Architecture of Gold Mineralization at Anomaly A of the Clarence Stream Deposits, Southern New Brunswick

By

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ABSTRACT

Anomaly A of the Clarence Stream gold deposits contains mineralized structures that bear geometrical relationships to regional folding events. Structural mapping at the regional scale reflects at least four deformational events, three of which appear to control the folded geometry of Anomaly A (D2, D3, and D4). F2 and F3 folds are in a coaxial relationship and are refolded into a dome and basin geometry by F4 folds. Structural analysis of a mineralization zone exposed at the surface indicates that gold mineralization is present within a quartz vein system that contains veins generated during both D2 and D3. Three-dimensional representation of Anomaly A created using drill-core data and *gOcad* suggests that the quartz vein system was emplaced in fault structures generated during D2 and formed in brecciated dilation zones during D3. Three of the four zones that make up Anomaly A have F2 hinge surfaces that can be linked in a fashion compatible with the style of F3 and F4 folds. The apparent continuity of these three zones indicates the potential for km-scale mineralized structures at Anomaly A.

RÉSUMÉ

L'Anomalie A du gisement aurifère Clarence Stream contient des zones minéralizées qui montrent des relations géométriques avec les épisodes de déformation régionales. Des quatres épisodes de déformation étudiés par l'entremise de carthographie structurale, trois semblent contrôler la géométrie de l'Anomalie A (D2, D3, et D4). Les plis P2 et P3 sont coaxiales et sont repliés en domes et basins par les plis P4. Une analyse structurale effectuée sur une zone minéralizée exposée à la surface indique que la minéralization aurifère est localisée dans un système de veines de quartz qui contient des veines générées durant D2 et D3. Des représentations en trois-dimensions créées avec le programme informatique *gOcad* à partir de donnés de forages suggèrent que le système de veines est localisé dans des zones de failles D2 ainsi que dans des zones de dilatation associées avec D3. Trois des quatres zones qui forment l'Anomalie A possèdent des plans axiaux P2 qui peuvent être liés par l'entremise d'une géométrie qui respecte le style des plis P3 et P4. La continuité apparente de ces trois zones indique qu'une structure minéralisée pourrait s'étendre sur plusieurs kilomètres à l'Anomalie A.

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Many thanks to Dr. Andrew Hynes who was an awesome supervisor and was always available when needed. This project would not have been feasible without financial support from Freewest Resources Canada Inc. Special thanks to Mackenzie Watson, Don Hoy, and George Murphy at Freewest. Thanks to Sebastien Castonguay whose partnership during regional mapping was greatly appreciated, and Eric de Kemp who provided valuable guidance in generating the 3D representations. Thanks to my family and friends for their encouraging support, especially Christine Iorio who played the role of a president's wife.

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PREFACE

The geometries of gold-mineralized bodies introduced during deformational events are commonly complex. It is a challenge for exploration companies to understand the geometry of such bodies and maximize drilling programs. The recent advent of three-dimensional visualization software now enables the elaboration of models that could not otherwise be constructed. The purpose of this project is to combine structural analysis at the regional- and deposit-scale and 3D analysis using drill-core data and 3D software to define the architecture of gold mineralization within a complexly deformed deposit. The first chapter of this thesis consists of the manuscript of a scientific article submitted to the journal "Exploration and Mining Geology". The second chapter presents a detailed description of the methodology involved in generating 3D representations of the deposit.

Chapter I

"Architecture of Gold Mineralization at Anomaly A of the Clarence Stream Deposits, Southern New Brunswick"

submitted to *Exploration and Mining Geology*

June 2005

Architecture of Gold Mineralization at Anomaly A of the Clarence Stream deposits, Southern New Brunswick.

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CONTRIBUTION OF AUTHORS

As I first author, I contributed to the article by performing geological mapping and structural analysis of the AD trench and of the region around Anomaly A. I interpreted and generated all 3D representations and wrote the entire manuscript.

Glenn G. Lutes worked as a consultant for Freewest Resources Canada Inc. (who own 100% of Anomaly A and Clarence Stream) and logged all drill cores of the property, extracting lithological and structural information. Mr. Lutes also reviewed the article.

Dr. Andrew J. Hynes supervised the project from beginning to end, offering guidance during field mapping and structural analysis as well as providing critical directions in the approach taken to create the 3D representations. Dr. Hynes also revised the manuscript several times which led to great improvement of the article.

Introduction

Since the year 2000, the Clarence Stream gold deposits of southwestern New Brunswick have been explored through extensive diamond drilling by Freewest Resources Canada Inc. The deposits comprise a combined inferred resource of about 250,000 ounces of gold and are potentially economically exploitable. The principal gold-mineralized zone (Main Zone) comprises shear-hosted quartz veins and stockwork located within a volcanic sequence of the Silurian Waweig Formation close to the Magaguadavic granite (Fig. 1). The Main Zone occurs along a NE-trending corridor at least 1.5 km long containing numerous minor zones of mineralization. The sites and shapes of gold-mineralized bodies along this corridor appear to be controlled by competency contrasts between gabbro dykes and surrounding felsic volcanic rocks (Castonguay et al., 2003), resulting in simple tabular NW-dipping bodies.

Mineralized bodies are also present in the adjacent polydeformed turbiditic units of the Ordovician Kendall Mountain Formation. There, diamond drilling has revealed the presence of four distinct shallow-dipping gold-mineralized zones (AD, MW, 93, and Murphy) separated by a few hundreds of meters (Fig. 2) that make up a ~1.5 km^2 region referred to as Anomaly A. Unlike the Main Zone, Anomaly A is polyfolded and exhibits a complex geometry.

It is of importance to ongoing exploration to determine structural controls on the gold mineralization and to investigate the potential for a large-scale structure or structures linking the four mineralized zones of Anomaly A. The purpose of this study is to examine the structural relationship between the four mineralized zones through structural mapping and 3D representation of the subsurface geology using drill-core data and *gOcad*.

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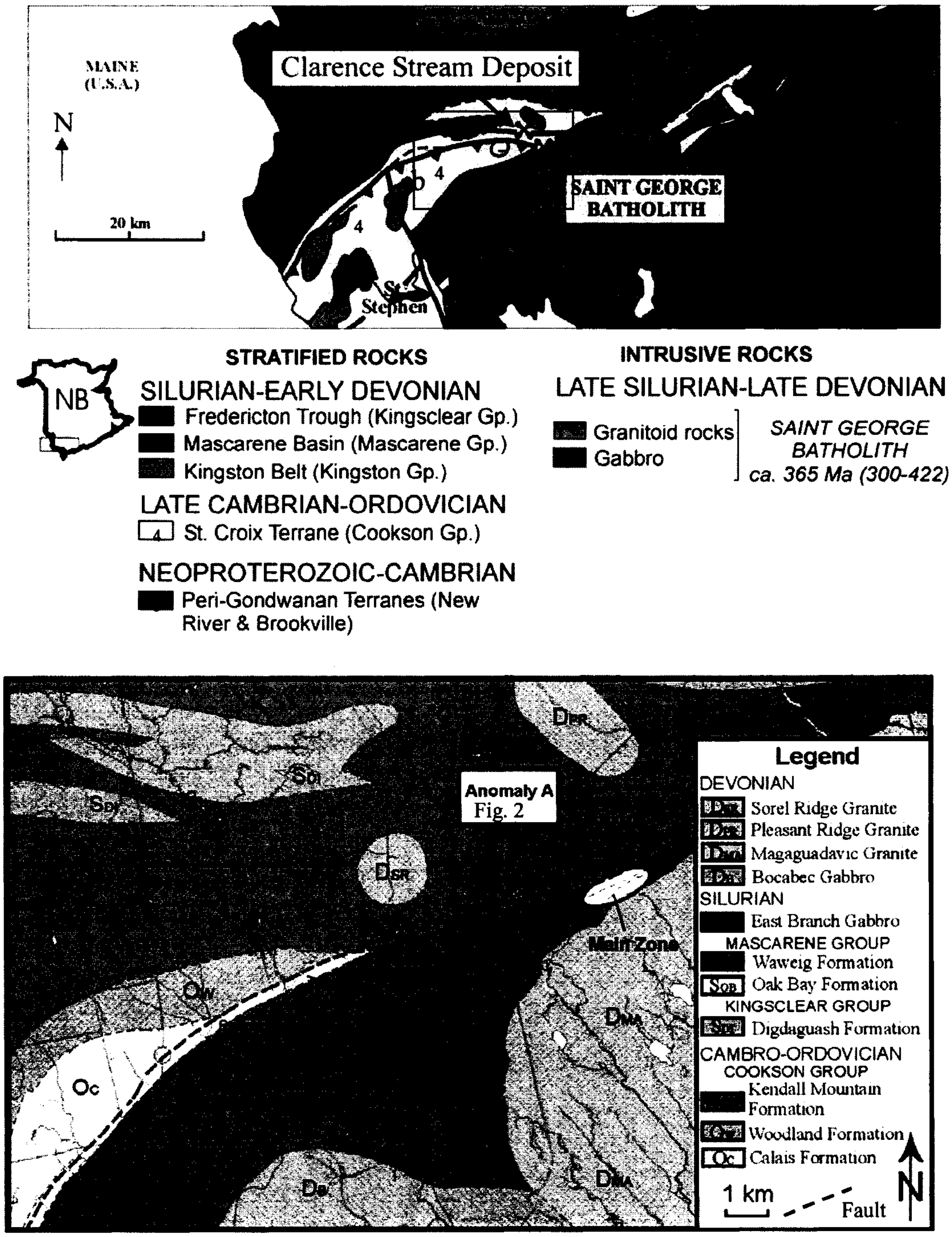

Figure 1. Geology of region around Clarence Stream gold deposit. a) General map of terranes surrounding the St-George batholith showing location of the Clarence Stream deposit. (Modified from Thorne and McLeod 2003). b) Simplified geological map of Rollingdam area showing location of Anomaly A and Main Zone of Clarence Stream deposit (Modified from Fyffe 1997 and Castonguay et al. 2003).

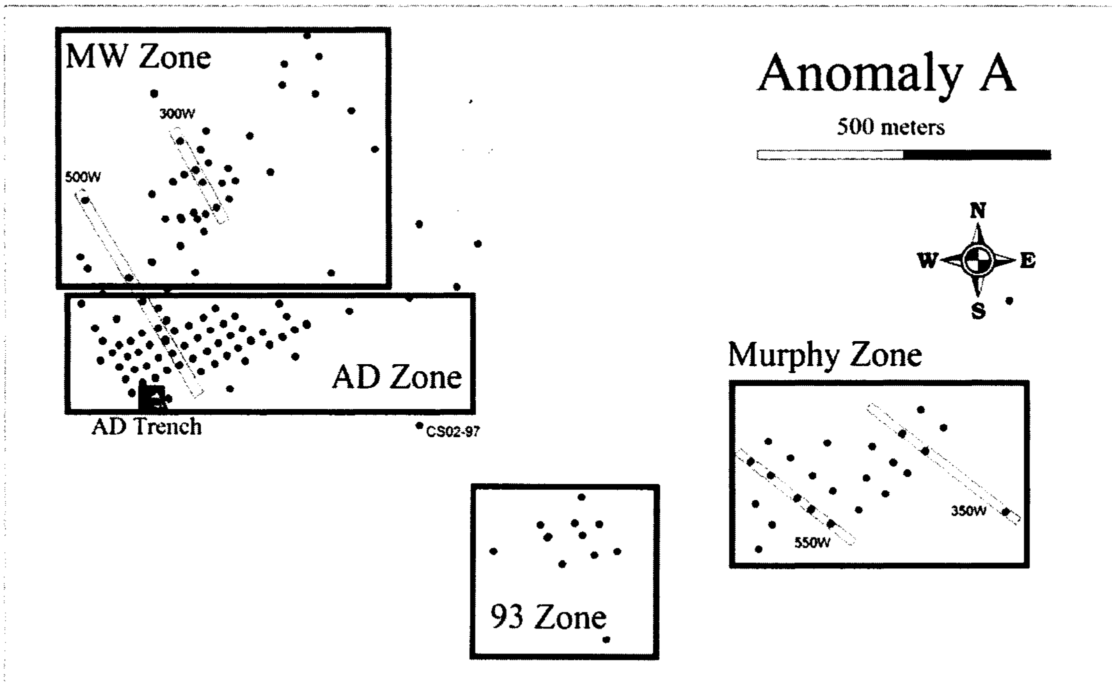

Figure 2. Surface area of the 4 zones of Anomaly A, including locations of drill holes and AD trench.

Regional Setting

The region around the Clarence Stream deposits, referred to as the Rollingdam area, is cut by the regional-scale Sawyer Brook fault that separates the sheared Silurian volcanic units that host the Main Zone from the polydeformed Ordovician clastic units that host the zones of Anomaly A (Fig. 1b). The Silurian volcanic units are penetratively deformed but are not complexly deformed compared with the polyfolded Ordovician units. Both the Ordovician and Silurian units were intruded by Devonian granitic to gabbroic intrusions associated with the nearby St-George batholith. The Clarence Stream deposits are located on the flank of one of these intrusions, the Magaguadavic granite, which is thought based on a geochemical study by Thorne et al. (2002) to have played a role in the generation of gold-bearing fluids. The Clarence Stream deposits are hence interpreted as intrusion-related distal deposits (Thorne et al., 2002, Watters et al., 2003, 2005).

It was recognized early in the drilling of Anomaly A that the mineralized zones are associated with brecciated structures subparallel to axial surfaces of isoclinal folds evident through changes of younging directions in drill cores (Lutes, unpublished report 2001; Castonguay et al., 2003; Watters et al., 2003). It was also recognized that multiple folding events affected the region and hence potentially controlled the geometry of Anomaly A. A proper understanding of these regional folding events is therefore crucial to the formulation of a structural model. A study by Castonguay et al. (2003) during the course of a Targeted Geoscience Initiative project (TGI) of the GSC was conducted to examine the structural framework of the region surrounding the Clarence Stream deposit. The following is a brief overview of the TGI study along with some new insights from the current study.

Evidence of four deformational events was found in the region. The earliest event (D1) is cryptic in that it appears to have produced only a cleavage. The effect of the D1 event on the regional geometry is hence not yet established. The strongest event that affected the region is the D2 event which produced tight-to-isoclinal folds (Fig. 3a) associated with an axial-planar penetrative cleavage. Based on the distribution of structural facings over the region, this folding event overturned rock sequences over regions of several kilometers. The subsequent deformational event (D3) generated moderately-plunging kink folds associated with a NE-striking crenulation cleavage. During the course of this study, it was noted that the D3 deformation generated conjugate sets of kink folds, one upright and one inclined, that produced box folds where they interfered (Fig. 3b). Shear joints associated with box folding were also locally observed (Figure 3b). The conjugate sets of F3 folds were found to be in a coaxial relationship with the F2 isoclinal folds, based on the distribution of F2 and F3 fold axes over the region (Fig. 4) and on fold interference patterns (Fig. 3a). A later event (D4) produced kink folds and local open folds associated with a steep NNW-trending cm-spaced cleavage and refolded the F2/ F3 coaxial geometry into a dome and basin geometry. The effect of the D4 deformation can be seen through systematic changes in the plunging direction of the F2/ F3 coaxial geometry, from NE to SW plunging (Fig. 4).

