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Dynamic Interpolation - Estimation in a Folded Environment at the Cosmo Deposit, Northern Territory, Australia

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ABSTRACT

The Cosmo Project falls within the Archaean to Palaeo-Proterozoic Pine Creek Orogen, one of the major mineral provinces of Australia.

The Cosmo Deposit is interpreted to be a series of steep northwest plunging gold mineralised vein, breccia and shear systems within the tight Howley Anticline and hosted within interbedded siltstones, mudstones, banded iron, phyllites, dolerite sills and greywacke.

A folded environment poses a number of technical challenges, particularly for estimation.

Handling of tightly folded and in some cases narrow domains might include sub-domaining for orientation, omni-directional 3D estimation within constrained domains or software enabled unfolding / un-wrinkling procedures (transformation of the data and estimate space into a 2D environment). Each technique has its own unique set of advantages and disadvantages.

A further method (one applied at Cosmo) is where the estimation parameters (specifically search and variography orientation) are modified in a frequent or “dynamic” sense to suit the orientation of the domain, whilst maintaining 3D space. Control of the resource estimation orientation can be done in several ways, including the use of sectional panels of a specific size or, alternatively, orientation sector divisions. The sector approach provides some significant reductions in processing time over the panel technique and could be applied in a number of software packages.

Three dimensional “dynamic” interpolation reconciles well with production data from Cosmo, whilst the sector method provides a practical technique that can be executed without the complications of transformation or the need for labour intensive orientation sub-domaining and with acceptable resource estimation run time.

INTRODUCTION

Following a review of the 2011 and 2012 resource models, Crocodile Gold engaged Cube Consulting to assist with development and enhancement of a prototype dynamic resource estimation technique, specifically using GEOVIA’s Surpac Mining Software, which currently has no dynamic estimation or unfolding capability. Two recommendations from the 2012 review were that the folding of the stratigraphy would be better honoured by employing a ‘dynamic anisotropy’ or ‘unfolding’ approach and that the current use of orientation specific sub-domains would increase the likelihood of implementation errors.

Development of dynamic estimation at Cosmo comprised an evolution of several scripted methods, including implementation of both panel and sector methods as well as the modification of the sector method using vector offsets to allow a smoothed application of estimation direction.

The aim of this paper is to outline those methods in a fashion that should allow scripts to be built to replicate the process not only in Surpac, but in any of the other major mining software packages (Datamine / Vulcan / GEMS etc.).

LOCATION AND HISTORY

The Cosmo Project is located within the Burnside Project area located in the Pine Creek region of the Northern Territory of Australia (Figure 1). It occurs between Adelaide River and Pine Creek 180km south-southeast of Darwin and 20km east-northeast of Katherine. Gold was discovered at Brocks Creek in 1871 and at Cosmo Howley in 1873. This was the prelude to a long period of alluvial working by Chinese miners and lode mining by English companies until 1914, followed by little activity in the area for the next 60 years.

Exploration for gold and base metals recommenced during the 1970s and 1980s. In 2004 a scoping study on the potential for Cosmo Deeps to be mined as an underground gold operation was initiated, with Crocodile Gold commencing production in 2011. (Pridmore and Bremner, 2013).

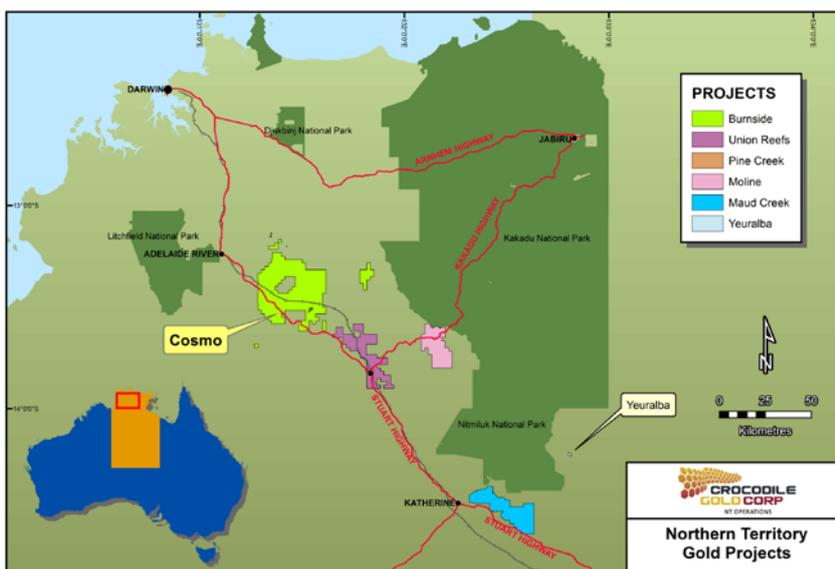


FIG 1 – Burnside Tenement Location, Northern Territory, Australia

GEOLOGY AND MINERALISATION

The Cosmo Project falls within the Archaean to Palaeo-Proterozoic Pine Creek Orogen (PCO), one of the major mineral provinces of Australia.

The Cosmo deposit geology is made up of a series of distal cyclical marine depositional events contained in a sequence referred to as the Upper to Middle Koolpin Formation. This formation consists of interbedded siltstones, carbonaceous mudstones, banded ironstone, phyllites, dolerite sills and greywacke units.

These units have been folded and faulted by a series of regional structural events during the PCO. This period of deformation lead to the formation of the local Burnside intrusion and the Cosmo Anticline, which is the main ore control at the Cosmo Deeps Mine. The Cosmo Anticline plunges 40 degrees to the north with the eastern limb slightly overturned to the west.

The Cosmo mineralization lies within a marine siltstone package located between the inner Zamu Dolerite sill and a more than 30m thick pyritic carbonaceous mudstone unit identified as the “PMC” unit. Four main lodes have been delineated for the Cosmo East Zone and two on the western limb of the Cosmo deposit. These are the 100 Lode, 200 Lode, 300 Lode and the 400 Lode on the eastern limb and the 500 and 600 Lodes on the western limb.

The width of the gold hosting siltstones is 30 to 50 meters in the footwall of the F1-fault and from several meters to over 50 meters in the hanging wall due to variably developed folding.

