3D Stratigraphic, Structural and Metal Zonation Modelling of the Sullivan Mine, Kimberley, British Columbia

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Abstract

Detailed mine scale data integration and modelling from historical drillhole data was undertaken for the giant SEDEX Sullivan orebody in Kimberley, British Columbia. This exercise resulted in 3D digital stratigraphic, structural and metal zonation (Pb, Zn, Ag, Fe) models. Over 4,000 drillholes with stratigraphic points and metal abundances were used from historical litho-stratigraphy-assay logs. Coordinate conversion from the Sullivan Mine grid to UTM coordinates and the geometric recalculation of the drill paths was undertaken to position the data to a more universally useable 3D data set. The data were developed into a geodatabase in ArcGIS and then exported to GoCad / SKUA for modelling. Metal zonation patterns corroborate previous studies that delineate the 3 main ore facies: Vent Complex, Transition and Bedded Ore zones. Locally, metal rich zones have abundance contours, which cut across the bedded mine stratigraphy giving support for an in situ replacement process. However, the major proportion of ore in the Bedded Ore zone is contained within the sulphide-rich Ore Bands predominantly the Main Ore Band. Variogram analysis was used on standard and transformed stratigraphic grids to help characterize metal and lithofacies distribution patterns in 3D. The 3D database and models give a detailed snap shot of a significant SEDEX deposit. This will contribute to a better characterization of the global SEDEX systems, as well as supporting local correlations within the Sullivan Sub-basin.

Introduction

With improving technology, geologists are able to model and interpret complex geological structures at depth. Previously, the mining industry interpreted geological

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bodies using close-spaced two dimensional sections to visualize trends in the third dimension. With the emergence of three dimensional imaging and modelling systems, the majority of modern mine records have been updated to include multi-dimensional digital models. These models improve visualization of the geological setting and allow for complex statistical analysis of three dimensional data with the aim of revealing ore system relationships.

The extent of the Sullivan orebody, a SEDEX deposit near Kimberley, British Columbia, was almost fully mined before the digital age. The deposit originally contained about 160 million tonnes of ore with a grade of 6.1% Pb, 5.9% Zn, 68 g/t Ag (Hamilton et al.,1982); however, when the deposit closed in 2001 due to depletion of its reserves, the mine had produced 149,173,608 tonnes of ore grading 5.65% Pb, 5.33% Zn, 62.1 g/t Ag (BC Minfile 082FNE052, 1985).

Until now, 3D modeling has been limited to small areas of active mining in the southeastern part of the deposit. Developing a larger scale model requires a large database of stratigraphic, structural, assay and drillhole data. Drillhole data was provided by Joseph and Ransom (2008). Other mine data was gathered from archived drill logs by several sources including Lydon et al. (2000) and Montsion (2014). To date no digital model encompasses the entire deposit or integrates metal zonation, stratigraphy and structural information in a 3D GIS (Geographic Information Systems) environment. This study is the first phase of developing a fully integrated three dimensional model of the Sullivan orebody.

This study seeks to model metal concentrations of lead (Pb), zinc (Zn), silver (Ag), and iron (Fe) of the Sullivan mine, utilizing horizon gridding with three dimensional kriging estimation techniques. The estimated metal zonation patterns can potentially be compared with a stratigraphic and structural three dimensional model in a more rigorous quantitative manner.

Geological setting

The Sullivan orebody is hosted by the Aldridge Formation of the Mesoproterozoic Belt-Purcell Basin which outcrops over an area of about 200,000 km^2 in Montana, Idaho and Washington of the U.S. and southeastern British Columbia in Canada (Lydon, 2007). The Belt-Purcell is an intracratonic rift basin and it consists of an early rift-fill sequence of deep water marine turbidites and intercalated tholeiitic sills, and a later rift-sag sequence consisting of shallow marine to lagoonal and fluviatile environments. The rift-fill sequence (turbidites and sills) is termed the Aldridge Formation in Canada and the Prichard Formation in the U.S. and is up to 12 km thick (Höy et al., 2000). The Sullivan orebody is located on the east side of the Purcell Mountains, British Columbia (Figure 1).

The Sullivan deposit and its host rocks have been affected by at least two phases of tectonic and metamorphic activity which caused deformation, faulting and metamorphism. There are two zones of sulphide ore (east and west), which are separated by a structurally complex Transition zone. The western zone has been

