevant drill holes from a much larger number of mines within these paleoenvironments.

VARIOGRAPHY AND KRIGING

New Allegheny Mine, West Virginia

The variography example described below is from a study done by Donovan and Renton (1998). To demonstrate the application of geostatistical methods to NP, MPA, NNP, and mineralogy in coal measures, an experiment was performed estimating overburden characteristics from a large number of drill holes placed at close distances in a working mine site. The samples were collected from cuttings of air-rotary holes drilled for setting explosives to break up overburden in advance of mining. The data generated in this study employed detailed sampling substantially exceeding that commonly employed in practice. The drill holes were spaced a minimum of 10 feet apart over a section of highwall 300 feet long.

The New Allegheny Mine (NAM) is located approximately 5 km east of Mt. Storm in Grant County, West Virginia, just south of the Maryland-West Virginia border. Samples were collected using air-rotary drilling, then analyzed for carbonate and sulfur as well as mineralogy. Analytical methods selected excluded alkalinity from siderite or potential acidity from non-pyritic sulfur. Patterns of spatial co-variation were then analyzed using conventional geostatistical techniques, fitting variance models to the spatial distribution of each variable. Specific goals of this analysis were to analyze the relative importance of small-scale variation (i.e.,

variations in properties at distances <30m) in ABA determination, and to estimate the drill hole separation at which variance in properties must be sampled to give sound predictive ABA estimates.

All variables (NP, MPA, and NNP (NP minus MPA); mineral percentages for calcite, dolomite, siderite, pyrite, total clays, and total carbonates) were vertically averaged for each drillhole location, weighting each sample linearly based on the sampling interval thickness. The dataset was thus treated as a two-dimensional array. Variography was performed on the vertically-averaged results for each hole using geostatistical routines included in the VARIOWIN package (Pannatier, 1995). Pair-comparison files (separation distance and variable values for each pair of locations) were prepared for each variable. Both semivariograms (covariance versus sample separation) and correlograms (correlation versus sample separation) were prepared using groupings of sample pairs classed by separation distance in 10 foot increments. The number of pairs in each interval group was 50 or higher, except for the interval group containing the most widely spaced pairs (the variogram tails), which are commonly statistically weak (Isaacs and Srivastava, 1989). Variogram models of exponential form were fit to the field data.

Parameters for each curve-fit included the sill (the variance approached asymptotically at large separation; essentially the maximum variance) and range (the distance at which the variogram value of the variance is 95% of the sill). The fitting was weighted towards the near-field (<100 feet) pairs, with variance at greater separations attributed to large-scale non-stationary spatial trends. No removal of spatial trends or reduction in non-stationarity was performed prior to variogram analysis, because the principal objective was to determine the spatial interval over which local-scale interpolation might be feasible.

Samples were collected from three sub-areas within the mine. Block 1 (12 drill holes, each 42 feet deep, sample interval 3 feet) was located stratigraphically above the Upper Kitanning coal. Block 2 (19 drill holes, each 21 feet deep, sample interval 3 feet) sampled the interval above the lower Freeport coal. Block 3 (15 drill holes, each 21 feet deep, sample interval 3 feet) sampled the stratigraphic interval above the Upper Freeport coal bed. Blocks 1 and 3 were immediately adjacent to each other, while Block 2 was approximately 150 feet north of Block 1 along the same highwall.

The sub-areas were separated by distances within which no samples were collected. As a result, the variograms are gapped in some separation intervals. Again, the large separation intervals contain information primarily on non-stationary differences (i.e., trends) between sub-areas or stratigraphic intervals. These differences may be significant at the scale of an entire mine but were not of principal interest in this investigation. Variograms show systematic increases in covariance with separation for variables that have strong large-scale spatial trends and uniform covariance with respect to separation for more stationary variables.

Table 6.9 shows the results of core 246-023 for ABA using continuous sample splits taken at 1-foot intervals. The NP data contain no siderite. This entire sequence is the target of mining at NAM. The overburden sequence is only weakly acidic (net NNP=-1.3). Vertical averaging sample results yields the following results:

Table 6.9. ABA results for core hole 246-023 at NAM (Donovan and Renton, 1998).

	NP	MPA	NNP
Mean	5.0	6.3	-1.3
Standard Deviation	5.6	12.0	14.7

Thus, as an entire sequence, the overburden for the NAM Pennsylvanian rocks are very slightly acidic, with localized zones of both high sulfur and carbonate content.

Figure 6.2 shows the distribution (from top to bottom) of NP, MPA, and NNP for all NAM samples (n = 53). NP (mean = 2.9) is approximately normally distributed with the exception of a pronounced mode at very low (near detection) values. The distribution for MPA is very similar in appearance, with a mean of 6.7 and a pronounced mode of near-undetectable values. In both cases, the low-concentration modes are comprised wholly of Block 3 (Upper Freeport), which exhibits low values of both sulfur and carbonate and was lithologically much siltier than the other two overburden sequences. The NNP is net acidic (mean NNP = -3.8) and is approximately log-normal in form with left (acidic) skew. One cluster of samples of Upper Freeport overburden has a near-neutral NNP; all other samples are net acidic, ranging from ~4 to ~20.

Frequency histograms for mineralogy show strongly bimodal distributions for total carbonates clays, and pyrite, all consistent with the NP/MPA results (Figure 6.3). The high modes (Blocks 2 and 3) in all three minerals are approximately normal. Histograms for carbonate minerals are shown in Figure 6.4. Calcite was not detected in any sample. Both dolomite (mean 0.2%) and siderite (mean 0.6%) are similarly bimodal, with greater separation between low and high modes for siderite (Figure6.8). As for other parameters, the modes are stratigraphically-related; Block 3 (Upper Freeport) samples are low in dolomite and had no detectable siderite. Siderite, but not dolomite, was removed in the NP determination process so the major source of NP and NNP for these samples is thought to be dolomite; its low concentration contributes to the very low NP values.

There is strong correlation between clay-mineral composition and both dolomite (R^2=0.86) and siderite (R^2=0.85) (Figure 6.5). A similar, but more scattered, relationship exists between pyrite and total clays. While highly significant, all three correlations and their trends are influenced by the strongly bimodal distributions shown in Figures 6.3 and 6.4. It may be inferred that the concentrations of all three minerals are present in higher concentrations in shales and in lower concentrations in sandstone/siltstone.