Geology of Anomaly A

Of the four zones discovered through diamond drilling at Anomaly A, the most significant are the AD and MW zones which contain intersections of mineralized zones attaining gold grades of up to 17.8 g/t over 10 meters and have a combined calculated inferred resource of 115,395 ounces. The Murphy and 93 zones contain relatively weak

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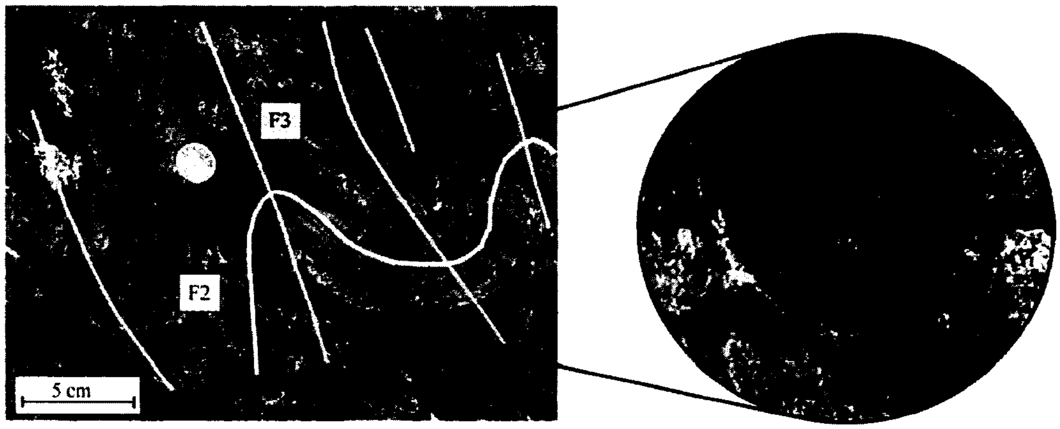

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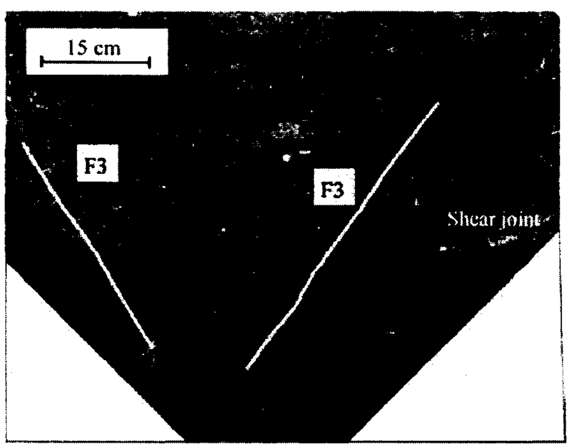

Figure 3. a) F2/ F3 interference pattern. The enlarged region shows the trace of the S1 cleavage folded by F2. b) Conjugate upright and inclined F3 folds yielding box geometry. White and yellow lines: hinge surfaces of F2 and F3 folds respectively. Black lines: traces of bedding in hinge regions. Red line (b): shear joint associated with box fold.

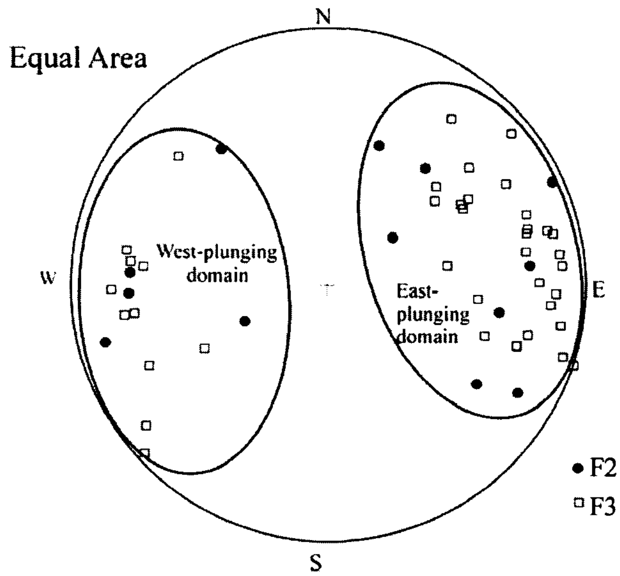

Figure 4. Equal area plot showing the distribution of F2 and F3 fold axes over the region of the Clarence Stream deposit. Filled circles and open squares symbols represent F2 and F3 fold axes respectively. Note how the two generations of folds have similarly oriented fold axes consistent with coaxial interference. F4 folds refold the F2/F3 coaxial geometry into a dome and basin geometry observable through the presence of east-plunging and west-plunging domains of F2/F3 fold axes.

mineralization with intercepts reaching gold grades of up to 5.85 g/t over 5 meters and are not included in current resource estimates. Gold is commonly present in quartz veins containing a macroscopic sulphide assemblage dominated by pyrrhotite, arsenopyrite, pyrite, and stibnite.

The bedrock around Anomaly A is poorly exposed and the surface geology of mineralized structures has been studied only in trenches dug by Freewest Resources Canada Inc. With the exception of a few meter-scale trenches mapped by Watters et al. (2003) at the Murphy Zone, the only significant exposure of a mineralized zone is the ~600 m^2 AD trench which was mapped in detail during this study. The AD trench offers the opportunity to study the structural relationships between gold-bearing structures and structural elements (folds and faults) at the surface. The bulk of this study is however based on subsurface information from 162 drill cores of length between 44 and 135 meters that were drilled to explore Anomaly A. The following sections describe the structural relationships between folding and gold mineralization that could be established based on drill-hole sections and detailed mapping of the AD trench.

Subsurface Geology Based on Drill Sections

Anomaly A is hosted within turbiditic greywacke, siltstone and argillite sequences of the Kendall Mountain Formation. Bed thickness varies from a few centimeters to several meters. Even though sandstone- and argillite-dominated packages can be recognized in drill cores, few sedimentary packages can be traced from hole to hole and used as marker horizons.

For each drill hole, the angle between bedding and core axis was measured (one measurement every ~5 meters) and younging direction was extracted from grading or cross-bedding (Lutes, unpublished reports 2001, 2002, 2003). Based on younging information, tens-of-meter-thick shallowly-dipping upward-facing and downward-facing structural panels can be identified and indicate the presence of isoclinal inclined folds consistent with the style of F2 folds observed at surface in the region. Changes in the attitudes of F2 axial surfaces are observed in drill sections and indicate the presence of F3 and F4 folds.

In all zones of Anomaly A, gold mineralization is localized within a 2 to 10 meter thick quartz vein system contained within a high-strain envelope bounded by brecciated horizons. The mineralized deformation zones are subparallel to axial surfaces of F2 folds which led previous workers (e.g. Watters et al., 2003, 2005) to suggest that they coincided with D2 thrusts. The potential for stacked mineralized horizons is indicated by the presence of smaller distinct zones above and below the main mineralization zone.

Structural Analysis of Mineralized Structures at the AD Trench

The main mineralized zone intersected in the subsurface of the AD Zone is exposed in the AD trench. The trench is located on the western edge of the AD Zone (Fig. 2) and exhibits a quartz vein system contained within deformed argillite and greywacke units. Lithological contacts are sheared and boudinaged, and are linked to a network of silicified brittle faults. Analyses of channel samples cut on the trench indicate that gold mineralization is present in the vein system as well as within silicified regions along lithological and fault contacts. This section presents structural relationships between folding and gold mineralization that were established based on structural analysis of the AD trench.

Folded Geometry of the AD Trench

The S2 fabric is generally found subparallel to bedding and is developed as a penetrative cleavage in argillite and as a pressure-solution cleavage in greywacke. The bedding and S2 fabric are folded by east- and west-plunging F3 folds and north-plunging F4 folds. F2 folds were not observed and their presence could also not be detected based on younging reversals, due to lack of facing criteria. Although crescents are commonly interpreted as resulting from fold interference, crescentic exposures of greywacke exposed in the trench are rather interpreted as being the product of boudinaging during D2 (Fig. 5). The pattern of the disrupted beds of quartzitic greywacke is complicated and is also probably due to boudinaging during D2. An F3 box fold is interpreted from the map pattern, and fold interference between the F3 box fold and an F4 fold is illustrated by the systematic change in the plunging direction of F3 parasitic folds from west-plunging to east-plunging (Fig. 5). The structure exposed in the trench is hence interpreted to represent a horizontal section through a refolded F3 box fold.

Gold-Mineralized Quartz Vein Analysis

The gold-mineralized quartz vein system is dominated by centimeter to meter-scale extensional veins (Fig. 6). These extensional veins can be divided into a moderately- to steeply-dipping NNE-striking set, a set emplaced subparallel to the S2 fabric (generally within argillite), and a moderately- to steeply-dipping ESE-striking set (Figure 7).

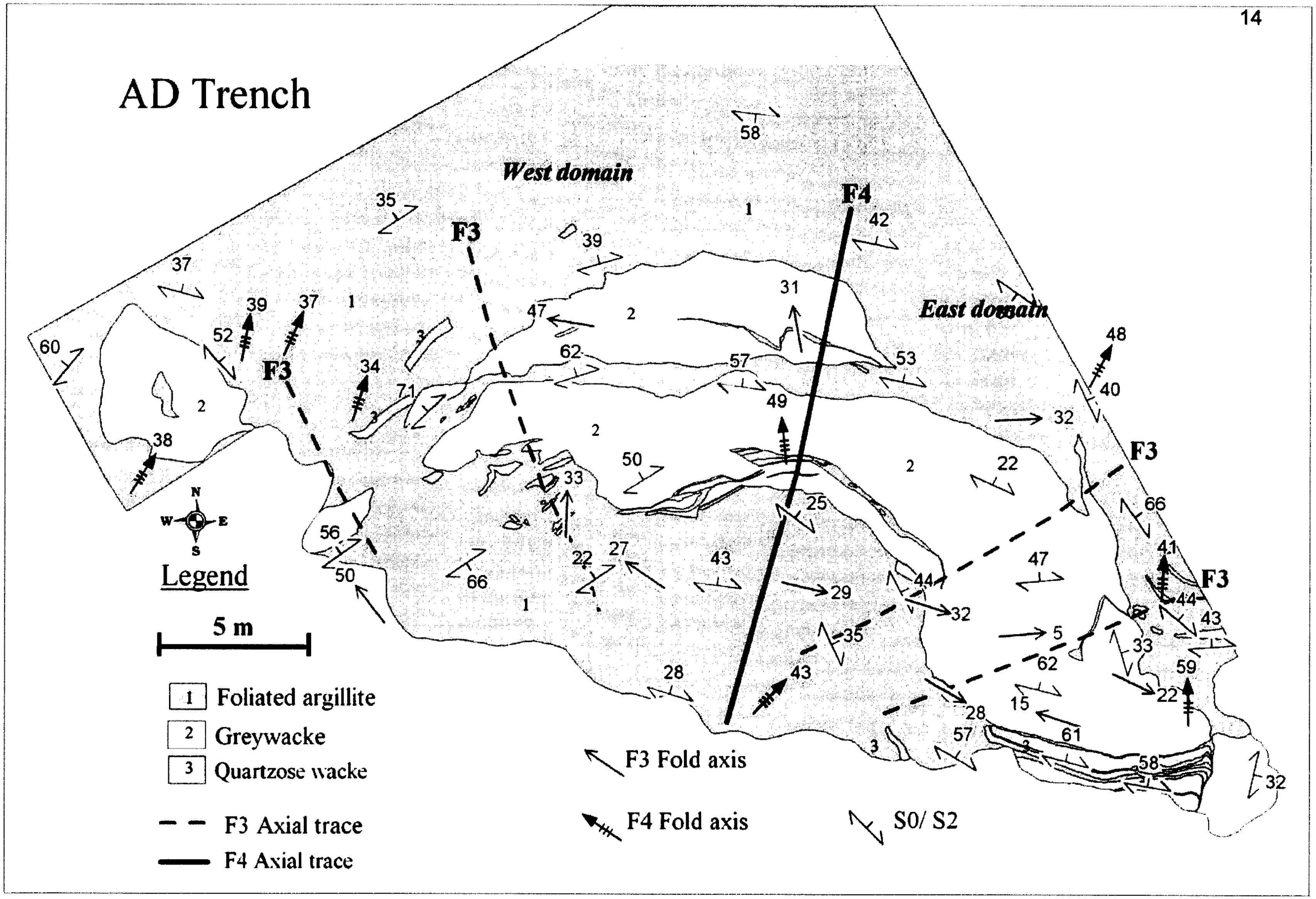

Figure 5. Structure of the AD trench.

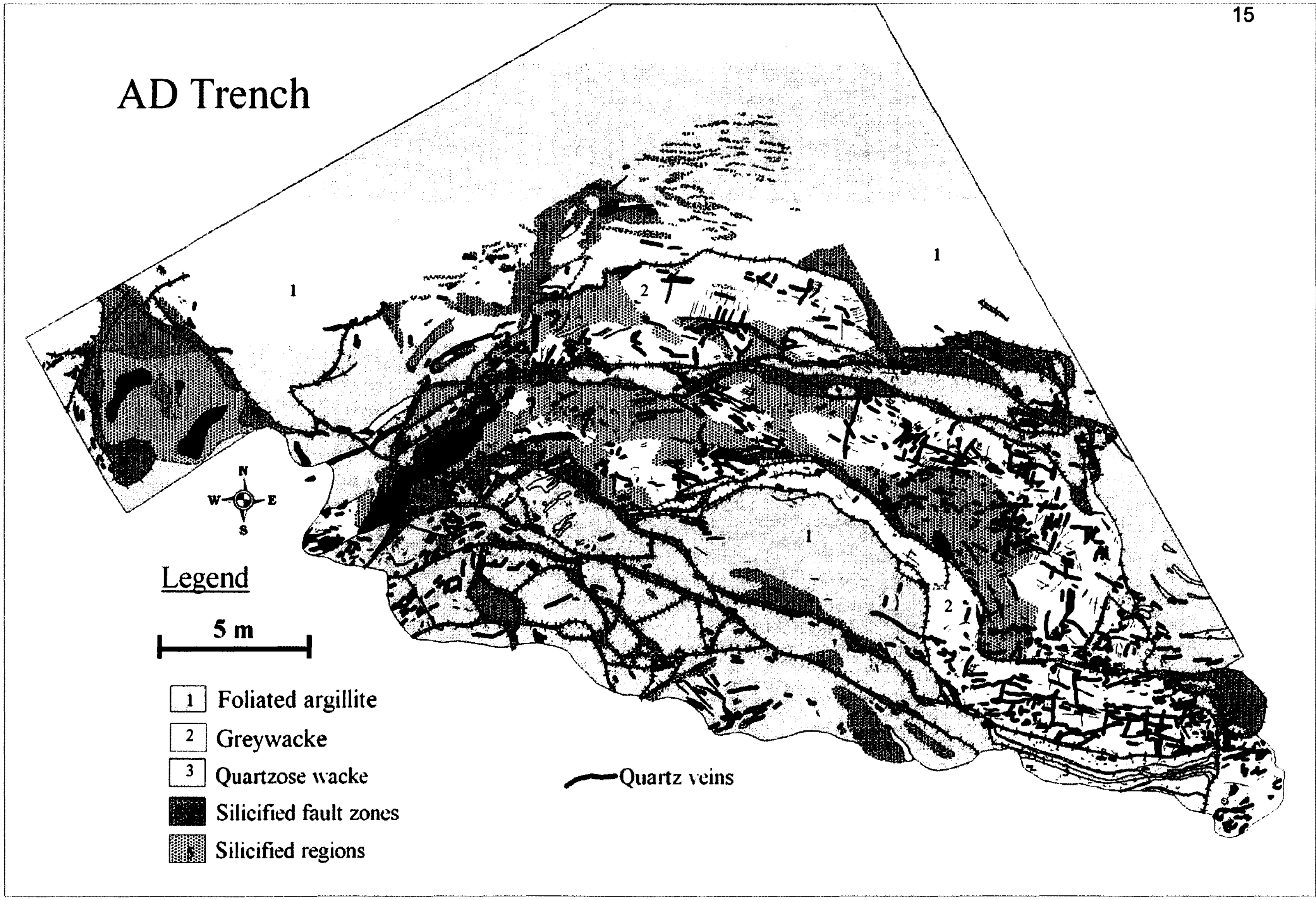

Figure 6. Gold-mineralized vein system and fault zones of the AD trench. Vein thickness is exaggerated (~10x).