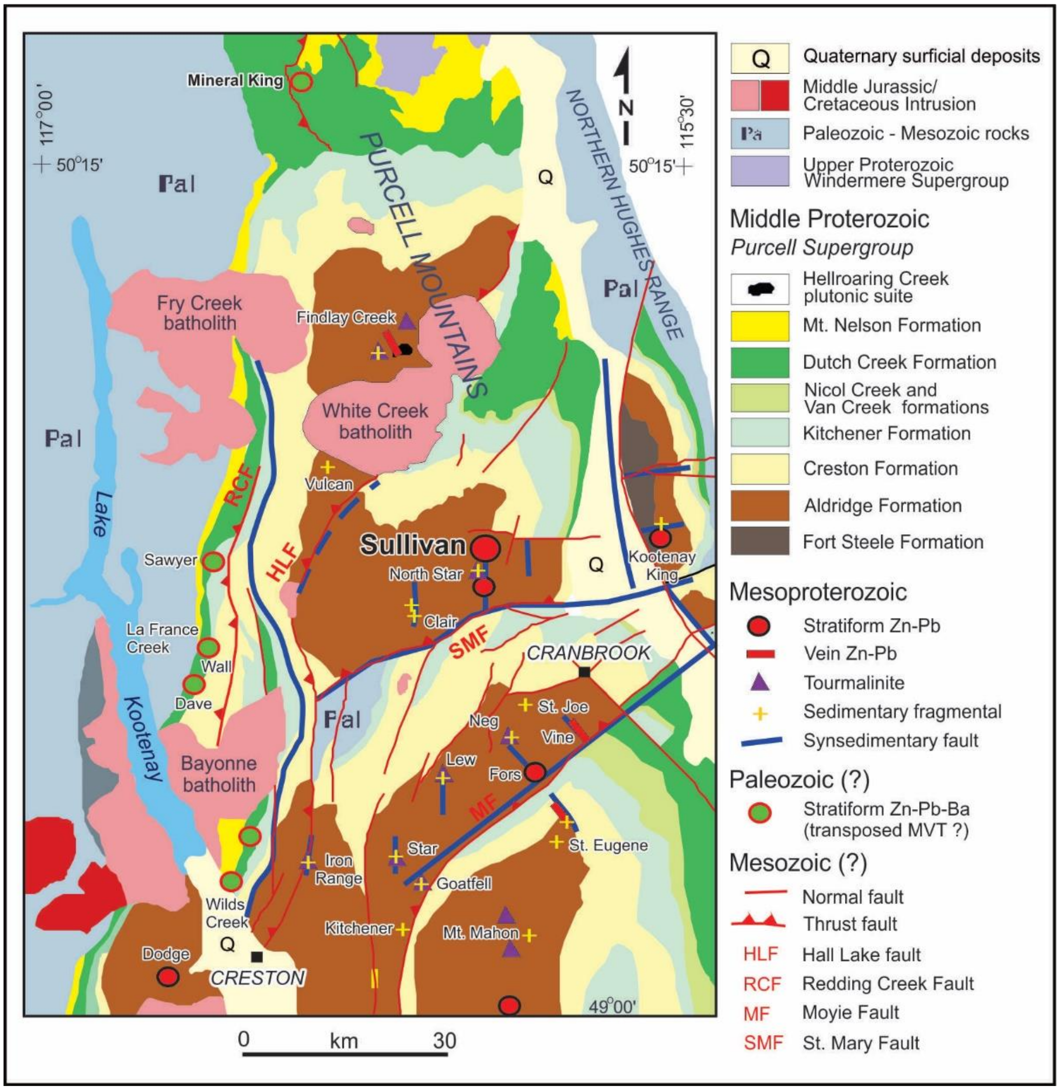


Figure 1. Location of the Sullivan mine in south-eastern British Columbia with geological map of the Purcell Anticlinorium. Overlay of SEDEX ore system elements (i.e. Sullivan and satellite massive sulphide deposits, tourmalinite alteration, sedimentary fragmental rocks and inferred synsedimentary faults). From Lydon et al. (2000).

termed the Vent Complex where metal enriched hydrothermal fluids emerged from the subsurface at the time of formation. Roughly 70% of the ore is contained within this zone (Lydon, 2007). The eastern zone contains the Bedded Ores, the separate ore layers being termed from the stratigraphic base to the stratigraphic top as the 'Main Band', 'A Band', 'B Band', 'C Band' and 'D Band' (Hamilton et al., 1982) (Figure 2). The major geologic features of the Sullivan deposit are illustrated in Figures 2 and 3.

Geological Formation

Sullivan is a SEDimentary EXhalative (SEDEX) deposit. SEDEX deposits form by the discharge of metalliferous hydrothermal fluids at and immediately below the seafloor of a sedimentary basin (Carne and Cathro, 1982). There has been some recent debate about how the Sullivan and other SEDEX deposits formed. Typically, at least part of a

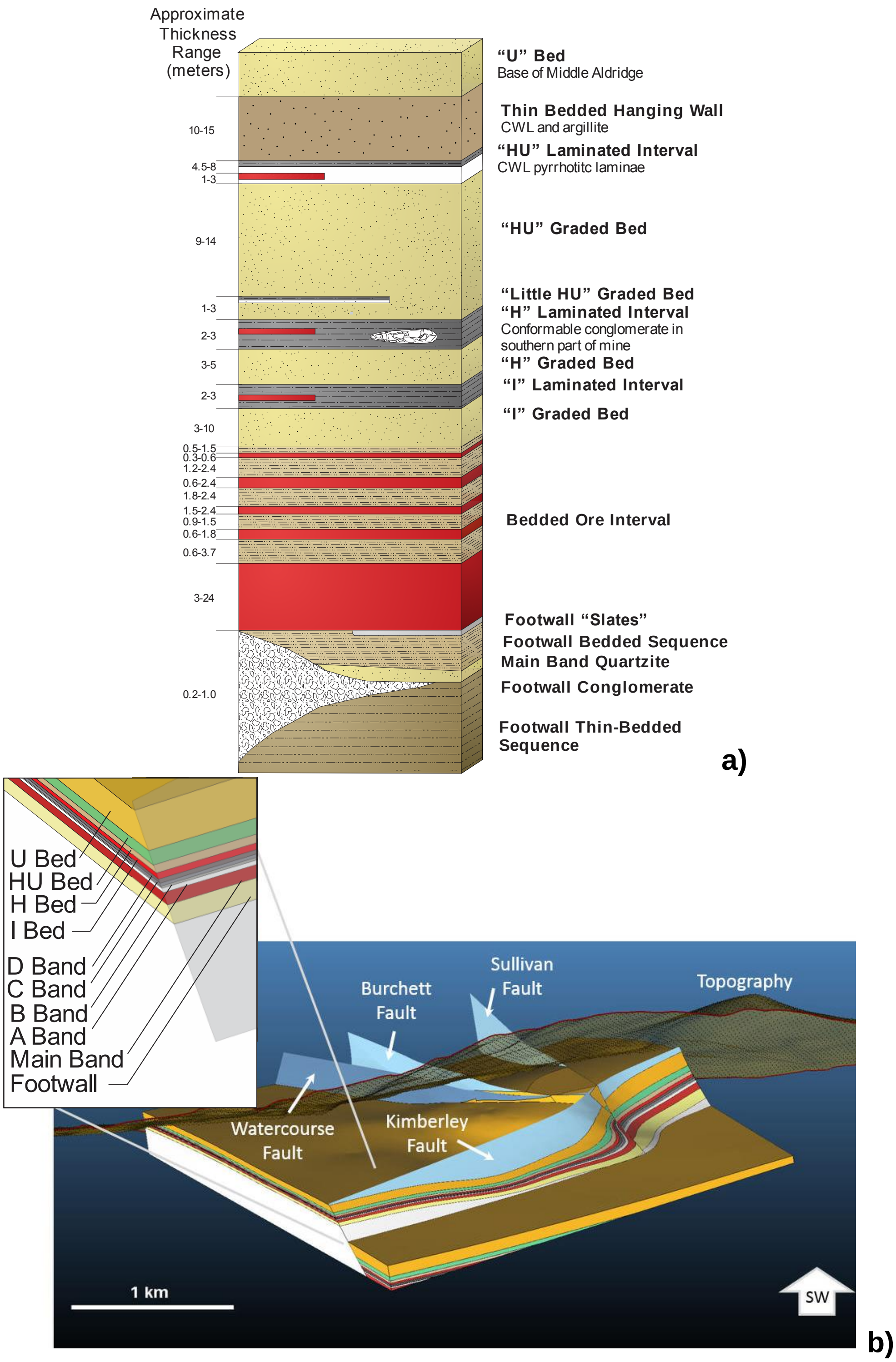


Figure 2. Bedded Ores stratigraphy from the eastern ore zone at Sullivan. a) Stratigraphic column of Bedded Ores (after Hamilton et al., 1982). b) Ore beds dipping to the northeast below surface topography.

