Geological Survey of Canada

3D Metal Zonation of the Sullivan Mine, Kimberley, British Columbia, Canada

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Introduction

With improving technology, geologists are better at modelling and interpreting complex geological structures at depth. Previously, the mining industry interpreted geological bodies using close-spaced two dimensional sections to visualize trends in the third dimension. With the emergence of three dimensional (3D) imaging and modelling of the subsurface, the majority of modern mine records have been updated to include multi-dimensional digital models.

The Sullivan orebody, a lead and zinc SEDimentary EXhalative (SEDEX) deposit near Kimberley, British Columbia, was almost fully developed before the digital age. 3D modelling has been limited to small areas of active mining in the southeastern part of the deposit. This poster presents a new model which includes the entire mine site and represents metal concentrations of lead (Pb) and zinc (Zn) of the Sullivan orebody. This model is derived from horizon gridding and three dimensional kriging estimation techniques. Estimated metal zonation patterns are compared with a stratigraphic and structural 3D models of mine stratigraphy. For a more rigorous quantitative presentation see Montsion et al. (2015) and deKemp et al. (2015).

This study complements the larger regional 3D reconstruction project conducted throughout the Purcell Anticlinorium, which produced a 3D model of the Lower-Middle Aldridge Contact (LMC) and a 3D database of stratigraphic Middle-Aldridge markers (deKemp et al., 2015; Schetselaar et al., 2015; de Kemp and Schetselaar 2015).

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.A. and southeastern British Columbia in Canada (Lydon, 2007). The Belt-Purcell is an intracratonic rift basin and it consists of an early synrift 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 siltites, argillites, and carbonates. The syn-rift turbidite-sill sequence is named the Aldridge Formation in Canada and the Prichard Formation in the U.S.A. and is up to 12 km thick (Hoy et al., 2000). The Sullivan orebody is located on the east side of the Purcell Mountains, British Columbia and can be found in the upper part of the rift-fill succession (Figure 1).

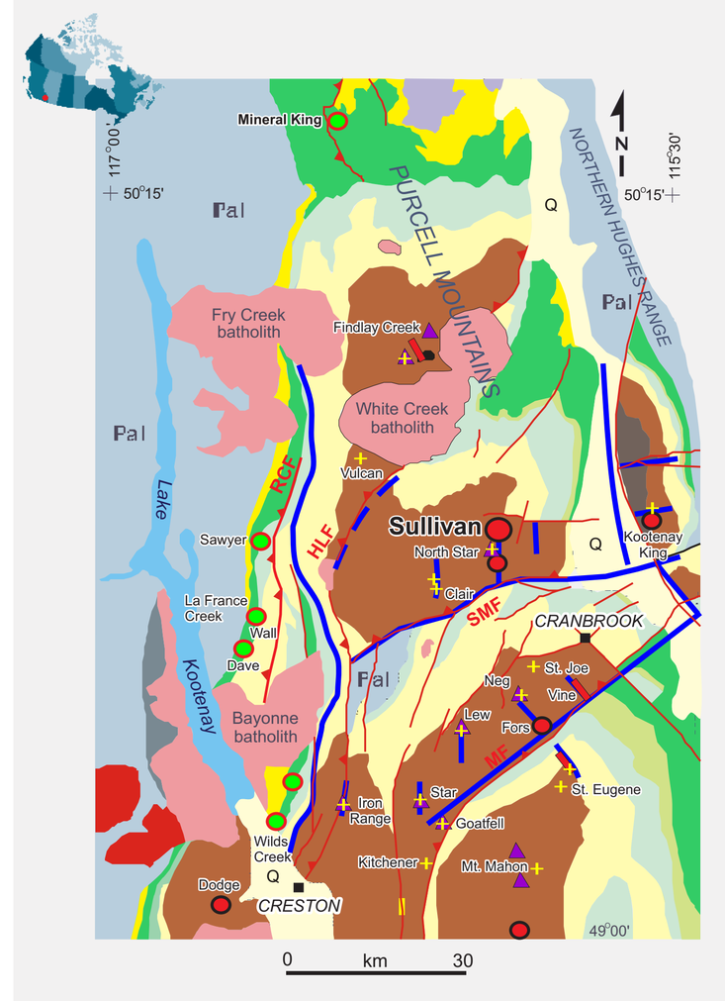


Figure 1 Location of the Sullivan mine in south-eastern British Columbia with geological map of the Purcell anticlinorium. Overlay of SEDEX ore system elements (Sullivan and satellite massive sulphide deposits, tourmalinite alteration, sedimentary fragmental rocks and inferred syn-sedimentary faults, from Lydon et a.,l 2000).

Figure 2 Folded bedded sulphide ore from the Sullivan deposit. (Sample courtesy of Paul Ransom)

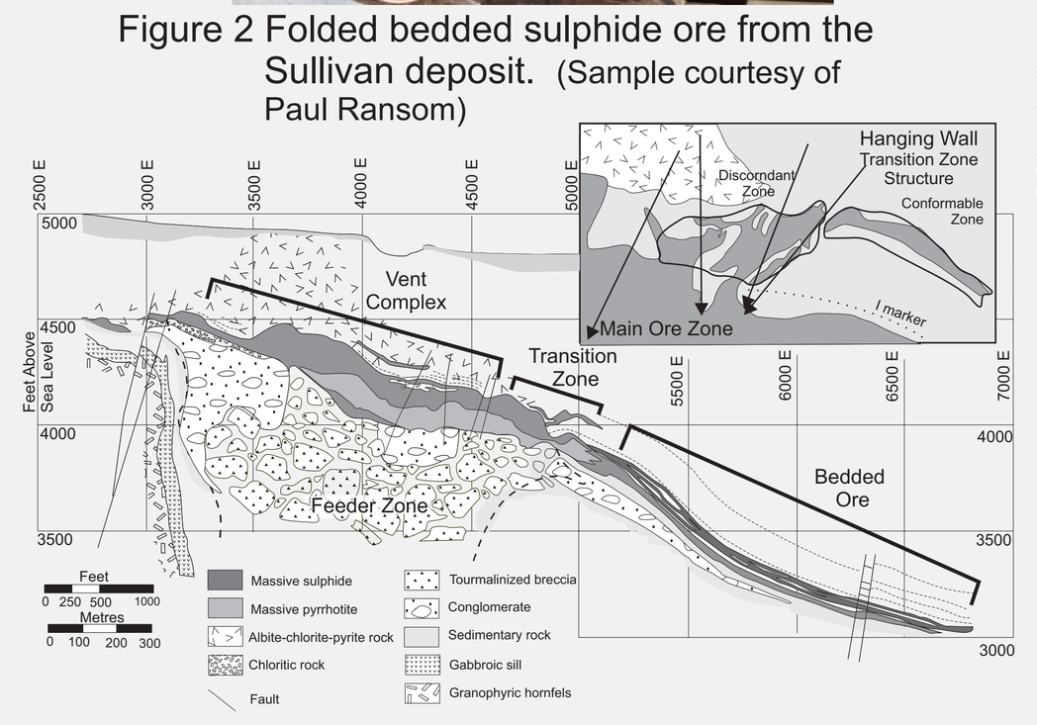


Figure 3 Generalized west-east geological cross-section at 11600N showing the distribution of the hanging wall sulphide zones (after Hamilton et al., 1982). The inset illustrates the complex nature of the "HU" sulphide zone along the transition zone (from Conly et al., 2000).