Figures 6.6-6.8 show sample variograms for the New Allegheny hole means, plotted as class separation versus variance. The total variance in the dataset (all points) is shown as a dotted horizontal line. The fitted exponential-model variance is the solid curve in Figures 6.6-6.8. The observed (sample) semi-variance is calculated so that each pair of points is counted only once; for this reason, such plots are often referred to as *semi-variograms.* As can be seen, the solid curve may stop increasing at a certain distance and become stable, i.e. it reaches a plateau. This plateau represents the upper limit, or sill, of the variance. The drill hole distance corresponding to the point at which the curve flattens out represents the distance beyond which the variance does not increase. This distance is called the range of the variable. The range is often used in a practical sense to

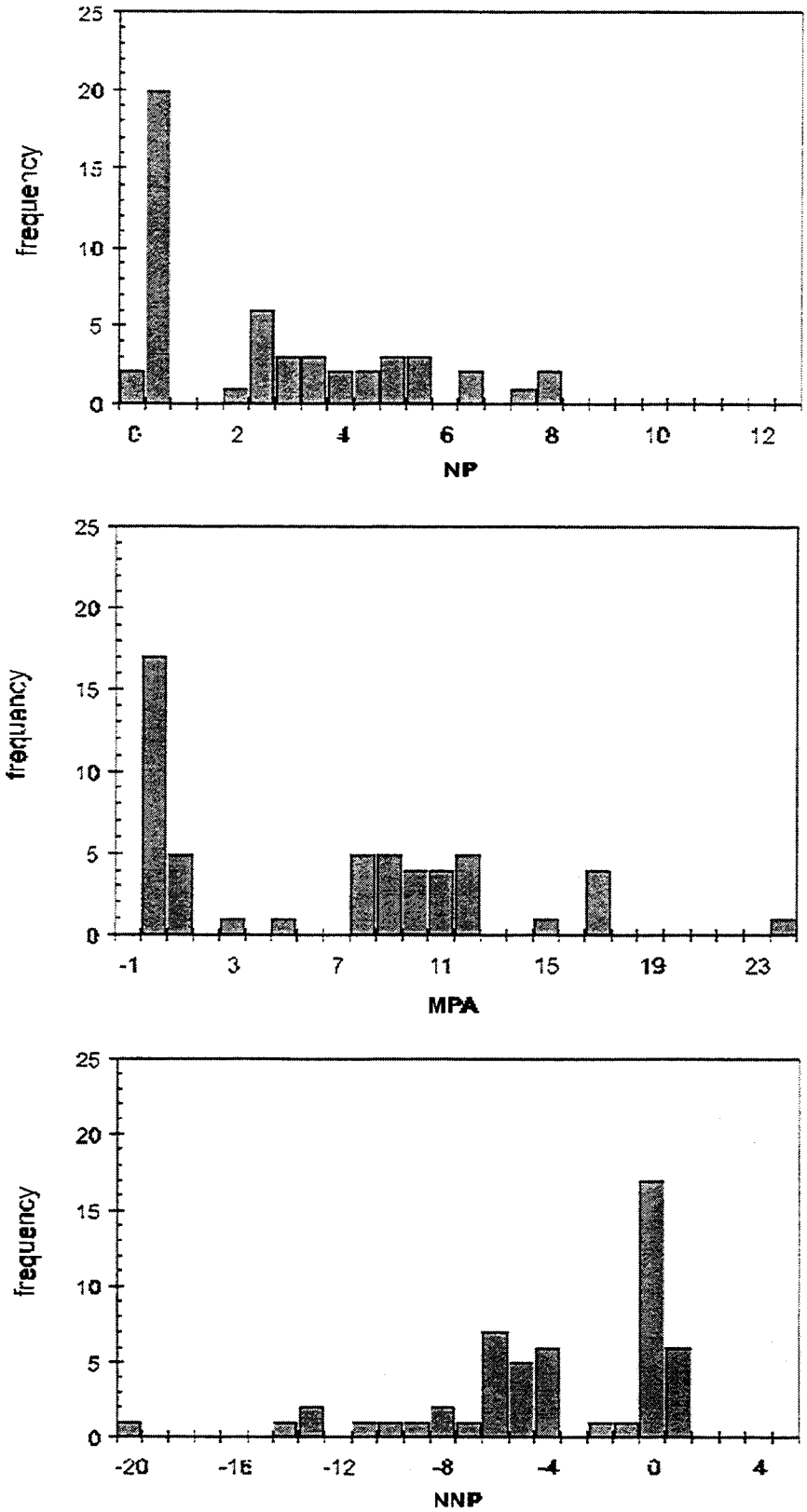

Figure 6.2. Frequency histograms for NP, MPA, and NNP for New Allegheny samples.