Over 70% of the known mineralisation is hosted within the 100 lode, while the 200 lode contains approximately 20%. The 200, 300, and 400 lodes are generally progressively lower in grade and more erratically mineralised.

These gold lodes are remarkably planar in the footwall of the F1 along the long eastern limb of the fold. The hanging wall lodes are more complex due to parasitic folding (many of which are isoclinal), causing localized thickening and shortening (Figure 2)(Pridmore and Bremner, 2013).

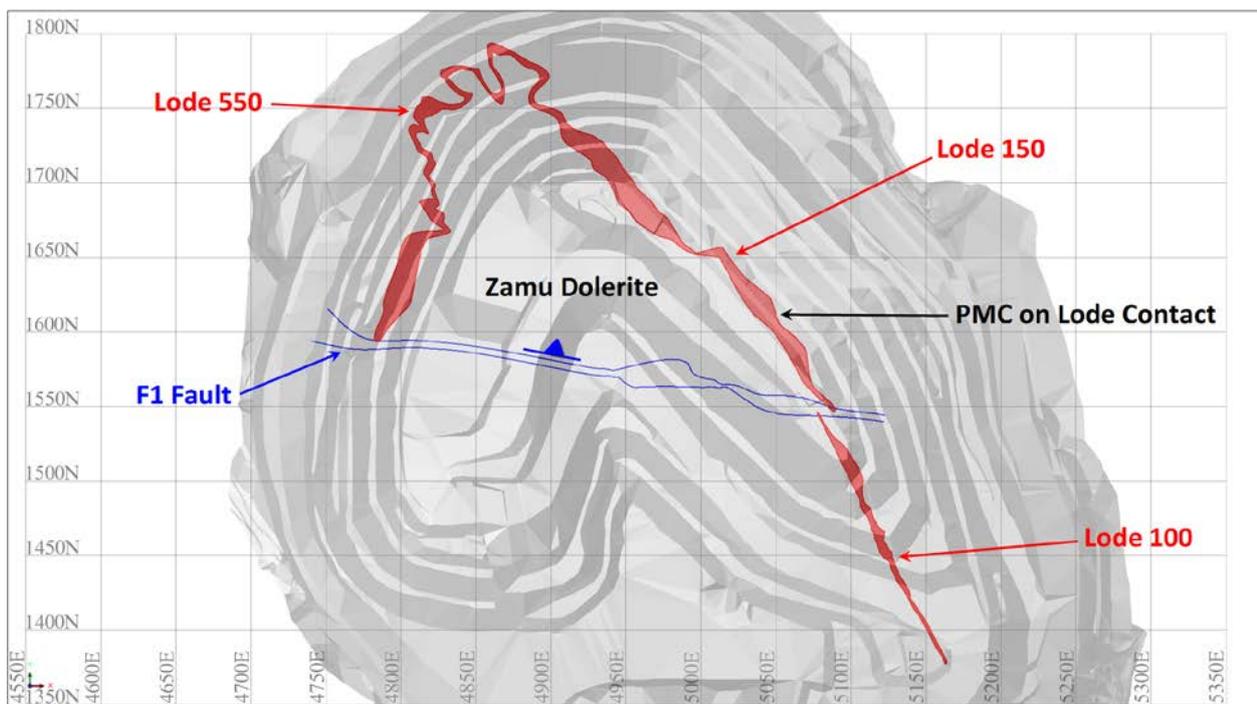


FIG 2 – Cosmo Geology Schematic (985 RL) with Pit Overlay

DYNAMIC INTERPOLATION AT COSMO

For the purpose of this paper, the term dynamic will be used to define an estimation process where the parameters, in particular the search and variogram orientations, are modified frequently. It represents an attempt to improve the estimate in a local sense and shares some similarities with the local geostatistics concept which is dedicated to the optimal local determination of parameters involved in variogram-based models (Geovariances, 2011) and with the dynamic anisotropy routines available in Datamine (Newton, 2014).

Crocodile Gold currently uses Surpac as its general mine planning software at Cosmo. As Surpac has no dynamic or unfolding routines available, a scripted solution to the problem was determined to be the only viable alternative.

The first generation that will be described is referred to as the “panel method” followed by its evolved product, the “sector method”. Both methods are the combination of a number of Surpac functions and trigonometry.

Panel Method

The Panel method represents the first of two scripted applications of a dynamic approach applied at Cosmo for estimating resources in the folded mineralised lode system. It relies upon the use of relatively small panels (gridded cells) to apply the estimate in a sequential fashion. Variography and search parameters are defined in an isotropic fashion with the dynamic process providing local orientation parameters (in a dip and dip direction format) sourced from the wireframe processing and anisotropic ratios fixed by the user.

There are several steps involved in the construction of the individual panels, which in turn are used for constraining the estimate and providing estimate orientation.

The first step comprises wireframe slicing to create evenly spaced panels that allow for wireframe inflections. Each lode wireframe is sliced on a nominated spacing, first in the vertical direction and then in a horizontal direction, using a centreline to help honour the wireframes curves. An illustration of this would be sectioning of the lode wireframe (Figure 3) in plan every 25 metres, followed by slicing of the plan based sections every 25 metres.

The result is a series of short strings running perpendicular to the wireframes surface (from the hanging wall through to the footwall) and uniformly spaced using the nominated separation. The lines form a uniform grid if viewed from an angle perpendicular to the orientation of the original wireframe (Figure 4).

Once the wireframe slicing process is complete, a centroid can be created for each individual slice line. These in turn are used to form individual triangles (each line centroid is grouped with two neighbours) that become part of a triangular mesh. The process of combining lines into triangles creates a single mid-plane surface from which the geometry (dip and dip direction) of the wireframe can be derived through the use of trigonometry (Figure 5).