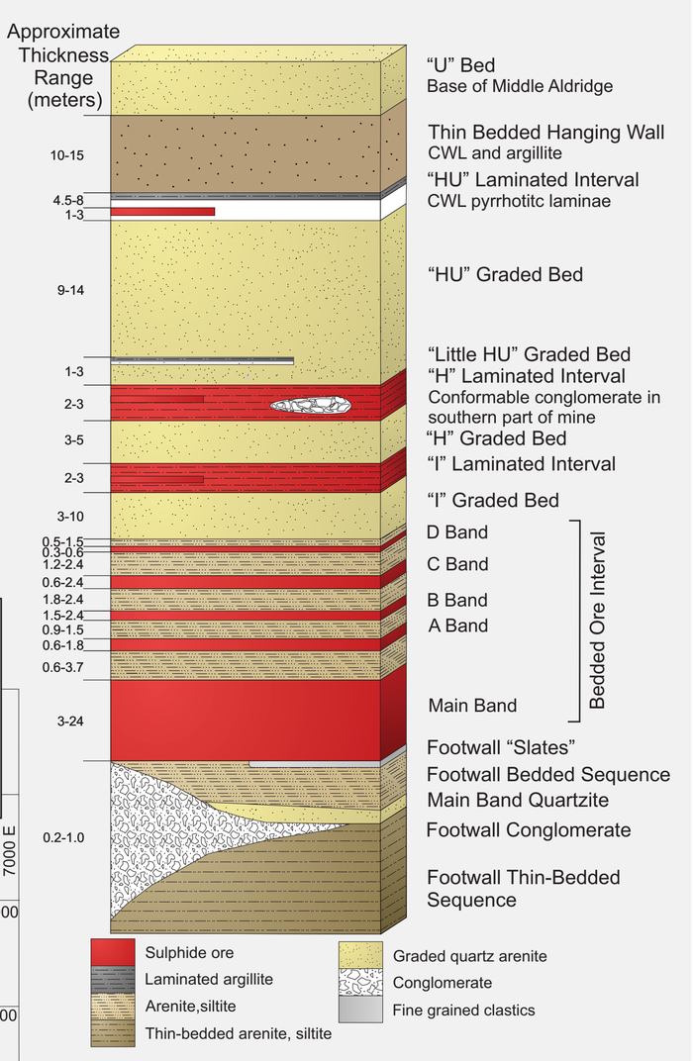


Figure 4 Bedded Ore stratigraphy from the eastern ore zone of the Sullivan Horizon (after Lydon, 2007)

The Sullivan orebody and its host rocks have been affected by at least two phases of tectonic and metamorphic activity (Figure 2). The first occurred during the "East Kootenay Orogeny" (1340 Ma) and the second deformation event was related to a final stage of rifting and magmatism (Lydon et al., 2000). The most significant deformation event occurred in the Cordilleran Laramide (150-110 Ma) orogeny. Local deformation effects include localized contorted folding, and tight north-south shallow plunging upright folds with slightly overturned to the east short limbs and irregular ore piercement structures as well as some low angle thrusting that can repeat mine stratigraphy.

There are two ore zone (east and west), which are separated by a structurally complex transition zone (Figure 3) (deKemp et al., 2015; Montsion et al. 2015). The western zone has been termed the 'vent complex' and is theorized to contain vents where metal enriched hydrothermal fluids emerged from the subsurface. Roughly 70% of the ore is contained within this zone. The eastern zone contains the bedded ores known as the 'Main Band', 'A Band', 'B Band', 'C Band' and 'D Band' (Figure 4) (Goodfellow and Lydon, 2007).

SEDEX Processes

SEDEX deposits form by the discharge of metalliferous hydrothermal fluids at and immediately below the sea floor of a sedimentary basin (Carne and Cathro, 1982). There has been some recent debate about how the Sullivan and other SEDEX deposits formed. Currently, there are two depositional models up for debate.

The first ore depositional model (Figure 5) postulates that once vented to the sea floor, hydrothermal fluids reacted with bacteriogenic H_2S rich, anoxic, bottom water and formed a metalliferous precipitate, thereby chemically trapping the metals. The precipitate fell out of suspension and was deposited as laminated sediments and lenses along the basin floor, giving a stratiform appearance (Goodfellow and Lydon, 2007).

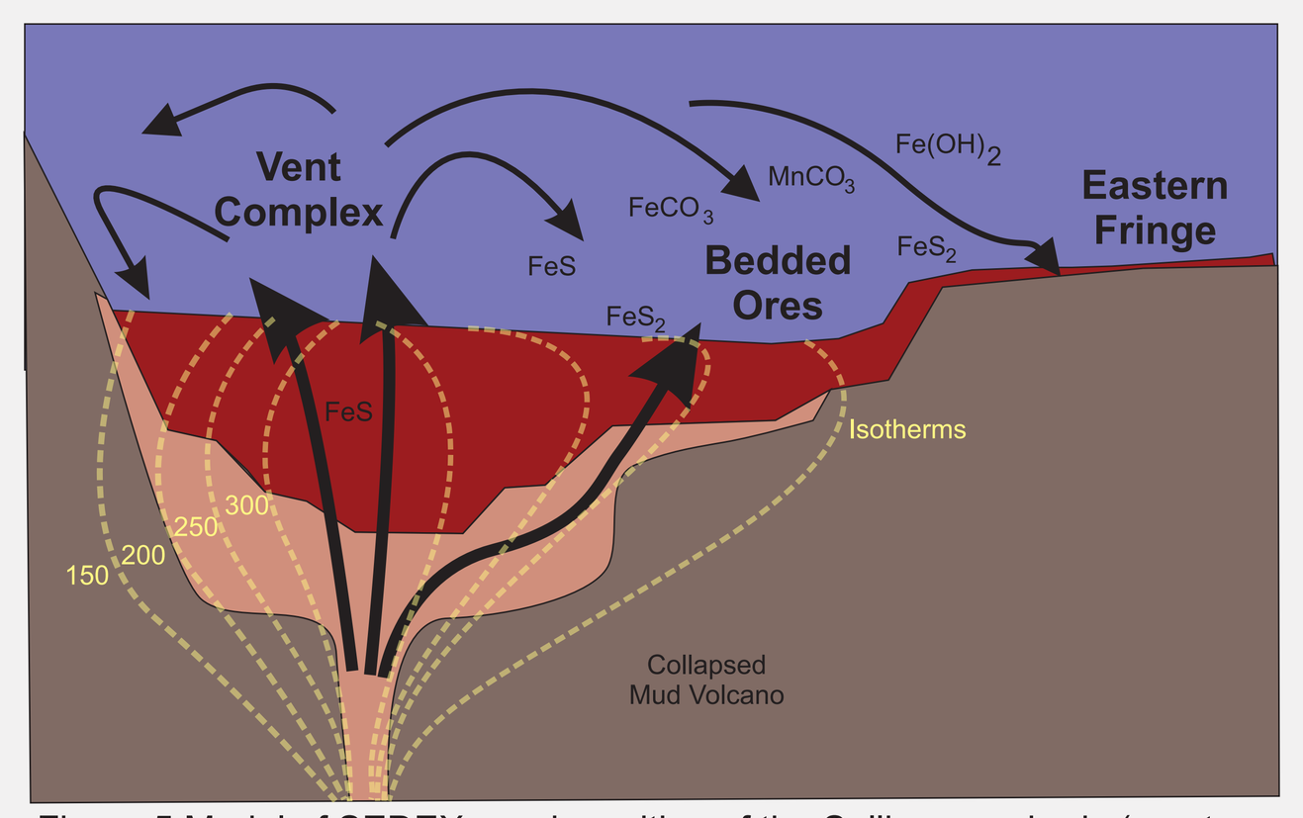


Figure 5 Model of SEDEX ore deposition of the Sullivan ore body (courtesy of Lydon)