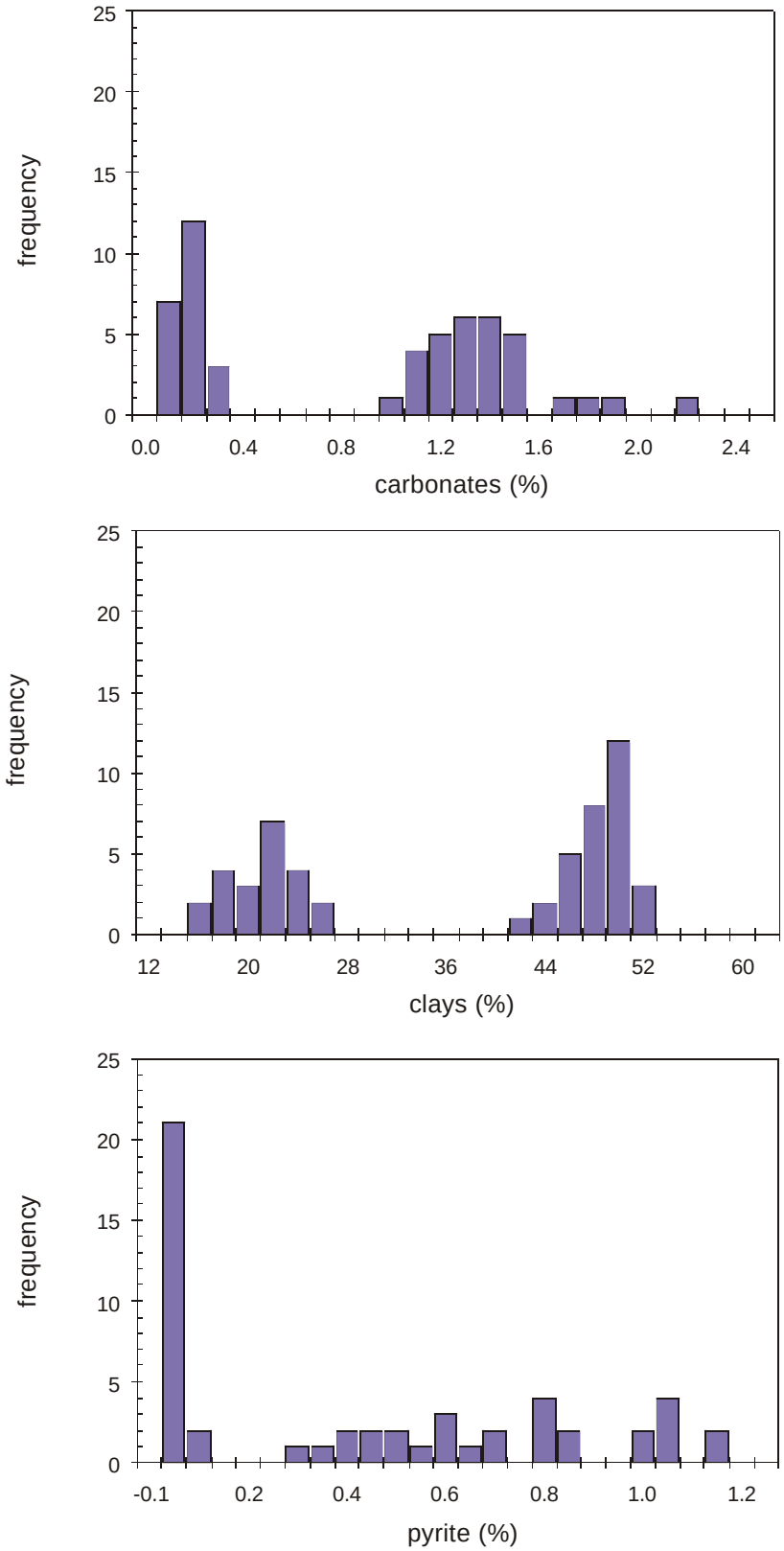

Figure 6.3. Frequency histograms for total carbonates, total clays, and pyrite for New Allegheny samples, determined by XRD.

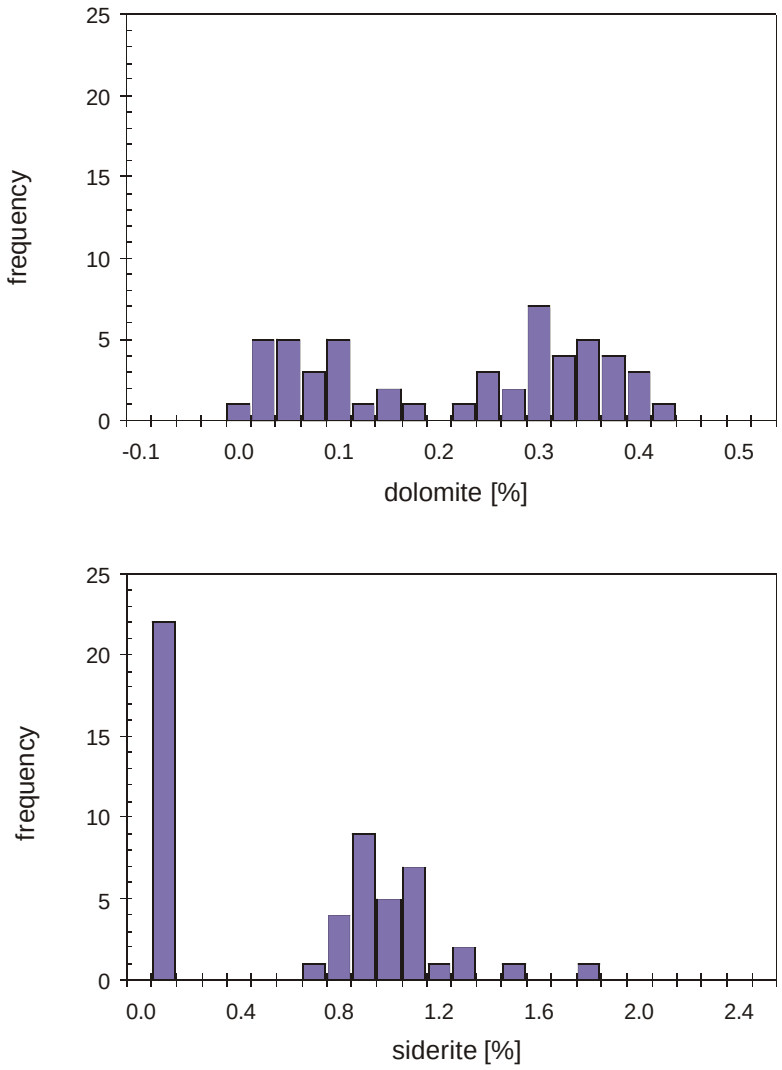

Figure 6.4. Frequency histograms for dolomite and siderite for New Allegheny samples, determined by XRD.

estimate the minimum sample spacing. Drilling closer than this distance generates more data than is needed; drilling beyond this spacing risks missing variation in the geochemistry.

Each variogram may be considered as a comparison of variance at different drill hole separations, relative to the variance for the entire dataset (the dotted horizontal line). Drill hole spacings with lower variance than that of the entire sample are relatively less dispersed (and more correlated with each other) than the dataset as a whole. If a dataset has considerable spatial correlation and has a mean that is spatially stationary (e.g., has second-order stationarity), it is expected that variance will be lower at close separations and, at greater separations, will increase to that of the dataset itself. For the exponential model, it is typical that the sill will approximate the sample variance and the range will represent the *decorrelation length*, beyond which correlation between points is low.

