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THREE-DIMENSIONAL INTEGRATION AND VISUALIZATION OF STRUCTURAL FIELD DATA: TOOLS FOR REGIONAL SUBSURFACE MAPPING

INTÉGRATION ET VISUALISATION 3-D DE DONNÉES STRUCTURALES DE TERRAIN: OUTILS POUR LA CARTOGRAPHIE GÉOLOGIQUE RÉGIONALE

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PREFACE

The primary objective of this thesis is to present techniques which could enhance geologists ability to make extended geological interpretations into the subsurface, and especially in regions which are characterized by two-dimensional surface data. Methods focus on the geological integration of field-based structural information in order to constrain the interpretation of variably scaled surfaces of geological interest. These techniques, with accompanying examples, contribute to the ongoing development of an evolving structural software 'tool-kit'. The techniques that are presented begin to bridge the gap from two-dimensional Geographic Information Systems (GIS) based geoscience visualization and modelling to three-dimensional Computer Aided Geometric Design (CAGD) approaches. Local field-based structural observations, which have regional geometric significance, are used to control the subsurface projection and propagation of map traces such as faults, shear-zones and other curvilinear geological contacts. Advanced interpolations such as B-splines, Discrete Smooth Interpolation (DSI), Bézier-based curves and surface patches, of clustered and sparse data are utilized in conjunction with knowledge-driven design tools within virtual three-dimensional editing environments (EarthVision® and gOcad®), to create simple speculative visualizations. It is these visualizations which then can be examined for geometric consistency with other subsurface data (e.g., seismic, magnetic, drill hole) as it becomes available.

The work presented is not meant to be a single system solution to the problem of regional subsurface mapping in complex terrains, but rather a means of promoting the discussion between bedrock geologists and professional software developers. Only when this discussion becomes more focused, and the needs of the regional bedrock mapping community are clearly articulated, can new interpretive tools emerge. Rigorous application of the presented techniques is beyond the scope of this study, but several idealized and actual field based examples are presented to emphasis the potential utility of the approach.

As digital map based geoscience information becomes more transferable to other agencies, explorationists and researchers, and the pressure to extract more interpretive value from geological map data increases, it becomes imperative that better tools for subsurface visualization need to be developed. The three-dimensional geometric approaches presented provide an initial path for what could become the routine combination of geological map based information, surface topographic data and the intuitive knowledge of a geological 'designer'. The results of this structural design process could add another interpretive layer to a set of value-added thematic views of an area of geological interest. The usefulness of extending two-dimensional map data into the subsurface is directly dependent on the interpretive quality of subjective mapping, the spatial accuracy of field observations, and the geometric and geologic descriptions provided in the structural field observation data set. The geological mapping community is encouraged to increase the availability and geometric information content of all field-derived data, as this is a prerequisite to future three-dimensional visualization and modelling efforts, and to project-based testing of the methods presented herein.

PRÉFACE

Cette thèse a pour but principal de présenter diverses techniques visant l'amélioration de l'interprétation géologique selon la profondeur, ceci particulièrement dans les régions caractérisées par des données clairsemées. On y présente diverses méthodes développées à partir de l'intégration géologique de l'information structurale de terrain ceci afin de contraindre l'extrapolation à partir de la surface selon différentes échelles et l'intérêt géologique. Les outils présentées ici, accompagnés d'exemples d'applications, s'inscrivent dans un processus continu qui évolue rapidement dans le domaine de la programmation structurale et qui vise l'implantation de toute une gamme d'outils de représentation et de modélisation tridimensionnelle. Les techniques présentées dans cette thèse visent à combler l'écart entre la visualisation et la modélisation géoscientifiques basées sur les Systèmes d'Information Géographique (SIG) à bidimensione et les approches tridimensionnelles de Conception Géométrique Assistée par Ordinateur (CGAO) qui sont, à l'heure actuelle, plus communément utilisées par l'industrie pétrolière. Les observations structurales effectuées localement sur le terrain ayant une signification géométrique régionale, sont utilisées afin de contrôler la projection vers la sous-surface et la propagation variable de tracés cartographiques tels les failles, les zones de cisaillement et autres contacts géologiques curvilignes. Des interpolations perfectionnées (courbes B-splines, DSI, courbes de Bézier et carreaux de surface) de données en grappe et clairsemées sont utilisées en correspondance avec des outils de conception dictés par la connaissance et contenus dans des éditeurs virtuels tridimensionnel (EarthVision® et gOcad®), ceci afin de créer des images spéculatives simples. Ce sont ces visualisations qui peuvent alors être vérifiées pour leur cohérence géométrique avec d'autres données de la sous-surfaces (données séismiques, magnétiques, et de levés de forage) à mesure que ces données deviennent disponibles.

Ce travail ne représente pas une solution absolue au problème de cartographie régionale de la sous-surface en terrains complexes, mais plutôt un moyen de promouvoir la discussion entre les géologues du substratum rocheux et les concepteurs professionnels de logiciel. De nouveaux outils d'interprétation verront le jour seulement lorsque cette discussion deviendra plus spécifique et que les besoins en visualisation tridimensionnelle de la communauté seront mieux exprimés. L'application rigoureuse des techniques présentées dépasse le cadre de cette étude, mais plusieurs exemples théoriques et réels dérivés du terrain sont présentés afin de démontrer l'utilité de l'approche.

À mesure que l'information géoscientifique dérivée des cartes numériques devient plus facile à transférer d'un organisme à l'autre et entre spécialistes de l'exploration et chercheurs, et que la pression d'extraire des données de cartes géologiques ayant une valeur interprétable augmente, il devient essentiel de développer de meilleurs outils pour la visualisation de la troisième dimension. Les approches géométriques tridimensionnelles présentées dans le cadre de cette thèse fournissent une première voie de ce que pourrait devenir la combinaison de routine de l'information dérivée de la cartographie géologique, des données topographiques de surface et de la connaissance intuitive du 'concepteur' géologue. Les résultats de ce procédé de conception structurale pourraient ajouter une autre couche interprétable à une série de vues thématiques à valeur ajoutée d'une région d'intérêt géologique. L'utilité de prolonger les données cartographiques bidimensionnelles vers la profondeur dépend directement de la qualité interprétable de la cartographie subjective, de l'exactitude spatiale des observations de terrain et des descriptions géométriques et géologiques provenant de l'ensemble des données d'observation structurale effectuée sur le terrain. La communauté de cartographie géologique est encouragée à augmenter la disponibilité et le contenu de l'information géométrique de toutes les données dérivées du terrain, puisque ceci représente un prérequis aux efforts futurs de visualisation et de modélisation tridimensionnelle et à la mise à l'essai basée sur les méthodes présentées ci-après.

Abstract

Three-dimensional computer modelling of geological phenomena is rapidly emerging as a field within the already mushrooming science of computer visualization. In geological applications three-dimensional interpretations are routinely performed through the use of two-dimensional map data and knowledge about the geological history of an area. These interpretations are traditionally depicted with isometric or perspective block diagrams and vertical or horizontal cross-sections. Constructing these three-dimensional snap-shots has been laborious, imprecise and limited to a single viewpoint. The methods presented here automate some of the more laborious tasks and enhance the three-dimensional interpretation environment. Methodology focuses on using field-based structural data, from a variety of scales, to create speculative three-dimensional surfaces that can be useful in addressing geological problems. These methods could help in resolving cryptic early fold geometry, extending stratiform mineralization and the subsurface interpretation of regional thrusts, unconformities or key lithostratigraphic boundaries. Several UNIX based programs are presented for performing the interpolation, extension and conversion tasks required in these approaches. Programs are implemented in conjunction with the commercial three-dimensional visualization and modelling software EarthVision® and gOcad®. Algorithms focus on the densification and variable projection of distributed three-dimensional data which share a common curvilinear geological feature. The result of the various interpolation and extension functions is the conversion of two-dimensional lines to three-dimensional surfaces.

A polynomial and hybrid B-Spline interpolation technique optimizes geometric property components. The automated data-driven technique is applicable for geological problems in which structures are constrained by local linear and planar measurements. Input features are topographic intersections of relatively continuous irregular curved surfaces, which have a near linear known depth predictability at some point along the structure. The local direction cosine estimates derived along surface traces of geological structures are interpolated, and direction vectors linearly projected to depth to form local

structural surfaces or 'ribbons'. The program is useful for depicting portions of variably plunging fold geometries as structural ribbons, which in-turn act as visual guides during interpretive fold construction. Idealized and actual field examples of regionally continuous shear zones and brittle faults are presented, along with the development of three-dimensional structural fabric trajectories, horizon propagation, and plutonic boundary geometry evaluation.

Semi-automated techniques are utilized with knowledge-driven interactive graphics. An interpretive or 'design' approach to surface construction is applied to low density data sets which are too sparse for standard global automated interpolation. Bézier curves and surface patches are implemented to act as interpretive construction lines that respect the constraints imposed by structural orientation data. The programs *hinge.awk, cast.awk, bspline.awk* and *bezpatch.awk* calculate the interpolated values from the spatial input data. Three-dimensional construction lines are defined by tangents to local planar features, and the projection of key geologic structures. Supporting the interpolation tools, the program *trace.awk* estimates the local strike and dip of vertices along elevation registered three-dimensional curvilinear map traces. The planar solution method can be applied in high-relief terrains, or to extend three-dimensional curvilinear features from sub-surface mining data.

Techniques are applied on field data from the low-relief and structurally complex Archean Abitibi greenstone belt. Speculative models can be created from such terrains, provided data is respected and appropriate methods are applied at a given scale. The field component focuses on extracting data from maps and optimizing the three-dimensional graphic editing environment for making better interpretations at outcrop, mine and regional scales.

Applied techniques used in this study include:

- *Three-dimensional structural symbology*: the visualisation of three-dimensional structural symbols representing point observations of bedding, lineations and foliation fabrics,

- *Structural attribution:* the attachment of structural point observations to linear features through the use of a proximity filter. This is done with the program *field.awk*,
- *Variable down-plunge projection*: the construction of custom down-plunge projections from surface traces,
- *Bézier-based graphics:* examples of interactive three-dimensional interpretations with Bézier-based curves,
- *Hybrid surface design:* a two-step approach to three-dimensional geologic surface design using both Bézier patches and discrete smooth interpolation (DSI), constrained by map traces and local slopes,
- *Three-dimensional Map propagation:* a method for propagating map elements using two-dimensional map data and field-based plunge models. The program *dive.awk* is presented as an example of a simple propagation.

The results of this study indicate that a constrained-interpretive approach to three-dimensional visualization is valid for interpreting large to small-scale geological structures, even if the data base is limited to two-dimensional map-based information. This geometric approach provides an initial development path for what could become the routine combination of extracted geological map based information, surface topographic and structural data, and the intuitive knowledge of a geological 'designer'. The developed techniques listed above and presented in this study enhance the field-based geologists ability to create communicable three-dimensional models of complex surfaces. Regardless of the state of visualization technologies, the success of three-dimensional geological modelling is still dependent on the data density, clustering and depth variability of known structural observations. Most important perhaps are the geological relationships of local and regional structures with the bounding surfaces being modelled. New software will be needed to assess the quality of geological models based on these input parameters.

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CHAPTER 1

Introduction

1. Introduction

This thesis is a contribution to the problem of subsurface mapping, providing numerous new approaches useful in regional geological mapping. Data used in the study is sparse, and representative of areas where subsurface relationships can only be inferred from surface mapping due to the lack of seismic, deep drill hole or mine excavation data. The approaches combine traditional structural interpretation methods with modern computer graphics techniques that are largely adapted from Computer Aided Geometric Design (CAGD). The approaches presented in the thesis are in no way meant to, nor are they able to, replace field-based or remotely sensed investigations. The approaches are meant entirely as a supplementary, but beneficial process to better conceptualize, communicate and test what is intuitively developed during the course of typical geological investigations.

Regional bedrock mapping is part of the ongoing geoscience program of governmental, academic and industrial institutions world-wide. Driven by the ever present need to resupply non-renewable mineral resources, and the need to understand the fundamental natural processes that shaped the Earth, regional bedrock mapping has become an expensive, multidisciplinary and inter-organizational endeavor. It has also become increasingly supported by emerging remote acquisition and informatics technologies. For example, a significant portion of Canada's regional bedrock mapping has been supported wholly, or in part, through LITHOPROBE, Canada's deep crustal seismic imaging program (Clowes et al., 1984). Satellite and airborne multi-spectral (e.g., SPOT, TM, Hyperspectral), microwave (RADARSAT, ERS1) and geophysical (MAGNETICS, GRAVITY, EM, MT) imaging technologies have provided the much needed objective regional geoscience support to more 'subjective' field-based geological investigations. The multidisciplinary and inter-organizational nature of regional mapping (e.g., NATMAP; St-Onge 1990) has benefited from the use of accurate digital topographic base maps, Digital Elevation Models (DEM), field-based data capture software (e.g., FIELDLOG©; Brodaric 1997), automated positioning and mapping through use of Global Positioning Systems (GPS) and Computer Aided Drafting (CAD). Over the last decade, many national geological surveys, and exploration corporations have also invested in the creation of Geographic Information Systems (GIS) compatible knowledge bases (Broome 1998; Brodaric, Johnson and Raines 1998; Zepic et al., 1998; Asch 1998; Knox-Robinson and Wyborn, 1997). Valuable geoscience information in the corporate depositories are being used to represent and analyze broad-scale geological features for mineral exploration and regional geologic compilations (Lewis 1997; Wright, Chorlton, and Goodfellow 1997).

Corporate GIS activities complement field mapping and laboratory-supported investigations such as U/Pb geochronology and geochemistry, to generate excellent science, and as a by-product, better quality, high resolution bedrock maps. Regional geological maps are, however, only representations of a thin slice of the Earth's present-day upper crust. Without further interpretations they provide little communicative information about the subsurface distribution of mapped rock types or tectono-stratigraphic evolution of an area to the non-expert.

The more difficult campaign on the horizon for the geoscience community is in extending our regional mapping into the subsurface, similar to that undertaken in the oil and gas sectors with isopach, structural contour and 3-D lithologic isosurface representations, and in time, through paleogeographic and palinspastic reconstructions. Having the capacity to visualize the complex structural and lithological relations that exist in 3-D, within the top few kilometers of the subsurface in any given region, would be of tremendous benefit. This is the zone from which mineral exploitation is economically and technologically feasible. It is also where complex spatial and temporal geological relationships are expressed in a 3-D geometry, that if known, could better constrain a complex lithospheric history. Extending regional mapping into the subsurface is not a new idea, as demonstrated by the early alpine workers such as Argand (1922) who understood mapping as not just documentation, but interpretation. Providing a complementary approach whereby 3-D mapping begins to be possible even in low relief terrain with limited outcrop, is a realizable goal for future geologists. This thesis presents some of the essential methods that will be needed as 3-D subsurface mapping becomes more important.

1.1 Needs for 3-D visualization

1.1.1 Mine-scale interpretation and visualization

It is difficult to directly observe the earth's subsurface structures. It is however our mental picture of what these structures look like, and how they evolved into present day geometry that drives broad geodynamic and mineral exploration models. For example the paleogeometry of a subduction zone has a direct impact on mineral potential models of upper-plate rocks. Exposure to metal bearing hydrothermal and altering metamorphic fluids, the development of regional high-strain zones that focus metal migration, and input of significant heat sources from ascending subduction related magmas, are all directly dependent on down-going slab polarity and angle (Polat and Kerrich, 1997; Moore, 1996; Nelson, 1996).

At the local scale many existing deposits are very well constrained geometrically through extensive drilling and seismic surveys. A medium-sized mine could have upward of several hundred kilometers of drilling through the main ore body. Also a mine could have over a dozen level workings along drifts, shafts and chamber excavations. These are geologically documented as soon as new observation surfaces are exposed, and used to spatially constrain the major geological units, and the main ore zones. In open pit situations the subsurface structures are slowly revealed at the work site. With time, and steady documentation throughout the extraction of the ore, it is possible to construct a reasonable geometric picture of the geology. These opportunities however do not give us the complete 3-D picture in itself, such as, for instance, a pathologist's autopsy of an internal organ. In the case of an autopsy, the entire object is extracted and directly experienced. In mineral exploration and ore reserve estimation, geologic interpretations are still needed. Mental or computed interpolations, and extensions are still required no matter how dense the drill core spacing. Rock characteristics from drill core, such as lithology, density, mineral type and abundance, are typically projected on to an interpretive plane. Spatial errors occur during these operations, depending on the logging techniques, the distance used and the direction of the projections to the interpretive planes. Rarely do interpreters use the entire drill core data set, or a buffered corridor of 3-D drill data, to directly interpret the plane sections, something which is possible in 3-D editing environments. Projection directions of the drill core properties onto sections are rarely defined on geological grounds, such as structural grain, but rather by a normal to the section. This results in a nearest distance plot of the data that for most applications is fine. More complex folding however, will result in a locally variable structure grain where simple shortest distance attachments of drill data to section planes can result in misrepresentation of the data.

Consequently, there is a need for data from drill cores, mine workings and open pits to be visualized directly in a 3-D interpretive environment, and explored before the data is extended onto the sections. Also, sections need not be vertical or horizontal but should be oriented to be the most useful for interpreting the structure. Usually this is along a down-plunge view, or across the main structural grain. In fact, there is no reason interpretive surfaces need be extended planes. It could be that important map units intersect a curved surface, such as a late, normal fault, and the drill core which pierces this non-planar surface needs to be interpreted directly. This on-surface interpretation capability is a feature of true 3-D editing environments. It is clear that this would be more useful than trying to do all the interpretations through 2-D views of what is inherently 3-D data.

There is also a need at the mine scale to examine 3-D data with the aim of discovering hidden geometric or property relationships that control ore distribution. Undertaking this examination with only sectional views is not tenable. For example an early fault which may have acted as a hydrothermal conduit for metal transport may at present be highly folded and offset by later faults. The mineralized envelope surrounding this early structure needs to be examined to determine what mineral abundances are present, and if there is some important spatial relationships to the fault surface. Individual sections may or may not represent key relationships, whereas proper symbolization of the drill core assay values and a 3-D surface representation of the complex fault could expose a critical relationship from a simple visual inspection in a 3-D viewer. If this were the case, further more quantitative sensitivity analysis could be undertaken to see what other properties may be influencing the ore distribution. For this approach, exact 3-D proximity and distance calculations would be needed along with a complex graphics engine to represent the relationships. Ore distribution is a 3-D and, considering time, a 4-D phenomena, and needs to be examined from more then a 2-D perspective as would be the case when examining mine data from sections alone.

1.1.2 Regional mineral exploration

All mines have a geological context which situates them in a broader geometric framework. Regional-scale folding, fault networks, stratigraphic position and proximity to intrusive bodies are all important components that control the geometric extent of ore in 3-D. Although the conceptual connections are vital to genetic modelling of the ore, it is a challenge to connect mine and regional-scale features spatially. This is because regional data is almost always 2-D and mine data is localized and 3-D. In addition, a mine may not have all the regional components, such as a specific marker unit, transecting the mine volume that may be detected by drilling or excavation.

However, it is still useful from a heuristic point of view to use conceptual models, backed up by surface data, that can accurately position the ore body in a regional perspective. This is vital in defining metalogenic domains and predicting the extent of mining camps. 3-D construction of regional structural models from 2-D map data would be extremely useful in characterizing these domains. For example, key regional surfaces are often used as an exploration guide as they can act as a constraining envelope to mineralized zones. The modeled regional surfaces may extend beyond local exploitable depths, practically less then 800 meters for a new deposit, yet there is a possibility that the surface may be exposed tens or hundreds of kilometers away in an area that could be exploited. Therefore it is worth while to attempt to develop a 3-D regional model beyond the mine site.

Mining data is proprietary, and usually managed separately at individual mines. It is rare to obtain a consistent geometrically leveled data base of 3-D drill, plan and section interpretations and geophysical data that transcends more than a single mine. It is rarer still to find such data that crosses property owner boundaries and includes public data at a regional scale. The geological features that control ore distribution on these properties are however almost always regional in scale (10-100 km). The need to establish regional controls on local mineral distribution is of fundamental importance. Nevertheless most of these studies are 2-D studies seeking to establish relationships by examination of maps. With 3-D visualization and modelling methods it is now possible to combine existing 2-D regional field and mine property data using integration techniques, to ensure that broad scale relationships can be established at the mining camp level.

1.1.3 Natural resources exploration

Natural resources exploration initiatives can occur at many scales. At the mine scale (1-5 km) dwindling reserves drive the need to develop new models to extend the life of a mine. The focus for individual mine exploration is on the local data set; geometric extension of the ore bearing horizons or controlling structures, more drilling and costly exploratory geophysics. At the mining camp scale (5-50 km) thematic studies (e.g. EXTECH industrial-government-academic studies, Wright et al. 1997) may focus on geophysical and high-resolution surface mapping to structurally and stratigraphically link specific deposits. At regional (50 ~ 250 km) and crustal (250 - 5000 km) scales, lithotectonic assemblages are examined through lithostratigraphic correlation studies, geochronologic studies, geophysical compilations and targeted field mapping. The approach provides a coherent, broad geological view within the context of a single or multiple orogenic events. Exploitable mineral resources are discovered by engaging in exploration at all these scales and coming up with a synthesis which puts local deposits into a broad geologic framework. Exploration success is dependent on the quality of this scale-independent synthesis, and the ability to keep the underlying processes in mind.

3-D visualization and modelling tools complement the synthesis effort. For example, instead of representing a lithotectonic assemblage boundary as a linear trace on a 2-D map it could be represented as a 3-D surface extended into and above ground. Representing map traces this way, as a ribbon, requires geological knowledge about the character of the boundary and its orientation. Through such a representation, the integration of the broader-scale geologic model is more likely to be consistent with local field observations. An integrated approach is exactly what is needed to link a mineral deposit, that may be completely within an allochthonous hanging wall volume of rock, to an orogenic-scale terrane boundary. Linkages of local phenomena to broad geologic concepts are easily communicated to the non-specialist with a 3-D representation. Without this possibility, we are left with showing clients 2-D maps, which most non-scientists find confusing, or cartoon sketches that may be 3-D, but do not directly link to map features and are single conceptual view points.

1.1.4 Geological evolution

Geological processes occur through space and time. The preserved history is recorded in discrete volumes of rock that may or may not be arbitrarily exposed at the Earth's present-day surface. The end point of a geological history is the present configuration of fabrics, bounding surfaces to volumes, and the rock property distributions that distinguish the volumes. The challenge of all geologists is to unravel what may be a long and complex sequence of events that led to this final state, and in the case of geological hazards, perhaps extend interpretations into the future.

All forms of modelling require a target data set to which the model can converge. The simulation of a geologic history is beyond the scope of this thesis study, however by providing a fuller description, through 3-D visualizations of the end point geometry, there could be better constraints to these simulations. Georeferenced 3-D models are more useful than 2-D geologic maps for unraveling the geological evolution of an area, provided that important features can be represented. Geologic processes never create a geologic polygon, yet a polygon is the most common depiction of a geological unit. For example, rocks which formed from the cooling of a volcanic flow during a single modern eruptive event can be depicted as a single rock unit over a broad area. The unit may be represented as a polygon or series of separate polygons on a map. This representation is a vertical projection of the locus of sub-aerial exposed volcanic flow limits onto a horizontal plane. However, the flow is in fact a volume, with upper and lower bounding surfaces that display continuously varying elevation. The limits of the flow may also extend further beyond the map representation in subsurface caverns, and below ice or water. The lower bounding 3-D surface is the old topographic surface and the flow top is actually new topography. From a geological evolution perspective, more can be done with the 3-D model in this case. Detailed flow direction vectors can be computed and volumetric calculations are more accurate. Many dynamic perspective or isometric 3-D views of the flow could be generated, which a non-expert can readily appreciate. Alternatively with 2-D map data, the analysis and representation are based on fixed overlay representations, depictions through structural contours, and 2 1/2-D GIS based analysis that can be computationally cumbersome.

At orogenic scales, such as a converging plate margin, deep seismic events can be interpolated into a continuous surface, and represented in 3-D along with other map-derived structures such as a major regional fold axis. Without using any statistical methods, in a 3-D visualization environment, the geometry of upper crustal structures, axial planes and fold vergence can be compared to the deeper crustal architectures along the modelled subduction zone. By representing map traces as surfaces and map units as volumes, the geologist is given an expanded view of rock relations both geometrically and temporally, which compliments the documented 2-D map relations. When complete volumes of rock can be extracted from a 3-D model, and rendered with a rich variety of symbolization schemes, it is possible to highlight an important tectonic, intrusive or depositional event that may provide some insight to the geologic evolution.

1. 2 The problem

The problem addressed in this study was the inadequacy of 3-D surface generation tools to meaningfully represent common geological structures. Representation of these structures for regional bedrock geologic mapping is difficult because data is not dense, is poorly distributed, and if available is often not properly used. The primary field data set from which map interpretations are made is generally poorly distributed for the scale of the mapping. It is not uncommon for data gaps to exist where it is really needed to constrain the more complex geometry of a structure, and over-abundant in simple structures, where dense control is not too critical. The problem of modelling complex geometries with limited data sets has not been adequately handled by existing software for regional-scale structures. Advanced visualization and modelling software such as EarthVision® and gOcad® that are used in this study are ideal for working with dense data sets (e.g. oil wells, subsurface mine data) and less complex surfaces. Although significant advancements have been made in treating complex fault networks, individual fault surfaces in these systems needs to be quite simple.

The oil, gas and coal industry which captures most of the 3-D geoscience modelling market, has been able to direct software development to deal with a level of structural complexity that is typically encountered in the most profitable regions. For the bedrock mineral exploration and mapping sectors a more specific suite of tools is needed. New functions are needed to visualize the structurally more complex geology that is often represented with sparse regional field data. However more rigorous subsurface interpretations could be conducted in complex terrain with the expansion of the existing 3-D tool-kit. Furthermore, expansion of the tool-kit would open the regional mapping and mineral exploration communities to the dynamically evolving field of scientific visualization.

1.3 Thesis objectives

The objectives of this study centre around the development of methods or techniques that will enhance better quality 3-D interpretations of geologic structures. Improved interpretations were anticipated by developing methods, that at a minimum, constrain spatial locations of modelled surfaces to the mapped geology, and the local slope of modelled surfaces with observed structural data. The objective was to create geologic surfaces from maps, resulting in a more rigorous methodology for the conversion of 2-D map-based data into 3-D rendered representations.

Surfaces can be tectonic, lithostratigraphic or igneous boundaries, but the key notion is that curvilinear representations of these features on a 2-D map are only expressing the eroded surface intersection of a much more extensive geologic surface. The goal was to provide new approaches and methods that perform the 3-D interpretation of that geologic surface in the subsurface by using advanced geometric extension and interpolation techniques. In summary the aim of this thesis was to test if 2-D data could be interpolated and extrapolated into the third dimension with the use of modern computer graphics techniques.

1.4 Methodology

The approach was to choose a map-based geological problem for which structural data existed or could reasonably be acquired, and attempt to make 3-D interpretations by extrapolating towards depth. Structures typically encountered in the course of regional bedrock or mining exploration mapping programs at ground surface provided data for this investigation. Surfaces in these regions can be overturned, with more than one depth intersection. Commonly surfaces are characterized by variable plunge having been subjected to polyphase deformation. Surfaces may also demonstrate complex interference patterns in which stratigraphic markers are repeated, in near vertically dipping geometries. Most importantly these structures are interpreted with an extremely limited data set exposed at the earth's surface.

3-D visualization and modelling software is a mature, well developed technology in many earth science applications such as oil and gas exploration, civil engineering, environmental studies and geologic hazards (Mayoraz 1993). Much of application development has been undertaken with the assumption that input data to model construction is 3-D and of a high density. However, most mining exploration and regional mapping programs do not have dense data. 3-D seismic methods for example are only recently becoming popular in mine exploration. If 3-D data, which is essential to accurately determining subsurface geometry, is available, it is nevertheless not a standard input into 3-D modelling and visualization packages, and as a result, often becomes ignored. The more typical situation is one in which the working data set is comprised of sparse, and clustered structural field data, with some interpreted geological contacts.

Industry standard software was used (EarthVision® and gOcad®) as graphics and integration tools, along with ArcInfo®, AutoCAD®, Fieldlog©, and Arcview® software for managing and extracting 2-D GIS data from the various maps. External programs were written in *awk* (Dougherty 1990), as new functionality was required. The *awk* programs that emerged from the study were planned to be portable, and readable by other software developers. The purpose of each program was to demonstrate with idealized, or field-derived data, a particular aspect of the data integration and improve the software so that valid 3-D map interpretations were possible.

The programs developed in the course of the thesis focused on the following:

1. Conversion of 2-D GIS based points, lines and structural attributes into 3-D.
2. 3-D symbolization of structural observations.
3. Extension by field constrained projection of map traces.
4. Construction of 3-D structural ribbons.
5. Use of sparse data interpolation and interactive editing curves (Bézier based construction curves).
6. Interactive surface editing approaches (Bézier patches and DSI interpolation).
7. Map element propagation techniques for modelling non-cylindrical folds.

1.5 Overview of thesis publications

The three published papers related to this Ph.D. thesis are directed towards 3-D earth science software developers and field-based structural geoscientists who are interested in advanced visualization. The central problem of creating geologically representative surfaces from sparse field data is the unifying theme. The papers provide an articulation of this problem, along with a series of approaches to the problem, and some actual examples of how techniques could be of benefit to the regional mapping community. Each set of techniques is a partial solution to surface development through the assignment of constraining field data by a geological expert. The focus of each paper is on surface rather than volume development, since volumes can generally be easily defined once the component surfaces are in place. More importantly, many key geological surfaces are expressed as 'map traces' when interpreted through a given field area. A map trace, in this study is presented as an intersection line between two surfaces, a topographic surface and a geologic surface. Exploitation of the geometric relationships between these surfaces and/or the associated structural data is common to all techniques. These reasonably defined geologic traces are easily extracted from maps and often have geometric field observations associated with them. Line work from maps, digital elevation models derived from topographic contours and tabular field data bases are employed in the generation of surfaces in all papers. The techniques build on those previously presented, starting with variable geometric projection (VGP) in the first paper, the computation of local trace geometry and the use of Bézier construction curves in the second, and finishing with the regional scale 'propagation' of map elements in the third paper.

Collectively the programs and approaches presented in the three papers form a 'tool-kit' for structural visualization and modelling of map-based data. Each paper treats a specific set of data and develops techniques that provide a possible avenue for structural visualization. The first 2 papers utilize both theoretical and real data sets, and focus on the attribution of 2-D data with elevation values and structural properties, advanced linear projections and 3-D Bézier-based design functions. The last paper presents a case study using field data collected by the author, and previous workers in the northeastern Abitibi subprovince. It presents the culmination of all the techniques articulated in the previous papers, along with a method for down-plunge propagation of map traces for regional non-cylindrical structures.

The first paper '*Variable 3-D geometrical projection of curvilinear geological features through direction cosine interpolation of structural field observations*' (de Kemp, 1998) presents a method for extending geological features such as faults, lithostratigraphic boundaries, or plutonic contacts. Geologic features are extrapolated at depth through a controlled variable geometric projection (VGP) which respects locally relevant structural field observations such as plunge and down dip directions.

The second paper '*Visualization of Complex Geological Structures using 3-D Bézier Construction Tools* ' (de Kemp, 1999) presents a scenario using CAGD tools for shaping curved geological surfaces. A series of examples is presented in which user defined 3-D curves form the graphic skeletons of more complex continuous geological surfaces. The examples start with simple Bézier curves and move toward more complex B-Spline curves. This constructed skeleton thus forms a dense enough framework from which standard interpolation techniques can be used to make continuous surfaces.

The third paper *'3-D visualization of structural field data: Examples from the Archean Caopatina Formation, Abitibi greenstone belt, Québec, Canada'* (de Kemp, 2000) implements VGP as structural ribbons in gOcad®, which are used as initial guides in the 3-D editing environment at the outcrop scale. Bézier surface patches are used for visualizing a mine scale F1 fold closure, and a new technique is presented for the modelling of a regional scale F2 non-cylindrical fold. Each scale uses field-based structural observations to constrain the modelled surface such that simpler projection methods used at local outcrop-scale yield to a more complex regional-scale 'plunge-model' propagation of map elements.

1.6 Results of investigations

The principal result of this investigation is a series of programs, refered to as *awk scripts,* for which 2-D map data is converted into the 3-D environment. Additionally, a general methodology for the treatment of map based structural data is developed for which present commercial software is inadequate. The publications explain the various methods.

The first paper *'Variable 3-D geometrical projection of curvilinear geological features through direction cosine interpolation of structural field observations'* (de Kemp,

1998) focuses on the technique by which field measurements such as a set of variable plunges of mesoscopic fold hinges can be used to constrain a projected surface. One of the most important results is the notion that projection functions can be easily adapted to incorporate clustered and varying field data. It is accomplished by first attaching structural field measurements to specific graphical elements, such as a trend and plunge of a mesoscopic fold hinge to an adjacent point on a map-scale fold trace. Constraining geometric points on the graphic object are then extracted from the spatial domain, and the direction cosines interpolated with spline techniques which respect the values of the controlling field data. Subsequently, continuous values are reconstituted into direction vectors that fully populate the graphics object and can be used to individually translate the vertices of the graphics object.

The method is an improvement over averaging structural field data (Charlesworth et al. 1975) with respect to simple uniaxial down-plunge projections, but it is still a fairly simplistic approach. The variable geometric projection (VGP) technique works well for structures which are essentially 'conical' or 'locally-linear', and is of benefit for visualizing these structures. Structures which have variable plunge at depth are not directly modelled with VGP. Projection lines from VGP can however be useful as visual guides by defining 'cross-over' regions where closures should exist in non-cylindrical structures (e.g., sheath folds, poly-deformed folds, regional intrusive contacts).