The second ore deposition model postulates that there was interaction between the hydrothermal fluid and sulphides in the shallow subsurface, regardless of whether the sulphides was bacteriogenic H_2S, hydrothermal H_2S, or pre-existing sulphide minerals. The 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 ore depositional models, the resultant sulphidic rock would show sedimentary textures.

Depending on where the precipitating reaction takes place, 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; however the second one, the more replacement driven process may have been the dominate one.

Methods

1. Assay data was extracted from scanned drill logs (Figure 6a), entered into a database (Figure 6b) and linear referenced to 3D drillholes (Figure 6c) from Sullivan mine survey records.

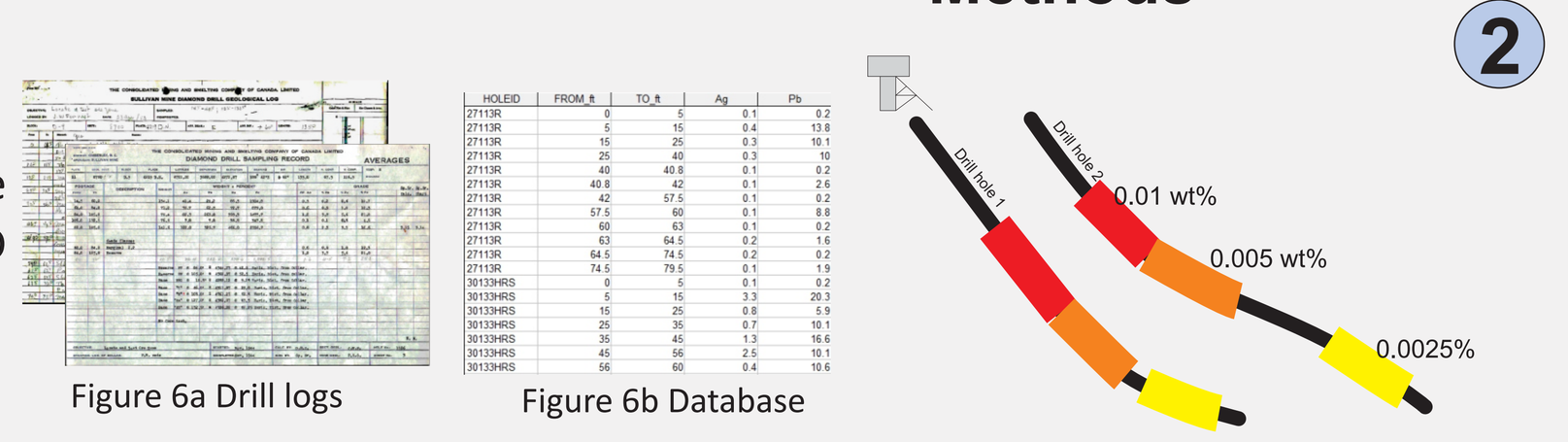


Figure 6a Drill logs
Figure 6b Database
Figure 6c Linear referenced drillholes

2. Assay data along drillholes are resampled at 1 m intervals along drillholes. (Figure 7). Each point is given 3D coordinates (XYZ)

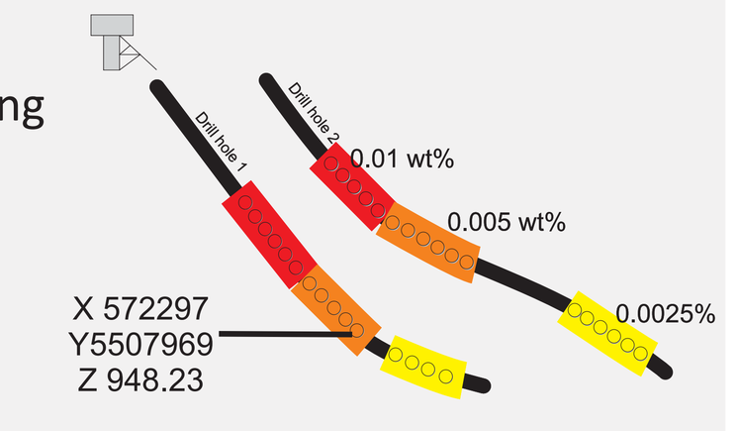


Figure 7 Resampled drill holes and assay data points in XYZ
Red indicates high concentration

3. Semi-variograms (Figure 8a)are used to analyse spatial trends in the data within a geographical range (Figure 8b). When spacial trends are understood, an interpolation model can be created to fill in unkowns between data points.

