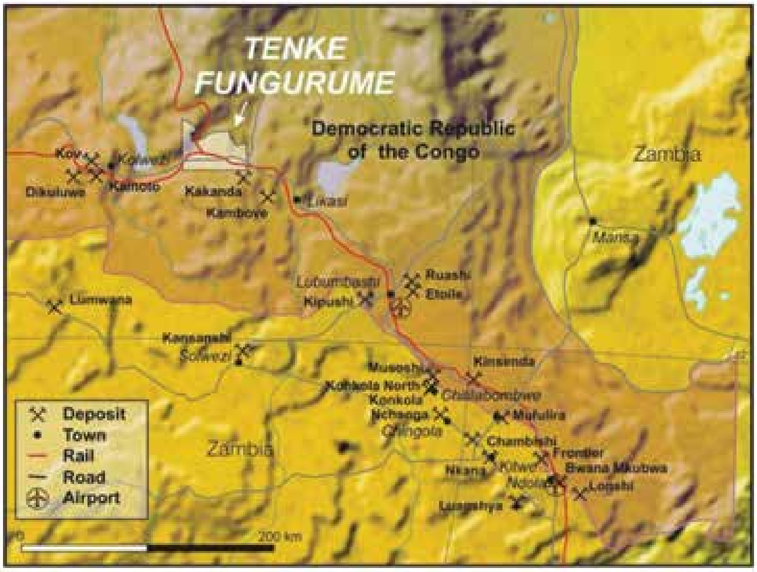
Dynamic unfolding-complex geology case study of Tenke-Fungurume deposits

by Justin Cardwell and Alyson Cartwright

Grade estimation is the cornerstone of long-range mine planning. Pit designs, metal recovery, mining costs, reserves calculations and reporting are all dependent upon a reliable grade model. If the geology is poorly understood or the interpolation methods and parameters have been haphazardly constructed, then massive financial losses will be the inevitable outcome. Therefore, a properly trained geologist must use all of the appropriate tools available including deposit knowledge and advances in modeling technology to construct the most geostatistically and practically sound long-range block model.

Figure 1

Location map of the Tenke-Fungurume mining district.



Certain deposits, such as the sediment-hosted deposits at Tenke-Fungurume, require an interpolation method that best suits the style of mineralization. In 2014, Hexagon Mining developed a tool in MineSight called dynamic unfolding (MSDU) that has the potential to improve upon previous Euclidean-based interpolation methods. MSDU utilizes the non-stationarity of a folded grade trend to more accurately construct variograms and improve interpolation results based upon a modeled three-dimensional surface.

Geology overview. The sediment-hosted Tenke-Fungurume mining district is located in the southeastern part of the Democratic Republic of the Congo (Fig. 1). The rocks within the district are primarily dolomites and shales from the lower half of the Roan Supergroup that were mineralized by ascending pregnant copper and cobalt rich brines within a massive sedimentary basin (Cailteux et al., 2005) (Fig. 2). These oxidized brines likely found a fluid channel in the porous RSC unit. The surrounding rock units provided a redox boundary for copper and cobalt precipitation along organic rich beds, forming a massive stratabound deposit that was later broken up by several subsequent tectonic events (Dewaele et al., 2006).

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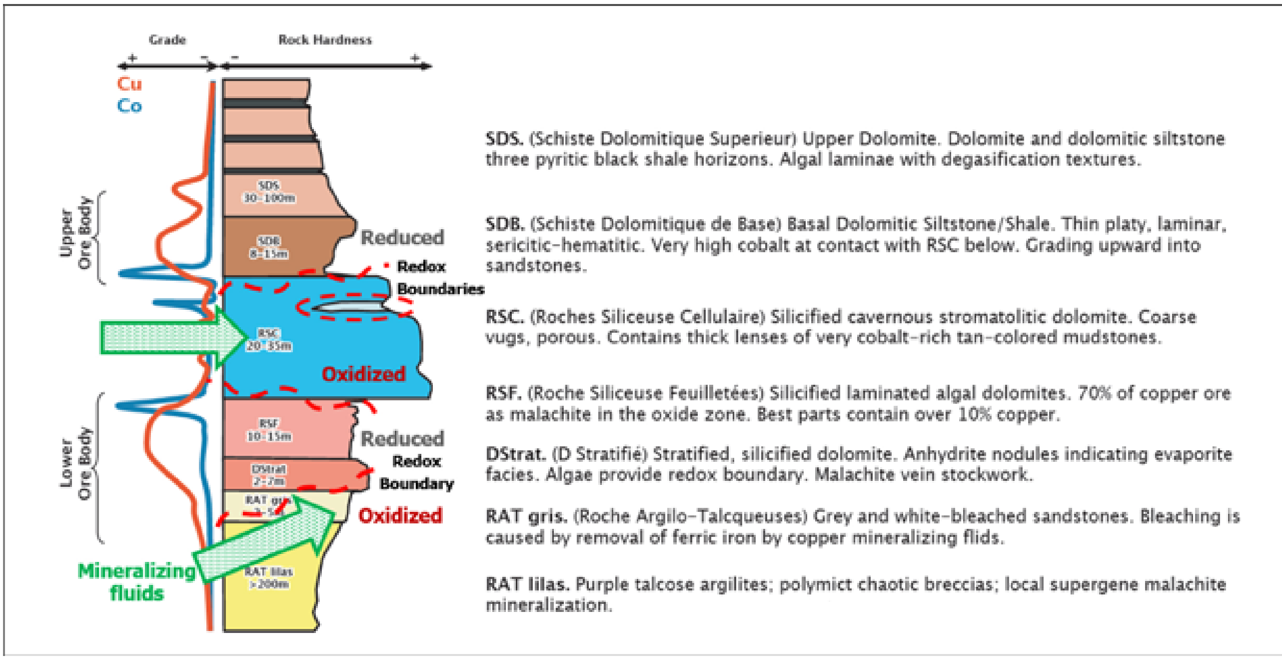
Layering and block orientations. To capture the bedding-controlled nature of the Tenke-Fungurume copper and cobalt mineralization, each lithology type must be subdivided into individual layers with uniform thickness (Fig. 3). The thickness of each layer is determined by the user, but should equal the bench height to achieve maximum resolution within each lithology type. Composites are back-coded from the model to achieve layer codes that match block locations.

