3D Geological Modelling of the Sullivan Time Horizon, Purcell Anticlinorium and Sullivan Mine, East Kootenay Region, Southeastern British Columbia

E.A. de Kemp
Geological Survey of Canada 615 Booth Street, Ottawa, ON, K1A 0E9
edekemp@nrcan.gc.ca

E.M. Schetselaar, M.J. Hillier
Geological Survey of Canada, 615 Booth Street, Ottawa, ON, K1A 0E9

J.W. Lydon
Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8

P.W. Ransom
9452 Clearview Road, Cranbrook, BC, V1C 7E2

R. Montsion
University of Ottawa, Ottawa, ON, K1N 6N5

J. Joseph
Geological Survey of Canada, 1500 - 605 Robson Street, Vancouver, BC, V6B 5J3

Abstract

Regional and mine scale 3D geological models, highlighting the Mesoproterozoic Sullivan time horizon (~ 1470 Ma) have been developed throughout the Purcell Anticlinorium in the East Kootenay region. The 3D geospatial model of the region has been constrained with an extensive surface and sub-surface database of stratigraphic, structural and geophysical observations distributed throughout the study area. The Purcell 3D activity, entitled Purcell-3D, was developed as a contribution to the “SEDEX” project of the Targeted Geoscience Initiative 4 (TGI-4) program over a 4 year period (2011 to 2015). The model includes what is locally referred to as the 'LMC' or Lower - Middle Aldridge stratigraphic contact, a map unit at the very top of the lower Aldridge Formation where the Sullivan Pb-Zn-Ag deposit is located. Local detailed and unique stratigraphy of the various ore and waste bands and closely associated beds inter-finger with the LMC boundary unit to form the Sullivan Sub-basin. The detailed Sullivan Mine model placed in the context of the regional LMC model, provides a much needed geospatial reference used to characterize and understand SEDEX ore systems. It also provides mineral exploration stakeholders with a key target horizon and spatial information from which to conduct further investigations.

Recommended citation

de Kemp, E.A., Schetselaar, E.M., Hillier, M.J., Lydon. J.W., Ransom, P.W., Montsion, R., and Joseph, J., 2015. 3D Geological modelling of the Sullivan time horizon, Purcell Anticlinorium and Sullivan Mine, East Kootenay Region, southeastern British Columbia, *in* Paradis, S., ed., Targeted Geoscience Initiative 4: sediment-hosted Zn-Pb deposits: processes and implications for exploration; Geological Survey of Canada, Open File 7838, p. 204-225. doi:10.4095/296328

Introduction

The Mesoproterozoic Aldridge Formation within the Purcell Anticlinorium in the East Kootenay region of Southeastern British Columbia, Canada, has been extensively mapped on surface, prospected and drilled and subject to numerous geological, geochemical, seismic, electromagnetic and potential field surveys. The Purcell-3D activity has been driven largely by the mineral potential of a region that is host to one of the world's largest Pb-Zn-Ag SEDEX deposits, the Sullivan Mine in Kimberley, British Columbia. This deposit has contributed close to $50 billion in current US dollars throughout its life. The abundant data collected over one century of mining and exploration activities, has been compiled, analyzed and interpreted in a 3D geospatial environment. Herein are the results of a 4 year GSC-led project focused on developing a 3D regional-scale structural and stratigraphic model.

Historically the tendency to examining basin architecture for indications of SEDEX deposits (e.g. presence of synsedimentary faults, sub-basins, geophysical responses, geochemical dispersal patterns) resulted in 'conceptual' models often influenced by corporate or individual bias which were difficult to test, to communicate and to reconcile among multiple disciplines. This is mitigated to a certain extent, as 3D geological modelling is increasingly being employed in mineral exploration. In historical, well-explored mining camps like Sullivan, we can take advantage of 3D modelling technology and expertise that exists. It is now possible to make a constrained 3D regional-scale model of a stratiform ore horizon, because laterally-persistent stratigraphic markers extracted from a digital geologic map series can be integrated with the same stratigraphic markers recognized in local clusters of drillholes. This regional-scale 3D geologic model can then be converted to a curvilinear grid, with the geometry defined by the contacts of the lithostratigraphic units. This geologic grid model can then in turn be used for future exploration targeting, taking advantage of a variety of quantitative analytical and 3D GIS query tools (de Kemp et al., 2010). This more regional scale 3D modelling is becoming important in enhancing geological understanding of the subsurface and exploring for mineral deposits at greater depths.

Objective and Scope

The main objective of developing the regional scale Purcell 3D model was to give a wider spatial perspective of the structural and stratigraphic geology of the subsurface. Building on a previous 2D GIS geoscience data compilation (9 Open File 1:50,000 scale geology maps covering NTS 82F01, 02, 07, 08, 09, 10, 15, 16, 82G04, 05, 12, 13), (Brown et al., 2011; Joseph et al., 2011a, b), a re-processed seismic compilation (Cook and Van der Velden, 1995) and using British Columbia TRIM Digital Elevation Model for vertical control, an initial 3D data set was developed for the Purcell Anticlinorium. This was supplemented with inclusion of identified markers and 3D path calculation from information contained in regional legacy drillhole logs (see Schetselaar et al., 2015 for details). From the integration of this extensive data set and some follow up field work in 2011 and 2012, a 3D structural and stratigraphic regional model of the southern Purcell Anticlinorium and a more detailed Sullivan Mine model were developed (see Figures 1, 2 and 3).

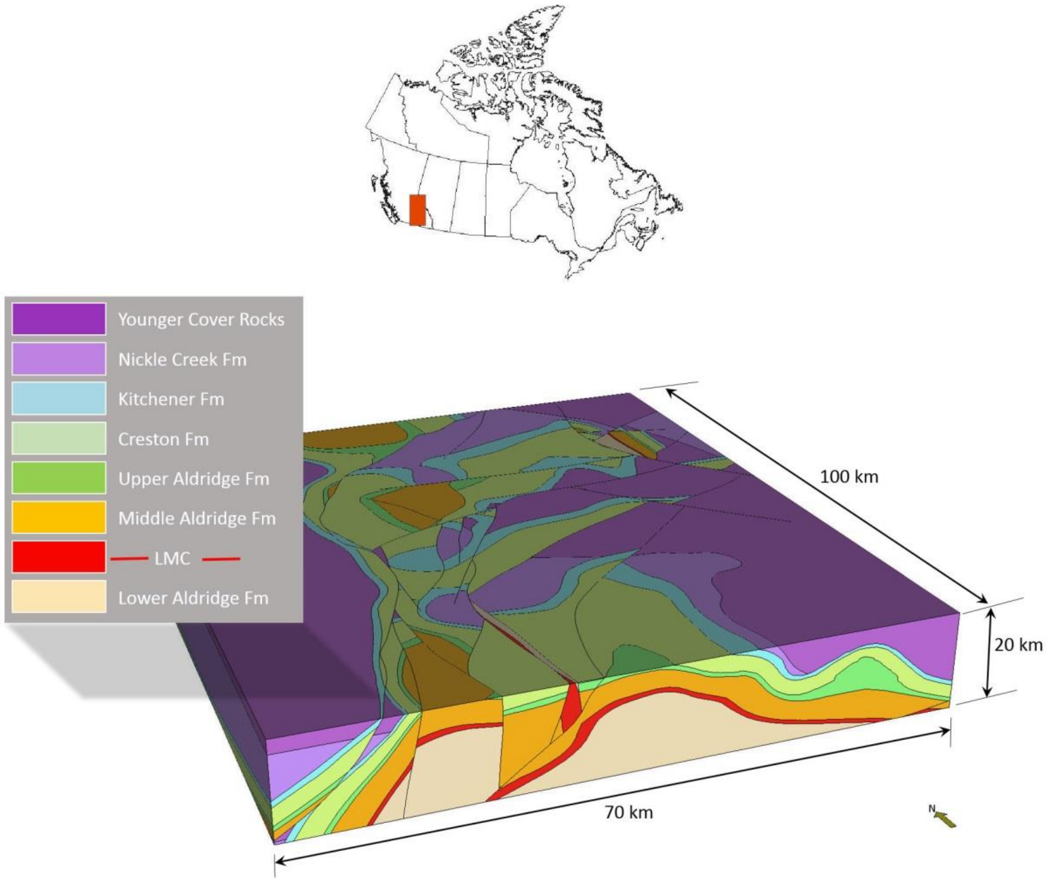


Figure 1. Location and regional extent of the Purcell-3D model. Thickness of Lower – Middle Aldridge (LMC) is approximate.

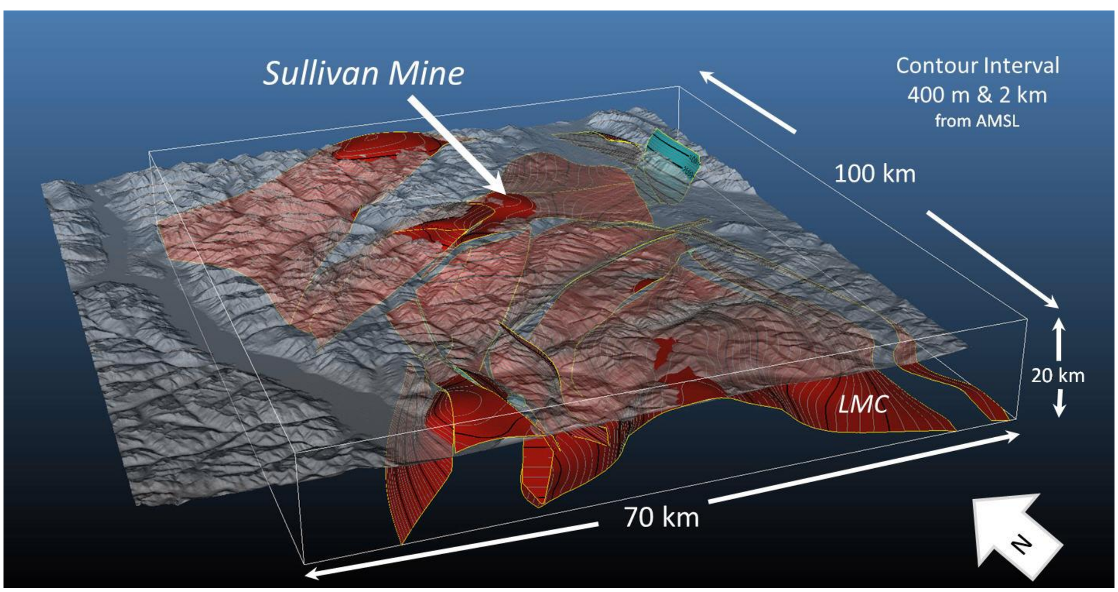


Figure 2. Red contoured surface represents the Sullivan time horizon or 'LMC' (Lower – Middle Aldridge contact) where the Pb-Zn-Ag Sullivan deposit is located. Contour interval is 500 m. AMSL = Above mean sea level.