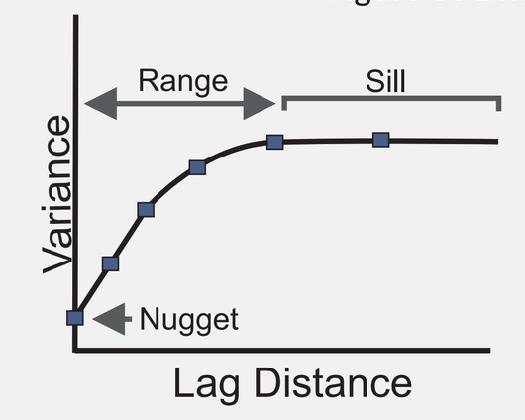


Figure 8a Semi-variogram, trend of data inside range container

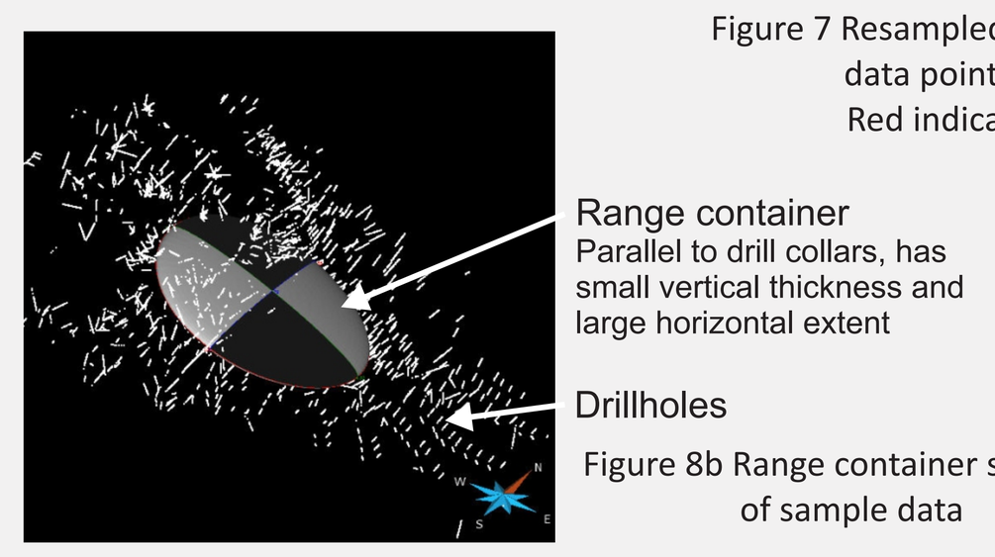


Figure 8b Range container shows location of sample data

4. Metal values are assigned to 3D grid cells (blocking)(Figure 9a). The grid is then used as a metal property container for geostatistical analysis.

The grid (Figure 9b) is built to mimic local geological trends using available stratigraphic and structural data. The new coordinate system in the grid is UVW instead of XYZ.

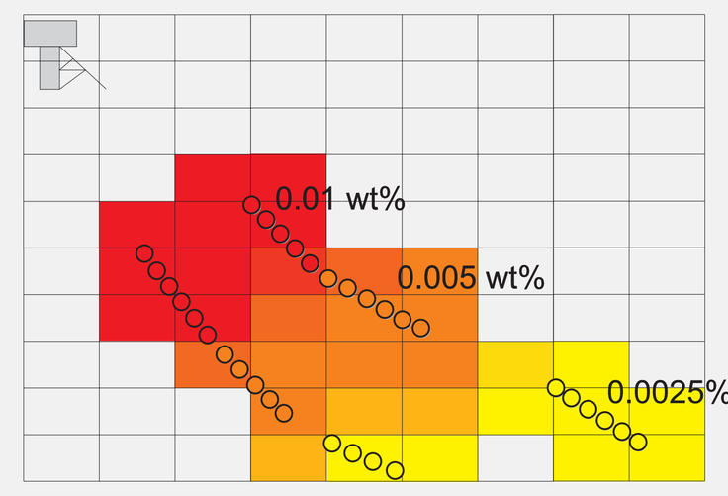


Figure 9a Blocking assay values

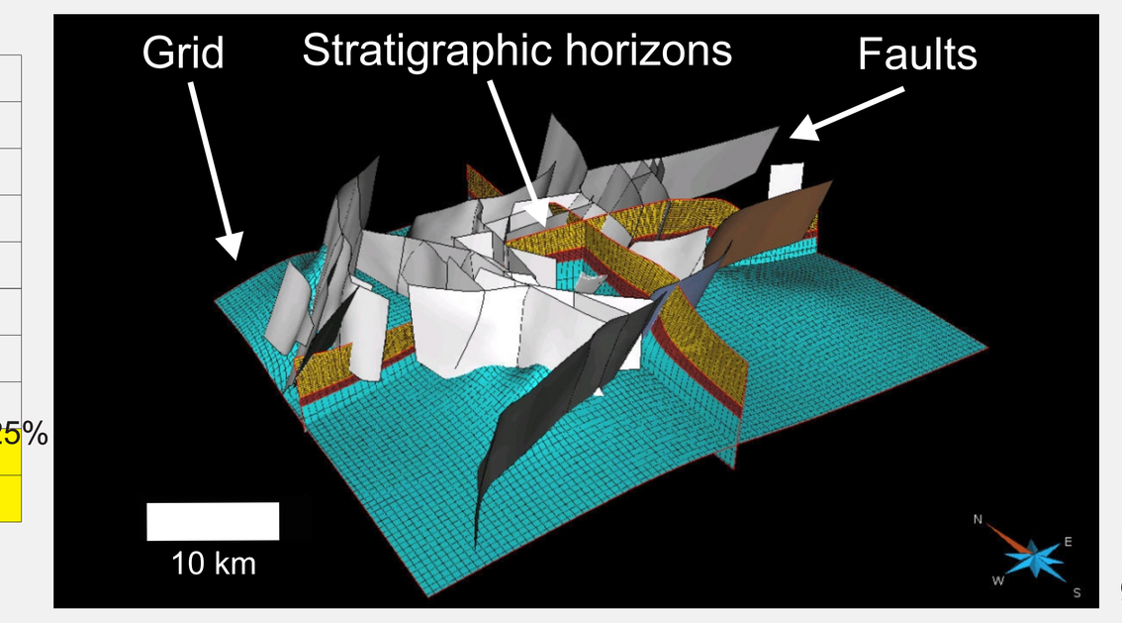


Figure 9b UVW geogrid with faults

5. Kriging interpolation was used to visualize ore metal concentrations. Kriging algorithms use weights to linearly combine neighbouring data points to estimate unknown values. The weights are given by a computed variogram model and search parameters. To model the Sullivan's assay metal concentrations, an ordinary kriging method was selected. Ordinary kriging assumes that the interpolated property and its average will vary spatially.

Geospatial Analysis

The metals Pb and Zn show a naturally skewed distribution(Figure 10 a and c). To emphasize the ore process we stretch these skewed data values with a log-transform before doing Inverse Distance Weighted (IDW) or Ordinary Kriging interpolation (Figure 10 b and d). After a metal property model is calculated, a back log transform is done to represent the natural ranges of our modelled results. Fe shows a non-skewed range of values, so we interpolate the values directly.