Prior to the introduction of MSDU, local anisotropy kriging (LAK) was used as the interpolation method of choice for Tenke-Fungurume deposits. LAK assigns an orientation for each block by calculating a dip and dip azimuth used to help define a search ellipsoid. Each block would effectively contain its own unique orientation, but the orientation is static and cannot adapt to any nearby deformation (Fig. 4). On a small scale, or for a larger relatively undeformed deposit, LAK works well to capture

Figure 2

Lower Roan Supergroup, also known as the mine series.



the overall orientation of a simple deposit. However, if a deposit is highly deformed, then LAK's usefulness collapses as local search ellipsoids fail to capture continuously changing regional bedding orientations.

Dynamic unfolding concepts

In response to the limitations in Euclidean-based grade estimation methods, MineSight created an unfolding toolkit consisting of two main components. The first step in the unfolding process is carried out with the Relative Surface Interpolator (RSI) tool, and the second is the MineSight Dynamic Unfolding tool (MSDU). The approach relies on finding the shortest distance between two points on a curved surface halfway between the points in question. This path, called the geodesic, has the property that it is locally straight, yet follows the trend of the 3D surface.

Relative Surface Interpolator (RSI). RSI allows users to tackle the problem posed by three-dimensional, nonlinear grade trends within a deposit. The RSI tool allows the user to generate a more detailed surface (representing the three-dimensional grade trend) based on one or two modeled input surfaces generated from the MineSight Implicit Modeler tool (MSIM). For example, the user can simply make a copy of a completed MSIM surface (Fig. 5) or choose to make an RSI surface halfway between two surfaces. The general idea is to make a detailed surface that best fits the grade trend of the deposit. Cube size, or level of detail within the surface, is controlled by the user as well. If an input surface is relatively flat, then a larger cube size will suffice. However, if the input surface is folded or generally convoluted, then a smaller cube size may be required to capture any severe undulations in the surface.

Dynamic Unfolding (MSDU). In order to use an RSI surface for variogram construction or interpolation purposes, the second step in

Figure 3

Layering codes from block model of Fwaulu deposit.

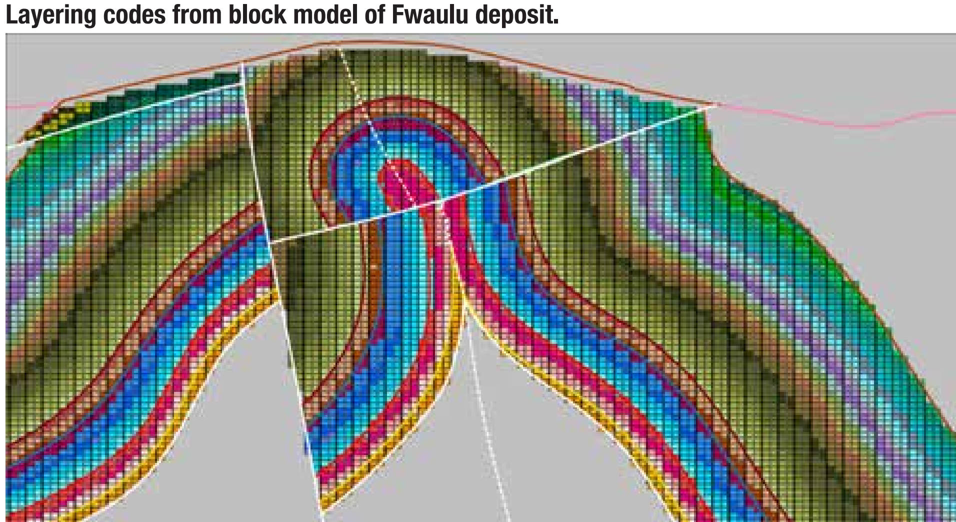
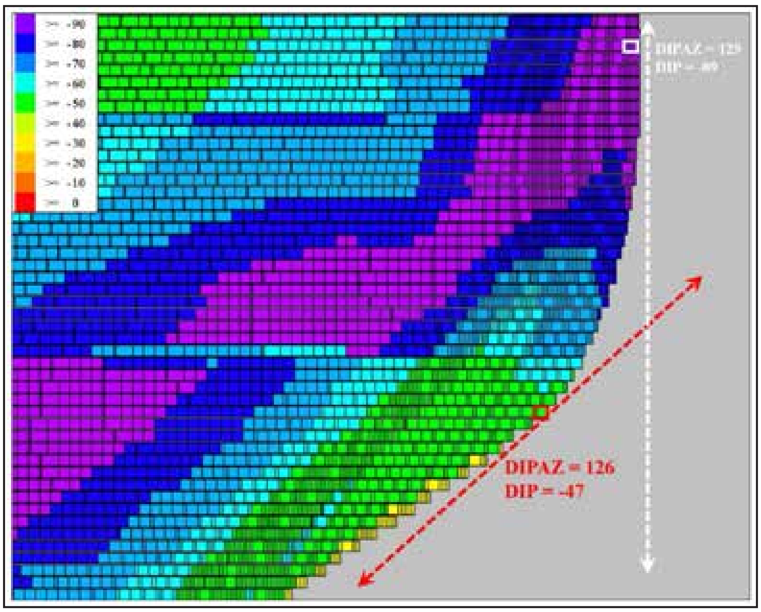