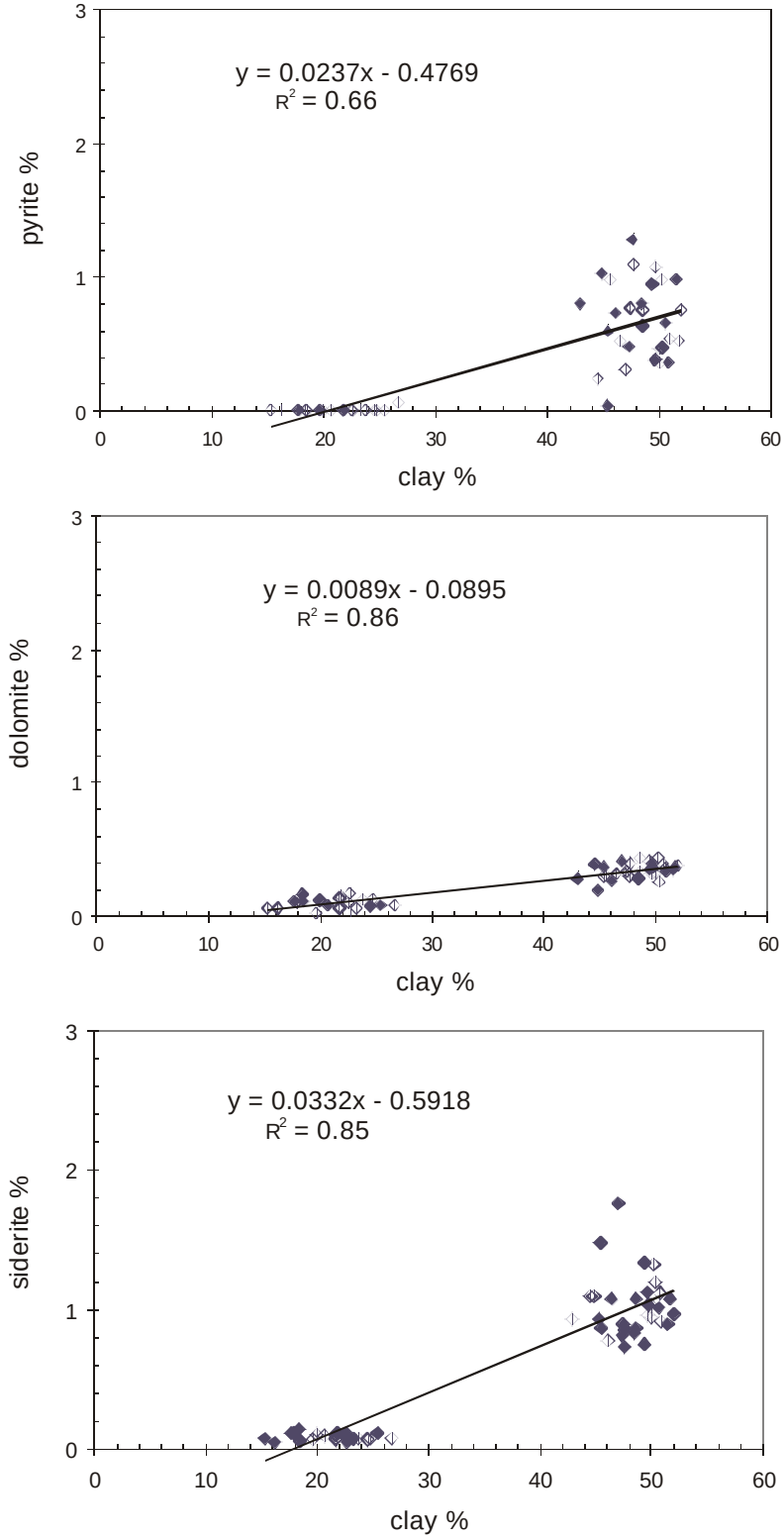

Figure 6.5. Percentage (wt/wt) clay minerals vs. pyrite (top), dolomite (middle), and siderite (bottom) for New Allegheny samples, determined by XRD.

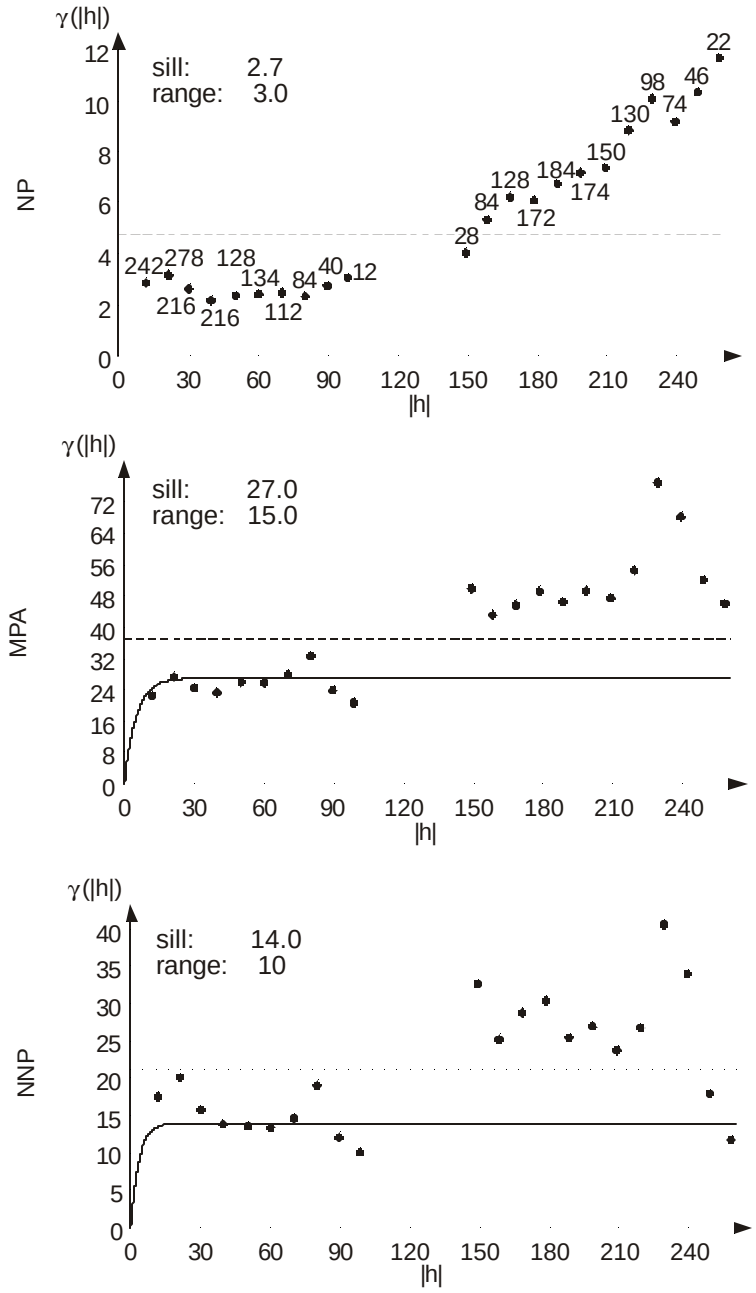

Figure 6.6. Variograms for NP, MPA, and NNP for New Allegheny samples. Dotted line is simple variance; solid line is exponential model. Number of pairs per class is shown on top variogram.