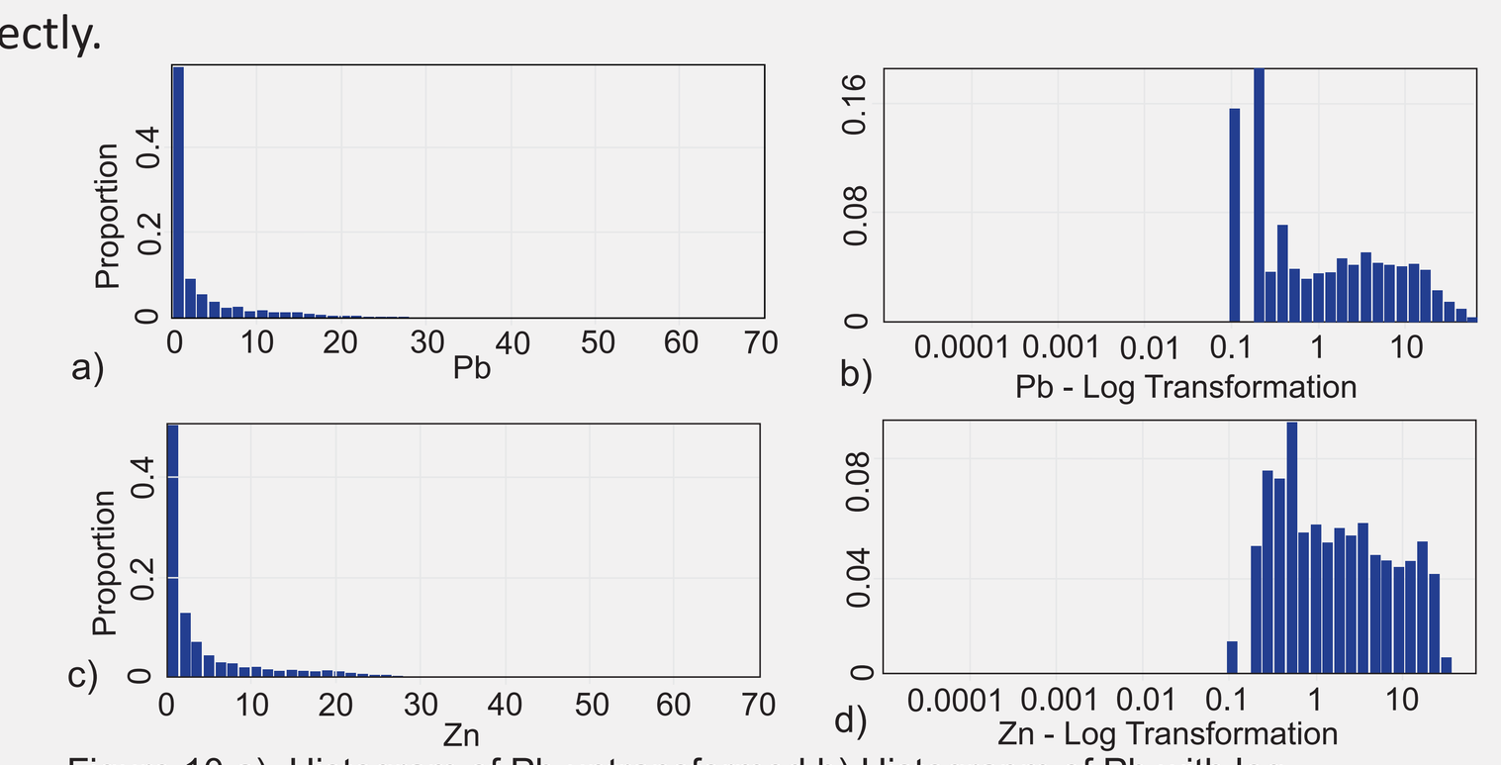


Figure 10 a) Histogram of Pb untransformed b) Histogrqpm of Pb with log-transformation c) Histogrqpm of Zn untransformed d) Histogram of Zn log-transformed. NPb= 109,626 NZn= 109,757

Geological impacts on semi-variogram patterns are prominent in the raw XYZ semi-variograms (Figure 11 a). Oscillations and/or drop-offs of point pair variability along the sills make variogram interpretations difficult and are probably controlled by the ore bands. Repeat metal concentrations and internal layering between ore and waste portions vertically cause variability to wax and wane along the sill. Alternatively, oscillations and discontinuities could be due to local folding and faulting. These patterns are smoothed out when geostatistical analysis is done with respect to the GEOGRID (UVW) (Figure 11 b and c) instead of raw (XYZ) Cartesian space.

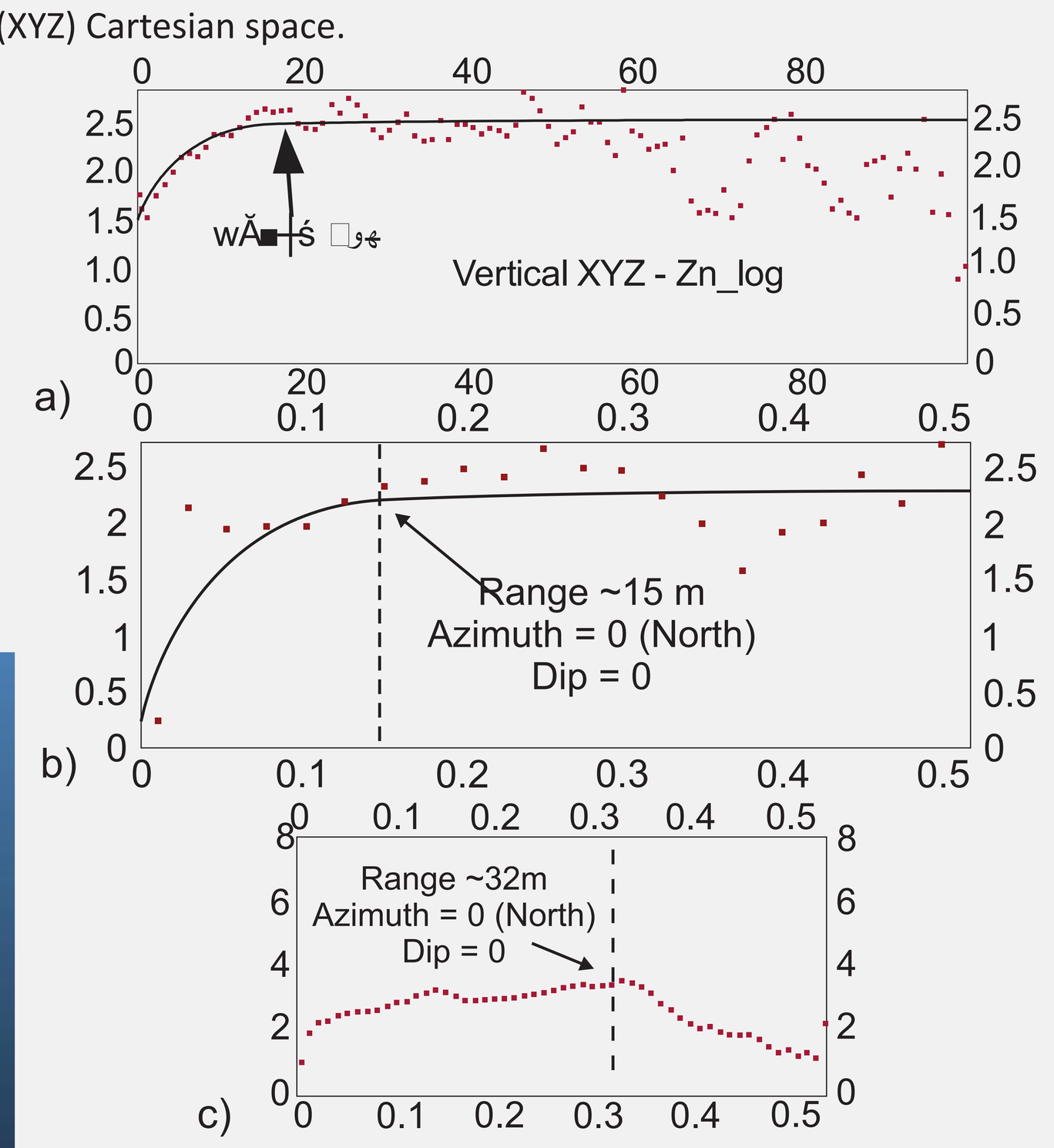
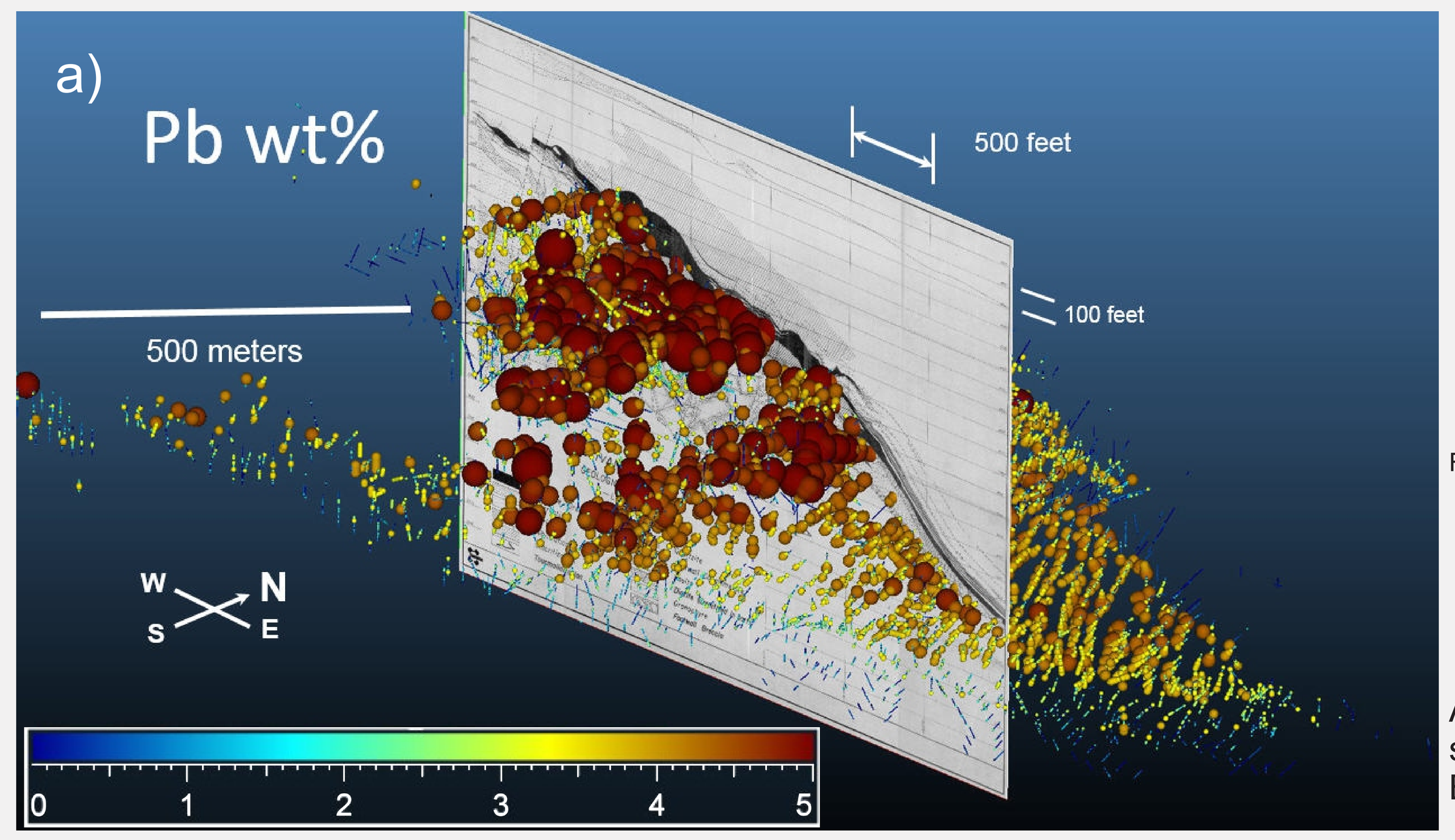