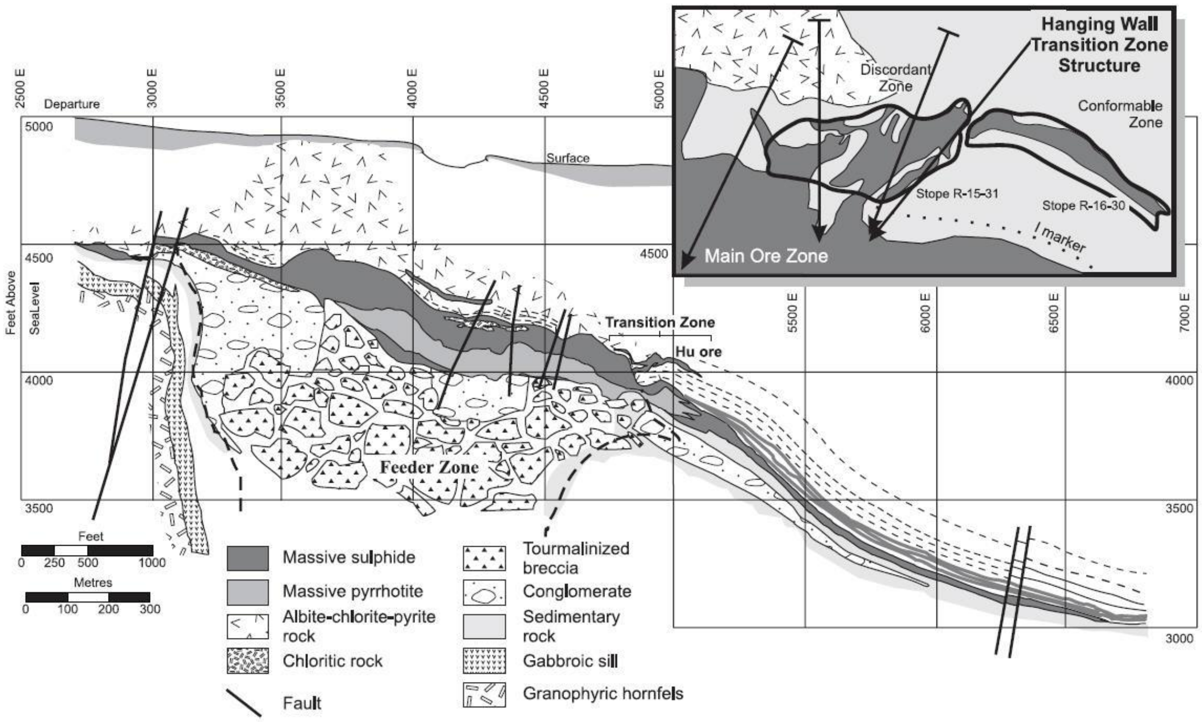


Figure 3. Generalized west-east geological cross-section at 11600N showing the distribution of the hanging wall sulphide zones (after Hamilton et al., 1982). The inset illustrates the complex nature of the "HU" sulphide zone along the Transition Ore zone (from Conly et al., 2000) and reflects a mechanical mobilization of sulphides along a major piercement structure (Paakki et al., 1995).

SEDEX deposit consists of concordant laminated ore beds, similar to those seen in the eastern Bedded Ores at Sullivan. The geometry, mineral assemblages and textures of these apparently stratiform sulphide deposits have given rise to two models of ore deposition. The first is nucleation of sulphides in the water column followed by precipitation as laminated metalliferous sediments parallel to bedding. The second is subsurface replacement of pre-existing laminated sediments with metal-rich sulphides along bedding planes of weakness (Goodfellow and Lydon, 2007).

Both models envisage hydrothermal fluids containing dissolved metals ascending through faults to vents on the seafloor, where the metals were precipitated by a reaction with hydrogen sulphide. This reaction can be represented by an equation that depicts a metal chloride complex ($MeCl_n$) reacting with dissolved hydrogen sulphide (H_2S) to form a metal sulphide (MeS), two hydrogen ions ($2H^+$) and *n* chlorine ions (nCl^-).

$$MeCl_n \quad + \quad H_2S \quad \overset{H_2O}{\longleftrightarrow} \quad MeS \quad + \quad 2H^+ \quad + \quad nCl^-$$

The result of the reaction is the formation of a metal sulphide precipitate. Through this reaction, metal precipitate is formed and hydrogen ion is released, which in turn alters the host rocks.

The first ore deposition model postulates that once vented to the seafloor, hydrothermal fluids reacts with anoxic bottom water containing bacteriogenic H_2S (formed by the reduction of seawater sulphate) to form a metalliferous precipitate, thereby chemically trapping the metals. The precipitate settled out of suspension and was deposited as laminated sediments on the seafloor proximal to the vent, giving a stratiform appearance to the mineralization (Goodfellow and Lydon, 2007). The second ore deposition model postulates that there was interaction between the hydrothermal fluid and sulphide in the shallow subsurface, with the sulphide source being bacteriogenic H_2S, hydrothermal H_2S, and/or pre-existing sulphide minerals. Sulphides were precipitated in pore spaces of the shallow sediments, thereby mimicking the porosity architecture of the sediments, or by replacement of pre-existing sedimentary or early diagenetic sulphides. In both cases, the resultant sulphidic rock shows sedimentary textures. Both models of ore deposition may contribute to a single deposit (Ridley, 2013). Both mechanisms of ore deposition probably contributed to development of the rich Sullivan orebody (Lydon et al., 2000); however one may have dominated during deposition. The most recent genetic model for the Sullivan deposit (Lydon, 2004) invokes heating of saline pore fluids by gabbro sill intrusion into unconsolidated sediments to form a large hydrothermal diaper, and the consequent leaching of metals from the sediments into a high salinity phase and boron of the sediments into a low salinity phase. The less-dense boron-rich fluids arrived at the surface first, forming the prominent footwall tourmalinite alteration zone beneath the Vent Complex, and the saline fluids arrived at the surface later, forming the Bedded Ores.

Deformation of the sulphide layers during the Cordilleran Laramide (150-110 Ma) orogeny is expressed as localized contorted folding (Figure 4), as tight north-south shallow plunging upright folds with slightly overturned to the east short limbs, and as irregular ore piercement structures (Figure 5). Additionally low angle thrusting can repeat the mine stratigraphy (Ransom and Merber, 2000). Overall these effects are most prominent in the Transition zone, between the main vent facies, on the west side of the Sullivan deposit, and the Bedded Ores zone on the east side of the deposit. The high ductility and strength contrast between various metal sulphides and host turbidite beds at the layer scale (1cm to 10 m) produced much of these deformation effects and the bigger scale strength gradient in the footwall between a mechanically rigid tourmalinized rock volume beneath the vent facies and weaker altered turbidites beneath the Bedded Ores facies producing the spatial distribution of the different styles of deformation (McClay, 1983; Lydon, 2004).

Results / Data Analysis

Through data integration and analysis, it was found that the Ordinary Kriging method (Isaaks and Srivastava, 1990), using an exponential semi-variogram model, best suited interpolation of the datasets. A structural and stratigraphic curvilinear grid or 'GEOGRID' was developed in GoCad/SKUA 3D modelling software from Paradigm® using drill core stratigraphic points (Lydon et al., 2000; Joseph et al., 2011b; Montsion, 2014), cross section points (Joseph et al., 2011a), and Ore Band tops and faults defined from previous work (Leitch and Turner, 2007). The Sullivan Mine GEOGRID follows the stratigraphic layering and proved useful for calculating the final metal models in the

Figure 4. Folded bedded sulphides from the Sullivan deposit. Sample courtesy of Paul Ransom.