Implementation of the VGP method was a first step to visualization of a complex surface. As a fully automated method, it can be used on large data sets and the actual program *push.awk* can also calculate simple uniaxial projections. The skeletal framework from the projection method is used to create structural ribbons that are demonstrated in the third paper. There, they are used to represent a F1 axial trace. Ribbons provide a simple approximation of the near ground surface geometry of map traces, both in the subsurface and in the air. They are useful guidelines during more advanced 3-D interpretations. Most surfaces however are not locally linear for any great depth but become curved at depth. Instead of using simple linear projections, design curves are employed when interpreting structures at depth. This was the focus of the second paper.

The second paper '*Visualization of Complex Geological Structures using 3-D Bézier Construction Tools* ' (de Kemp 1999) presents the case for using interpretive and interactive graphics design tools in shaping complex poorly constrained geological surfaces. The Bézier-based design tools that are presented have been actively employed in the Computer Aided Geometrical Design (CAGD) community for several decades and are widely used in 2-D desktop graphics, 3-D engineering and animation software. Design tools of this nature fall under the umbrella of 'parametric' graphic techniques. Parametric graphics are defined by the geologist with a few spatial control points and grip handles which effectively move a given curve or form surface towards a geologically meaningful representation. Bézier, de Casteljau, B-Spline curves and surface patches, coons patches, and non-uniform rational B-splines (NURBS) are all parametric design tools that are not in wide use in advanced earth science visualization and modelling software. Parametric graphics can be useful in sparse data situations, for which design applications, in which smooth aesthetically pleasing forms can be shaped with just a few control points. The parametric design oriented graphics are therefore not of great benefit to Petroleum applications, which usually have a wealth of data. Data densities in oil and gas applications are often adequate for fully automated interpolation using minimum tension (EarthVision®) or discrete smooth interpolations (DSI-gOcad®).

Other reasons for not including parametric design tools in earth science 3-D modelling software are perhaps more technical. The Bézier based graphics presented in this second paper are 'parameterized' graphics, making them difficult to handle computationally. This means that each graphic object can be described by incrementally adjusting a single parameter or variable; for curves (t), or two variables (u, v) for surface patches and more for properties (u, v, P1, P2, P2...). The spatial density of the graphics will be determined by the resolution of each of the 'parameterizations'. A simple Bézier curve with 3 controlling points could have 100 points on the curve if it was parameterized (t) from 0 to 1 at a resolution of 0.01 parameter spacing. The common approach for graphics design software is to store only the control points, the curve method and the parameter spacing or specified resolution (Farin, 1997) which facilitates efficiency in terms of memory space and computational resources. If a model is rotated, only the defining elements are transformed. When resources are available the curve can be re-parameterized.

However, if larger objects are created by seaming together individual parametric graphics, problems may occur. Calculating the volumes from enclosing parametic surfaces for example, can be computationally very demanding. Graphics objects can have differing resolutions (e.g., mesh or grid densities), resulting in edge inconsistencies and instabilities with composite surfaces, that bring about problems when defining 3-D volumes. A high degree of precision is needed to control the parametric objects. Implementation of high precision graphics is costly in 3-D space when double-precision values are required in 3 directions over geographical coordinate ranges. Precision issues also impact on non-parametric surface generation methods, but because of the dynamic nature of parametric graphics, these problems become especially acute. The proposed solution from this research is to use parametric tools only where needed, and only at the initial design stage, and then to convert to atomic-based graphic objects.

Hybrid parametric graphics construction methods employed during iterative geologic interpretation will no doubt increase the overall computational requirements. The impact of introducing new methods, which are computationally costly, will have to be assessed, and the benefits of more intuitive graphics tools must be demonstrated in real projects. Parametric tools for the earth science may also need some added constraint functions to ensure that boundaries of surface patches are respected, but in general, it should be possible to store and manipulate the parameterized surface or curve as a separate fully described spatial object (e.g., atomic-based). Component parameterized surfaces are then combined into more extensive surfaces, which are no longer parametric objects, but a subclass of an entirely new geological object. These converted surfaces are simply sets of 3-D points in space, or connected triangulated meshes. No control-point parameters need be associated with this type of converted surface.

The result of this component of the study was the identification of the need for a set of interactive parametric functions that compute primary frameworks or graphic skeletons that match map traces and geometry observations. Without these functions, 3-D interpretations become cumbersome. In addition, a program referred to as *trace.awk,* was developed for extracting strike and dip information from map traces. The newly developed program could be utilized when geometric field data is unavailable. The program will compute best results with structures in high relief terrain that have been mapped with high degree of accuracy.

The last paper '*3-D visualization of structural field data: Examples from the Archean Caopatina Formation, Abitibi greenstone belt, Québec, Canada*' (de Kemp 2000) presents several 3-D models of structural form surfaces at the outcrop, the mine and regional levels. A bi-parametric Bézier surface patch generation program, referred to as *bezpatch.awk,* was developed using EarthVision® control point files. Conversion utilities were developed for point and line files to exchange input and output data between EarthVision® and gOcad®. The programs, *ev2gocad.awk* and *gocad2ev.awk* were written to facilitate the conversions, and to allow for the representation of the surface patch and other program results in both visualization systems. A map element propagation program, *dive.awk*, was also created to demonstrate the use of regional plunge data in controlling 3-D structural visualization at depth.

Results demonstrate that visualizing local structures in a constrained-interpretive 3-D environment can enhance the interpretation of broader scale structures. Another important result is that poorly distributed structural data, in essentially flat terrain can still provide some constraints on the visualization and subsurface mapping of structures. The last paper of the thesis tests all previously developed programs and their applicability within a field project, and additionally, expands the tool-kit with several new techniques.

At the outcrop-scale, 3-D digitizing environments are enhanced with the use of VGP frameworks. Surface normals to represent stratigraphic topology, facing directions and simple 3-D symbolization as disks for planar elements and S2 fabric form surfaces. The goal at the outcrop scale is to give the geologist full control over the shaping of surfaces with interpretive 3-D editing tools while providing access to 3-D represented structural elements. As discussed in the paper, virtual 3-D editing environments are still very cumbersome. For the programs used in this study (EarthVision® and gOcad®), there is still no GIS like data base engine that can be accessed through selection of the 3-D graphics objects, and vice versa 3-D objects can not be identified through data base queries. Other visualization packages such as Vulcan-MapTek, MicroMine, Lynx, GemCom are more optimized for 3-D data management of open pit and underground mines. There are, in fact, many GIS-like operations for attribution control, spatial operators and object transformations that are not readily accessible through the 3-D environment. As geologists, who have grown accustomed to 2-D GIS functions, start to use 3-D visualization and modelling tools beyond CAD, they will certainly expect these functions to be present. No doubt this will be an active area of future research and development for 3-D earth science software designers.

At the mine-scale, interpretation is enhanced by having visual access to the key outcrop scale fold solutions appropriately coloured for facing direction. With these in place and with a ribbon-like F1 fold axial surface, it is possible to make a general F1 fold solution that respects the local fold geometry and topology. For this example, a single (u=5,v=19) Bézier patch was employed. The control grips used to edit the structure provides the interpreter with a means to re-parameterize or regenerate the surface patch with each control grip adjustment. The real-time dynamic regeneration of the surface atoms has not been implemented. Digitizing of the control-grip network is done as a separate process. This network of points is subsequently batch processed with the *bezpatch.awk* program to produce the fold patch at a specified resolution for each (u,v) parameterization direction. Finally the surface patch is represented as a 3-D line skeleton in EarthVision® or gOcad®.

As pointed out in this last paper, Bézier patches, as well as simple Bézier curves, need to have a well ordered and regular knot-sequence (control point network or control frame). Problems emerge if the interpreter is expected to manage the control-point ordering. Ideally, the method should allow an interpreter to begin with a simple (u,v) patch that is a flat or simple primitive surface of specified (u,v) resolution. Grip points should be pre-ordered from the start, and the interpreter should then have the freedom to move the spatial location of these grips at will, shaping the patch dynamically into a desired geometry. With enough grip-points, a structure would need only minor local adjustments using Discrete Smooth Interpolation (DSI) to constrain the surface to map traces, seismic interpretations or drill core, if available. Patch functions could be improved by the automatic assignment of constraining tangent points from structural observations, and the presentation to an expert of a moveable control frame that is essential to this interpretive process. The introduction of such dynamic and constraint-based patches for the modelling of complex geological surfaces will be a significant step towards enhancing the geologists ability to quickly visualize structures.

Another contribution of this study is the regional down-plunge propagation technique adapted from Stockwell (1950). Any map-element (e.g., point on a map) can be propagated through a virtual subsurface and collected on a specific profile plane, or aggregated with other map elements to make a 3-D surface. The propagation of map elements is controlled by a plunge model that the interpreter has developed, based on geologic experience and mapped plunges. The major assumption, as with all projective methods, is that the structure is continuous at depth, and that modelled depth geometries have some accuracy. It is beyond the scope of this study to asses the accuracy with testable examples for which at depth geometries are known. The propagation technique is similar to the physical geometry techniques that have been used for years. Perhaps the biggest danger with the technique is that it provides the opportunity for totally automated un-realistic surfaces to be created from any plunge model. The decisions that go into plunge model development, and the structural relationship of the plunge model to the map elements or map trace, are critical. If there is not enough plunge information to constrain a model, then the resultant surface will be questionable. Ideally there should be a way to assign some degree of confidence in the plunge models so that these confidence values can be mapped as a property to the resultant surface.

A limitation of the technique as implemented through the program code, referred to as *dive.awk,* is that it has been developed only for steeply dipping axial surfaces. As the Caopatina Formation F2 folds are characterized by near vertical axial-planes, they provide a simpler scenario in which the map-elements are projected along a vertical curtain beneath the interpreted F2-axial trace. This would be a problem with shallow dipping folds, such as in some fold and thrust belts. Updating of the code in *dive.awk* will have to be done to model these types of structures. The program *dive.awk* was developed to demonstrate the general concept of 'map element propagation', and to initiate more rigorous development by professional software developers in the future.

1.7 Subsurface mapping

The thesis demonstrates that tools can be developed to make field constrained structural models in complicated geology settings, and thus highlights the importance of acquiring and properly managing structural field data. Structural field observations can potentially aid in the interpretation of regional-scale features that were initially deemed unimportant. Unfortunately, field data bases do not always include detailed descriptive field observations from which the larger regional map interpretations were made, and it is rare to find usable structural field information within them. The development of a tool-kit that enhances the value of this data may however inspire mapping and exploration organizations to use their structural field data in a more proficient manner.

The tools presented in this study also act as a prototype for more robust software which needs to be created by professional software developers. Future work will likely focus on optimization strategies, and more flexible criteria for constraining surfaces to specific observation points. An exciting possible next step in research is to use the structural models, produced by the methods presented herein, as the basis for complete volume specification. Discrete rock volumes can then be assigned physical properties from which pseudo potential fields such as synthetic gravity, magnetic and electro-magnetic fields may be modelled. Long-term research focusing on the development of co-optimization strategies of these multi-theme data sets may produce results that given enough field constraints, can start to more accurately reproduce real scenarios. 3-D geoscience visualization and modelling is still in its infancy. Provided that field-based geologists, who are excellent at visualizing complex structural data, have some input into tool development, it will continue to be an exciting field to work in for years to come.

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CHAPTER 2

Variable 3D geometrical projection of curvilinear geological features through direction cosine interpolation of structural field observations

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Abstract

A UNIX program is presented for densifying and variably projecting distributed 3D data points sharing a common geological feature. Polynomial and hybrid B-Spline interpolation techniques are optimized for both sparse and abundant regional, clustered structural data sets. This tool, called push.awk, will be most useful in geological situations in which structures are constrained by several geometrical observations, are parts of relatively continuous irregular curviplanar surfaces and have a near linear known depth predictability at some point along the structure. Suggested applications are determination of some types of variably plunging fold geometries in mine exploration, depth prediction of regionally continuous shear zones and brittle faults, development of 3D structural fabric trajectories, horizon propagation, and plutonic boundary geometry evaluation. Simple uniaxial and variable projective methods need to be used in an appropriate context and in conjunction with the whole range of available statistical and interpretive 3D tools in order to achieve high quality geologic visualizations with predictive value. It is the effective incorporation of geometric field data into visualization and predictive geotechnologies that will increase the potential for sub-surface interpretation in complex geological settings.

2.1 Introduction

The geometrical prediction of geological structures from field data at various scales has traditionally been confined to the classic structural "down plunge" view and the trigonometric assembly of block diagrams with physical mechanical methods (Marshak and Mitra 1988, Ragan, 1985), or more recently through digitally-computed planar 3D perspective views (Schetselaar 1995, Sides 1994, Charlesworth et al. 1975) . The actual assignment of field constrained geometry to an observed geological surface is presented most often in a densely symbolized cartographic representation and relies heavily on the observer's intuitive 3D cognitive, projective, and extension faculties to perform the depth visualization of a given geological feature (de Kemp, 1996). This process of visualization can be greatly enhanced by the densification of additional structural levels or sections from proximal field observations, drilling or seismic methods, but at an early stage in any geological investigation, these methods are economically and logistically prohibitive. In regions of high relief such as in many active orogenic belts, the structural information is usually very dense, being readily available from surface examination, or through integration of DEM and feature extraction from remote sensing interpretation (McMahon and North 1993). Prediction of subsurface structures in these regions has thus been of a reasonable nature (Mayoraz 1993). Mineral exploration and geological mapping programs also occur in relatively flat, poorly exposed Shield regions where in many situations the prediction of sub-surface geometries is extremely difficult. In this case the general tendency is for qualitative assessments to be made, based on known surface geometric styles, mapped surface traces and some statistically constrained projections (Charlesworth et al. 1975). The results of these studies are usually presented as subjective cartoon models that mining companies can only use as a general exploration guide. In addition, as most classic projective methods are unixial projections, they are limited to predicting those structures which are inherently cylindrical or which formed entirely within a homogeneous co-axial strain field. The simple tool presented here is an initial attempt to deal with these problems, by providing a method for creating geometric scenarios that at least minimally respect the field observations of some types of non-cylindrical structures and provides both regional mapping and mineral explorationists the ability to make speculative 3D predictions and visualizations quickly. In addition, several projective options have been built into the program which can uniformly project data in the classic manner. The output is readily usable in any 3D visualization package by extracting the X,Y,Z data points in the first few fields of the output file that define the projected data envelope.

2.2 Methodology

The program uses well documented interpolation techniques applied to each of the independent direction cosines (alpha,beta,gamma) of known points along the trace of the geological feature (Press et al. 1986, Farin 1997). The choice of interpolation technique is dependant on the number of structural control points provided by user. If less than 6 structural control points are provided a polynomial of the order of N + 1 (N = number of control points) is used, with 6 or more control points a hybrid B-Spline iterpolation is utilized. The interpolation is thus optimized for a broad range of data sizes which the program autosenses. The results are achieved by first decomposing the geometrical information content into three component direction vectors, usually refered to as the direction cosines, from the trend and plunge (or dip-direction and dip). The three direction cosines are defined as the three shortest angles between each of the orthogonal cartesian co-ordinate axis X,Y, Z and a line in 3D space that passes through the origin (figure 1). Using angles in degrees, the general formulas for converting structrual field measurements to component direction cosines of the angles alpha, beta, gamma (α,β,γ) are as follows;

cos(α) = cos(dip/57.2958) * sin (azimuth/57.2958)

cos(β) = cos(dip/57.2958) * cos (azimuth/57.2958)

cos(γ) = sin(dip/57.2958)

Where azimuth is a dip direction for planar elements and a trend for linear elements.

Next, each point along the exposed structure trace, herein also referred to as the 'feature train', that has field constrained data, is added as a control point knot for a near exact fitting interpolation. By using the direction cosines rather than the azimuth and dip direction or plunge, the interpolation can be conducted on quadrant independent values. This avoids radical numeric gaps in crossing over Cartesian quadrant boundaries. For example directly interpolating between two control point values of 350° and 10° azimuth will yield a value near 170° instead of a value near 360° or 0°. More importantly the cosine directions for high volumes of data, in which the B-Spline technique is used, are treated in a non-spatial manner during the interpolation and are parameterized uniformly regardless of data density and clustering (figure 2). The results of combining data volume auto-sensing, the conversion to direction cosines and the uniform paramiterization for B-

Splining are predictive surfaces which have a smooth variability and a high degree of conformity with the observed structural data (figure 3a,b,c,d). Once the interpolation has been conducted, the intermediate feature train vertices are updated with the newly predicted geometry values. This updating is accomplished by 're-spatializing' the prediction curves by using the XYZ-distance curve as a spatial index to the feature train vertex location (figure 2). This hybridization of the B-Spline is what allows highly variable and clustered data to be interpolated smoothly in a non-spatial context while keeping a link to the spatial locations for later densification. Once the cosine functions have been computed, the three output values are used as elements of a geometric vector which is used to calculate the resultant down or up-projected points. Using the vector formulation the densified and interpolated geometry properties can be extended by local linear projection for a given distance with the following formulas;

$$X1 = X0 + (distance * \cos(\alpha))$$

$$Y1 = Y0 + (distance * \cos(\beta))$$

$$Z1 = Z0 - (distance * \cos(\gamma))$$

Where distance is the user specified projection distance in map units, and X0,Y0,Z0 are *the spatial start location and* X1,Y1,Z1 *the resultant end point of the projection.*

The cosines are then re-combined to calculate azimuth/dip direction and dip/plunge, for attribute assignment to the projection line.

Preparation of the input file of the program requires that the 3D path of the feature line be assigned X,Y map coordinates and an elevation value, Z, (in the map units and the geographic projection for the area). These linear paths could represent a significant geologic map unit boundary such as a Formation top, a narrow shear zone or a brittle fault trace. Surface feature traces and proximal structural measurements can be assigned Z values by back-sampling from the elevation values of a datum corrected and georeferenced DEM (Schetselaar 1995). For sub-surface situations, curvilinear features which are known to occur at depth can be similarly extracted from structural isopach maps with the same method, or, the route can be assigned X,Y,Z values from successive sampling of the planimetric map levels and/or vertical sections from mine data, georeferenced deviation-corrected drill core, or from depth-corrected seismic profile lines. If both surface and subsurface information exists, the data segments are simply combined after 3D georeferencing has been assigned, into a sequential list such that the top and bottom of the record list corresponds to the start and finish of the curvilinear feature path. It is in fact irrelevant whether the data are extracted from surface or from underground as this method will be able to project up or down plunge. For example, in conducting stratigraphic correlations in deformed areas, up plunge models could be constructed from two potentially common horizons but from spatially separate surface feature trains for geometric comparison, a useful exercise in any correlation project.

Once a sequential list of 3D point occurrences along the route have been established, an estimate of wether the structure extends in a near-linear fashion with depth must be made. The depth estimate is highly subjective, and may not be applicable through the entire feature trace, especially for structures that plunge in a strongly non-linear fashion such as complex high-frequency type I interference folds. Geologists need to draw from their own experience, the geometrical style of similar structures in the area and from other documented geometries of similar features. If there is at least one point along the feature train for which a known linear extension can be assigned then there is at least some confidence that the structure can be reasonably modeled. Without this information a rule of thumb is to not assign more then half the distance of a single wavelength spacing of a known feature to the projection distance. For example, an outcrop scale macroscopic fold with 400 m wavelength could not be depth-projected for several kilometers unless there was geometric evidence along the fold path or from similar styles of folding known to occur in the region supporting such a liberal distance assignment. A projection distance of <= 200 m would be more appropriate in this case. Also, there is no necessity for structures that are behaving linearly at one point to have consistent geometrical style throughout. With these cautions in mind this tool is thus intended for a quick first look assessment, in order to visualize the context of more complex structures, so future investigations can be better targeted.

The method outlined herein has produced what appears to be reasonable models for linearly plunging structures, since the predicted data envelope respects the field observations and is smooth and continuous. It remains to be seen how well the generated points conform to a complete mapped structure. The method used here is variable in the sense that it applies variable direction vectors along the data train during the interpolation as opposed to bulk projecting the entire data set uniaxially. Each adjacent point can potentially be assigned a different projection direction. However, it is also a static method since it computes equally spaced predicted depth positions along the same direction vector, that is, it is behaving in a locally non-variable and linear fashion. In general, this means that local surfaces along the predicted structural envelope look like diverging or converging segments of irregular conics. The structural surface predicted by this program will not take into consideration any rheological effects at high degrees of curvature along the data train, which could be a factor in folded layers derived from originally planar and stiff rheologies. There is usually a directional dependence during fold development in general non-coaxial high-strain fields for zones of high curvature, such as hinges, to migrate towards the shear plane (Hanmer and Passchier 1990). Thus when there are no control points about high curvature regions, such as fold hinges, the interpolation will simply follow the trajectory of the nearest control points. If these control points are however on opposite fold limbs and are near equidistant from the hinge trace, then the depth trajectory of the fold hinge could be visuallized. Otherwise the degree of curvature of the data train has no effect on the the interpolation. This program would also not be applicable for example in predicting the entire amplitude of a sheath fold surface envelope since these structures are by definition locally non-linear. At increased modeled distances towards the inside of a synformal sheath, the projected lines would simply cross over. This cross-over point would be much further than the real hinge cone, providing a maximum convergence target, and depending on the degree of curvature along the sheath axis, could be a reasonable estimate if the bulk of the down axis curvature is confined to a few meters of the sheath's hinge. A more reasonable model could be achieved in this situation by generating a series of incremental projections with updated converging direction vectors. This could be done in an iterative process with updating rules controlling the convergence of the evolving structural envelope until the maximum curvature of the structure is reached, that is, at the hinge point of the sheath cone. An alternative approach would be to visually inspect the zone of maximum convergence from the projection line cross-overs. A digitized point in this zone could act as a control grip for more complex parametric surfacing techniques commonly used in computer aided geometric design (such as a bi-parametric Bézier surface or NURBS). Automation of this approach may be a task for future development, but with this program the only way to deal with multi-directional non-linear structures is to insert proposed data points with plunging geometries appropriate to the terrain, in an iterative fashion, at intervals along the fold axial surface and then building a series of tie-lines connecting these converging sections. The program should be used with these limitations in mind.

There are, however many continuous structures that can be variably projected with several known data points. Understandably, better results will be obtained for those structures which show a tendency towards local linearity for at least a minimal accepted distance at the scale of interest. The best rule of thumb is to obtain as many field observations to act as structural control data points as possible, and to only model the portions of structures that have a linear style at depth. As with any interpolation approach, no solution is unique and will only help to focus the next stage of our investigations, at which point the model is obsolete and will require updating (Oreskes et al, 1994).

2.3 Program operation

The program PUSH is an AWK program and runs in a UNIX based operating system environment (Dougherty 1990, Vigneresse 1995). Most commercially available versions of UNIX have AWK interpreters that will successfully run this program. The entire program listing can be retrived via the IAMG ftp site with an example input data file at iamg.org. The push.awk program and the input file test.dat are compressed into a pkzip file called push.zip on this site, and will be periodically updated. See the IAMG web site at http://www.iamg.org for file down loading instructions. The input data file structure is ASCII space or tab delimited fields with X, Y and Z in the first three fields, azimuth (or dip direction) and plunge (or dip) fields in the fourth and fifth field respectively. All other fields are ignored. The header comment lines are preceded with "#" and have keyword requirements outlined in Appendix-A. These keywords are needed to assign field names and to re-order the incoming data. The input and output file formats have been optimized for use by the 3D modeling and visualization program EarthVision© from Dynamic Graphics Inc., which was also used for the visualization of application examples presented herin, but compatibility with other 3D packages could be easily achieved by editing the program to reformat the output. Anyone familiar with AWK or C programming languages and a familiarity with their own visualization package should be able to accomplish this. Please refer to Appendix-A and Appendix-B for more detailed file format descriptions.

The operational modes of the program are controlled by command line arguments. The usage is summarized by just typing push.awk <enter> and a text summarizing the program operation and syntax will be printed to screen. The following session summarizes command line arguments and other usage details;

```
%push.awk <enter>

        Note : Input file must be a scattered data file and
              a positive map unit plunge distance given. Incremental
              distance is optional as well as 'v' for variable assignment.
              Dip directions and dip angles can be used to extend
              planar data down, or, up dip. Right hand rule data must
              be converted to dip directions. All linear elements are
              processed as trend = Azimuth and plunge = Diplunge in
              decimal degrees geographic, in which North is 0 or 360
              and azimuth is measured clockwise. A horizontal plunge
              is 0 and a vertical plunge is 90 degrees. See main text
              for operation.

usage: push.awk <inputfile.dat> <plunge_distance,{increment}>{v}{c}{Azimuth}{Diplunge}

produces output file with same header as <Input_name>.dat  file...

       Input file: <Input_name.dat>        Outputfile :<Input_name_push.dat>
```

The simplest case is for a non-variable projections in which a uniaxial projection with one trend and plunge being assigned to the entire data set.

```
e.g. % push.awk test.dat 100 235 56
```

Here all the data points in the input file test.dat are projected 100 meters downward at 56 degrees down from horizontal and in the 235 degree azimuth direction.

An up-plunge view of the same could be achieved by preceding the plunge value with a negative sign.

```
e.g. % push.awk test.dat 100 235 -56
```

Note that up-plunge projections are not controlled by a negative distance but by the plunge value. There is no limit on projection distances but standard rules apply for plunge ranges -90 to +90 and azimuths from 0 to 360. A projection of only those input data points for which observed azimuth and plunge data exists and can be made by just specifying a distance argument and an input data file.

```
e.g. % push.awk test.dat 100
```

This will make a single projection pair for all observable points and will flag and ignore all values out of normal range as non-data. The example files listed in the Appendix are assigned "999" to indicate that no geometry attribute exists in that record. Incremental data points along the projection lines can be produced by adding a comma "," and a segment distance. Segment distances should always be less then the total projection distance.

```
e.g. % push.awk test.dat 100,25
```

To produce a variably projected data envelope a lowercase "v" is added as the third argument to the program, along with a fourth optional "a" for average cosine method or "i" for interpolation of the cosine directions. For the simple case of using an average of azimuth and plunge directly with no cosine calculation or interpolation, the "v" is used with no other arguments. This option should be used for demonstration purposes only as it is very quadrant dependant. For example the average of 300^{o} and 60^{o} azimuth by this simple direct non-component arithmetic averaging gives $(300 + 60) / 2 = 180^{o}$ completely opposite to the expected value of north.

```
e.g. % push.awk test.dat 100,25 v
```

This is included for comparison when using the cosine averaging method which is called by specifying "a" after the "v" argument.

```
e.g. % push.awk test.dat 100,25 v  a
```

In both of these cases a uniform trend and plunge will be assigned to the non-observed data points. The observable points are respected and projected accordingly. The user is encouraged to compare the know point projections to those achieved by averaging the direction cosines or those from averaging the known azimuth and plunge directly. In many cases there is a noted difference in final result and should be a strong visual reminder to always use the directional components instead of direct computation of the strike and dip values for projection averaging.

Finally the direction cosine interpolation method is used by specifying a lowercase "i" as the final argument (figure-2). This will create an output data file with common line identifiers in the LINEID field indicating a common projection line for the predicted X,Y,Z points at the specified segment spacing. This LINEID field can then be used along with any user defined class value for symbolization, in the default case used here, it is called RADVAR for 3D symbology control such as tube radius.

```
e.g. % push.awk test.dat 100,25 v i
```

2.4 Applications

This tool was developed specifically to deal with a geological visualization problem in an Archean polydeformed turbidite sequence in which variable plunge directions are the norm. The applicability of this tool to that problem remains to be seen and will be reported on later. In the meantime it seems apparent that the wider community could benefit from this program for a preliminary prediction and visualization for some types of geological surfaces. The main instances are in situations in which the structures in question have local depth near-linearity that can be estimated.

In some cases, variably plunging fold geometries can be observed to be locally near-linear at depth from mine workings, or the along plunge departure from near-linearity at any one point along the fold train occurs at a much lower wavelength spacing than along the surface fold trace. Often this is the case because of later more gentle superimposed folding on a higher order pre-existing fold. For these cases at least a partial depth variable projection may produce reasonable results. Developing structural scenarios for variably plunging fold geometries for mine exploration is thus an obvious application such as the idealized multi-plunging idealized fold depicted in figures 3a,b,c and d.

Probably the most applicable use for the variable projection would be for horizon propagation in moderately deformed terrain. In this situation (figure 4) a continuous geological horizon with known local near-linear continuity, confirmed from well drilling for instance, could be pushed (hence the program name push.awk) into the ground along its surface trace, or subsurface structural contour segment, in the directions of confirmed linearity. At a fine incremental sample spacing the propagated horizon surface can be back sampled for specific structural levels to produce structural contours for map posting or simply surfaced directly through minimum curvature or as a buffered 3D property for overturned structures. At least as a first estimate in frontier situations surface geometry measurements could be used in the case in which no local near-linearity could be predicted from drilling or seismic surveys and the variable projection made to conform to these down-dip directions. The standard unixial projection mode could also be used to define the inside and outside topological partners of the initial variably generated scattered data envelope (figure 3c). Most structural surfaces have regions which can be constrained in this manner for treatment as a zero property surface. This is a better method to create property wrappers for three dimensional gridding then just assigning a single dimensional offset to the inside and outside structural scattered data envelope.

Prediction of the maximum convergence point or divergence aprons of dome and basin structures, sheath folds and diapiric bodies (salt domes, porphyries, gneissic domes etc.) given enough surrounding field measurements could be also be possible (figure 5a,b). However, as mentioned earlier, the projective method outlined here will produce an asymptotic converging or diverging envelope to the structure as it departs from local near linearity, but is still usefull as it could be used as a control appron for more complex interactive parametric surface development.

Regional planar and linear fabric trajectories could also be predicted by processing a data stream of poles to planar elements, or linear elements directly (figure 6a,b). The data stream would be populated by traverses along the densest data path, with unknown data at specified intermediate spacings. In this manner one could for instance digitize a sample train along a pluton boundary and predict the fabric at intermediate surface locations. These fabrics can then be symbolized and represented in traditional map form. Confidence levels could be assigned to the predicted values based on proximity to known field data or outcrop density. Depth projection of fabrics becomes especially useful in polydeformed terrains where the visualization of earlier fold geometries are masked by the later superimposed folding and fabric development. In the initial stages of visualization and prediction of earlier structures it is necessary to view the pre-existing structural elements in the context of these later fabrics. In this way it could be possible to test for stratigraphic and structural discontinuities such as earlier fold axis by visually traversing along the latest generation 3D fabric surfaces. Fabric visualization is also important in establishing vergence and younging relationships in traditional mapping at surface and even more so when attempting to predict the depth behavior of complex fold geometries. Being able to provide a generalized regional fabric trajectory to some moderate depths can only act to enhance this interpretive process.

In higher relief regions such as many active orogenic belts it is often possible to extract known portions of the map traces of regionally occurring brittle faults or shear zones by back sampling the DEM for an X,Y,Z data train. These pieces of the data train along with several associated geometrical field observations could be used to predict the locations of the missing surface breaks (figure 7a,b), for instance at zones under talus, under water or hidden by vegetation. Selective up/down-dip lineations (not stretching lineations out of the shear plane) which exist in the slip plane combined with actual shear/slip plane dip-directions at enough points along a section of alpine terrain could be used to make a predictive surface of the shear zone, provided the zone had some lateral continuity. Also, if unknown structural breaks or ramps occurred laterally these may even be predicted to be present if lateral extensions of the known geometry did not match the map pattern in the projected regions. These same possibilities will apply to any major geological discontinuity if they are near curviplanar features and have some depth control such as from seismic, drilling or mine data.

2.5 Discussion

Ideally, a propagation function is required which would be able to perform spatial updating for degrees of curvature along a propagational trajectory path. This would be extremely useful in modeling more complex geometries. Piecewise convergence or divergence functions could be built into the iterative steps during incremental projections which would increase or decrease the degree of curvature of the propagating scattered data envelope, making it depart from local linearity, producing a constrained propagational surface. The exact degree of departure from local linearity to apply along the feature data train is a difficult estimate, as several physical factors conspire to produce the final geometry of a continuous structure, such as rock rheology, fabric anisotropy, strain field dynamics and initial orientation (Hanmer and Passchier 1990) and ultimately must be estimated from real 3D data from a given or similar structure in the region. In addition, these parameters are changing at different rates throughout the evolution of a given structure and, most disconcerting of all, if a parametric map could be reasonably estimated it would most likely be non-transferable to other similar looking geometries because each has its own unique rate history in which some factors, such as fluid pore pressure, play a stronger role. These are difficult if not impossible to model even in controlled physical environments or in finite element approaches (Malavieille 1984, Dixon and Tirrul 1991, Willett et.al 1993). The approach suggested here is simply to begin to construct surfaces which at least have some resemblance to real world examples and which are created by geometrically replicating the intuitive projective and propagative extension functions that characterize a structural geologist's day to day cognitive habits. Hopefully, by starting with the simple scenario of curvilinear, variably plunging but locally linear structures we have a base from which to begin to look at more complex structures.

2.6 Conclusion

The program outlined here is a simple scenario tool which allows mappers a first quick look for interpretation of structures that may be behaving in a locally linear fashion. Many explorationists are interested in structures which locally conform to this simple scenario or have camps which can be broken up into structural blocks which approach these conditions. It remains to be seen if this or similar projection interpolation tools can be useful by testing them in areas where a complete 3D data set exists for rigorous testing and future development.

It is becoming increasingly clear that integrated tool-sets, which incorporate and respect primary field observations, need to be developed for the exploration and regional mapping communities. With the recent emphasis on digital field data capture and the increased availability of 3D digital mine data, it is now incumbent upon geoscience data integration specialists to be able to use field information in a predictive fashion. Ideally the 3D toolbox for geoscientists will continue to evolve for spatial geometric visualization and modeling, and also for non-spatial component analysis as well. Users of this program are encouraged to provide feedback to the author for future development, and for potential new application areas in the earth sciences. Updates will be supplied to the IAMG web site as they become available.

