

Modeling Multiple Coal Seams Using Volume Functions

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Volume or distance functions provide an approach to simultaneously model multiple coal seams in cases where direct isochore mapping is intractable due to the number of coal seams and complexities such as pinch outs and bifurcation. The technique aims to precisely locate facies boundaries through local refinement. A new program is introduced which creates this variable from indicator data. The methodology of this technique is described. The modeling method produces results in 'intervals' format. Two programs have been created for visualization and gridding..

Introduction

Numerical modeling of multiple coal seams is an important problem in the increasingly important exploitation of coal bed methane (CBM) from thick stratigraphic sections. Multiple thin seams are commonly encountered and are exploited for gas production. Methods such as deterministic mapping, gridded seam models, and cell-based models each have their weaknesses. Deterministic mapping, such as solids models, are limited to small areas and are only capable of representing limited complexity. Moreover, there is no measure of uncertainty. Gridded seam models are only capable of representing relatively few coal seams and have difficulty handling coal seams pinching out and splitting due to partings. These techniques do not facilitate the quantification of uncertainty. Cell-based models from techniques like indicator simulation and truncated Gaussian show poor connectivity. Utilizing a volume function avoids these problems.

The requirements for the approach are a map of the total thickness and a file containing coal seam interval data in a 'from-to' format for each x-y location. This method utilizes a new variable, termed 'faci-dist,' defined as the shortest vertical distance to a facies boundary. Where this distance is zero a boundary between facies exists. At each x-y location, the total coal thickness is estimated using global ordinary kriging, after which a faci-dist value is estimated at every elevation. The boundary cutoff (initially zero) is adjusted until the total thickness estimated from the faci-dist values is equal to the total thickness estimated using global kriging. This enables facies boundaries to be located with great precision. Once this has been accomplished at every location, the picks can be plotted using a plotting program or they can be converted into a typical cell-based model using a rastering program.

Data Preparation

A popular method for gathering coal data is by the use of gamma-ray logs. This method is the most versatile of the geophysical logs as it does not require fluid in the hole, is not sensitive to small variations in hole diameter, and can be used to detect coal beds through well casing. It works by recording the natural gamma radiation from rocks adjacent to the drill hole. Coal has a much lower radioactivity than other rocks and can therefore be identified this way (Wood, et.al, 2003). Part of a typical log is shown in Figure 1. Applying the cutoff to the gamma ray column allows the creation of an indicator for the presence of coal (see Figure 2). There are other methods for gathering coal data. Whichever method is used, it is required that the data be converted to an indicator format.

Other conditions must also be met for this procedure. The volume function method only works for data where the drill holes have all been drilled vertically, or are all parallel to each other. If the drill holes are not vertical, but are parallel, a rotation is necessary to ensure that all the data along a drill hole have the same areal coordinate. The data should also have been transformed to stratigraphic coordinates.

The volume function itself is quite simple. It is applied at every data point to generate a new variable. It is defined as the shortest distance to a facies boundary with the two facies being coal and non-coal. The new variable is termed *faci-dist*. It is given a negative value when in coal and is positive when otherwise. The sign itself is not important; we simply need a way to be able to tell when we are in and out of coal. `Faci_dist` has been created to generate and append this new variable. It requires few parameters: the name of the file with the indicator data, the column numbers for the columns containing the drill hole number, x, y, stratigraphic z coordinates, and indicator, and lastly the name of the output file with the *faci-dist* variable appended. This program performs a simple calculation and is extremely fast. Figure 3 shows the *faci-dist* value added to the previous figures. The actual boundary between facies is assumed to be half-way between adjacent data points of different facies. The data file with the *faci-dist* variable is now ready to be used as input to the modeling program.

The data is also used to calculate total coal thickness at every drill hole. This is trivial and proceeds much the same as *faci-dist* calculations (Figure 4)

Modeling Process

The modeling is performed using the `coal_picks` program. Three outputs are produced: a 2-D model of total coal thickness, a 3-D model of *faci-dist* estimates, and a file containing picks for every x,y location. The first step in the generation of these outputs is to compute the total coal thickness at every drill hole. This is computed using the gamma-ray data. The program scans through each hole summing the thickness in stratigraphic units. This process effectively creates a 2-dimensional coal thickness data set.

Every x,y location is now visited and the following takes place at each location. First, the total coal thickness is estimated using global kriging (Neufeld, 2005). This kriging method uses every data point in the estimation of every location (see Figure 5). Eliminating the ‘search’ for data eliminates the artifacts that are characteristic of kriging with local neighborhoods. The kriging process assigns every drill hole a weight, λ_j , based on the covariances between the data and the unknown location.

