Designation: D8215 – 21

Standard Practice for
Statistical Modeling of Uncertainty in Assessment of In-place Coal Resources[1]

This standard is issued under the fixed designation D8215; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Assessment of coal tonnage in-place is a fundamental factor in evaluating the commercial feasibility of any deposit. Equally important is an appraisal of the reliability that can be placed in the drilling data available for an estimation. Traditional methods for quantitatively expressing uncertainty use reliability categories based simply on the distance between drill-hole data within the boundaries of a coal bed. A significant limitation of the distance approach is the inability to express uncertainty in terms of how close a resource estimate is to the true value.

This practice provides a geostatistical methodology to calculate the uncertainty of an in-place, coal resource estimate, both at the deposit and block level. In addition to examining the drilling pattern both within and outside the coal bed, other factors influencing the complexity in the geology are also considered, resulting in realistic estimates of uncertainty. Most importantly, the uncertainty is expressed directly in tons of coal. Like other coal properties, uncertainty can be used to rank the resources in classes.

1. Scope*

1.1 This practice covers a procedure for quantitatively determining in-place tonnage uncertainty in a coal resource assessment. The practice uses a database on coal occurrence and applies geostatistical methods to model the uncertainty associated with a tonnage estimated for one or more coal seams. The practice includes instruction for the preparation of results in graphical form.

1.2 This document does not include a detailed presentation of the basic theory behind the formulation of the standard, which can be found in numerous publications, with a selection being given in the references (**1-3**).[2]

1.3 This practice should be used in conjunction with professional judgment of the many unique aspects of a coal deposit.

1.4 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

NOTE 1—All values given in parentheses after SI units are stated in inch-pound units.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D621 Test Methods for Deformation of Plastics Under Load (Withdrawn 1994)[4]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5549 Guide for Contents of Geostatistical Site Investigation Report

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[1] This practice is under the jurisdiction of ASTM Committee D05 on Coal and Coke and is the direct responsibility of Subcommittee D05.07 on Physical Characteristics of Coal.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The last approved version of this historical standard is referenced on www.astm.org.

***A Summary of Changes section appears at the end of this standard**

D5922 Guide for Analysis, Interpretation, and Modeling of Spatial Variation in Geostatistical Site Investigations

D5923 Guide for Selection of Kriging Methods in Geostatistical Site Investigations

D5924 Guide for Selection of Simulation Approaches in Geostatistical Site Investigations

2.2 *ASTM Manuals, Monographs, and Data Series:*[5]

MNL11 Manual on Drilling, Sampling, and Analysis of Coal

3. Terminology

3.1 *Definitions:*

3.1.1 *average, n*—mean.

3.1.2 *bin, n*—each of a set of the adjoining intervals used for separating numerical values according to magnitude.

3.1.3 *cell, n*—any of the subdivisions of a seam whose centers are the nodes in a regular grid.

3.1.4 *confidence interval, n*—a range of values calculated from sample observations and supposed to contain the true parameter value with certain probability of coverage.

3.1.4.1 *Discussion*—For example, a 95 % confidence interval implies that if the estimation process were repeated many times, then 95 % of the calculated intervals would be expected to contain the true value.

3.1.5 *cumulative distribution function, n*—a mathematical expression providing the probability that the value of a random variable is less than or equal to any given value.

3.1.6 *estimation, n*—the process of providing a numerical value for an unknown quantity based on the information provided by a sample.

3.1.7 *geostatistics, n*—a branch of statistics in which all inferences are done by taking into account data, the style of spatial fluctuation of the variable(s), and the location of each observation.

3.1.8 *grid, n*—a regular arrangement of crossing lines, such as the threads in a square mesh. The intersection points are the nodes.

3.1.9 *histogram, n*—a graphical representation of an empirical probability distribution.

3.1.9.1 *Discussion*—The values of the random variable are divided into multiple intervals called bins; all values are allocated to the bins; final relative counts are displayed as bars that are proportional to the empirical probabilities.

3.1.10 *kriging, n*—a group of geostatistical estimation methods formulated to minimize estimation errors in a minimum mean square error sense.

3.1.11 *lower quartile, n*—in a split of a ranked sample into four parts of equal size, the divider between the two partitions below the median. It is synonymous with the 25th percentile.