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Appendix - A

test.dat : is an example of an input data file conforming to Earth Vision Dynamic Graphics Inc. 3D scattered data file format. Required push.awk program comment lines are preceeded by the "#" character and, in order of appearance, in the input file are : #Version, #Format and # ... AZIMUTH , #...DIPLUNGE for respecting input data geometries. Only the case sensitive keywords "Version", "Format", "AZIMUTH" and "DIPLUNGE" are necessary in the input header. The required input file data fields are $1=X, $2=Y, $3=Z with $4=AZIMUTH and $5=DIPLUNGE as optional for location of geometry data. Additional fields from input data file are ignored. All fields are space or tab delimited free form ASCII. Other input formats can be attributed in the first 3 comment lines,

```
ie:     # Type: Other 3D package
        # Version : 100'th release of Other package
        # Description : Manually entered data from digital slave
```

Note the space seperating the "#" comment indicator in the header lines so the adjacent text string is recognized as the second field. For details on the UNIX nawk or awk record scripting language see Dougherty, D. 1990. "sed & awk " UNIX Power Tools by O'Reilly & Associates, Inc. See main text for more details and the IAMG web site at http://www.iamg.org for full program listing.

```
______________________ Start of test.dat ________________
# Type: scattered data
# Version: 1
# Description: Converted Scatered data file from tietag.awk
# Format: free
# Field: 1 x
# Field: 2 y
# Field: 3 Z
# Field: 4 AZIMUTH
# Field: 5 DIPLUNGE
# Field: 6 LINEID
# Field: 7 FEATUREID non-numeric
# Field: 8 FEATURECOL non-numeric
# Field: 9 P
# Field: 10 STATUS non-numeric
# Projection: Universal Transverse Mercator
# Zone: 18
# Units: meters
# Ellipsoid: Clarke 1866
# End:
501840.5351024   5474268.429501   1000   290   78    "TURBIDITE-LAYER"   3   0   Sect-undef
501839.5016629   5474272.304899   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501838.3390435   5474279.797335   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501838.0806836   5474287.935671   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501838.7265833   5474292.586149   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501839.5016629   5474294.136308   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501840.9226422   5474295.040568   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501842.3436215   5474295.169747   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501843.6354208   5474294.782208   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501845.9606596   5474293.619588   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501852.0321166   5474290.00255    1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501857.199314    5474286.773052   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501867.2753489   5474280.959955   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501872.5717262   5474278.505536   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501876.0595844   5474277.601276   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501879.1599029   5474277.601276   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501880.839242    5474278.117996   1000   350   56    "TURBIDITE-LAYER"   3   0   Sect-undef
501881.6143216   5474278.893076   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501882.5185812   5474280.314055   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501882.6477611   5474282.251754   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501882.6477611   5474286.385512   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501882.6477611   5474291.552709   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501882.906121    5474294.265488   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501883.8103805   5474296.849087   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501885.2313598   5474297.624166   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
501887.5565986   5474297.624166   1000   999   999   "TURBIDITE-LAYER"   3   0   Sect-undef
```

501890.0110174	5474296.332367	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501892.723796	5474293.102869	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501895.9532944	5474288.064851	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501899.9578724	5474279.538975	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501903.4457306	5474270.3672	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501904.9958898	5474265.716722	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501907.4503086	5474260.032805	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501910.0339073	5474253.702988	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501913.5217655	5474248.148251	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501916.8804438	5474243.756133	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501918.430603	5474242.464334	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501921.5309215	5474240.914175	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501924.6312399	5474239.880735	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501926.6981189	5474239.364016	1000	999	999	"TURBIDITE-LAYER"	3	0	Sect-undef
501930.315157	5474238.847296	1000	135	25	"TURBIDITE-LAYER"	3	0	Sect-undef

Appendix - B

test_push.dat : example of an output file header and the 10 first densified and projected lines generated with push.awk set to 100 meters projection with 25 meter increments. Assigned geometries using variable cosine interpolation and extension with 3 control points. The command line issued to generate test_push.dat was :

push.awk test.dat 100,25 v i <ENTER>

All output X,Y,Z data points are assigned to shared lineID's for later visualization as lines. A radius factor is assigned which can be used for 3D line symbolization. All AZIMUTH and DIPLUNGE fields for starting points that are out of normal cartesian ranges such as "999" are assigned subsequent predicted projected points, but are re-reported in their geometry fields for identification in the output file. See main text for more details and the IAMG web site at http://www.iamg.org for full program listing.

________________ Start of test_push.dat ________________

```
# Type: scattered data
# Version: 3.01
# Description: push.awk > test_push.dat
# Description: Projection distance = 100 map units
# Description: Incremented at 25 map units
# Description: 3D data points dynamically assigned
# Description: with cosine polynomial interpolation and extension
# Description: Converted Scatered data file from tietag.awk
# Format: free
# Field: 1 x
# Field: 2 y
# Field: 3 Z
# Field: 4 AZIMUTH
# Field: 5 DIPLUNGE
# Field: 6 LINEID
# Field: 7 RADIUS
# Projection: Universal Transverse Mercator
# Zone: 18
# Units: meters
# Ellipsoid: Clarke 1866
# End:
501840.54 5474268.43   1000.00  290   78    1   0.50
501835.65 5474270.21   975.55   290   78    1   0.50
501830.77 5474271.99   951.09   290   78    1   0.50
501825.88 5474273.76   926.64   290   78    1   0.50
501821.00 5474275.54   902.19   290   78    1   0.50
501839.50 5474272.30   1000.00  999   999   2   0.50
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501829.54 5474278.65   951.41   303   76    2   0.50
501824.56 5474281.83   927.12   303   76    2   0.50
501819.58 5474285.00   902.83   303   76    2   0.50
501838.34 5474279.80   1000.00  999   999   3   0.50
501833.28 5474285.34   976.15   318   73    3   0.50
501828.22 5474290.88   952.30   318   73    3   0.50
501823.16 5474296.42   928.46   318   73    3   0.50
501818.11 5474301.96   904.61   318   73    3   0.50
501838.08 5474287.94   1000.00  999   999   4   0.50
501833.07 5474295.61   976.74   327   68    4   0.50
501828.05 5474303.29   953.48   327   68    4   0.50
501823.04 5474310.97   930.23   327   68    4   0.50
501818.02 5474318.65   906.97   327   68    4   0.50
501838.73 5474292.59   1000.00  999   999   5   0.50
501833.79 5474301.31   977.10   331   66    5   0.50
501828.85 5474310.04   954.20   331   66    5   0.50
501823.92 5474318.77   931.30   331   66    5   0.50
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501839.50 5474294.14   1000.00  999   999   6   0.50
501834.60 5474303.22   977.23   332   66    6   0.50
501829.70 5474312.31   954.46   332   66    6   0.50
```

501824.80 5474321.39	931.69	332	66	6	0.50
501819.90 5474330.47	908.92	332	66	6	0.50
501840.92 5474295.04	1000.00	999	999	7	0.50
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501831.20 5474313.87	954.71	333	65	7	0.50
501826.35 5474323.29	932.07	333	65	7	0.50
501821.49 5474332.70	909.42	333	65	7	0.50
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501832.70 5474314.54	954.92	334	64	8	0.50
501827.88 5474324.22	932.38	334	64	8	0.50
501823.06 5474333.90	909.85	334	64	8	0.50
501843.64 5474294.78	1000.00	999	999	9	0.50
501838.85 5474304.71	977.56	334	64	9	0.50
501834.07 5474314.64	955.12	334	64	9	0.50
501829.28 5474324.56	932.68	334	64	9	0.50
501824.50 5474334.49	910.24	334	64	9	0.50
501845.96 5474293.62	1000.00	999	999	10	0.50
501841.26 5474303.99	977.74	336	63	10	0.50
501836.55 5474314.36	955.49	336	63	10	0.50
501831.85 5474324.73	933.23	336	63	10	0.50
501827.14 5474335.11	910.98	336	63	10	0.50

...

...

...

Figure Captions

figure 1. Decomposition of azimuth and dip direction (or trend and plunge) angles into component direction cosines alpha, beta, and gamma during control point preparation.

figure 2. B-Spline interpolation approach using splined XYZ distance as index for locating intermediate points in non-spatial uniform parameter-value space. Sphere on top left indicates spatial radius condition for inclusion of field observations adjacent to the feature train.

figure 3a. 3D visualization of input file test.dat, an idealized fold trace before interpolation. Three control points are indicated with extended trend and plunge. See Appendix-A for full record listing of file test.dat depicted here.

figure 3b. Output file test_push.dat visualization after variable interpolation of direction cosines using push.awk for 100 meters projection incrementally sampled at 25 meters. Increasing absolute Z values along the projection lines are colour coded from red for shallow depths, to blue for greatest depths. See Appendix-B for partial record listing of file test_push.dat.

figure 3c. test_push.dat with Z slabbed portion of resultant 3D model. The volume slab portion of the model was generated by 3D minimum tension gridding of inside and outside surfaces directly adjacent to the interpolated fold envelope. Slab colour of red indicates pattern of inside region and purple the outside region.

figure 3d . Perspective view of test_push.dat looking up-plunge from the topological inside of the structure to surface. Note the wide divergence in azimuthal range and the general continuity of the surface envelope.

figure 4. Simple case scenario for surface propagation by variable down dip projection along the regionally mapped bedding plane trace.

figure 5a. Plan view of idealized pluton margin configuration. Field measurements assumed to be indicative of pluton boundary geometry. Dip direction and dip of control points are indicated.

figure 5b. 3D visualization of variable projection of pluton margin data train. Cross over lines from converging projection lines have been removed.

figure 6a. Idealized trend surface map of interpreted regional fabric trajectories. Only proximal field observations to the fabric trace will be assigned to the data train for interpolation.

figure 6b. Variable down plunge projection of the regional fabric traces symbolized as narrow tubes colour coded by depth.

figure 7a. Map of idealized thrust trace through alpine terrain. Dashed portion of thrust indicates unmapped region which was modeled by variable up-dip projection of known thrust trace to the east. Projection lines are indicated by "T" lines ornamented along the thrust break.

figure 7b. Perspective view of alpine region from figure 7a, a DEM intersected by a thrust surface. Thrust surface and projection lines are indicated by linear white tubes. Note that the thrust surface ramps up elevation contours to the east, or to the top right of the image.

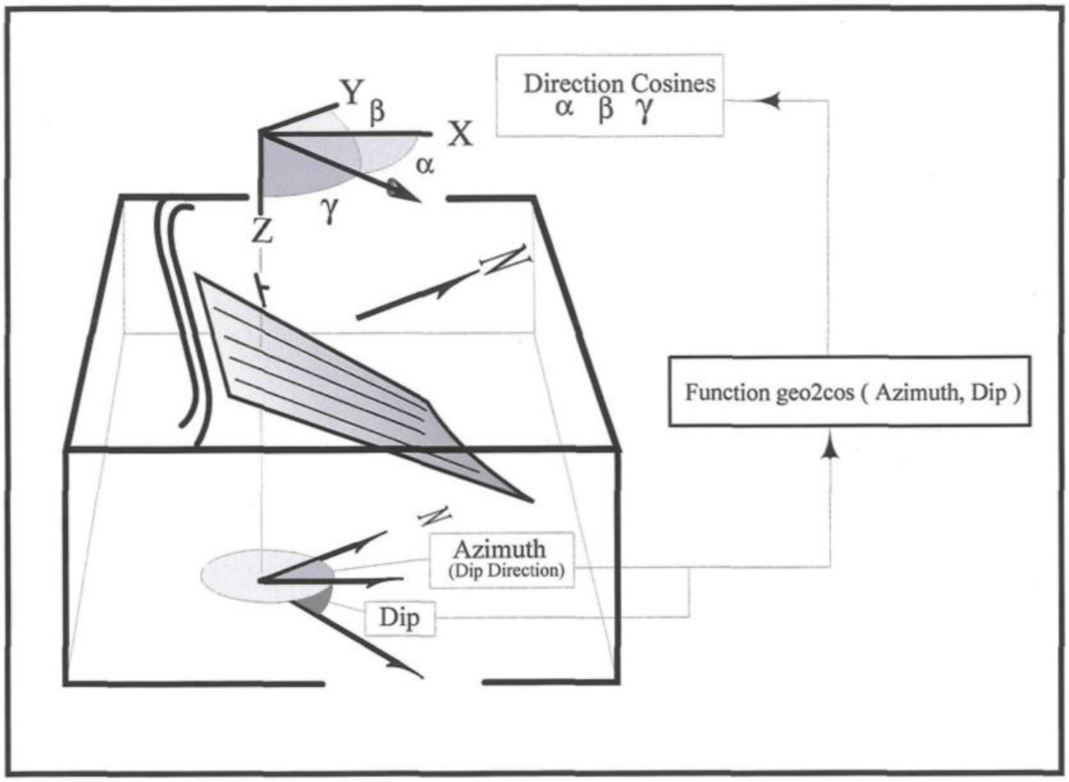

Direction Cosines
α β γ
Y
β
X
α
Z
γ
N
Function geo2cos (Azimuth, Dip)
N
Azimuth
(Dip Direction)
Dip

Figure 1

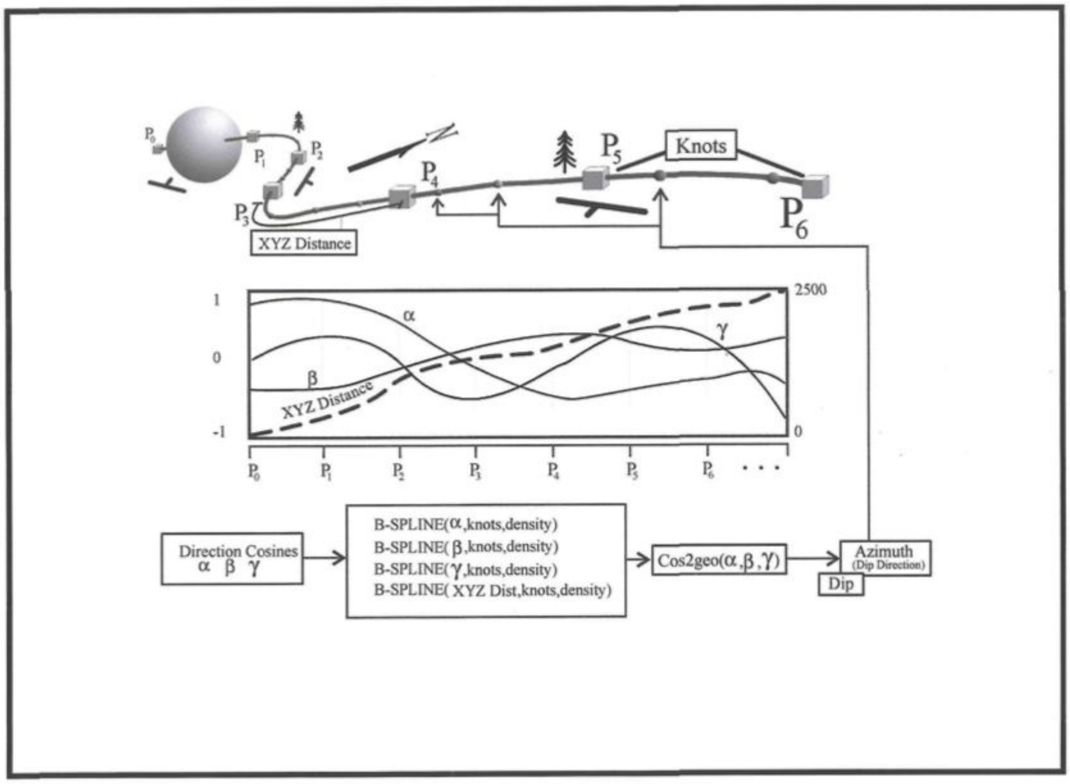

P0
P1
P2
P3
P4
P5
Knots
P6
XYZ Distance
1
0
-1
2500
0
α
β
γ
XYZ Distance
P0
P1
P2
P3
P4
P5
P6
. . .
Direction Cosines
α β γ
B-SPLINE(α,knots,density)
B-SPLINE(β,knots,density)
B-SPLINE(γ,knots,density)
B-SPLINE(XYZ Dist,knots,density)
Cos2geo(α,β,γ)
Azimuth
(Dip Direction)
Dip

Figure 2

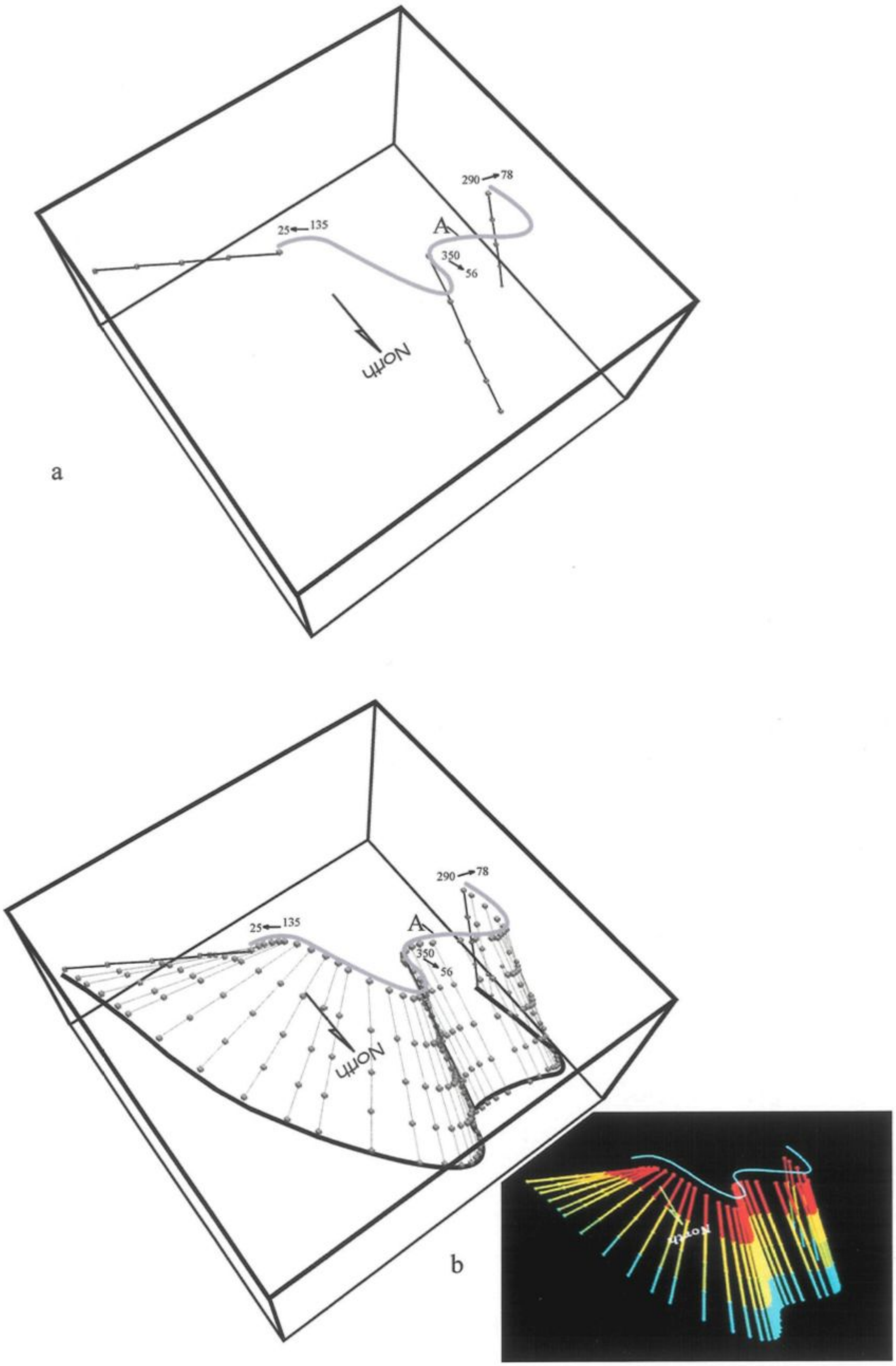


Figure-3

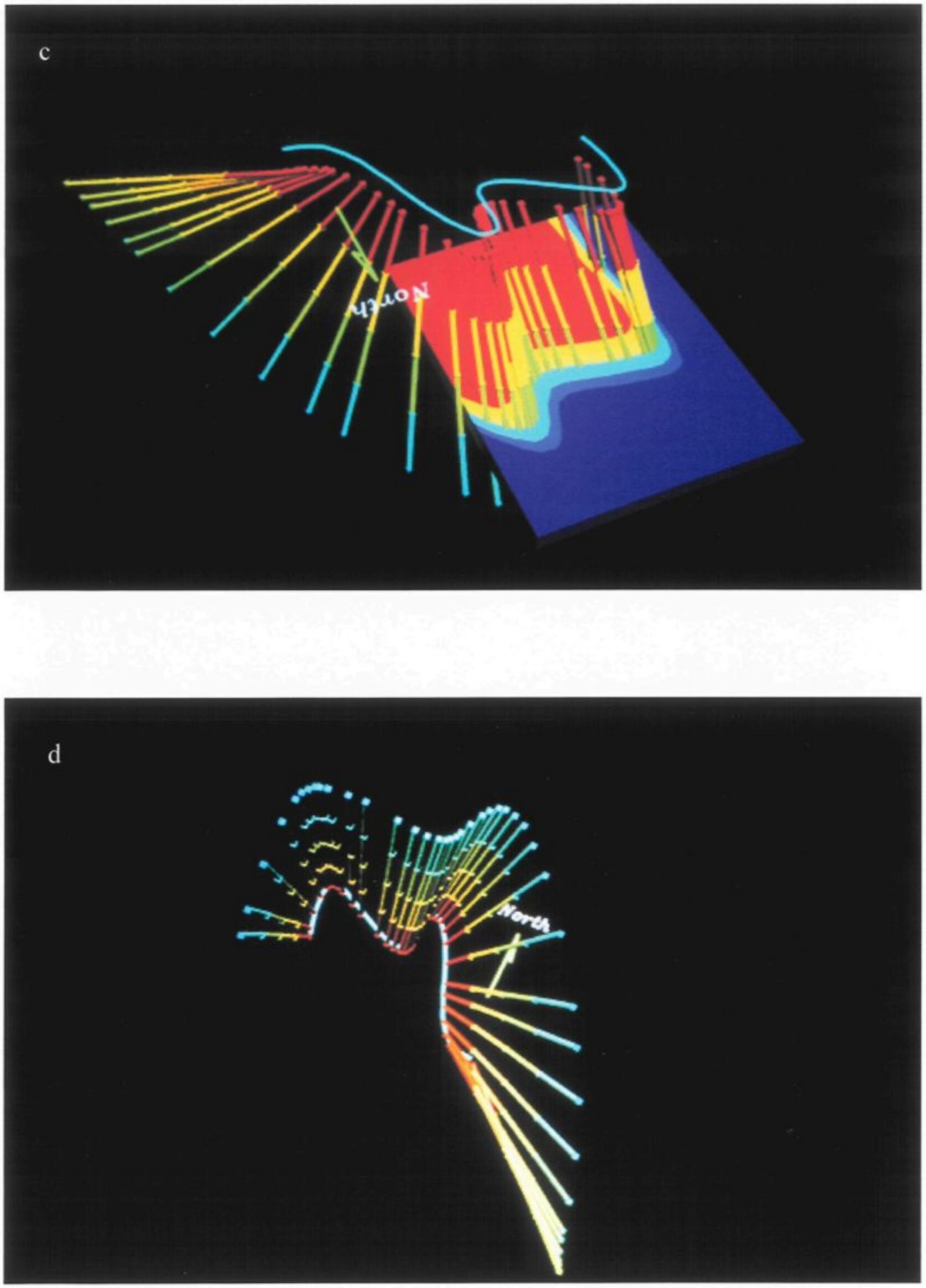


Figure-3

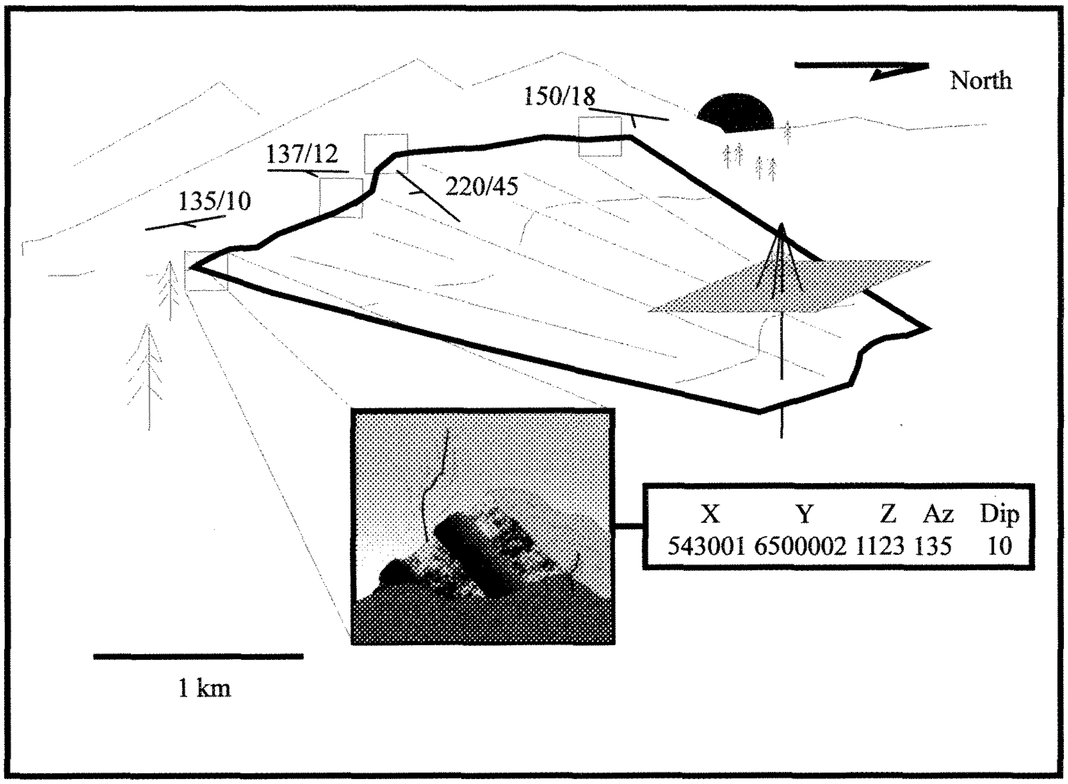

North
150/18
137/12
220/45
135/10
X Y Z Az Dip
543001 6500002 1123 135 10
1 km

Figure 4

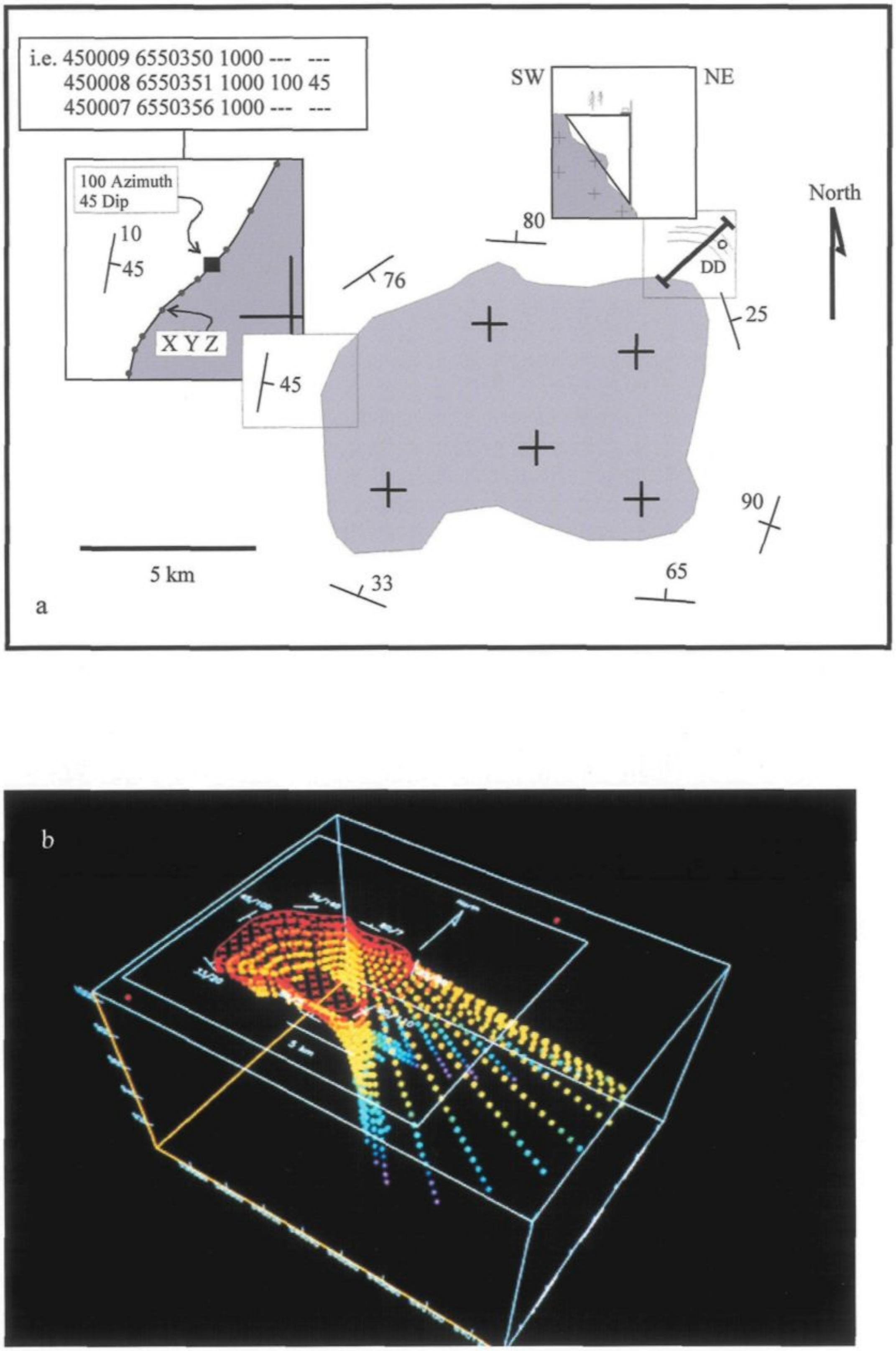
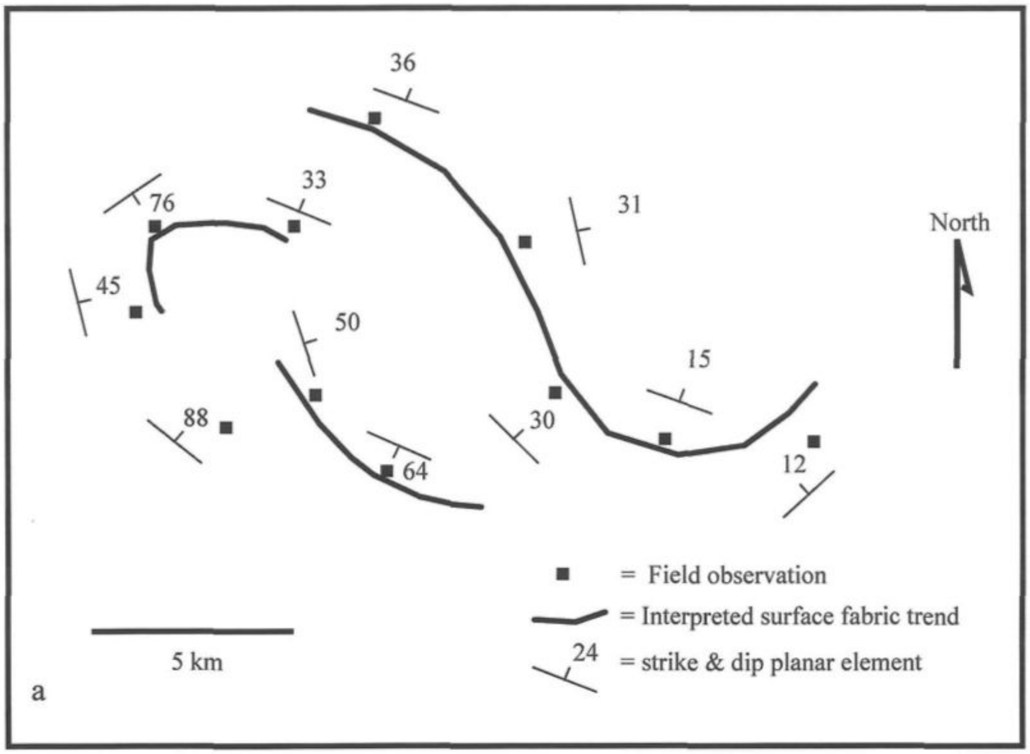

i.e. 450009 6550350 1000 --- ---
450008 6550351 1000 100 45
450007 6550356 1000 --- ---
100 Azimuth
45 Dip
10
45
X Y Z
45
SW
NE
80
76
DD
North
25
90
5 km
33
65
a
b

Figure 5


36
33
76
31
North
45
50
15
88
30
64
12
= Field observation
= Interpreted surface fabric trend
24
= strike & dip planar element
5 km
a