Figure 4

A horizontal three-dimensional block model view of dip (created by LAK workflow). Each block contains a vector defined by a dip and dip azimuth (dashed lines). The orientation assigned to each block helps to define its local search ellipsoid. Where beds are folded, the block orientations become meaningless, because the orientation of the surrounding blocks changes rapidly (white and red boxes highlighting individual blocks). Folding adversely affects anisotropy perpendicular to bedding and along strike of the bedding. Euclidean distances used in LAK become largely erroneous.



the MSDU workflow is to run the RSI surface with the composite data to calculate geodesics. Geodesics are calculated using the Fast Marching Method. This algorithm can be thought of as similar to superimposing a Cartesian grid on the surface and propagating a signal outward from a source point (for instance a composite). When the signal reaches a given grid point, that point is labeled with the time it took for the signal to reach the point. It is similar to Dijkstra's algorithm applied to a grid-shaped network.

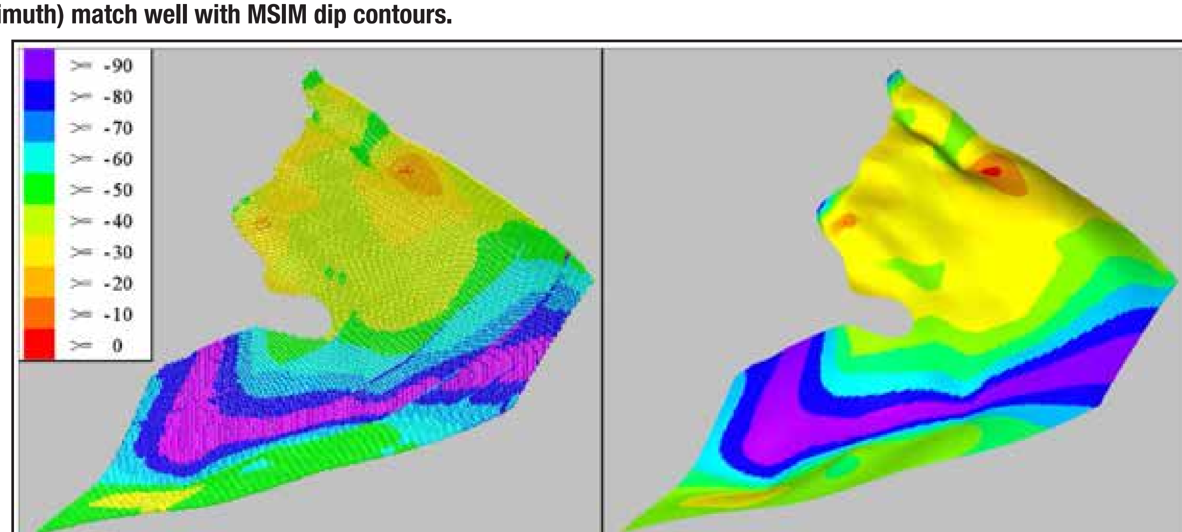
The user selects the composites that are relevant to the modeled grade trend, or the composites that will be used for statistical analysis and kriging in relation to the input RSI file, and grids the composite data along the input RSI surface. The output Fast Marching Results (FMR) file contains all point (composite) locations in terms of relative distance to and along the input RSI surface (Fig. 6). This is the critical last step in the MSDU file construction because geostatistical analysis and interpolation runs in MineSight will access the gridded FMR file and retrieve relative point locations anywhere along the input RSI surface.

Correlograms: Sage vs. MSDU

Prior to MSDU, Sage software was used to construct correlograms for LAK interpolation runs (Fig. 7). Sage has the ability to combine pairs from individual layers from a given rock type into a single correlogram. Considering the fact that the mineralization at Tenke-Fungurume is stratabound, combining each layer from a single lithology into one correlogram adds an extra dimension of confidence in correlogram construction over other Euclidean-based software. However, Sage uses Euclidean distances to find matching pairs, so in a highly

Figure 5

The image on the left shows dip values in blocks from one layer (created by LAK workflow). Dip and dip azimuth block values help define the orientation of a nonlinear local search ellipsoid. The image on the right shows dip on an MSIM surface. As dip and dip azimuth change along the surface, so too does the orientation of the search ellipsoid. Blocks populated with dip (and dip azimuth) match well with MSIM dip contours.

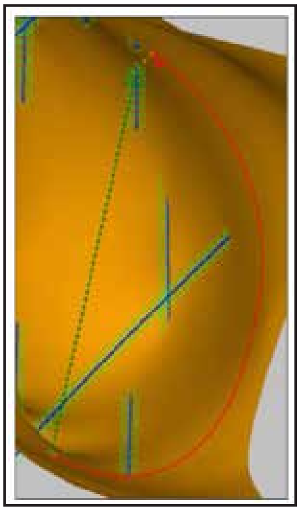


deformed deposit, the layer combining strategy becomes less meaningful as the desired distances between paired data becomes largely erroneous.