Figure 6.6 shows variograms for NP, MPA, and NNP from the NAM samples. The values of the number of holes per separation interval are posted on the first (NP) variogram; these show that interval size exceeds 70 holes for all but the outermost 2 intervals and the intervals bracketing the sampling gap from 100-140 ft. All three variograms are fitted by a pronounced sill at 60-80% of the sample variance, extending from very close range (3-15 ft) to <u>at least</u> 100 ft. The top two variograms show that there is a stable sill for both

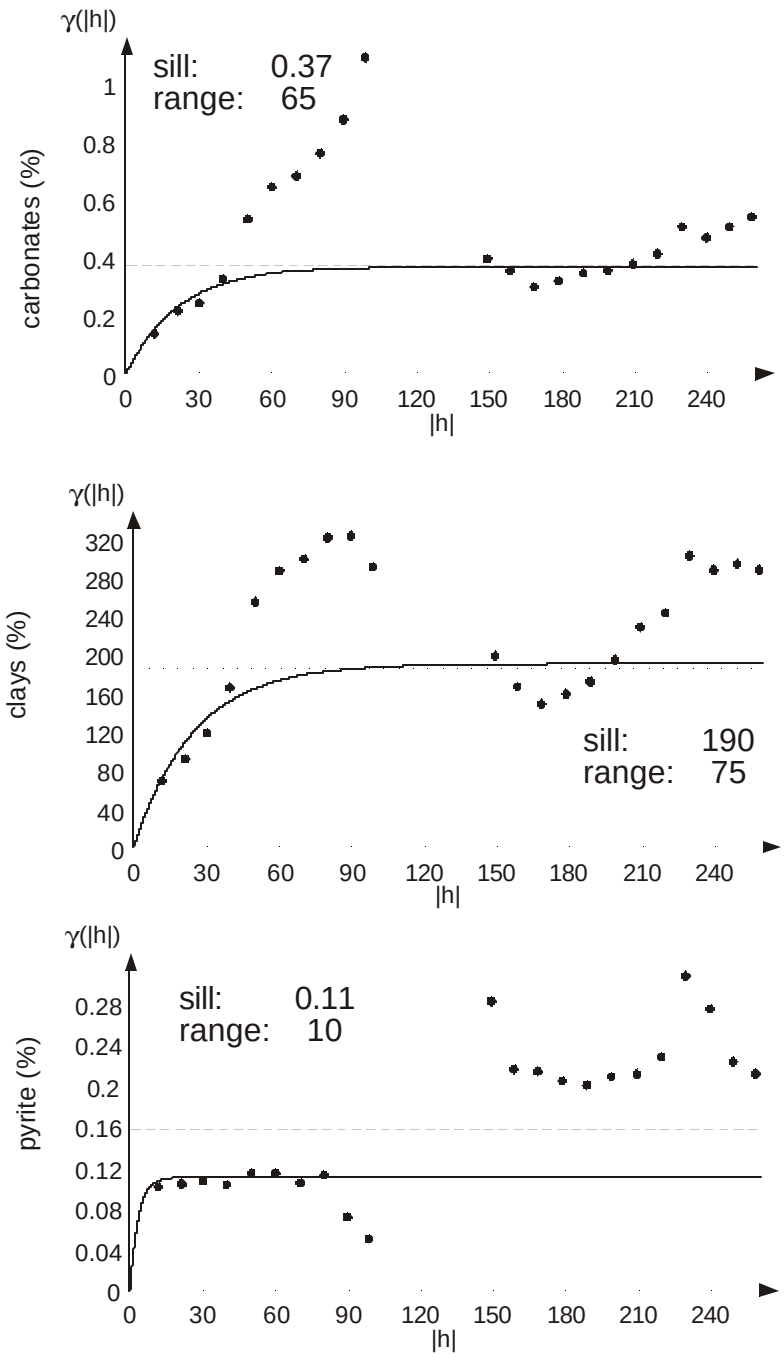

Figure 6.7. Variograms for carbonates, clays, and pyrite for New Allegheny samples, all determined by XRD. Dotted line is sample variance; solid line is exponential model.

NP and MPA that extends from close separation of at least 100 feet, and that it may extend further within each stratigraphic interval.

Figure 6.7 shows mineralogic variograms for total carbonates (siderite + dolomite, as no calcite was detected), total clays, and pyrite, all by XRD. Similar variograms are seen for dolomite and siderite (Figure 6.8). All except pyrite show exponential ranges of about 60 feet; for pyrite it is much closer (10 feet),