Figure 11 Variogram analysis. a) Vertical semi-variogram for Log transformed Pb from the entire Sullivan data b) GEOGRID (UVW) based horizontal, north trending semi-variogram for log transformed Zn c) GEOGRID (UVW) based semi-variogram for log transformed Pb indicating smoother short (0.05) and long (0.3) ranges. Short range used for kriging metal zonation models



After linear referencing assay points to drill holes, points are symbolised to show areas of high metal concentration (Figure 12). Both metals (Pb and Zn) showed significant accumulation in the western half of the deposit and minor bedded accumulation in the eastern half. This finding supports the established ore geometry of the western Vent Complex and eastern Bedded Ore (Lydon, 2000; Goodfellow and Lydon, 2007; Lydon 2007).

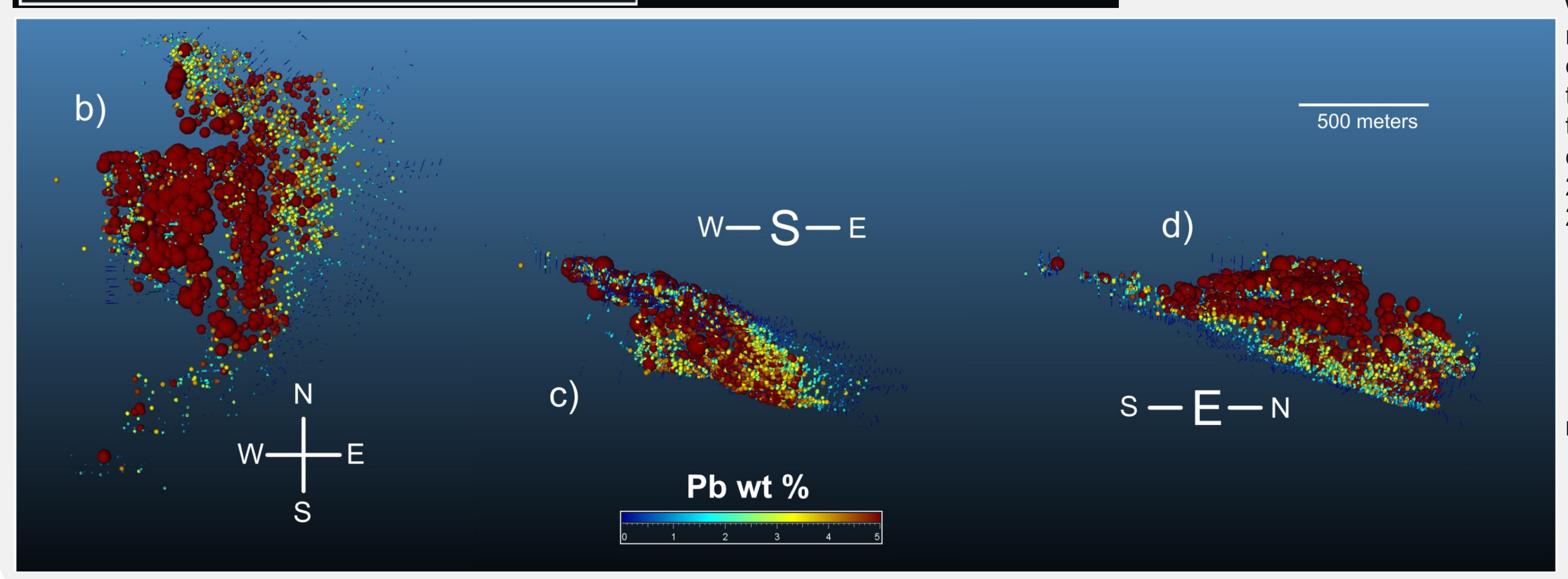


Figure 12 Pb assay value distribution in Sullivan mine a) Northwest view superimposed on 11600 N cross-section from Freeze (1966) b)Top view c) Southern view d) Eastern view

Interpolation Results

The interpolation results from Pb, Zn and Ag show many similarities with a strong north-south to 160-340° trend for high concentration zones, especially for the bedded ores (Figure 13).