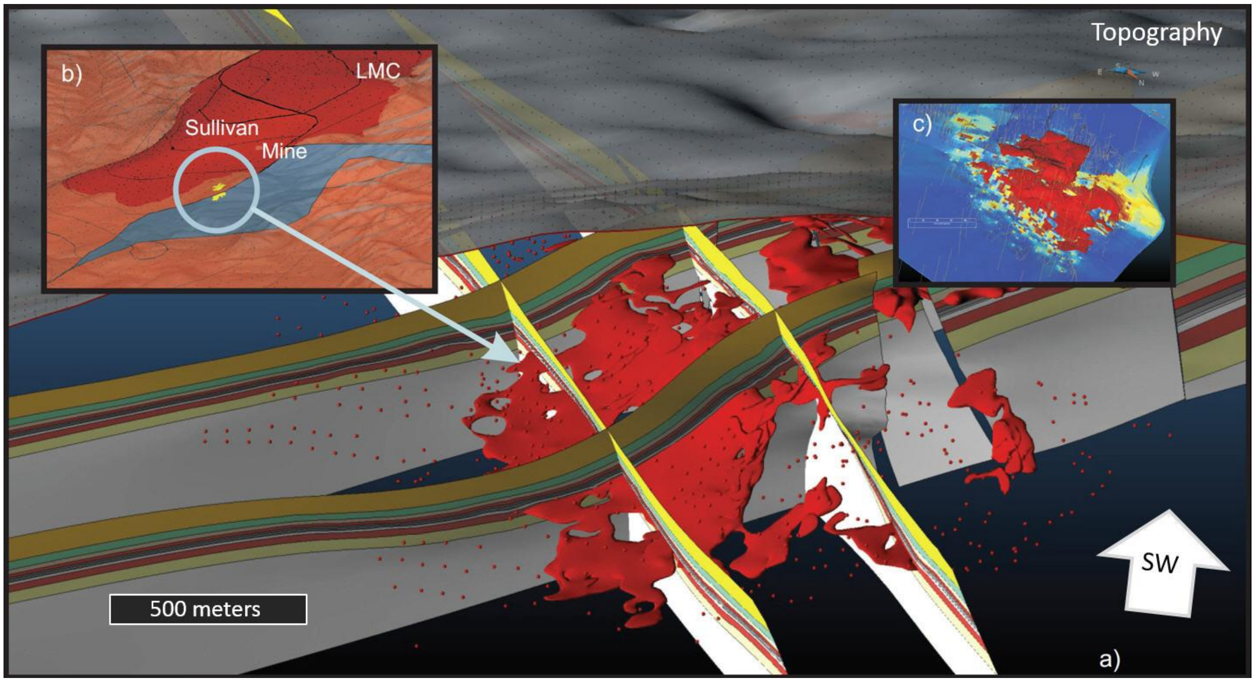


Figure 3. Sullivan Mine model looking towards the southwest. a) Orebody in red and mine stratigraphy cross-sections with top Main Band markers as red points; b) location of Sullivan Mine (yellow) along the regional LMC (Lower – Middle Aldridge contact) modelled surface (red); c) Kriged Pb zonation map at top of Main Band. See Montsion et al. (2015) for details of Sullivan Mine model.

Beyond the new drillhole database and Sullivan 3D model (Schetselaar et al., 2015; Montsion et al., 2015) a 3D interpretation was made for the mine site. The development of useful 3D geological models at various scales (mine, camp or *brown-field*, regional or *green-field*) is critical for coherent geologic data integration, prediction and ultimately targeting. 3D geologic modelling and integration has been successfully applied in mineral exploration and in mine camps worldwide over the last two decades (Pflug and Harbaugh, 1992; Dubois and Benn, 2003; Feltrin et al., 2009; Schetselaar et al., 2010). However, to go to broader scales (i.e. regional), new 3D modelling methods are needed where the distribution of subsurface constraints is generally sparse. Interpretive support is needed for constructing regional-scale 3D geological models, such as interpolation tools, that estimate spatial continuity or 'trends' of subsurface geological contacts beyond drillhole and outcrop constraints. In a conformable series of strata, this can be achieved by incorporating, in addition to drillhole markers, strike and dip measurements of the strata. These bedding orientation data are either acquired at surface by geological mapping or in the subsurface by drillhole measurements or analysis of bedding-drill core angles. This is an underdeveloped area of research in which sample distribution and anisotropy of the structures being modelled play an important role. For this reason we included a significant research component in the Purcell 3D activity for the development of new interpolation methods in sparse data environments. Results of this work are presented in Hillier et al. (2014, 2015). If key exploration features, such as a prospective target horizon, can be better interpreted and spatially integrated with other 3D data (electromagnetic, potential fields, seismic, drillhole data), then reproducible subsurface models of mineral systems can be generated and used in *green-field* mineral exploration.

The regional and Sullivan 3D model and supporting geoscience data presented herein are currently in GoCad / SKUA 2014 software from Paradigm®. The LMC (Lower-Middle Contact) horizon, markers points, structural observations, faults, younger Purcell stratigraphy above the Aldridge Formation and the DEM, will be released also as exported DXF, GoCad ASCII, ArcScene and Leapfrog scenes and as a 3D GIS geodatabase release in ArcGIS in the near future.

Geologic Context

The Purcell Anticlinorium in the East Kootenay region of southern British Columbia (Figure 4) is a 100 km scale shallowly northward plunging upright fold system (Price and Sears, 2000; Sears, 2007) with a shallowing upward sequence from deeper water basin turbidites to basin edge facies carbonates (Höy, 2000; Lydon et al., 2000). The succession of the Belt-Purcell Supergroup represents a major pericratonic rift-fill succession (Chandler, 2000) formed at the leading western edge of North America in Mesoproterozic times (1.47 – 1.40 Ga) and extends from the East Kootenays in Canada through northern Washington, Idaho, Montana to Wyoming in the US (for more information see: Price and Sears, 2000; Sears, 2007; Lydon et al., 2000; Lydon, 2007).

Commonly referred to as the Belt-Purcell, in Canada it has over 25 km in stratigraphic thickness (Figure 5) with the Lower Aldridge (15 km) being extensively thickened by Moyie gabbro-dioritic sills, at least one of which was most likely a significant heat engine for the evolving Sullivan SEDEX system (Lydon, 2007). The Sullivan (Pb, Zn, Ag) SEDEX deposit and its hosting Sub-basin sits within and is enveloped by the distinctive and regionally extensive uppermost unit (20 metres thick in the Kimberley region) of the Lower Aldridge Formation (Ransom and Lydon, 2000). This interval, termed the LMC (Lower-Middle Contact), consists predominantly of massive carbonaceous wacke laminate (CWL) (Ransom and Lydon, 2000). The Middle Aldridge Formation, is about 2.5 km thick and is dominated by turbidites and contains numerous diagnostic laminated siltstone markers (Huebschman, 1973) recognized by Cominco geologists in the mid-1960s. The sets of unique micro laminae of these markers have been correlated over distances as great as 300 km (Figure 6). The stratigraphic position of these markers is exploited by exploration geologists to target the LMC.

There are two early pulses of deformation and metamorphism in the region. The first event referred to as the East Kootenay Orogeny (1350-1300 Ma, McMechan and Price, 1982) terminates rift related sedimentation, involves folding, regional metamorphism and granitic intrusion (i.e. Hellroaring Creek stock). The second event, the Goat River orogeny (900-800 Ma) is a Windermere equivalent uplift event, involving block faulting and low-grade metamorphism. These events produce at least one high-grade sillimanite-bearing metamorphic zone along the St. Mary River within the Lower Aldridge and higher grade looking rocks in the core of the anticlinorium north of the Hall Lake Fault (McFarlane and Pattison, 2000) and south of the Moyie Fault. Generally rocks in the region are metamorphosed in the sub-greenschist facies and display well preserved primary structures common in turbiditic sediments, such as graded bedding

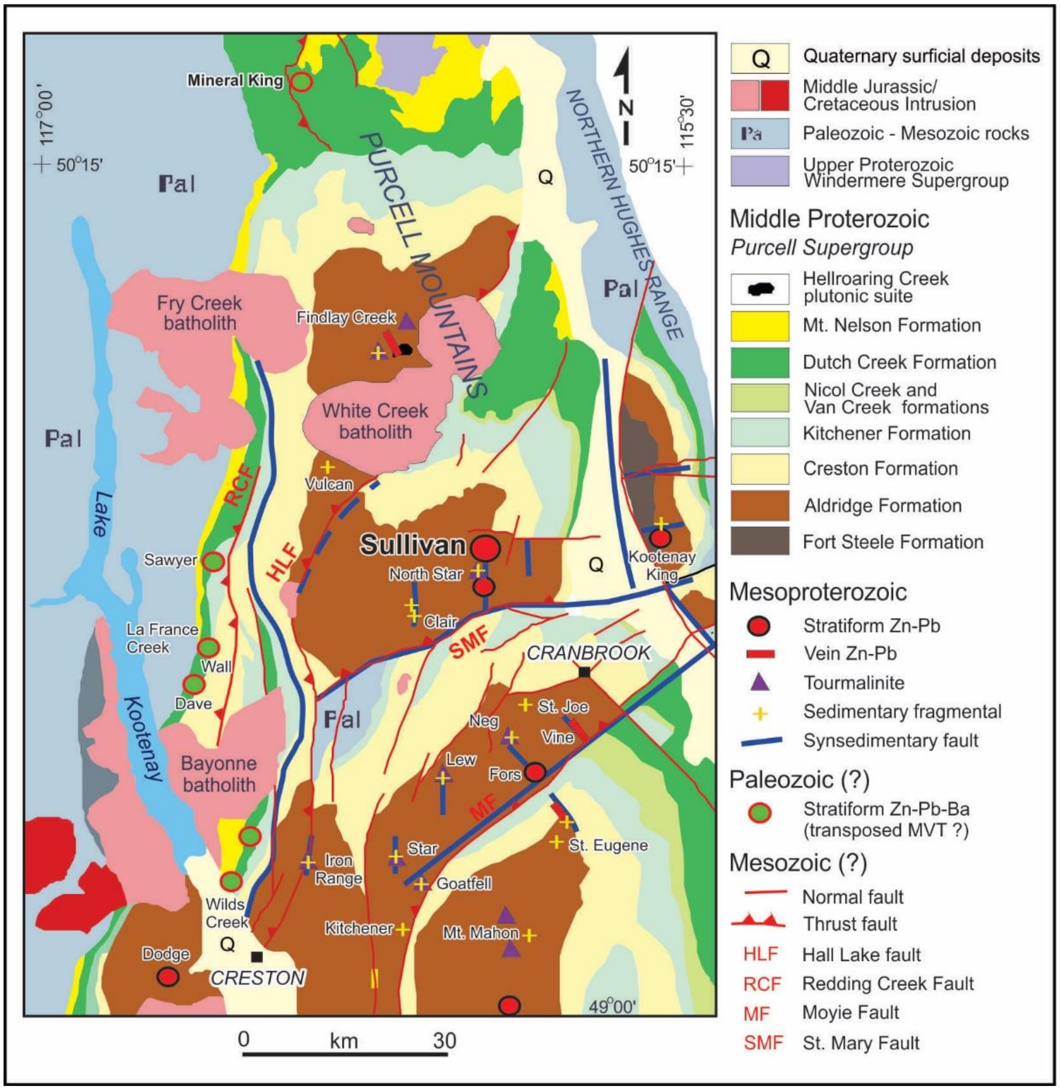


Figure 4. Generalized geological map of the Purcell Anticlinorium with overlay of SEDEX ore system elements (Sullivan and satellite massive sulphide deposits, tourmalinite alteration, sedimentary fragmental rocks and inferred synsedimentary faults; from Lydon et al. (2000).