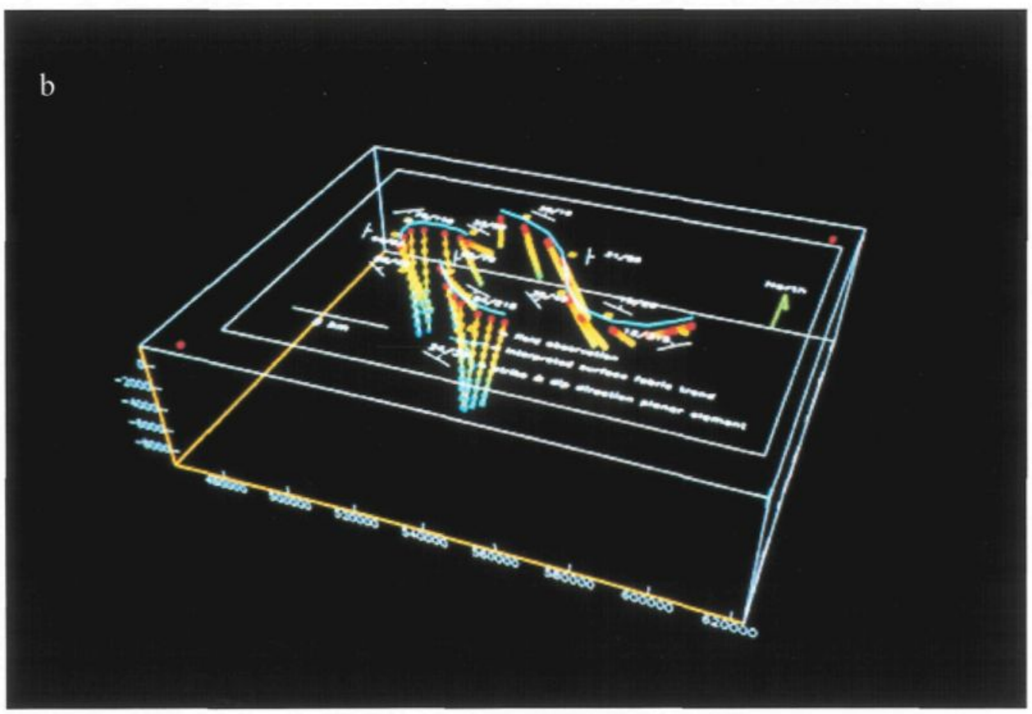

b

Figure 6

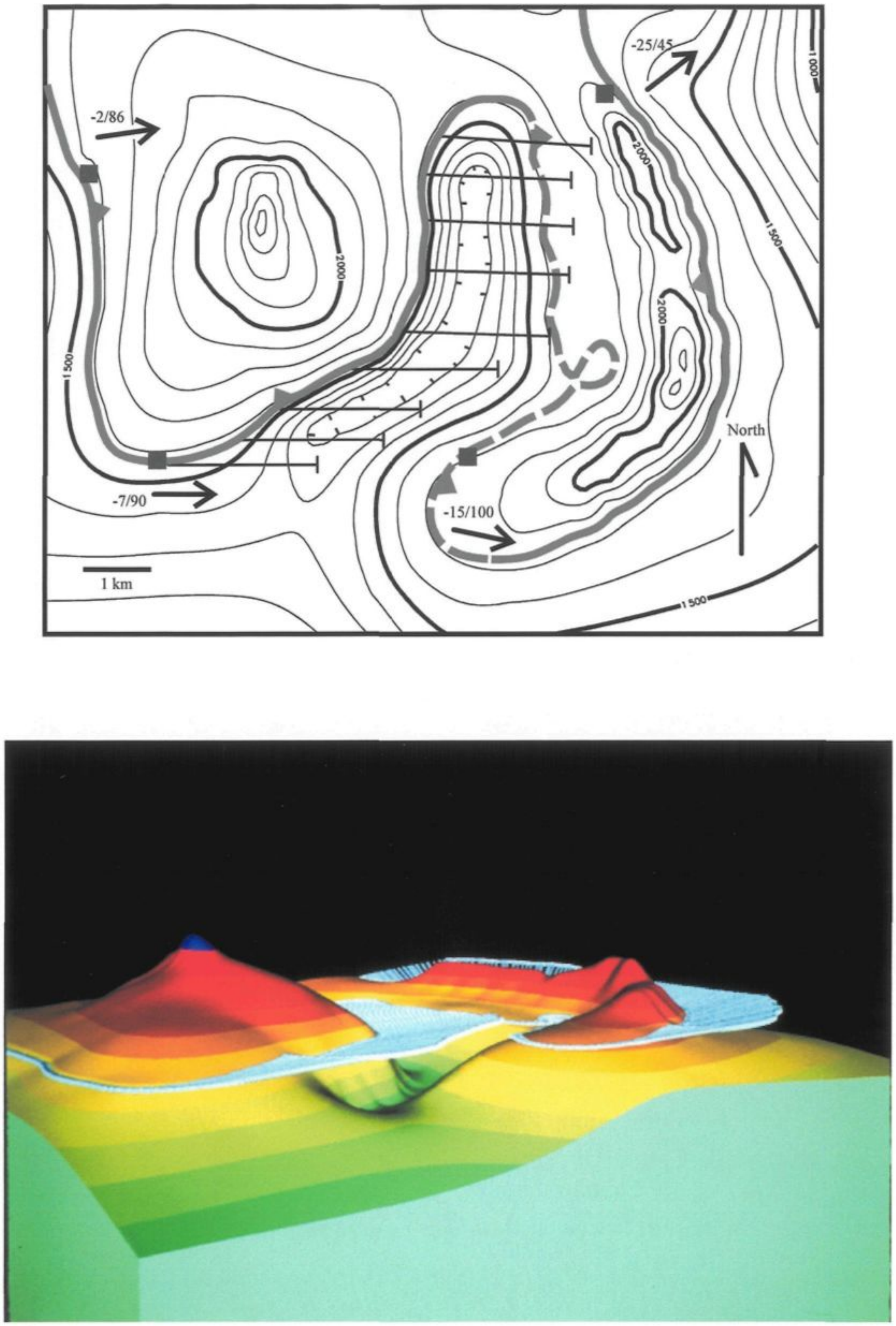

-25/45
1000
-2/86
2000
2000
1 500
2000
2000
1 500
North
-7/90
-15/100
1 km
1 500

Figure 7

CHAPTER 3

Visualization of Complex Geological Structures using 3-D Bézier Construction Tools

This chapter represents a reformatted version of a paper published in 1999 in *Computers and Geosciences*, v.25, no.5, pp.581-597, by de Kemp.

Abstract

Various 3-D visualization methods use structural field data to constrain geological models. One approach is to employ 3-D β-Splines, a class of Bézier curves, to densify point data sets too sparse and clustered for spatial interpolation. Bézier curves are implemented to act as construction lines that respect the constraints imposed by structural orientation data. These 3-D construction lines are defined by tangents to local planar features, and the projection of key geologic structures. A method is presented that estimates the local strike and dip of vertices along elevation registered 3-D curvilinear geological features. The local direction cosine estimates derived along the surface traces of geological structures are interpolated, and linearly projected to depth. In regions where sub-parallel relationships exist between local and regional scale structures it is possible to constrain modeled regional geometry to the field data. The success of any 3-D geological modeling exercise is dependent on the data density, clustering and depth variability of known structural observations, and the geological relationship of local structures to regional bounding surfaces. Ultimately, methodologies to generate geological models from regions of sparse data will need to be able to combine Computer Aided Geometric Design (CAGD) tools with constraining software, which respects structural field observations. Several examples are given to emphasize this point.

3.1 Introduction

Geologists involved in the interpretation of geological structures are constantly trying to minimize discrepancies between conceptual models and primary field observations. A geologist with an aptitude for resolving these discrepancies will often produce potentially useful interpretations. This skill is characterized by the ability to visualize complex 3-D objects while drawing on the experience of similar structures in other geological settings. Interpretation from sparsely distributed data is the core problem facing regional mappers and requires more than just the empirical mental visualization skills of the structural geologist. Consequently, a range of visualization techniques in support of this process has evolved from the early manual to more recent digital methods. For example, various projections of 3-D orientation data on lower hemisphere plots (Phillips 1971, Knox-Robinson and Gardoll 1998, Smith and Gardoll 1997), 3-D block diagrams (Lobeck 1958, Ragan 1985, Dueholm, Gard and Pedersen 1993, Hatch 1994), stacked cross sections in perspective views (Ragan 1985, Schetselaar 1995), structural contouring techniques (Marshak and Mitra 1988, Ragan 1985), and more recently integrated GIS products such as structurally symbolized image maps (Nash and others, 1996, Schetselaar 1996, and Harris and others, 1994). All of these are designed to enhance the interpretive environment so decisions can be made in a more rigorously constrained manner.

The goal of this paper is to present a number of techniques that are an extension of such tools to constrain interpretive geometries of regional structures with observed field data in 3-D. Several examples are presented on how 3-D visualizations can be generated from sparse structural field data. The techniques presented are in themselves only a small part of an evolving interpretive tool-kit for regional visualization of structural data in 3-D (de Kemp 1998, McGaughey and Vallée 1997, Mallet 1997, Jessell and Valenta 1996).

Several UNIX AWK programs (Dougherty 1990) that use the techniques discussed in this paper can be found on the International Association for Mathematical Geology web site at www.iamg.org. A brief summary of command line arguments can be found in Appendix-1, along with a brief outline of Bézier curve theory in Appendix-2. Much of the visualization represented in this article was produced in a 3-D modeling and visualization software package called EarthVision©. Similar visualizations could be accomplished by minor reformatting of output files from the included AWK programs appropriate to other 3-D packages such as GoCAD©, Vulcan© or Noddy©.

3.2 Creating geological models from sparse data sets

It is possible to make general estimates of the geometry of geological objects from sparse data sets, even when no ancillary data such as drill core, seismic images, or mine workings exist. However, the non-unique character of a given solution limits its use only to a general guide in modeling. In fact, it is quite natural for a structural geologist to mentally visualize geometrical solutions to a limited data set, and to articulate these solutions as regional scale cross sections or block diagrams (Dueholm et al. 1993, Hatch 1994, Ragan 1985). As additional information becomes available, these visualizations or structural models will tend towards a unique solution. Integral to the structural modeling process is the exercise of sketching, projecting, and extending surface features to depth. However, the difficulty in making 3-D interpretations when only sparse surface data exist, is that depth interpretations are based on extensions beyond the range of the control data set, whereas surface boundaries are based on interpolation from within the range of control data (Jessell and Valenta 1996, Mallet 1988). Subsurface boundaries produced from computed or interpreted extension techniques should thus be treated as speculative. They are non-observable, inferred surfaces that are only locally constrained by the spatial locations and geometric character of field data.

Geological bodies are volumes of rock that in many cases had originally continuous bounding surfaces. Given sufficient data density, standard interpolation techniques are available to create the surface models required to visualize a given geological body (Briggs 1974, Hamilton and Jones 1992, Tipper 1992). These methods are optimized for calculating a near exact fit of the control data by interactively minimizing the error between individual control points and the cells of the modeled surface (Mitásova and Mitás 1993, Mallet 1989).

Subsequent modification through intrusion, shearing, brittle faulting, and erosion can partition these volumes into discrete blocks. As a consequence, the disrupted surfaces are more difficult to manipulate and represent in a computer. They require more advanced algorithms that can cope with rapid changes in slope, or sharp discontinuities. These types of surfaces can be modeled by localizing the tension of the interpolation (Mitásova and Mitás 1993) at highly variable regions. This involves reducing the allowed local error at discontinuities and relaxing it at less variable but sparser regions. Alternatively these data can be handled by ensuring that adjacent points across discontinuities are not interpolated (Mallet 1989, 1997, 1988).

3.3 Bézier tools

In general, the existing interpolation functions are fully automated, processing the input control point data from drill core, seismic profiles, or mine workings, to produce a densified regular grid, an irregular triangulated network of closely fitting points, or a fully contoured rendering (Hamilton and Jones 1992, Tipper 1992). Unfortunately, structural information is rarely sufficiently dense to use in such automated approaches. However, many structural geologists are intuitively comfortable with extension, curve fitting, and interpreting the subsurface geometry from limited field data (Ragan 1985). Much of the preliminary visualization is accomplished by partitioning structures into statistically similar geometric regions or 'domains'. Geological elements in these domains can be uniformly projected along an axis that is constrained by field observations such as fold plunges, intersection or stretching lineations in higher grade terrains. The result is a simple 3-D view based on assumptions of how the structure extends at depth and which can be reconciled with models from adjacent structural domains. The guidelines for model construction in the tools presented here are similar, in that each observation makes a contribution to the overall regional model and any given solution must respect the spatial and geometric properties of the field observations.

What is lacking is a set of digital projection and interpolation utilities that works dynamically, with limited control data, in an interactive and iterative manner. These utilities are needed so that a range of speculative mental solutions to complex geological geometries can be generated quickly, and presented to others for discussion, testing and revision.

There is a whole range of already developed tools that could begin to fill this gap from the field of computer aided geometric design (CAGD), referred to collectively as parametric design tools. Bézier curves belong to this family of tools. The mathematical formulation and extension from existing physical spline tools emerged in the late 1950's and early 1960's. Bézier based functions are now used extensively in automotive design, ship building, aerospace manufacturing, and a range of other engineering and design applications. In all of these fields, esthetics must be combined with strict geometrically constrained product specifications (Farin 1997, De Paor 1996). These tools produce an infinite number of solutions for fitting a curve to a limited control set (Figure 1). Bézier based tools mathematically produce smooth continuous curves with only a few control points that can be easily manipulated to represent complex geological structures. Defects related to polynomial interpolation such as large amplitude folds, that result from interpolating close sub-parallel control points with hi-order polynomials do not occur when using Béziers (De Paor 1996). When these tools are combined with trajectory information from down plunge projections of ground control points, a series of speculative geological construction lines can be used to densify a model to a level where it can be interpolated directly by other fully automated interpolations such as Discrete Smooth Interpolation (DSI; Mallet 1989).

In a simple case, and with the following assumptions, a folded surface could be parametrically described using a simple three-point parabolic Bézier curve. The assumptions are:

• Two control points are available that fall on a folded surface. The locally observed orientations at these control points produce intersecting planes from surfaces tangents (ie: a non-isoclinal structure); Down dip vectors of these tangent planes ideally intersect each other, or cross over within a minimum threshold distance e.g. Figure 1a, 2);

• the point of nearest convergence of these vectors can be estimated (smallest distance);

• the surface being visualized is continuous (ie: no faults);

• the distance between the two control points is equal or smaller then the fold half wavelength; (i.e. that is, there is only one closed curve between the end control points).

A program *hinge.awk* was designed to take these assumptions into account (see Appendix-1). It interpolates a simple quadratic curve from two control points, that have known dip and dip-direction, and one user-defined point near the hinge area (Figure 1a). This third point is herein referred to as a 'grip point' since it is not a spatially fixed control point but is movable by the geologist. Grip points are defined interactively in a 3-D editor by visual inspection. While keeping the other control points fixed in space, the grip points can be manipulated to produce a Bézier line with the desired shape and degree of curvature for a local part of a structure. A series of separate Bézier curves can be constructed from adjacent paired sets along a regional structure forming a kind of raw design skeleton. Alternatively the grip points can be estimated by examining an entire field of converging down plunge projections that were originally computed by using Variable Geometric Projection (VGP). VGP preserves and blends variable down plunge projections throughout a structure, rather then using the standard down plunge method that averages over the structural observations in a domain to compute one uniaxial projection (de Kemp 1998).

More complex geologic structures can be constructed when only two known control points are available and when there is some information available about the style and topololgy of a fold. In these situations, a more advanced Bézier can be used (Figure 1b) that estimates a curve with the general de Casteljau formulation (Farin 1997, De Paor

1996). The program *cast.awk* can be used to perform this type of Bézier interpolation (see appendix-1). Albeit more speculative, additional grip points collectively forming a grip frame, can be inserted in order to form a single smooth but complex construction line. These are now truly 3-D space curves (ie: curves that contain non co-planar points), which if implemented with a fully interactive user interface for the 3-D editing of grip points, could facilitate the local representation of a variety of geological enveloping surfaces, such as a fold train of tight to near-isoclinal folded strata (figure 1b). The general guidelines for using this type of tool would be:

- Identification of at least two locations with known x,y,z position to act as control points at the ends of the curve, where tangent information is also available from structural observations,
- qualitative verification of compatibility in style of curvature being visualized, ultimately based on the known style of folding in the region, and
- construction of the curves by adding grip points according to the wavelength and style of the folds.

Providing an editable 3-D control frame for the geologist attempting to visualize various fold solutions may not be necessary when more than two control points are obtained, for example when several drill holes intersect a tightly folded horizon. If local surface continuity is assumed, the control points can be used to generate a near exact fitting smooth curve without a user defined grip frame. This is the approach for a family of Bézier graphics tools called β-Splines (Farin 1997) which of the three Bézier methods produces the least speculative results. These are generally implemented as third degree moving Bézier functions, more commonly referred to as piecewise cubic splines (Figure 1c). These functions compute a near exact fit of the local data along with a series of associated control frames. In most 2D graphics software applications such as Corel Draw© and Adobe Illustrator© the user has access to the local grip frames for editing pieces of the β-Spline curves after the initial interpolation. These functions are usually used to smooth out coarse construction lines in one pass. β-Splines take into consideration data clustering and try to optimize local control polygon generation by minimizing the degree of curvature for each piece of the curve. The geological benefit is that a sparse, variably distributed data set could be interpolated with a continuous smooth curve that still respects the data regardless of its spatial distribution. Updating the curve as more data are obtained is also possible without affecting the entire curve. Most field geologists are quite familiar with these graphics tools in the construction of 2D maps, block diagrams and idealized structural diagrams. The transfer of skills to manipulate the same spline tools in a 3-D environment would be natural, provided that grip point editing, segment selection and interpolation densities could be easily controlled. AutoCAD© provides much of this functionality with the SPLINEDIT command (Allen 1995). 3-D geological surface representations need to have these types of construction lines as a primitive framework or design 'skeleton' with local editing capabilities in a 3-D georeferenced co-ordinate system (figure 2).

The *bspline.awk* program is provided here to interpolate a sequentially ordered 3-D data set of unlimited size using the β-Spline technique. The code used in the program is modified from Farin (1997) in which the mathematical formulations can also be found. In addition to the suggested guidelines for using *hinge.awk* and *cast.awk*, the *bspline.awk* program should be used for more complex visualization such as in polydeformed terrain when:

- facing criteria are available so that traditional vergence rules can be applied to visualize higher frequency and non-cylindrical fold trains;
- local polydeformed structures reflect the regional fold pattern and can be placed in a sensible regional structural context;
- additional control points are available at depth from projected surface features, drill core, cross-hole seismic picks or 3-D seismic surveys.

3.4 Characterizing the geometry of surface traces

In high-relief areas or in mine situations where direct structural field observations are lacking because of incomplete surveying, ground cover or inaccessibility, the local geometry of a given geological feature trace can still be characterized. This can be done through the traditional three-point solution (De Paor 1991, Chorowicz and others, 1991) or through regression of local geological feature and terrain intersection points (Morris 1991, McMahon and North 1993). These solutions assume a local planar behavior of a geological surface or fabric, estimating the strike and dip of the best-fitting plane at local observation points from a minimum of at least three nearby points. This method is similar to classical geological construction methods for creating structural contours from geological boundaries that intersect common elevation contours (e.g. Marshak and Mitra 1988, Ragan 1985). A utility called *trace.awk* has been written to automate this process, and as a supplement to the other Bézier-based programs presented herein. The program allows the geologist to control the local search parameters for the planar solution. This utility accepts an EarthVision© ASCII point data file that describes the (3-D) curvilinear (trace) for the geological feature of interest. The trace could be a map unit boundary, a discrete shear zone, an axial plane, or a form line (Figure 3a). Arguments provided include, the maximum and minimum limiting distance defining the search of points that will be included in the calculation, and the minimum and maximum cutoff angles. These angles are important since the error in these methods increases drastically as adjacent points become co-linear (Chorowicz et al. 1991, Preparata and Shamos 1993). Distance and angle conditions can be set to avoid this situation. The 3-D distance calculation for each point of the data set to its neighbours is calculated by:

$$D = \mathrm{sqrt}(dX^2 + dY^2 + dZ^2)$$

Where D is the distance and dX,dY,dZ are the X,Y,Z component distances between the points. All points that fall into the distance max-min cutoffs will be selected for further processing and are used on the final planar solution. The angles between point pairs are then calculated by application of the dot product;

$$\theta = \arccos(V1 \bullet V2 / |V1| x |V2|)$$

Where θ is the interior angle between a three point set of P0, P1, P2, with adjacent vectors V1 = P1-P0 and V2 = P2-P0. P0 is the point where the geometry is being estimated. The program will default to a max-min distance between 1000 and 10 meters and a max-min angle for adjacent points of between 170° and 10°. The program can be set internally to calculate the local planar solutions using three different methods within the defined tolerance window. These are:

- the simple three point solution;
- an averaged and distance-weighted solution to all adjacent triple pairs;
- a planar least-squares trend solution through a data cluster.

Statistical properties of the normals (to planes) can be determined to check for local variations in the averaging or trend solution method. This may be useful in characterizing a given terrain as conforming to or departing from local planarity. In complex polydeformed terrains it is likely that local variability will be high. If this is the case, the geologist can reduce the search window until the variability is minimized. Also, where structural field observations are present the accuracy of interpreted contacts and other geological feature traces can be assessed. The primary benefit of this tool is that it can quickly solve the local planar geometry for regionally extensive and dense geological surface traces in a single pass, (Figures 3b, c). The surface trace can then be densified and projected at depth for visualization with VGP and the geometry interpreted in a 3-D graphics environment (Figure 3d). In this way the geologist has a method, in the absence of direct field observations, of rigorously extending an entire geological surface trace into the subsurface and qualitatively assessing local geometry in the context of the regional structures.

3.5 Case study : Kiglapait Intrusion, Labrador, Canada

In order to demonstrate the utility of 3-D Bézier-based construction methods, a digital georeferenced field data set was obtained by digitizing the observations of primary igneous layering collected by Morse (1969), from the layered troctolite, olivine-gabbro Kiglapait intrusion in Nain, Labrador, Canada (Figure 4, de Kemp and others, 1997, de Kemp and Desnoyers 1997). The 3-D construction method outlined here for the Kiglapait intrusion is potentially applicable to other geological bodies of regional extent that occur in a spatially continuous fashion. It is most applicable in situations in which the orientation of specific structural elements, such as sedimentary bedding, igneous layering or gneissosities, reflect regional-scale boundaries. The geological maps and assumptions used in this model were also derived from the work of Morse (1969). His interpretation was that the intrusion behaved as a contiguous magmatic system resulting from various crystallization stages in a continually fractionating magma. The pluton displays internal igneous layering near the regional boundaries of plutonic phases that in many cases reaches parallelism to these same regional contacts. In addition, the key assumption for this visualization was that the lateral continuity observed from the map pattern along boundaries of the troctolite and olivine-gabbro unit, continue at depth to form a continuous surface across the pluton. These enveloping boundary surfaces define an igneous body that is likely to conform to a bowl or lopolith shaped structure as predicted by the regional trajectories of primary igneous layering which all trend down dip into the centre of the intrusion (figure 4).

With this foundation, an attempt was made to visualize the lower surface of the troctolite (Lower Zone) and olivine gabbro (Upper Zone) by integrating field observations of primary igneous layering and surface traces of map unit boundaries.

All field observations were digitized, spatially georeferenced and re-projected to the appropriate map projection for this region (UTM Zone 20 NAD27) in FIELDLOG© (Brodaric 1997). These data and the troctolite surface trace were registered to mean sea level in EarthVision©, using a digital elevation model exported from Arc/Info© GIS (Figure 5a). Next, specific field observations of the strike and dip of primary igneous layering were assigned to vertices of the map unit boundaries, using a 500 meter search distance from the field observations (Figure 5b). The program *field.awk* is provided for this operation which allows specification of the 3-D search distances and which assigns the geometric properties to points along the surface trace. For this example, a search distance less than 500 meters resulted in an under-populated boundary. Choosing a limit greater than 500 meters began to include field observations that were not approaching parallelism to the pluton contacts. The orientation data of the lower intrusive contact and the upper zone contact of the troctolite were then interpolated using VGP (de Kemp 1998) and projected down-dip for 10 kilometers. At this distance all projection lines from opposite sides of the pluton crossed over. This produced a swarm of converging projection lines that roughly intersects the intrusion axial surface (Figure 5c). For demonstration purposes it was assumed that the outside walls of the intrusion were dipping stepper at surface than at depth. In other words the intrusion was assumed to flatten out toward the core. This allowed the use of simple three point Bézier control frames (figure 1a,2) to develop the intrusion contact surfaces. However in most mafic intrusions the magmatic accumulations near the core tend to cause a gravitational inversion with the enclosing country rocks, producing a sagging, more lopolith shaped structure, with increased dips near the centre (Cawthorn,1996). If that were the case, the cross over regions should only be used as a general guide and more grip points would have to be added to create more complex construction curves. These would be inserted to all the individual curves, with the aim of increasing the degree of curvature of each surface at the core and steepening the dips at depth. Alternatively only the inner surface could be modeled with steeper more lopolith like shape with a 5 or 7 grip point Bézier curve (figure 1b) and the outer surface using the simple 3 point Bézier construction curve (figure 1a), so that the overall enveloping surface defines a lopolith like body.

Using the simpler, bowl-like scenario, several local, fairly obvious convergent points were then inserted in the projection cross-over regions. These regions were better visualized by repeatedly changing the view plane in a 3-D editor and reducing the number of projection lines to the local converging region. Only those projection lines which helped in creating the local interpretation across the pluton, needed to be selected. These interpreted convergent points were then interpolated with a 3-D β-Spline using the included program *bspline.awk*. This new construction line was then reinserted into the model as a 3-D intrusion axis or "grip line" which was used to shape the geometry of the floor of each unit of the intrusive body (Figure 5d). In this example the emphasis was in producing a first pass geometric framework which could be further constrained by other methods, and therefore no initial consideration was given to estimating and maintaining a maximum and minimum unit thickness in the creation of the models. For example the Upper and Lower Zone contact could be generated by constrained thickness interpolation in EarthVision© using the bottom of the intrusion as a datum and the thickness range derived from local projections of the map pattern. However there would still be the requirement to construct at least one of the datum surfaces with only constraining field data.

Having established a curvilinear grip line ('control curve' in GoCAD©), points were then extracted from it and the unit map traces to build up a series of simple Bézier construction lines (figure 2). These construction lines are defined by three points. Two fixed control points at the ground surface, located on the map unit boundary where the construction line is kept tangential to the planar field measurements, and one grip point taken from the interpreted intrusive axis (Figure 6a). The program *hinge.awk* was used for this purpose with predictive mode set to off, as the grip point was inserted manually. This process results in a series of 3-D curve-lines that become tangential at ground surface to the igneous layering and that have a minimum slope near the intrusion axis. These form the construction lines for the entire model. Once a sufficient number (~ 12) of these interpreted 3-D Bézier construction lines were produced, surfaces representing the volume boundaries could be generated using standard 3-D minimum tension surface interpolation techniques (Figure 6b; Briggs 1974, Mitásova and Mitás 1993). These geological surfaces combined with the regional DEM surface allow for the construction of two completely enclosed geologic volumes, the Kiglapait Lower Zone troctolite and the Upper Zone Olivine-gabbro.

This model can now be sliced to reveal internal geometries, examined for geologically interesting intersections, or represented in a coherent 3-D perspective view (Figure 6c, d).

3.6 Discussion - Confirmation and validation of models

Validation of the Kiglapait model presented here was beyond the scope of this study as the main purpose here was to demonstrate the 3-D Bézier construction approach, however some discussion is in order as these constructions have the potential to be a bit misleading to say the least. Visualizations of complex geological objects are tentative representations of reality. The "truth value" of these visualizations is difficult to assess in the absence of control data at depth. A simple approach is to cross-validate a model with interpretations from other intermediate sources (Davis 1986). For example, a mine model created primarily from vertical sections, could be sliced horizontally at appropriate levels and compared with the available horizontal mine plans to assess the compatibility of the interpolated model boundaries. Caution is required here since both vertical and horizontal interpretive CAD sections developed at mine sites are often derived from the same source drill core data. CAD sections also vary in distance to drill paths and often need to be projected normal to the CAD plane. Large errors can result in this process when structures become more complex, with structural grain at low angles to the section plane and where drill paths diverge from the sections. The same confirmations could be done in the case of the Kiglapait intrusion, by producing several sets of Bézier construction curves at orthogonal directions across the intrusion. The assignment of field measurements could also be varied. For example a wider search area or stronger distance weighting could be set for selecting a particular data set. Final surfaces resulting from these different assignment methods can be compared, examining residuals and the internal error range displayed to identify specific problem areas (Davis 1989). Drill core data, if available, could be used to test whether modeled surfaces are reasonable down to the first few kilometers where they have access. These control data tend to be very clustered providing excellent local control but only at a few widely separated localities. Another approach would be to cross validate from depth corrected seismic sections and/or other geophysical data (McGaughey and Vallée 1997, de Kemp and Desnoyers 1997). For instance, in the case of the Kiglapait intrusion, a complete 3-D grid could be forward modeled starting with the Bézier constructed model, using a tool such as Noddy© (Jessell and Valenta 1996, Pinto and Casa 1996), producing a gravity and/or magnetic response. These artificial responses could then be mapped and compared to the actual survey data. In addition magnetic and/or gravity responses from forward modeling tools could act as a target data set for inverse modeling (Li and Oldenburg 1996).

Having more GIS-like access to an external 3-D georeferenced data base could also improve this confirmation process. As it is, the applications used to visualize control and constraining data (ie. EarthVision© and GoCAD©) are not well organized in an object-oriented environment. It is cumbersome to separate out a set of relevant structural measurements from a field database and then use these in construction line development. A new data set must be created at each stage of the modeling. With a robust object data base underlying the 3-D visualization environment several different visualizations could be more efficiently produced from the same primitive control data, employing a range of interpolation and extensions algorithms, including the Bézier based ones presented here.

The modeled Kiglapait surfaces are constrained by nearest (3-D) distance to mapped field observations within the intrusion map area. This constraint method could benefit from an improved technique for the assignment of regional structural measurements to feature traces. For example, structural field observations could be selected by considering not only the distance to a set of observations but also the geological context. Had the Kiglapait igneous fabric observations been part of a regional structural data set that was used in the modeling, it would have been useful to pre-select only measurements within the troctolite unit. Also pre-selection would be useful in modeling regional décollement surfaces so that preference for observations from either the foot wall or hanging wall could be made, as the independent blocks tend to have different structural domains. Similarly individual magmatic phases may have a more demonstrable parallel relationship to bounding surfaces being modeled.

Field data could also be geometrically examined by looking at orientation normals of the map unit boundary, favouring the selection of measurements that are parallel to contacts. The *field.awk* program can be internally modified to perform this check at specified angle cut-offs (see appendix-1). The depth projection and interpolation of geometric data points could also be made more dynamic by allowing users to pick sub-surface grip points and adjust them, to be geometrically consistent with seismic, drill core, or gravity data (McGaughey and Vallée 1997, McGaughey 1997). These 3-D geological shaping tools need to evolve into truly interactive and user-friendly applications that explorationists can use directly, so that several iterative attempts at a model can be produced without extensive preparatory data integration work. This will ultimately allow the interpreter to visualize and present interpretations to colleagues, and to select targets for detailed follow-up work, keeping in mind that any model is only as good as the data that went into its construction.