The next step is to cycle through every z-cell at that x-y location and estimate a *faci-dist* value at those cells using the 3-D *faci-dist* data. First, we search for all of the data located within a certain vertical distance above and below the location being estimated. This search is constrained by the vertical search standard deviation and the number of standard deviations (both are input parameters). The weight for each data is calculated using the equation that defines the normal distribution:

$$w_{i,j}(z_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{z_i - z_o}{\sigma}\right)^2}$$

Where z_i is the stratigraphic elevation of the data value being considered, z_o is the elevation of the location being estimated, σ is the vertical search standard deviation, and $w_{i,j}(z_i)$ is the weight given to the data at elevation z_i . The weights of all the data considered from one drill hole are constrained to sum to the weight given that drill hole by global kriging:

$$w_{i,j}(z_i) = \frac{\lambda_j}{\sum_{i=1}^{n_j} w_{i,j}(z_i)}$$

The estimate is then calculated by taking the sum of every data value multiplied by its respective weight for every drill hole. The following relation demonstrates how the estimate is calculated:

$$v = \sum_{j=1}^N \sum_{i=1}^{n_j} d_{i,j} \cdot w_{i,j}(z_i)$$

Where v is the *faci-dist* estimate, N is the number of drill holes, n_j is the number of data considered at a given drill hole, $w_{i,j}(z_i)$ is the weight standardized weight assigned to the data, and $d_{i,j}$ is a data value from drill hole j (see Figure 6).

An estimate is generated for every cell in the vertical column associated with location x,y as illustrated in Figure 7. We then go to those locations where two vertically adjacent cells where their faci-dist values are on opposite sides of the cutoff, also illustrated in Figure 7. We estimate a faci-dist value at a higher resolution between these two locations in order to more precisely locate the boundary elevations (see Figure 8).

Once the boundary elevations have been precisely located, the total coal thickness is calculated and compared to the total coal thickness estimated using global kriging. If the kriged estimate is greater than the thickness calculated from the faci-dist estimates, the faci-dist cut-off is increased, and if it is lower the cut-off is decreased. In the example, the kriged estimate was 8.0m, therefore the cut-off must be increased. A cut-off of 2.0 is tried and the process of visiting the boundary locations and estimating at a finer scale repeated. A new thickness is calculated and compared to the kriged estimate. If still not correct, the cut-off is adjusted and the process repeated until the faci-dist thickness is within 1% of the global kriging thickness.

Figure 9 shows the results for a cutoff of 2.0. This cutoff gives a thickness of 11.1m. The cutoff must be reduced in order to reach a thickness of 8.0m. Figure 10 shows the results of using a cutoff of 0.5. The thickness is now 7.95m, which is within tolerance of 8.0m. Once the thickness is within tolerance, the boundary elevations are written out to the picks file for that x,y column. We move to the next x,y-location and repeat the procedure again, beginning with a global kriging estimate. Figure 11 summarizes Figures 7-9. It shows how adjusting the faci-dist cutoff changes the calculated thickness. The cutoff is changed and the thickness calculated until the calculated thickness is reasonably close to the estimated thickness.

This estimation procedure proceeds very rapidly making it possible to have a relatively small initial vertical cell size. Even grids with up to 3 million cells are within reason.

Program

The `coal_picks` program was modified from the `kt3d_gl` program and requires slightly different parameters. The parameter file is shown in Figure 12. Line 5 specifies the data file containing the gamma ray and faci-dist data. Line 6 gives the column numbers containing the drill hole, x-, y-, and stratigraphic z-coordinates, the gamma-ray values, gamm-ray cutoffs, and faci-dist variables. Line 7 indicates the output file for the 3-D faci-dist estimates while line 8 specifies the output file containing the 2-D total coal thickness model produced by global kriging. The faci-dist estimates file is of little use, but it does serve as a debugging file if needed. Line 9 specifies the file to contain the picks data in the from-to format. Line 10 indicates how precisely to report the picks by signifying how many decimal places to report them to. Lines 11-13 are the typical GSLIB grid parameters. As mentioned, the program is capable of handling a much finer vertical grid scale. Line 14 specifies the vertical grid discretization. This parameter tells the program how many finer points to estimate when precisely locating the boundary elevations. Line 15 is where the type of kriging is specified, typically ordinary kriging is used. Line 16 indicates the vertical search standard deviation, indicating how much data is used to generate faci-dist estimates. Line 17 specifies the number of standard deviations to consider, typically 2 or 3. Line 18 on is for specifying the faci-dist variogram model in typical GSLIB format.

Visualization

Having data output in picks form as opposed to the typical cell-based format created a need for a program that would plot this data. This program has been created and is called `pickselplt`. This program is able to explicitly locate the boundary elevations for plotting. It plots the given slice one column at a time and locates the boundary elevations. The parameters are very similar to its predecessor `pixelplt`, with slight modifications. The trimming limits and realization number parameters are no longer useful and have been removed. This program is only suited to viewing cross-sections and, as such, the option of plotting an aerial slice has been removed. There is also no need for any vertical grid specification. An option has been added which allows the drill holes which fall within the slice to be shown on the plot. If this option is chosen the file with the drill hole information must be specified. There is also an option to change the vertical scale of the plot.

Gridding

Picks data is not in a format suited for various tasks such as flow simulation and mine planning. Both of these tasks are suited for cell-based models. As such, a program has been developed which will convert the picks data into a cell-based model containing the proportion-of-coal. This is based on what proportion of the cell's thickness is occupied by coal. The program that performs this operation is called `grid_picks`. The only parameters it requires are an input file, a grid specification, and an output file.