3.1.12 *mean, n*—a measure of centrality in a sample, population, or probability distribution. For a sample, the sample mean is equal to the sum of all values divided by the sample size:

$$\bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i \tag{1}$$

3.1.13 *median, n*—in a probability distribution or ranked sample or population, the divider evenly splitting the observations into two halves of equal size: a half of lowest values and a half of highest values; it is a measure of centrality and is synonymous with the 50th percentile.

3.1.14 *normal distribution, n*—the family of symmetric, bell-shaped functions that expresses the probability, $f(x)$, that the random variable will be between any two values of x:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{2}$$

where μ is the mean and σ is the standard deviation of the probability density function. See Fig. 1.

3.1.15 *percentile, n*—in a probability distribution, sample, or population sorted by increasing observation value, each one of the 99 dividers that produce exactly 100 subsets with equal number of observations.

3.1.15.1 *Discussion*—The dividers are sequential ordinal numbers starting from the one between the two groups with the lowest values. The dividers denote the proportion of values below them.

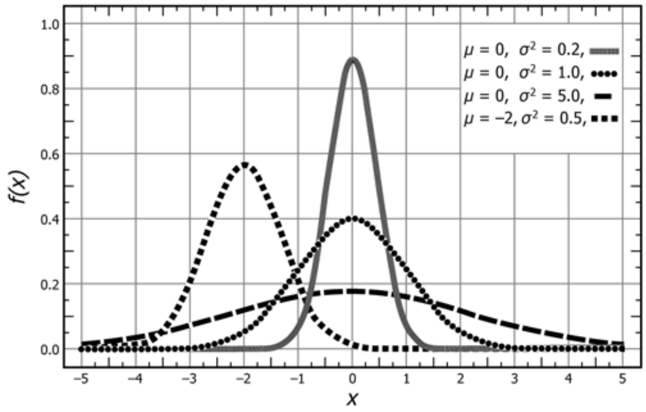

FIG. 1 Examples of Normal Distributions

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[5] For referenced ASTM publications, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org.

3.1.16 *population, n*—the complete set of all specimens comprising a system of interest and from which data can be collected.

3.1.16.1 *Discussion*—For the tonnage of a deposit, the population is any exhaustive set of weight measurements that could be taken, thus adding to the deposit weight.

3.1.17 *probability, n*—a measure of the likelihood of occurrence of an event.

3.1.17.1 *Discussion*—It takes real values between 0 and 1, with 0 denoting absolute impossibility and 1 total certitude. Sometimes probabilities are multiplied by 100 to express them as percentages.

3.1.18 *probability density function, n*—a mathematical expression, *f*(*x*), describing relative likelihoods in a random variable.

3.1.18.1 *Discussion*—For discrete random variables, *f*(*x*) directly provides the likelihood of each random variable value; for a continuous random variable, the area under *f*(*x*) between any two values of the variable provides the likelihood of the interval.

3.1.19 *probability distribution, n*—probability density function.

3.1.20 *quartile, n*—in a distribution, ranked sample, or population, any of the three dividers that separate the observations in four parts of equal size.

3.1.21 *random function, n*—a collection of random variables.

3.1.22 *random variable, n*—the collection of all possible outcomes in an event or study, and their associated probability of occurrence.

3.1.23 *realization, n*—an observed or simulated outcome of a random variable, such as three tails in flipping a coin or a map of a random function.

3.1.24 *resource, n*—a numerical representation of the amount of a commodity in the ground.

3.1.25 *sample, n*—(*a*) in geology, a specimen taken for inspection, analysis, or display; (*b*) in statistics, a representative subset of a population comprising several observations.

3.1.26 *sample size, n*—the number of specimens in a subset of a population, which coincides with the number of observations when there is one variable.

3.1.27 *standard deviation, n*—the positive square root of the variance.

3.1.28 *stochastic simulation, n*—mathematical modeling of a complex system using probabilistic methods involving random variables.

3.1.29 *upper quartile, n*—in a split of a sample into four parts of equal size, the divider between the two partitions above the median; it is equivalent to the 75th percentile.