3.7 Conclusions

The visualization tool-kit available to the structural field geologist for efficiently building field-constrained subsurface models requires upgrading. The traditional method of manually or digitally reconstructing perspective or orthographic views is both cumbersome and restrictive. Updating the view as new control data arrive requires cumbersome reconstruction, and is still only restricted to a one viewpoint, single scale visualization. In the approach presented here a new control data point could be used to adjust an individual graphic component of the model without a complete redefinition of all the construction lines. Alternatively, the complete automation of visualization is not realistic when dealing with complex geological surfaces that have sparse control points, regardless of scale. There are simply too many interpretive decisions to be made by an expert during the construction process for automatic methods to be effective. The simple *awk* programs presented here are designed to stimulate the development of a more complete, robust suite of interactive geological design tools. The ideal approach for software development is to provide a complete set of interactive and interpretive spline-like 3-D editing tools for speculatively extending and interpolating known structural control points. The development of this tool-kit needs to occur in close consultation with field-oriented structural geologists who can prioritize the key functions required for developing constrained visualizations. Emphasis needs to be placed on using variously scaled field data, and towards a specific geological problem, in which several visualizations can be of heuristic benefit. High priority should be given to:

- Development of design tools for sparse field-based control data. Interactive and intuitive control point, grip point and frame-controlled Bézier and β-Spline tools for complex 3-D surfacing of geological features. The ability to spatially adjust these curves by snapping them to other adjacent surfaces such as; bedding (S0), fold axes (F1,F2,...) fabric traces (S1,S2,...) and the ability to blend these construction lines into more complex composite control lines (Figure 7). For example taking all the Kiglapait Bézier construction curves and constraining them to an interpretation line from a 3-D seismic survey, representing the floor of the intrusion;
- The ability to insert control points from structural field observations that constrain the local surface orientation, using both planar (strike-dip) and linear (trend-plunge) elements (Figure 6a). For example the Kiglapait surfaces could be locally reoriented by structural information from mine workings or seismic surveys if they were available. Local Bézier curves that control these surfaces in the vicinity of the mine workings could be modified to be tangent to these observations and the derived surfaces re-interpolated to respect the new curves.
- Flexible non-linear projections and propagations, or sweeps, of surface traces. This would facilitate the development of locally non-cylindrical structures. The

Kiglapait body is regionally and locally non-cylindrical so the linear projection of surface elements and use of cross-over regions presented here is biased towards the modeling of steep walled intrusions. Non-linear projection techniques would be able to utilize a plunge model for a region and propagate a surface element to depth in conformity with that model. A variety of projections could be useful, including; user defined, on trace property controlled, Variable Geometric Projection (VGP), functional geometric (using trigonometric functions such as sin()), point convergent (migrating an element to a target), plane convergent, 3-D curve line convergent, rotational; Figure 7);

- Further development of 3-D symbolization for multi-generational linear, planar and construction line structural elements. This would facilitate interpretation and analysis of the specific elements that are directly related to the structure being modeled (L1,L2…,S0,S1,S2, F1,F2,…; Figures 3d,5a,7);

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APPENDIX-1

3-D graphics AWK tools for geologists

The following list summarizes the awk scripts used in this study along with a few other awks programs which may be helpful in sampling and reorganizing data. Theses awk programs will be periodically updated at the International Association for Mathematical Geology web site at http://www.iamg.org.

wrap.awk - produces 2 point sets (scattered data files) for inside and outside of a specified geological feature. A buffer distance, in map units, must be specified. Wrap is used on planar data sets such as mine sections or plans.

```
Note : Input file must be a scattered data file and
         a data file unit Offset distance given.

usage: wrap.awk <inputfile.dat> <Offset>

produces 2 files...
Inside file: INSIDE_file.dat        Outside file : OUTSIDE_file.dat
         (with property = 1)  (with property = -1)
```

range.awk - A point set extraction tool which selects a specified data cube range from a larger existing point set.

```
usage: range.awk <in_file> <show|extract> {head|raw} {Xmin,Ymin,Zmin}
                  {Xmax,Ymax,Zmax} {XField,YField,ZField}

Note: input file must contain (X,Y,Z) records allways.

   When EarthVision header is not present user must
   specify XField,YField,ZField numbers.
```

hinge.awk - A three-point Bézier quadratic curve which fits 2 control points of a fold surface, and is controlled by a single grip point beyond the hinge closure.

```
usage: hinge.awk <in_file> <hinge_pnts> {line-id} {last|first|record} {out_file}

Note: input file must contain (X,Y,Z) records in triples such that:

              n record = surface point
            n+1 record = hinge control point
            n+2 record = adjacent surface point
```

cast.awk - A multi-grip point Bézier curve which allows the user to define a complex grip frame. Used in constructing non-symmetrical off plane 3-D curve.

usage: cast.awk <in_file> <hinge_pnts> {line-id} {last|first|record} {out_file}

bspline.awk - A batch splining tool which does a local best fit to the spatial locations of the control data set. Appropriate for clustered and heterogeneous data sets. Useful for visualizing continuous horizons at drill core or seismic picks.

usage: bspline.awk <in_file> <out_file> <seg_density> <seg_degree>

trace.awk - Solves for a local plane at specified search tolerances along a geological surface trace. Assumes some degree of local planarity.

```
        Note : Input file must be a scattered data file with at least
        the first three space delimited fields as X,Y and Z.
    Program defaults to dip direction format, specify
    argument as  R  for right hand rule output.
        All planar elements are processed as decimal degrees geographic,
        in which North is 0 or 360 and azimuth is measured clockwise.
        A horizontal dip is 0 and a vertical dip is 90 degrees
    See main text for operation.

usage: trace.awk <inputfile.dat>

optional {min_dist}{max_dist}{min_angle}{max_angle}{D|R}{output_file}

ie:  trace.awk S0trace.dat
     trace.awk S0trace.dat 10 1000 # # R S0dips.txt
     trace.awk S0trace.dat # # 5 160

default  produces 1 output file with same header as Input.dat file

Input file: <Input_name>.dat Outputfile :<Input_name_trace>.dat
```

field.awk - Searches the 3-D neighborhood around single vertices of a curve and conditionally assigns the nearest structural field observations within a user specified distance. Compares (X, Y, Z) input from the vertices list against (X, Y, Z) input from the structural field data base using;

Distance = sqrt(sq(dx) + sq(dy) + sq(dz)).

usage: field.awk <in_file> <struct_file> <distance> {struct_AZfield,struct_DIPfield}

```
        Note: input file must contain AZIMUTH or DIPAZM field.
                    When EarthVision header is not present the user must
                    specify the geometry fields in the structure data file.
```

To change the method for the selection of field measurements so that linear orientations will be approaching parallelism to the surface trace, make sure the Georule variable is set to Profile. This is located at the variable initializations at the beginning of the program. Cut off angles can be adjusted in the same section with the MinSection_angle variable. The default is 45°, in which case any plunge measurements more 45° from the vertical projection curtain of the trace will not be used. In Profile mode each point of the trace potentially receives the structure attribute by an inverse distance weighting and a direction vector averaging. This feature in combination with the distance argument can be used to populate a profile line crossing structural domains. The result is a "profile model" which can be used as the basis for more advanced projections.

Appendix-2

Bézier and β-Spline graphics tools for geologists

The approach used in these tools is an extension of simple linear interpolation between two points. In three dimensions a point P can be continuously interpolated between A and B by replacing incremental values of t from 0 to 1 in the following way:

$$P = (1 - t)\,A + t\,B \qquad (1)$$

P can be considered as a point in Cartesian space X,Y,Z. The dimensional properties are considered independently of each others such that the functional solution is dependent on the parameter t directly. For example replacing t with .25 will estimate the parametric distance 25% of the way between A and B. A simple C algorithm to produce a uniformly densified line at 1/1000'th increments between A and B can be written as :

```
for (i=1;i<1000;i++) {
        t = i/1000
        Px = (1- t)*Ax + t *Bx
        Py = (1- t)*Ay + t *By
        Pz = (1- t)*Az + t *Bz
        }
```

This can be expanded from the linear case in (1) to planar quadradic solutions (Figure 1a) in which A and B are on line end points and G is a 'grip point' controlling the convexity of curvature of the parabola and P is the set of curve solutions:

$$P = (1-t)^2 A + 2\,t(1-t)G + t^2 B \qquad (2)$$

The implementation could take the form:

```
for (i=1;i<1000;i++) {
        t = i/1000
Px = (1- t)^2 * Ax + 2* t * (1- t) * Gx + t^2 * Bx
Py = (1- t)^2 * Ay + 2* t * (1- t) * Gy + t^2 * By
Pz = (1- t)^2 * Az + 2* t * (1- t) * Gz + t^2 * Bz
        }
```

For more complex situations requiring more control points a more advanced Bézier can be used (Figure 1b) which estimates the curve with the general de Casteljau (Farin 1997) formulation as follows:

$$P^r_i = (1-t)\,A^{r-1}{}_I\,(t) + t\,B^{r-1}{}_{I+1}(t) \qquad (3)$$

with : $r = 1,\ldots n$ n = number of points
$i = 0, \ldots n-1$

The implementation can be accomplished with three nested loops to estimate each degree level of intermediate line segment until a final internal point on the curve is reached for a given parametric value in t:

```
degree = n - 1
for (i=1;i<1000;i++) {
        t = i/1000
        for (r=1; r<= degree; r++)     {
```

```
        for (i=0; i<= degree - r; i++)      {
        Point[i]x= (1 - t) * Pointx[i]  +   t * Pointx[i+1]
        Point[i]y= (1 - t) * Pointy[i]  +   t * Pointy[i+1]
        Point[i]z= (1 - t) * Pointz[i]  +   t * Pointz[i+1]
                  }
        }
Px = Pointx[0]
Py = Pointy[0]
Pz = Pointz[0]
}
```

(note that the degree is the number of points - 1)

Finally a piecewise implementation of a Bézier curve in which a moving cubic (or higher) function predicts the grip frame locally so as to interpolate through the actual control points is often refered to as a cubic β-Spline (Figure 1c). The benefit is local control without disturbing the entire curve and the ability to come close to respecting the actual control points, even in dense clustered situations.

For a more comprehensive treatment the reader is referred to Farin (1997) and De Paor (1996).

Figure Captions

Figure - 1: (a) Simple 3 point Bézier quadradic parametric curve solution. Computed by *hinge.awk.* (b) Multi-point Bézier curve. Computed by *cast.awk.* (c) β-Spline curve with moving local 4 point Bézier solutions. Computed by *bspline.awk.*

Figure – 2: Idealized summary of Bézier based 3-D graphic editing terms used in the text.

Figure - 3:

a) 3-D curvilinear geological trace. Depth colour coded with purple and blue deepest to yellow and red at highest elevations. Data provided by Dan Gibson, from Northern Frenchman Cap Dome, Monashee Mountains, British Columbia.

b) Mean normal triangulated planar solution. Note the change in down dip angle from near horizontal in the distance to near vertical in the foreground.

c) Feature trace with the planar solution visualized as disks oriented in the true 3-D configuration, and snapped to the digital elevation model. Vertical exaggeration is 2.0

d) Densified and extended feature lines with VGP (variable geometical projection). Extended projection lines are all from the base of a quartzite unit. Note the steep antiformal convergence of the projection lines in the upper portion of the image and the apparent shallow synformal inward convergence of the projection lines in the lower part of the image. Implied in this visualization is that there is an inflection point along the main fold axis shown as a red dashed line.

Figure - 4: Location of the Mesoproterozoic Kiglapait intrusion, and map distribution of the Upper and Lower zone of the layered intrusion, Nain Labrador - NFLD, Canada. Data from Morse (1969), Wheeler and others, (1997) and de kemp and others, (1997).

Figure - 5:

a) 3-D orientation regional primary igneous layering visualized as disks at surface of DEM, Kiglapait layered intrusion, Labrador, Canada. Inset shows detail of the same. Note the possibility of false clustering of traditional map symbols in high slope regions. Data from Morse (1969).

b) Depth corrected unit boundary with attached geometrical attributes which passed the 500 meter search criteria from *field.awk.*

c) Convergent projection lines of the lower troctolite boundary.

d) At depth lower intrusive axis (at white arrow) interpreted by the use of a β-Spline along converging projection lines.

Figure - 6:

a) User picked 3-point Bézier curves using the lower modeled intrusive axis 'grip line' as a guide. Tie-lining or direct interpolation approach will now surface the entire structure.

b) From below visualization of the base surface of the Lower Zone troctolite.

c) Model slice showing thickness variation and pinch-out at the intersection of the base of Upper and Lower zone surfaces.

d) Standard 3-D perspective view with no vertical exaggeration. Note the reduced effect of topography when dealing with a moderately plunging structure over regional scales.

Figure - 7: Conceptual diagram of a Bézier controlled complex fold visualization tool. Separately controlled insertable grip handles are used to model the local form of S0, F1 and F2 surfaces. Spatially weighting control points with degrees of tension and constraining structural field measurements could narrow the range of possible solutions. See also figure 3d where a hinge line inflection occurs along an axial surface similar to that along F1 depicted here.

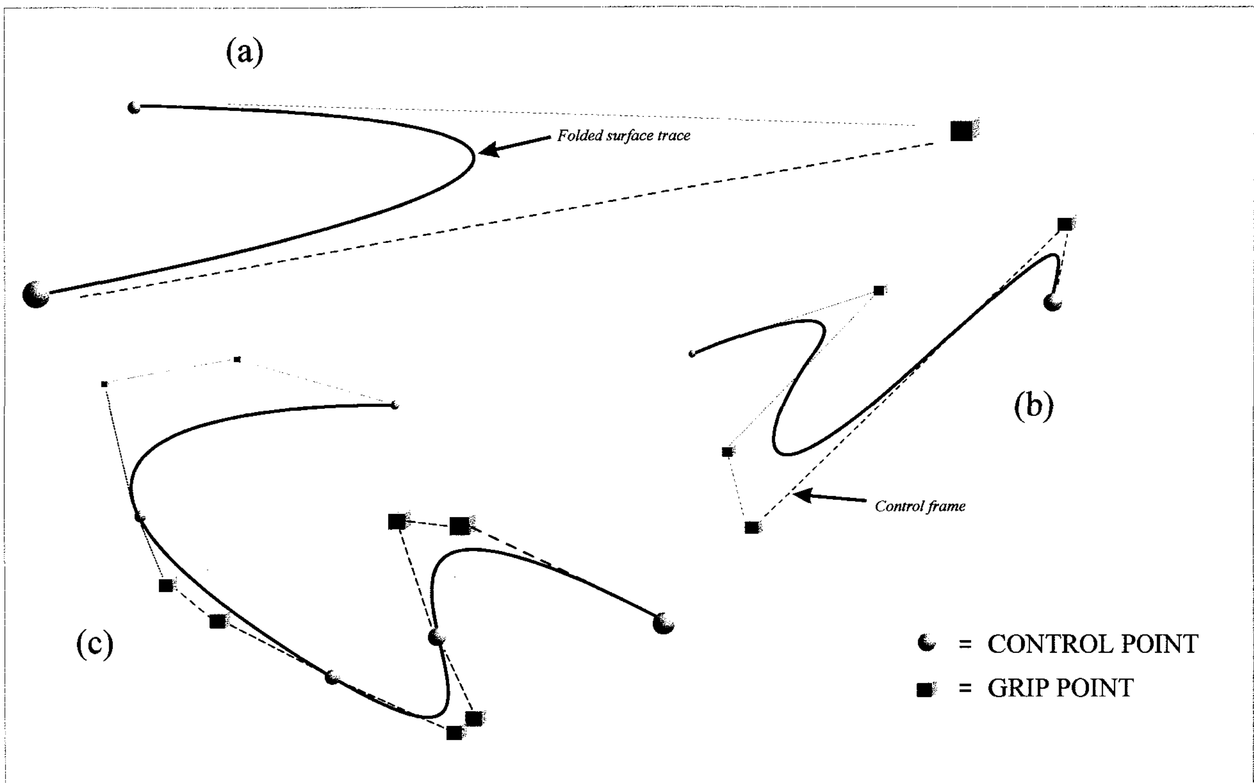
(a)
Folded surface trace
(b)
Control frame
(c)
= CONTROL POINT
= GRIP POINT

Figure 1

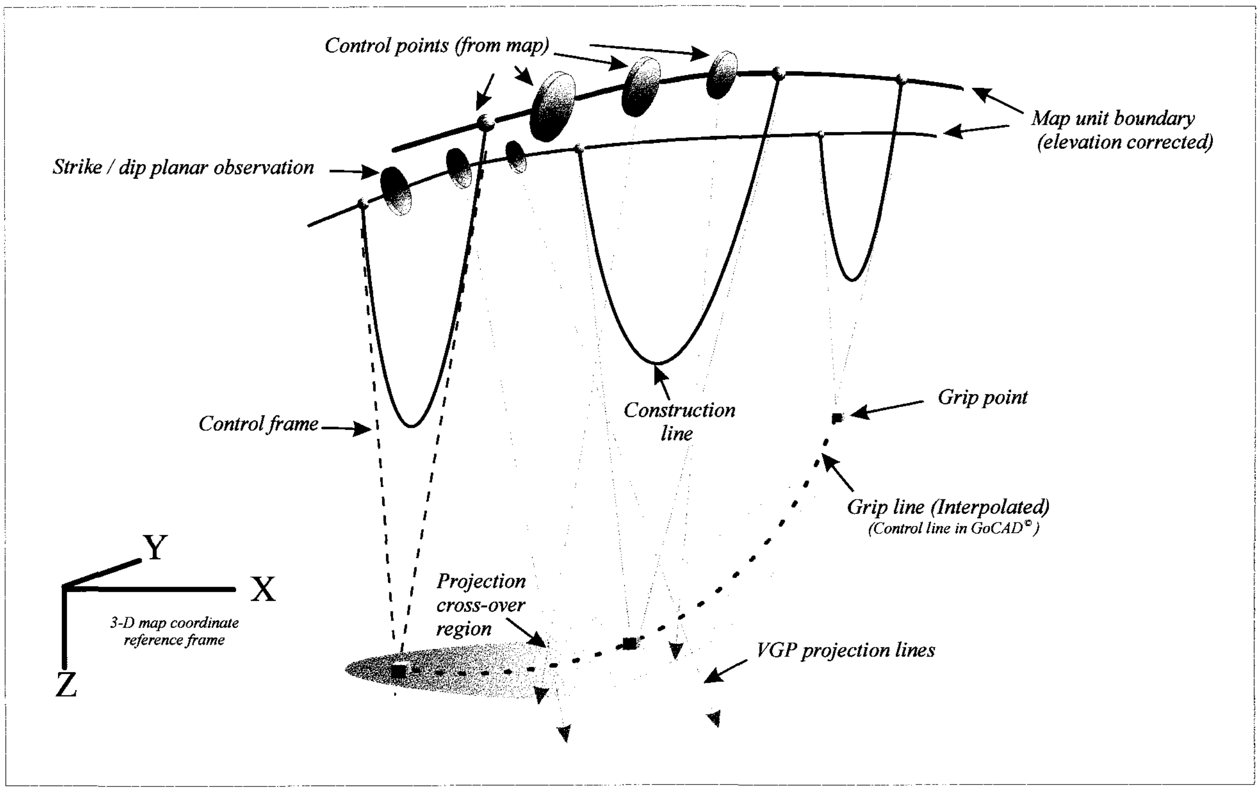
Control points (from map)
Map unit boundary
(elevation corrected)
Strike / dip planar observation
Control frame
Construction
line
Grip point
Grip line (Interpolated)
(Control line in GoCAD©)
Y
X
Z
3-D map coordinate
reference frame
Projection
cross-over
region
VGP projection lines

Figure 2

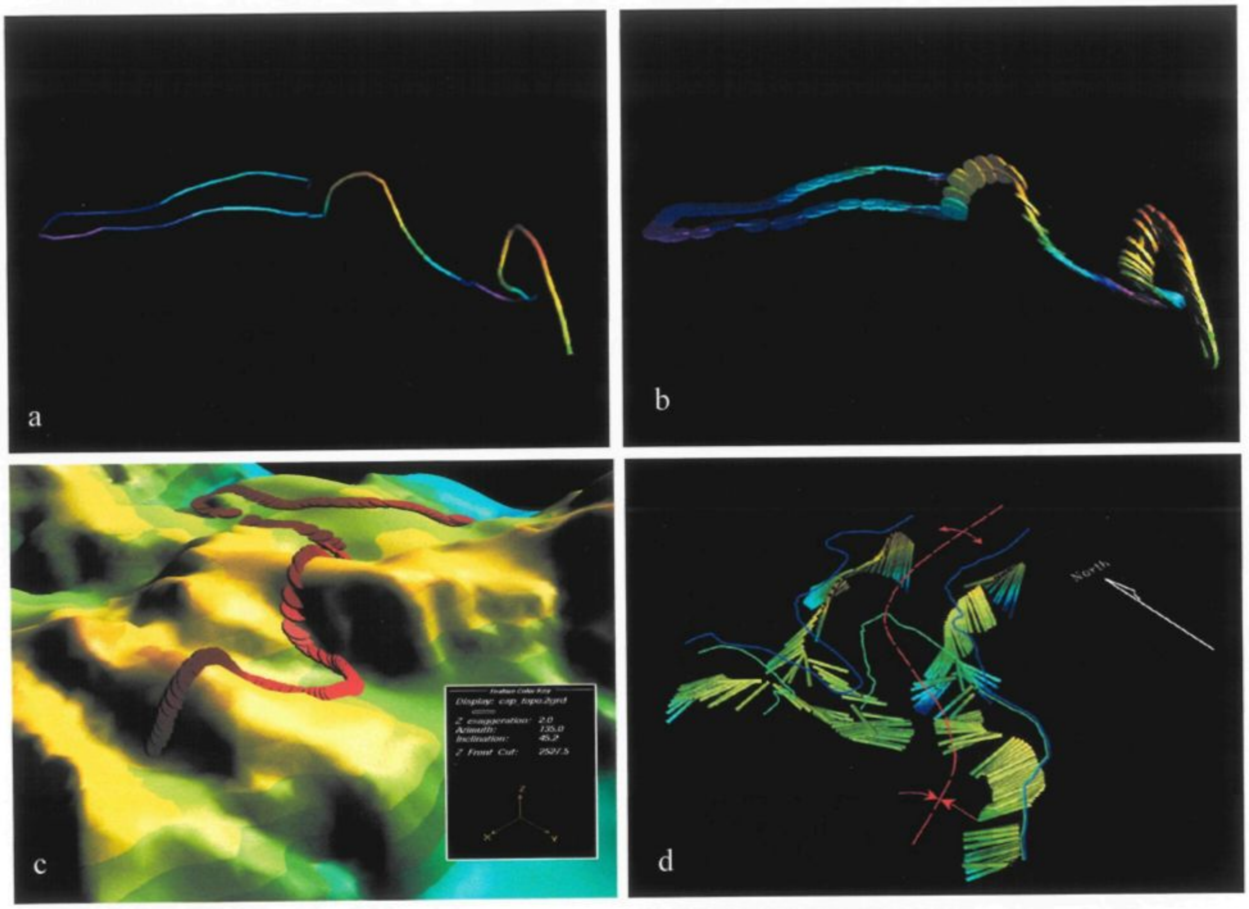

Figure 3

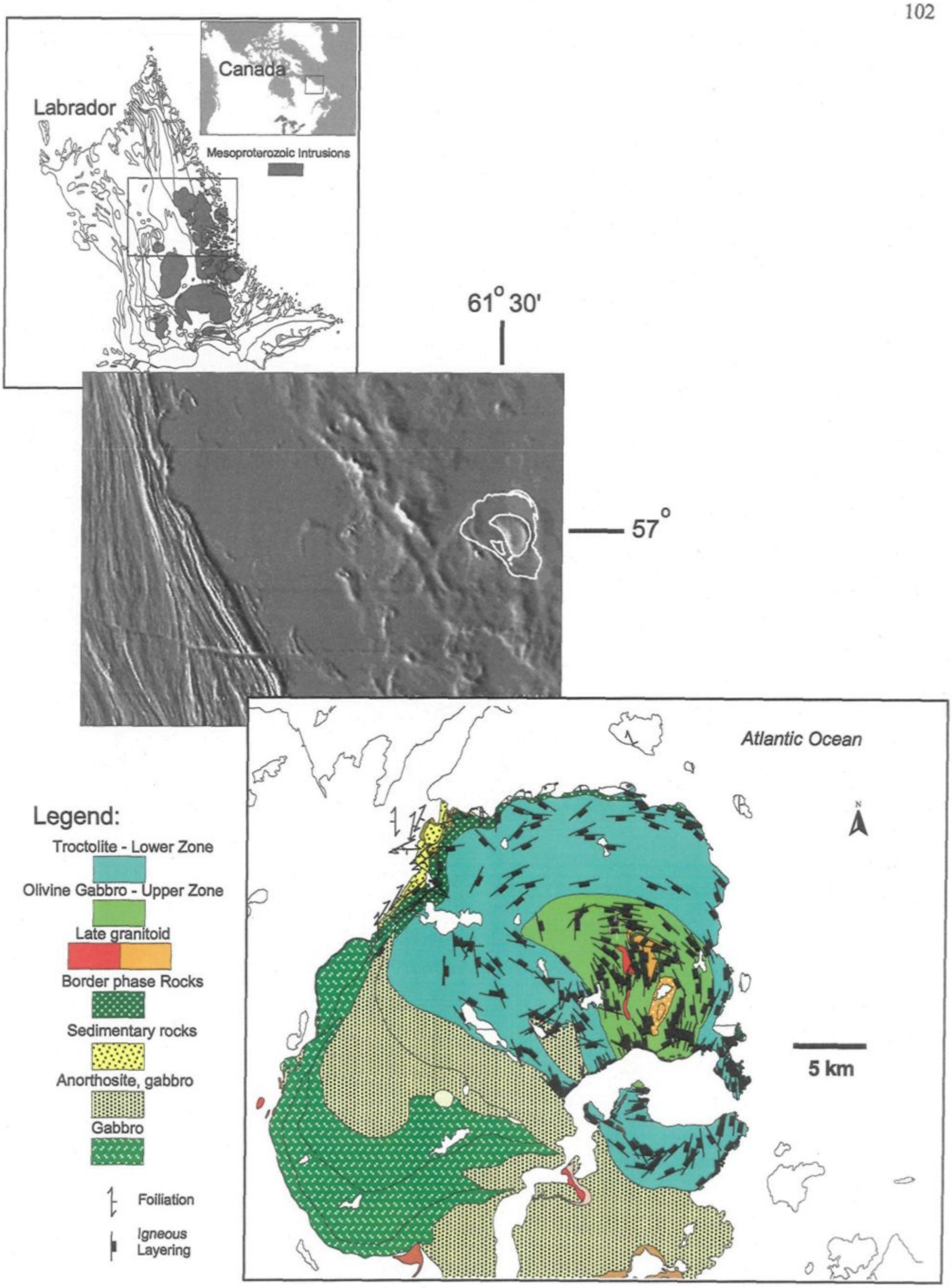
Canada
Labrador
Mesoproterozoic Intrusions
61° 30'
57°
Atlantic Ocean
N
5 km
Legend:
Troctolite - Lower Zone
Olivine Gabbro - Upper Zone
Late granitoid
Border phase Rocks
Sedimentary rocks
Anorthosite, gabbro
Gabbro
Foliation
Igneous Layering

Figure 4

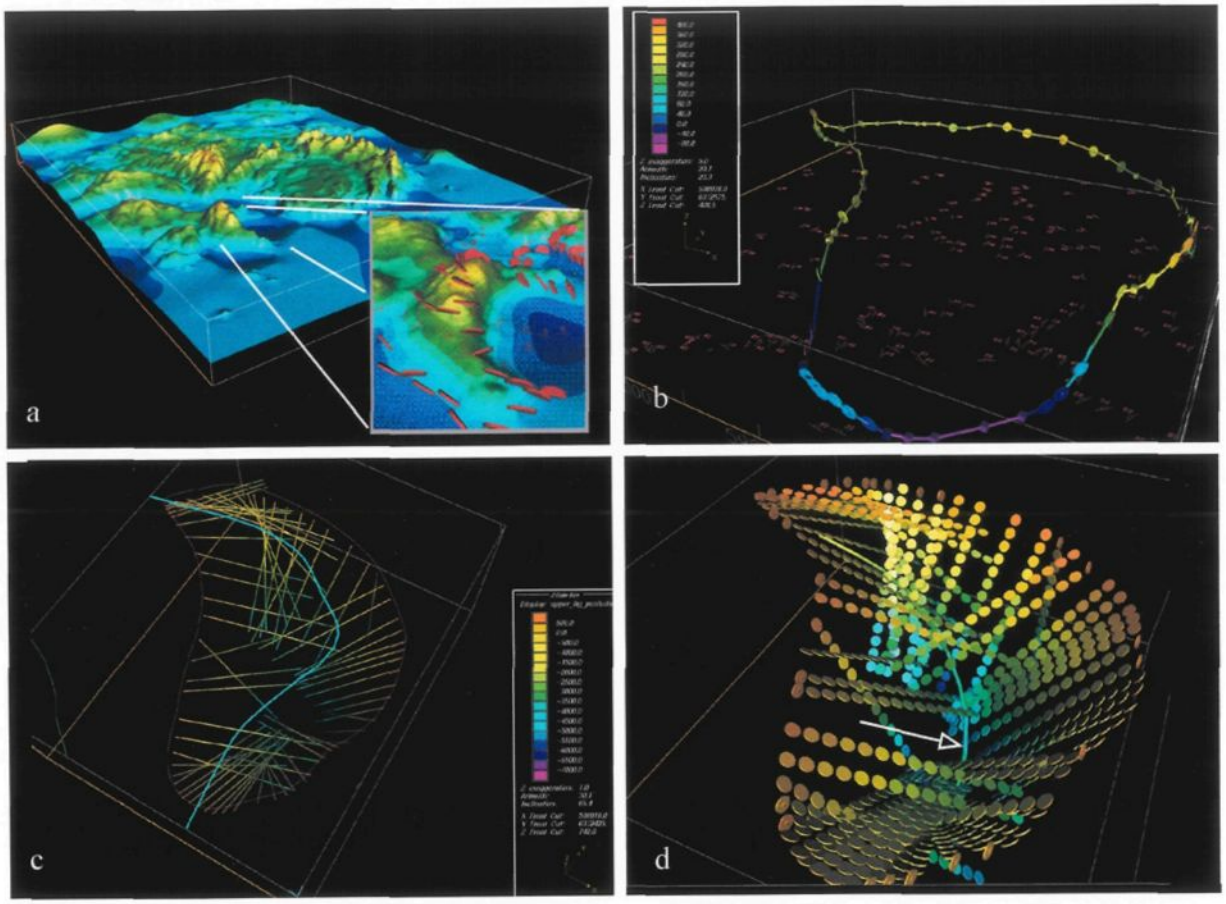

Figure 5

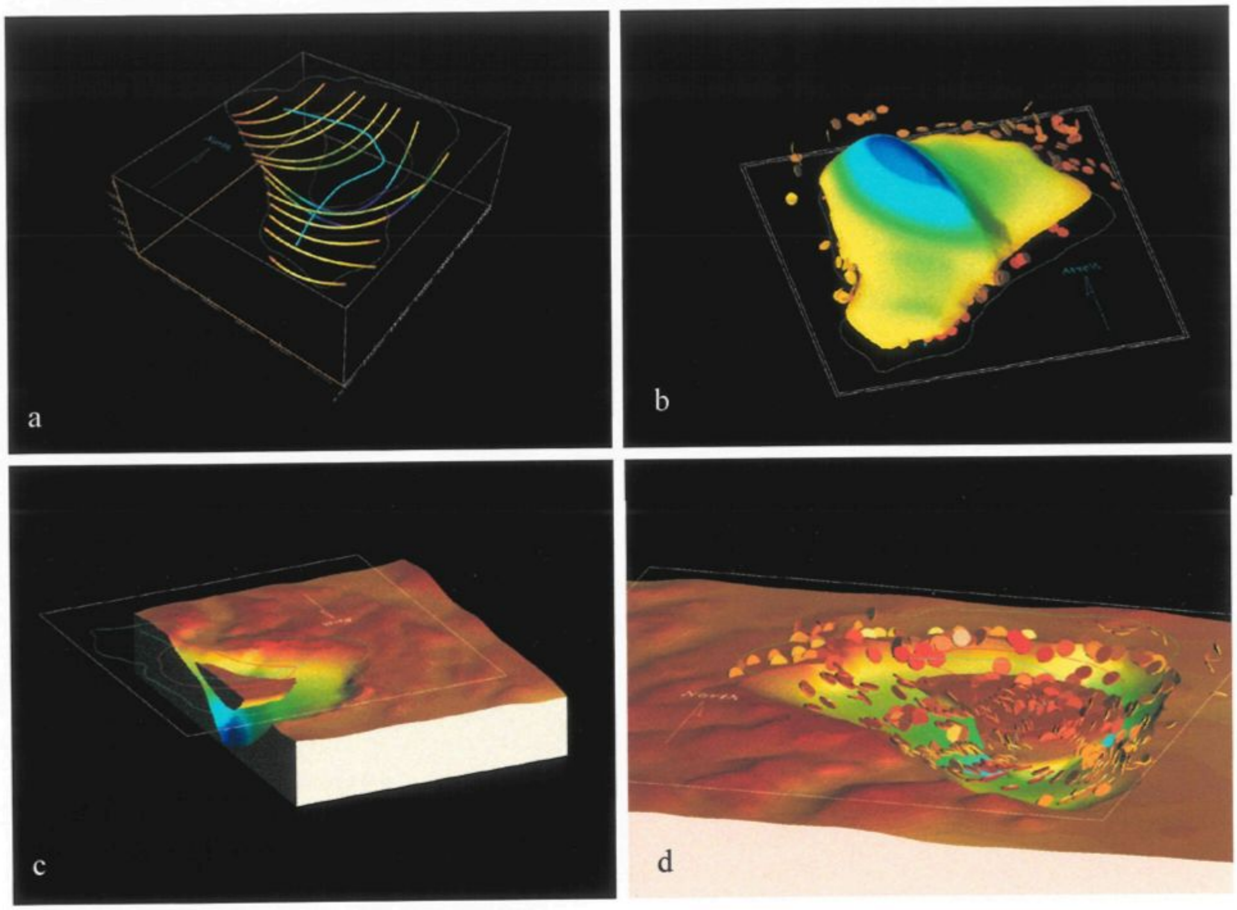

Figure 6

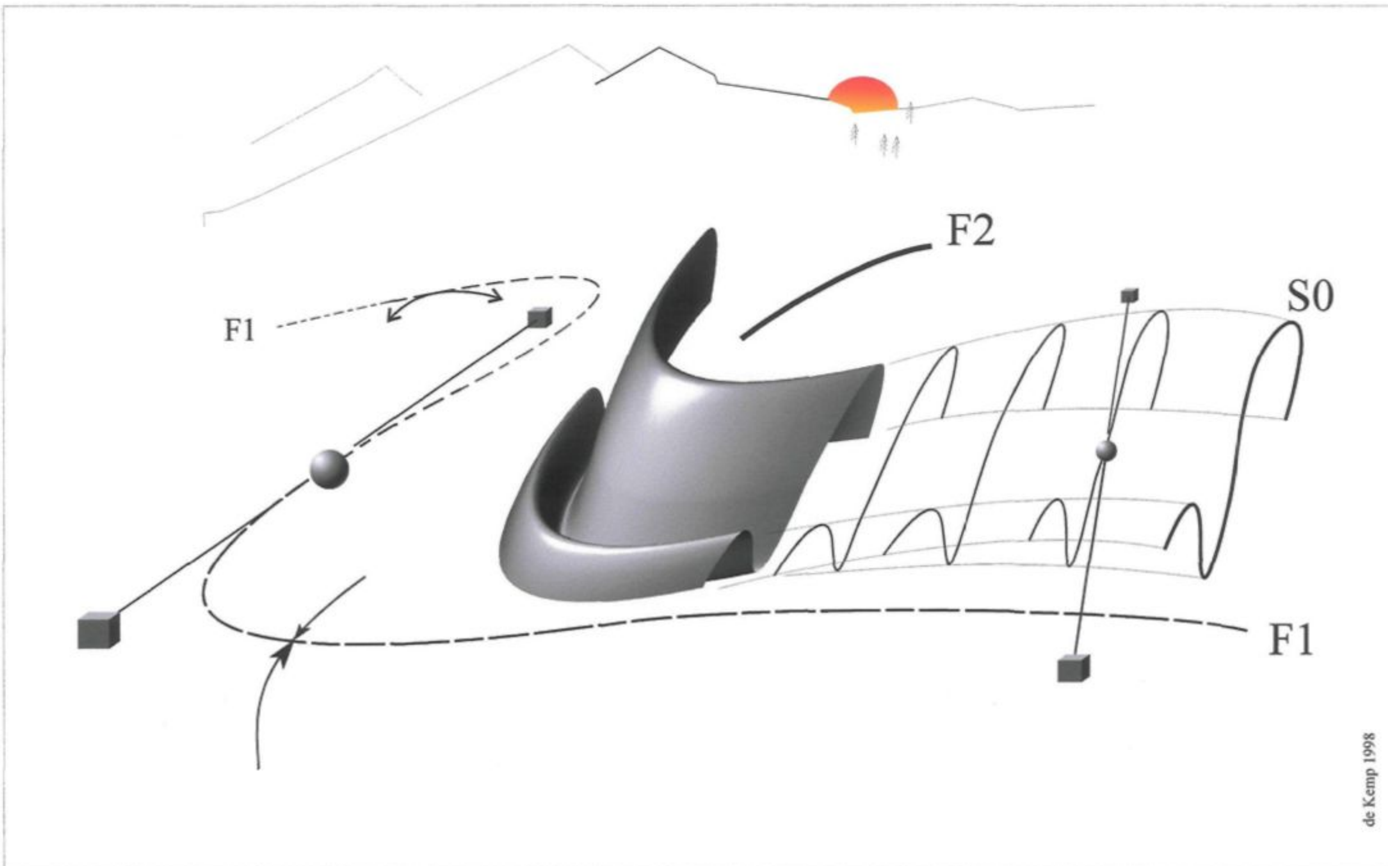

Figure 7

CHAPTER 4

3-D visualization of structural field data: Examples from the Archean Caopatina Formation, Abitibi greenstone belt, Québec, Canada

This chapter represents a reformatted version of a paper published in *Computers and Geosciences*, v.26, (2000), pp.509-530, by de Kemp.