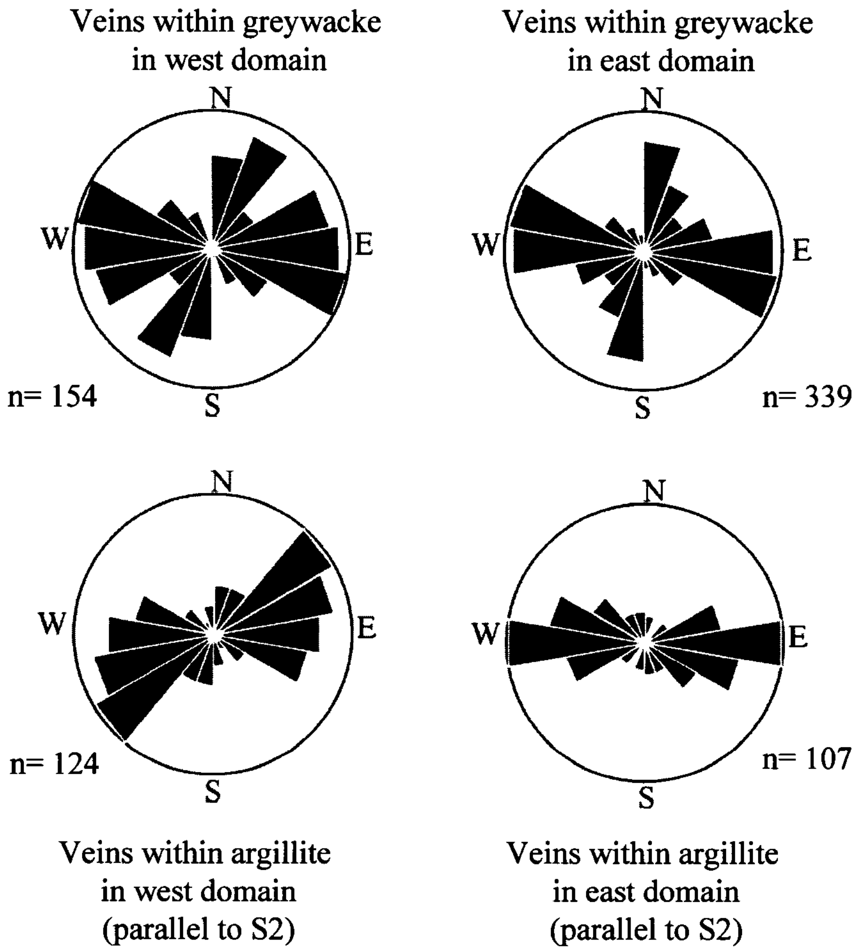

Figure 7. Rose diagrams showing strike of extensional veins.

The NNE-striking veins contain the S2 fabric (Fig. 8a) which indicates that they formed before or during D2. Even though the veins predate D3, they are emplaced orthogonal to the fold axes of F3 folds. One way to explain this geometrical relationship between D2 veins and F3 folds is that the veins were generated orthogonal to the fold axis of F2 folds early during D2, later on affected by S2, and then rotated about the F3 fold axis whose attitude is similar to the F2 fold axis due to the coaxial relationship between F2 and F3 folds. During D3, the veins hence remained unaffected by F3 folds. This scenario is consistent with the hypothesis of Watters et al. (2003, 2005) that the gold mineralizing event was synchronous with D2.

The veins emplaced subparallel to S2 are sheeted, sigmoidal, and thicken in the noses of F3 folds (Fig. 8b) which suggests that they were emplaced in dilation zones produced by F3 kinking, and consequently that gold mineralization was also generated or remobilized during D3. Watters et al. (2005, this issue) determined that a secondary mineralized zone located stratigraphically above the AD Zone is dominated by these sheeted veins and could represent a mineralized D3 structure of significant size. The existence of post-D2 gold mineralization is also supported by the fact that on the AD trench, gold-mineralized veinlets are locally found in brittle faults that cut through S2.

The relationship between folding and emplacement of the subvertical ESE-striking veins is more ambiguous than for the other two sets of extensional veins. Although these veins are locally axial planar to F3 kinks (Fig. 8c) (suggesting syn-D3 age of formation), they appear to be affected by S2 (suggesting pre or syn-D2 formation) in hand specimen. Two scenarios could explain these contradictory observations. One scenario is that the veins were generated pre or syn-D2 (therefore affected by S2) and F3 kink folds later nucleated on the veins due to weak cohesion surfaces between vein and

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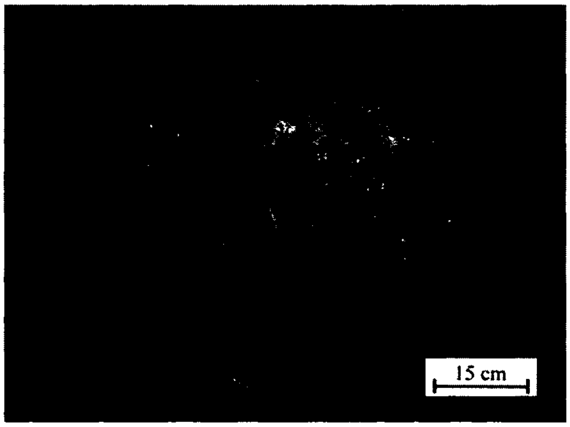

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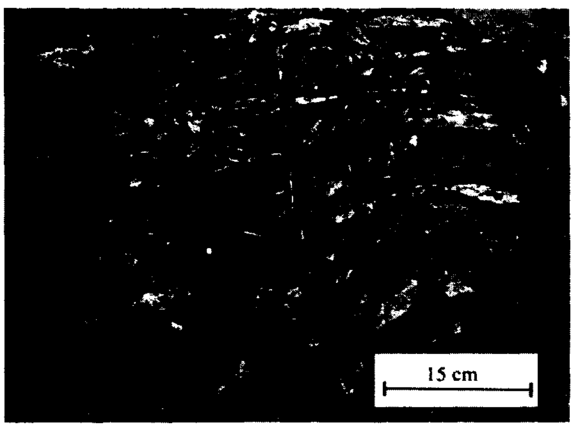

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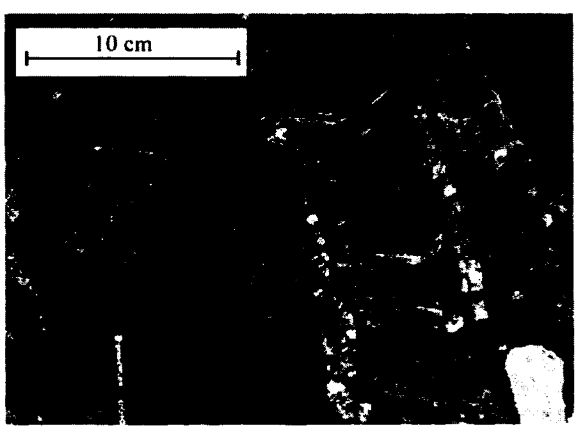

Figure 8. a) Extensional vein affected by S2 and emplaced parallel to F3 profile plane. b) Sheeted extensional veins emplaced in F3 fold (black lines outline vein boundaries). c) Extensional veins emplaced in hinge surfaces of F3 kinks (black line traces bedding/

S2).

host rock. The other scenario is that the veins were actually emplaced in the axial surfaces of F3 kinks during D3 and the fabric affecting the veins is not a cleavage but rather a growth fabric that parallels and resembles the S2 cleavage in hand specimen. The latter scenario is favored because it offers a mechanism for vein emplacement whereas the former does not. However, until thin section work is performed on these veins, this issue will not be resolved.

In summary, structural analysis indicates that the gold-mineralized deformation envelope exposed at the AD trench consists of quartz veins emplaced during both D2 and D3. This observation stresses the importance of identifying the relationship between D2 and D3 structures in the subsurface since gold mineralization could potentially be associated with both structures.

Three-Dimensional Representations using *gOcad*

Visualization of the geology in 3D enables the investigation of structural relationships between folds and mineralized structures that could not otherwise be observed. We are principally interested in comparing the geometrical relationships between F2 folds, F3 folds and gold mineralization in each zone. Since lithological markers are rare and not continuous through each zone, effort was initially directed to identifying structural panels of uniform younging direction so that the hinge surfaces of F2 folds could be reconstructed. Following this, the refolded geometry of F2 folds permits localization of F3 and F4 folds.

Methodology

Creating Surfaces Using gOcad and Sparse

The software *gOcad* with the structural application *Sparse* was chosen to generate the 3D representations. *Sparse* gives the user the freedom to create smooth surfaces based on geological interpretation rather than on an automatic interpolation algorithm such as that supplied by *gOcad.* Folded surfaces can therefore be created respecting the style of the different fold phases observed during surface mapping. The method for building a surface using *Sparse* requires the creation of a set of subparallel curves, referred to as a grip frame, that makes up the skeleton of the surface to be built (Fig. 9a). A surface is then created by interpolating between curves in the cross-curve direction using a non-uniform rational b-splines (NURBS) interpolation (Sprague and de Kemp, 2005) (Fig. 9b). If need be, the surface can easily be edited by modifying the grip frame.

Orienting Bedding Measurements

Although the drill cores are not oriented, bedding attitudes can be constrained to two possible attitudes if the angle between bedding and core axis is measured and the attitude of the F3 fold axis can be estimated (Fig. 10a). The example in Figure 10 is for a core axis with the attitude 89°@211° and a bedding measurement oriented at 43° to the core axis. The small circle on the equal area plot (Fig. 10a) represents all possible attitudes for the pole to bedding (making an angle of 47° (90°-43°) with the core axis). Fortunately, drill holes were drilled along sections sub-perpendicular to the trend of F3 fold axes and sub-parallel to F4 axial surfaces. Each drill section therefore falls within a domain of consistently oriented F3 fold axis. If a surface for a lithological marker can be created in *gOcad* (e.g. base of a thick argillite unit), the attitude of the F3 fold axis unique

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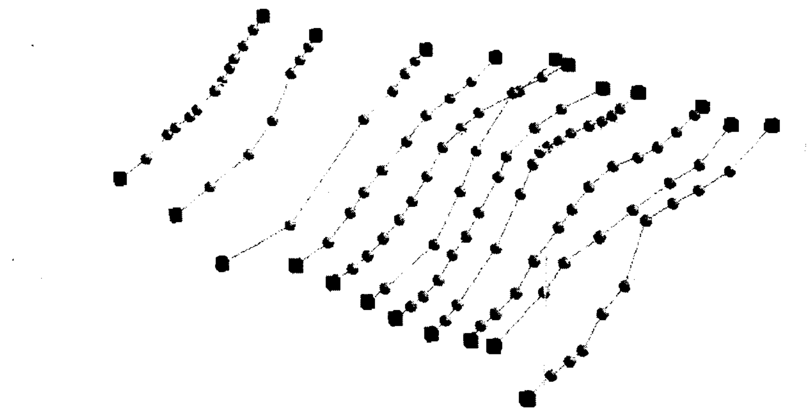

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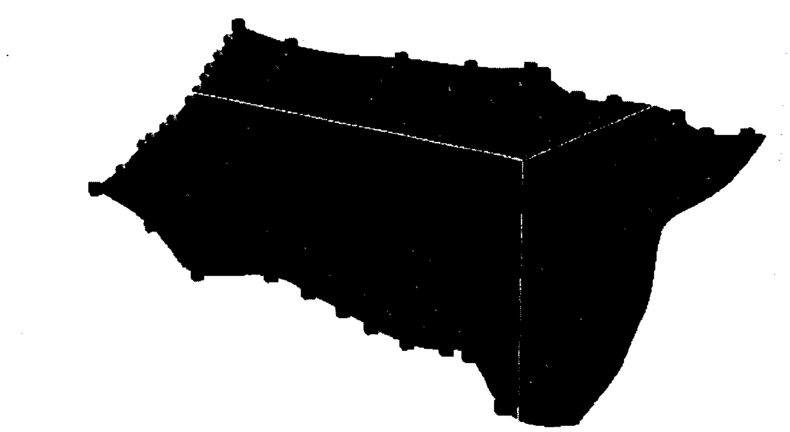

Figure 9. a) Example of a grip frame. b) Surface generated through NURBS interpolation of grip frame.