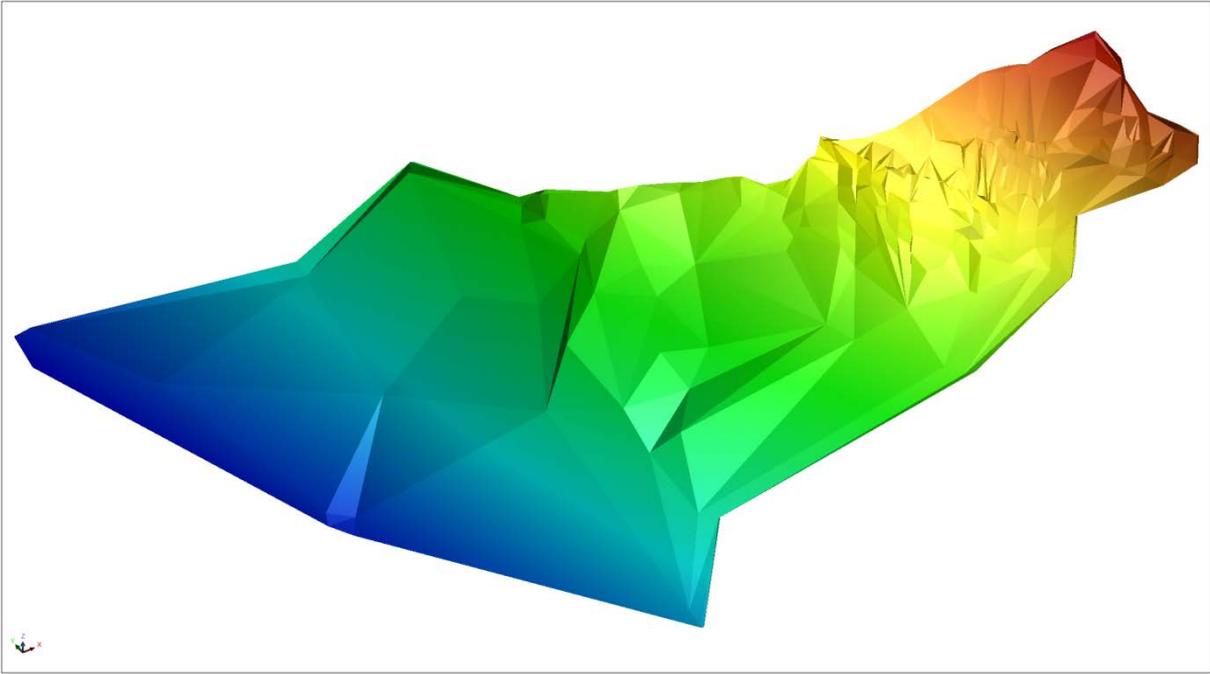


FIG 3 – One of the larger eastern limb lodes at Cosmo, Orientation is striking to 340° and near vertical (View is oblique looking North-East)

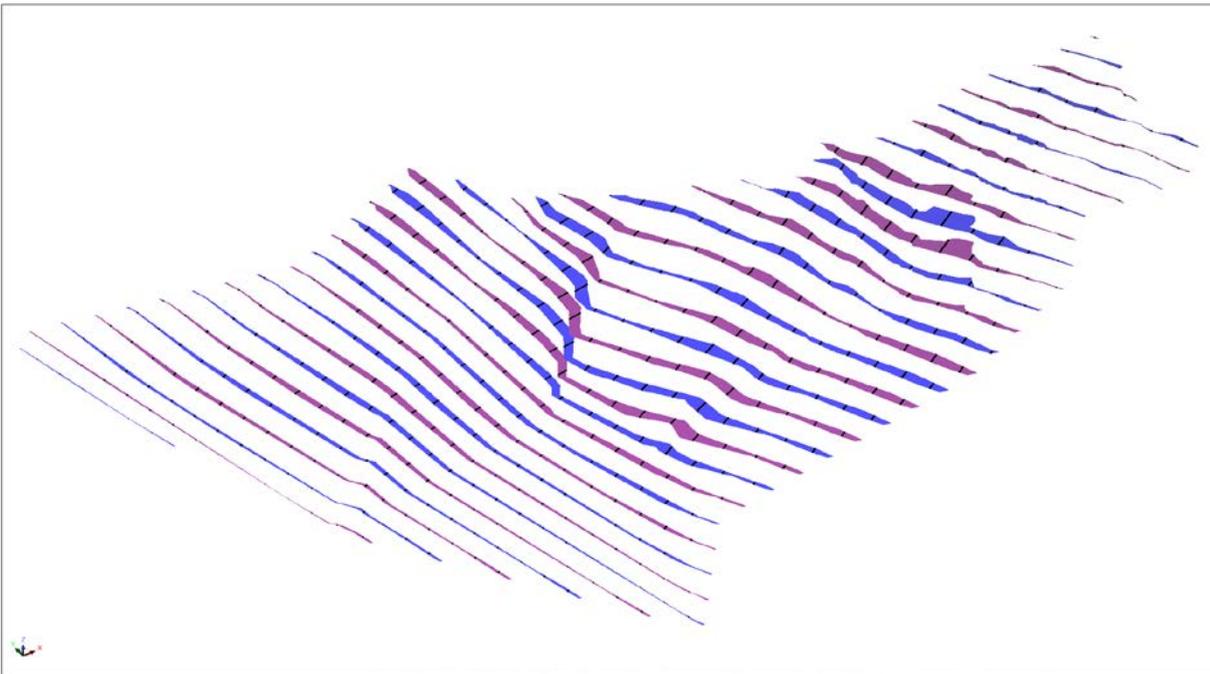


FIG 4 – Sliced Wireframe (Lode 100): Displaying horizontal slices, perpendicular section strings in black (View is oblique looking North-East)