3.1.30 *variance, n*—a measure of spread in a sample, population, or probability distribution. For a sample, it is equal to the sum of the square of all observations minus the mean divided by the sample size minus 1:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(z_i - \bar{z})^2 \qquad (3)$$

3.2 For definitions of other terms used in this standard, refer to Olea (**4**); Test Methods D621; Terminology D653; and Guides D5549, D5922, D5923, and D5924.

4. Summary of Practice

4.1 The practice has two phases: data gathering and preparation of a geologic model. These phases assess two forms of uncertainty associated with in-place coal resource calculations: uncertainty in total coal tonnage and uncertainty in the modeling at the cell level.

4.2 All available geologic information is used to create the model of seam thickness and other variables if required by the geological complexity, so that geologic or technically feasible boundaries of individual coal seams, or of the entire deposit, can be taken into account in the modeling.

4.3 The deposit is subdivided into cells. Geostatistical modeling, stochastic simulation in particular, is applied to the coal seam data. The simulations create a series of two-dimensional maps (realizations), each honoring the original data and having the same probability of being the correct solution. Different types of sampling and deposits require applying different procedures. Annex A1 and Annex A2 are a toolkit for the practical modeling of scenarios with various degrees of geologic complexity.

4.4 Results from the realizations and tonnage calculations are summarized in two graphs, one for each form of uncertainty: (*a*) a numerical approximation to the probability distribution (histogram) of the total coal resources denoting uncertainty in the magnitude of the deposit and (*b*) a graph displaying uncertainty in cell by cell assessment as measured by a 90 % confidence interval plotted against cumulative tonnage and cell count. The user can select any desired uncertainty boundaries from this graph to subdivide the deposit according to the degree of reliability of interest in the analysis of cell tonnage calculations.

5. Significance and Use

5.1 Traditional methods for expressing geological uncertainty consist of preparing reliability categories based simply on the distance between drill hole data points, such as the one described by Wood et al. (**5**) that uses only the drill holes within the coal bed. A major drawback of distance methods is their weak to null association with estimation errors. This practice provides a methodology for effectively assessing the uncertainty in coal resource estimates utilizing stochastic simulation. In determining uncertainty for any coal assessment, stochastic simulation enables consideration of other important factors and information beyond the geometry of drill hole locations, both in and out of the coal bed, including: non-depositional channels, depth of weathering, complexity of seam boundaries, coal seam subcrop projections, and varying coal bed geology for different seams due to fluctuating peat depositional environments. Olea et al. (**6**) explains in detail the methodology behind this practice and illustrates it with an example.

5.2 For multi-seam deposits, uncertainty can be expressed on an individual seam basis as well as an aggregated uncertainty for an entire coal deposit.

5.3 The uncertainty is expressed directly in tons of coal. Additionally, this practice allows the statistical analysis to be presented according to widely-accepted conventions, such as percentiles and confidence intervals. For example, there is a 90 % probability that the actual tonnage in place is 314 million metric tons ± 28.8 million metric tons (346 million tons ± 31.7 million tons) of coal.

5.4 The results of an uncertainty determination can provide important input into an overall risk analysis assessing the commercial feasibility of a coal deposit.

5.5 A company may rank coal resources per block (cell) based on the degree of uncertainty.

6. Software

6.1 Mathematical modeling of a coal deposit requires the use of computer programs for the fast and precise performance of numerical calculations.

6.2 Use of geostatistical software packages available to the public that are capable of generating probabilistic geologic mapping in the form of kriging estimations and stochastic realizations, such as those by Remy et al. (**7**) or Geovariances (**8**), are required.

6.3 Application of the standard also requires a program capable of performing grid operations, such as converting thickness maps to tonnage maps, and preparing the summaries described in Sections 9 and 10. A suite of 15 standalone utility programs is publicly available (Olea and Shaffer, **9**).

NOTE 2—Relevant grid operation programs applicable to Practice D8215 have not been widely available, either commercially or in the public domain. Those interested in applying Practice D8215 have been required to develop their own codes, making it more difficult to use the standard practice. The publication of the source code of 15 supplementary computer programs that can be used to perform the more specific aspects of the modeling will facilitate the implementation of Practice D8215 for the determination of uncertainty in coal resource assessments.

7. Sampling and Data Preparation

7.1 Prepare a database that ideally is free of institutional uncertainties, such as insufficient drilling depth, inconsistency in picking the top and bottom of a seam, or errors coding the data (MNL11).