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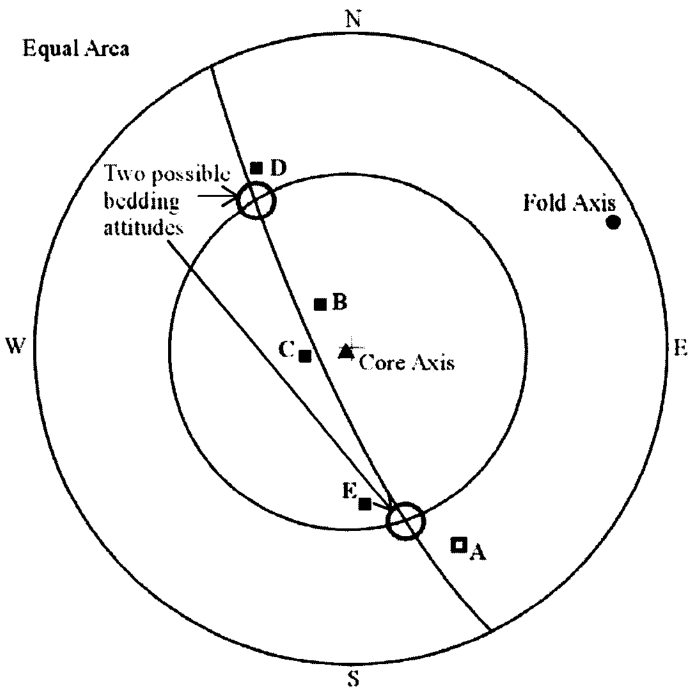

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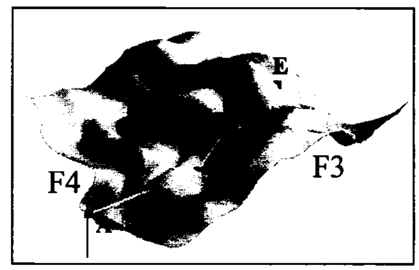


Figure 10. Method used to reorient bedding measurements in drill cores (see text).

to each section can be determined by extracting bedding attitudes from the marker surface along a digitized line parallel to the section (Fig. 10b) and using the extracted bedding attitudes to generate a π plot and find the F3 profile plane (Fig. 10a). Once the F3 profile plane is determined for a given section, the correct attitude of each bedding measurement has to be chosen from the two possible attitudes. For bedding measurements located in vicinity of a lithological marker, the choice between the two possible attitudes is based on the attitude of the marker. For example, assuming that the bedding measurement of Figure 10a is located in the vicinity of the marker, the correct attitude for the pole to bedding is the south-plunging one since it is the closest to the attitude of the marker at the site where the drill core intersects the marker (open square labelled "A" on Figure 10). When no constraints based on lithological markers can be used, the choice between the two possible attitudes is based on other drill sections or on the author's own interpretation of the folded geometry. When bedding measurements are parallel or perpendicular to the core axis, only one attitude is possible. Each bedding measurement of each drill core of the section is individually oriented and imported into *gOcad*. This operation is then repeated for each drill section.

Interpreting F2 Hinge Surfaces

Once the attitudes of bedding measurements have been determined and imported into *gOcad* along with their facing criteria, the positions of hinge surfaces of F2 folds can be identified. This task is locally challenging because of the complexity of the sub-surface geometry and the presence of multiple facing reversals. Some assumptions concerning the nature of these reversals are therefore necessary in identifying the F2 structures. These assumptions are:

(1) No reverse grading is present in the sedimentary units.

(2) The only faults affecting the geometry are those that could be detected in drill cores.

(3) Repeated facing reversals (e.g. syncline to anticline) present over an interval of 5 meters or less are parasitic and do not represent major structures.

(4) F3 and F4 folds do not overturn rock sequences over significant distances (> 25 meters).

Moreover, any model must take into account the attitudes of local lithological markers (if present) and the styles of F3 and F4 folds observed during mapping.

Results

The following section presents the results of the 3D modelling for each zone of Anomaly A. All surfaces were created in Sparse using grip frames digitized from drill sections.

Murphy Zone

The 3D representation of the Murphy Zone was constructed from 25 drill holes. Surfaces created include the base of the mineralized zone (Fig. 11), the top and base of a ~20 meter thick argillite unit observed below the mineralized zone (the rest being thinly bedded argillite-siltstone-sandstone units and thick sandstone beds), and four F2 axial surfaces. The top surface of the argillite unit was used to estimate the attitude of F3 fold axes so that bedding measurements could be oriented following the method described above. The final 3D representation of the Murphy zone is illustrated in Figure 12. Cross section 350W (Fig. 13a) shows that F2 synclines and anticlines present above and below

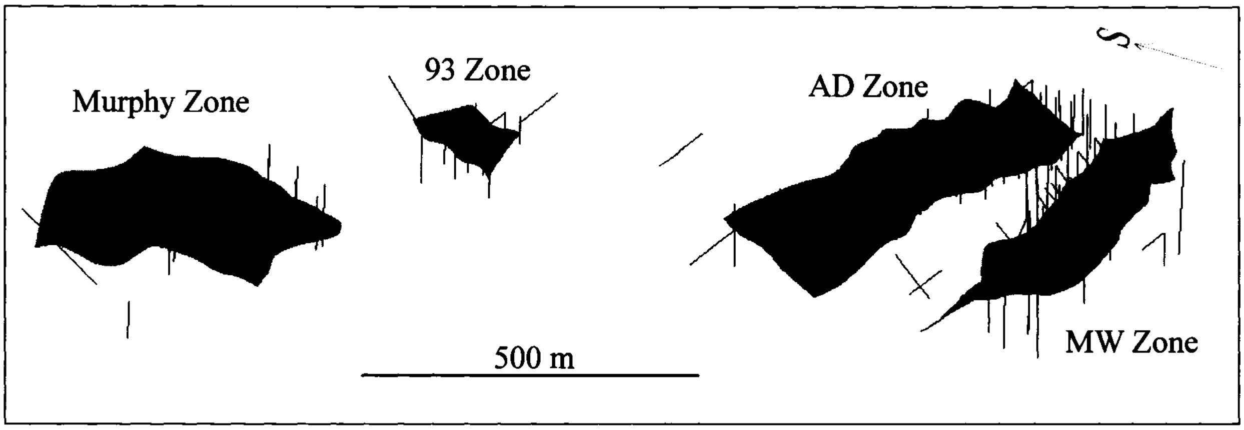


Figure 11. Three-dimensional representation showing the base of the mineralized envelope of each zone of Anomaly A. Black lines represent drill holes.

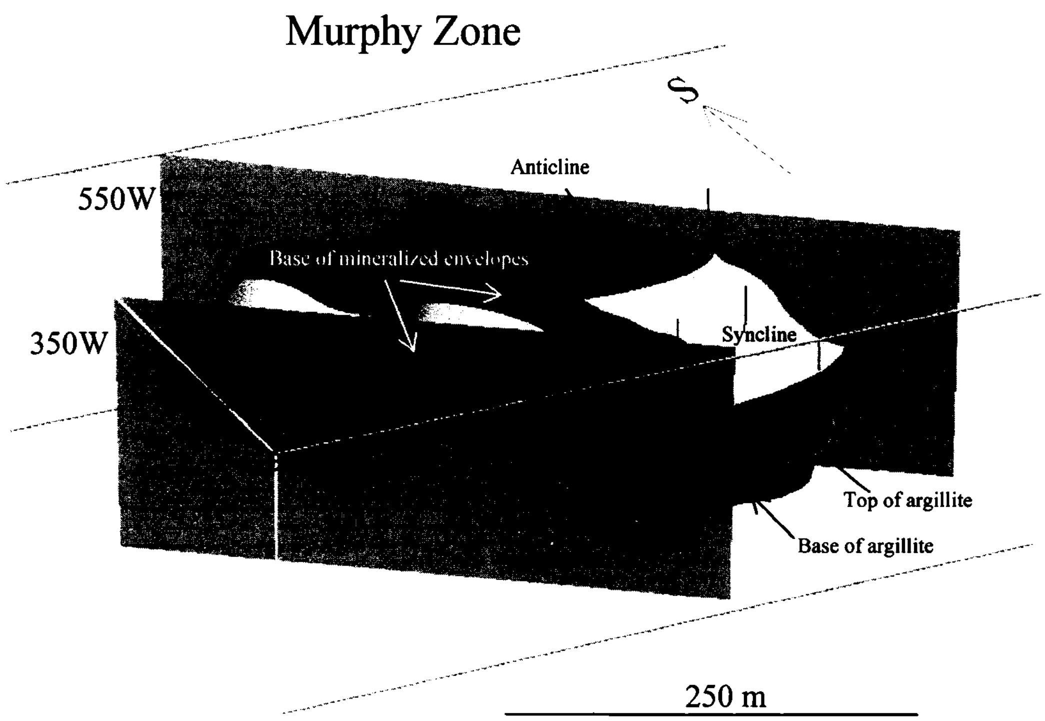
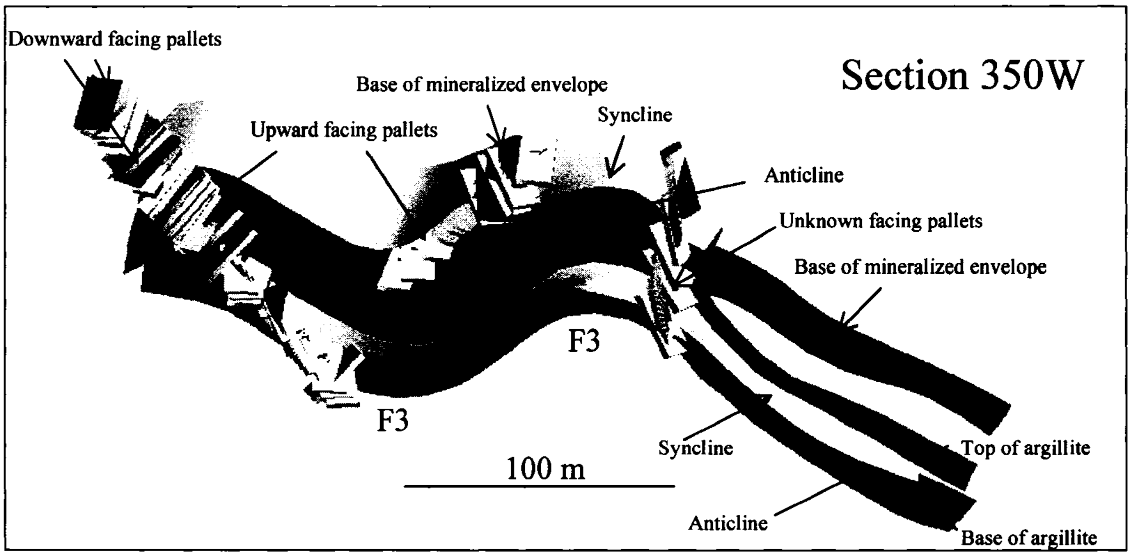


Figure 12. Three-dimensional representation of the Murphy Zone. Red surfaces represent the base of mineralized envelopes. Yellow and blue surfaces represent F2 hinge surfaces (yellow: syncline, blue: anticline). Dark grey surfaces represent the top and base of a thick argillite unit. Black lines represent drill holes. Shaded vertical surfaces labeled 350W and 550W indicate locations of sections displayed in Figure 13.

a)



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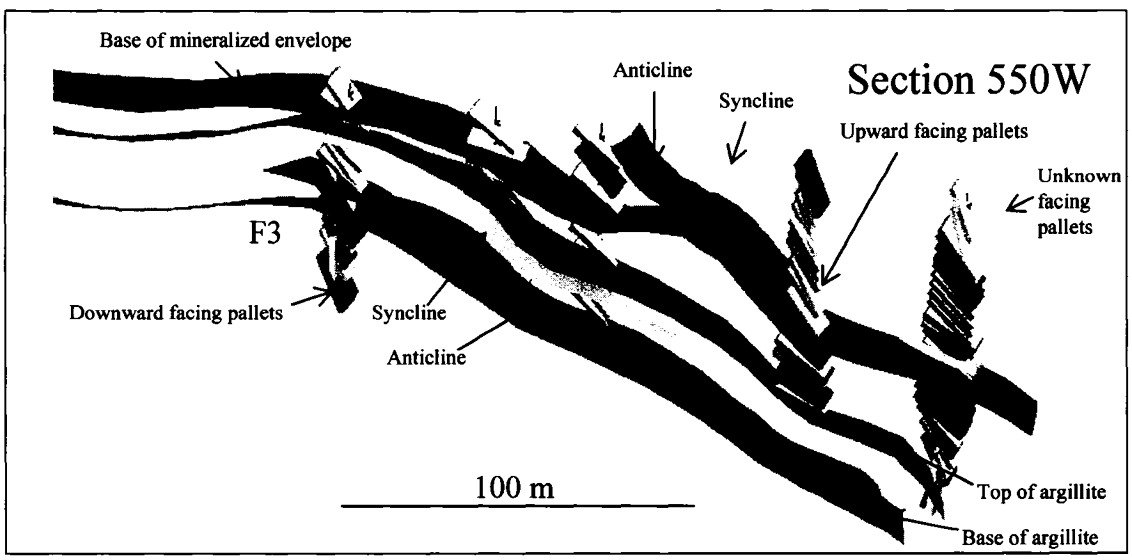


Figure 13. Sections of the Murphy Zone showing surfaces and oriented bedding measurements. Yellow pallets indicate upward facing, blue pallets indicate downward facing, white pallets indicate no facing information. Red surfaces represent the base of mineralized envelopes. Yellow and blue surfaces represent F2 hinge surfaces (yellow: syncline, blue: anticline). Dark grey surfaces represent the top and base of a thick argillite unit. Black lines represent drill holes. Locations of sections are shown on Figure 12.

the mineralized horizon are folded by F3 folds along with the mineralized zone. Importantly, cross section 550W (Fig. 13b) shows that F2 hinge surfaces are cut at a shallow angle by the mineralized zone which implies movement on the mineralized deformation envelope. Although it looks as if the F2 hinge surfaces are offset by a normal sense of motion, the fact that the argillite unit is not present above the fault suggests that the hinge surfaces above and below the fault represent different structures. The sense of motion on the fault is therefore undetermined. The fact that the mineralized zone is folded by F3 folds along with the F2 hinge surfaces suggests that it is probably a D2 structure, and it may well represent a thrust fault as suggested by Watters et al. (2003, 2005).

93 Zone

The 93 zone was studied through 11 drill holes. Two thick (~25 meters) units of argillite are present above and below the mineralized zone. Since the argillite above the fault is upward facing and the argillite below is downward facing, the mineralized zone is interpreted to coincide with the hinge surface of an F2 anticline (Fig. 14). However, it should be noted that the younging reversal could alternatively be due to movement on the mineralized zone which superposed two panels of different younging directions. Unfortunately, the available data do not permit distinction between the two scenarios. Facing reversals locally occur at the extremities of certain holes which could be due to parasitic folding or to the presence of other synclinal hinge surfaces slightly outside the data field.

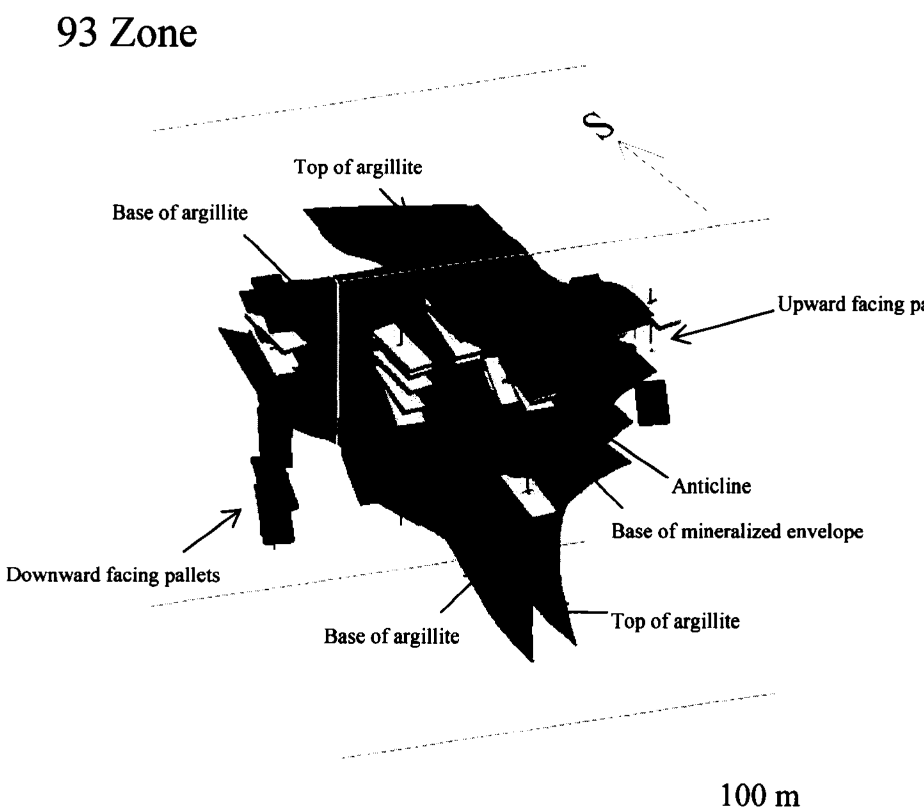


Figure 14. Three-dimensional representation of the 93 Zone showing surfaces and oriented bedding measurements. Yellow and blue pallets indicate upward and downward facing respectively. The red surface represents the base of the 93 zone. The blue surface represents an F2 hinge surface (anticline). Dark grey surfaces represent tops and bases of thick argillite units. Black lines represent drill holes.