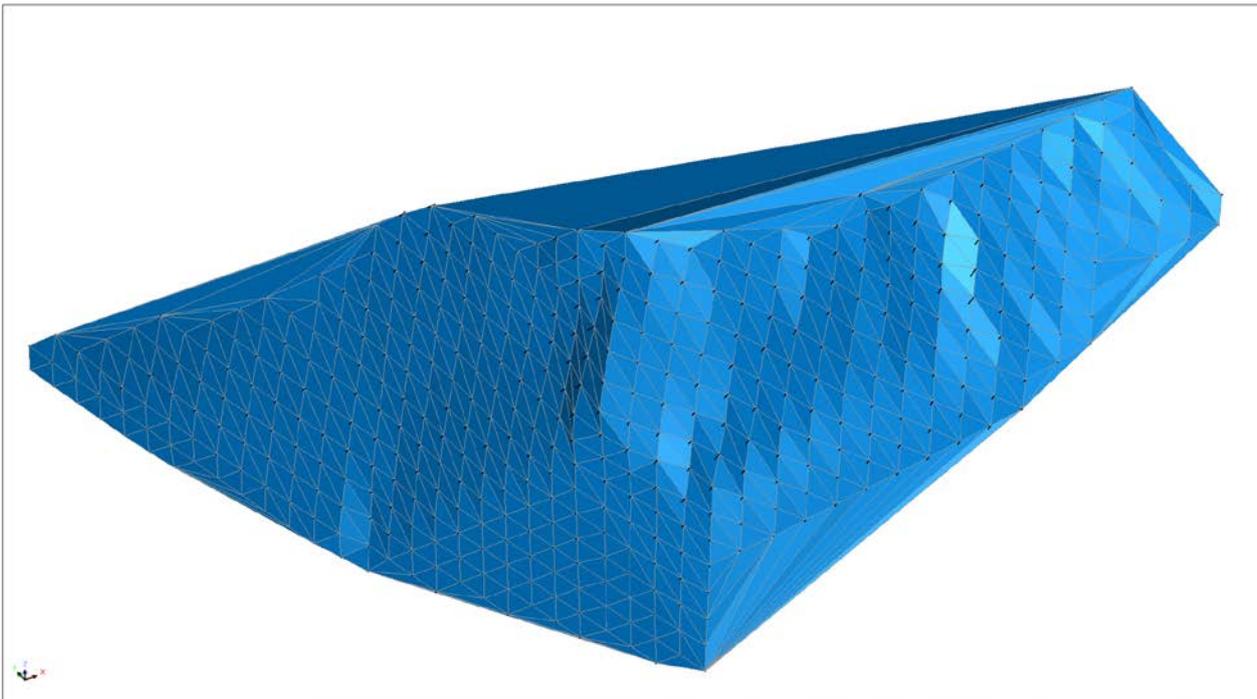


FIG 5 – Mid-plane Surface (Lode 100): Displaying mid-plane surface triangles and section strings in black. (View is oblique looking North-East)

The dip and dip direction is stored individually for each triangle in the mesh allowing for further processing to create the constraining panels.

With a mid-plane surface created, individual triangular panels can be extruded the full width of the lode perpendicular to the orientation of each mid-plane surface triangle, providing a solid from which the estimate can be constrained (Figure 6).

The final step for this method estimation by Ordinary Kriging is reasonably simple but time consuming in Surpac due to the use of individual panels. Each panel is used as a constraint combined with the lode wireframe to complete an estimate on the blocks within. In some of the bigger lodes the number of estimates required to complete the process may number around 1000. This requires significant processing time, in the order of several hours to a day, on a reasonably powerful computer.

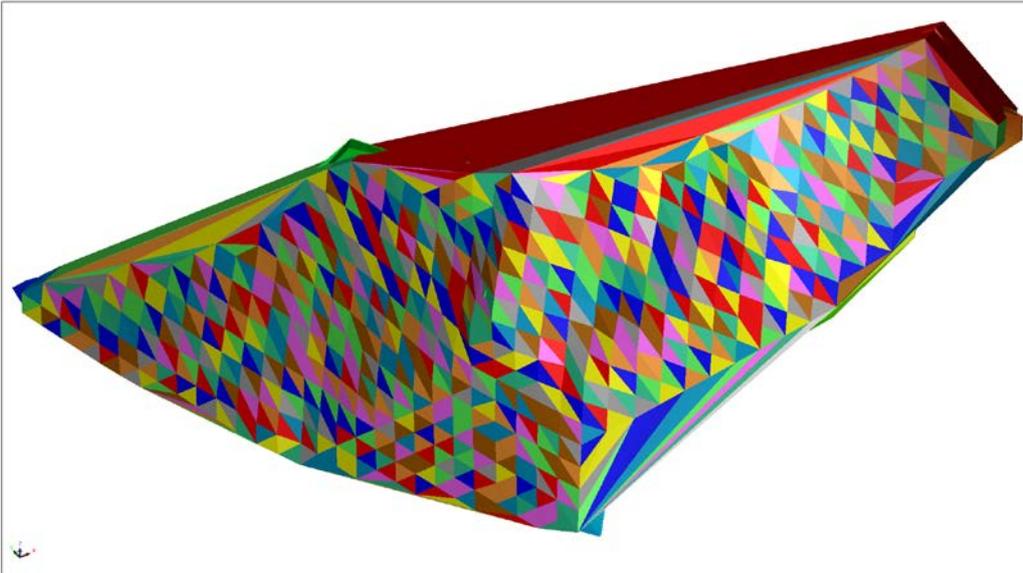


FIG 6 – Triangular Panels (Lode 100): Displaying triangular panels (View is oblique looking North-East)

Sector Method

The Sector method is a different approach to dynamic estimation, with the aim of eliminating the cell grouping created by the panel technique and reducing the time required for an estimate to be completed. It represents an evolution of the panel technique and also solves a shortfall with the panel methods ability to handle tight recumbent folding (Figure 7). It operates by grouping cells into sectors based on angular (geometric) tolerance rather than cells that are adjacent to each other. Instead of dividing the domain into a grid, the domain is split into increments of the spherical / polar co-ordinate system. In a simple sense, the estimates are divided into groups based on dip and dip direction.