Examples

Some small schematic examples have been created consisting of two drill holes 200 m apart with a coal seam located at various elevations. This has allowed the effect of the standard deviation parameter to be observed as well as to see how well connected a seam will be. The first example shown in Figure 14 demonstrates the effect of changing the standard deviation. As expected, the coal seam has increased connectivity as the standard deviation increases. The second example demonstrates how connectivity changes as the coal seams move farther and farther apart from each other while keeping the standard deviation constant. This is shown in Figure 15. The seam seems to stretch and stretch until it finally 'snaps off' at a spacing of about 9m.

A 3-D example is also demonstrated. The faci-dist data is shown in Figure 16. There are 39 drill holes in an area that is 5000x3000m. The stratigraphic thickness values fall between -65 and 935 and encompass approximately 30 seams of coal. The 3-D model of faci-dist values and 2-D map of thickness values are created concurrently. These models are shown in Figure 17 and Figure 18. The facies boundary elevations, or picks, are located at every x-y location and are shown in Figure 19. This model exhibits excellent connectivity. The numerous thin coal seams are located quickly and precisely.

Conclusions

Past methods of modeling coal seams do not always produce satisfactory results. Their weaknesses include issues such as poor connectivity, low level of detail, and an inability to account for uncertainty. The modeling method presented herein utilizing a volume function-created variable is a good way of creating a model of coal seams. The speed at which it operates along with the ability to precisely locate facies boundary elevations makes it a powerful modeling tool.

References

- Deutsch, C.V. and Journel, A.G., 1998, *GSLIB: Geostatistical Software Library: and User's Guide*. Oxford University Press, New York, 2nd Ed.
- Neufeld, C., Wilde, B.J., (2005) *A Global Kriging Program for Artifact-Free Maps*. Report 7. Centre for Computational Geostatistics.
- Wood, G.H., Kehn, T.M., Carter, M.D., Culbertson, W.C. (2003) *Coal Resource Classification System of the U.S. Geological Survey*. Geological Survey Circular 891. Accessed August 7, 2007 from <http://pubs.usgs.gov/circ/c891/geophysical.htm>

DEPTH	GR
95.0000	55.5305
95.2000	62.1743
95.4000	66.6423
95.6000	70.8051
95.8000	66.0405
96.0000	60.9297
96.2000	57.4937
96.4000	58.7225
96.6000	59.0709
96.8000	59.6743
97.0000	62.9478
97.2000	72.7079
97.4000	79.2542
97.6000	81.5287
97.8000	79.4331
98.0000	79.2383
98.2000	86.5813
98.4000	86.7438
98.6000	85.5150
98.8000	84.2557
99.0000	87.6331
99.2000	91.4308
99.4000	92.9442
99.6000	82.1484
99.8000	71.5317
100.0000	67.6746

Figure 1: A typical log containing columns for depth and gamma-ray values.

DEPTH	Ind
95.0000	0
95.2000	0
95.4000	0
95.6000	1
95.8000	0
96.0000	0
96.2000	0
96.4000	0
96.6000	0
96.8000	0
97.0000	0
97.2000	1
97.4000	1
97.6000	1
97.8000	1
98.0000	1
98.2000	1
98.4000	1
98.6000	1
98.8000	1
99.0000	1
99.2000	1
99.4000	1
99.6000	1
99.8000	1
100.0000	0
100.2000	0
100.4000	1
100.6000	1

Figure 2: The log with a cutoff applied indicates coal (1) and non-coal (0).

DEPTH	Indicator	Faci-Dist
95.0000	0	0.5
95.2000	0	0.3
95.4000	0	0.1
95.6000	1	-0.1
95.8000	0	0.1
96.0000	0	0.3
96.2000	0	0.5
96.4000	0	0.7
96.6000	0	0.5
96.8000	0	0.3
97.0000	0	0.1
97.2000	1	-0.1
97.4000	1	-0.3
97.6000	1	-0.5
97.8000	1	-0.7
98.0000	1	-0.9
98.2000	1	-1.1
98.4000	1	-1.3
98.6000	1	-1.3
98.8000	1	-1.1
99.0000	1	-0.9
99.2000	1	-0.7
99.4000	1	-0.5
99.6000	1	-0.3
99.8000	1	-0.1
100.0000	0	0.1
100.2000	0	0.1
100.4000	1	-0.1
100.6000	1	-0.3

Boundary is assumed to be half-way between 97.0 and 97.2
 $(97.0 + 97.2) / 2 = 97.1$

At depth = 98.0
 Faci-Dist = $98.0 - 97.1 = 0.9$
 when in coal, faci-dist is negative, therefore
 faci-dist = -0.9

Figure 3: The depth and the presence of coal are used to solve the volume function defined as the shortest distance to a facies boundary. The actual boundary is assumed to be half-way between two adjacent different facies data points.

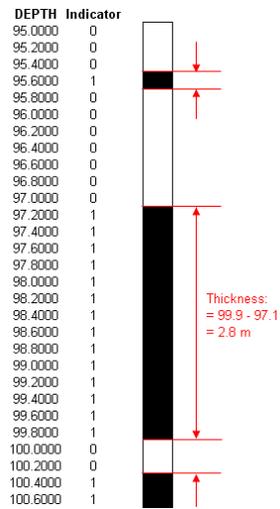


Figure 4: Total coal thickness is calculated by taking the midway points at facies boundaries and calculating the difference.