load casts and flame structures, which constrain younging direction in modelling. The main phase of deformation occurred in the Phanerozoic, with the western Cretaceous-Tertiary Laramide orogeny, which produces the common folding and thrusting patterns observed in rocks of the region (Price and Sears, 2000; Sears, 2007). These are characterized by upright, east vergent, shallow, north-plunging folds separated by wider spaced more regional east-north-east trending, northwest-dipping, generally dextral, top to the east thrust systems that affect the entire stratigraphy of the Belt-Purcell (Figures 7 and 10). The last significant movement occurred from extensional fault systems in the

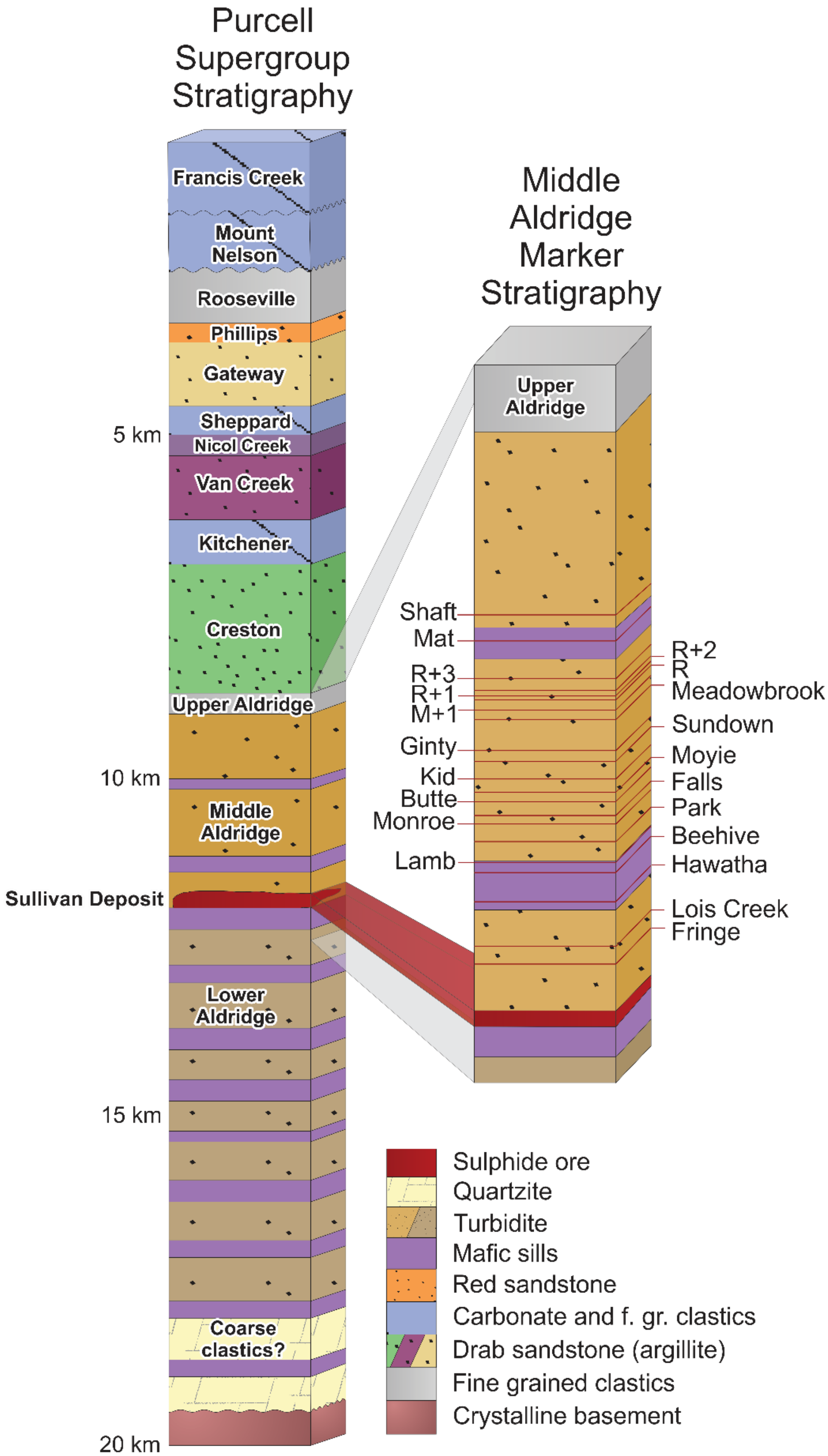
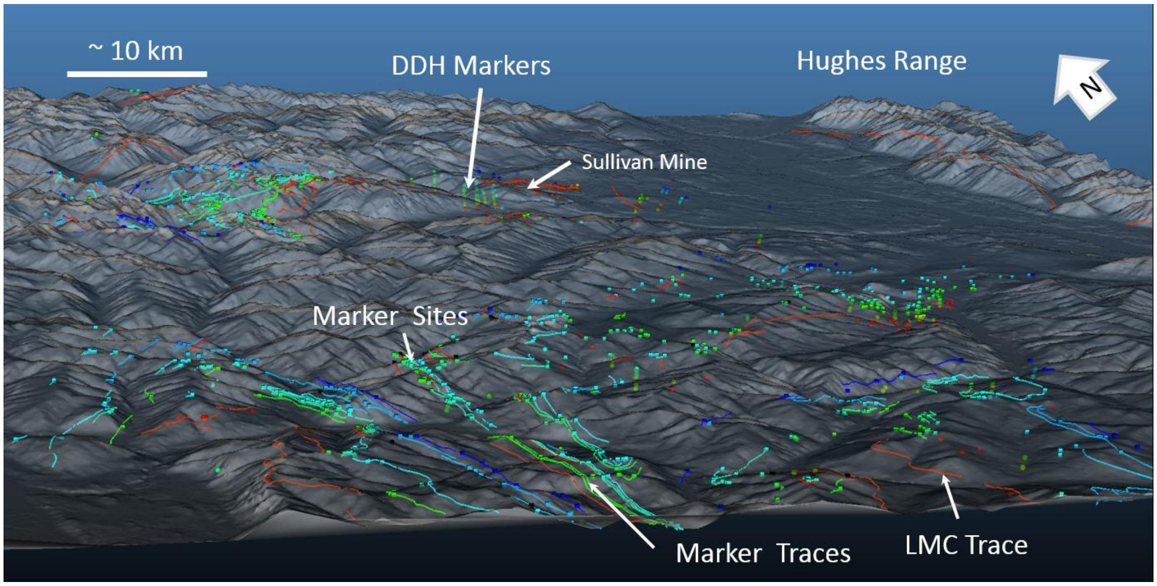


Figure 5. General lithostragraphic column of the Purcell Supergroup after Höy et al. (2000). Marker stratigraphy after Hagen (1983).

Eocene (50-33 Ma), such as the Rocky Mountain Trench (RMT) with up to 10 km of throw and which cuts the eastern portion of the Purcell Anticlinorium. It is important to appreciate that the deformation history that has affected the region has completely re-oriented and dissected the original Purcell Basin geometry, obscuring the effects of features responsible for controlling ore formation. We believe that in order to better understand the ore system, we need to treat the deformation as part of that system with 3D reconstruction, and ultimately 4D structural restoration. This will all contribute to developing a more precise understanding of ore forming processes.


a)



b)

Figure 6. Individual ‘marker beds’ of the Middle Aldridge Formation are used to correlate stratigraphic position throughout the Purcell Anticlinorium. a) Photo demonstrating marker matching exercise, in this case part of the SUNDOWN marker section from standard set several km away. b) Distribution of makers from sites and drillholes (dots) and traces on topographic surface. Each colour indicates the trace of a different marker. Red starts at the LMC and progress to green and blue indicating the highest marker in the middle Aldridge stratigraphy.

Results / Data Analysis

Geospatial Database Management

Much effort was applied to organize all spatial data used for this project including the sub-surface constraints from drillhole and seismic data used for modelling the Sullivan time horizon. All the relevant geoscience data, including those from legacy archives, were stored in a 3D GIS environment in which the various source datasets were inspected, standardized, corrected and reconciled. Development of this 3D geospatial data store has been critical to the success of this project and represented over 80% of the total effort. The 3D data integration activity included compilation of a drillhole database from the legacy archives of exploration programs consisting of 675 drillholes with over 1000 lithostratigraphic markers (Schetselaar et al., 2015), subsurface data from the Sullivan Mine (over 4000 drillhole logs) and surface mapped contacts as well as more than 11,000 surface structural measurements, including bedding and foliation. In addition, all 2D seismic profiles acquired from previous projects (Cook and Van der Velden, 1995), as well as 2D potential field forward models (Thomas et al., 2013) were imported into the 3D GIS database.