AD and MW Zones

The 3D representations of the AD and MW Zones were constructed from 70 and 56 drill holes respectively. Surfaces created include the base of the main mineralized zone, a secondary mineralized zone located above the AD Zone, the bottom of a 30 to 50 meter thick unit of argillite, and two F2 hinge surfaces that could be followed through both zones (Fig. 15). The argillite unit was also mapped through both zones and was used to estimate the attitude of F3 fold axes. The main mineralized deformation envelopes of the AD and MW zones dip towards each other (Fig. 11, 15). It is not clear whether the two zones are part of the same structure or not, although the fact that brecciation and mineralization is considerably less intense in holes drilled between the two zones suggests that they represent two distinct structures.

Several younging reversals are observed in both zones which complicates the interpretation of F2 axial surfaces. Nonetheless, one overturned panel (region between anticline and syncline) could be consistently traced from one zone to the other. This overturned panel defines a box fold geometry at the MW zone (Fig. 16) and the overall geometry of the AD and MW zones is thought to reflect interference between conjugate F3 folds (Fig. 15). Contrary to what is observed at the Murphy and 93 zones, the geometrical relationship between F2 structures and mineralized zones is not consistent with the interpretation that the mineralized zones coincide with D2 thrusts. Indeed, the mineralized zones do not appear to be folded along with the bedding and cut through lithologies and F2 hinge surfaces without any evidence of offset (Fig. 16). Moreover, F2 hinge surfaces which are continuous from one zone to the other are cut twice by the mineralized zones (once at the AD Zone and once at the MW Zone). These observations suggest that the mineralized zones at the AD/ MW Zones do not represent D2 thrusts.

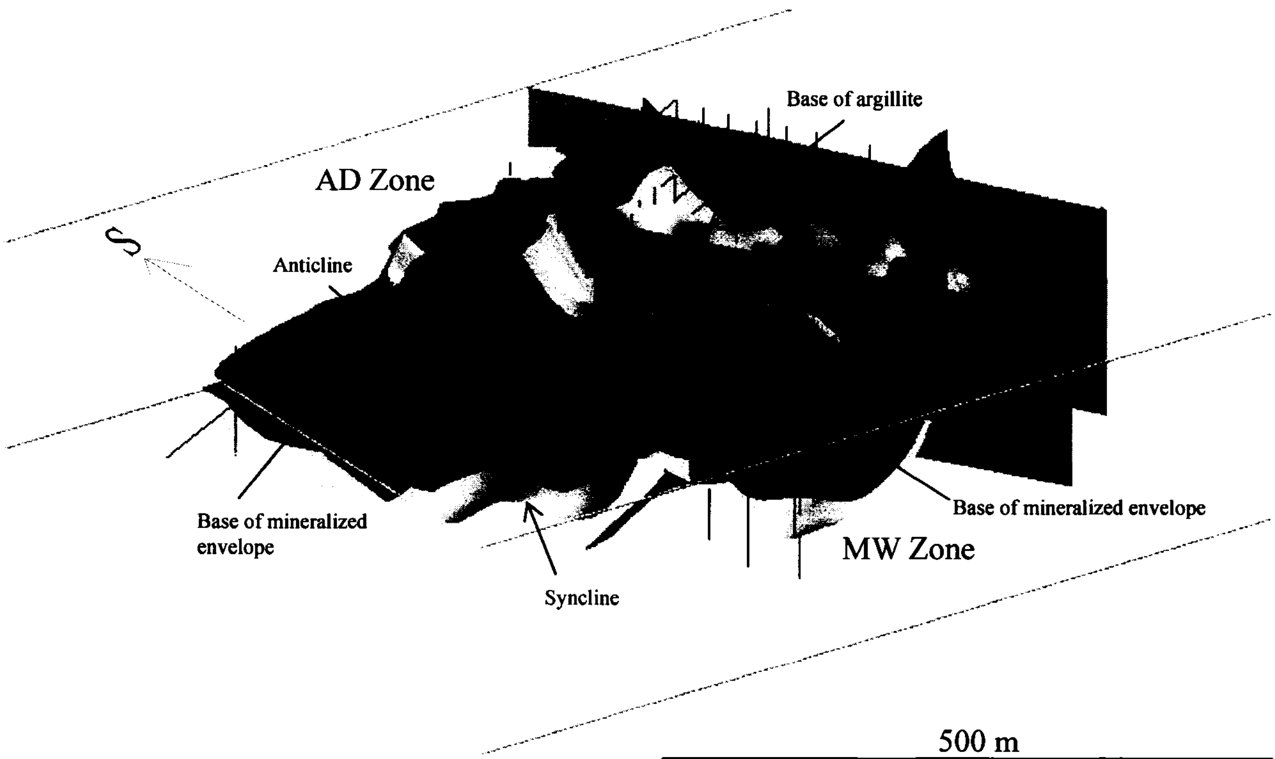
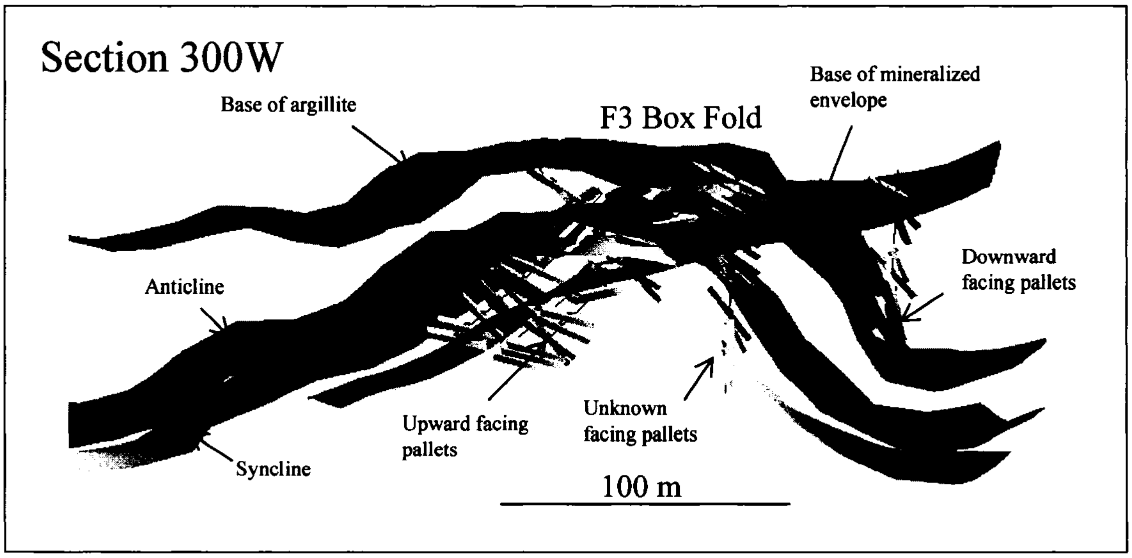


Figure 15. Three-dimensional representation of the AD and MW Zones. Red surfaces represent the base of mineralized envelopes. Yellow and blue surfaces represent F2 hinge surfaces (yellow: syncline, blue: anticline). The grey surface represents the base of a thick argillite unit. Black lines represent drill holes. Shaded vertical surfaces labeled 300W and 500W indicate locations of sections displayed in Figure 16.

a)



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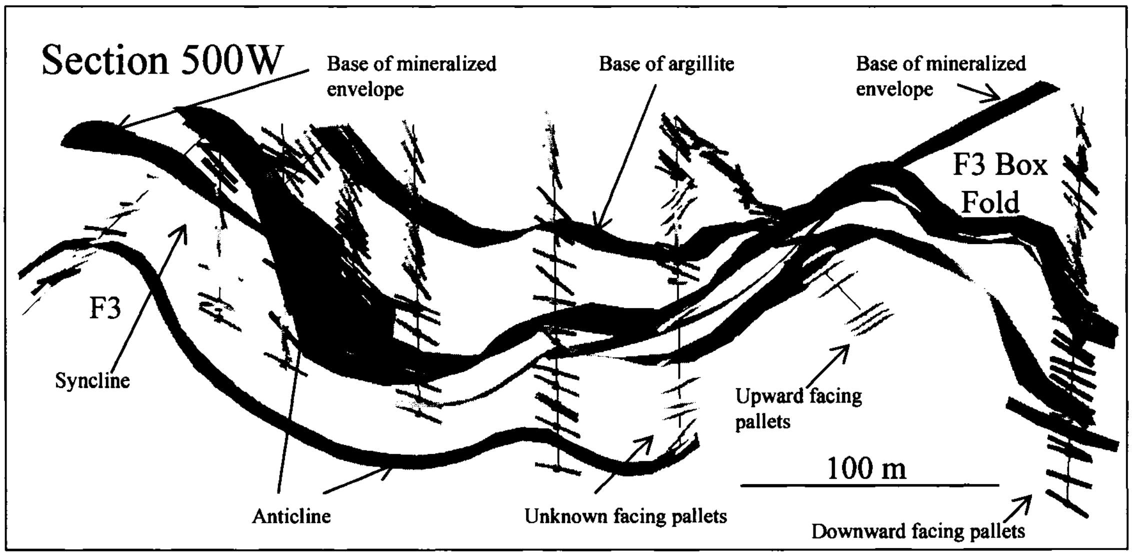

Figure 16. Sections through the AD and MW Zones showing surfaces and oriented bedding measurements. Yellow pallets indicate upward facing, blue pallets indicate downward facing, white pallets indicate no facing information. Red surfaces represent the base of mineralized envelopes. Yellow and blue surfaces represent F2 hinge surfaces (yellow: syncline, blue: anticline). The grey surface represents the base of a thick argillite unit. Black lines represent drill holes. Locations of sections are shown on Figure 15.

Moreover, the mineralized zones cut through the box fold geometry (Fig. 16) in a fashion potentially analogous to shear joints observed in outcrops (Fig. 3b). This observation may suggest that the mineralized deformation zones of the AD and MW zones represent conjugate structures associated with F3 box folds.

Discussion

The 3D representations suggest that the Murphy and 93 Zones represent D2 structures, whereas the AD and MW Zones coincide with D3 structures. Structural analysis on the AD trench indicates the presence of D2 and D3 veins in the mineralized deformation envelope of the AD Zone which suggests that the AD Zone, and potentially the MW Zone, represent D3 ore zones superposed on a preexisting D2 mineralized envelope. It is therefore plausible that the main mineralization event occurred synchronous with D2 and produced structures extending over the entire A Anomaly that were later locally remobilized into (or generated in) D3 structures. Whether or not the higher tonnages of the AD and MW Zones are related to the remobilization process still needs to be determined.

Continuity of D2 Structures

Even though gold mineralization was apparently remobilized during D3, the possibility that mineralized D2 structures extend over the entire A Anomaly still has to be considered. This section focusses on the continuity of F2 axial surfaces between the four zones. The argument for assessing the continuity of F2 axial surfaces is that since D2 mineralized horizons potentially represent D2 thrusts, showing that the axial surfaces are continuous between the zones would increase the potential for the mineralized deformation envelope to be present between the zones. A model connecting F2 axial surfaces would be considered valid if the linked surfaces had a folded geometry that respects the styles of F3 and F4 folds observed at the surface.

Continuity between AD and 93 Zones

About 500 meters separate the 93 Zone from the AD Zone. A key aspect of the interpolation is to determine the asymmetry of F3 folds between the zones. Fortunately, one drill hole (CS02-97) is located between the two zones and has bedding measurements oriented either parallel or perpendicular to the core axis, which gives only one possible asymmetry (Fig. 17). Hole CS02-97 also indicates the presence of gold mineralization within a 3 meter thick deformation zone located above an F2 syncline. Based on the asymmetry extracted from that drill hole, it is actually possible to link up F2 axial surfaces of the AD and 93 zone through an interpolated geometry that respects the style of F3 folds (Fig. 18). Although this interpolation does not prove continuity between the zones, it indicates the potential for km-scale F2 structures extending over Anomaly A. The fact that the mineralized horizon observed in hole CS02-97 is located above a syncline and not above an anticline as in the 93 Zone suggests that they probably represent distinct structures consistent with a stacked-style of mineralization.

Continuity between Murphy and 93 Zones

Based on the 3D representations, F2 hinge surfaces of the Murphy and 93 Zones do not appear to be correlative. Whereas the Murphy Zone has two anticline/ syncline pairs, the 93 Zone only exhibits one anticline (and potentially a syncline above and/ or below the anticline as mentioned above). Many scenarios are possible to explain this disparity. It is possible that rock units are boudinaged from one zone to the other so that lithologies and structural panels cannot be traced. It is also possible that a ~N-S strike-slip fault is present and offsets the two zones. Even though subsurface data do not enable us to determine the actual relationship between the two zones, the scenarios mentioned

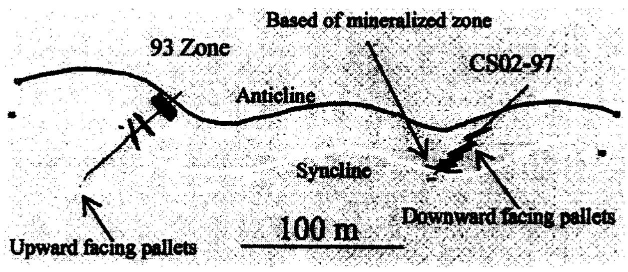

Figure 17. Section showing the asymmetry of F3 folds between the AD and 93 Zones based on bedding information from hole CS02-97 (looking SW). Yellow and blue pallets indicate upward and downward facing respectively. The red line represents the base of a mineralized zone observed in hole CS02-97. The yellow and blue lines represent F2 hinge traces (yellow: syncline, blue: anticline). Black lines represent drill holes.