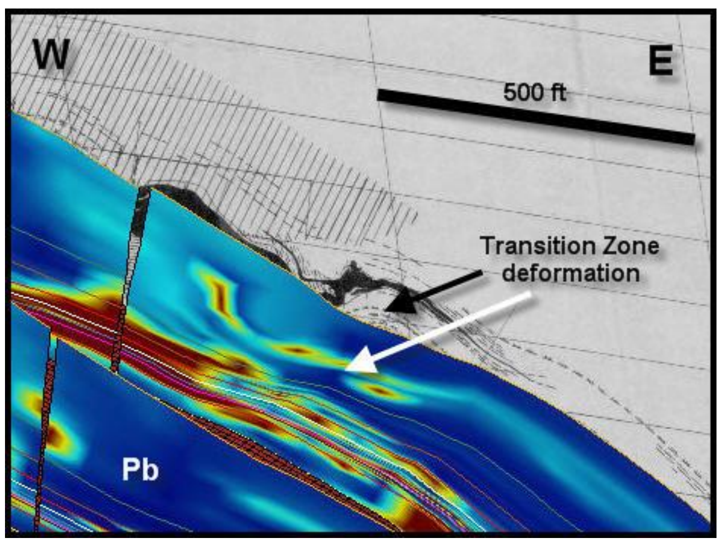
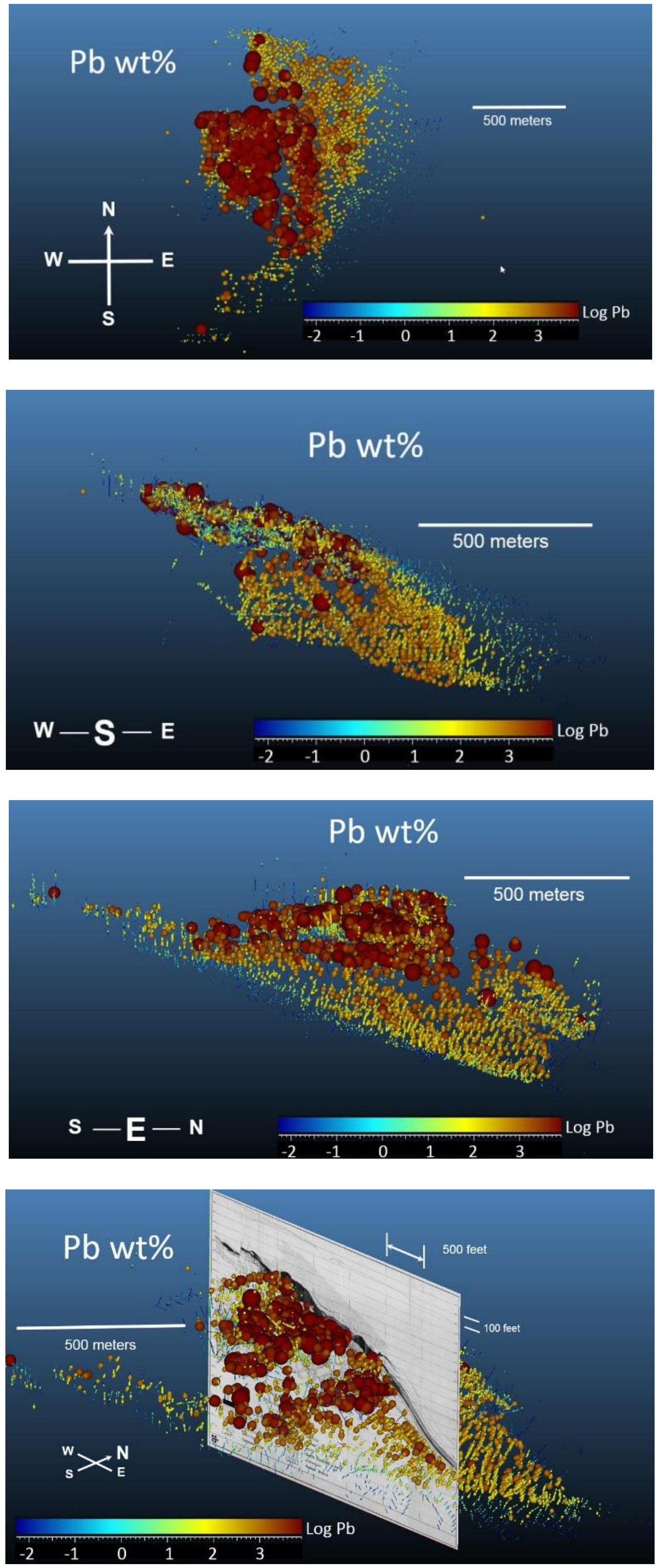


Figure 5. Transition zone deformation, hanging wall piercement cusp structure (Paakki et al., 1995) shown on historical Cominco general mine section (black and white section) and on interpolated Pb (Ordinary Kriging) sections in foreground. View looking to the north.

Bedded and Transition Ores, but a simple Cartesian grid, based on UTM coordinates, was used to calculate the Vent Complex zone. The Vent Complex metal modelled results were then sampled back into the GEOGRID for representation and comparison. All four metals (i.e. Zn, Pb, Ag, Fe) showed similar concentration in the Vent Zone where there is one large volume of high metal content (Figure 6), consistent with the maximum fixation of metals in and around a submarine hydrothermal vent. The laterally continuous metal-rich bands in the eastern ore zone (Figure 7), supports the concept of a sedimentary origin or control to the geometry of the deposit. These zones are separated by a structurally complex transition region where the Bedded Ores have been tectonically contorted and mechanically remobilized during thrusting of the Laramide orogeny (McClay, 1983; Paakki et al., 1995).



a) b) c) d)

Figure 6. Pb assay value distribution in Sullivan mine. a) Top view; b) southern view; c) eastern view; d) northwest view superimposed on 11600 N cross section. From Freeze (1966).