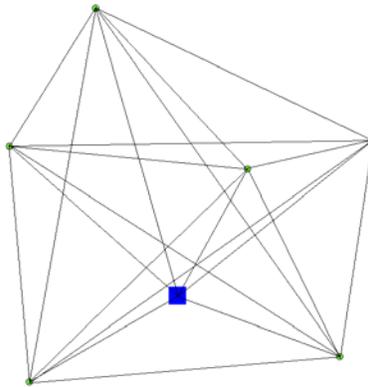


Figure 5: A schematic of global kriging.

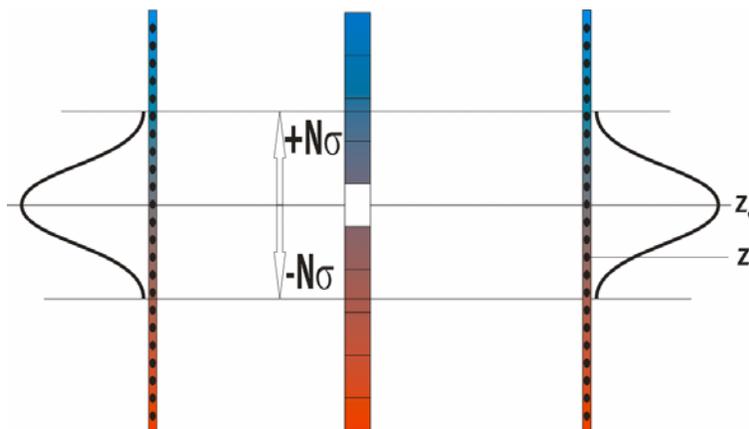


Figure 6: This figure illustrates the vertical search. The search is limited to those data that fall within $N\sigma$ of the location being estimated. It also demonstrates how the data are weighted based on their elevation.

Depth	Faci-Dist Estimate
0.25	9.31
0.75	8.80
1.25	8.29
1.75	7.79
2.25	7.29
2.75	6.79
3.25	6.29
3.75	5.79
4.25	5.29
4.75	4.79
5.25	4.29
5.75	3.79
6.25	3.29
6.75	2.79
7.25	2.29
7.75	1.79
8.25	1.29
8.75	0.83
9.25	0.44
9.75	0.05
10.25	-0.33
10.75	-0.71
11.25	-1.10
11.75	-1.48
12.25	-1.86
12.75	-2.24
13.25	-2.62
13.75	-2.70
14.25	-2.29
14.75	-1.79
15.25	-1.29
15.75	-0.79
16.25	-0.29
16.75	0.21
17.25	0.71
17.75	1.21
18.25	1.71
18.75	2.21
19.25	2.71
19.75	3.05

← Boundary Location

← Boundary Location

Figure 7: An illustration of a column of faci-dist estimates generated for one x,y-location. Wherever there are vertically adjacent cells with faci-dist values on opposite sides of the cutoff, faci-dist estimates are generated at a finer scale in order to more precisely locate the facies boundary location.

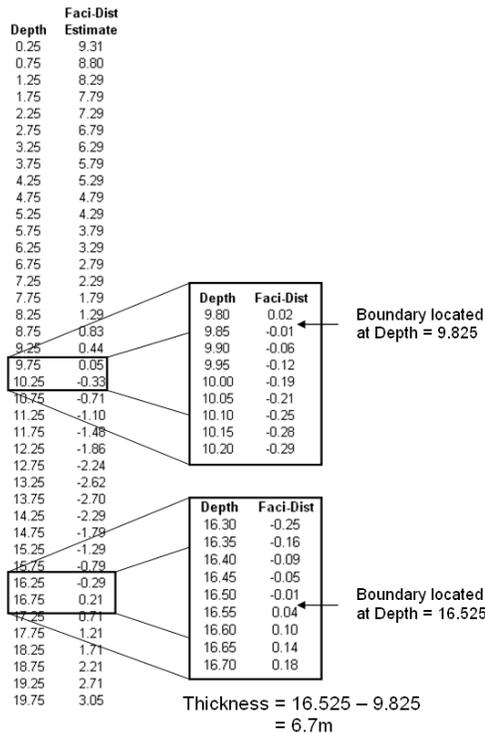


Figure 8: At the boundary locations, the faci-dist variable is estimated at a finer scale in order to more precisely locate the boundary locations. The thickness is calculated and compared to the thickness estimated using global kriging. In this case, the thickness was estimated to be 8.0m. The calculated thickness is 6.7m, so the cutoff must be increased and the boundaries relocated.