To alleviate the problem posed by Euclidean-based pair matching, MineSight allows the user to select an input FMR file to use for variogram construction (Fig. 8). The user can filter the composite data to attain the desired composites to use as an input. MineSight Data Analyst (MSDA) then reads the chosen FMR file and matches the user-selected composite data with the gridded composite data found within the file to construct variograms. MSDA then uses distances attained from the FMR file to find various matching pairs. In a highly deformed stratabound deposit such as Tenke-Fungurume, finding matching pairs based upon a deformed surface will greatly improve and increase confidence in variogram construction. Experimenting with different bandwidths and window sizes in any direction allows the user to determine the direction of greatest spatial continuity along a given surface, even if that surface is highly deformed.

Figure 6

A folded section of an RSI input surface. Green circles represent filtered composites used to create an output FMR file. The red line shows the unfolded path (geodesic), or path along the grid from the selected composite to a chosen location on the surface; the dashed green line shows the Euclidean path taken from the selected composite to the surface; and the yellow line shows the path from the composite to the nearest point on the input surface. The unfolded distance is 175.5 m (575.9 ft) and the Euclidean distance is 115.3 m (378.3 ft), a difference of 52 percent.



Search ellipsoid and anisotropy: LAK vs. MSDU

LAK was designed to capture the orientation of each block for kriging purposes. With each block containing its own unique orientation, or vector, changes in the strike or dip of the layers can be captured locally. The block orientations, in turn, would aid in the determination of local search ellipsoids. While the orientation was not technically accurate for a large area, it was nevertheless a major improvement over any other software that used a single search ellipsoid for an entire deposit. Each block also contains its own defined anisotropy in terms of direction and magnitude. In the case of Tenke-Fungurume, or any other stratabound deposit, anisotropy is most always defined as being perpendicular to bedding (in some cases x and y are not isotropic either). Considering each block contains its own unique orientation, so too does each block contain its own unique, but stationary, z-axis direction. By default, a value of 0.33 is stored in the blocks as the anisotropy ratio.

MSDU functions similarly to LAK in some regards, but with greater flexibility and with local as well as regional non-stationarity capabilities. For example, the z-axis with MSDU is defined as the direction perpendicular to the input RSI surface and will change through space in response to changes in strike and/or dip (Fig. 9). Hence, no block contains orientation information since the RSI surface determines all local and regional orientations. This also has a grandiose effect on the assigning of kriging weights. The search ellipsoid used by any given block is no longer dependent upon the contained dip and dip azimuth numbers, but is relative to the input RSI surface and, therefore, nonlinear. The search ellipsoid changes in response to changes in orientation of the input RSI surface. Therefore, if a stratabound deposit is highly deformed, then that deformation will be reflected in the undulating search ellipsoid and assignment of kriging weights.

Figure 7

A copper correlogram constructed using Sage software. No bandwidth limitations were chosen and a window of 360º was selected in order to maximize the number of pairs found.

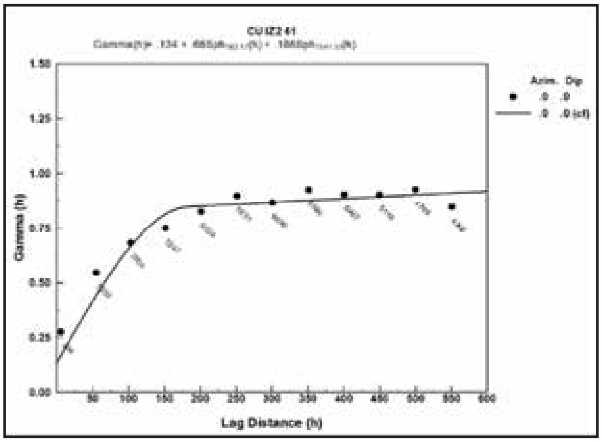
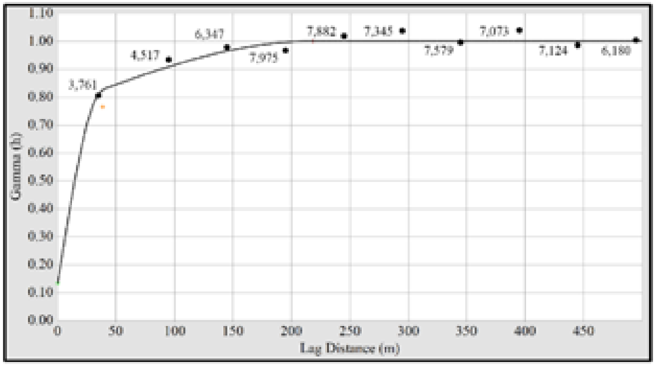


Figure 8

A copper correlogram constructed using an FMR file in MSDA. As with Sage, the same data set was used, no bandwidth limitations were enacted, and same data selection criteria was used for correlogram construction.



Fwaulu: LAK kriging vs. MSDU kriging

The Fwaulu deposit within the Tenke-Fungurume mining district was used as a test between LAK and MSDU. To provide a useful comparison, the same kriging input parameters were used for each domain that includes layer grouping, cutoffs, number of composites used, minimum number of composites used, maximum number of composites used, and relative search distances for both LAK and MSDU. The only differences were the correlograms (constructed differently by Sage and MSDA) used and the external use of LAK vs. the internal use of DU within MineSight. Grade estimation was conducted over the entire model (10 domains for each layer combination) for copper and cobalt.