Abstract

A series of 3-D visualization approaches is presented with the aim of developing better interpretation tools for field-based geologists. Structural data from outcrop, mine and regional scales are used to create speculative 3-D surfaces that can be useful in addressing geological problems. These tools could help in resolving cryptic early fold geometries, extending stratiform mineralizations and the sub-surface interpretation of regional thrusts, unconformities or key lithostratigraphic boundaries.

Using sparse data sets from the low-relief and structurally complex Archean Abitibi greenstone belt, I have demonstrated that speculative models can be created from such challenging terrains, provided that existing data are respected and that appropriate methods are applied at a given scale. Examples focus on optimizing the 3-D editing environment for making better interpretations. Applied techniques include custom projections of surface traces, 3-D digitizing, simple Bézier surface patches, and non-cylindrical fold construction using field based plunge models. These are implemented as several UNIX AWK programs in conjunction with commercial 3-D visualization and modeling software gOcad® and EarthVision®.

This integration and visualization study shows that complex fold geometries can be more rigorously constructed using constraining structural field data, but that current 3-D technologies are still very cumbersome for hard rock applications. Future development of field based case studies that will help validate and communicate the benefit of these methods is much needed, and will hopefully better articulate specific requirements to

software developers. Professional 3-D software developers are encouraged to work towards implementation of these types of programs in order to move the regional mapping community beyond 2-D and 2½ -D GIS-based modeling.

National surveys and explorationists who are responsible for the collection, management, and archiving of geoscience data need to be diligent in maintaining their structural field data. This will be especially critical as 3-D visualization and modeling techniques, such as those I have presented here, become available to the bedrock mapping community.

4.1 Introduction

Creating geologically relevant 3-D models from low relief, poorly exposed and geologically complex regions is a daunting if not impossible task. In the absence of drill core, high resolution seismic data or mine data, these regions are open to a wide range of interpretations. It is therefore important that these interpretations are constrained to the geometric possibilities provided by field observations: local strike/dip or plunge/trend measurements of planar and linear structural elements, top indicators, locations of surface traces and fold styles. This paper summarizes an approach to 3-D integration of these data with an emphasis on the use of projection functions and interactive 3-D editing methods, with examples taken at a local outcrop scale (10-200 meters), mine scale (100 – 2000 meters) and regional scale (1-50 kilometers). The integration tools used in these examples are coded within Unix *awk* scripts (Dougherty, 1990) described previously (de Kemp 1998, 1999) along with a new non-cylindrical fold projection utility called *dive.awk,* presented herein, and in more technical detail in Appendix-1. Awk proved to be an excellent programming tool because simple ASCII record ordered geometry files could be easily and quickly processed without constantly recompiling during code editing. It has reasonable pattern matching and geometry functions that were sufficient to perform the extensive geometric algorithms used in this study. These programs are downloadable from the International Association for Mathematical Geology web site at http://www.iamg.org and will be updated periodically. All of these utilities have been used in conjunction with GoCAD® and/or EarthVision® 3-D visualization and modeling software in a UNIX environment.

Development of computer generated geological surfaces presented herein occurs in an environment that enhances interpretations and automates the visualization tasks that are so cumbersome in manual methods such as traditional block diagrams. The modeling techniques are primarily based on the notion that field observations from a given area have structural relevance to the surfaces being modeled at depth (Jessell and Valenta 1996, Charlesworth et al. 1975, Spark and Williams 1995, Lisle 1988) and can be used to interpret broader structures at the surface of the earth (Argand 1922,1928, Schwerdtner 1977, Lisle 1999).

Continuous geological surfaces can be complex such as an overturned fold having multiple depth intersections. They can be topologically enclosed such as an ore-body, and they can be very convoluted as a result of polyphase folding. Creating a geometric model that approximates these structures from sparse control data requires an interpretive environment that combines flexible interpolation and extrapolation functions along with a powerful 3-D editing and graphics display engine. Many CAD (Computer Aided Design) engineering packages do not provide the ability to generate complex surfaces from few control points or the ability to model surfaces based on geologic rules. For example allowing separate bedding surfaces to join in a fashion that respects their depositional tops. Animation packages are difficult to use with GIS-based field data, and are designed to make virtual scenes using a host of primitive objects that have very little geological representation or significance. Advanced CAGD (Computer Aided Geometric Design) has many of the complex 3-D surface and volume-shaping tools needed for geological modeling, but these tools are not designed to work with geological data in map based coordinate systems. They are also prohibitively expensive for field-based visualization. Although these technologies are steadily converging, they are still distinct and limited in what they can provide as an interpretive 3-D environment for geologists. The approach presented here overcomes some of these limitations, and is meant to generate some interest in the further development of interpretive virtual geological environments, specific to the needs of field-based structural geologists.

These needs are:

• the ability to display all relevant 2-D map based data such as symbolized structure data, geographic reference features, geological contacts and map units, co-registered imagery such as orthophotos, satellite or airborne geophysical data,

• access to standard interpretive tools such as stereographic projection plots, structural domain analysis tools and cross-section development tools,

• the ability to establish control points from field observations and assign geologic relevance to them,

• Interpolation routines which respect strike/dip or trend/plunge at these control points,

• a 3-D interpretive editing environment which is intuitive to a structural geologist, allowing efficient dynamic rotations, translations, scale jumps and data selections.

The approach is illustrated with visualization examples of F1 and F2 folds from an Archean turbidite basin in the northeastern Abitibi greenstone belt of Québec, Canada. At various scales, the 3-D interpretive environment that I present is no different in principle than the development of an interpretive 2-D structural map. The only difference is that another dimension has been added. For every dimensional direction, for a 2-D map or a 3-D model, estimates and assumptions must be made, at least in a qualitative way, about surface continuity, variability and predictability of the structures.

4.2 Geological context

The study area is dominantly underlain by lower to mid-greenschist facies turbidites of the Archean Caopatina Formation (Fig. 1), although local metamorphic grade may reach as high as mid-amphibolite facies (Lauzièr et al 1989). The turbidites are part of the Cycle-1 metasediments of the Northern Volcanic Zone in the northeastern Abitibi greenstone belt (Mueller et al. 1996, Mueller and Donaldson 1992). The ca. 2.76 Ga Caopatina Formation is represented in the field area by rocks ranging from coarse felsic epiclastics, including clast supported conglomerates, to interbedded mudstone-slate couplets. Centimeter scale A-E Bouma-type bedded turbidites dominate the Caopatina Formation, with laterally continuous near vertically dipping beds. Numerous primary structures in the better exposed areas display well-preserved grain gradation, flame structures, and a ball and pillow geometry providing excellent stratigraphic top indicators needed in resolving the topology of local folds (Lauzièr et al 1989). The area is flat, with less than 50 meters of vertical relief and has very poor exposure of bedrock, which is estimated at < 1% of the land cover.

Previous 1:20,000-scale bedrock mapping by the MRN (Ministère des Ressources Natural du Québec) (Lauzièr et al 1989, Midra et al. 1992, Mueller et al. 1994), and detailed 1:500-scale plane-table mapping by the author (de Kemp et al. 1994) form the structural field data set. These data, coupled with recently acquired high resolution (25 meter gridded) aeromagnetic and EM surveys (MRN 1994,1995a,b) in the Caopatina region has resulted in a more detailed delineation and characterization of the Caopatina Formation (Fig. 2).

Three regional ductile folding events and at least one late, localized, dextral shearing event have contributed to shaping the present day bedrock geometries throughout the area. D1 deformation results in tight folding of the Caopatina stratigraphy as evidenced by numerous structural facing direction reversals along S2 and F2 traces through over 30 km of the structural basin strike length (Fig. 3). The absence of a regional distributed S1 fabric, the lack of unequivocal F1 fold hinges, and the presence of numerous syn-sedimentary dewatering structures (Fig. 4) throughout the formation suggest that D1 folding occurred as a thin-skinned event, in the uppermost crust. Possibly, the pore fluid pressure to lithostatic load ratio was quite high, producing localized slumping. Such slumps may have provided localized reversals and possibly nucleation sites for later recumbent F1 folding and thrusting. The lack of outcrops and the paucity of anomalous magnetic marker horizons within the Caopatina Formation make it near impossible to discern whether local facing direction reversals are dominantly the result of syn-sedimentary or tectonic processes (Elliott and Williams, 1988). Tight to open asymmetric F2 fold structures predominate in the area, with the main east-west trend of the Caopatina Formation coinciding with the regional scale F2 Druillettes synclinorium (Lauzièr, Chown and Sharma 1989) (Fig. 5). The F2 folds are generally east-west trending with 25-60° plunging hinges. S2 cleavage is parallel to F2 fold hinges throughout the region (Fig. 6). Axial planes of F2 folds are near vertical displaying parallel foliation fabric which is penetrative throughout the Caopatina basin metasediments. These fabrics often produce classic bedding cleavage intersection and refraction fabrics which are perpendicular within competent arenaceous-wacke beds and near parallel in pellitic beds. Gentle to open F3 cross folding occurs at a regional scale with northeast axial orientation. Locally this folding is of minor significance and expressed as rare kink banding and occasional chevron folding.

The opportunity for a 3-D data integration and visualization study of this area was apparent since orientation and top indicators, where exposed, are easily recognizable (Fig. 7), providing good geometrical and topological control for fold interpretation. Classical methods for bedding trace interpretations using fold style, cleavage/bedding intersections and vergence rules could be used. The spatial frequency of both F1 and F2 folds was low enough that continuous models could be interpreted at either outcrop, mine or regional scales, and also there was a definite need for interpolation and extrapolation tools due to the poor outcrop density.

This terrain is typical of Archean shield regions of Canada and throughout the world, where poor exposure and low relief are the norm. For this reason the techniques that are presented here should be applicable to a host of other terrains for which field based 3-D visualization would be of benefit.

4.3 Outcrop-scale visualization

In the Caopatina region, one area with high outcrop density was selected for detailed F2 - fold visualization (Fig. 2 and 6). At the outcrop scale of 10-100 m, the spatial frequency of turbidite folding is much higher then that resolvable by the high resolution aeromagnetic survey (Fig. 5). Structural variations in the turbidite units are also not discernable in the aeromagnetic data along 100 m spaced flight lines (Fig. 8A). This limits the visualization, at the outcrop scale, to be constrained only by the structural data. In this area, F2 hinge lines conform to a L2 stretching and S0/S2 intersection lineation. These two elements can thus be used to control the local projection of F2 folded surfaces. From observing the geometric relationships of the better exposed fold surfaces throughout the area it was clear that local structural elements (F2/L2, S2) were near cylindrical in character (see stereographic projection in Fig. 6). These folds could thus be used to constrain outcrop scale models since the macroscopic F2 folds were characterized by low plunge variability to shallow depths, and fold styles were scale independent. Several 3-D fold interpretations were made by attaching directional properties of macroscopic hinge lines (F2), intersection (S0/S2) and/or stretching lineations (L2), and primary turbidite bedding orientations (S0) to mapped bedding traces (Fig. 8B). Structural elements were selected by closest distance within a 5 meter buffer to the S0 trace. These F2/L2 elements (red lines in Fig. 8B) were then interpolated along the length of the map trace.

Uniaxial and variable geometric projection (VGP) (de Kemp 1998) of the S0 map traces provided a useful 3-D framework from which fold models were developed. Many outcrops provided little information about plunge variability at depth, so as a rule I projected map elements, in this case the 2D points of the S0 trace, up to half the horizontal wavelength spacing of the folds. Once the projection framework is set up within the 3-D editor ('3-D Viewer' in EarthVision® and '3-D Camera' in gOcad®), it is a simple task to decide on a series of digitizing planes on which interpretations can be made (Fig. 8B,C). It is not possible to do a freehand drawing in empty 3-D space without somehow assigning a viewer screen depth or manually translating the 3-D cursor at successive vertices. A digitizing plane or other surface object needs to be present to give the viewer depth coordinates as a 3-D line is being drawn. Interpretive construction lines are drawn on these planes, with Bézier (Farin 1997, De Paor 1996, de Kemp 1999) and/or Discrete Smooth Interpolation (DSI, Mallet 1997, 88, 89) methods for line smoothing, at successive horizontal or vertical levels through the framework.

Automatically projecting the surface trace of any structure that has variable plunge, and using the extrapolated fold traces directly to define a surface can cause topological errors, surface drop-outs and sharp edge effects. Topological errors occur as adjacent edges of the same surface become flipped with respect to depositional tops. Surface drop outs occur when projection lines converge into a complex bundle. Surface development using a triangulated mesh in these constricted areas will often have empty facets or unwanted sharp edge facets. For this reason the fold trace projection lines were only used here as a general guide in the fold design. The interpreter decides how the surface will migrate at depth by generalizing enveloping surfaces or introducing new curves to create a consistent fold topology and style (Fig. 8C). For non-cylindrical folds the projection line cross-over regions can be used to define areas of surface convergence at fold troughs (de Kemp 1999). It is important that the subjective exercise of interpreting the fold through 3-D digitizing of construction lines be undertaken by a geologist. Ideally, this person will be able to narrow the range of fold solutions to a given set of field data by taking the whole geological context of the model into consideration.

The S2 form surfaces have a simple geometry, and since F3 folding at this scale is minor, it was possible to create local 3-D S2 foliation surfaces by extending theses elements to depth. Placing other structural elements such as relevant bedding symbols as

3-D disks, adjacent hinge lines and S2 foliation curtains in the 3-D environment can enhance the interpreters ability to shape the fold geometry. For example by acting as a guide while digitizing fold closures to be co-planar with S2 fabrics (Fig. 9 A,B). Certainly some practice working with a 3-D editor is required so that cursor movement, the 3-D reference frame and the model elements, can be navigated efficiently. Once several construction lines are drawn these can then be directly interpolated with DSI and used to define a continuous surface (Fig. 8D).

Using this method, many alternative surface constructions could be made, with a range of fold geometries. Some of the a priori assumptions used in these constructions came from my own mapping experience and knowledge of the local fold patterns observed during detailed mapping in the area. These included;

- keeping the enveloping surface smooth,
- maintaining correct asymmetries of minor parasitic folds,
- keeping all major and minor folds in the structure axial planar to S2,
- keeping the style of folding consistent with others in the area (in this case they were similar class 2 using the Ramsay fold classification (Ramsay 1967),
- no discontinuities (faults) were allowed at the outcrop scale.

Structural form surfaces can now be represented in a variety of ways to aid in extending the structural interpretation. As a continuous 3-D mesh, each facet on the surface has directional properties from which normals can be calculated (Fig. 8B,C,D). A useful operation is to create a duplicate surface by incrementally offsetting the surface along normal vectors. This will help to visualize fold topology by combining a surface top and bottom. Without a surface normal available to propagate this offset there would be no way to represent the topology of complex overturned surfaces. Variable colouring, shading and contouring of the surfaces can be altered to increase the interpretability of surfaces.

4.4 Mine-scale visualization

Several of the outcrop scale 3-D models were combined with intervening structural data to create a 3-D model covering 1.5 to 3 kilometers, typical of a medium sized hardrock mine. The purpose was to resolve the local F1 fold vergence by visualizing the S0 surface in an area for which there was evidence of an F1 closure. Developing a method for 3-D visualization of a particular F1-F2 interference pattern could help in the regional tectonic interpretation and more importantly provide an approach which might be used in other similar geological situations. The presence of a repeated, < 5 m thick, mafic-intermediate volcanic flow, parallel to turbidite bedding, coupled with F2 facing direction changes along F2 fold axial traces provided evidence for the interpretation of an F1 closure (Fig. 6).
Other assumptions used were;

- beds were continuous or had negligible fault offsets between northern and southern limbs of the F1 fold,
- that the structure was closing at depth and to the west at ground surface,
- that the intersection of extended opposite F1 fold limbs would form a guide for defining the F1 hinge at depth.

The approach at this hypothetical mine scale was modified from the outcrop-scale method in two ways. Firstly, an initial surface was modeled by creating a continuous Bézier surface or 'patch', which provided the general geometry and topology of the F1 fold. Secondly this fold was reshaped by constraining or ‘snapping’ the upper portions of the Bézier fold surface with the detailed S0 surface trace using DSI. In other words using the S0 trace as a 'control line'. This two-step approach allows the geologist to create an initial topologically sensible and dense structure, and then follow up by fine tuning the model from detailed surface data.

Bézier patches are an extension of Bézier curves (Farin 1997, Farin and Hansford 1998, DaPoar, 1996). The benefit of using Bézier patches is that a continuous 3-D surface is produced from a single 3-D control network of points instead of just producing a curve-line from a simple control frame (Fig. 10). In addition with a Bézier patch it is easy to produce geometric surfaces with continuous smooth properties with relatively few control points, unlike other 3-D spline surfaces such as NURBS (Fisher and Wales 1991) or DSI generated meshes (Mallet 1989), which are excellent for design work with a lot of control data. NURBS unfortunately are not available in gOcad® or EarthVision®. The other distinction is that editing a single control point effects the entire Bézier patch whereas it will have only local effect on a NURB. The program *bezpatch.awk* will create a surface patch at a specified density in the u and v paramiterization directions for EarthVision® data files (see Appendix-2). This program uses a simple Bézier patch implementation since only the four end control points are spatially fixed. The rest of the control frame points are moveable 'grip points' that shape but are not coincident with the modelled surface. The ordering of points within the control frame, also referred to as a knot sequence, is very important to make a proper surface. Ordering can be cumbersome as there is no a priori way of knowing how a given spatial arrangement of control points will influence the modeled surface just from location alone. The same spatial arrangement of grip points can produce very different fold structures if the knot sequence is altered (Fig. 10). This necessitates rigorous progressive digitizing of the control network without re-ordering any points, or the manual encoding of the knot sequence in a 3-D editor (Fig. 11). Once the control network is encoded, and as long as the knot sequence is unchanged, the spatial locations can be moved to adjust the surface geometry of the patch.

To interpret the mine-scale F1 fold structure an environment was set up with a continuous S0 bedding formline and an F1 fold axis trace, projected to a shallow depth of 100 m (Fig. 12A). Only the local F2 and L2 data were used to control these ribbon-like visual guides, and it was assumed that the S0 surface could depart from parallelism with these ribbons at depth. The control frame that defines the F1 Bézier patch was digitized at 200 meter intervals on vertical serial slices roughly perpendicular to the F1 axis, starting near the ground surface closure. In this case none of the F2 or L2 linear elements were used to model the F1 hinge trajectory at depth and hence there is considerable freedom to interpret the structure. However, the minimal fold design requirement was that the control network had to respect the location and orientation of the S0 trace and the interpreted F1 fold axis trace (Fig. 12B). This requirement would necessitate the orientation of the F1 hinge to be plunging to the east at a moderate angle.

Once the Bézier surface is created from the control network, the shallow parts of the surface can be constrained by using the S0 trace as a control line, to effectively pull the Bézier surface to itself (Fig. 12C). The surface to control line snapping can only be partially automated since the snapping directions, also called 'shooting directions' in gOcad©, are optimized to be directed to the nearest point of an object. In more convoluted regions of a structure, selecting the nearest point to an object from a control line may cause a surface to pinch in on itself producing topological errors. In these problematic regions individual control points, and associated direction vectors can be manually edited to respect the desired fine-scale geometry, so that unwanted surface intersections do not occur. After these constraint points have been inspected along the S0 control line, the entire Bézier surface and the control line are interpolated again with DSI. One iteration of DSI will alter the surface details of the fold and shape it to the geometry of the control line. More smoothing of the overall structure with DSI can remove some unwanted 'pin-cushion' effects caused by localized ruggedness imposed by the control points which do not move. Finally a continuous 3-D fold representation is made which respects the limited field information and is consistent with mapped F1 fold topology in this area (Fig. 12D).

For this Bézier patch a 19 x 5 control matrix was used. This is 95 interpretive control points that need to be digitized on 19 separate vertical planes to give a first approximation of the fold topology. This process is cumbersome mainly because I have implemented it in awk which batch processes a control network outside of gOcad®. What is ultimately needed is for the interpreter to have access to a simple default surface patch inside the 3-D editor, with pre-defined orientation, simple shape, control point and surface densities. This could then be edited dynamically so the user could immediately see the results of editing grip points. 3-D geoscience software developers should give serious consideration to adding this functionality as it could be very useful for initial fold construction with sparse data.

4.5 Regional-scale visualization

Regional scale (1-50 km) geological map elements can be extended to depth and made to represent non-cylindrical surfaces using the classical technique of Stockwell (1950). Modifications of this technique have been used to interpret regional structural and metamorphic variations in structurally complex terrain through the creation of structural composite sections (King 1986, Lucas 1989). This method effectively projects mapped field geology through a vector field, tracing out a non-cylindrical reference surface or 'datum' surface similar in appearance to the classic alpine interpreted surfaces of Argand (1922). As with the other methods presented herein, this technique is based on the assumption that local structures observed at the surface of the earth tend to reflect similar geometry of related regional scale structures at depth (Fig. 13) (Stockwell 1950, Schwerdtner 1977). The core of the technique is the use of a 'plunge model' through which selected map elements can be propagated in 3-D space. The regional-scale visualization focuses on the use of this technique as implemented in gOcad©.

4.51 Plunge model development

The program *dive.awk* is an implementation of the Stockwell approach using simple vector geometric techniques (Farin and Hansford 1998) to visualize a possible 3-D regional geometry of the F2-folded Caopatina turbidite - metavolcanic contact (Appendix 1). This program examines a 'plunge model' for a given regional structure and uses this as a geometric index to project map elements such as a folded stratigraphic or tectonic boundary (Fig. 14).

The plunge model was developed using *field.awk* in profile mode (Appendix 1) which spatially selects field data along the interpreted F2 Druillettes Syncline fold axis of the Caopatina turbidites (Fig. 15). F2 hinges and related stretching and intersection lineations within a 3 km buffer of the F2 axial surface trace were included into the plunge model calculations, as this distance seemed adequate to populate the F2 axial trace without extremely large gaps. This distance also represents 10 percent of the regional F2 axial plane strike length, and a distance in which plunges would be representative of the keel zone of this type of steep structure. I selected the plunge measurements that make up the control points of the plunge model based on several assumptions. These are;

- plunge orientations close to the F2 axis should have more influence on the model,
- local plunge variations could be smoothed out by averaging within a local neighborhood in order to better reflect the regional trend,
- plunges that trend at high angles to the regional F2 axis, reflect localized interference folding not the overall regional east west trend,
- minor F2 folds along the regional axis are topologically simple with long limbs up consistent with the field observations throughout the region,
- the F2 axial surface was assumed to be steep, near vertical but with moderate to shallow plunge.

The plunge data is thus processed by selecting plunges within the buffer distance. These are then inverse distance weighted and the direction cosines averaged. Shallow plunges trending at high angles to the section once projected onto the fold axial surface will produce false steep apparent plunges. These are assumed to be more reflective of local structures and given minimal weight. This should result in the selection of only those plunge elements that are most likely related to the general east-west regional fold trend, and the smoothing of local structural domain variations into statistically dominant plunge values. The elements of the plunge model are ordered so that the trough point of a folded structure is the starting end. Also plunges that are oriented back towards the starting end are flipped to indicate rising plunges. This is allowed because folding is assumed to be topologically simple. For example a plunge model that starts in the west and finishes in the east that contains a 45° westward down-plunge element would have this element re-oriented to be an eastward 45° up-plunge value. Plunge elements are thus pre-processed through a geometric filter called *flow.awk* (Appendix -1) which ensures all vectors are consistently pointing down-stream along the model and avoiding facing plunges. In this manner the plunge model can now be used as a 3-D propagation map or graphical index for defining the local vector field.

In addition, records within the plunge model file can become re-ordered when they are saved in gOcad©. The program *flip.awk* (Appendix - 1) will reverse this if required. *Dive.awk* always expects to have an input plunge model which has its first record near the start point of the projection.

The extreme west end of the plunge model, near the F2 trough point, was assigned a plunge of 77° based on the intersection line from the adjacent north and south turbidite-greenstone contacts as determined by stereographic projection. This was necessary as there was no direct plunge data available from that area. All these linear elements along the fold axis can than be interpolated using VGP (de Kemp, 1998) if the raw plunge model is sparse, or DSI (Mallet, 1989) for denser data sets, to fill the entire length of the F2 axial trace with continuous plunge values.

4.52 Regional datum development

The mapped geologic contact between Caopatina turbidites and the enclosing Obatogamo mafic volcanics is quite well constrained by previous 1:20,000 field mapping (Lauzièr, Chown and Sharma 1989) and can be used as a regional surface datum to model the F2 geometry. It can also readily be correlated to a line of regional contrast in total field magnetic susceptibility that forms a western closure and has textural anisotropy in the turbidite structural basin compatible with field structures (Fig. 2). For this study the sediment-volcanic boundary was extracted from the 20,000-scale mapping and re-interpreted using the magnetic data (MRN 1995 a,b, 1994). In addition, this contact was corrected to 350 m mean sea level, to be compatible with the existing 3-D field data set. Assuming this boundary was continuous at depth and had geometry related to the field observed F2 structures in the region, it could then be used to seed a non-cylindrical propagation controlled by the plunge model. The result is a regionally relevant 3-D geological datum (Fig. 16).

In the absence of regional scale thickness information the only way to control how far each element would project was to incrementally project along the plunge model segments, which in this case are on vertical panels, updating the plunge orientation as it moves along the F2 axial-trace. Although the shape of the propagation path should generally reflect the fold keel geometry, steep plunge angles can produce extremely deep structures. To avoid this effect, a plunge angle weighting was introduced to skew the structures for steepness so that the deepest parts of the resulting model would be compatible with reasonable geological depths. From recent deep seismic imaging of other supracrustal segments of the Abitibi greenstone belt, it is possible that similar lithotectonic assemblages may penetrate to mid-crustal levels (Jackson et al. 1990, Lacroix and Sawyer 1995), allowing for structures to reach down to about 17 kilometers present day depth. This formed a rough depth limit to adjust this weighting factor. Ideally an improved method for accumulating the plunge elements needs to be developed which better maintains a normal propagation path to steep field observations. However, the main goal here is to show the 'propagation' concept which can hopefully be exploited for specific visualization tasks in which 2D map data can be given a 3-D representation.

Once the plunge model is made, all of the Caopatina Formation boundary map elements were propagated with it, forming a field of stream lines that characterize the regional F2 geometry. The map elements in this case are each treated separately by picking a start point at the nearest location along the F2-axial trace, and only using the plunge model elements to the east of it. In addition to using plunge values, the propagating map elements will also follow any wandering of the F2-trace at ground surface so that the general map pattern is also continued at depth. Trajectory lines were then smoothed with DSI and selected manually to compose a single surface (Fig. 16).

The porpoising of the map-elements with a variable plunge model, can produce trajectories which break above the ground surface (Fig. 17). This has been the case in other regions were this technique has been applied and found to correlate well with mapped structural windows into underlying units or a thinning of units above the datum surface (King 1986). In the Caopatina case, the easternmost surface corresponds with complex fold patterns likely related to F1-F2 interference folding in banded iron formation near the margin of a large intrusion. Archean banded iron formation is common along volcanic – turbidite transitions in many greenstone belts including this region (Lauzièr, Chown and Sharma 1989). F2 modeled surface breaks do coincide with these magnetic patterns and could indicate that the regional surface is shallowing out. Alternatively this could indicate that the modeled datum surface reflects imposed (Fig. 18) emplacement related geometry from the adjacent pre to syn-F2 Druillettes/Hazeur tonalite-granodiorite intrusion.

4.6 Discussion: Variations in scale dependent methods

A schematic overview of the model building procedure, at the various scales, for this case study is presented in Fig. 20. At the outcrop scale the 3-D digitization environment is very knowledge driven, allowing the interpreter full control over the development of construction lines. The advantage is that, given a high degree of geological expertise concerning the style and geometry of the folds, an interpreter could create a host of locally realistic fold structures. The problem is that 3-D digitizing is still very cumbersome. 3-D cursors are not dynamically linked to hand movements until an existing object is picked (such as in gOcad®), or need to be given successive axis positions to insert single points only, such as in EarthVision®. Also structural elements that are essential to a given interpretation such as the local F2 plunges and S0 bedding and top information are not readily retrievable from a structural data base attached to the 3-D environment. Generally there is no GIS capacity to do spatial range selections and queries of point observational data sets in these environments. Field data needs to be pre-selected and organized in separate data files specific to each individual system. Symbolization of the various planar and linear elements and distinctions between generational data (S0,S1,S2) are also not easily represented once they are brought into a single data file. These hindrances conspire to discourage use of these tools by geologists, or worse, force application specialists who may not be geologists to make misleading or meaningless interpretations.

For mine-scale visualizations that are composed of a group of outcrop scale models, it is easy for the geologist to get overwhelmed with data even though it may be all on ground surface. The strategy at the mine scale is to visualize the structural elements that will enhance the interpretation. Only the most critical fold representations are needed here along with generalized traces of bedding and important fabrics. At this scale interpretive input is very important. The interpreter also requires considerable skill in using Bézier-based construction tools to link fold limbs through the subsurface and also familiarity with the use of Bézier patches to create the coarse topological surface models. Unfortunately, until these tools become more user friendly, with dynamic control of grip points and with a much richer symbolization for structural elements, the environment will remain too cumbersome for the average geologist to work in. Using DSI to constrain these coarse construction lines and surface patches to mapped surface traces, drill core intersections, or seismic interpretations will become increasingly important. Having a vector-based topological model for more complex geological surfaces (GoCAD ®) allows all outcrop-scale interpretations to be viewed at the mine-scale where a new set of interpretations can be made. A grid based topological model (EarthVision ®) places serious scale-dependent performance constraints on the complexity and size of models since the high resolution grid cell size must be carried through the entire model. Persons responsible for future 3-D systems development must recognize that geological interpretations are rarely fixed to a single scale, and are influenced by variably scaled source data sets. Better generalization of 3-D elements during scale jumps and a more efficient scale independent 3-D topology will be of benefit in making these intermediate scale interpretations in the future.

The method used for the regional model is dominantly a data driven technique. It is meant to be used as a first general estimate to fold appearance and will tend to over estimate steep plunges (>70). It has been presented here as a conceptual example of how structural geologists could generate 3-D surfaces from 2-D map data through propagation algorithms. A more rigorous development is required to validate the use of this method for specific types of non-cylindrical folds in a variety of terrains.

The *dive.awk* program requires no interpretations other than setting a maximum limiting depth for the model once a plunge model and map trace have been chosen. The advantage of this is that datum surfaces for regionally distributed map traces can be computed relatively quickly and objectively. However several alternative structural models could be produced using variants of the input parameters used in the regional plunge model. The disadvantage is that geological rules such as the maintenance of stratigraphic thickness or continuity do not apply. To incorporate these constraints would require further modeling with other interpolation techniques to move the surfaces in line with these geological constraints. Also when the plunge model is itself tightly folded it is difficult to avoid limb collisions at depth. For example applying *dive.awk* to the mine scale data set using a local plunge model produces an interesting but geologically impossible surface at depth as F1 limbs begin to intersect each other (Fig. 19). In this study intermediate plunges along the regional plunge model are computed with VGP or DSI. These plunges could also be calculated more rigorously using precise spherical interpolation using quaternions

(DePaor 1995) but this along with other logical enhancements remains to be implemented by professional software developers.