7.2 Like in the distance methods, if drill hole locations are in some system that is not Cartesian, such as latitude and longitude, convert the values to Cartesian coordinates, such as Universal Transverse Mercator (UTM) coordinates or state plane coordinates (for example, ArcGIS, **10**).

7.3 In addition to location, minimal information shall include thickness for the seam(s) to assess.

7.4 If some drill holes show that the seam is missing at certain locations, use the thickness values to prepare a second dataset of indicators denoting presence or absence of the seam:

$$thickness\ indicator = \begin{cases} 1, \text{ if thickness} > 0 \\ 0, \text{ if thickness} = 0 \end{cases} \quad (4)$$

7.5 If outcropping or depth of burial is a concern, surface elevation and roof elevation(s) data are also required.

8. Procedure for Modeling the Deposit

8.1 *Gridding:*

8.1.1 Subdivide the study area into a regular grid. The rectangular shape of the study area with sides parallel to the coordinate axes usually forces to either truncate the lateral extension of the seam or include areas beyond its boundaries.

8.1.2 Avoid having cells too large that more than 5 % of the drill holes land in the same cell with at least one other drill hole. One fourth the average distance to the closest drill hole is a reasonable default.

8.1.3 The cell area shall not be less than the area of the smallest detail of interest to capture in the modeling.

8.2 *Mapping:*

8.2.1 If drill holes indicate that the seam is missing at some locations or the seam does not extend over the entire study area, use kriging to produce a map of the thickness indicators to have a first approximation of the seam extension.

8.2.2 Complete the modeling of the seam boundary generating multiple realizations (maps) of the thickness indicators within the restricted areas determined in the previous step. The realizations take advantage of freedoms in fluctuations that are possible in between data locations, always honoring the data and the style of spatial variation. Coal seam predictions using stochastic realizations tend to stabilize after 40 realizations to 80 realizations (de Souza et al., **11**). Thus, generate at least 100 thickness realizations to safely capture uncertainty in the characterization.

8.2.3 Generate an equal number of realizations for thickness using some of the same software. The extension of each thickness map shall be conditioned by one of the indicator realizations generated in the previous step.

8.3 *Tonnage:*

8.3.1 The last step in the preparation of the deposit model involves the use of coal density for conversion of thickness to tonnage realizations.

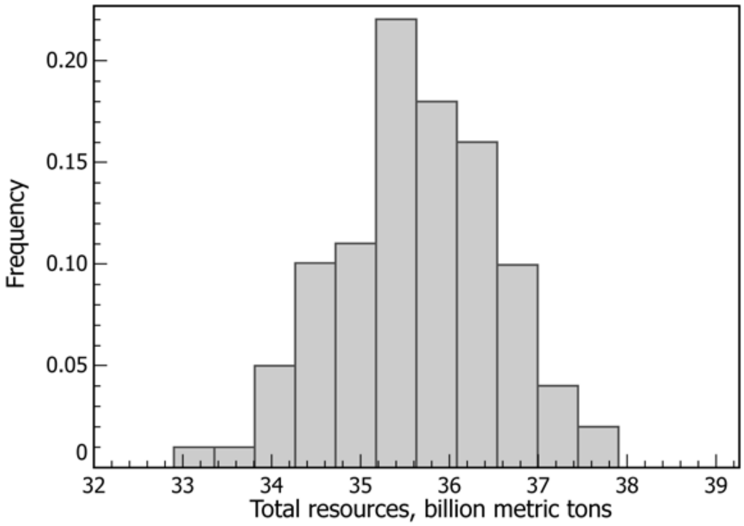
8.3.2 Different drilling patterns and geology require different procedures to model the geology. Annex A1 and Annex A2 include approaches for the modeling of the most typical situations.

9. Uncertainty in Total In-place Tonnage

9.1 For each realization, add the coal tonnage for all cells in the study area. Each tonnage realization contributes one value. If there are 100 tonnage realizations, there will be 100 values for total tonnage that together numerically characterize the random variable total tonnage.

9.1.1 Summarize the results as a histogram plus a tabulation of summary statistics to facilitate interpretation (Fig. 2).