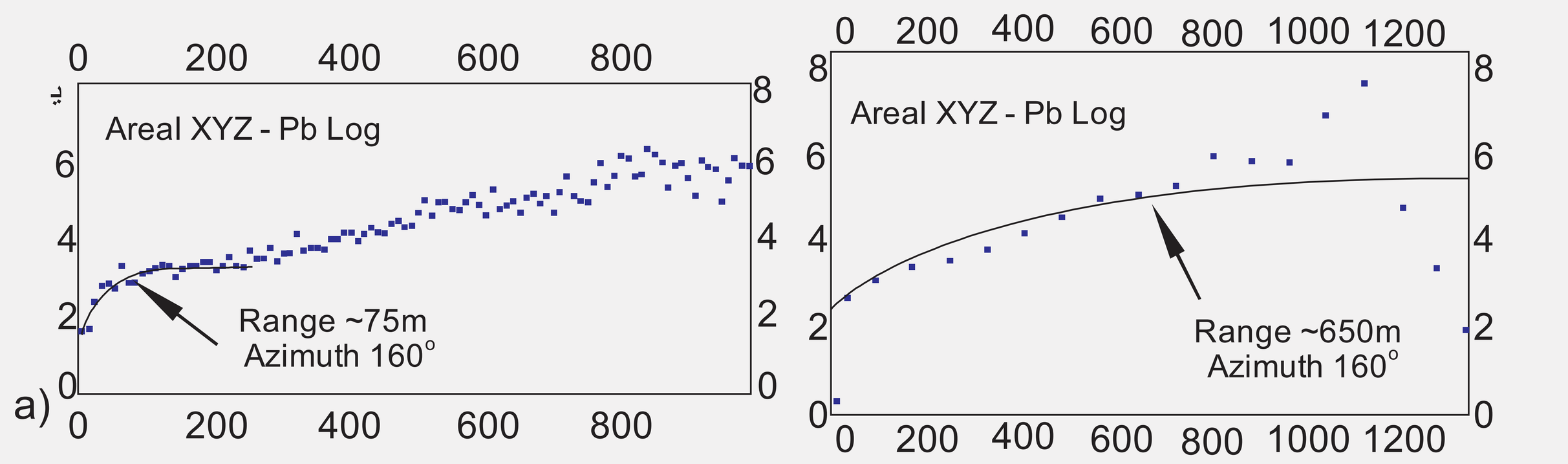
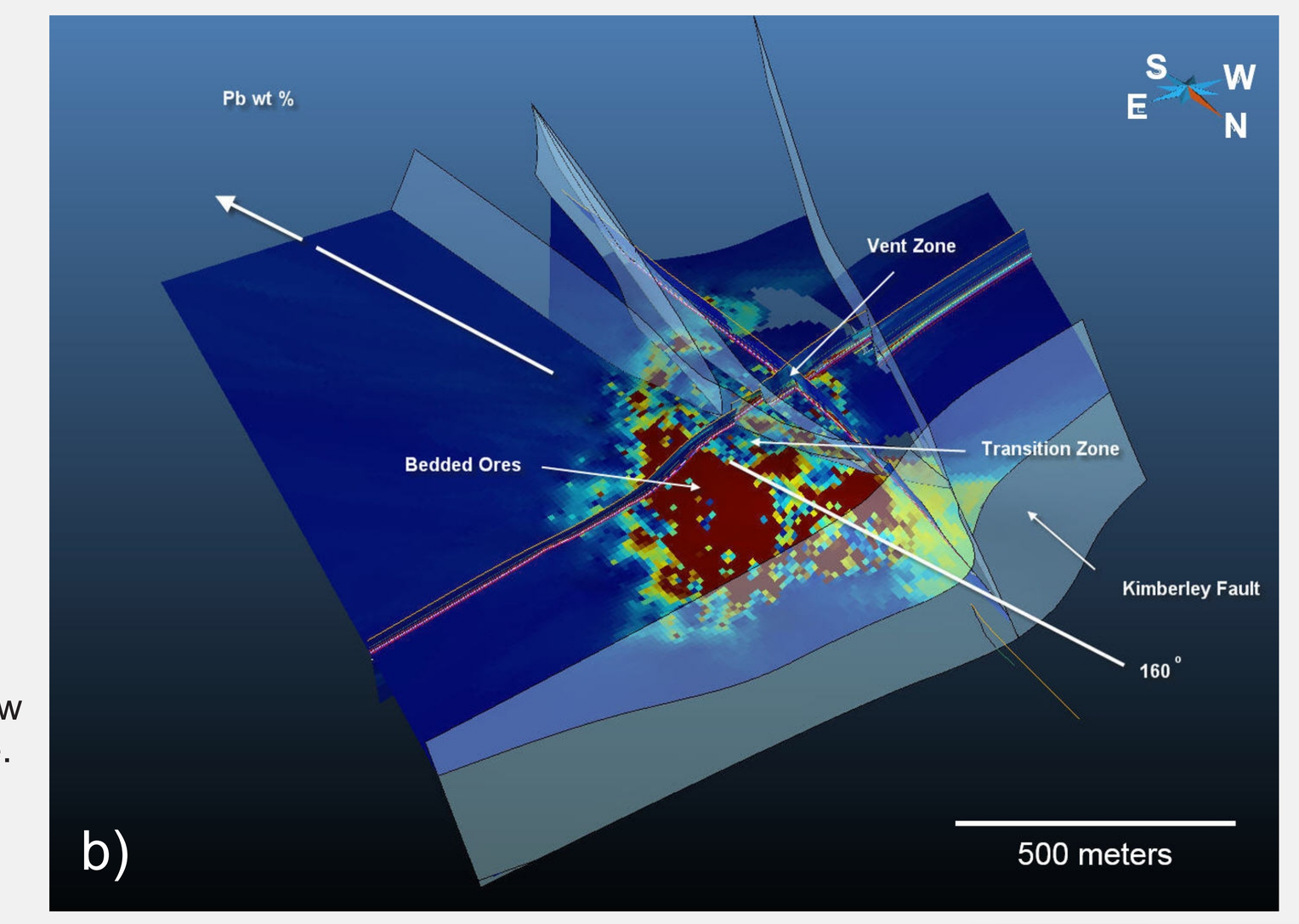
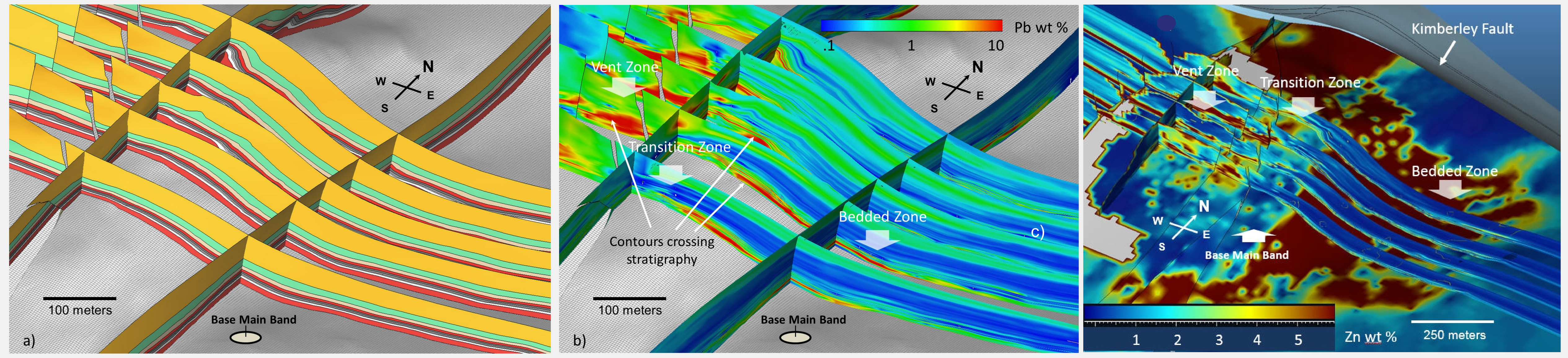