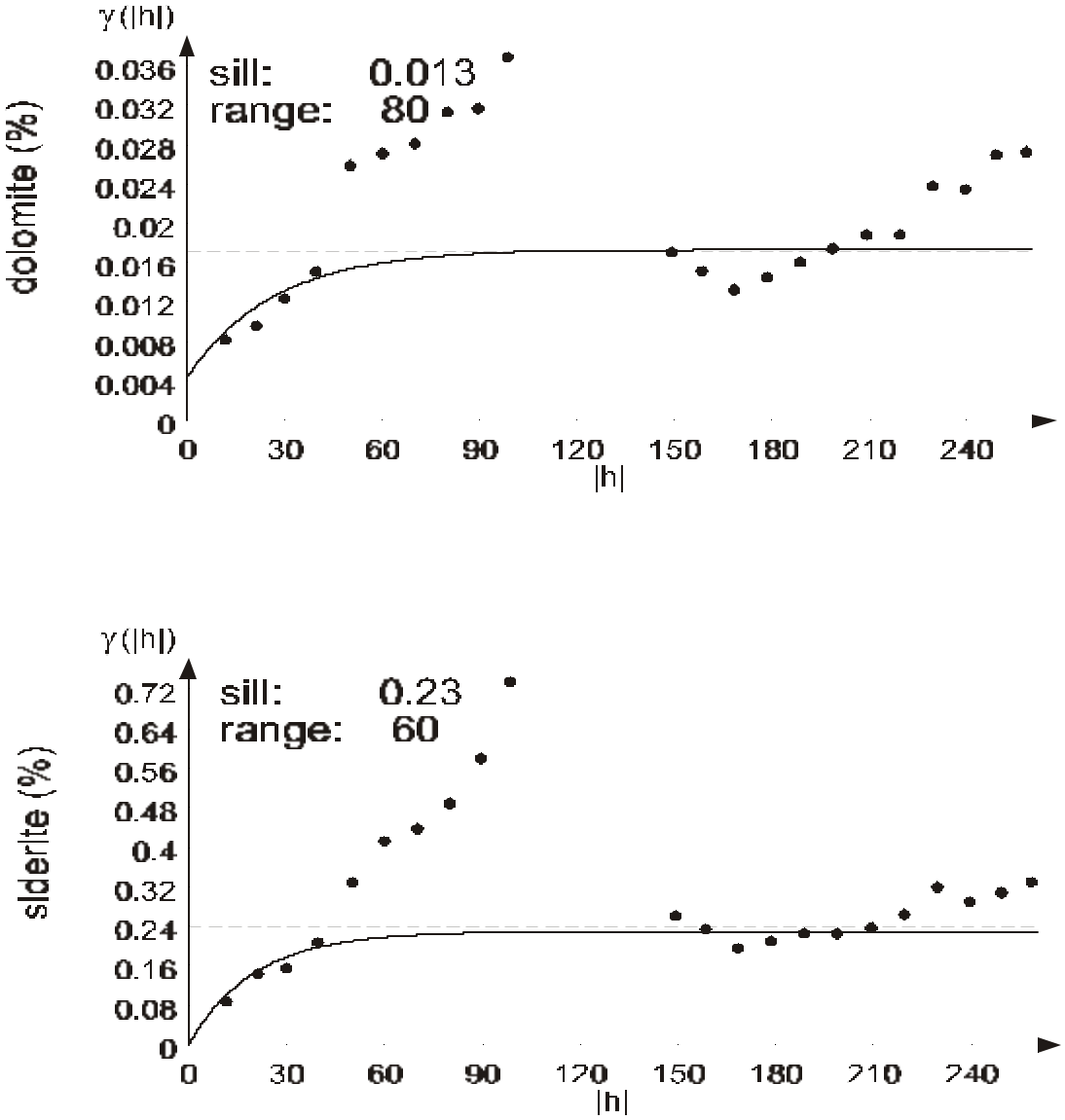

Figure 6.8. Variograms for dolomite and siderite for New Allegheny samples, both determined by XRD. Dotted line is sample variance; solid line is exponential model.

essentially a pure nugget effect. The sill for clays and carbonates, however, has a spatial interval of quite high variance from 60-100 feet. This type of variogram is frequently caused by non-stationarity and local anomalies (Isaaks and Srivastava, 1989). This may be caused by the distinctly bimodal distribution of clays, dolomite, and siderite, all of which are abruptly non-stationary across adjacent Blocks 1 and 3. This artifact of the variography, while spatial, is essentially stratigraphic; Upper Kitanning overburden (Block 1) is much higher in both carbonates, clays, and pyrite than the much sandier Upper Freeport overburden (Block 3). The non-stationarity is less pronounced for pyrite and may be exaggerated for the XRD carbonates because their abundance in Block 3 is close to detection limits and shows compressed variance (see the low modes of Figures 6.3 and 6.4).

Except for dolomite, siderite, and clay minerals, all variables demonstrated a broad, stable sill to at least 100 feet separation, attributed to a low degree of spatial variability within overburden sections at these spacings. Beyond 150 feet, increases in variance occurs in both NP and MPA, ascribed to a large-scale spatial and/or stratigraphic trend. This large-scale variation would need to be understood in order to estimate spatialy-varying moments of these variables in a reasonably accurate fashion.

Significance of Results

The NAM site was net acidic (average NNP = -3.8) with low carbonate concentrations and moderate acidity (mean MPA=6.7). Variables tend to be bimodally distributed within the mine, but normally distributed within specific overburden intervals. There was a strong tendency for pyrite, dolomite, and siderite to covary with clay mineral percentage, suggesting that these reactive minerals are concentrated in shales. The trend was strongest for siderite.

Four types of spatial covariance may be observed within an individual site, and were observed for the NAM case study:

- covariance between overburden intervals (stratigraphic covariance),
- covariance from one hole to another nearby location (nugget covariance),
- covariance over distances of 100's of feet (primary spatial trend), and
- covariance of localized pods of alkalinity in contrast with the surrounding primary spatial trend (anomalous covariance).

Stratigraphic covariance must be analyzed for each specific interval. This may be done using high-resolution (1 to 5 feet) vertical sampling intervals, then averaging over larger intervals (the overburden between 2 major coals, for example). For NP, MPA, and MPA, the variance in this closest interval was very close to that of the sill extending out to about 100 ft. This suggests that there is little primary trend in the 100 ft separation range and that there was, for this mine, little to be gained by small-scale (<80 ft) sampling.

A primary covariance trend was observed as a prominent sill extending out to about 100 feet, with an increase in covariance beyond 150 ft. This suggests that separations more distant than about 150 ft may be too widely spaced to provide accurate estimation of the spatial trend.

Anomalous covariance regions for this particular site appear to be restricted to carbonate minerals and NP, not pyrite and MPA. The scale of these regions will generally be site specific and cannot be known a priori; thus a goal of any sampling scheme must be to identify any such anomalies and to determine at what spacing they might be observed. If anomalous alkaline regions are large and of sufficiently high NP, their omission in a sampling scheme might induce considerable error (underestimation of NP) in the ABA process. Similarly, their inclusion by random chance in a small sample as an outlier would tend to overestimate NP. The size and frequency of the anomaly is thought to be the key factor in their location.

The primary spatial trend is the principal objective in sampling to estimate ABA. Based on this study, the trend would be estimated by samples from 100-200 feet in separation. The trend is gradual and continuous for MPA and noisier for NP; also, NP was observed to show local anomalies of <100 feet dimension,

which could influence ABA estimation in some cases. At a separation of 200 feet per hole, a sampling density of one hole per acre would result. However, the number of holes would also be dependent on the configuration of the mine; for example, a long narrow mine of one acre size would require more holes than a mine that was square shaped.

Planning to deal with anomalous covariance in carbonate values is very problematic. For anomalies in which the contrast with the primary trend mean is not great, additional nested sampling may not be required. However, additional, more detailed sampling should be considered for localized areas of mines with large deviations from the mean (>2 standard deviations), at a scale much smaller than that of the primary trend and similar (or smaller) than that of the anomalies themselves. The purpose of this sampling should be to determine whether or not carbonate anomalies are present. If any prominent carbonate-rich anomalies are indicated, these regions may be explored in greater detail to determine their size as well as average concentration. This suggests that a stratified sampling program is required where localized high carbonate zones are anticipated to be present and available for neutralization.

This case study reaffirmed the benefit of mineralogical analysis of carbonate phases. In the absence of such information, care must be taken to exclude siderite from NP estimates. The implications of this study with respect to mine planning in general is that evaluation of data obtained from overburden shot holes drilled in advance of mining, by the methods used in this study or otherwise, can be useful. It permits one to evaluate overburden characteristics on a local scale prior to mining, which should be helpful in identifying the need for selective handling or alkaline addition as mining progresses.

Skyline Mine, Tennessee

This case study is based on work done by the Office of Surface Mining's Knoxville Tennessee Field Office in evaluating the AMD potential of overburden associated with mining operations in South Central Tennessee (Office of Surface Mining, 1997; 1998). The Skyline Coal Company Mining Complex (Skyline Mine) provides a good example of an active mining area where AMD discharges were known to exist from past mining, and where high density sampling helped delineate areas where future AMD problems would likely occur if appropriate actions were not taken to avoid or prevent them.