Figure 10 shows the LAK and MSDU kriged cobalt grades for layer 6101 of domain 1 (domains 1 and 2 for LAK only). Due to the severe folding, an artificial hinge line was constructed to separate the lithology on either side to prevent blocks from finding closely neighboring composites residing directly across the tight fold for LAK kriging. Because MSDU is capable of searching around a tight fold along a surface, no hinge line was required for kriging purposes.

While kriging trends are similar between LAK and MSDU, zonation is more evident in Fig. 10 for MSDU due to the absence of a hinge line. Near surface areas, away from the hinge line, the deposit reveals high grade zones of cobalt with grades in excess of 1 percent. A high grade cobalt cutoff grade of 1.28 percent was used for layer 6101 with a radius of 20 m (65 ft)(beyond the specified radius a composite exceeding the cutoff grade will be truncated to 1.28 percent in the kriging algorithm). Because LAK uses Euclidean distances, these high grade zones become artificially truncated much faster than for MSDU, which uses distances along a surface. The exception is when edge effects are considered. This is due to the fact that composites in Euclidean space reside closer to one another, thereby diluting the influence of a relatively high grade composite much faster. Therefore, in highly folded deposits, MSDU has the potential to increase the number of blocks and overall tonnage of high grade material. Conversely, MSDU also has the potential to increase the number and overall tonnage of low grade material.

A distinct break in interpolated absolute block grade differences and percent differences is evident in the hinge line in Fig. 11. Zones of MSDU TCo percent > LAK TCo percent abruptly change to zones of LAK TCo percent > MSDU TCo percent across this boundary. While this line of demarcation can occur in interpolation zones where the same composites are used for MSDU and LAK, the change from areas of MSDU TCo percent > LAK TCo percent to areas of LAK TCo percent >MSDU TCo percent are generally gradual. However, if LAK uses fewer composites than MSDU due to tight folding, then abrupt changes in grade will occur for LAK and an artificial look produced.

Tables 1 and 2 show the

Figure 9

The image on the left shows a search ellipsoid for LAK (major = 300 m (985 ft) minor = 300 m (985 ft), and vertical = 100 m (328 ft)) in green. The block of interest, in blue, has a dip of -61° and a dip azimuth of 201°. The image on the right shows an MSDU search ellipsoid (major = 300 m (985 ft), minor = 300 m (985 ft), and vertical = 5 m (16 ft)) in green. Note how the search ellipsoid changes with varying surface orientations.

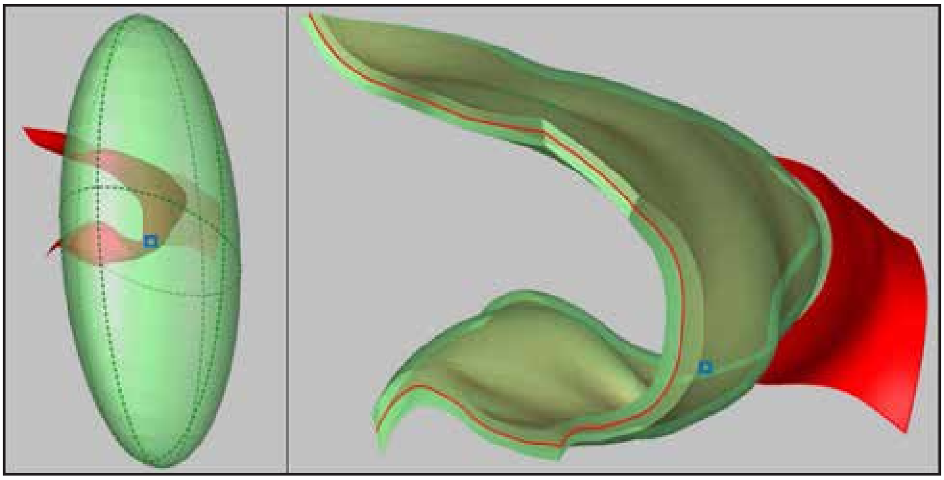
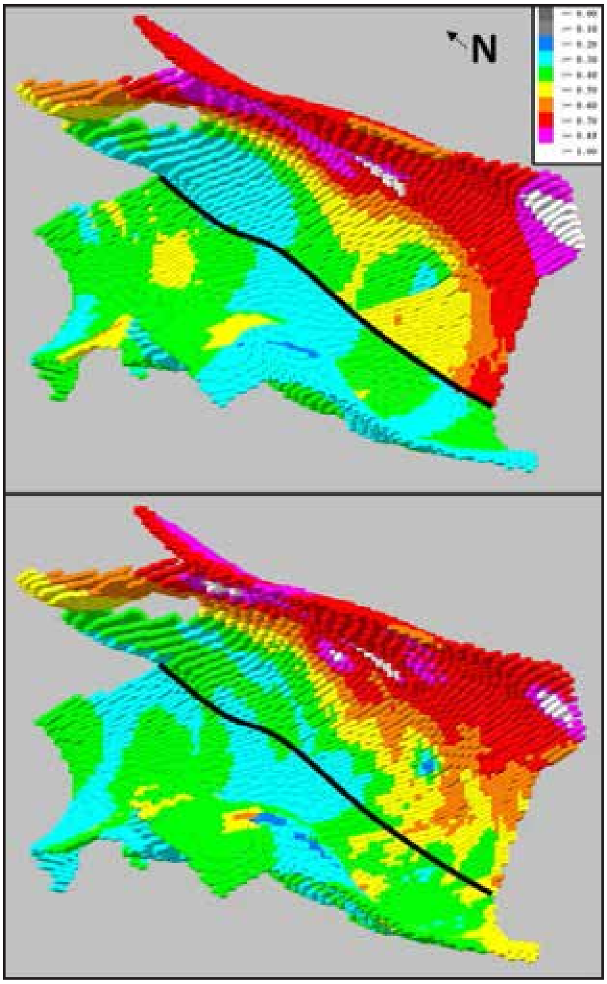