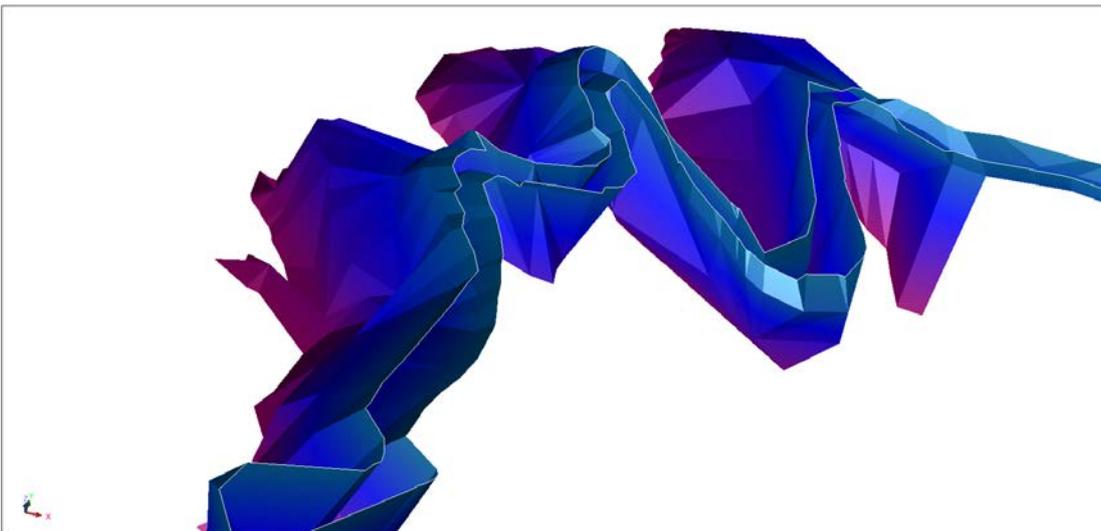


FIG 7 – Lode 550: Recumbent parasitic folding in the hinge of the Howley Anticline, dipping approximately 50° to 340° (View is oblique looking North-North-West, 1040RL to 990RL visible)

There are two main steps in this process, the first involving the attaching of dip and dip direction values to each block model block and the second being the use of these values to control the estimate.

A technique for deriving dip and dip direction is to use the triangle facets from the defining wireframe. If a centroid for each triangle is created, the vertices can be used (solved as a three point problem matrix) to derive a dip and dip direction for each centroid point (Figure 8). In a situation where very large or long and narrow triangles are present, further points can be created mid-way between the centroid and individual vertices or midway between the centroid and triangle edges. Once a “point cloud” of triangle centroids is available, they can be used for population of the block model block attributes via an estimation technique such as nearest neighbour. If a method other than nearest neighbour was to be used for this process (inverse distance / ordinary kriging etc.) consideration of how orientations would be smoothed is required. This is discussed in more detail in the use of Vector Offset / Displacement.

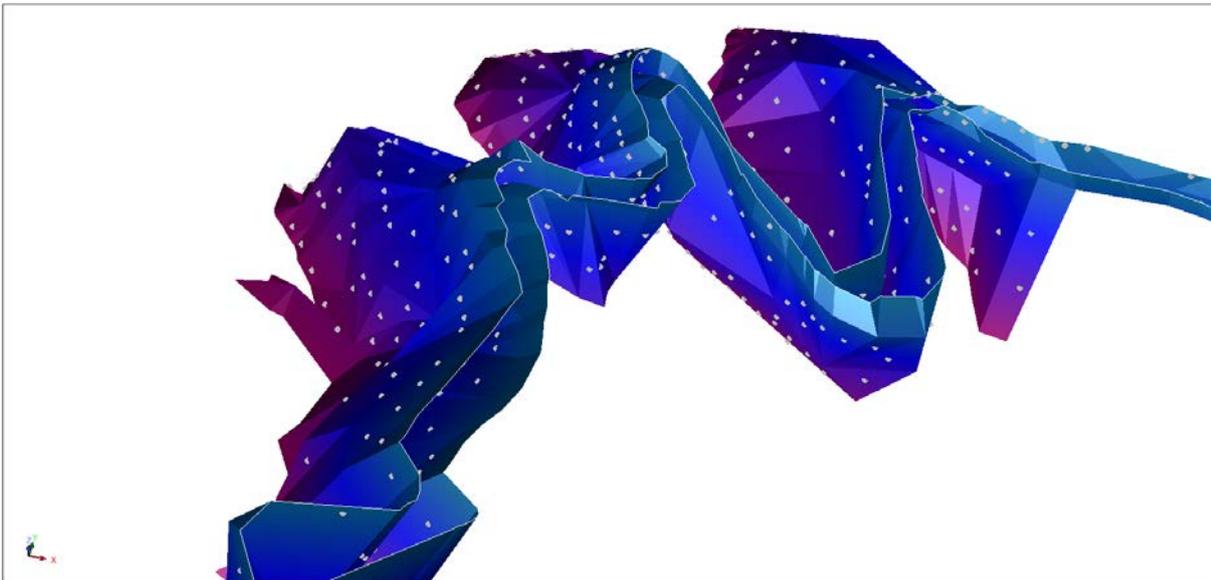


FIG 8 – Wireframe displaying calculated triangle centroids containing dip and dip direction information (View is oblique looking North-North-West, 1040RL to 990RL visible)

At Cosmo, a nearest neighbour estimation was performed with an isotropic (omni-directional) search, the logic being that there is no preferential direction when assigning orientation and the nearest wireframe orientation should be the one applied. The density of centroids points was also reasonably high, meaning that most blocks were populated with reasonably short distances to the informing point. Validation of assigned orientations can be carried out using a simple colour scheme and the model sectioned where appropriate (Figure 9).