The Skyline Mine Complex consists of four operations, the Glady Fork, Pine Ridge, Brush Creek #1 and Big Brush Creek #2 mines. The Sewanee Coal seam is mined at all four sites. Draglines, bulldozers, and front-end loaders were utilized for the mining and reclamation operations. The stratigraphic sequence of the mining area includes the Sewanee Conglomerate, Whitwell Shale, Sewanee Coal, and Newton Sandstone. To evaluate the AMD potential at the Skyline Coal Co. Big Brush Creek #2 mine, the applicant drilled 23 drill holes. This is equivalent to one drill hole per 40 acres. Drill hole data from the existing Big Brush # l Mine was also evaluated since it was drilled on 500 foot centers (5.7 acres) (Office of Surface Mining, 1997). Previous sampling used a drill hole spacing on one-half mile centers (Office of Surface Mining, 1998). NNNP values were determined for each drill hole and the results were plotted on mine maps. The resulting data were grouped into three categories, NNP> 10; < 10 NNP > 0; and NNP <0.

The drill hole data for Big Brush Mines #1 and #2 (Office of Surface Mining, 1997) were analyzed by univariate frequency analysis, variogram analysis, and kriging. Three-dimensional modeling software was also used, but this discussion is limited to the statistical analysis. Universal kriging software was used to interpolate the data at the Big Brush #1 mine and extrapolate into the adjacent (at that time proposed) Big Brush Creek #2 mine. The Kriging program calculated a predicted NNP value for empty cells based on cells that contained drill hole data. Ninety-nine drill holes were used in the simulation.

Almost every drill hole showed some acid/toxic forming material, primarily in the Whitwell Shale. Acid/toxic material was also associated with the Lantana coal seam in the western portion of the proposed permit area. A weighted NNP value was calculated for each hole in the Whitwell Shale zone, which contains most of the pyritic material(Office of Surface Mining, 1997). The NNP values for the drill cores appear to be normally distributed with a mean NNP for all drill cores of 7, with a variance of 10 (Figure 6.9).

The statistical technique of semivariogram analysis was used to evaluate proper drill spacing. As described in the introductory material to this section and the previous case study (New Allegheny Mine), variogram analysis calculates the semivariance between each pair of drill holes located so many feet apart. The difference is squared and summed, then divided by the number of pairs squared. This produces a semivariance for a distance *h*. Then another set of drill holes located a slightly larger distance apart is analyzed. The result is a plot of semivariance verses drill hole distance. The line is fitted to one of several distributions for a proper fit. If the plot results in a plateau, or sill, the distance at which the semivariance flattens out is deemed to be the optimum drill hole spacing. Drilling closer than this distance generates more data than is needed; drilling beyond this spacing risks missing variation in the geochemistry.

In this case study:

- The variogram analysis provided an impartial evaluation of drill hole spacing and appeared to confirm an optimum drill hole spacing of about 650 feet or 200 m (Figure 6.10).
- The variogram and kriging exercises showed that there are areas with good and bad weighted ABA values, and that high and low values are clustered.
- Most of the acid-forming materials are confined to the southern 1/3 of the permit area.

Through intense geologic sampling and overburden analyses, this study identified a potential for acid or toxic drainage in the backfilled material if not addressed during mining and reclamation operations. Skyline had to design a detailed, site specific, and complex Toxic Material Handling Plan. Four acid-producing zones that would be disturbed were identified: 1) the shale immediately under the Sewanee coal seam, 2) coal fines remaining in the pit after mining, 3) lenticular sandy shale zones within the Whitwell Shale, and 4) the Lantana coal seam, which will not be recovered but will be incorporated into the backfilled spoil material.

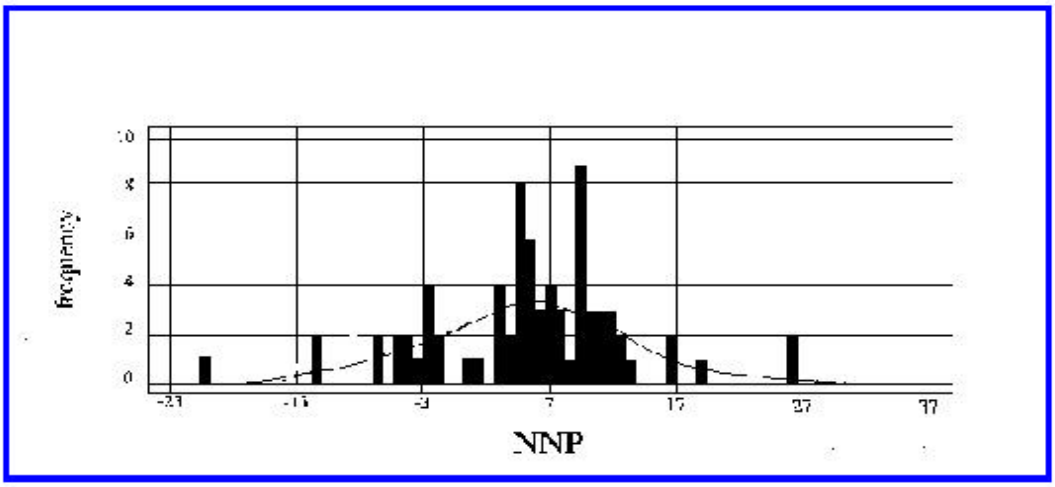

FIGURE 6.9. Histogram of NNP values at the Skyline Mine.

VISUALIZATION AND THREE-DIMENSIONAL MODELING

Jewett Mine, Texas

This case study, from Behum and Joseph (1997), applied three-dimensional modeling software to evaluate overburden characteristics at the Jewett Mine. ***earthVision*** can produce, among other things, three-dimensional models of overburden characteristics (e.g., pH, sulfur content, etc.) and volumetric calculations of selected overburden zones. This software is available to permit reviewers and reclamation specialists in Federal, State, and Tribal regulatory agency offices in all coal-producing states through the Technical Information Processing System (TIPS) of the Office of Surface Mining. The purpose of this study was to demonstrate the capabilities of ***earthVision*** in AMD prediction and mine planning, although the results were not actually used to identify acid-forming zones or develop material handling plans during mining.