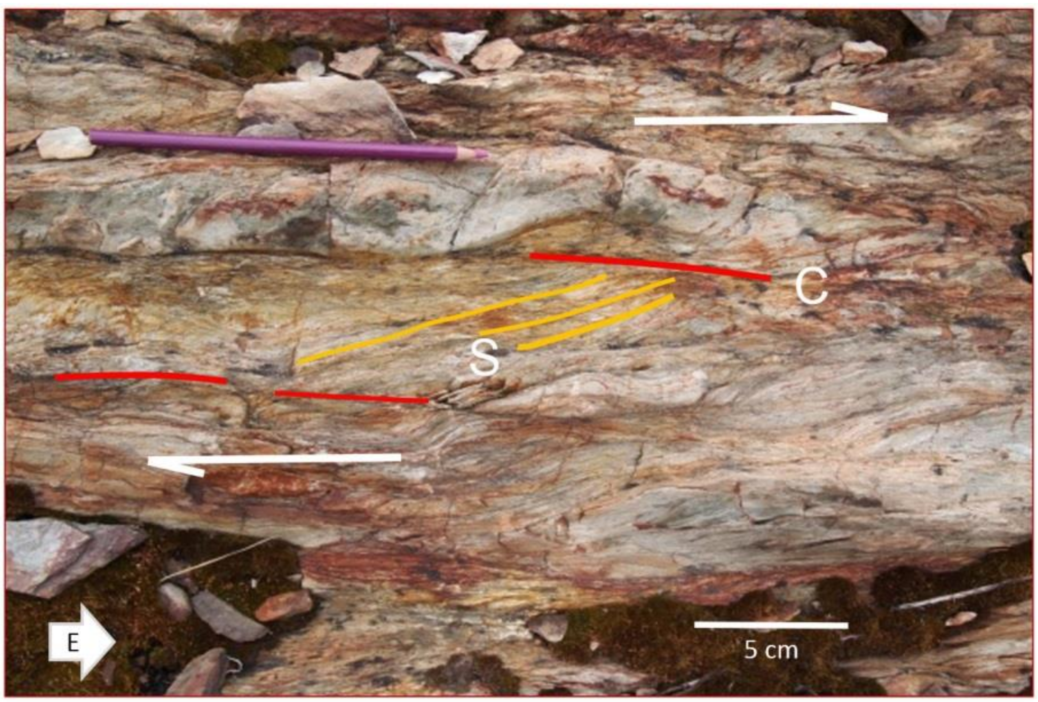


Figure 7. C-S fabric developed in Lower Aldridge turbidites, hanging wall of Moyie Thrust, indicating apparent dextral sense of movement. View towards north.

3D Modelling of Lithostratigraphic Surfaces and Faults

An innovative calculation engine was developed during the course of the Purcell 3D project, based on an implicit modelling approach. The approach is widely used in 3D geological modelling (i.e. Geomodeller, GoCad/SKUA, Leapfrog), but we extend and enhance the approach with an algorithm entitled GRBF (General Radial Basis Function, see Hillier et al. 2014, 2015) (Figure 8). This new algorithm employs markers of lithostratigraphic contacts (from drillholes and outcrop data) as well as structural orientation data (bedding, fold axis) to compensate for the sparse and clustered distribution of drillholes on a regional scale. This allowed us to model faults and horizons without use of oil and gas seismic interpretation workflows dependent on 3D seismic surveys, which do not exist for this area.

The GRBF method is useful in upscaling and integrating mine and regional data by making it easier to develop consistent models that use both dense and sparse data. For example, regional distributed outcrop-scale contacts and dense drillhole contacts can be combined with strike and dip data to model the contact surface.

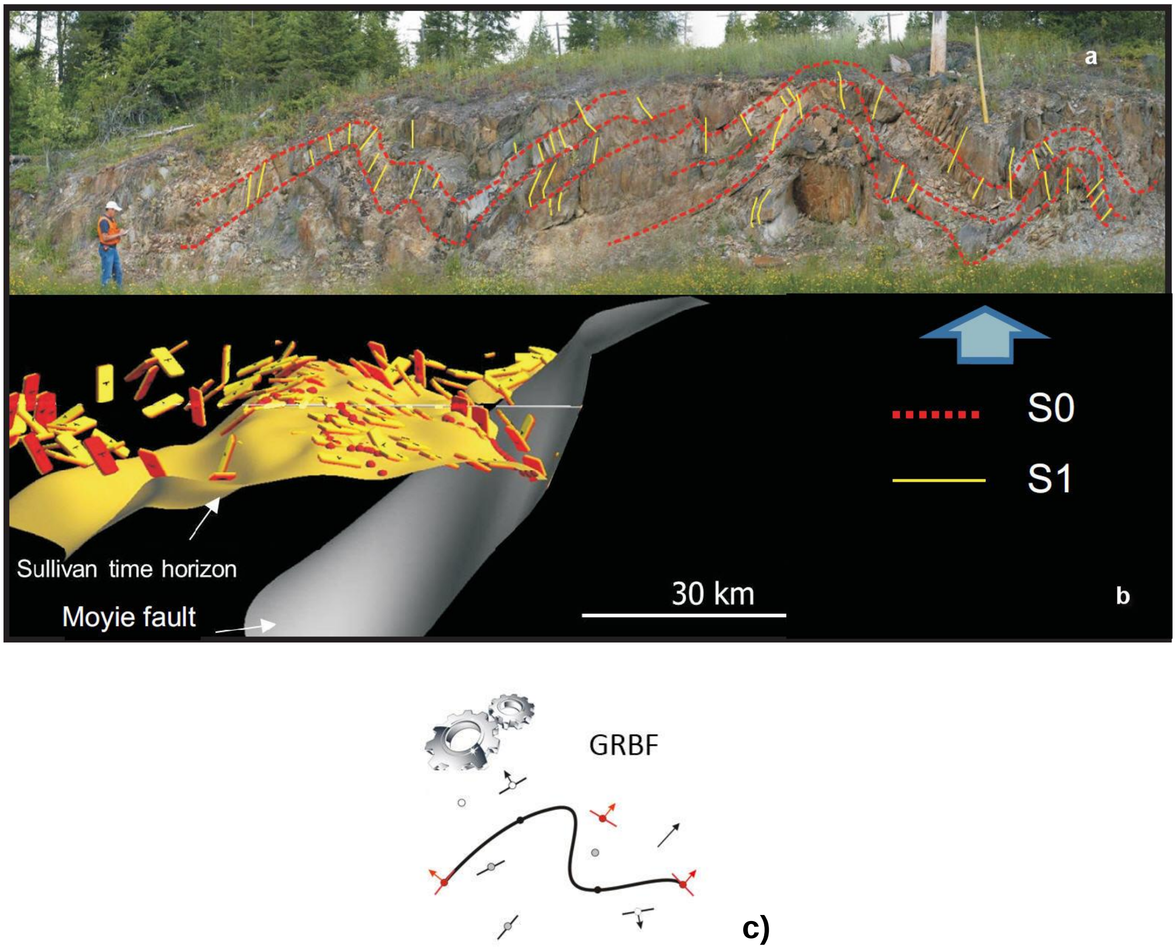
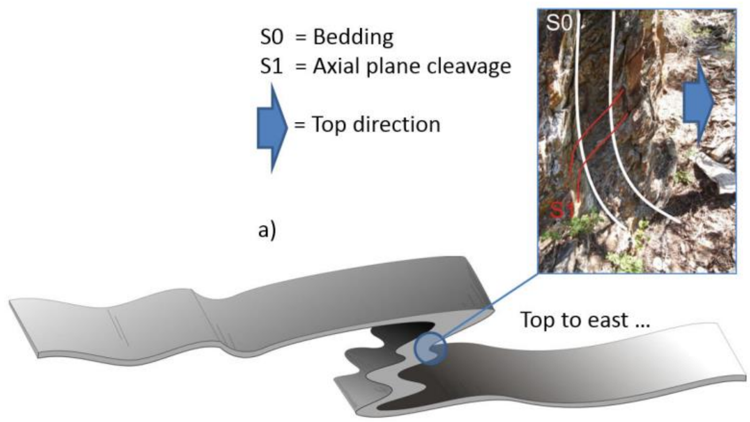


Figure 8. a) Geologic measurements of S0 (bedding) and S1 (axial plane cleavage) at outcrop scale can constrain larger features, such as the LMC regional surface viewed in b). c) LMC is interpolated with a new implicit algorithm called GRBF (General Radial Basis Function), which enables the input of bedding orientation and contact locations.

Discussion/Models

Structural Analysis and Modelling

Bedding-cleavage relationships, fold vergence and the plunge geometry of fold axis of outcrop-scale folds in Aldridge Formation and younger rocks generally fit with the regional scale picture of an east to south-east vergent shallowly north-plunging upright fold and thrust system produced during Laramide convergence (Figure 9a, b).In order to better model the Purcell Anticlinorium, the region was divided into structural domains (Figure 10a), which are areas bounded by significant faults. The domains are also divided at a finer scale into local sub-domains (Figure 10b), which display more common structural styles, and are at least partially bounded by faults. Individual domains can display strong internal contrasts in structural style, which become more accentuated within sub-domains. For example, the Goat sub-domain where rocks of the Creston and Kitchener formations are exposed through a series of steep thrust faults bounding steeply dipping units (Figure 10b) contrasts with the apparently flatter less faulted St. Mary’s domain (Figure 10a).



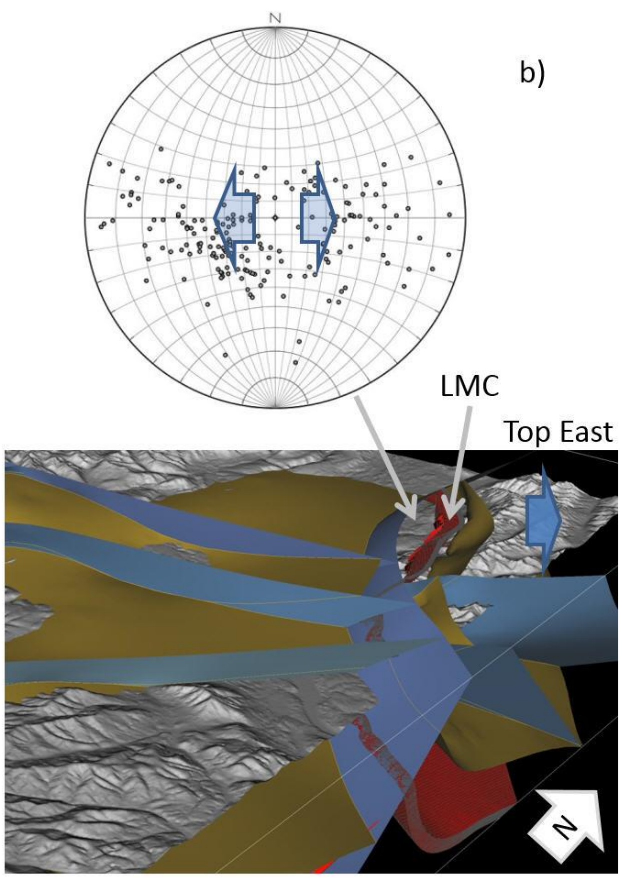


Figure 9. Fold geometries throughout the Purcell Anticlinorium are generally characterized by upright, shallow (5º-25º) north plunging, east verging and occasional short eastward overturning of fold limbs. These folds patterns show up at outcrop-, mine- and regional-scales. a) Measurement of bedding and cleavage orientations and intersection angles along with top indicators support development of the 3D model. b) In the Rocky Mountain domain, outcrop-scale overturned structures are reflective of the regional steep to overturned character of the region; for example this is well illustrated by the LMC (red plane). The blue surfaces are regional faults, and the olive green surface is the top of the Middle Aldridge formation. The stereonet shows poles to bedding in the Rocky Mountain domain. The blue arrows show the directions of rotation of these poles, thus indicating fold axis of rotation.