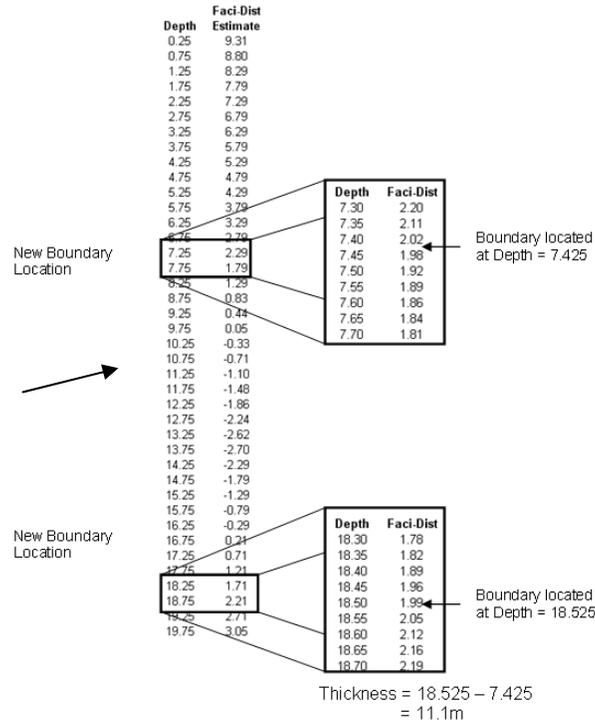


Figure 9: New boundary elevations are located with a cutoff of 2.0. This cutoff gives a thickness of 11.1m, which is too high. We must now try a cutoff between 0 and 2.

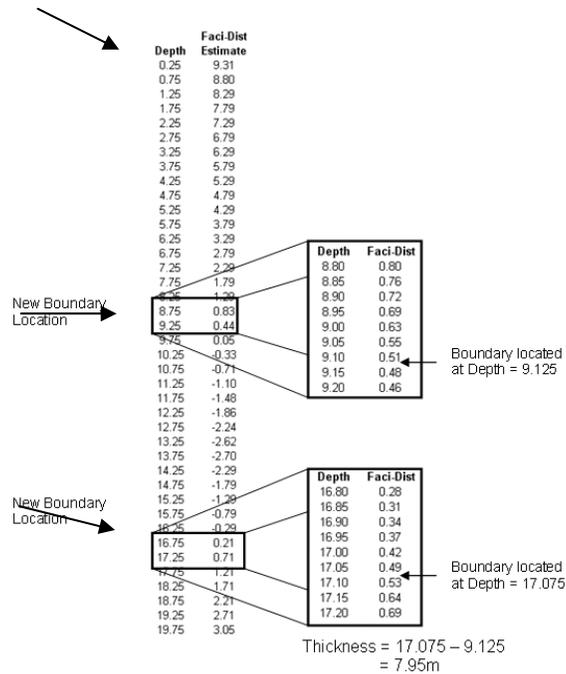


Figure 10: The cutoff is now 0.5. This locates new boundary elevations. The finer grid locates the boundary elevations at 9.125 and 17.075 which give a thickness of 7.95m.