9.1.2 Fig. 2 allows probabilistic analyses not possible to perform applying distance classification methods. For example, with 90 % probability, the deposit has at least 34.181 billion metric tons (37.678 billion tons) and it does not have more than 37.192 billion metric tons (40.997 billion tons), which is equivalent to stating that there is a 90 % probability that the magnitude of the resources is 35.686 billion metric tons ±



No. of realizations	100
Mean	35.642
Std. deviation	0.884
Maximum	37.628
95th percentile	37.192
Upper quartile	36.280
Median	35.632
Lower quartile	35.105
5th percentile	34.181
Minimum	33.354

FIG. 2 Example of Display of Total Tonnage Uncertainty

1.506 billion metric tons (39.337 billion tons ± 1.660 billion tons) of coal. The value 35.686 billion metric tons (39.337 billion tons) is the average of the 34.181 billion metric tons (37.678 billion tons) and the 37.192 billion metric tons (40.997 billion tons). The value 1.506 billion metric tons (1.660 billion tons) is equal to one-half the difference between the 37.192 billion metric tons (40.997 billion tons) and the 34.181 billion metric tons (37.678 billion tons).

10. Determination of Uncertainty at Cell Level

10.1 Use the same set of tonnage realizations to model uncertainty throughout the deposit at the cell level. For this determination, it is necessary to group the values in the tonnage realizations by cell. Assuming that there are 100 realizations, there will be 100 values per cell when the seam extends over the entire study area.

10.2 The values at each cell numerically define one random variable per node modeling the uncertainty in tonnage at each cell.

10.3 Considering that ordinarily there are thousands of nodes per seam, some simplification is in order. The best alternative is to keep the spread between the 5th percentile and the 95th percentile, which constitutes a confidence interval with coverage of 90 %,[6] termed the 5 to 95 spread.

10.4 Rank the 5 to 95 spreads by increasing value and calculate the sum of the mean tonnage for all cells with less than or equal spread.

10.5 Display the result as the cumulative curve in Fig. 3,

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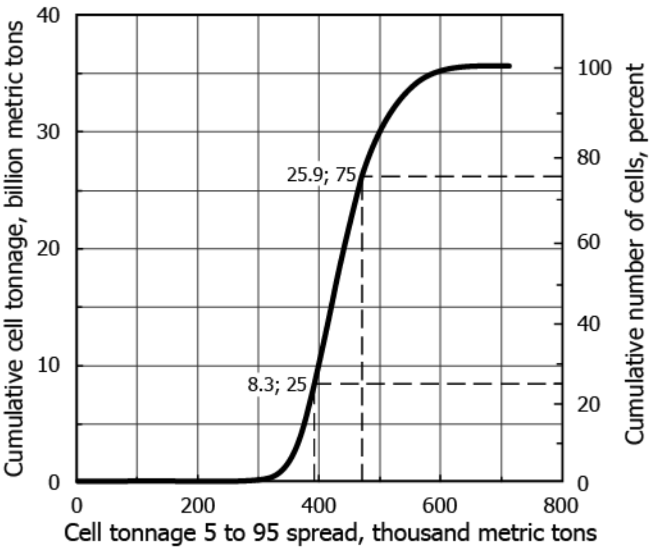
[6] The longer the interval, the less precise is the modeling.



Number of cells	63480
5 to 95 spread summary statistics thousand metric tons	
Mean	434.876
Std. deviation	60.681
95th percentile	547.185
Upper quartile	469.820
Median	428.012
Lower quartile	392.690
5th percentile	349.061

NOTE 1—The curve provides the same 5 to 95 spread as related to the cumulative cell tonnage on the left and as related to the cumulative number of cells on the right.

FIG. 3 Example of Display of Uncertainty at the Cell Level

with uncertainty increasing to the right in the horizontal axis. The scale to the left denotes the cumulative tonnage and the one to the right, the cumulative frequency. Hence, for example, there are 8.3 billion metric tons (9.1 billion tons) of coal in 25 % of the cells for which the spread of estimated tonnages is at most 392.690 thousand metric tons (432.867 thousand tons).