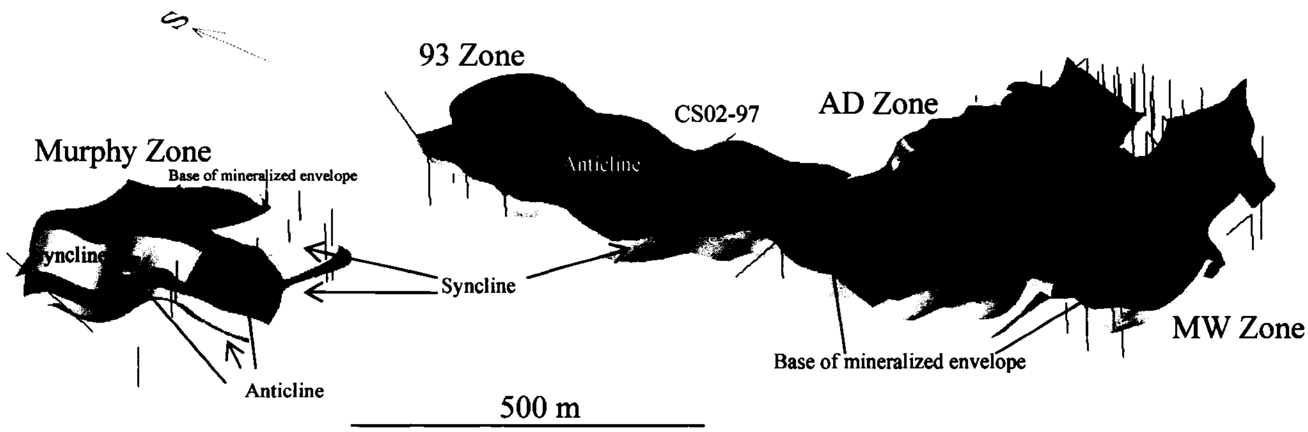

Figure 18. Three-dimensional representation of Anomaly A. Red surfaces represent the base of mineralized envelopes. Yellow and blue surfaces represent F2 hinge surfaces (yellow: syncline, blue: anticline). Black lines represent drill holes.

above are both interesting from an economic point of view. The former implies the presence of a large-scale structure and the latter indicates the presence of stacked mineralized zones of significant size.

Conclusion

Gold mineralization at Anomaly A is contained within deformation envelopes bearing geometrical relationships to folded and faulted structures generated during regional deformational events. Three-dimensional representations of Anomaly A indicate that the mineralized envelopes at the Murphy and 93 Zones appear to coincide with D2 faults whereas mineralized envelopes of the AD and MW Zones probably represent conjugate shear joints associated with F3 box folds. Gold remobilization (or generation) during D3 is consistent with structural characteristics of mineralized quartz veins observed in the AD trench. It appears, therefore, that gold mineralization was ongoing throughout D2 and D3.

The structural relationships between folds, faults, and mineralization would have been difficult to determine without the help of visualization software. The use of *gOcad* with the structural application *Sparse* proved to be a very useful and powerful tool in generating 3D representations of complexly folded geological surfaces. It provided the freedom of interpreting geological features that could not be interpreted through an automatic interpolation algorithm.

ACKNOWLEDGMENTS

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Chapter II

Methodology Used in Creating 3D Representations

The objective of this chapter is to describe explicitly the methodology involved in creating 3D representations of Anomaly A. All examples and sections used in this chapter are based on the AD and MW Zones. The same methodology was applied to the other zones.

Why Visualizing in 3D?

The purpose of creating 3D representations of Anomaly A is to enable visualization of complex structures (e.g. refolded folds) in order to define structural relationships between mineralized structures and structural features (folds and faults) that would otherwise be difficult to observe. Without 3D representations, geologists are forced to visualize a 3D geometry through a sequence of 2D cross-sections. The 3D representations provide otherwise-abstract information simply by looking at them. When dealing with complexly deformed structures, 3D representations hence become extremely useful.

Choosing the Right 3D Engine

The software chosen to create the 3D representations is *gOcad*. The software *gOcad* offers state-of-the-art 3D visualization and contains many built-in functions useful for exploration and mining purposes (e.g. user friendly drill-core import function). A structural application named "*Sparse*" also offers many useful functions and was added to the basic *gOcad* package. The most significant application of *Sparse* regards the interpolation method used to create surfaces. The geometry of a surface created from a series of cross-sections is a function of the computerized method used by the 3D software to interpolate between cross-sections. Whereas *gOcad* uses a triangulation interpolator, *Sparse* uses a non-uniform rational b-splines (NURBS) interpolator which creates smooth surfaces that are more geologically realistic. Other useful *Sparse* applications used in this study include a function to grab strike-and-dip measurements on surface parts of an existing surface, the ability to display strike-and-dip measurements as 3D structural palettes, and the ability of using cross-sectional curtains to directly digitize in the 3D environment.

Constructing Surfaces Based on Drill Core Markers

This section describes the steps followed to create surfaces based on geological features that can be traced from hole to hole. These surfaces include the bases of mineralization envelopes and lithological markers.

Since the drill holes at Anomaly A were drilled along parallel sections, the subsurface data can be displayed through a series of parallel vertical 2D cross-sections. Let's consider that we want to build a surface for the base of a thick unit of argillite present at the AD/ MW Zones. The first step is to identify the argillite unit and interpret its geometry in each hole of a given section (Fig. 19). Where present, bedding measurements that are perpendicular or parallel to the core axis are used to constrain the interpretation (Fig. 19). The established geometry of well constrained sections can be used to interpret sections that are not as well constrained. Importantly, the interpretation of the geometry must respect the styles of fold observed at the surface.

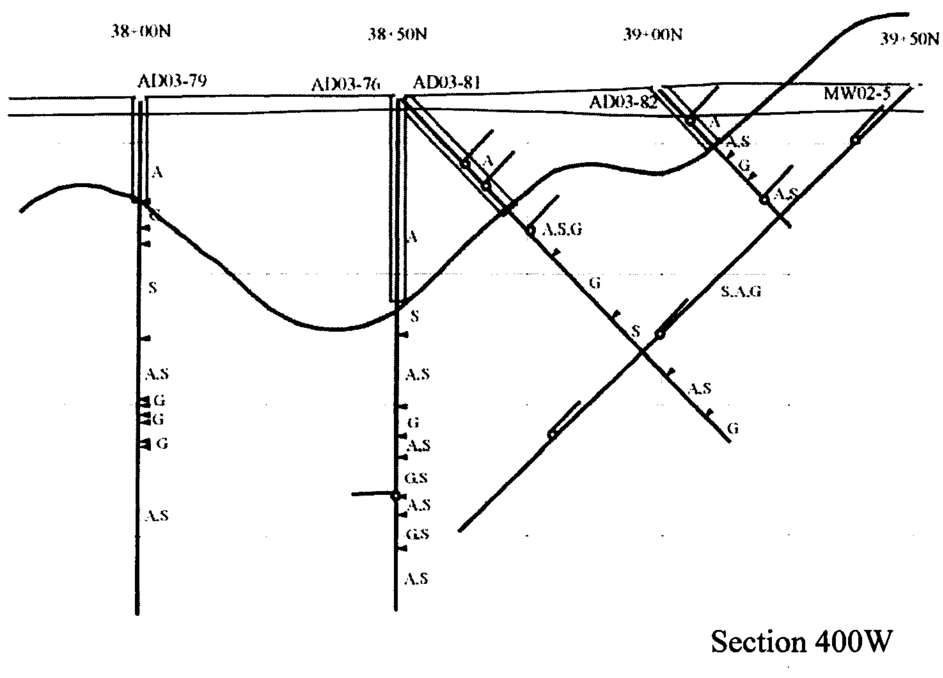


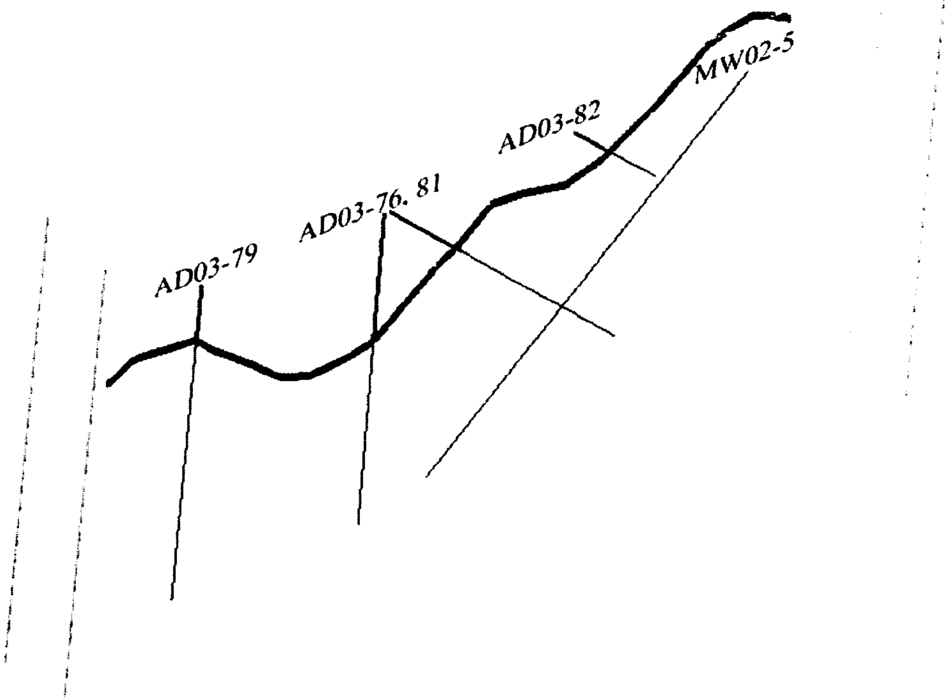
Figure 19. Example of a drill section on which the geometry of the base of an argillite unit is interpreted (red line). Legend: A: argillite, S: siltstone, G: greywacke. Black bars indicate bedding attitudes.

The interpreted geometry of the base of the argillite unit is then digitized as a line in *gOcad* (Fig. 20a). This procedure is repeated for each section which gives a series of subparallel lines (Fig. 20b). Using *Sparse*, the series of lines is converted to a "grip frame" that represents the skeleton of the base of the argillite unit (Fig 21a). The spacing of the nodes on each line is dictated by the number of nodes required to produce a smooth line. The order in which the lines are interpolated is specified within the grip frame by clicking on the lines in the appropriate order. This procedure is required to ensure that the interpolation is performed only between adjacent lines and produce a coherent surface. *Sparse* then interpolates between the lines of the grip frame to generate a smooth surface (Fig. 21b). Although *gOcad* also offers the possibility of creating a surface from a series of subparallel lines, the surface it creates is not as smooth as the one created by *Sparse* (Fig 21c, d). The same method is used to create a surface for the base of the mineralization envelope although in that case bedding information is not used. Nonetheless, markers of the mineralization envelope are present in most holes so that its geometry is well constrained.

Constructing F2 Hinge Surfaces Based on Younging Criteria and Bedding Attitudes

An important part of this thesis focusses on creating surfaces representing hinge surfaces of F2 isoclinal folds. This is done by identifying upward- and downward-facing panels and creating a surface passing through points where the reversal occurs. As mentioned in the article, some assumptions regarding the nature of the reversals have to be made. However, because of the large degree of freedom in interpreting the geometry of F2 hinge surfaces, some other constraints need to be established. Since F2 folds are

a)



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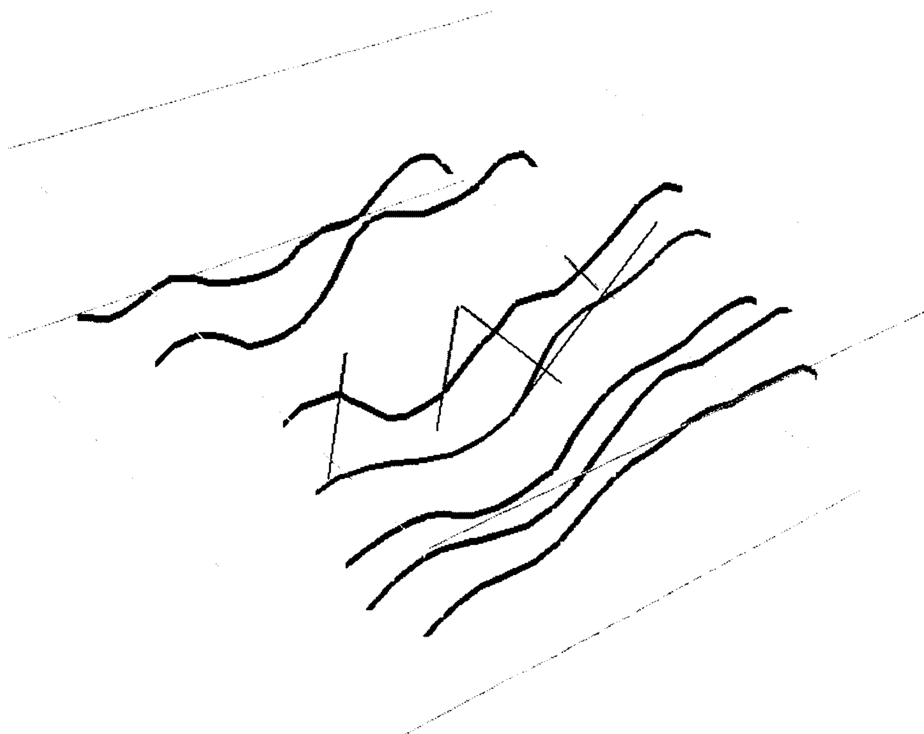
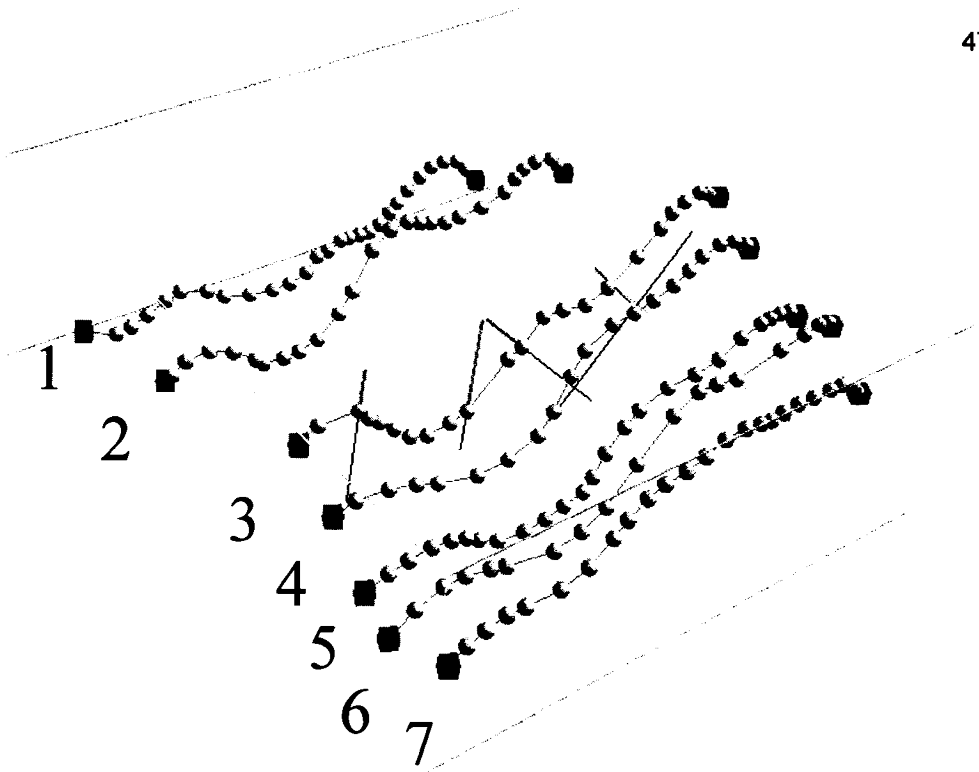