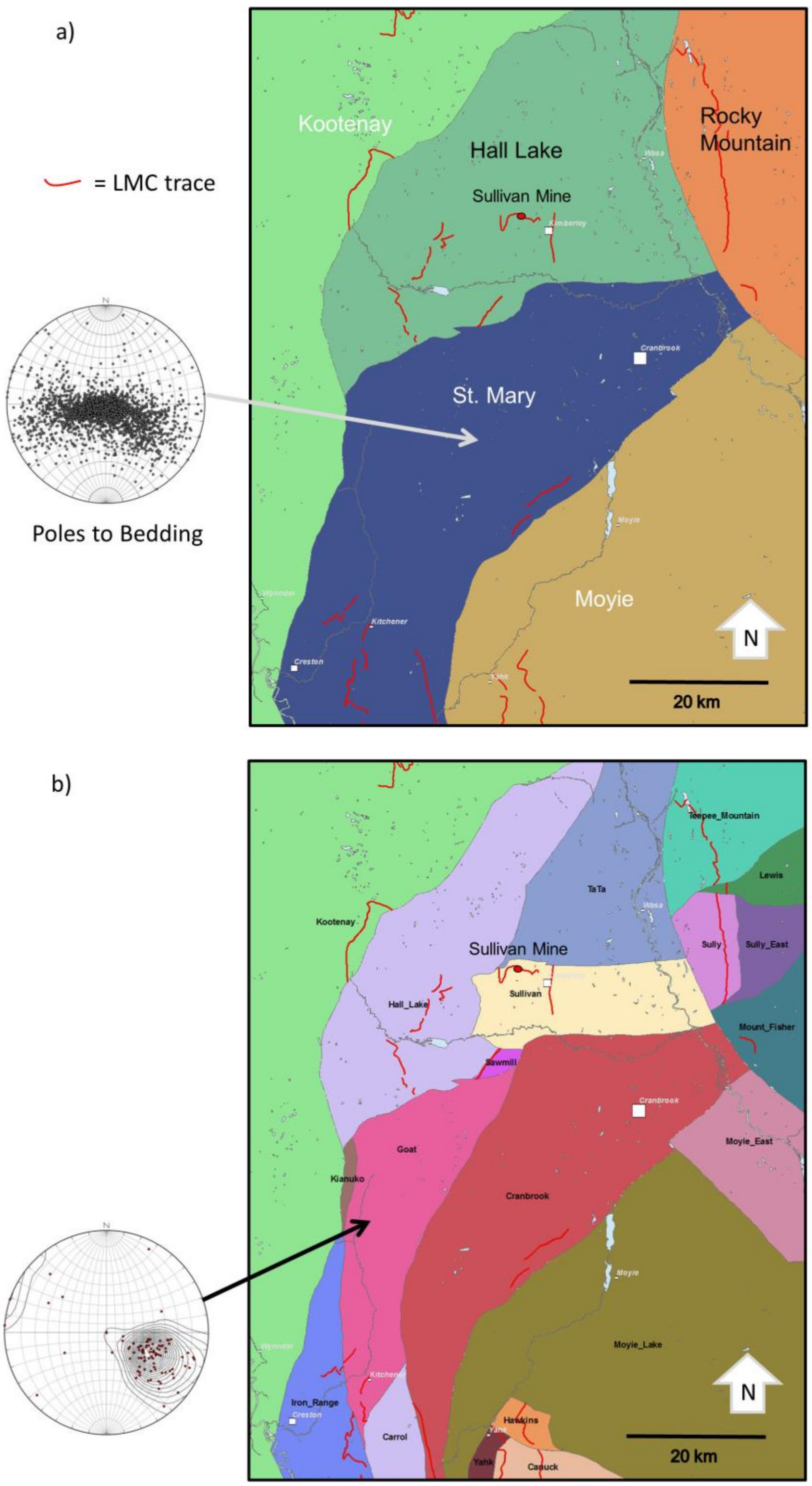


Figure 10. Reconstruction of the regional structural architecture involves characterization of structural domains, which corresponds to fault blocks. Domains are separated into a) coarse regional domains, and b) finer structural sub-domains. Significant contrasts can exist between domains at all scales. Regional domains can mask internal steep structures; for example a) St. Mary's domain (poles to bedding shown on the stereonet) masks the predominately steep features of the Goat sub-domain show in b).

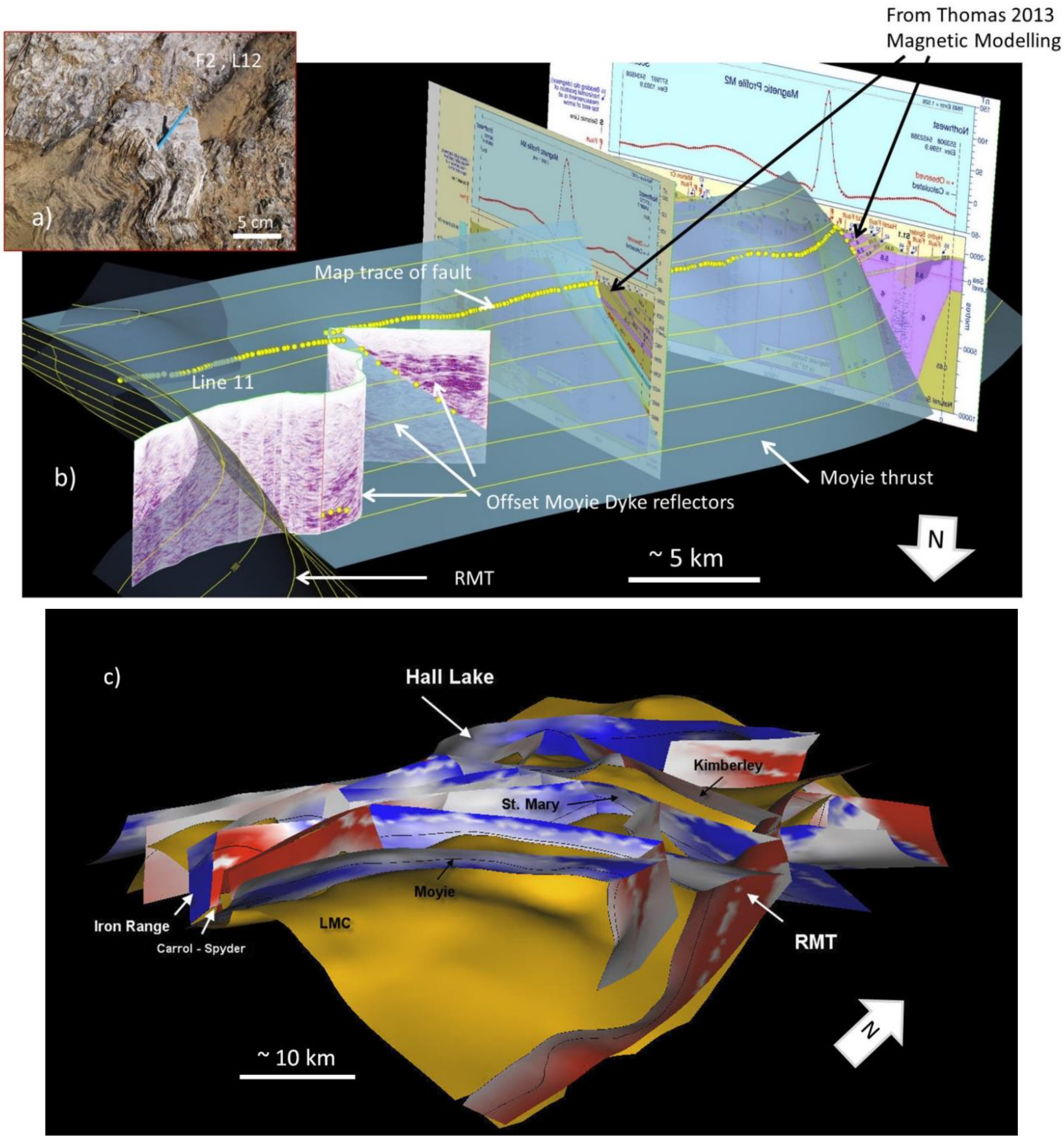
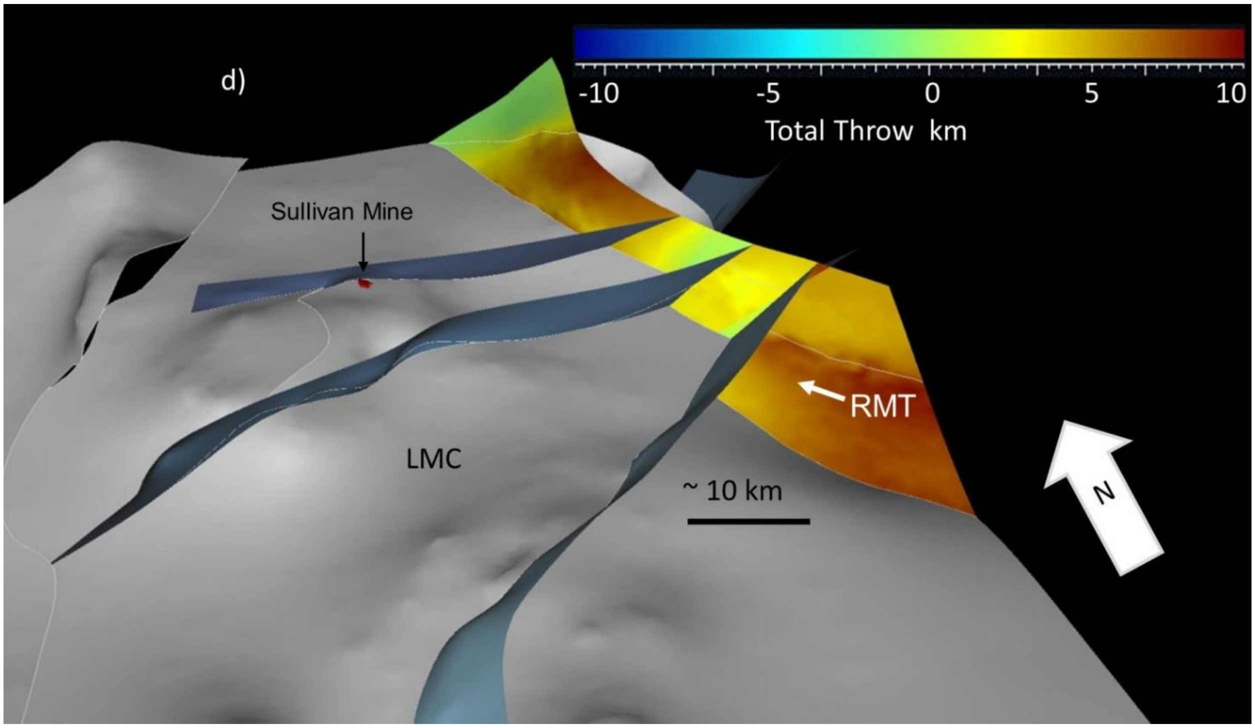