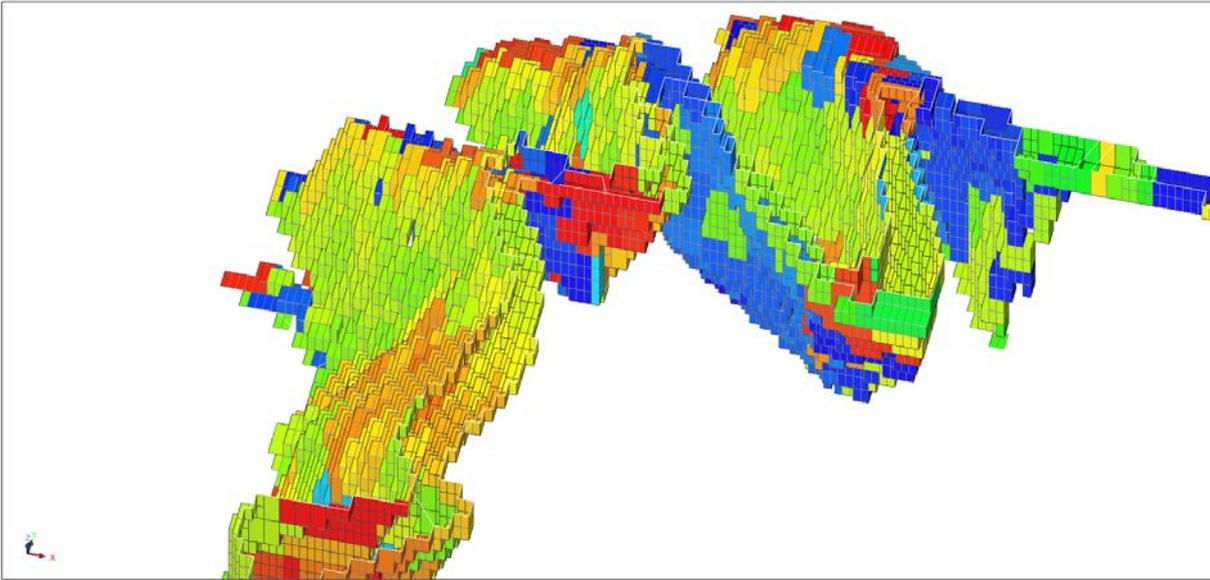


FIG 9 – Block model coloured by dip direction post nearest neighbour (View is oblique looking North-North-West, 1040RL to 990RL visible)

Estimation is strategically different from the panel technique, in that the process uses an orientation set for the search and variogram while applying a sector (angular corridor) when constraining the blocks used in the estimate.

If an exhaustive block by block logic was to be used, each block in the model would require individual interpolation using the block's stored dip and dip direction. (a sub-note to this is that Surpac has no way of applying stored block values to an estimate). This would prove impractical in terms of time taken. A 10° tolerance on dip and dip direction was deemed to be sufficiently accurate for dynamic orientation at Cosmo, with blocks being selected based on their dip and dip direction category (sector). For example, blocks with a dip between 40 and 50° and dip direction between 60 and 70° were assigned estimate orientations of 45° and 65°, respectively.

A further reduction in estimation time can be gained by creating a grouped report of populated sectors for the domain and then only attempting estimation on sectors that are populated. In some scenarios this could reduce the number of estimates significantly.

Vector Offset / Displacement

The population of dip and dip direction attributes can be enhanced with the use of displacement values for each co-ordinate rather than raw dip and dip direction values.

The convention for dip direction values is one using a spherical / polar co-ordinate system, in that the dip direction value represents an angle (0-360°) away from the pole. This format makes it difficult to use any system for block estimation other than nearest neighbor. An illustration of this was raised in the sector methodology discussion. For example an average of two dip directions, 90° (due east) and 270° (due west), would give an inconsistent result of 180° (due south).

A solution is to use a differential approach in the Cartesian system rather than spherical co-ordinates. If a single point with known dip and dip direction is taken, a temporary point can be created and the differences in x, y and z (dx, dy and dz) can be calculated. Once dx, dy and dz are known for each point (or triangle centroid) an estimate for each differential can be formed using multiple informing points (the values are additive). It then remains to back calculate dip and dip direction given estimated values for dx, dy and dz.

Handling of vertical triangles is a more problematic. For example, if a point has a dip of 90°, the dip direction loses its meaning. As dip direction, even for vertical triangles, has importance in estimation (especially where anisotropy is used) it becomes essential to resolve a value. A solution is to create a second set of dx, dy and dz values based on a temporary point with an assigned dip (an example might be 45°) and an untouched dip direction. Where a vertical triangle is encountered the second set of dx, dy and dz values can be used for resolution of the dip direction while the first set of dx, dy and dz values can be used for dip calculation.

Use of multiple informing triangles (dip and dip-direction points) allows a simple method such as inverse distance to be applied for the dip and dip direction estimate. Depending on the maximum number of samples, inverse distance power and orientation / anisotropy (if any can be established), the final orientation values can be smoothed to a level desired by the user.

ESTIMATE VALIDATION AND RECONCILIATION

Validation of the Cosmo estimates created using the panel method was carried out using a combination of swath plots, grade tonnage curves and visual validation.

In swath plot comparisons (Figures 10 & 11), each estimated domain is compared against both the composites used to inform the estimate and an omni-directional (isotropic) estimate using the same search dimensions and variography.