Figure 20. a) Base of the argillite unit of Figure 19 imported in *gOcad*. b) Base of the argillite unit for a series of sections imported in *gOcad*.

a)



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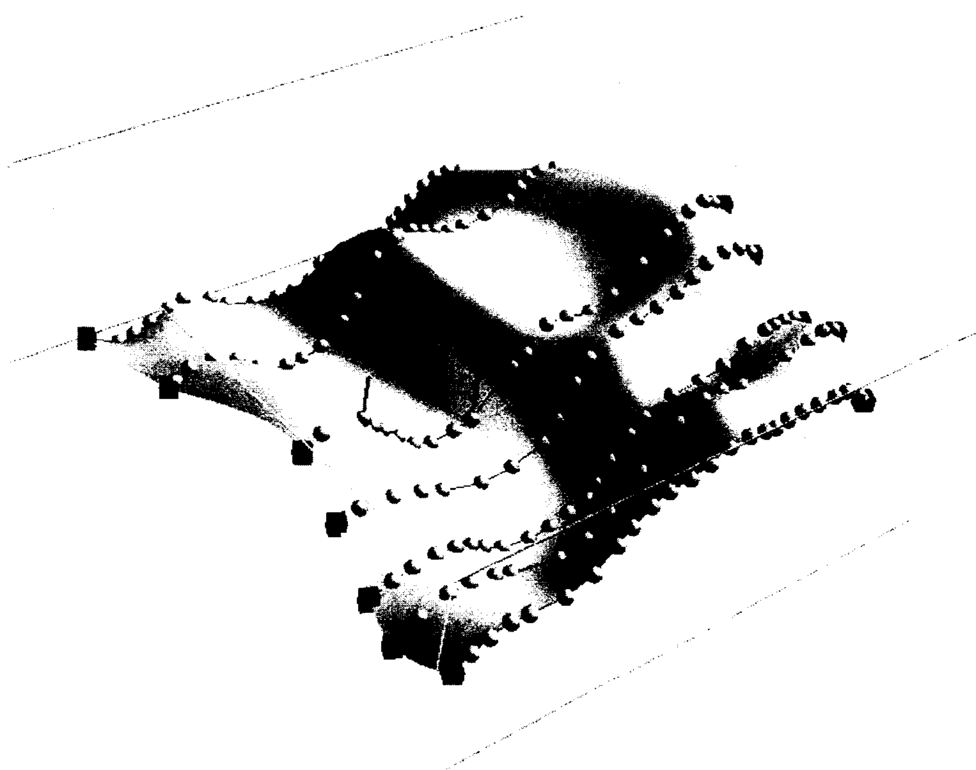
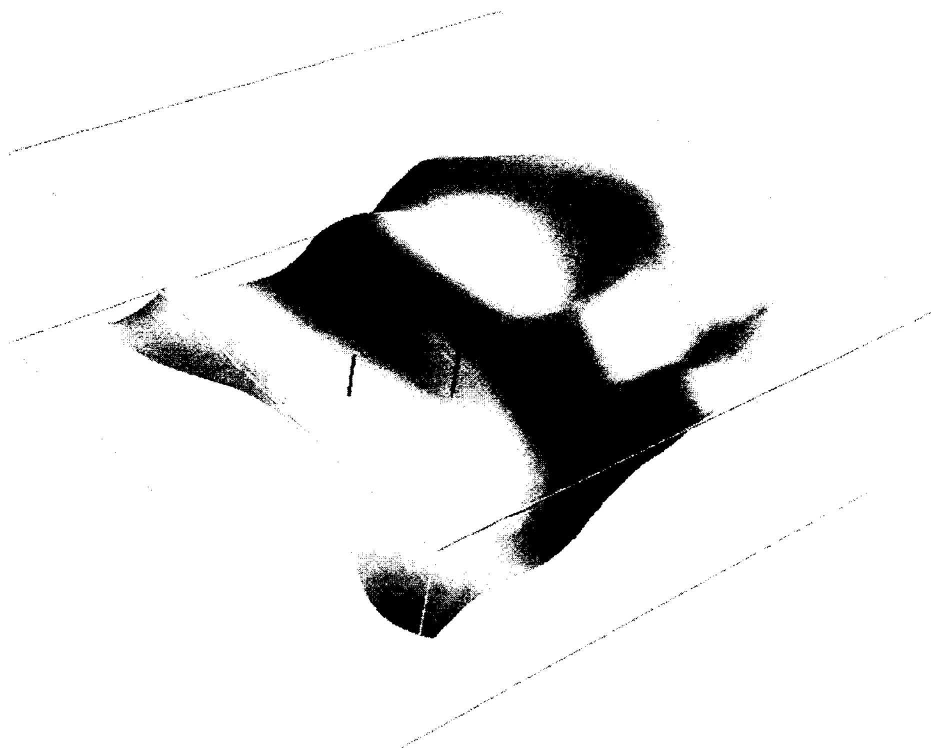


Figure 21. a) Grip frame for the series of lines of Figure 20b. Numbers indicate the order in which the interpolation is performed. b) Interpolated surface through the grip frame.

c)



d)

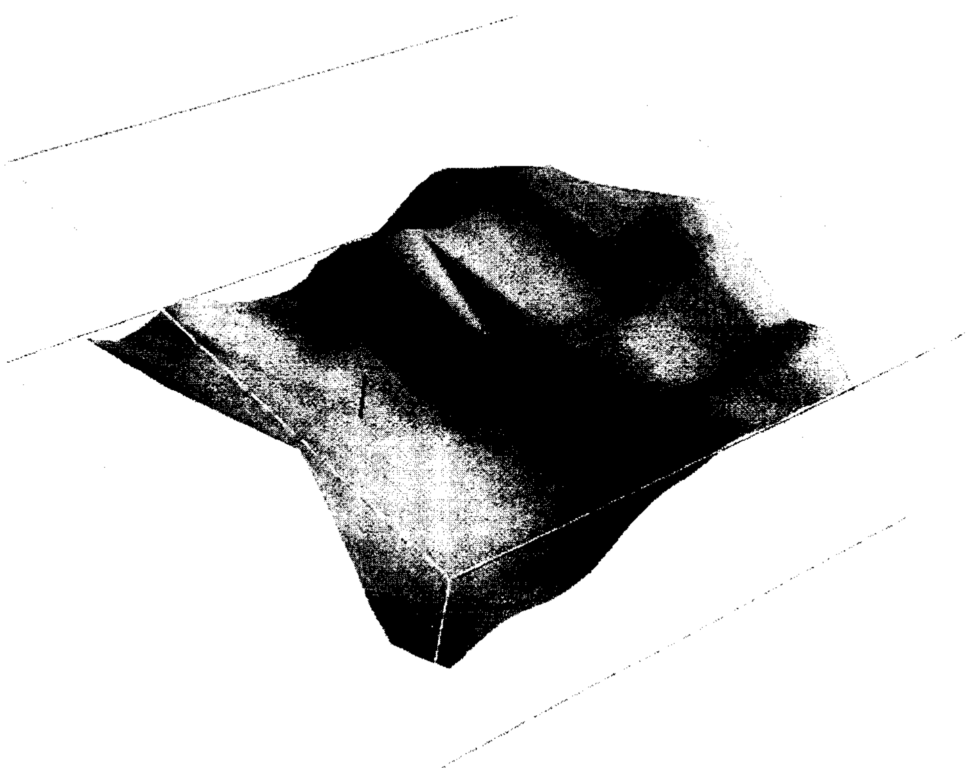


Figure 21. c) d): Comparison between the smooth surface created by *Sparse* (c) and the polygonal surface created by *gOcad* (d).

isoclinal, bedding attitudes are a useful piece of information in the interpretation. A method was hence elaborated to orient bedding measurements based on the angle between bedding and drill-core axis so that facing information and bedding attitudes could be combined to better constrain the interpretation.

Orienting Bedding Measurements

Estimating F3 Fold Axes

The method used to orient bedding measurements consists of estimating a fold axis in the vicinity of the hole we want to orient so that there are only two possible attitudes for a given measurement. Criteria for choosing between the two possible attitudes are described below. Because drill holes are located along sections that are perpendicular to the trends of F3 fold axes and subparallel to F4 axial surfaces, an F3 fold axis can be defined for all holes of a given section. The F3 fold axis for a given section is determined by extracting bedding measurements from an already constructed lithological surface (e.g. base of argillite unit) along the drill section. This is done by digitizing a line on the lithological surface, along the drill section (Fig. 22a). The orientation vector[1] of the lithological surface at the site where a node of the digitized line is present is extracted through the *Sparse* command "Grab Orientation Vectors from Surface". The orientation vectors can then be converted into strike-and-dip measurements through the command "Convert Orientation Vectors to Dip/ Dip Azimuth". The strike-and-dip measurements are then plotted on an equal area plot and the F3 profile plane for the section is determined by finding the best cylindrical fit to the data (Fig. 22b). To orient a given measurement from a drill hole of the section, a small circle whose center corresponds to

[1] An orientation vector is a dip-line

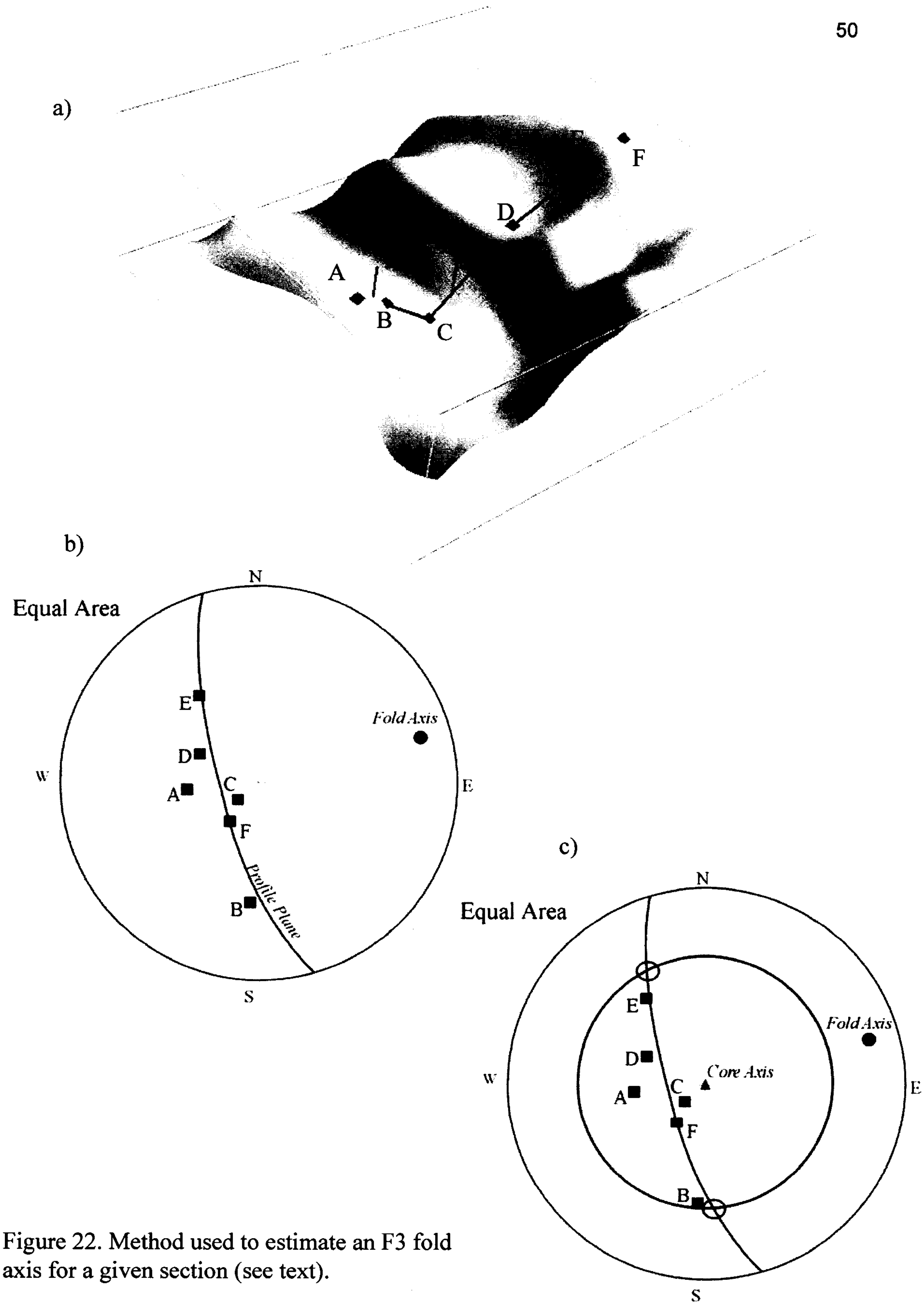


Figure 22. Method used to estimate an F3 fold axis for a given section (see text).

the attitude of the drill hole and whose radius is defined by 90°- "angle between core axis and bedding" is constructed. The possible attitude for the pole to bedding is then constrained to two possibilities (Fig. 22c). One of the two attitudes is chosen (see next section) and is extracted from the equal area plot. This procedure is repeated for each measurement of each hole of the section, and the entire procedure is repeated for the other sections.