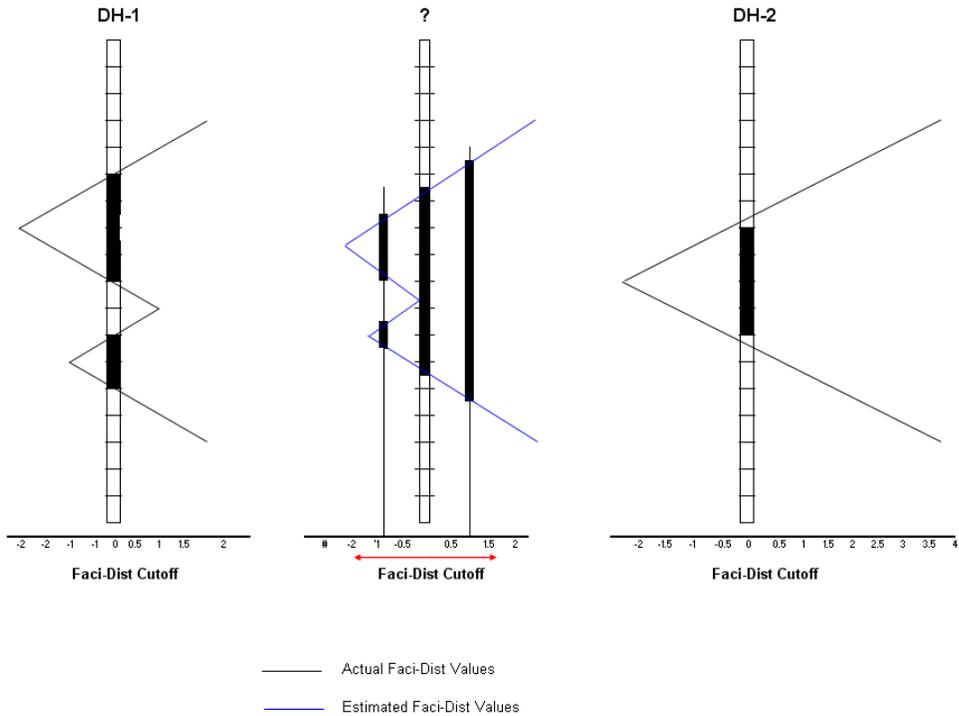


Figure 11: This figure summarizes the preceding three figures by showing visually how adjusting the faci-dist cutoff will change the calculated thickness allowing it to be reconciled with the thickness estimated by global kriging.

```

1 | ----- Parameters for COAL_PICKS -----
2 | *****
3 |
4 | START OF PARAMETERS:
5 | ../data/cluster.dat          -data file with faci-distance data
6 | 1 2 3 4 5 6                 - columns for DH,X,Y,Z,Coal Ind,Faci-Dist
7 | estimates.out                -file for faci-dist estimates output
8 | thickness.out                -file for 2-D global kriging output
9 | picks.out                    -file for picks output
10 | 2                             -number of decimal places to report picks to (1-6)
11 | 50 0.5 1.0                  -nx,xmn,xsiz
12 | 50 0.5 1.0                  -ny,ymn,ysiz
13 | 1 0.5 1.0                   -nz,zmn,zsiz
14 | 10                           -vertical grid discretization (5-25)
15 | 0 2.302                      -0=SK,1=OK,2=LVM[resid],3=LVM[(1-w)*m(u)],5=exdrift
16 | 2                             -standard deviation of vertical search
17 | 2                             -number of standard deviations to consider
18 | 1 0.2                        -nst, nugget effect
19 | 1 0.8 0.0 0.0 0.0           -it,cc,ang1,ang2,ang3
20 | 10.0 10.0 10.0              -a_hmax, a_hmin, a_vert
21 |

```

Figure 12: The parameter file for coal_picks.

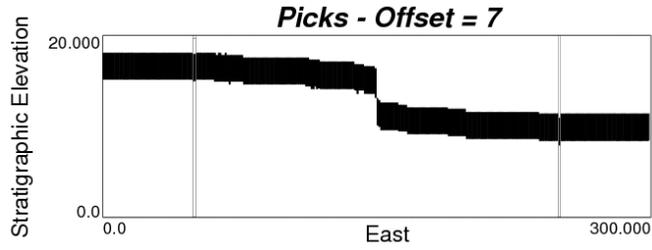


Figure 13: An example of the output produced by `pickselp1t` showing both a coal seam and the drill holes.

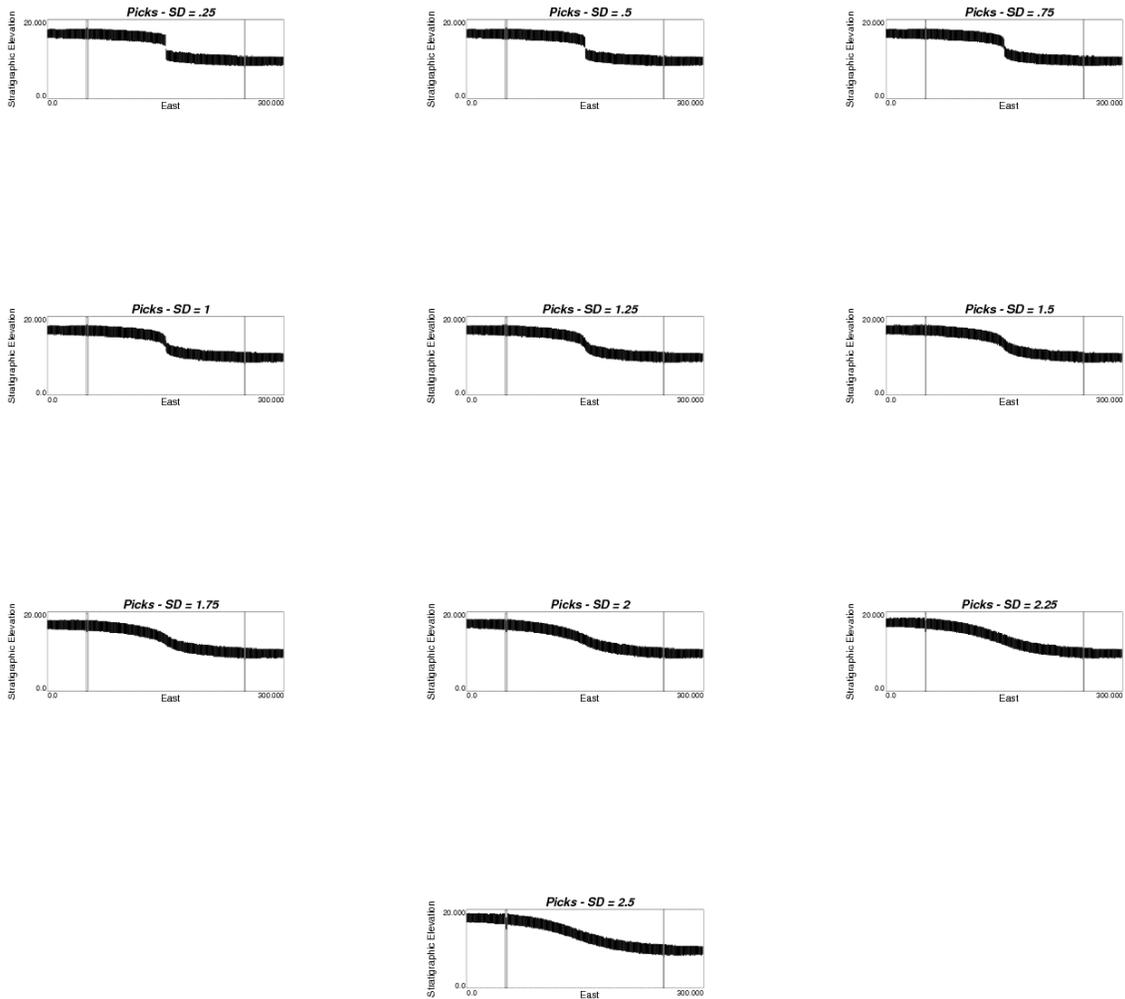


Figure 14: The effect that standard deviation has on the connectivity of a coal seam. Everything is held constant except the vertical search standard deviation which is varied from 0.25 to 2.5. As the standard deviation increases, the connectivity increases.