The Jewett Mine is a large surface operation in Eastern Texas. This study focused on the area to be mined between 1994 and 1999 within Area D, the study area, with emphasis on overburden handling in 1994. The topography of the area is characterized by low hills capped by iron-cemented Carrizo Formation sands. The L6 seam was the principle lignite seam mined in Area D; three other overlying seams were also mined wherever possible. A large dragline and a bucket wheel excavator were used to remove most of the poorly consolidated overburden. The Carrizo Formation sand was selectively handled by a pre-stripping operation, which stockpiled part of the material, followed by placement of the sandy sediments directly above the mine

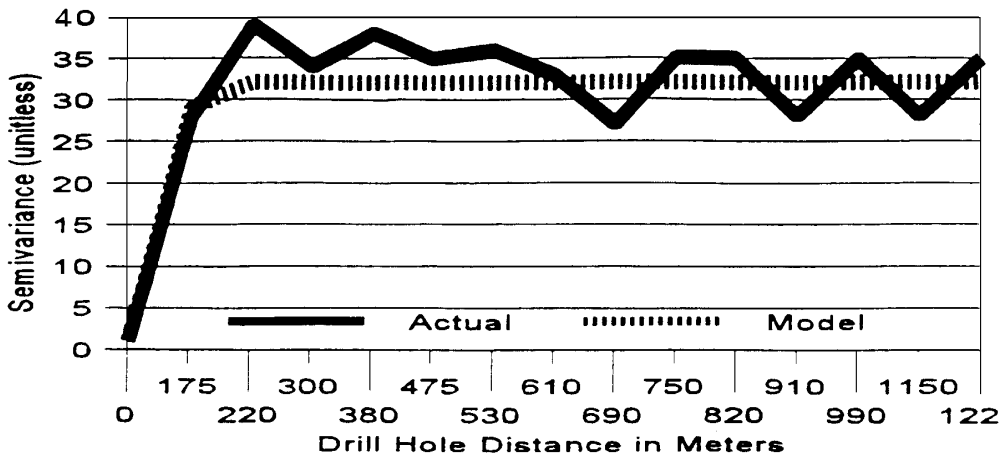

Figure 6.10. Semivariogram of NNP vs. sample distance for Skyline Mine samples.

by the dragline. Figure 6.11 is a three dimensional model of the site.

The acidity of the overburden in this part of Texas is the principle impediment to environmental protection. The State environmental regulatory authority, the Texas Railroad Commission, requires that the cover material have a pH of more than 5 to provide a cover material suitable for plant growth. In his study of an area immediately west of the 1994-1999 permit area studied by Behum and Joseph (1997), Hasan (1995) found that the overburden characteristics were quite variable due to primarily lateral facies changes. In contrast, the overlying Carrizo Formation sands have a more persistent geochemistry, typically a neutral pH, and it is easily identified in the field by color.

earthVision was used to calculate volumes of materials within the selected area. Overburden characteristics were clipped to the 1994 extraction area by a polygon. Volumetric analysis indicated that the Carrizo Sand in the 1994 area is thin and most of it is inadequate for use as cover material without the addition of more suitable material. It also showed that the L6 overburden extracted in 1994 had an overabundance of material in excess of -5 tons $CaCO_3$/1000 tons of material, but that there was limited neutralization potential (<20 tons $CaCO_3$/1000 tons of material).

The overburden sample spacing for this mine should have been smaller than that actually used. Based on the ***earthVision*** modeling, the lateral stratigraphic variation in this area indicates that the optimum spacing should approach the 200 by 200-foot borehole spacing recommended by Hasan (1995). At other sites, the necessary sample spacing will depend on the consistency of rock unit thickness and chemistry, but if the grid cell spacing is coarse, ***earthVision*** may not be able to calculate three-dimensional property volumes. The impact of the oxidized zone should also be evaluated. This can be done by contouring the

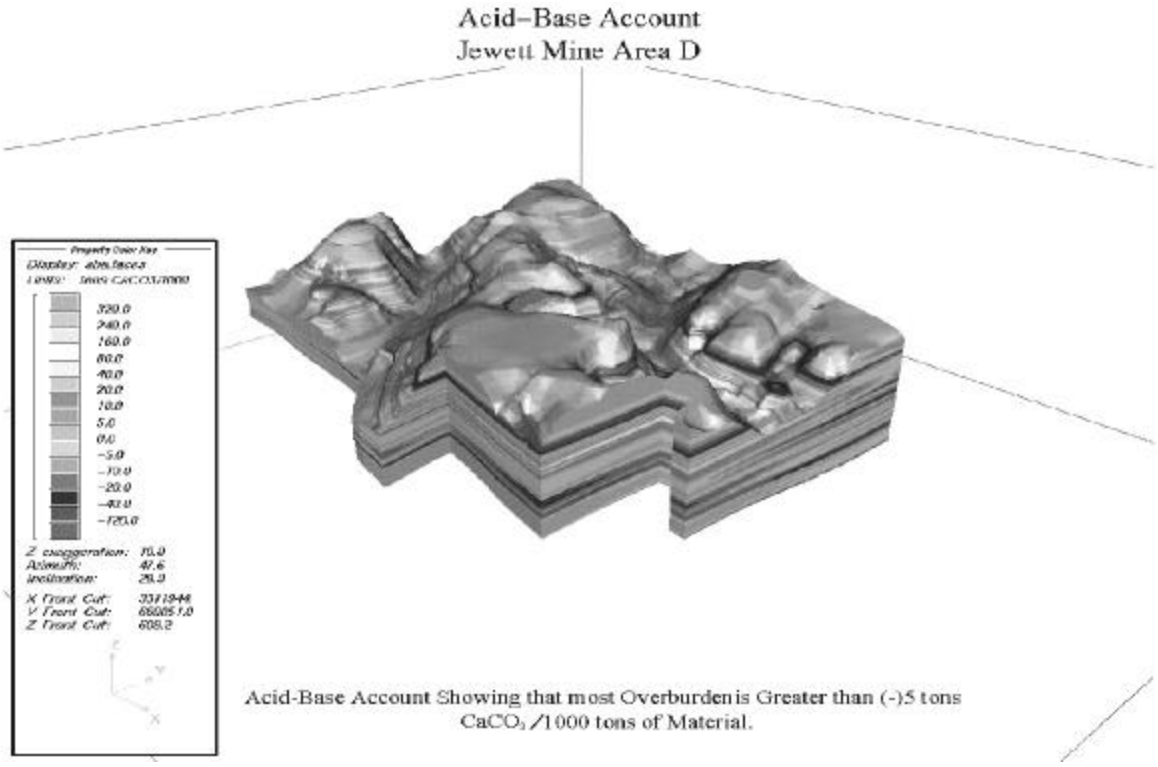

Figure 6.11. Three-dimensional acid-base account diagram for the Jewett Mine, Area D.

elevation of the base of this zone by a two-dimensional grid and by modeling the strata above and below this grid surface separately, in the property gridding.