Figure 10

The top image shows three-dimensional LAK cobalt block grades filtered for layer code = 6101. The bottom image shows MSDU cobalt grades. A clear break in the block grades can be seen in the middle of the top image (black line) due to the installation of a hinge line interpolation boundary. The black hinge line in the bottom image shows approximate location of artificial hinge for reference (but was not required or used in MSDU).



debugged output for a particular block just above the hinge line in Fig. 10 (outlined in red). Only three mutual composites were found by both MSDU and LAK (highlighted in red in Tables 1 and 2) due to the installation of the hinge line interpolation break for LAK. For the closest hole found by both interpolation methods - drill hole 11 - the MSDU distance (taking into consideration anisotropy) is 53.5 m and 48.3 m (175 ft and 158 ft) for LAK. The difference in distance used to assign kriging weights is 5.2 m (17 ft) or 9.7 percent, while the difference in assigned kriging weight is 0.11371 or 54 percent.

The farthest composite in common is drill hole 294. Here the MSDU distance is 110 m (360 ft) and the LAK distance is 99.3 m (325.9 ft) for a difference of 10.7 m (35 ft) or 9.7 percent. The difference in assigned kriging weights is 0.05797 with a difference of 39.7 percent. As a result, differing correlograms coupled with different distance calculations for MSDU and LAK produced major differences in block grades for the highly folded area. The MSDU interpolated cobalt grade for this block is 0.47 percent and 0.75 percent for LAK, a difference of 37 percent.

For the composites found in common, absolute differences in distance were minor but on a percent basis, the differences were moderate. Due to the presence of a fold hinge artificially separating the lithology into two domains, few composites were found in common by LAK and MSDU resulting in massive discrepancies in assigned kriging weights and calculated grade. However, over short distances with minor surface undulations, MSDU produces noticeable differences in distances in comparison with LAK. Relatively small differences of 5 percent or 10 percent may not have a noticeable effect on modeled variograms, but they will produce similar differences in assigned kriging weights (assuming all the found composites are the same between LAK and MSDU). Therefore, grade interpolation on a block-by-block basis could deviate moderately between LAK and MSDU. Over the breadth of an entire deposit, however, moderate to immense grade differences virtually disappear.

Figures 12 and 13 show grade profiles for the entire Fwaulu deposit. LAK and MSDU closely mimic one another, layer-by-layer, with only trivial differences in grade. Based on the spatial distribution of drill holes and the vast area comprising an entire deposit interpolated grades will tend to average out no matter which method is used. While block-to-block grade differences may be substantial when comparing LAK to MSDU, overall grade by layer is similar.

Average LAK cobalt grade by layer matches well with the average MSDU grade. Where cobalt grade spikes at the top of the RSF and bottom of the SDB, the layering strategy implemented was able to isolate high grade layers. Both LAK and MSDU reflect the high grade portions of the Fwaulu deposit and deviate minutely from one another.

Similar to cobalt, LAK and MSDU kriged copper grades by layer match well for the Fwaulu deposit. In fact, average copper grades are almost identical for the two methods by layer with only a slight difference residing within the higher grade RSF unit. Isolated spikes in LAK and MSDU grade by layer, at the base of the SDB for example, match well with the nearest neighbor estimate.

Tenke-Fungurume

Figure 11

The image on the left is a three-dimensional view of absolute differences in block cobalt grades between LAK and MSDU. Green blocks indicate LAK TCo > MSDU TCo and blue regions indicate MSDU TCo > LAK TCo. The image on the right shows cobalt percent differences between LAK and MSDU. Green blocks indicate LAK TCo > MSDU TCo. Small red box outlines debugged block. Both images are filtered by cobalt interpolation zone = 1 and 2, LAKLR = 6101, and LAK TCo or MSDU tco > 0.25 percent. The hinge line separates cobalt interpolation zone 1 and is used in LAK only.