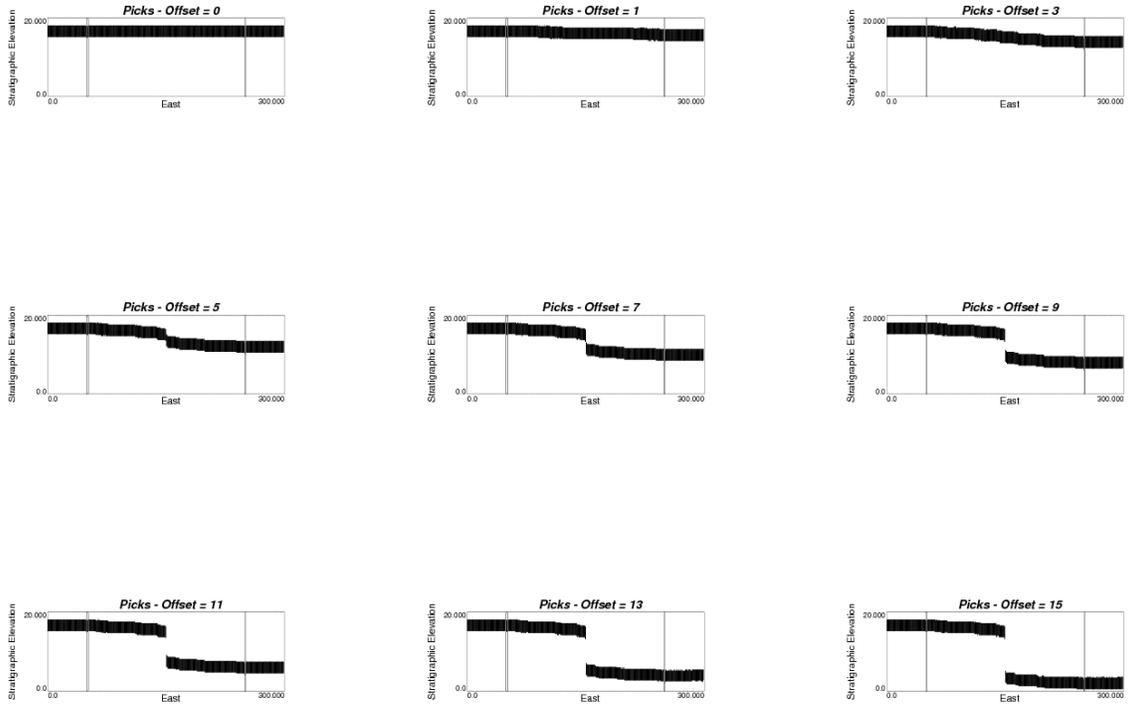


Figure 15: This figure demonstrates how the connectivity changes as the coal seams become more and more offset. Eventually, at an offset of 9m, the seam ‘snaps off’ and is no longer connected.