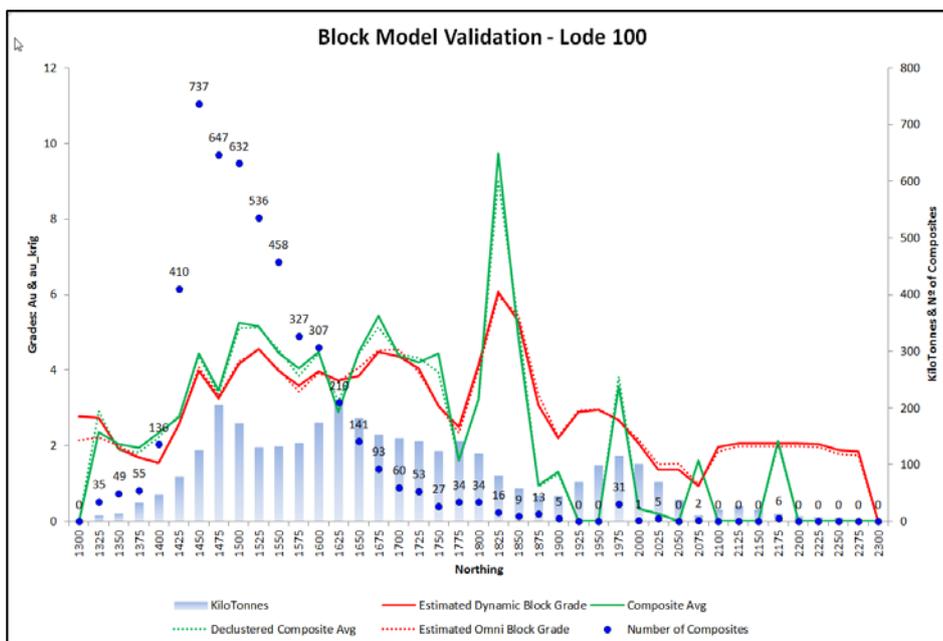


FIG 10 – Swath Plot Validation of Lode 100 by Northing

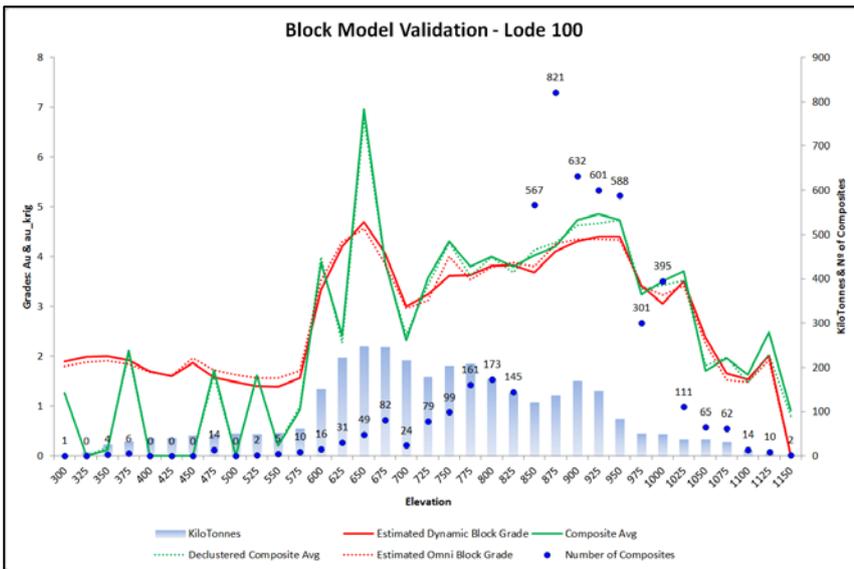


FIG 11 – Swath Plot Validation of Lode 100 by Elevation

Comparison of the estimate against an isotropic check estimate constrained within the domain provides a semi-local scale to global scale confirmation of the dynamic estimate result.

Confirmation of the application of dip and direction was done visually using exported search ellipses and by examination of portions of the block model coloured by sector (Figure 9).

Reconciliation against a mill provides the best method of estimate validation and data available from Cosmo suggests an improvement in grade prediction when comparing the reserve against grade control actuals (milled). The dynamic technique was implemented at Cosmo during December 2012 and has helped reduce average grade prediction to within 1% of production (Figure 12).

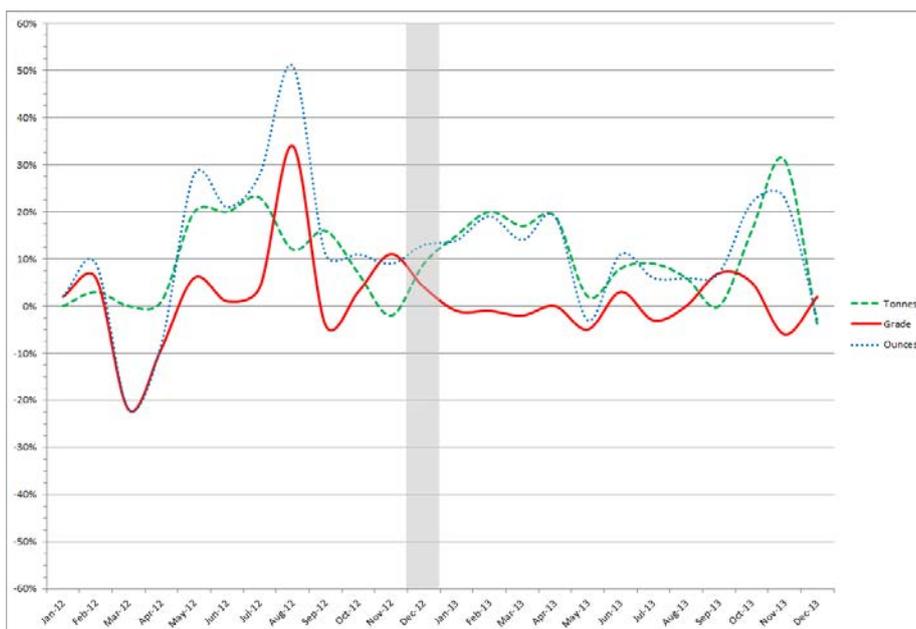


FIG 12 – Cosmo Reconciliation Differences – Mined to Reserve 2012 / 2013 (Dynamic Estimate implementation in grey)

Increased tonnages apparent in Figure 12 are attributed to over break around a lode footwall fault (F10) and minor unplanned development tonnage increases (stripping, higher backs and fillets). These tonnes whilst not planned are not included as dilution, as the development is predominantly within the mineralised zone.

COMPARISON AGAINST OTHER TECHNIQUES

Other options for handling a deposit such as Cosmo include, but are not limited to

- Unfolding (available in Datamine & GEMS)

- Dynamic Anisotropy (Datamine)

- Tetra-modelling (Vulcan)

- Bend Modelling (Vulcan)

- Un-wrinkling (GEMS)

- Isotropic estimation

- Domaining for orientation

As is the case with every estimation technique, dynamic estimation has its own unique set of advantages and disadvantages.

Unfolding techniques represent the more sophisticated method for handling of folded data and depending on the application, there can be issues with the transformation to unfolded space (use of projection planes) as well as the unfolded space being distorted with respect to sample spacing. Often there are limited options for validation of the data, once unfolded. The process is also relatively complex and as a consequence can prove difficult to understand.

Isotropic or omni-directional estimation when constrained within the domain boundaries may produce a reliable global estimate. However, any cross structure variability will be lost in the estimation process and in some instances this is undesirable, especially if the mining width is less than the mineralization width.

Domaining for orientation is one of the simpler techniques, with the data being split for each major change in orientation. Ironically, while the process may be simpler, the dataset complexity with a larger number of domains leads to an increased probability of human error and requires some thought on estimate transition from one sub-domain to the next (application of hard or soft boundaries).