Figure13 a) Variogram indicates strong bedding controlled metal anisotropy for Pb and Zn within the Bedded zone, as well as a subtle 160° trend in metal content b) Plan view of Sullivan orebody with delineation of Bedded Ores, Transition Zone and Vent Zone. Kriged Pb Assay values at the top of the Main Band show 160°/340° trend



When the volume is interpolated, using variogram analysis of assay data points (Figure 13a), metal concentration trends show similar geometry to mine stratigraphy (Figure 13b) (McClay, 1983, Paakki et al., 1995).



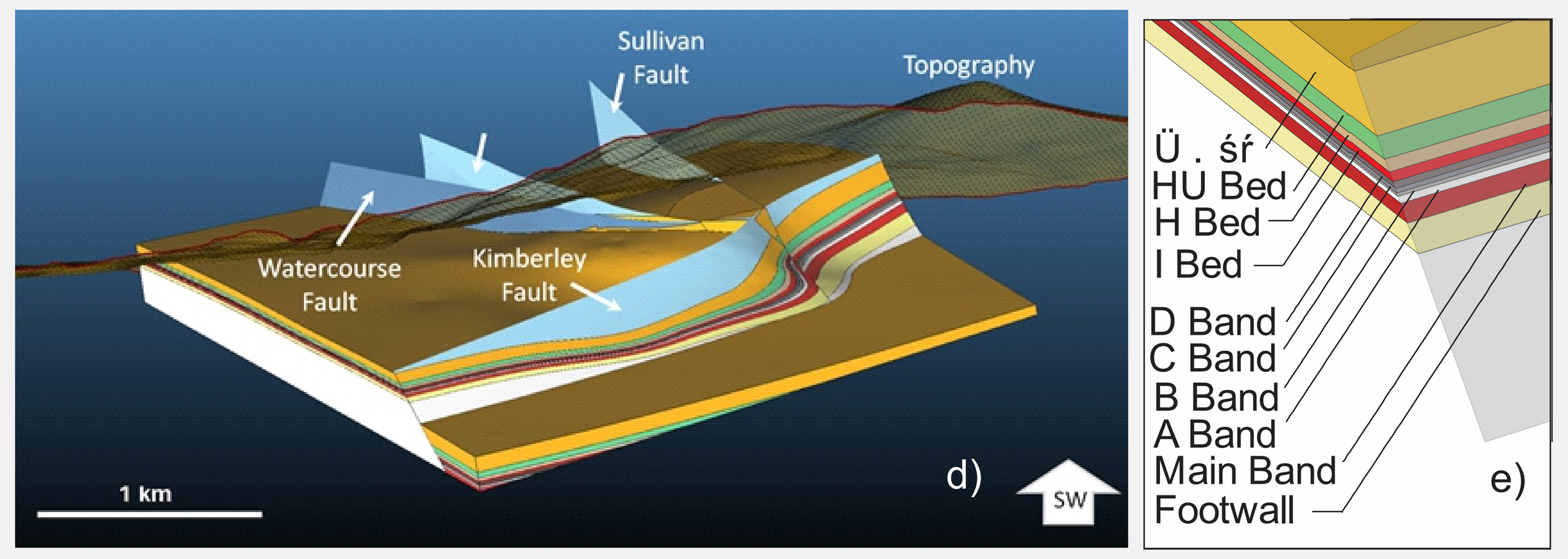


Figure 14 Close up east-west vertical cross-sectional views of Sullivan stratigraphy (a) and kriged Pb-Zn ratio (b) indicates strong continuity with contours transecting the Main Band. Additionally, linear concentration zones to the east are unsupported anomalies from the interpolation. (c) Inverse distance weighting interpolated Zn values. (d) Ore beds dipping to the northeast below surface topography. (e) Sequence and colour scheme of the Bedded Ore zone.

Metal zonation patterns clearly corroborate previous studies that delineate the 3 main ore facies: Vent Complex, Transition, and Bedded Ores (Lydon et al., 2000; Montsion, 2014). Locally, the metal rich zones have abundance contours (Pb and Zn), which cross-cut the mine Band stratigraphy giving support for an *in situ* replacement process (as opposed to an exhalative only process), however the major concentration of ore is constrained to the Main Ore Band (Figure 14). T

Conclusions

- Metal zonation patterns in Figure 12 clearly corroborate previous studies that delineate the 3 main ore facies (Vent, Transition and Bedded Ore zones).
- Locally, the metal rich zones in Figure 14 have abundance contours which can transect through ore stratigraphy, supporting a replacement ore deposition model which occurred mostly in the vent and transition zone.
- The interpolation results in Figure 13 show many similarities with a strong north-south to 160° – 340° trend for high concentration zones, especially for the bedded ores.
- The elongate 160° trend indicated in Figure 13 by variogram analysis also matches reasonably well with several proposed syn-sedimentary graben systems from previous studies (Hagen, 1983; Höy et al., 2000; Turner et al., 2000), such as the Sullivan-Stemwinder-North Star trend, Sullivan west graben, the Clair trend, and the Star and Lew trends (Moyie Block).
- The variograms in Figure 13 show both local and regional trends which are strongest for Pb and to a lesser extent for the other metals (Zn and Ag). There is a short ~ 75 metre at a 160 degree trend and a much longer regional trend in the same direction, up to at least ~ 650 metres.
- Sullivan region, the Mine stratigraphy and geological information (lithofacies, structures, assays, and alteration) can be compared to information from regional exploration holes, since they now have a common 3D spatial framework. This could prove useful for future work in delimiting the extent of the depocentre or sub-basin hosting the Sullivan deposit, and providing leads for exploration throughout the Purcell Basin.

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