Figure 11. Data integration and 3D interpretation of the regional fault network. Major fault traces from 2D maps were corroborated with field observations of high strain zones represented by C-S fabrics, steep F2-L12 mega-crenulation L12 intersection lineation (photo in a), as well as contrasting stratigraphic levels. b) Integration of seismic data from 2D (3 sec depth corrected) profiles (Cook and Van der Velden, 1995), dip estimations from cross sections and magnetic modelling (Thomas et al., 2013) illustrated for the Rocky Mountain Trench (RMT). c) The interpreted 3D fault traces and dip estimates are input into the GRBF calculation which outputs a 3D fault surface. Once the stratigraphic and fault surfaces are developed the local throw of faults can be calculated to produce on-fault displacement values for the major thrust faults (blue) and normal faults (red). This displacement field could in turn be used to constrain future fault restoration models.

d)



e)

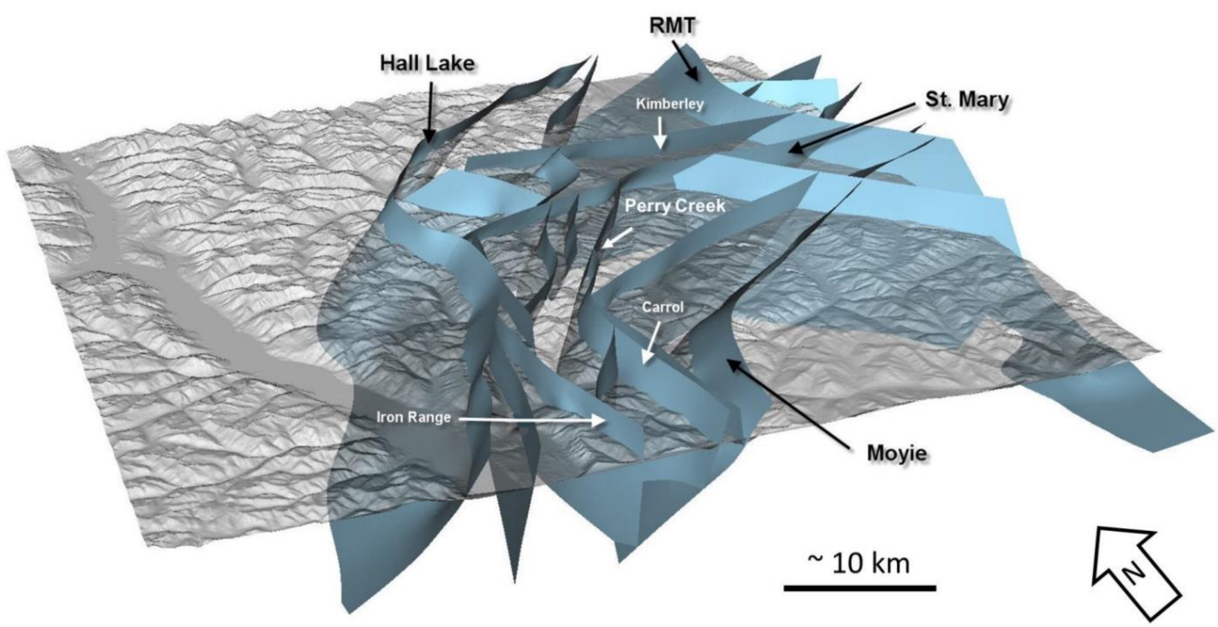


Figure 11 (continued). d) Differential displacement on the Rocky Mountain Trench (RMT) showing normal offset of 2 to 10 km. e) Final fault network model.

Units overlying the Aldridge Formation are exposed in the Goat domain, which sits in the footwall of the St. Mary Fault. Throw on the St. Mary Fault creates this contrast in stratigraphic level. Additionally, reverse and normal throws of steep local faults in the Goat domain show a more complex earlier movement history than in the St. Mary domain. The central St. Mary domain poses a modelling challenge north of the Perry Creek Fault (Figure 11d) where the Middle Aldridge markers are not exposed and drilling on the northern edge of the domain has not penetrated deep enough to intersect the Middle Aldridge strata. In contrast, the Moyie Lake domain south of Moyie Lake has broad open folds with relatively shallowly dipping beds that are laterally continuous for kilometres. Perhaps one explanation is the structural strengthening from the greater than 50% volume of Moyie sills within the Lower Aldridge Formation underlying much of the Moyie Lake domain. The structural characteristics of a given domain between these two end-member styles determines how these areas can be modelled in 3D, and in turn, the degree of predictability for mineral exploration strategies.

Other areas in the 3D model also show local steepening of the LMC; for example between the Carrol and Spyder normal faults in the south of the study area (Figure 11c), as well as overturned LMC in the Hughes Range east of the RMT. It is interesting that the model indicates some local overturned horizons only on the east footwall side of these normal structures. One possible explanation is that these steep zones may be localized by early, more regional, Laramide upright and eastward verging fold hinges which could provide axial zones of weakness for later extensional breaks.

The 3D modelling indicates along-strike differential displacement along many of the major faults (Figure 11). This can be observed along the Hall Lake Fault, St. Mary Fault, and RMT. There is a high degree of uncertainty in displacement estimates of these faults, which perhaps are over or under estimated where data is most sparse. However, the uncertainty is worth noting as this could help either improve the model (assuming specific fault segments must show less partitioned displacement fields) or the patterns may indicate the complex partitioning history of movement along these networks. For the RMT, late differential normal movement may explain any lateral differential displacement along perpendicular faults truncated by the RMT such as the Moyie and St. Mary thrust faults, which also abut along the RMT. Significant internal deformation of Laramide compressional fabrics is expected in areas of extreme block faulting with rotations up to 56° indicated by reconnaissance paleomagnetic study of late Cretaceous plutons east of the RMT (Ransom et al., 2015). Importantly, partitioned extensional movement along the RMT could account for throw discrepancies along adjacent St. Mary and Moyie thrust-related transverse faults. Such complicated fault histories are likely to occur on several other faults as well. Previous studies have suggested several stages of movement history along the Kimberley Fault, acting on an early graben system transfer feature, overprinted by local Laramide folding and reverse dextral motion and later dominant sinistral transcurrent (Eocene ?) motion (Turner et al., 2000). Identification of the Sullivan Mine stratigraphy north of the Kimberley Fault makes this early graben-related link for the Kimberley Fault impossible. Eocene extension in piano key like partitions along the RMT, superimposed on a fold and thrust system, which in turn may have earlier syndepositional history, would be difficult to restore since original throws on the earliest fault systems are not easily recovered.

The regional fault model presents one interpretation of the present day fault topology, largely interpreted from surface geological map patterns. More work needs to be done to determine the importance and relative timing of the faults if proper kinematic restoration studies are to be undertaken.

Metal Zonation and Mine Stratigraphic Modelling

Detailed mine-scale data integration and modelling from historical drillhole data was under-taken for the Sullivan Mine (Montsion, 2014; Montsion et al., 2015). This exercise resulted in a 3D digital stratigraphic, structural and metal zonation (Pb, Zn, Ag, Fe) model (Figures 3, 11 and 12). Over 4,000 drillholes with stratigraphic picks (i.e. determination or estimation of the depth of a specific horizon in the subsurface) and metal abundances within the Sullivan Mine were used from historical litho-stratigraphy-assay logs. Coordinate conversion from Sullivan Mine grid to UTM NAD 83 Zone 11 and geometric recalculation of the drillhole paths was done to position all the extracted information more accurately. The data were developed into a geodatabase in ArcGIS and then exported to GoCad / SKUA for modelling. For details on the conversion, integration methodology and the linear geo-referencing used in ArcGIS, see Montsion et al. (2015).

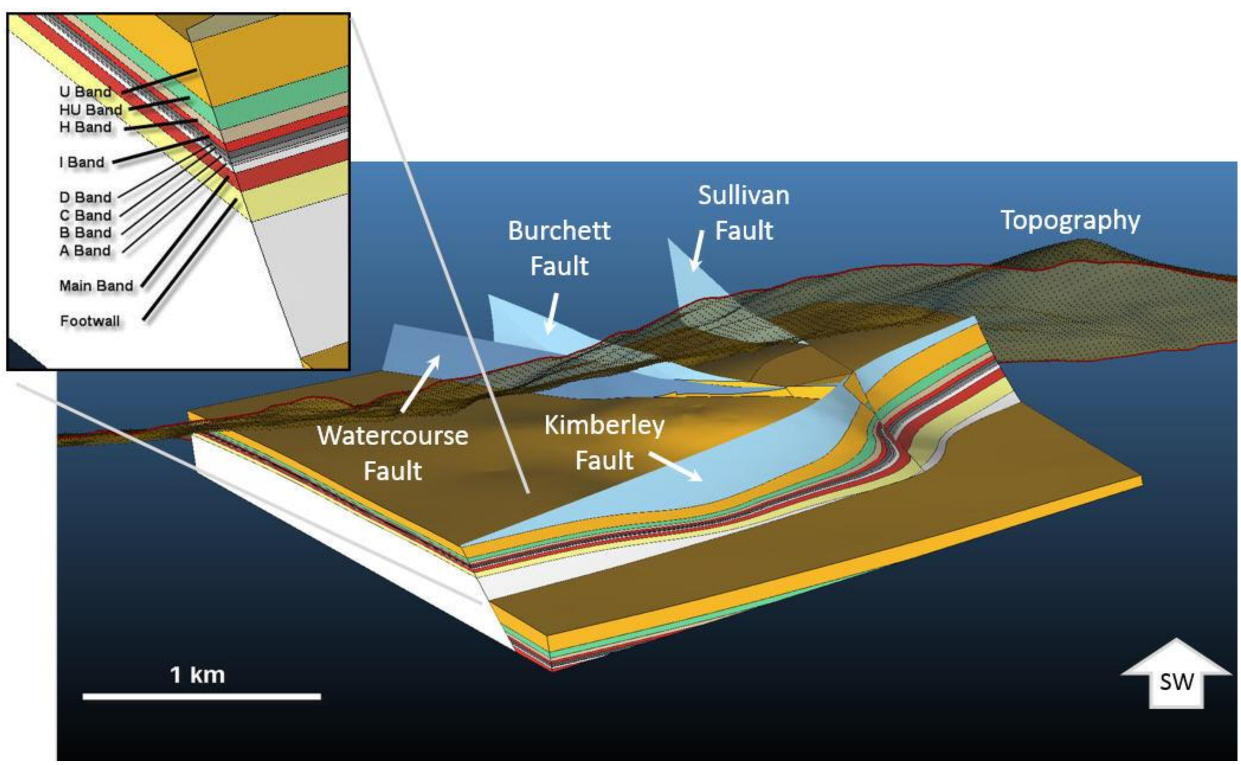


Figure 12. Sullivan Mine volumetric model representing the mine Band stratigraphy and major faults. Inset showing detailed Ore Band stratigraphy. The mine structural stratigraphic model is a curvilinear gridded volume referred to as a GEOGRID in GoCad/SKUA software, which acts as a container for metal and lithostratigraphic property modelling. View from the northeast to the southwest.