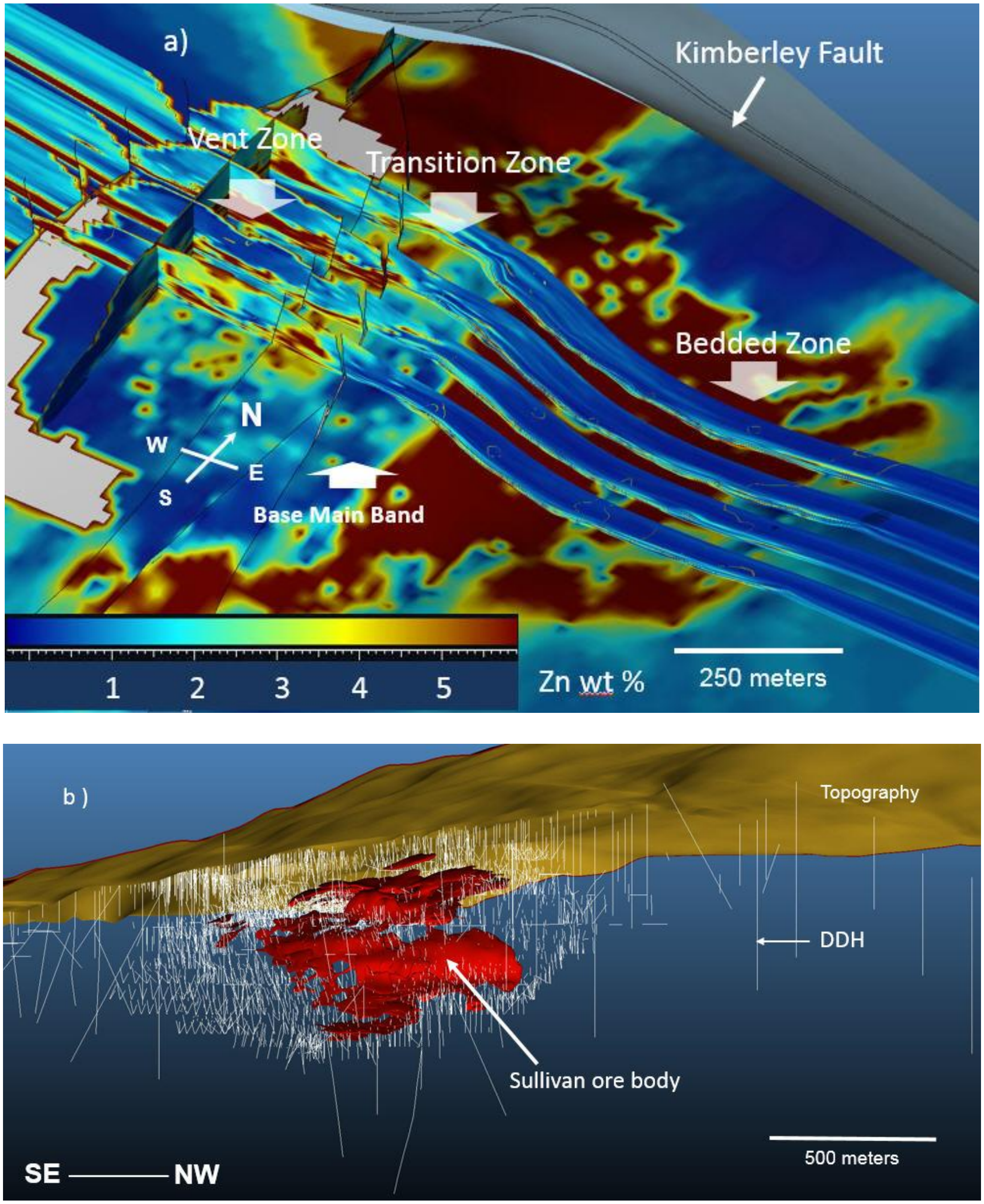


Figure 7. Bedded Ore geometry. a) Inverse distance weighting interpolated Zn values; b) distribution of drillholes and red zone of >10% Zn below brown surface topography (view from the northeast).

Statistical Analyses

Histograms

The metals Pb, Zn, and Ag show a naturally skewed univariate pattern (Figure 8). To emphasize the ore process, we stretched these skewed data values with a log-transform before doing Inverse Distance Weighted (IDW) or Ordinary Kriging interpolation. After a metal property model was calculated, a back log transform was done to represent the natural ranges of our modelled results. Fe showed a non-skewed range of values, so we interpolated the values directly.

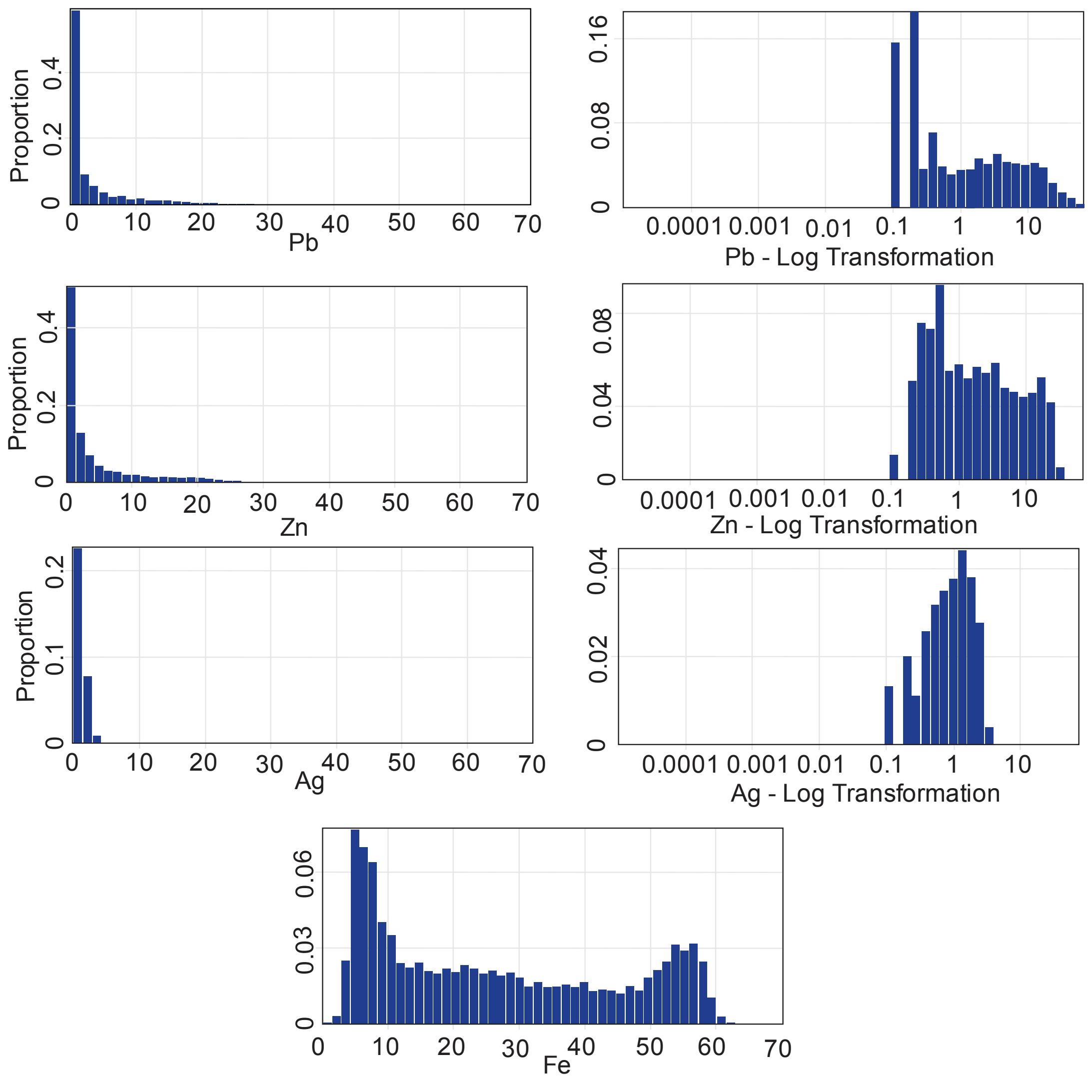


Figure 8. Histogram summaries of all Sullivan mine data. NPb = 109,626, NZn = 109,757, NAg = 101,364, NFe = 109,777.