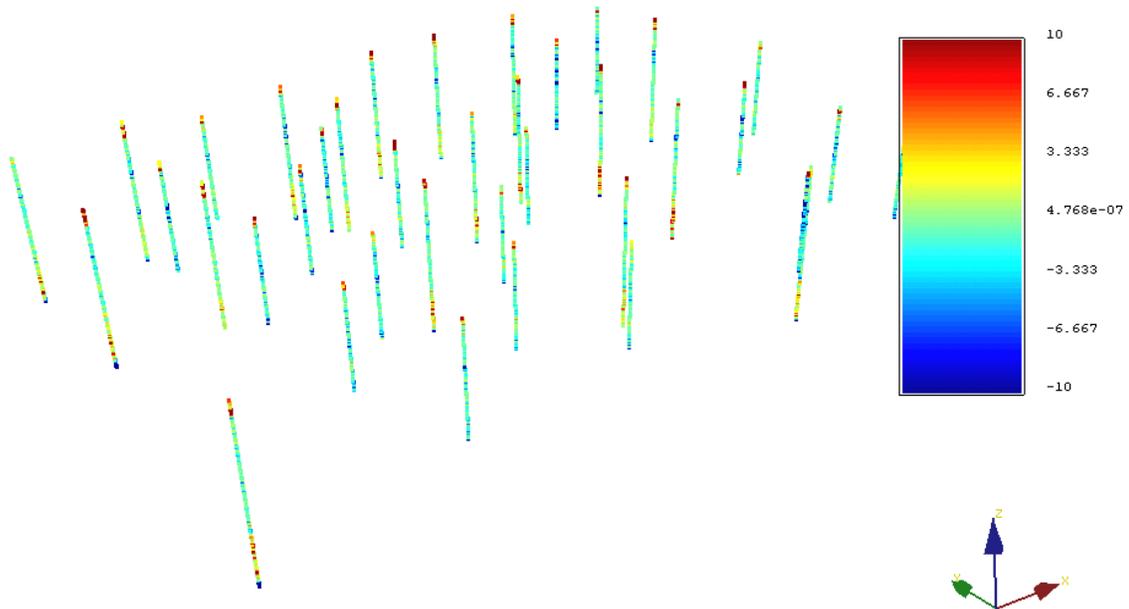


Figure 16: Data for a 3-D example. The values represented are the faci-dist values.

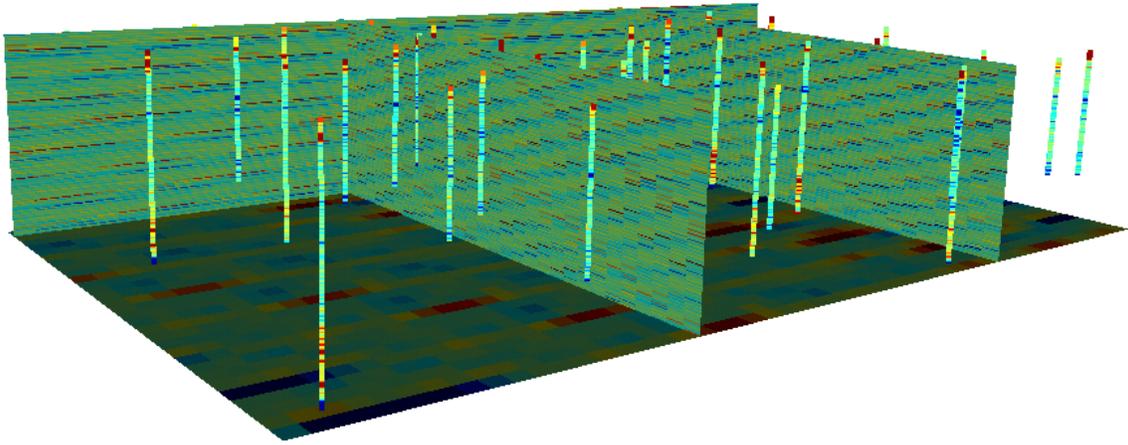


Figure 17: The populated model of faci-dist estimates.

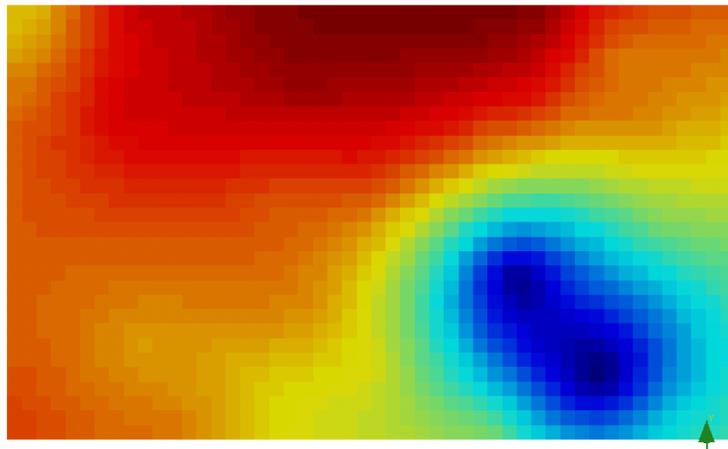


Figure 18: Total coal thickness map, produced by global kriging during the modeling process.

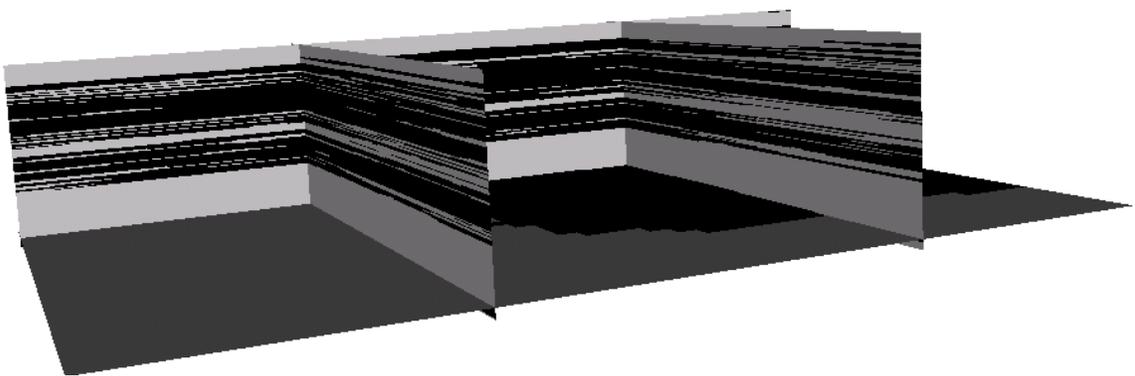


Figure 19: The final picks model.