The sector method has a number of advantages and disadvantages (Table 1) that should also be considered. It provides an easy to understand technique utilising local estimation direction and is not subject to the complications of unfolded space. It has potential pitfalls in wireframe coarseness, lack of sampling in tightly folded areas and the risk of samples from parallel limbs being used.

TABLE 1

Advantages and Disadvantages of the Sector Method

Advantages	Disadvantages
Results are easy to understand (uniform ellipse dimensions are used).	Assumes pre or syn-deformational mineralization, or if post-deformational, that mineralization is strongly associated with stratigraphy, as is the case with Cosmo.
Allows use of a local (block scale) estimation direction.	Wireframe resolution (size of triangles) could pose a risk if the triangles are much larger than the domain width. This can be mitigated by increasing the number of informing points for each triangle. Long skinny triangles are also potentially problematic
Not subject to distorted space (as created by some unfolding techniques).	Lack of informing samples in the hinge areas of tight folds.
Doesn't require a particular projection orientation as some unfolding routines do, hence not affected by overturned (overlapping in 2D) interpretations.	Tight folding may introduce the risk of the estimate finding samples on a nearby parallel limb; this is mitigated to a degree by choosing to use moderate anisotropy.
Anisotropy allows cross structure variability to be honoured as much as possible (avoidance of cross structure "striping" that is evident when a generalised domain orientation is implemented).	Dataset plunge not accounted for (equi-dimensional in major and semi major directions).
Will run reliably with tight folding.	

If wireframe coarseness (large triangles relative to block size) was to become problematic, a smoothing technique using vector displacement could be applied along with insertion of multiple triangle points (points located between the triangle centroid and vertices).

Lack of informing samples and the risk of using samples from parallel limbs can be mitigated to a degree with the use of sensible anisotropy parameters.

CONCLUSIONS

A folded environment poses a number of technical challenges, particularly for estimation.

Dynamic Interpolation represents an attempt to improve the estimate in a local sense by modifying local search orientations.

Crocodile Gold currently uses Surpac as its general mine planning software at Cosmo. As Surpac has no dynamic or unfolding routines available, a scripted solution to the problem was determined to be the only viable alternative (Figure 13).

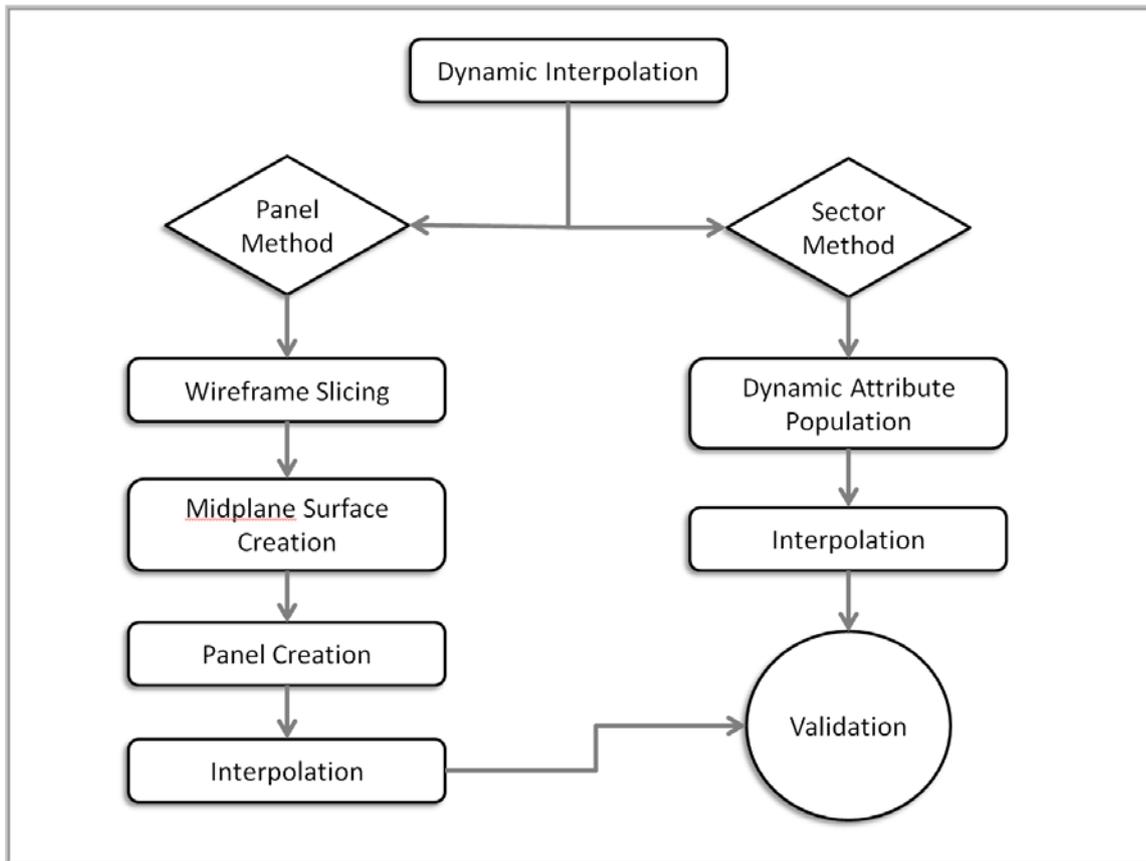


FIG 13 – Dynamic Interpolation Flow Diagram

The Panel method represents the first of two scripted applications of a dynamic approach applied at Cosmo for estimating the folded mineralised lode system. It relies upon the use of relatively small panels (gridded cells) to apply the estimate in a sequential fashion.

The Sector method is a different approach to dynamic estimation, with the aim of eliminating the cell grouping created by the panel technique and significantly reducing the time required for an estimate to be completed. It represents an evolution of the panel technique and also solves a shortfall with the panel methods ability to handle tight recumbent folding.

Dynamic Interpolation has a number of advantages, that include the use of a local (block scale) estimation direction. It provides easy to understand results that are not subject to the complications of unfolded space. It could be implemented in a number of deposit styles that possess varied domain orientations and at Cosmo, dynamic interpolation has improved grade reconciliation against the mill.

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