Spatial Statistics

Geological impacts on semi-variogram patterns are prominent in the raw XYZ semi-variograms which can be difficult to interpret, especially with oscillations and/or drop-offs of point pair variability along the sills (Figure 9a). These could be controlled by the

Ore Bands, which repeat metal concentrations and display internal layering between ore and waste portions vertically. Alternatively, oscillations and discontinuities could be due to local folding and faulting. These patterns were smoothed out when geostatistical analysis was done with respect to the GEOGRID (UVW) instead of raw (XYZ) Cartesian space (Figure 9b). The GEOGRID was modeled after the geometry of mine stratigraphy (Figure 9c).

Within the GEOGRID coordinate system, the gross geological influences were minimized because the grid was already reflecting the spatial continuity of the data. This was especially true where there was good stratigraphic control, such as in the Bedded Ores. It was possible to evaluate the accuracy of the grid using point pair oscillations along the semi-variogram sill. If oscillations were present, the container grid didn't accurately represent the gross geology within the study area. Despite the deficiencies inherent in the container grid model, the amplitude of waves within the GEOGRID semi-variogram plots were reduced compared to plots in XYZ space, thus indicating that the Sullivan GEOGRID was reasonable to use for this exercise.

Implications for Exploration

From the Sullivan Mine modelling exercise, metal zonation patterns clearly corroborate previous studies that delineated the 3 main ore zones (Vent, Transition and Bedded) as shown in Figure 10 (Freeze, 1966; Hamilton, 1982; Lydon et al., 2000). Locally in the Bedded Ores, the metal rich zones have abundance contours which cut across ore stratigraphy (Figure 11), but the major concentration of metals in the Bedded Ores is in the Main Band (Figure 12). Through data integration and analysis, it was found that the Ordinary Kriging method using an exponential semi-variogram model best suited the metal datasets of the stratigraphically concordant ore layers. The use of a curvi-linear stratigraphically and structurally constrained container grid, dramatically increased auto-correlation and, therefore, estimation results. Making similar geological grids for other SEDEX deposits should prove useful. The spatial trends of the interpolated concentrations of Pb, Zn and Ag, are similar to a strong north-south to 160º-340º trend reflecting structural attitudes and thicknesses in the Bedded Ores. This trend is visible in Figure 10.

The variograms show both local and regional trends, which are strongest for Pb and to a lesser extent for Zn and Ag. There is ~ 75 metres with a 160º trend and a much longer regional trend for at least 650 metres in the same direction. These trends match with the orientation defining the start of the Bedded Ores on the east side of the Sullivan deposit. The elongate 160º trend indicated by variogram analysis also matches reasonably well with the directions of several proposed synsedimentary graben systems delineated by previous studies (Hagen, 1983; Höy et al., 2000; Turner et al., 2000), such as the Sullivan-Stemwinder-North Star trend, Sullivan west graben, Clair trend, Star trend, and Lew trend (see Figure 1). The analysis supports the interpolation of data within a horizontal distance range of 0.5 to 1 km (i.e. parallel to bedding) and vertical range of < 100 m in the Middle Aldridge Formation.

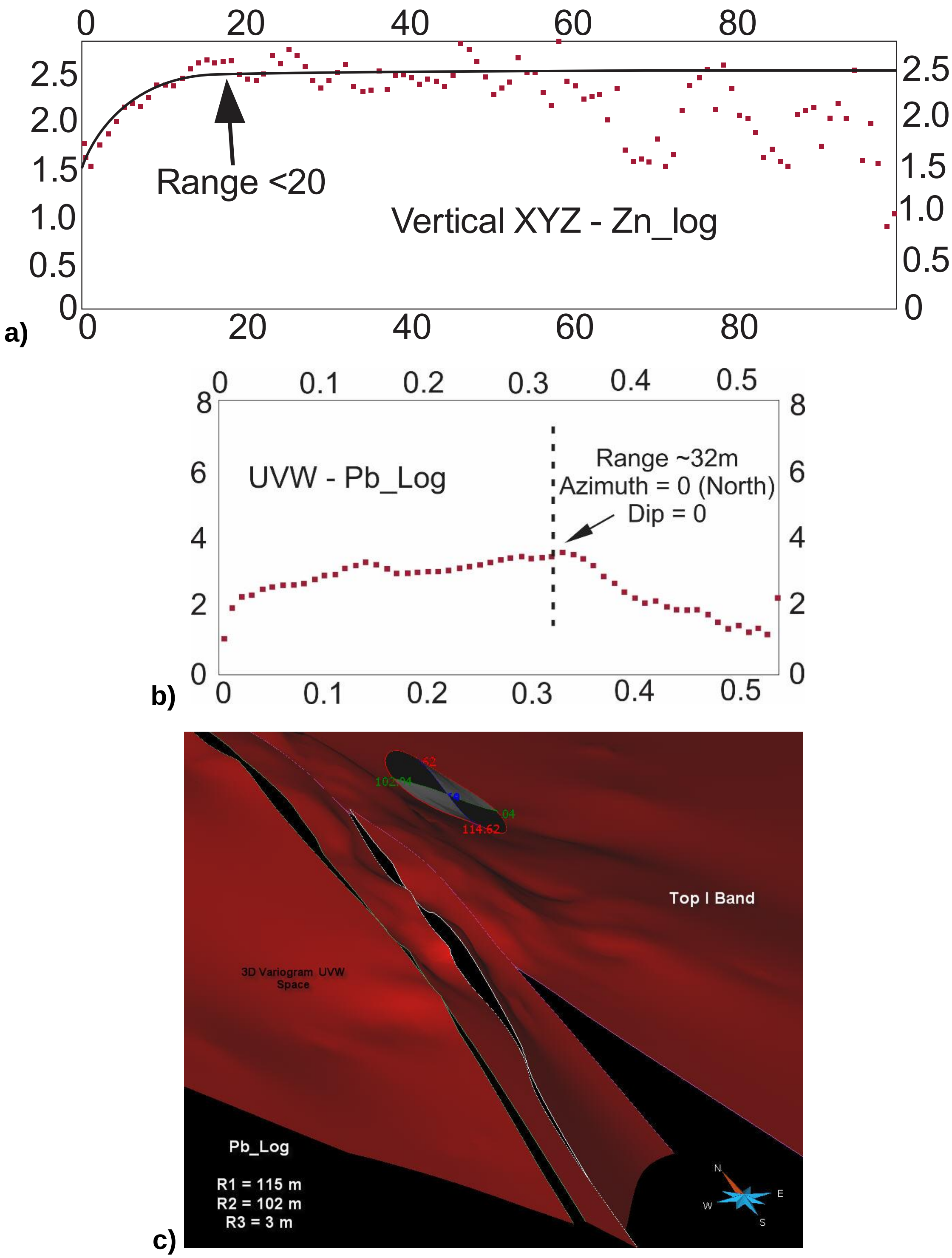
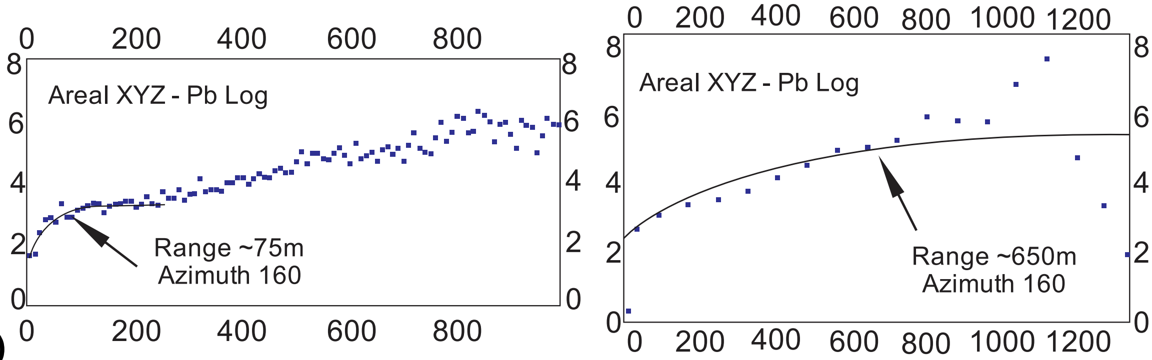