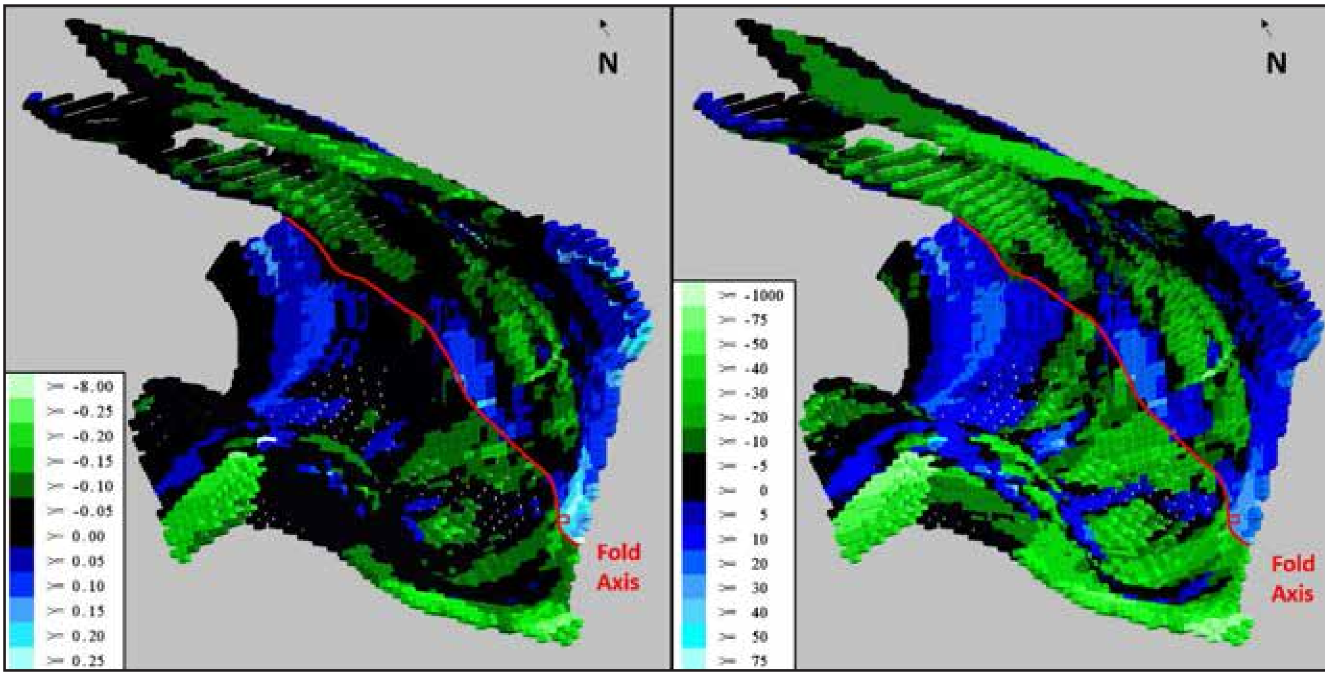


Table 1

MSDU debugged block at location 40707.5 Easting, 8830508.75 Northing, and 1271.25 Elevation. Kriged block grade = 0.47 percent TCO and variance = 1.04931. A search distance of 300 m (985 ft) was used.

ID	Dist (m)	Easting	Northing	Elev.	TCO%	Kriging Weight
11	53.5	407696.1	8830525.0	1315.4	0.809	0.09680
294	54.4	407713.6	8830473.2	1240.1	0.490	0.14614
11	56.4	407697.2	8830526.3	1317.3	0.211	0.08945
199	61.6	407657.4	8830483.6	1269.6	0.017	0.07847
199	63.5	407657.4	8830483.6	1272.1	0.257	0.07287
114	77.4	407651.5	8830542.5	1293.8	0.184	0.06992
114	79.8	407651.5	8830542.5	1296.3	0.536	0.06572
171	82.8	407677.3	8830444.8	1276.8	0.195	0.04933
171	85.0	407677.4	8830444.9	1279.3	0.959	0.03891
113	89.0	407678.6	8830442.3	1280.7	0.056	0.03510
113	90.4	407678.6	8830442.3	1283.2	0.073	0.04056
164	97.1	407611.4	8830516.3	1281.7	1.078	0.06026
78	98.7	407609.5	8830514.0	1280.5	0.184	0.05891
294	110.0	407715.2	8830474.7	1364.2	1.040	0.09757

Conclusion

Two interpolation methods, LAK and MSDU, were tested on the Fwaulu deposit for copper and cobalt grade estimation. Each method utilized a layering strategy to subdivide and isolate grade within each lithology type. However, LAK is restricted to Euclidean space for variogram construction, kriging weight assignment and interpolation search ellipsoids, while MSDU is far more dynamic and can utilize modeled three-dimensional surfaces for non linear use. Due to complex folding, differences in interpolated copper and cobalt grade between LAK and MSDU can be quite substantial on a block-by-block basis. High and low grade zones may also be more abundant for MSDU because composite distances follow curved surfaces rather than simple and shorter straight lines as with LAK. However, over an entire deposit, differences in interpolated grade between LAK and MSDU tend to shrink considerably to matching levels.

The use of MSDU over LAK in an exploration model likely will not be a determining factor in the feasibility of a project. However, grade differences

Figure 12

The Fwaulu deposit cobalt grade profile by layer.