4.7 Conclusions

As structural field data, associated geological map-traces and digital topography are being made available by mapping institutions in GIS compatible formats (de Kemp and Desnoyer 1997, Broome 1998, Zepic et al. 1998, Asch 1998, Brodaric, Johnson and Raines, 1998), the possibility of making extended sub-surface interpretations by geoscientists continues to grow. This study focuses on the three basic scales of map observation, outcrop (10-200 m), mine (100 - 2000 m) and regional (1-50 km) at which 3-D interpretations can be made by using simple field-based structural observations. These observations are routinely collected, but are still difficult to acquire in GIS formats appropriate to 3-D modeling (Wright et al. 1997, Lewis 1997, Knox-Robinson and Wyborn 1997). That is digital, record ordered, accurate spatial data sets with X,Y,Z structural features, quality, azimuth and dip or plunge information, and good descriptions linking these observations to regional structures. Geological surveys, other mapping institutions, and explorationists should be encouraged to make these data more available in useable formats so other 3-D studies can be undertaken. Continued development of a robust structural tool kit that incorporates both automated and interpretive functions, focusing on optimizing 3-D editing environments, advanced sparse interpolation and propagation functions, will likely result from continued testing and application in the context of active regional mapping programs.

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Figure Captions

Fig. 1 - Location of Archean Caopatina Formation study area (red boxes), northeastern Abitibi greeenstone belt, Grenville structural province. Regional magnetic field data with location of study area (middle image) provided by Warner Miles, Canadian Geophysical Data Centre, Geological Survey of Canada. High resolution (lower image), 100 meter flight line spacing, 25 meter gridded total magnetic field airborne survey of Caopatina region (MRN 1994, 1995 a,b). Strong values increase from yellow to brown. Low values decrease from green to blue.

Fig. 2 - North shaded, high resolution total field aeromagnetic image of Caopatina Formation and surrounding granitoid plutonic and volcanic rocks (MRN 1994, 1995 a,b). Extent of image matches that depicted in Fig. 3. Interpreted boundary of Caopatina sediments and volcanic rocks outlined with dashed white line. Magnetic intensity variation is coloured from magnetic lows in green, to highs in brown and red.

Fig. 3 - Distribution of regional scale F1and F2 axial traces, and F2 fold related linear elements; hinges, intersection and stretching lineations. Note co-planar distribution of F2 linear elements on regional S2 fabrics. L2 is not localized (see stereographic projection) indicating non-cylindrical F2 folding at this scale. Box indicates location of detailed study area (see Fig. 6) for outcrop and mine scale visualizations.

Fig. 4 -

A) Soft sediment mudstone rip-up fragments suspended in feldspathic Caopatina wacke matrix. Fragments formed during deep water syn-sedimentary scouring from slump induced gravity flows.

B) Syn-sedimentary slump fold developed in Caopatina formation turbidite unit. Note lack of any consistent penetrative cleavage sub-parallel to fold axis, and numerous cm-scale fully detached sand pillows that have migrated into adjacent pelitic beds.

Fig. 5 - Typical, open to tight, moderately plunging folds (F2) in Caopatina Formation sediments. Mesoscopic folds display 'Z' asymmetry and plunge moderately east. Photo is looking south.

Fig. 6 - Detailed study area used for outcrop and mine scale 3-D field integration. Note L2 hinge lines and stretching lineations generally lie within the plane of F2 and S2 structural elements. L2 is localized (see stereographic projection) indicating near cylindrical F2 folding at this scale.

Fig. 7 - High angle S2/S0 bedding cleavage relationship in Caopatina turbidite beds. Tops from grain gradation to right of photo (east). Pencil is parallel to parasitic 'M' fold just to the left of photo, and is also in plane of S2 spaced cleavage.

Fig. 8 - Outcrop scale construction of moderately plunging F2 anticline.

A) Outcrop scale map superimposed on high resolution aeromagnetic values. Red indicates magnetic high and blue a magnetic low. Vertical dimension is used here to depict total magnetic variation only. Three helicopter flight lines at 100 meter spacing control interpolated magnetic surface (MRN 1995a). Note high spatial frequency of mapped structures compared to low magnetic variability. Steeply dipping turbidite structures are magnetically transparent, even along flight paths (boxed lines). Geometric modeling at this scale is thus only constrained by field observations.

B) Linear projection lines from bedding traces provide rough guide to interpret the structural contours. Note that using only down-dip projection lines as opposed to down-plunge lines can produce apparent, and possibly misleading, steeper plunges as shown on left limb of fold.

C) Complete surface made by collecting all the interpreted structural contours (from 8B) and interpolating across these contours with DSI (Discrete Smooth Interpolation) in GoCAD©.

D) Normals (white lines) to F2 folded surface can be used to create top and bottom topologic pairs. F2 folded surface coloured for steepness. Flatter areas are yellow and brown. Steep areas are red to white.

Fig. 9 - 3-D symbolization of structural elements.

A) Initial step of 3-D outcrop-scale visualization. Planar elements are represented in true 3-D orientation as yellow disks. Key S0 traces are digitized (blue curves) and will act as graphical control to extended surfaces. Yellow line represents interpreted F1 axial surface trace in this area. White lines indicate S2 fabric trajectory. North is to left of image.

B) 3-D extended foliation curtains (red surfaces) help decide where to place F2 fold closures at depth (green and yellow surface). North is to top of image. Stratigraphic tops are to left of image or west. Red line represents S0 bedding trace.

Fig. 10 - Bézier-based patches are useful for interactively creating continuous surfaces with few control points. They are however difficult to control due to complex record ordering required to control bi-variate interpolation. Re-ordering node number of control points in A) can yield very different structures as seen in B). Shaded cells in B) indicate re-ordered nodes. Note that the spatial location of control nodes is not altered from surface A) to B).

Fig. 11 - When Bézier patches are used to model more complex geological surfaces they are also susceptible to becoming disordered and misrepresent an intended structure. Spatially identical sets of control points (spheres) and grip points (boxes) are used in A) and B) to represent different folds. In A) nodes (control points and grip points) are not ordered in sequence across fold limbs and hence produce ribbon like structures that simply mimic an outside control frame. In B) nodes are sequenced across limbs and hence are able to continuously represent fold geometry, including axial regions and hinge lines (shown by dashed red line).

Fig. 12 - Mine-scale 3-D data integration .

A) Mine-scale plan view of several 3-D outcrop models. Individual surfaces are coloured red for depositional tops and green for bottom. Interpreted F1 axial surface is indicated by folded blue ribbon. Interpreted S0 surface trace is indicated by green line. Outcrop locations are light gray. Surface trace of volcanic marker unit is shown as folded bright red line. Note overturned (green side up) folds in upper part of the image.

B) Coarse first estimate of mine scale F1 fold geometry using 3-D Bézier surface patch. Grip points (red cubes) are interactively adjusted to shape local fold geometry. Surface is coloured according to depth. Surface topography is negligible. Fold length is about 2 km.

C) General Bézier F1 form surface is constrained by and 'snapped' to 'control line', which in this case is an interpreted S0 map trace. Manual adjustment of these constraint points may be required as complex fold topology can not always be automatically constrained.

D) Final interpolated mine-scale model of re-folded F1 syncline. Surface is represented by triangulated and rendered interior red surface (top) and a rendered green surface (bottom).

Fig. 13 - Graphical summary of regional scale down-plunge method of A) Stockwell (1950) implemented in B) this study in gOcad©. Note that map elements that start at ground surface **A** are propagated along vertical curtain representing projected regional axial surface trace, and are incrementally projected to **A'**.

A = Start point of map element; map trace vertex.
A' = End point of propagated map element A.
P0 = Plunge model element; point with direction property on plunge model.
P1 = Point off section plane unit distance from P0 in local plunge direction.
P01= Next vertex along plunge model.
V = Plunge direction vector defined by line from P0 to P1.
PZ = Point arbitrary distance below P01.
P2 = Normal projection of P1 onto section plane. Yellow triangle P0-P1-P2 can be off section.
P3 = Intersection of projection line P0P2 with P01-PZ.
ΔZ = Vertical offset distance between P01 and P3.
P0'= Previous propagated map element.
P3'= Next propagated map element.

Fig. 14 - Starting point of this composite regional down plunge method is A) collection of plunge information along the axis of regional fold. This geometric information is then re-ordered along 'start' and 'end' points of interpreted axial trace B), along with accounting for back-plunging structures C) and then collected into 'plunge model' depicted in d. D). Sectional view from 90° horizontal rotation of plane view shown in c. Plunge model provides geometric summary of the fold core (vertical scale exaggerated for emphasis) and is used to propagate map elements along regionally non-cylindrical path into sub-surface. See King (1986) and Lucas (1989) for other regional examples.

Fig. 15 - F2 regional plunge model for Caopatina area. Red lines are plunge element vectors that are used as cumulative geometric index for map element propagation.

Fig. 16 - 3-D representation of modeled regional F2 folded turbidite-volcanic contact. Note variable plunge of keel of structure, which simply mimics variable plunges along regional axial surface trace. Plunge model used to construct fold is shown in red lines along axis.

Fig. 17 - Variety of non-cylindrical structures can be modeled through use of 'plunge models' providing that there is geometric similarity of surface plunges to the at depth surface.

a) Any map element **A** can be propagated along subsurface path to **A'** through use of vector based plunge model.

b) Geometries at depth are modeled as 'flattening out' when the field plunges are behaving similarly.

c) Structures of variably plunging surfaces that culminate above erosion level could potentially be represented.

Fig. 18 - Complex folding in highly magnetic Caopatina Formation rocks (white arrows), most likely banded iron formation, roughly coincident with predicted culmination in eastern area of modeled regional F2 fold (MRN 1995a). Blue lines are lake outlines.

Fig. 19 - Mine-scale fold model, also depicted in Fig. 12D), in this case using automated Stockwell method. Notice that the high degree folding (F2 overprint) of plunge model causes limb collisions at depth (white arrow).

Fig. 20 - General summary of procedures used for outcrop, mine and regional visualizations.

Appendix-1

dive.awk

Produces a series of projected streamlines from map elements such as a folded contact. The propagated map elements are projected in accordance with an input 'plunge model' that acts as a geometrical look-up table. The plunge model is created first with *field.awk* and checked with *flow.awk* for reverse plunges that need to point down stream.

```
Input format: GOCAD pline *.pl blank delimited ASCII

Output format file <out_file.pl> : GOCAD Format see:
    http://www.ensg.unancy.fr/GOCAD/doc/Fileform.fm.html#433425

  Notes : X,Y,Z first three fields of input file.

   Farin, G. and Hansford, D. 1998, The Geometry toolbox for graphics
    and modeling,
  A.K.Peters, Natick Massachusetts, p.288
  http://www.akpeters.com

  Options <feature_line> A 3D CURVE LINE that will be projected


  Updated code as of August 10, 1998, 2:30 pm

    Copyright© August 1998 - Eric de Kemp
      Ottawa, Canada
```

Screen response for usage of dive.awk program:

```
   usage : dive.awk <plunge_model.pl> {feature_line.pl} {out_file}

For creating a 3D curve-line projection model
used in the projection of folds of double curvature
```

August 10, 1998 de Kemp

field.awk

Searches the 3-D neighborhood around single vertices of a curve and conditionally assigns the nearest structural field observations within a user specified distance. Compares (X, Y, Z) input from the vertices list against (X, Y, Z) input from the structural field data base using;

Distance = sqrt(sq(dx) + sq(dy) + sq(dz)).

usage: field.awk <in_file> <struct_file> <distance> {struct_AZfield,struct_DIPfield}

```
Note: input file must contain AZIMUTH or DIPAZM field.
When EarthVision header is not present the user must
specify the geometry fields in the structure data file.
```

To change the method for the selection of field measurements so that linear orientations will be approaching parallelism to the surface trace, make sure the Georule variable is set to Profile. This is located at the variable initializations at the beginning of the program. Cut off angles can be adjusted in the same section with the MinSection_angle variable. The default is 45°, in which case any plunge measurements more than 45° from the vertical projection curtain of the trace will not be used. In Profile mode each point of the trace potentially receives the structure attribute by an inverse distance weighting and a direction vector averaging. This feature in combination with the distance argument can be used to populate a profile line crossing structural domains. The result is a 'plunge model' which can be used as the basis for more advanced projections.

flow.awk

Checks that all GoCAD plunge model elements are pointing down-stream along the plunge model.

```
usage : flow.awk <plunge_model.pl> {out_file}

For preprocessing a 3D curve-line projection model.
   Harmonizes projection flow directions. Used BEFORE
DSI or Bspline Iinterpolation. Only works on GoCAD Pline files.
            July 29, 1998 de Kemp
```

flip.awk

Reorderes a GoCAD or EarthVision ascii data data file so last and first points are flipped.

```
usage : flip.awk <in_data_file.dat/.pl> {out_data_file}

For flipping EarthVision or GoCAD data records
Only points and lines implemented at this time

            July 30, 1998 de Kemp
```

GoCAD2ev.awk

Converts a GoCAD pline to an EarthVision scattered data file retaining the line information.

```
usage : GoCAD2ev.awk <in_file.pl> {out_file.dat}
```

ev2GoCAD.awk

Converts an EarthVision scattered data file to a GoCAD data file.
Works for vertex, and line sets. Plevel option allows posting of structural contours as lines.

```
usage : ev2GoCAD.awk <in_file.dat> <vertex|pline|plevel|surf> {out_file.mx}
```

```
Not implemented for surfaces and non-geometric properties yet.
Assumes X,Y,Z as first three fields.
```

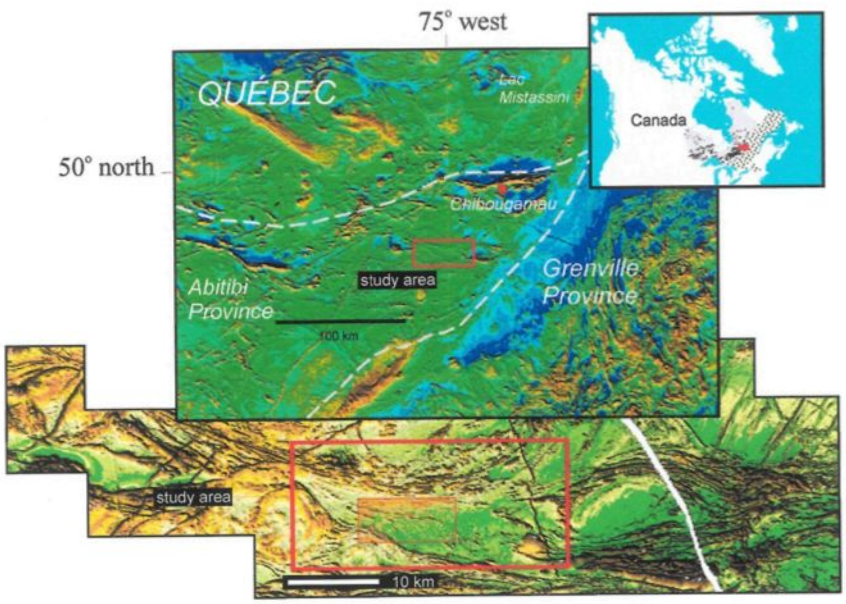

75° west
50° north
QUÉBEC
Lac Mistassini
Canada
Chibougamau
study area
Abitibi Province
Grenville Province
100 km
study area
10 km

Figure 1

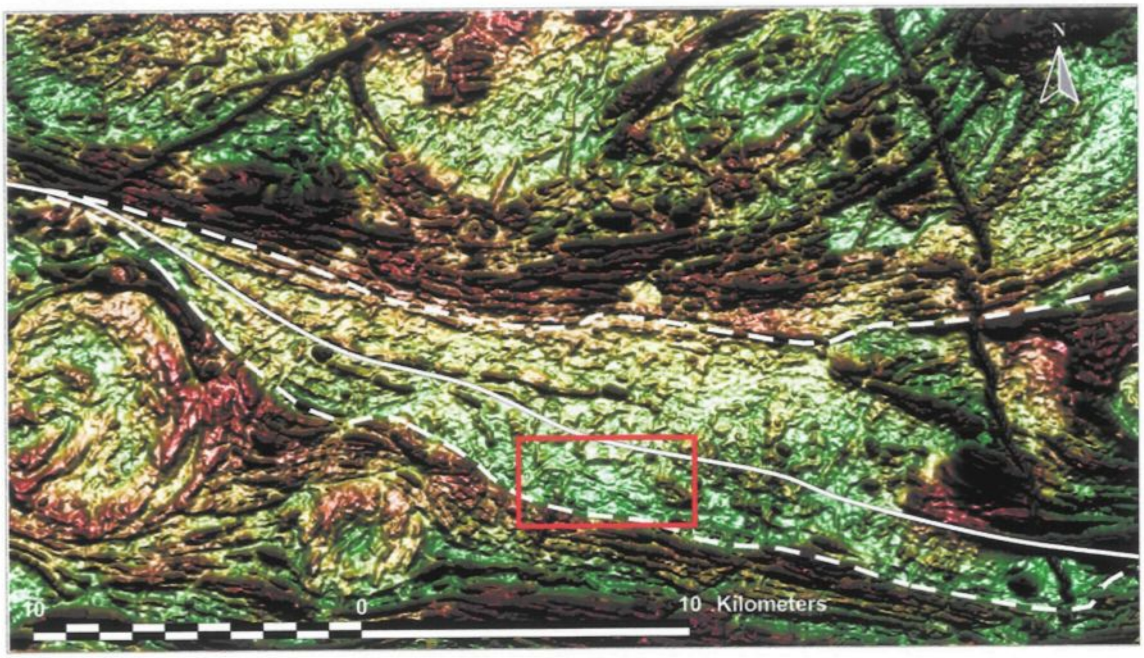


Figure 2

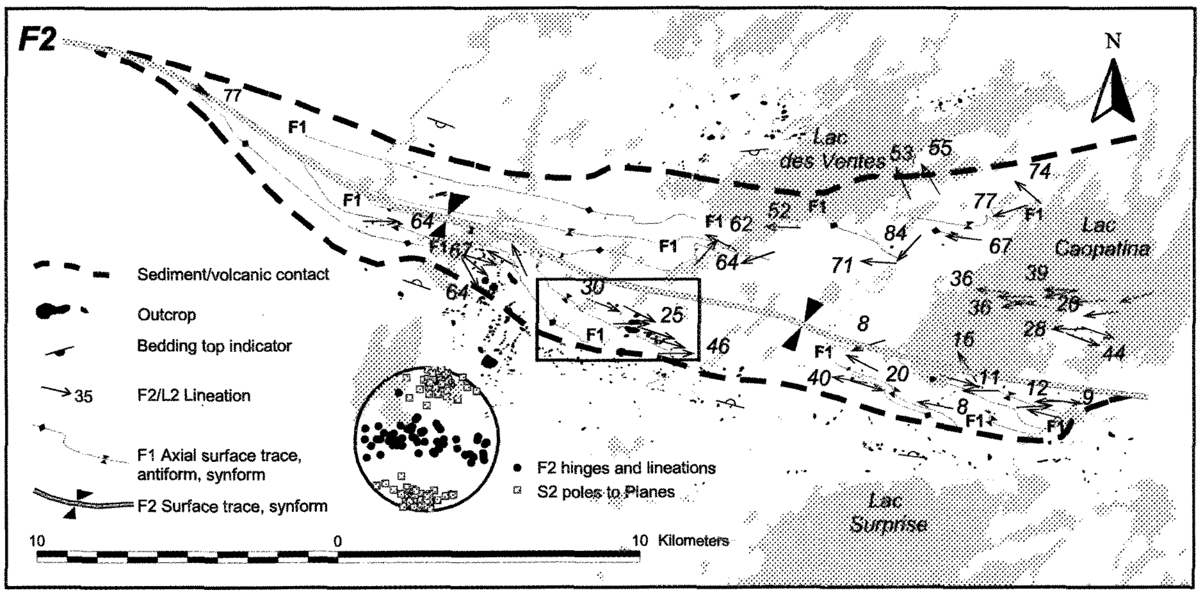

F2
N
Lac des Ventes
Lac Caopatina
Lac Surprise
Sediment/volcanic contact
Outcrop
Bedding top indicator
35
F2/L2 Lineation
F1 Axial surface trace, antiform, synform
F2 Surface trace, synform
F2 hinges and lineations
S2 poles to Planes
10
0
10 Kilometers

Figure 3

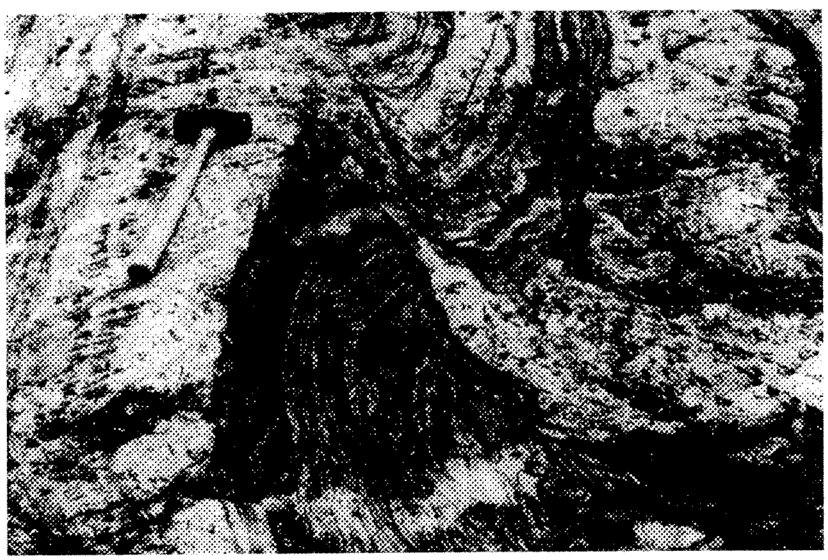


Figure 4

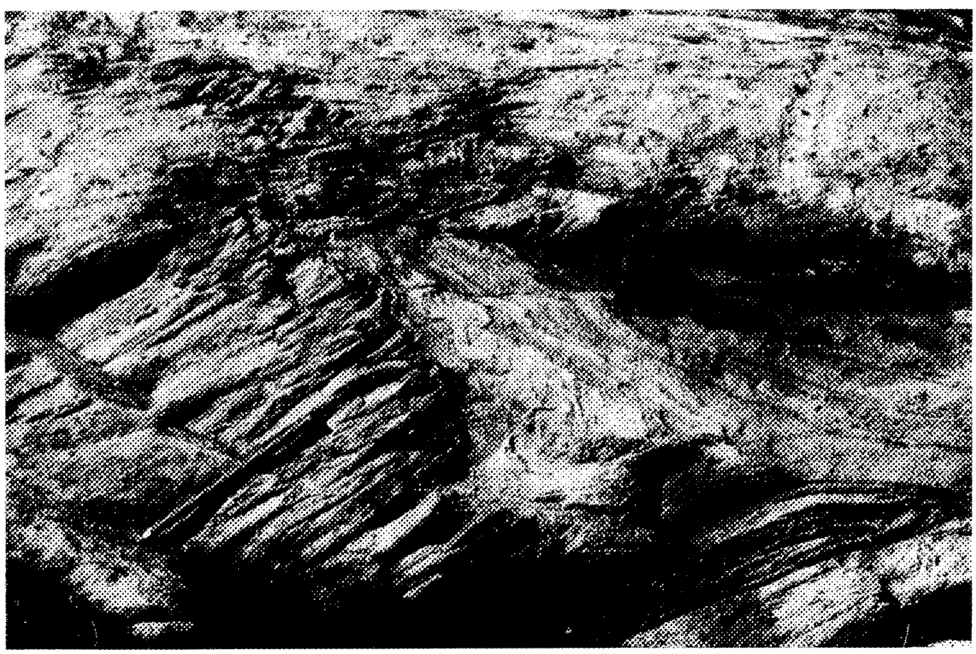


Figure 5

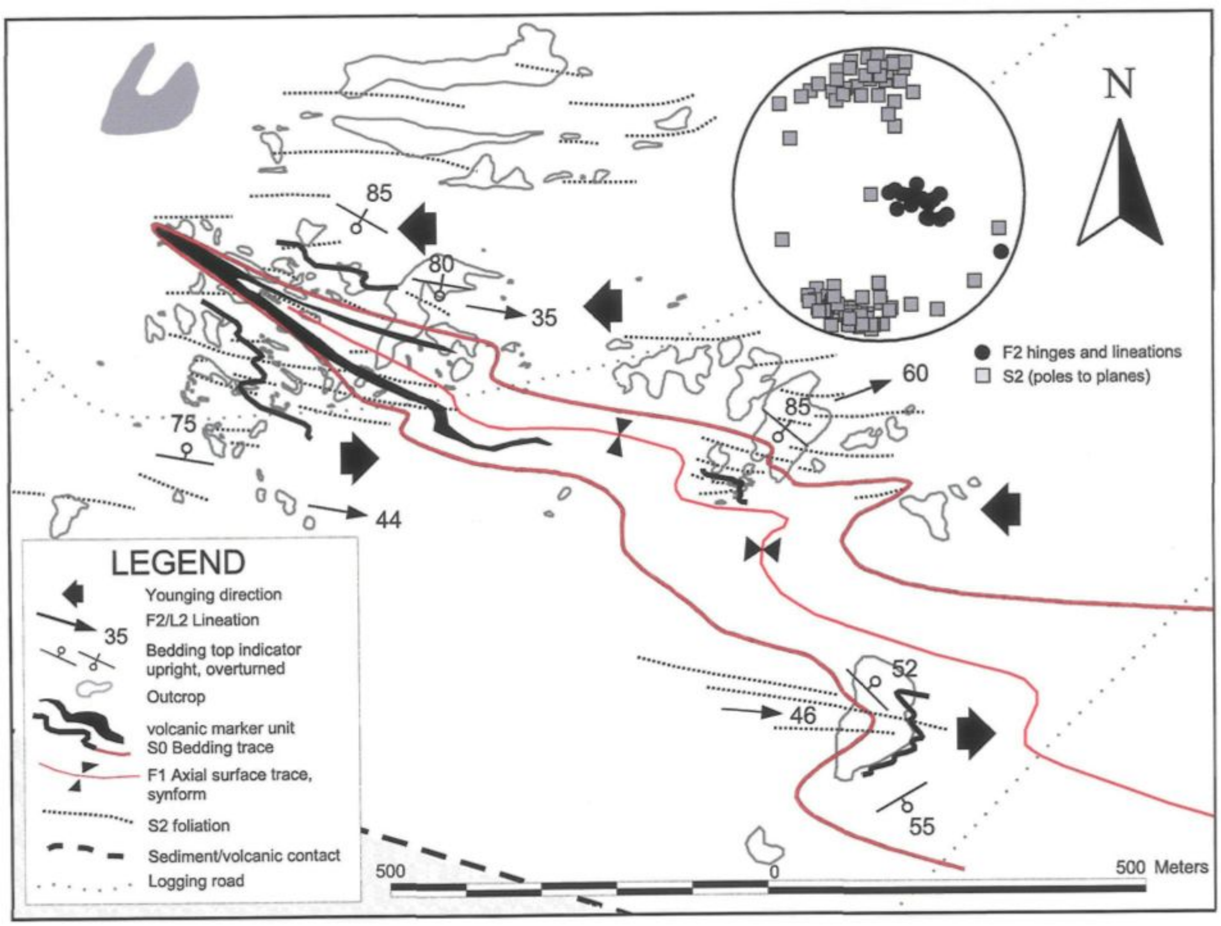

N
85
80
35
60
85
75
44
52
46
55
F2 hinges and lineations
S2 (poles to planes)
LEGEND
Younging direction
F2/L2 Lineation
35
Bedding top indicator
upright, overturned
Outcrop
volcanic marker unit
S0 Bedding trace
F1 Axial surface trace,
synform
S2 foliation
Sediment/volcanic contact
Logging road
500
0
500 Meters

Figure 6

Figure 7

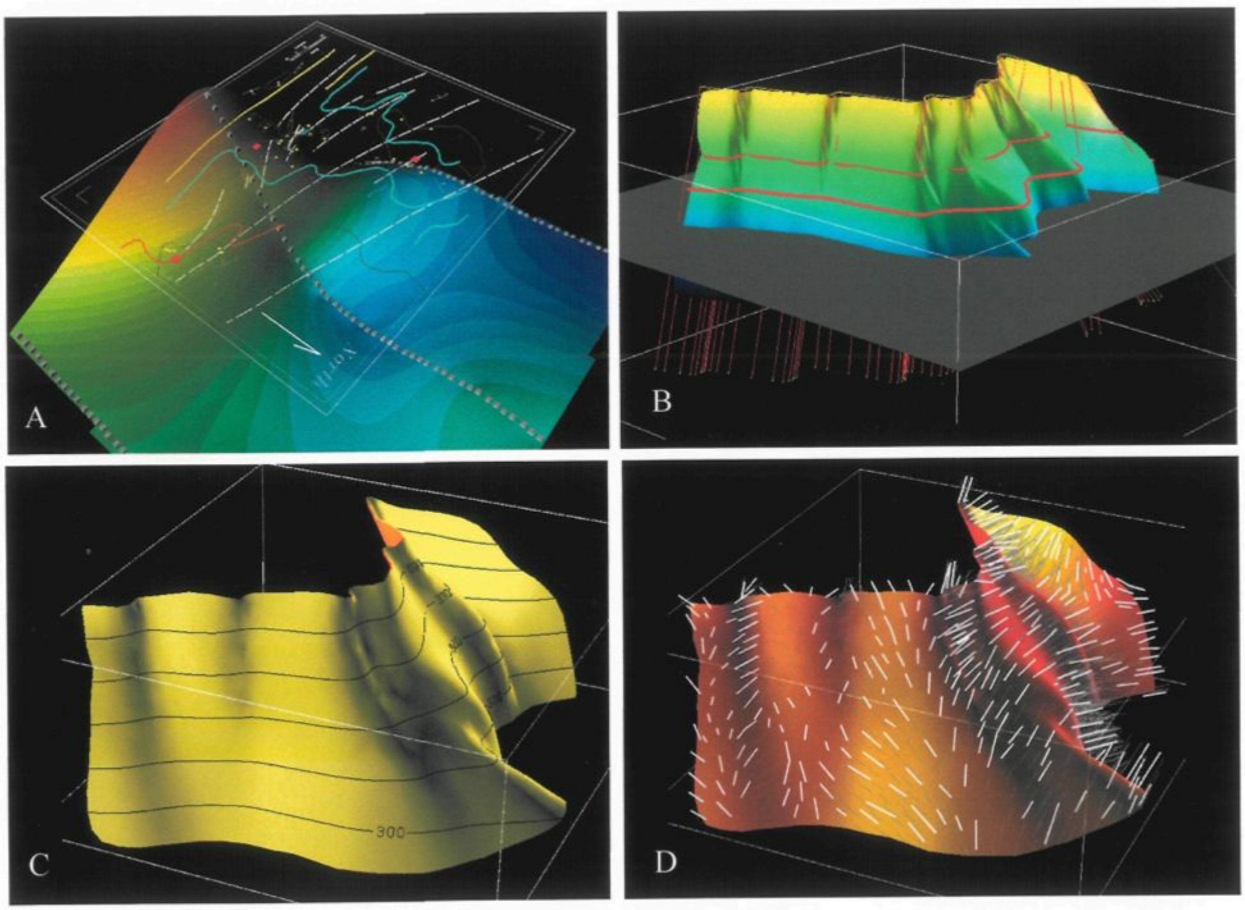


Figure 8

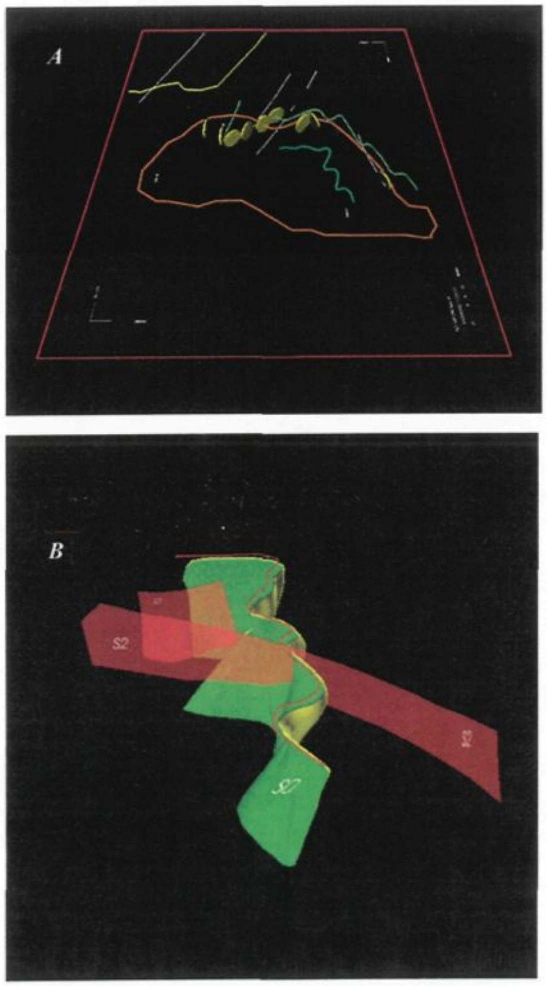
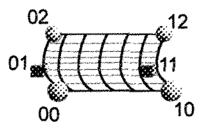
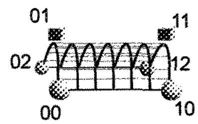


Figure 9



Record	Node	X	Y	Z
1	00	5500	1000	100
2	01	5500	1002	95
3	02	5500	1005	100
4	10	5510	1000	100
5	11	5510	1002	95
6	12	5510	1005	100

(A)



Record	Node	X	Y	Z
1	00	5500	1000	100
2	02	5500	1002	95
3	01	5500	1005	100
4	10	5510	1000	100
5	12	5510	1002	95
6	11	5510	1005	100

(B)