From the Sullivan Mine modelling exercise, the 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 3). The variogram trends show local as well as more regional trends which are strongest for Pb and to a lesser extent for Zn and Ag. There is a short ~ 75 m trend and a much longer regional Pb trend up to ~ 650 m at 160º (Figure 13b). This trend matches well with the orientation defining the boundary of the bedded ore on the east side of the Sullivan deposit. The variogram analysis also matches reasonably well with several proposed synsedimentary graben systems from previous studies (Hagen, 1983; Turner et al., 2000) such as the Sullivan-Stemwinder-North Star trend, Sullivan west graben, the Clair trend, and the Star and Lew trends of the Moyie Lake domain. The analysis supports the development of horizon controlled estimations using existing Pb and Zn assay data to other prospective Middle Aldridge sediments at the 0.5 to 1 km scale, and vertical ranges of less than 100 m. Tourmaline occurrences at the Sullivan Mine essentially delineate the extent of the vent facies, so the presence of tourmaline can be considered a proximal indicator within 100-200 m of the active ore system.

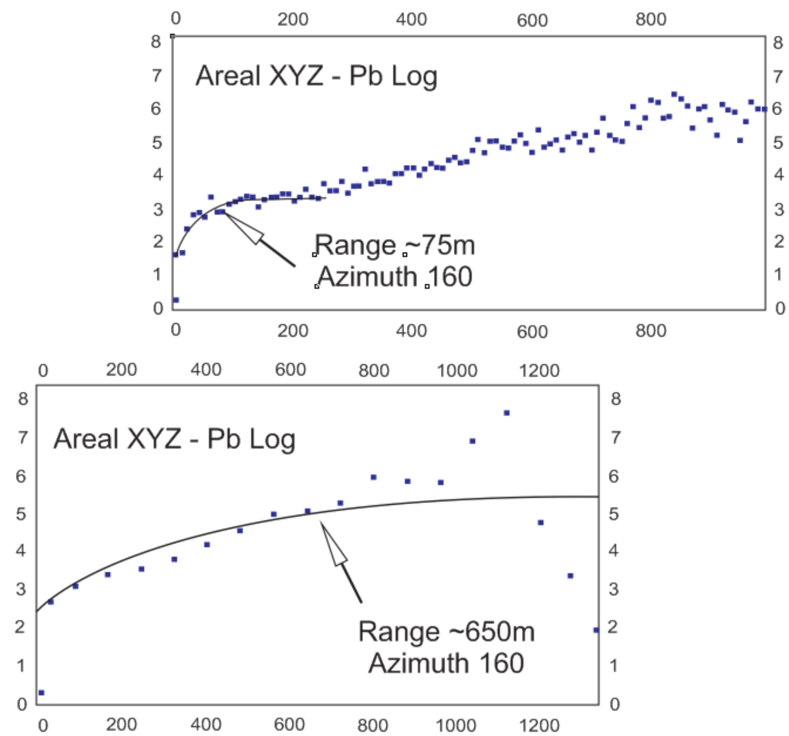


Figure 13. a) Semi-variogram has horizontal axis as distance in metres, vertical axis is semi-variance. Direction for both diagrams is 160º. Variogram analysis indicates strong bedding controlled metal anisotropy for Pb, Zn and Ag within the Bedded Ores; short lag and long lag semi-variograms of Pb indicate two ranges, a 75 metres and a farther 650 metres range both in the 160º direction.

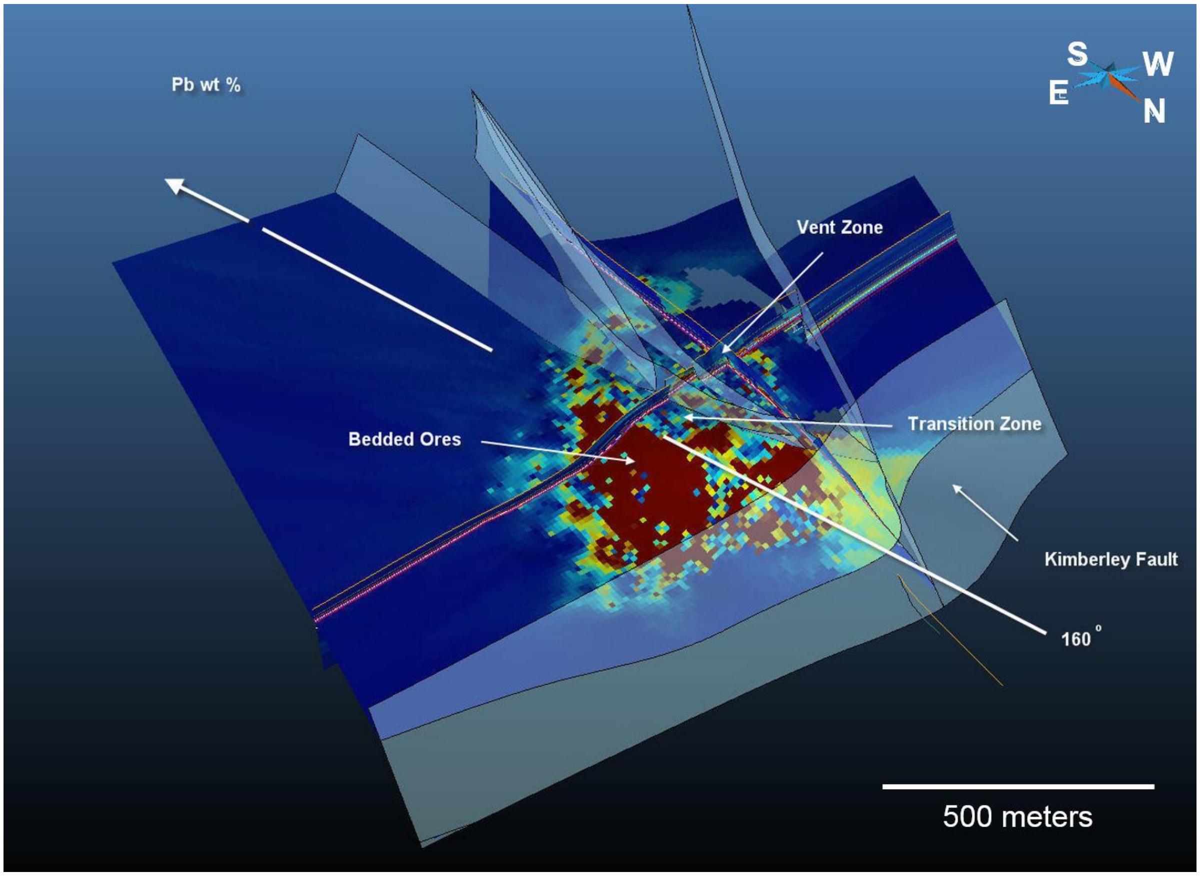


Figure 13b) Kriged Pb assay values at the top of the Main Band of the Sullivan deposit showing plan view and highlighting the 160º trend.

Implications for Exploration

There are several opportunities for enhancing exploration for SEDEX deposits in the East Kootenay region through the development of the Purcell 3D models. First, there is now a 3D framework to more accurately set up specific targeting activities. All surface and sub-surface data and modelled objects are 3D, and in a common UTM coordinate system. All of this information is stored in one repository, which saves mineral exploration companies time and money. Practically and because of this, there is now a block by block mapping of depth and dip estimation for the LMC throughout the region. The model provides a depth estimate and structure (dip estimate) of the SEDEX-hosting Sullivan time horizon, as well as a reference datum for drill targeting in the region. Of interest are areas containing steeper, and occasionally, overturned LMC, such as the Hughes Range, east of the RMT, and the Spyder-Carrol fault block. There are also many areas, which have relatively shallow LMC, that are in the north-south to 160-180º trend line with known deposits (i.e. St. Eugene and Star). It would be advantageous to develop more detailed 3D models in prospective areas such as Findlay Creek, Vulcan, Vines, and Kootenay King (Figure 4).

Second, the value of new data can be immediately enhanced by integration with the existing 3D database. Many exploration companies face the challenge to upscale information available in densely drilled mine sites to regional 3D models in sparsely drilled environments. Our case study demonstrates how integration of geological map, drillhole and geophysical data is leveraged in a 3D environment to support interpretation of the entire ore system, thereby increasing the potential for deep discovery.

Third, data management best practices supporting 3D geological modelling can only benefit the mineral exploration industry. The development of the Purcell Anticlinorium and Sullivan Mine models demonstrates how important it is for exploration and ore system studies to use modern data management practices. The efficacy gains when everyone is looking at the same data sets in a realistic 3D interpretive environment are multifold. Initiating this cultural shift toward rigorous spatial data management and 3D modelling allows for full use of 3D GIS as a decision support tool, quantitative targeting (Figure 14), training, and supporting regional scientific analysis.