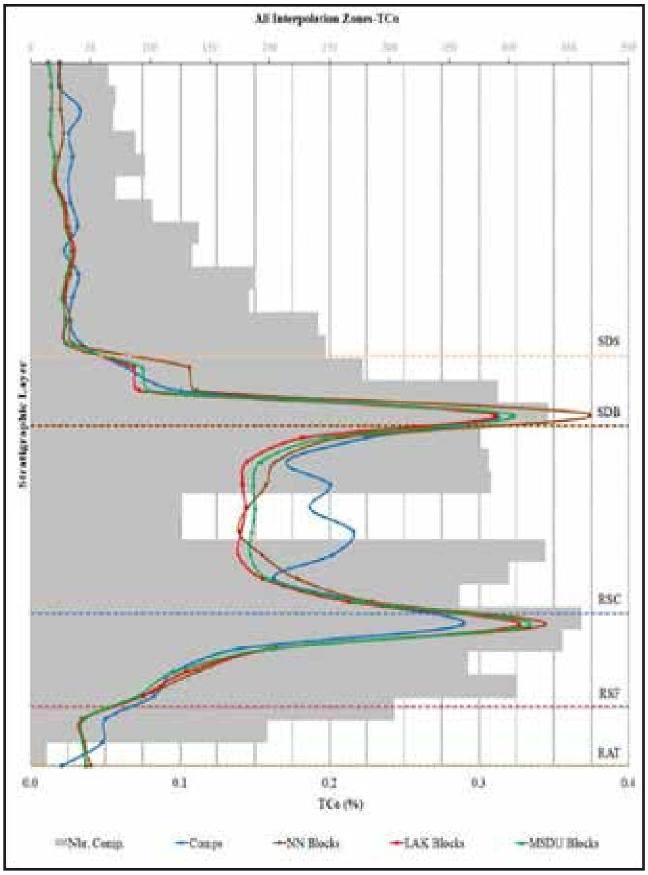
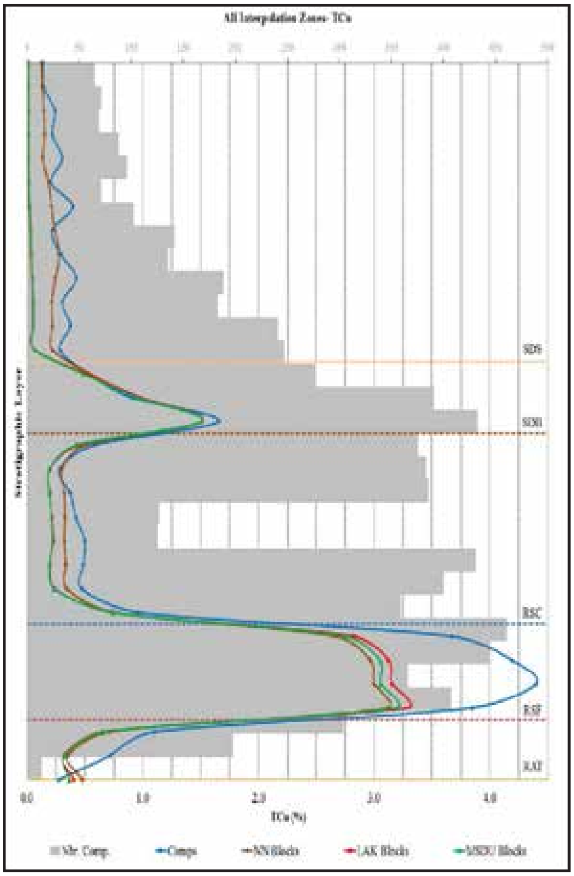


Figure 13

Fwaulu deposit copper grade profile by layer.



between the two methods can produce enough local variation to alter pit designs and overall mine planning. Considering MSDU possesses the capability to capture three-dimensional grade trends, its use should inspire more confidence in grade estimation than other static interpolation methods when dealing in stratiform deposits. ■

Table 2

LAK debugged block at location 40707.5 Easting, 8830508.75 Northing, and 1271.25 Elevation. Kriged block grade = 0.75 percent TCo and variance = 0.78077. Search distance of 300 m (985 ft) used.

D	Dist (m)	Easting	Northing	Elev.	TCO%	Kriging Weight
11	48.3	407696.1	8830525.0	1315.4	0.809	0.21051
11	50.2	407697.2	8830526.0	1317.3	0.211	0.19401
114	90.5	407650.8	8830543.0	1333.1	0.651	0.05495
114	92.6	407650.8	8830543.0	1336.1	0.066	0.04578
294	99.3	407715.2	8830475.0	1364.2	1.040	0.08817
4	120	407665.9	8830491.0	1382.4	1.280	0.01881
199	128.8	407659.8	8830485.0	1388.5	1.280	0.03875
199	130.6	407659.9	8830485.0	1390.5	0.208	0.04317
76	144.9	407827.4	8830448.0	1325.0	0.933	0.05277
167	145.4	407827.1	8830447.0	1326.1	1.280	0.05168
76	145.9	407827.4	8830448.0	1327.6	0.688	0.05168
167	146.4	407827.2	8830447.0	1328.5	0.978	0.05252
165	159.1	407610.7	8830517.0	1397.2	1.28	0.09720

References

Caliteux, J.L.H., Kampunzu, A.B., Lerouge, C., Katputo, A.K., and Milesi, J.P., 2005, "Genesis of Sediment-Hosted Stratiform Copper-Cobalt Deposits, Central African Copperbelt," *Journal of African Earth Sciences*, Vol. 42, pp. 134-158.

Dewaele, S., Muchez, Ph., Vets, J., Fernandez-Alonzo, M., and Tack L., "Multiphase Origin of the Cu-Co Ore Deposits in the Western part of the Lufilian Fold-and-Thrust Belt, Katanga (Democratic Republic of the Congo)," *Journal of African Earth Sciences, Vol. 46*, pp. 455-469.

Hitzman, M.W., Selley, D., and Bull, S., 2010, "Formation of Sedimentary Rock-Hosted Stratiform Copper Deposits through Earth History," Society of Economic Geologists Inc., Vol. 105, pp. 627-639.

Jackson, M.P.A., Warin, O.N., Woad, G.M., and Hudec, M.R., 2003, "Neoproterozoic Allockthonous Salt Tectonics during the Lufilian Orogeny in the Katangan Copperbelt, Central Africa," *GSA Bulletin*, Vol. 115, No. 3, pp. 314-330.