Choosing between the Two Possible Bedding Attitudes

The choice between the two possible attitudes of a given bedding measurement located in the vicinity of the lithological surface from which the fold axis is defined is made based on the attitude of the lithological surface near the bedding measurement (Fig. 23). On Figure 23, the correct attitude for the pole to bedding is the north-plunging one since it is the closest to the attitude of the marker at the site where the drill core intersects the marker (open square). For bedding measurements located at considerable distance from a lithological marker, the correct attitude is interpreted based on sections where an interpretation of the geometry at the same stratigraphic level could be established based on a lithological surface or bedding measurements with attitude perpendicular to the core axis. In some instances, the choice between the two possible attitudes has to be made based on an interpretation. For example, Figure 24 shows two different interpretations of a section of the AD Zone based on possible bedding attitudes. Since the overall dip of the argillite unit previously modelled indicates that the strike of each bedding measurement is usually at high angle to sections of the AD/ MW Zones, the traces of the two possible bedding attitudes on the section more or less correspond to the maximum angle between measured bedding and core axis (i.e. their traces on the section are close to their dip-line).

a)

b)

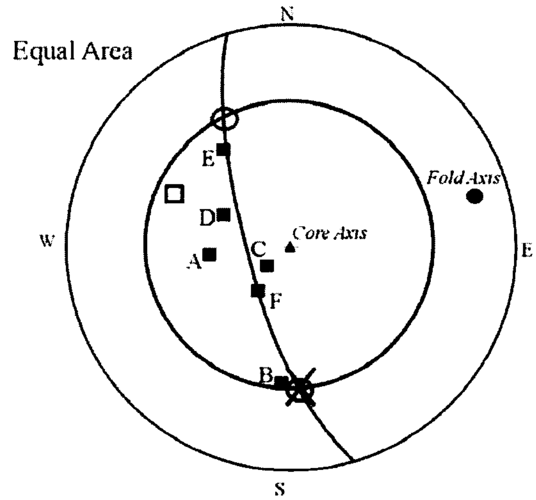
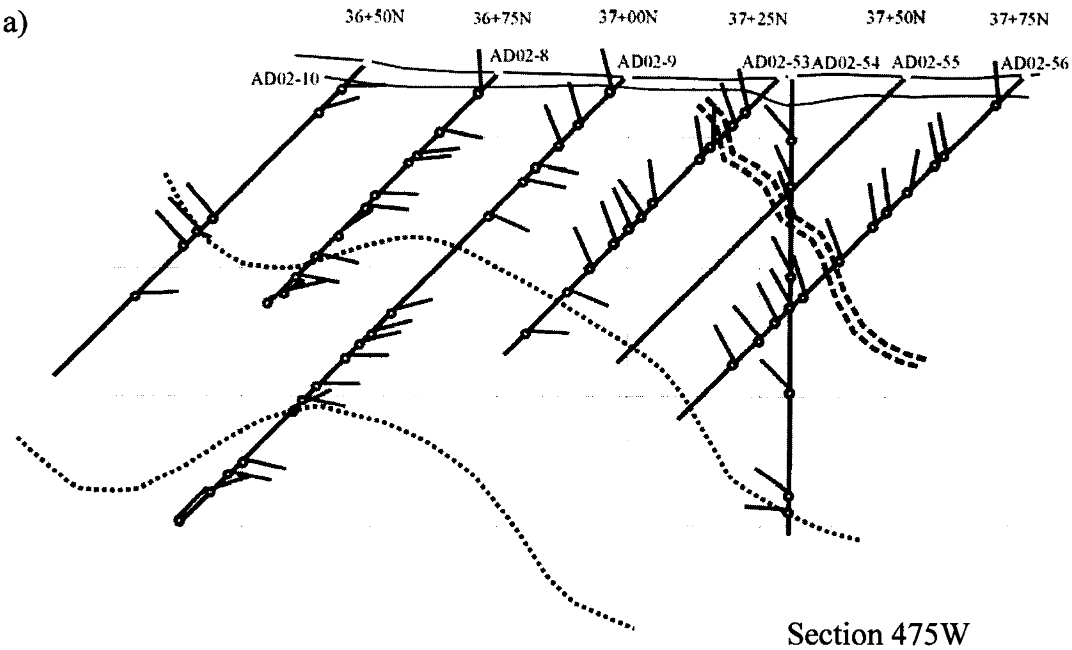


Figure 23. Example of how the choice between the two possible attitudes of bedding is made for measurements located close to the lithological surface. This example is for a bedding measurement on hole AD03-76 that makes an angle of 35° with the core axis. The radius of the small circle is then 55° since it represents all possible attitudes for the pole to bedding. The attitude of the pole of the oval region on (a) is represented by the open square on (b). The green circle on (b) indicates the correct bedding attitude.

a)



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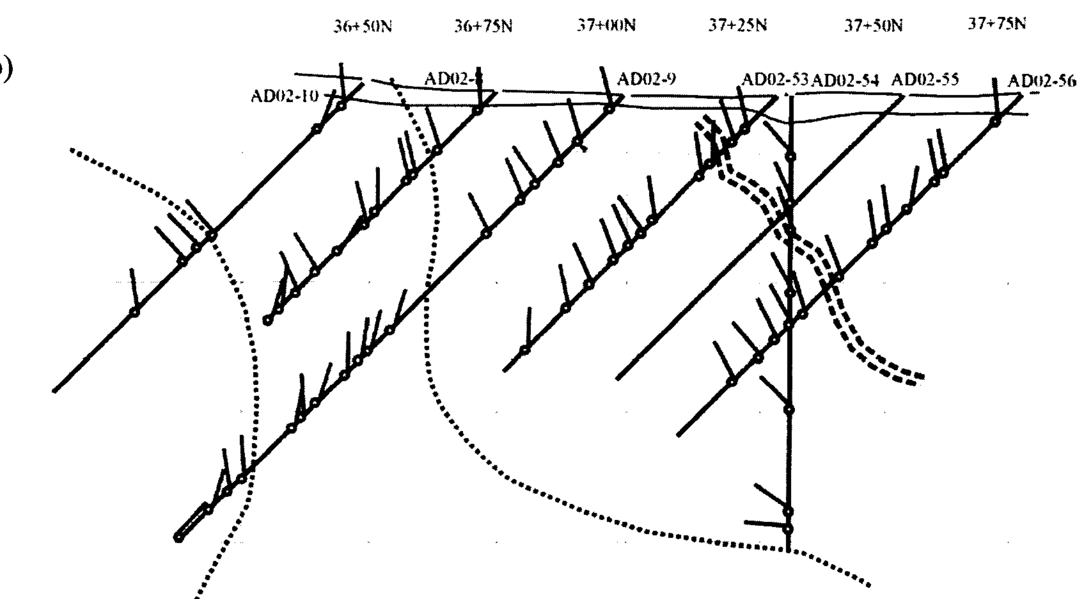

Figure 24. Example of 2 different interpretations based on possible bedding measurements. Black, green and red bars indicate bedding attitudes. Thick dotted lines represent base and top of a lithological marker (greywacke bed). Regular dotted lines represent interpreted folded bedding geometry. The dimension of each square is 25 x 25 meters.

The traces of the two possible attitudes are hence symmetrical across the drill core. In this case, one is generally dipping to the south and the other to the north if the hole is vertical, and steeply-dipping or shallowly-dipping if the hole plunges at ~45°. Part of the section on Figure 24 is well constrained due to the presence of a lithological marker (black measurements) but the southernmost part of the section is not constrained at all (green or red measurements). The choices of bedding attitudes for that part of the section are therefore selected based on a preferred asymmetry. In this case, the preferred asymmetry is the one that generates a box fold geometry (Fig. 24a, green measurements) since it is a parallel geometry consistent with the style of F3 folds observed at the surface. Although the angles of bedding traces on the section are not exact, this exercise is only used as a guide to choose between the two possible attitudes. The correct bedding attitudes (consistent with the F3 plunge) are displayed as structural palettes in *gOcad.*

Constructing F2 Hinge Surfaces

Creating Structural Palettes for Bedding Measurements

Once all bedding measurements are oriented, they can be imported in *gOcad* along with their facing information. The measurements for a given hole are imported by using the *gOcad* command "Add Well Marker from Z/ Measure depth Value" where the name of the marker, its depth, and its attitude are specified. A marker is named as follows: "AD_500W_Upward_Facing", so that the zone, the section, and the facing information of the marker are specified. All markers having the same name are automatically grouped in the same family of markers by *gOcad.* Before the markers can be displayed as structural palettes, some procedure is required. First, the markers have to be converted to a points-set using the *gOcad* command: "New Points from Well

Markers". Then, the attitudes of the markers have to be converted to orientation vectors using the *Sparse* command: "Initialize VSet Structural Graphics". The points are then converted into structural palettes using the *Sparse* command: "Dip Plane Graphics from Orientation-Atomic Group". Once the structural palettes are created, they are color-coded based on their facing information (blue: downward-facing, yellow: upward-facing, white: unknown-facing) (e.g. Figure 25).

Interpreting F2 Hinge Traces on Cross-Sectional Curtains

The traces of F2 hinge surfaces are directly interpreted on cross-sectional curtains where 3D structural palettes of oriented bedding measurements and their facing information are displayed, along with available lithological surfaces (Fig. 25). Often, the geometry of the traces is not well constrained so that other sections are consulted. Ultimately, all the sections are consulted until the geometry respects the data displayed on all sections. However, it should be mentioned that the final geometry is a function of my interpretation and that it does not necessarily represent a unique solution.

Once the traces of F2 hinge surfaces are interpreted on each section, surfaces can be built following the grip frame method described above. It is common that hinge surfaces located close to each other cross over each other due to the interpolation. These cross-overs can be corrected using the *gOcad* function "Edit Global/ Remove Cross-Overs". The hinge surfaces are then color coded (blue: anticline, yellow: syncline). The final F2 hinge surfaces can then be displayed along with the surfaces created in 2.2 (Figure 26).

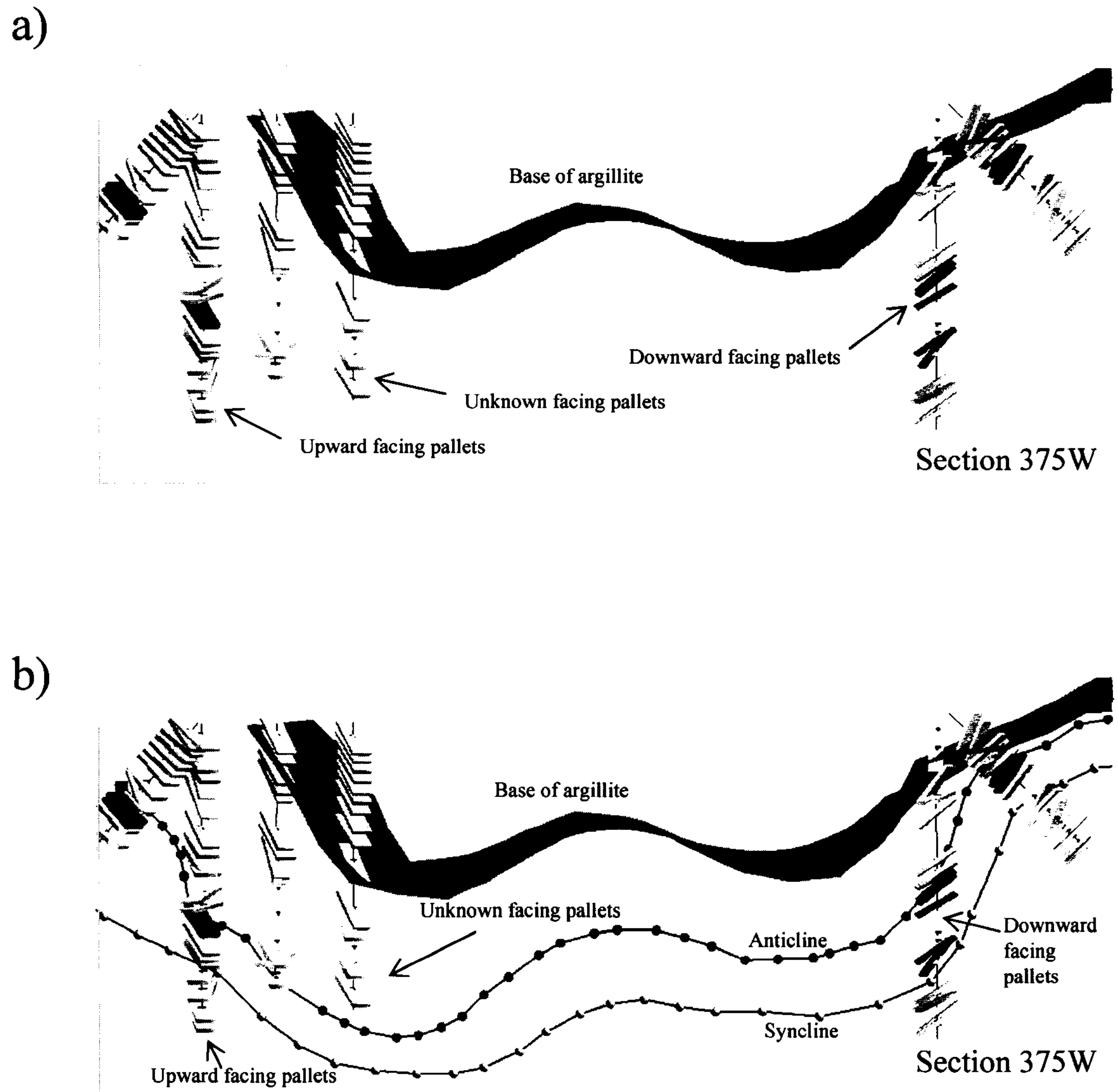

Figure 25. Interpretation of F2 hinge surfaces based on bedding attitudes and facing information. Yellow, blue, and white structural palettes correspond to upward-facing, downward-facing, and unknown-facing data respectively. Yellow and blue lines represent syncline and anticline hinge traces respectively. Grey surface represents base of argillite unit.

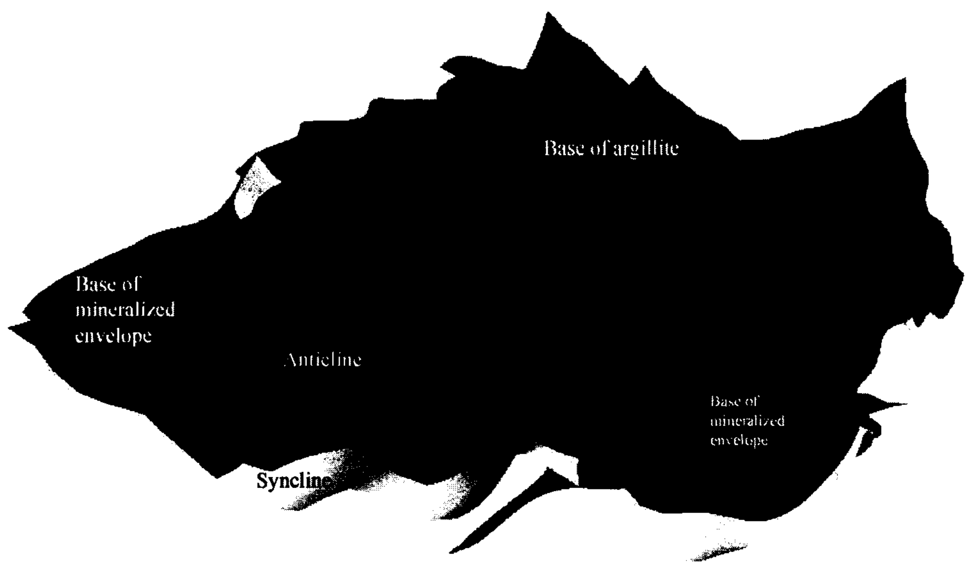

Figure 26. 3D representation of the AD/ MW Zones. Grey: base of argillite, blue: F2 anticline hinge surface, yellow: F2 syncline hinge surface, red: base of mineralization envelope.

Conclusion

The software *gOcad* with the application *Sparse* enables the creation of 3D models that are not automatic and are a function of a geologist's own interpretation. The method elaborated to generate representations of Anomaly A is unique in that it exploits ad hoc structural particularities of the deposit (e.g. the fact that drill sections are oriented sub-perpendicular to the trend of F3 fold axes and subparallel to F4 axial surfaces enables us to estimate an F3 fold axis for an entire section). Geological models constructed through a 3D engine that offers the freedom of using these ad hoc particularities are, in my opinion, ground-breaking.