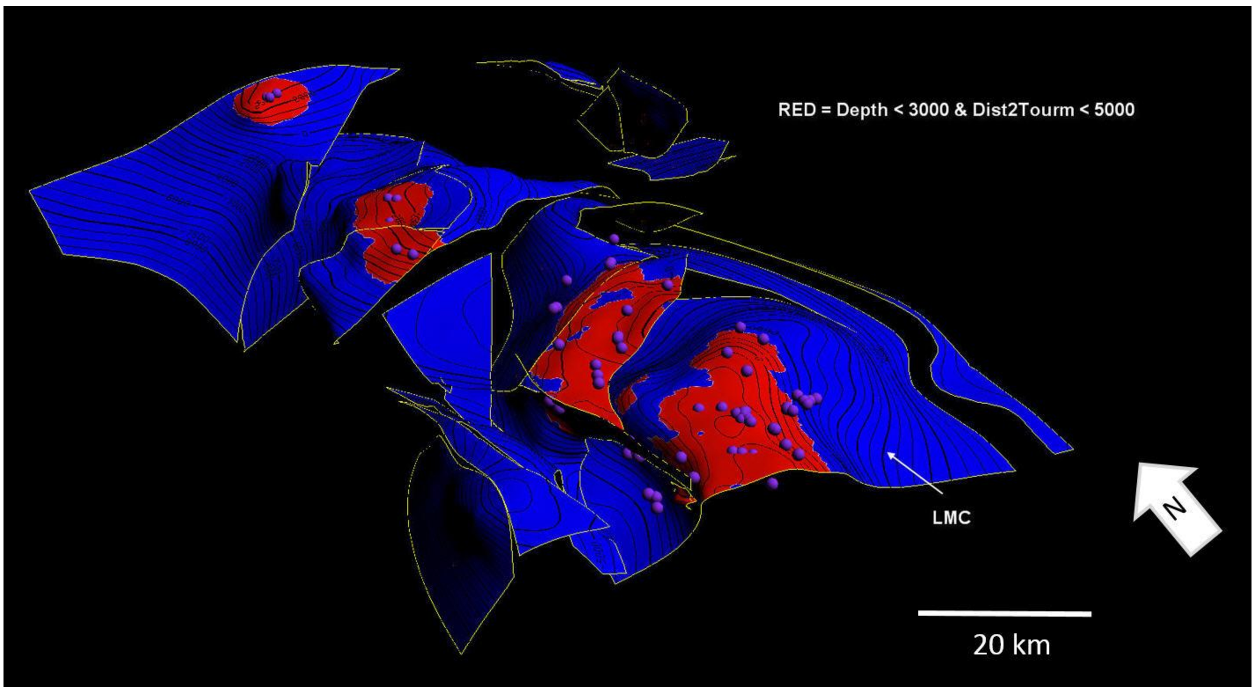


Figure 14. Example of simple exploration query using the LMC surface (blue), digital elevation model and occurrences of tourmaline (purple spheres). Favorable zones shown in red are defined by depth from topographic surface (not shown) to LMC < 3 km and distance to an occurrence of tourmaline less than 5 km.

Future Work

New drilling or field observations will be more accurately plotted within the 3D model, potentially giving more meaningful representation to the data while explorationists try to reconcile and interpret these in a consistent spatial framework. Significantly for the 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.

Studies of the association between early tectonic and/or synsedimentary structures through regional inter-marker thickness and lateral lithofacies variation estimates, can now be better addressed. Ultimately doing a full structural kinematic restoration would improve our understanding of the paleo-geographic setting of the Aldridge Formation and the discovery of SEDEX deposits. Undertaking a palinspastic restoration was beyond the scope of the current study but the development of the regional 3D Purcell model makes this a possibility for future work.

Acknowledgements

We gratefully acknowledge and appreciate the collaboration of local expertise and data provision by individuals and corporate entities which made this project a success, including: Dave Grieve and Fiona Katay (BCGS, Ministry of Energy and Mines, British Columbia), Jason Jacobs (East Kootenay Chamber of Mines), Teck Resources Limited, Tim Termuende and Chuck Downie (Eagle Plains Resources Inc.), TerraLogic, Dave Pighin, Craig Kennedy and Ted Sanders, Quinn Smith (MMG). We enjoyed the wealth of knowledge and field trip guidance provided by Paul Ransom and Trygve Höy, as well as from Margo McMechan (GSC). We thank Fred Cook for kindly providing the Seismic data along with Gilles Bellefleur (GSC) who helped with the data conversion. The GRBF software development applied in this project was undertaken in collaboration with Mira Geosciences Ltd. through a collaborative industry-government research agreement, their support in continuing to advance 3D modelling methods for mineral exploration is gratefully acknowledged. Academic software was generously provided through the GoCad Research Consortia by Paradigm® and Mira Geoscience Ltd.

References

Brown, D.A., MacLeod, R.F., Wagner, C.L., and Chow, W., (compilers), 2011, Geology Skoocumchuk, Cranbrook, Moyie Lake, Boswell, Dewar Creek, Yahk River, Kaslo, Crawford Bay, St. Mary Lake, Grassy Mountain, British Columbia: Geological Survey of Canada, Open Files 6301-6310, 2011; 10 sheets, doi:10.4095/288543-288546, doi: 10.4095/288563-288568

Chandler, F.W., 2000, The Belt-Purcell Basin as a low-latitude passive rift: implications for the geological environment of Sullivan type deposits, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 1, p. 82-112.

Cook, F.A., and Van der Velden, A.J., 1995, Three-dimensional crustal structure of the Purcell Anticlinorium in the Cordillera of southwestern Canada: Geological Society of America Bulletin, v. 107 (6), p. 642-664.

de Kemp, E.A., Monecke, T., Sheshpari, M., Girard, E., Lauzière, K., Grunsky, E., Schetselaar, E.M., Goutier, J., Perron, G., and Bellefleur, G., 2010, 3D GIS as a support for mineral discovery: Geochemistry - Exploration, Environment, Analysis, v. 11, p. 117-128.

Dubois, A.J., and Benn, K., 2003, Structural analysis and three-dimensional modelling of the southwestern Sudbury Basin: implications and recommendations for mineral exploration: Ontario Geological Survey, Open File Report 6121, 38 p.

Feltrin L., McLellan, J.G., and Oliver N.H.S., 2009, Modelling the giant, Zn–Pb–Ag Century deposit, Queensland, Australia: Computers & Geosciences, v. 35, p. 108–133.

Hagen, A. S., 1983, Sullivan-North Star graben system: unpublished report, Cominco Ltd., 11 p.

Hillier, M.J., d e Kemp, E.A., and Schetselaar, E.M, 2015, Implicit 3D modelling of geological surfaces with the generalized radial basis functions (GRBF) algorithm, *in* Paradis, S., ed., Targeted Geoscience Initiative 4: Sediment-hosted Zn-Pb deposits: processes and implications for exploration: Geological Survey of Canada, Open File 7838, p. 253-266.

Hillier, M.J., Schetselaar, E.M. de Kemp E.A., and Perron, G., 2014, 3D modelling of geological surfaces using generalized interpolation with radial basis functions: Mathematical Geology, v. 46, p. 931-953.

Höy, T., Anderson, D., Turner, R.J.W., and Leitch, C.H.B., 2000, Tectonic, magmatic and metallogenic history of the early synrift phase of the Purcell Basin, southeastern British Columbia, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 1, p. 32-60.

Huebschman, R.P., 1973, Correlation of fine carbonaceous bands across a Precambrian stagnant basin: Journal of Sedimentary Petrology, v. 43, p. 688-699.

Joseph, J.M.R., Brown, D., MacLeod, R., Wagner, C., Chow, W., and Thomas, M., 2011a, Purcell Basin interactive maps, British Columbia: Geological Survey of Canada, Open File 6478; 1 CD-ROM, doi:10.4095/289069

Joseph, J.M.R., Brown, D., and Walker, R., 2011b, Diamond drill-hole database of the Purcell Basin: Geological Survey of Canada, Open File 6549; 1CD-ROM, doi: 10.4095/288015

Lydon, J.W., 2007, Geology and metallogeny of the Belt-Purcell Basin, *in* Goodfellow, W.D., ed., Mineral Deposits of Canada: A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5, p. 1-27.

Lydon, J.W., Paakki, J.J., Anderson, H.E., and Reardon, N.C., 2000, An overview of the geology and geochemistry of the Sullivan Deposit, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 1, p. 505-522.

McFarlane, C.R.M., and Pattison, D.R.M., 2000, Geology of the Matthew Creek metamorphic zone, southeast British Columbia: a window into Middle Proterozoic metamorphism in the Purcell Basin: Canadian Journal of Earth Sciences, v. 37, p. 1073-1092.

McMechan, M.E, and Price, R.A., 1982, Transverse folding and superposed deformation, Mount Fisher area, southern Canadian Rocky Mountain thrust and fold belt: Canadian Journal of Earth Sciences, v. 19, p. 1011-1024.

Montsion, R., 2014, Zonation of Pb, Zn, Ag and Fe along the Sullivan Horizon, Kimberley, British Columbia, Unpublished B.Sc. thesis, Carleton University, Ottawa, April 2014, p. 72.

Montsion, R., de Kemp, E.A., Lydon, J., and Joseph, J., 2015, 3D stratigraphic, structural and metal zonation modelling of the Sullivan Mine, Kimberley, British Columbia, *in* Paradis, S., ed., Targeted Geoscience Initiative 4: sediment-hosted Zn-Pb deposits: processes and implications for exploration; Geological Survey of Canada, Open File 7838. p. 236-252.

Pflug, R., and Harbaugh, J.W., 1992, Computer graphics in geology: three-dimensional computer graphics in modeling geologic structures and simulating geologic processes: Springer-Verlag, Berlin; New York, 298 p.

Price, R., and Sears, J., 2000, A preliminary palinspastic map of the Mesoproterozoic Belt-Purcell Supergroup, Canada and USA: Implications for the tectonic setting and structural evolution of the Purcell anticlinorium and the Sullivan deposit, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 1, p. 61-81.

Ransom, P.W., and Lydon, J.W., 2000, Geology, sedimentology and evolution of the Sullivan Sub-basin, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no.1, p. 440-469.

Ransom, P.W., Day, T., and Enkin, R., in press, Block faulting of the northern Hughes Range east of the Rocky Mountain Trench near Kimberley, British Columbia.

Schetselaar, E., de Kemp, E., Ransom, P., Buenviaje, R., Nguyen, K., Montsion, R., and Joseph, J., 2015, 3D Drill-hole database of the Purcell Anticlinorium: Geological Survey of Canada, Open File 7817, 14 p.

Schetselaar, E., Pehrsson, S., Devine, C., Currie, M., White, D., and Malinowski, M., 2010, The Flin Flon 3D knowledge cube: Geological Survey of Canada, Open File 6313, 2010; 35 p., doi:10.4095/285614

Sears, J., 2007, Belt-Purcell Basin: Keystone of the Rocky Mountain fold-and-thrust belt, United States and Canada: Geological Society of America Special Papers, 433, p. 147-166.

Thomas, M.D., Schetselaar, E.M., and de Kemp, E.A., 2013, Magnetic contribution to 3D crustal modelling in the Purcell Anticlinorium, southeastern Cordillera (Poster): Geological Survey of Canada, Open File 7321, doi: 10.4095/292187

Turner, R.J.W., Leitch, C.H.B., Höy, T., Ransom, P.W., Hagen, A., and Delaney, G.D., 2000, Sullivan graben system: District-scale setting of the Sullivan deposit, *in* Lydon, J.W., Höy, T., Slack, J.F., and Knapp, M.E., ed., The geological environment of the Sullivan deposit, British Columbia: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 1, p. 295-332.