Figure 9. Variogram analysis. a) Vertical semi-variograms for Log transformed Pb and Zn from the entire Sullivan data; b) GEOGRID (UVW) based semi-variogram for log transformed Pb indicating smoother short (0.05) and long (0.3) ranges. Short range used for Kriging metal zonation models. c) Perspective close up view of top of I Bed showing distance converted semi-variogram ranges and 3D black and white ellipsoid. Notice relatively short distance in R3 which is roughly vertical or cross strata direction, which reflects our desire to optimize interpolation for stratiform mineralization at least in the Bedded Ores.



a)

b)

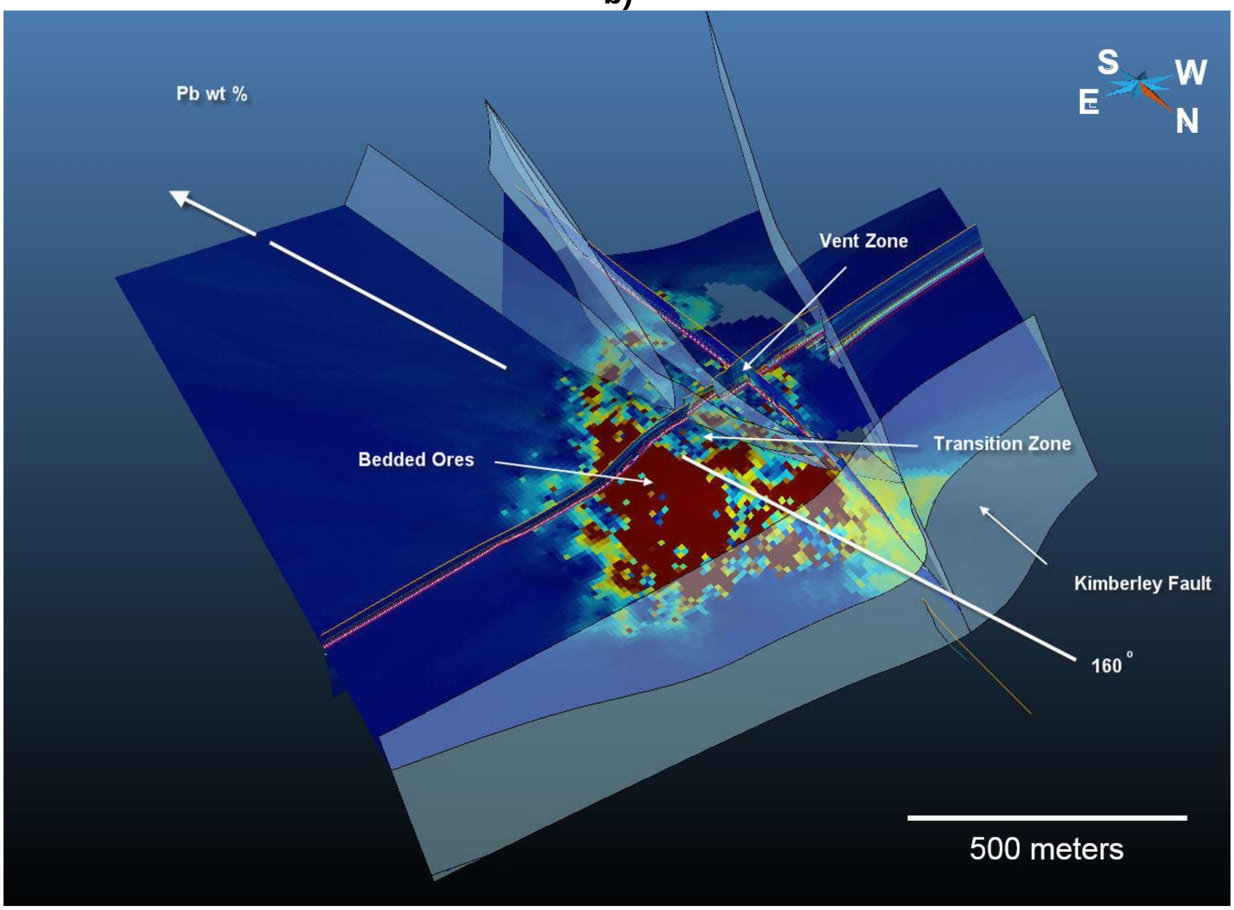


Figure 10. a) Variogram analysis indicates strong bedding controlled metal anisotropy for Pb, Zn and Ag within the Bedded Ores, as well as a subtle 160o trend in metal content; b) plan view of Sullivan orebody with delineation of Bedded Ores, Transition Zone and Vent Zone. Kriged Pb Assay values at the top of the Main Band show 160°/340° trend.