10.5.1 The cumulative display allows partial aggregation in classes. For example, it is possible to group the cells into three bins with the dividers being the lower and upper quartile: 392.690 thousand metric tons (432.867 thousand tons) and 469.820 thousand metric tons (517.888 thousand tons). The group with the 25 % most accurate nodes contributes 8.3 billion metric tons (9.1 billion tons), the intermediate group has 17.6 billion metric tons (19.4 billion tons), and the least reliable 25 % of the cells adds 9.7 billion metric tons (10.7 billion tons). The result is the triad (8.3, 17.6, 9.7), which is analogous to a triad of measured, indicated, and inferred tonnages of the distance classification methods.

10.5.2 First property of Fig. 3 is to provide a genuine level of uncertainty associated with each cell or group of cells. In the previous example, for the first group, the 5 to 95 spread is at most 392.690 thousand metric tons (432.867 thousand tons).

10.5.3 A graph such as Fig. 3 allows flexibility in the event of interest to consider bins because there is freedom to specify the two parameters defining a partition: number of classes, and location of the dividers. In addition, the dividers have units of coal tonnage, not as distances in miles or kilometers as in the distance classification methods.

10.5.4 When using bins, there is no overlapping in the magnitude of the uncertainty values—the 5 to 95 spreads.[7]

10.5.5 Figs. 2 and 3 are not redundant; they provide supplementary information with neither one being able to supply information provided by the other with the sole exception of the mean total tonnage.

11. Report

11.1 Include a table with all data and possible preparations, such as conversion of coordinates.

11.2 Disclose the computer program(s) used in the modeling.

11.3 Specify all assumptions made in the modeling.

11.4 Justify main selections, such as the grid cell size, the method(s) used to generate the realizations, and number of realizations.

11.5 Display and discuss results as required in this standard practice (Figs. 2 and 3).

12. Keywords

12.1 coal resources; confidence interval; estimation; geostatistics; probability distribution; realization; simulation

ANNEXES

(Mandatory Information)

A1. TOOLKIT FOR MODELING OF IN-PLACE TONNAGE IN SEAM

A1.1 Simplest Scenario

A1.1.1 *Assumptions*—The simplest scenario is one in which simultaneously across the study area:

A1.1.1.1 There is only one coal seam.

A1.1.1.2 A single volume to tonnage conversion factor is sufficient to characterize the entire study area.

A1.1.1.3 The thickness data are evenly distributed over the entire study area; there are no significant parts of the study area without data.

A1.1.1.4 All drill holes penetrate the seam, implying that during the formation of the coal there were no non-deposition spots or areas completely eroded.

A1.1.1.5 No meteoric oxidation has taken place because the seam is sufficiently deep.

A1.1.1.6 There are no faults with significant displacements.

A1.1.2 *Procedure*—Under these circumstances, do the following:

A1.1.2.1 Define the cell size and the study area, which combined together specify a grid of nodes at the center of each cell.

A1.1.2.2 Apply stochastic simulation to generate at least 100 realizations of thickness.

A1.1.2.3 Convert the thickness realizations into tonnage realizations by multiplying all node values by the appropriate conversion factor.

A1.1.2.4 Summarize the uncertainty by preparing the graphs described in Sections 8 and 9.

A1.2 Coal Seam is Discontinuous

A1.2.1 *Assumptions*—All assumptions in A1.1 are still valid, except for A1.1.1.4. For an example of this case, see Olea and Luppens (**13**). Now and in the following scenarios, modeling of the thickness realizations requires several extra steps.

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[7] When using additional drilling for validation, errors in each distance classification class show instead high overlapping (for example, Olea et al., **12**).

A1.2.2 *Procedure*—When the coal seam is discontinuous, do the following:

A1.2.2.1 Define the grid discretizing the study area.

A1.2.2.2 Transform the data to presence-absence indicators in such a way that for each drill hole:

$$thickness\ indicator = \begin{cases} 1, \text{ if thickness} > 0 \\ 0, \text{ if thickness} = 0 \end{cases} \tag{A1.1}$$

thus, generating a second dataset.

A1.2.2.3 Use the indicator data to generate at least 100 thickness realizations.

A1.2.2.4 Apply stochastic simulation to produce as many realizations of thickness.

A1.2.2.5 Randomly pair the thickness realizations and the indicator realizations and compare the grids to model those cells in which the seam is absent. When the indicator is 0 at a cell, such cell is eliminated from the thickness realization and coded as a blank.

A1.2.2.6 Convert the thickness realizations to tonnage realizations by multiplying all non-blank values by the appropriate conversion factor.