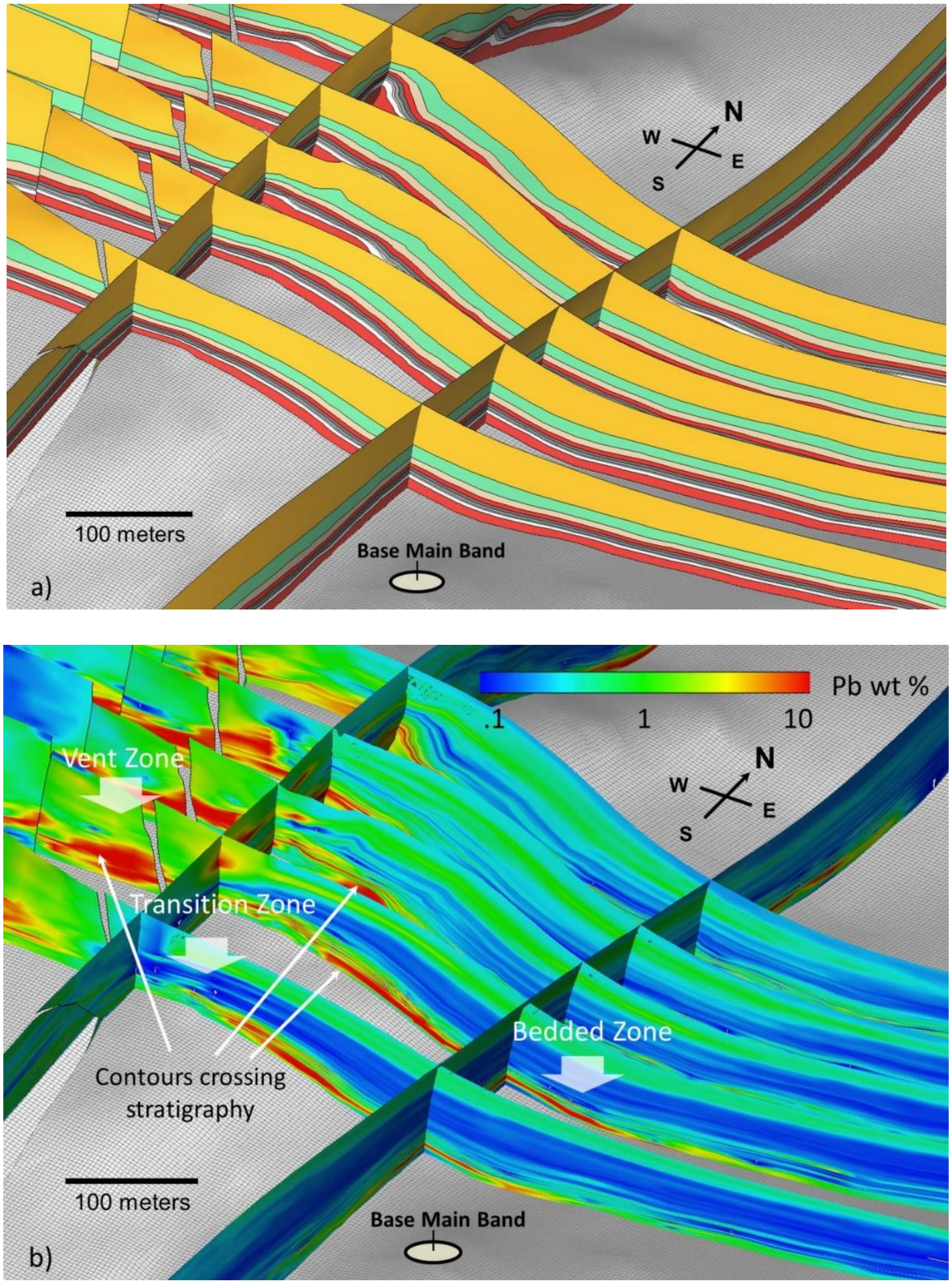


Figure 11. a) Close up of east-west vertical cross-sectional views of Sullivan stratigraphy (refer to Figure 2 for coloured legend scheme); b) same sections with Kriged Pb-Zn ratio indicating strong continuity with Main Band stratigraphy but also disconformity of Main Band crossing contours in the Bedded Ores. Linear concentration zones to the east are unsupported anomalies from the interpolation.

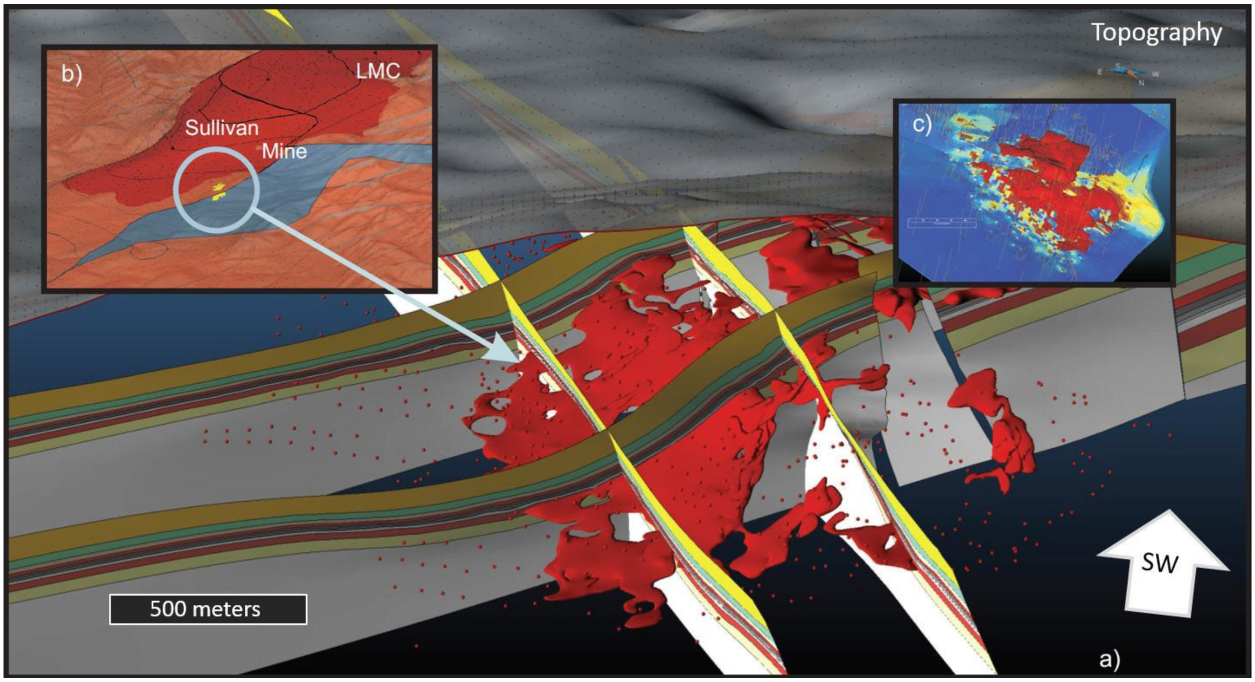


Figure 12. Sullivan Mine model looking towards the southwest. a) Orebody in red and mine stratigraphy cross-sections with top Main Band markers as red points); b) location Sullivan mine (yellow) at regional Lower – Middle Aldridge Contact (LMC) modelled surface (red), also looking to the southwest; c) Kriged Pb zonation map at top of Main Band.

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