A1.2.2.7 Generate the summary graphs described in Sections 8 and 9.

A1.3 Coal Seam is Discontinuous with Large Areas Devoid of Data

A1.3.1 *Assumptions*—All assumptions in A1.1 are still valid, except for A1.1.1.3 and A1.1.1.4.

A1.3.2 *Procedure*—Under the present circumstances, do the following:

A1.3.2.1 Specify the cell size, and number of columns and rows defining the grid covering the study area.

A1.3.2.2 Prepare indicator data as in A1.2.2.2.

A1.3.2.3 Apply kriging to the indicator data and create a kriging standard deviation map.

A1.3.2.4 Discard from further modeling all cells with unacceptable high kriging standard deviation, considering 0.5 as a default cutoff.

A1.3.2.5 Generate at least 100 presence-absence indicator realizations.

A1.3.2.6 Apply stochastic simulation to the data to generate as many thickness realizations as indicator realizations.

A1.3.2.7 Do a second round of cell discarding by repeating the step in A1.2.2.5.

A1.3.2.8 Convert the modified thickness realizations to tonnage by multiplying all non-blank cell values by the appropriate density conversion factor.

A1.3.2.9 Prepare the types of uncertainty summaries exemplified by Figs. 2 and 3.

A1.4 Coal Seam is Discontinuous with Large Areas Devoid of Data and Shallow Enough to be Partly Oxidized (Weathered)

A1.4.1 *Assumptions*—Half of the assumptions in A1.1 are invalid now, leaving standing A1.1.1.1, A1.1.1.2, and A1.1.1.6. For an example of a deposit falling in this situation, see Olea et al. (**12**).

A1.4.2 *Procedure*—For this type of seam, do the following:

A1.4.2.1 Specify the parameters defining the study area.

A1.4.2.2 Create a second dataset by transforming the thickness data to thickness indicators as in A1.2.2.2.

A1.4.2.3 Use the indicator data to generate at least 100 indicator realizations.

A1.4.2.4 Prepare as many thickness realizations as indicator realizations.

A1.4.2.5 Compare the realizations as in A1.2.2.5 to emulate nondeposition and paleo-erosion.

A1.4.2.6 Acquire digital elevation data to have the surface elevation at the center of each cell.

A1.4.2.7 Use roof elevation data to generate at least 100 realizations for the elevation of the coal seam roof.

A1.4.2.8 For each cell of every roof realization, calculate oxidation indicators:

$$oxidation\ indicator = \begin{cases} 1, \text{ if } surf.\ elev.\ - roof\ elev.\ > d \\ 0, \text{ if } surf.\ elev.\ - roof\ elev.\ \leq\ d \end{cases} \tag{A1.2}$$

where *d* is the constant oxidation depth.

A1.4.2.9 Generate as many oxidation indicator realizations as thickness realizations.

A1.4.2.10 Discard oxidized cells from the deposit by pairing and oxidation indicator realizations and eroded thickness realizations in A1.4.2.5.

A1.4.2.11 Convert the realization resulting from the previous step into tonnage realizations by scaling all non-blank cells by the appropriate weight conversion factor.

A1.4.2.12 Produce the distributions modeling uncertainty in total tonnage and cell tonnage described in Sections 8 and 9.

A1.5 Coal Seam Has Sufficient Data on Coal Density

A1.5.1 *Assumptions*—At least assumption A1.1.1.2 is not true.

A1.5.2 *Procedure*—Exact steps will depend on which other assumptions are not true. At least in the cases of the previous four scenarios, the steps remain all the same, except for the step one before the last converting coal thickness to tonnage. Now, instead of such step:

A1.5.2.1 Use the density data to generate as many density realizations as thickness realizations.

A1.5.2.2 Randomly pair the density realizations and the thickness realizations in scenario A1.1 or the corrected thickness realizations in the other situations.

A1.5.2.3 Multiply the pairs of grids. The results are in-place tonnage grids.

A1.6 Coal Seam is Faulted

A1.6.1 If the geology is the same on each side of the fault(s), proceed with the modeling ignoring the fault(s). If the realizations are displayed, leave blank areas along the vertical projection of the slips(s). Otherwise:

A1.6.2 Subdivide the seam in as many blocks as necessary and model each block separately.