Figure 10

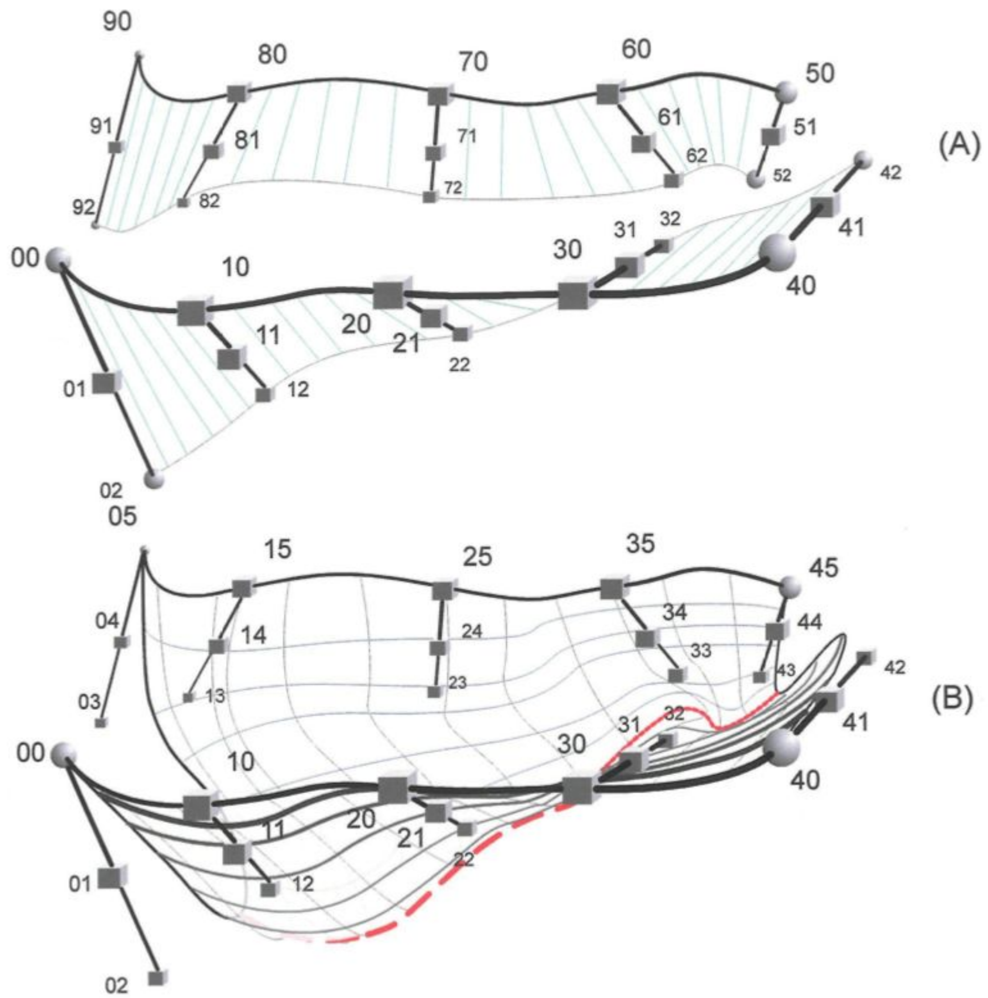

90
80
70
60
50
91
81
71
61
51
(A)
92
82
72
62
52
42
00
10
30
31
32
41
40
20
11
21
22
01
12
02
05
15
25
35
45
04
14
24
34
44
33
03
13
23
43
42
(B)
31
32
00
10
30
41
40
11
20
21
22
01
12
02

Figure 11

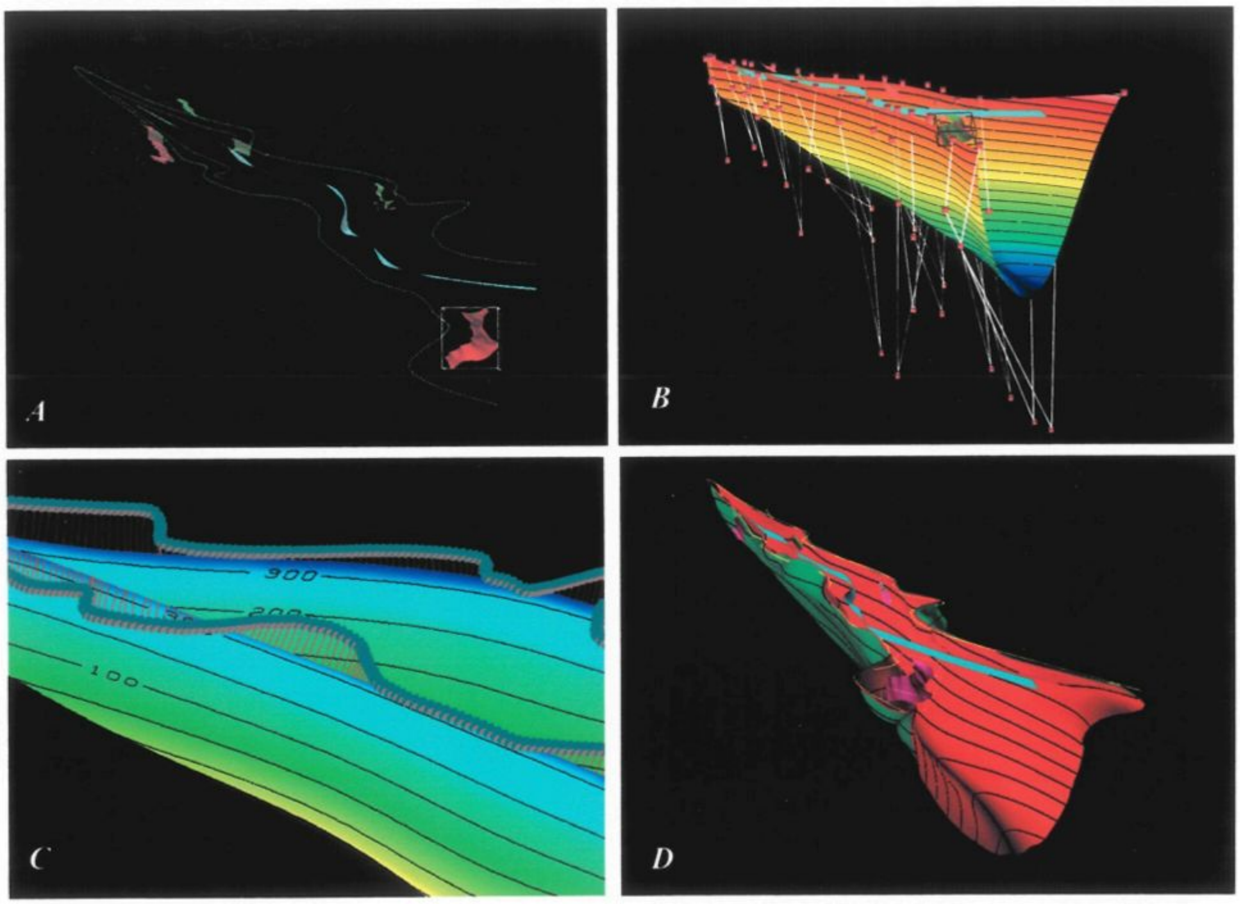


Figure 12

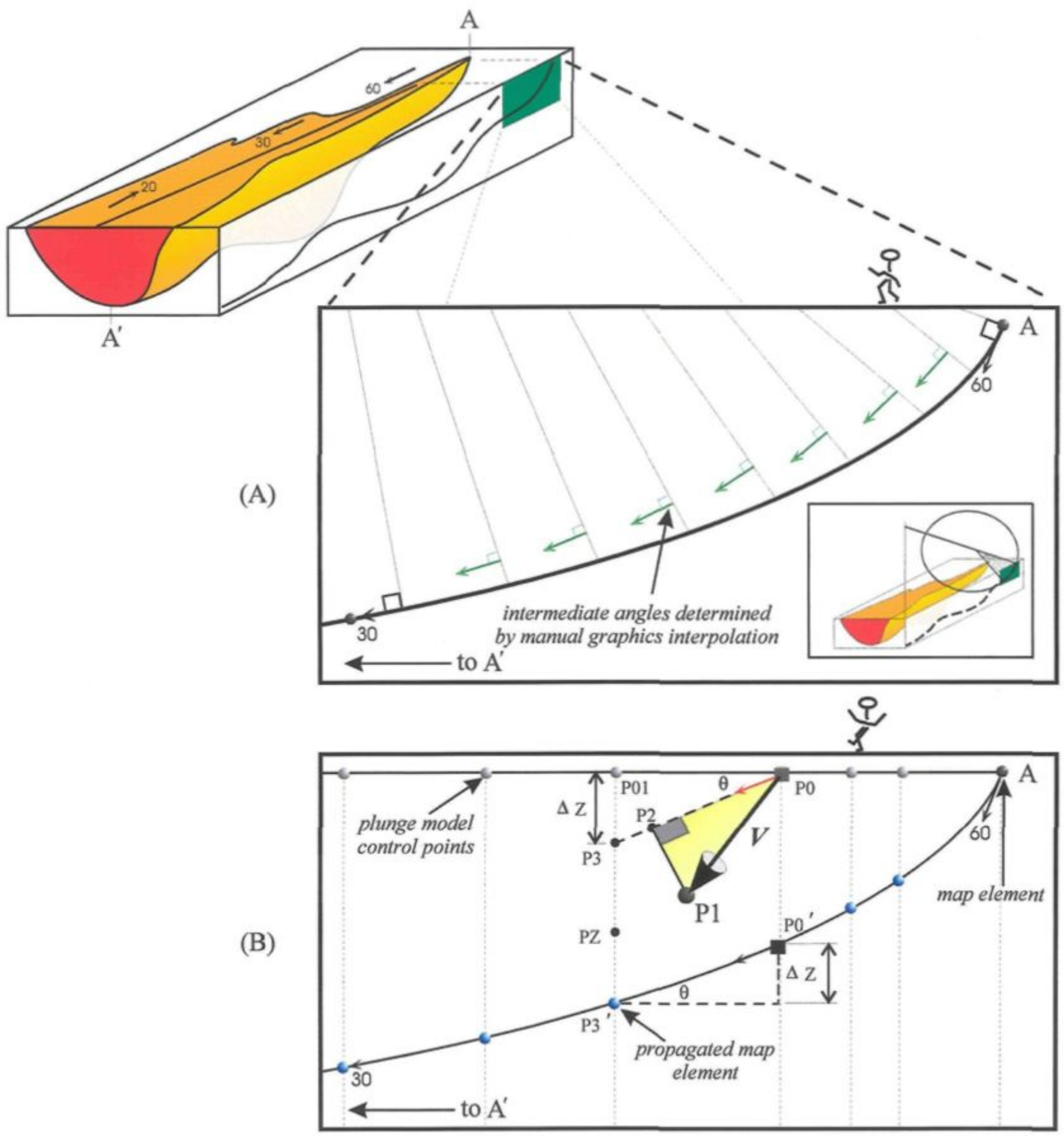
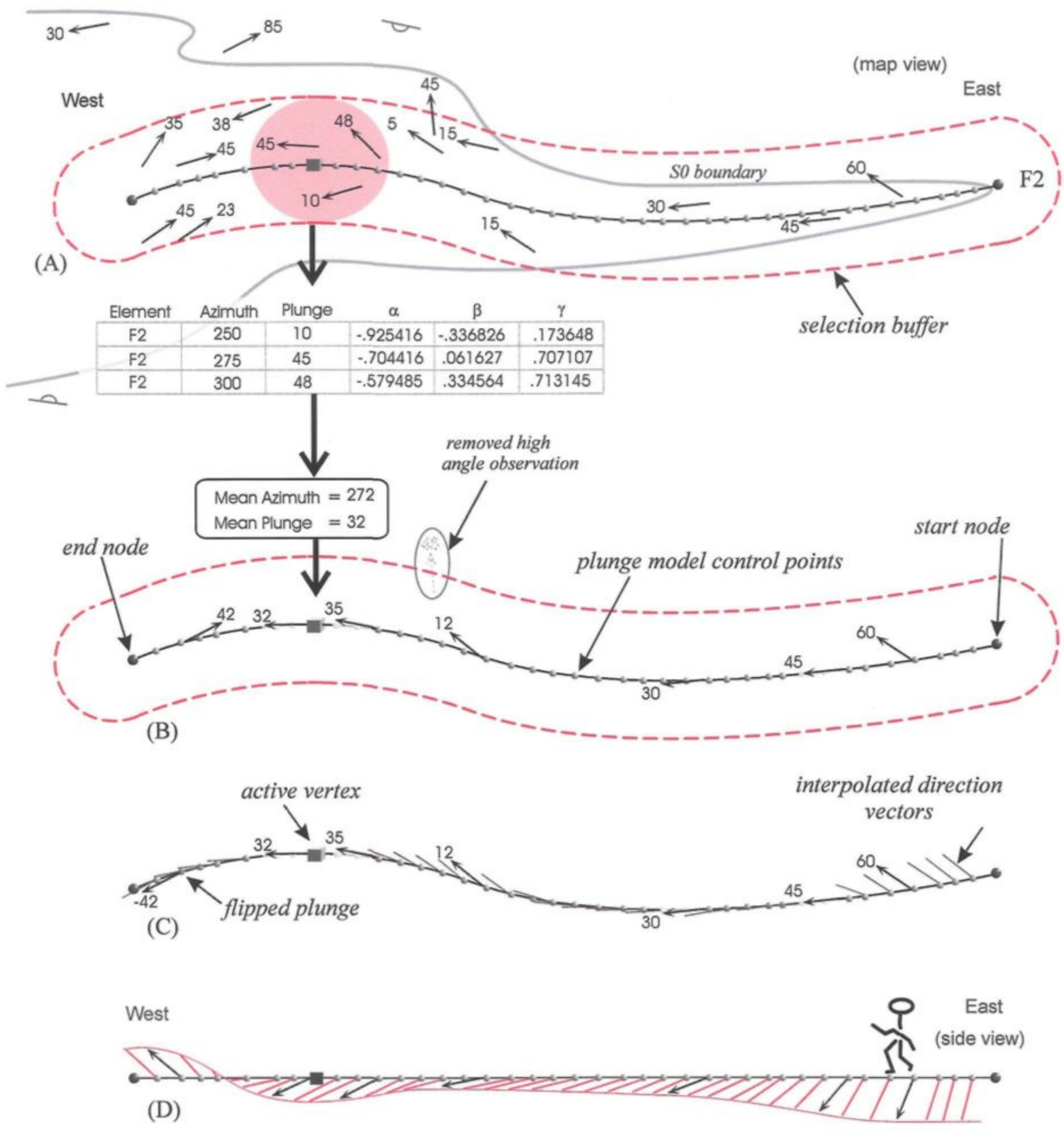

A
60
30
20
A′
A
60
(A)
intermediate angles determined
by manual graphics interpolation
30
to A′
A
P01
θ
P0
Δ Z
P2
plunge model
control points
P3
V
60
P1
map element
(B)
PZ
P0 ′
Δ Z
θ
P3 ′
propagated map
element
30
to A′

Figure 13



Element	Azimuth	Plunge	α	β	γ
F2	250	10	-.925416	-.336826	.173648
F2	275	45	-.704416	.061627	.707107
F2	300	48	-.579485	.334564	.713145

Figure 14

Figure 15

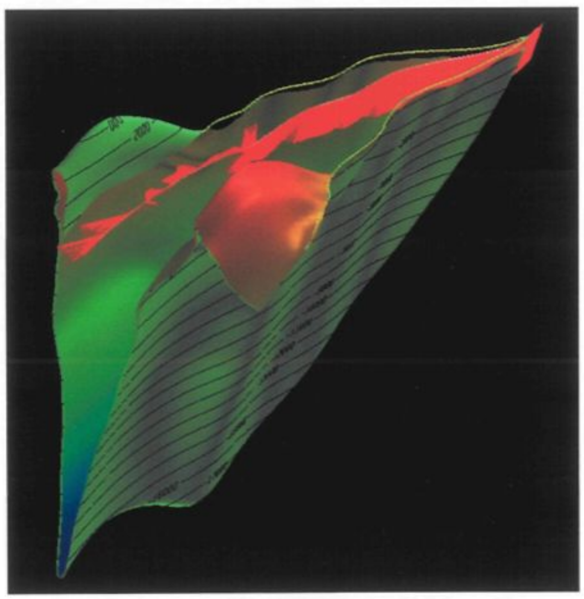


Figure 16

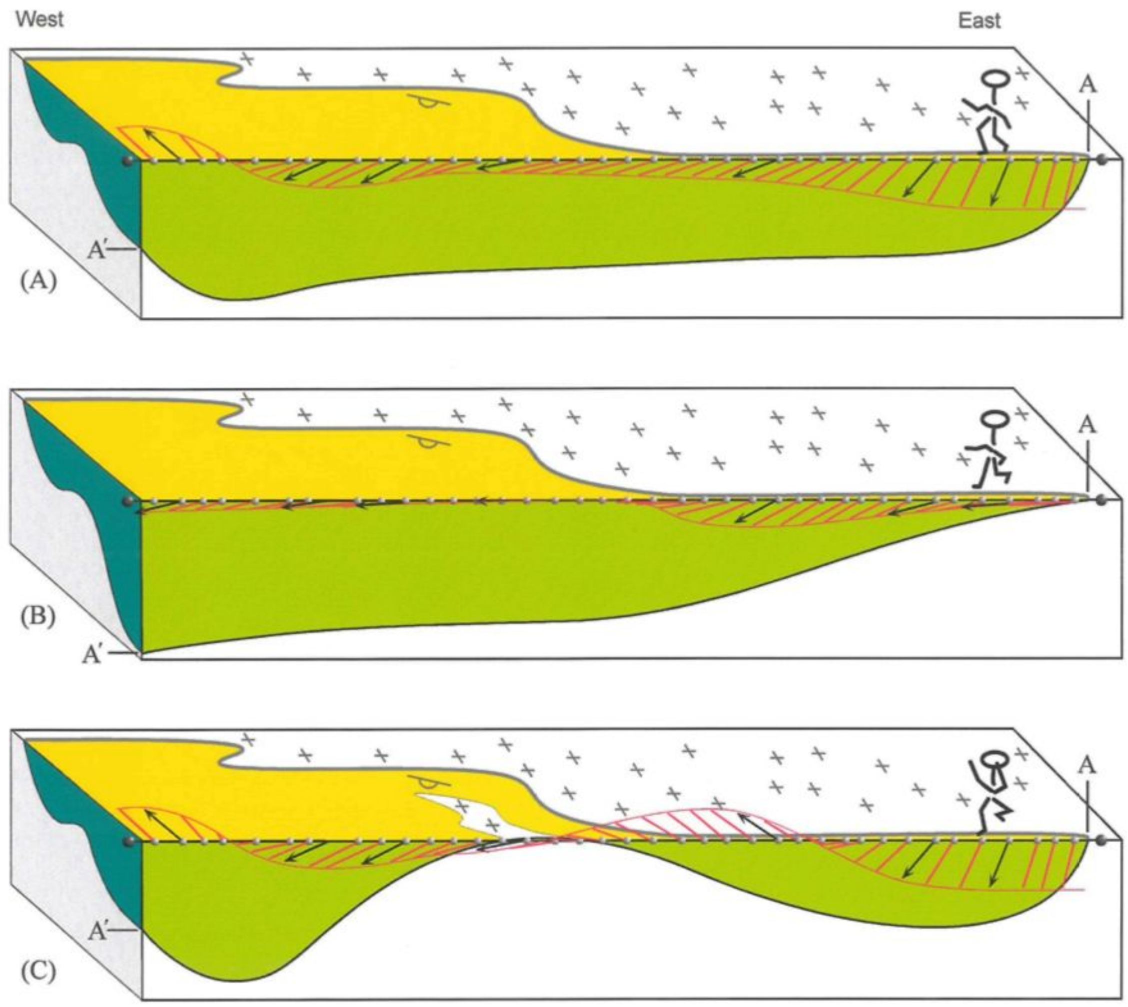


Figure 17

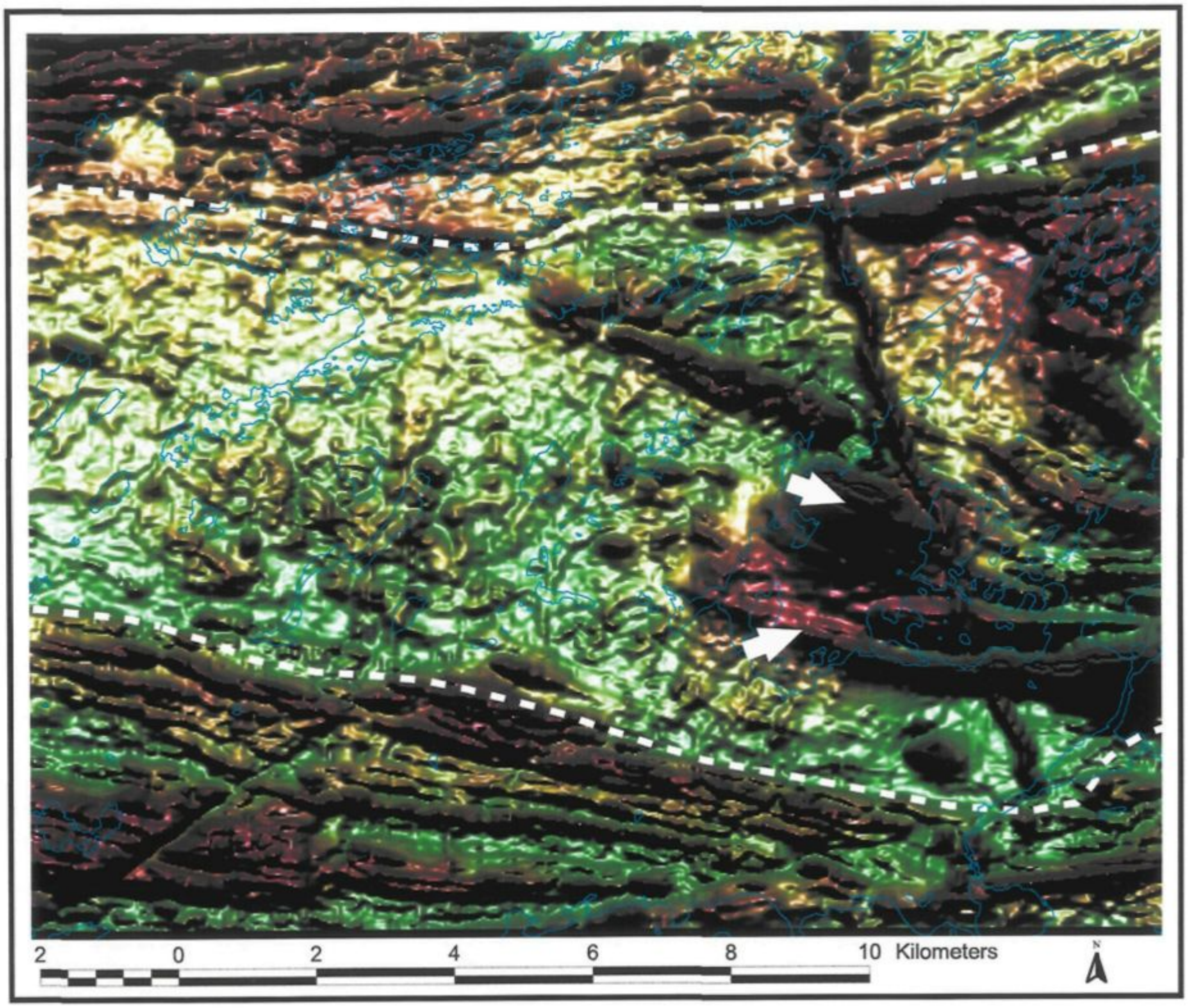


Figure 18

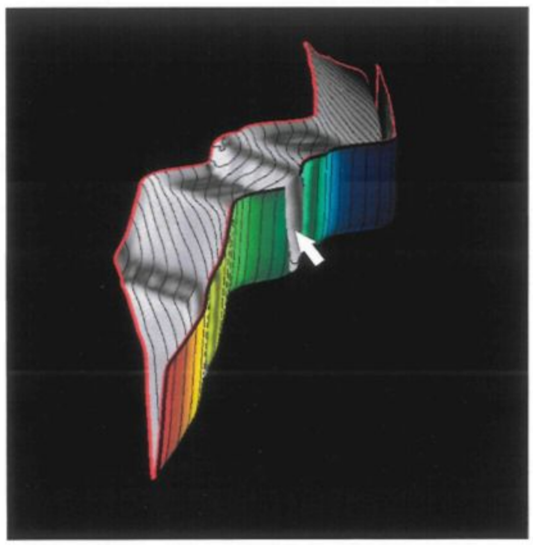


Figure 19

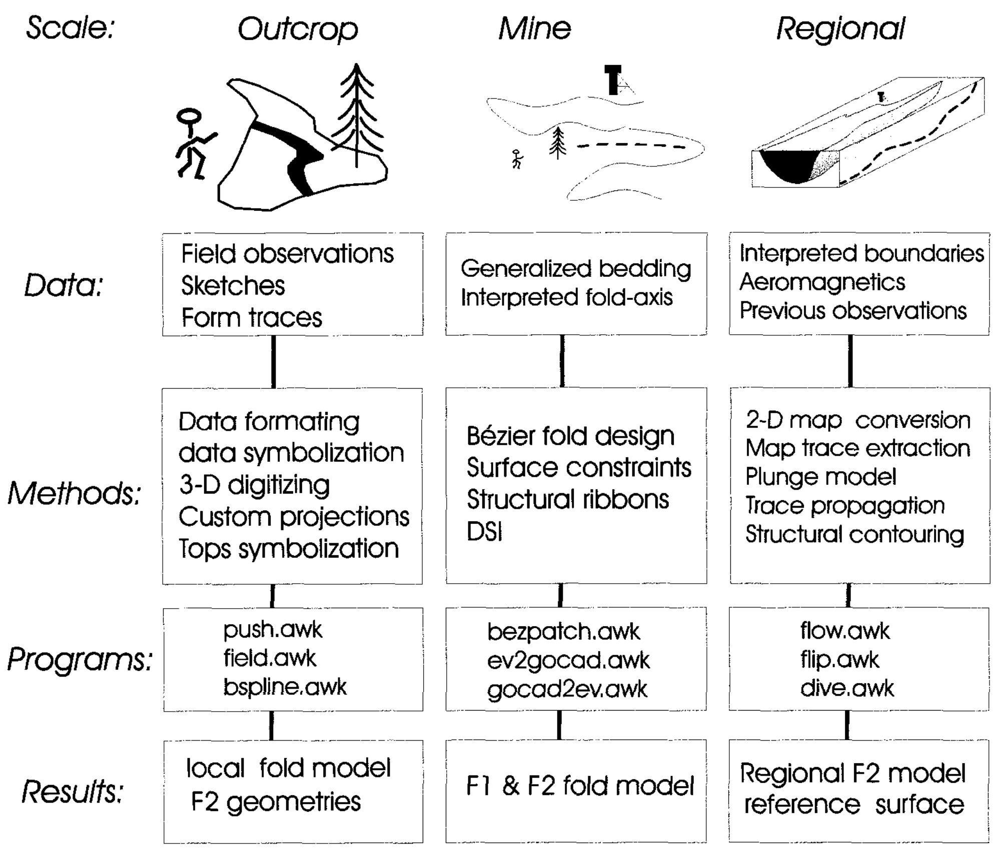

Scale:
Outcrop
Mine
Regional
Data:
Field observations
Sketches
Form traces
Generalized bedding
Interpreted fold-axis
Interpreted boundaries
Aeromagnetics
Previous observations
Methods:
Data formating
data symbolization
3-D digitizing
Custom projections
Tops symbolization
Bézier fold design
Surface constraints
Structural ribbons
DSI
2-D map conversion
Map trace extraction
Plunge model
Trace propagation
Structural contouring
Programs:
push.awk
field.awk
bspline.awk
bezpatch.awk
ev2gocad.awk
gocad2ev.awk
flow.awk
flip.awk
dive.awk
Results:
local fold model
F2 geometries
F1 & F2 fold model
Regional F2 model
reference surface

Figure 20

CHAPTER 5

Discussion and Conclusion

5.1 Discussion

5.1.1 Context and relevance

Geologists have been making subsurface interpretations by extrapolating surface mapping for years (Argand 1922, 1928, Wegmann, 1929). Numerous interpretations have been represented with detailed mine-projections (Williams, 1991; Bleeker, 1990), regional scale structural contours (Hamilton, 1978; Hansen, 1971) and orogenic-scale cross sections and block diagrams (Calvert et al. 1995; Clowes, 1993; Twiss and Moore, 1992; Chown et al. 1992; Lucas, 1989; King, 1986). Subsurface interpretations are often derived through the use of down-plunge projections methods (Stockwell, 1950; Mackin, 1950) to create geological profiles and 3-D block diagrams (Wojtal, 1988). Methods have been developed for the computer generation of complex structures from cross-sections in alpine terrain (Mayoraz 1993) for structural geology, engineering and hazards applications, and in mining applications for ore body delineation (McGaughey and Vallée 1997). More model-driven approaches to achieve 3-D subsurface interpretations, based on a model geologic history (Jessell and Valenta 1996) and which can compare modelled and surveyed geophysical responses, are also available. The newer computer based approaches demonstrate the power of emerging 3-D visualization and modelling software.

The key contribution of the papers in this thesis is that subsurface interpretations can now be made more rigorously and directly from 2-D map-based structural data. The previous manually-derived models had to be redrafted to change the view point and internal examination of surface relationships was not possible. Recent digital methods depend on an input geologic history (Jessell and Valenta 1996), or already interpreted 3-D data from vertical sections (Mayoraz 1993) or mine workings (McGaughey and Vallée 1997). With the incorporation of selected structural field observations, linear map data can now be extrapolated to represent surfaces at depth, or the equivalent eroded above ground extensions.

Several variants of a surface model could be created for evaluation just by changing the selection parameters of the structural field data set, altering the surface construction method, or forcing intermediate models to be constrained by other interpreted control lines. This is important for exploration companies that commonly examine several model scenarios before committing to the next level of an investigation. Because models are referenced in the same geographical coordinate system as the source map elements, it is possible to combine several map features and the derived surfaces into true 3-D solid objects or volumes that can be individually or collectively represented. Subsequently several temporal re-constructions could be used to represent the geologically essential fourth dimension of a given terrain.

5.1.2 Validation

A complete validation of the structural models created through application of the various methods is not the intention of this thesis. This would require prohibitively expensive drilling, detailed geophysical profiling and extensive stripping of overburden for the outcrop and mine scale models. In the case of the Kiglapait and Caopatina regional models that reach more than 8 kilometers depth, it is impossible to validate the accuracy without advanced focused deep crustal seismic techniques. There is, however, a need to assess the validity of the methods presented in the study, and to see if they are useful in gaining geologic insight. Such a validation study would require a dense 3-D data set for which the subsurface structures are reasonably well known, and which could be predicted from applying the methods to 2-D map based data. This data set would have to contain a wide range of scales, and represent a wide range of geological structures for which methods could be applied in various manners. Invariably, mine data sets would have almost no useful 2-D structural data on surface or have subsurface structures which were quite simple. An alternative could have been to undertake extensive cross validation studies. This could be done by making several models from exclusive sub-sets of the control data. As these models are already derived from sparse data sets, it is not too difficult to predict that there will be large divergences in the local behavior of structures. Cross validation could also be undertaken by sampling the final surfaces, and producing synthetic structure control points, which could be compared with the input values. Matching input and output data, however, does not validate the methods used other than to determine that they are reversible. Alternatively a 3-D physical model could be constructed from silly putty for testing methods. The model could be seeded with iron fillings at random or key boundary locations, and x-rayed after slicing the model at specific Z levels. The entire model could thus be reconstructed digitally with a corresponding point and surface datasets. A sub-set of the point and line data could be used to predict the complete surfaces within model and confidence estimates could be made for each combination of input point and line data. Another approach, which still needs to be attempted is the use of gravity and magnetic survey data which are available for the Kiglapait and high-resolution regional magnetic data for the Caopatina examples. Using a forward modelling package such as Noddy® (Jessell and Valenta, 1996), regional 3-D structural models could be used to generate synthetic geophysical images. These synthetic and surveyed images could be quantitatively compared, and the structural models updated accordingly.

The more important validation of these methods occurs at the qualitative level. Is there new geologic insight that emerges from this approach? The core geologic problem of the Caopatina field study (de Kemp 2000) was the lack of geologic insight into the relationship of F1 and F2 folding. By creating 3-D visualizations at the outcrop scale it is quite clear to an interpreter using the 3-D editor that an F1 closure was present in the detailed study area. By constructing the various visual aids such as structural ribbons, F2 fabric curtains and surface map traces, it was relatively straightforward exercise to interpret the form and topology of this F1 structure. The 3-D model articulates a useful single interpretation of the early F1 fold. It also shows the effects of superposed tight F2 folding on the F1 fold. From the 3-D visualization work, a scenario is available that is consistent with the field data; facing directions, style of folding, plunge of structures and dip of bedding. The implications of the structural model, if it is at all accurate, are that the mine scale composite F1 and F2 fold is a type-3 fold (Ramsay 1962), with an F1 axial plane being near parallel with F2 hinge lines. Overturning of the short northern F1 limb, and orientation of the F1 synclinal axis suggest that this early structure was locally effected by northwestward directed motion. In addition, compilation of regional top reversals along S2 foliation trajectories indicate that F1 structures are abundant and discordant with the main interpreted regional turbidite-volcanic contact. The modelled 3-D regional F2 surface of this contact, when displayed with the local mine scale composite F1/F2 fold, indicates that it may be discordant to local F1 fold axis. The geologic implication is that the regional turbidite-volcanic contact could be locally discordant, possibly a thrust, related to late F1 folding but with motion predating F2 structures.

Geologic insights derived from 3-D visualization of the Caopatina data requires further investigation. The issue however for this thesis is not that there is in fact an early thrust fault at the base of the Caopatina Formation, but that there was new questions and possibilities that arose by doing the modelling exercise. It is the emergence of new geological possibilities that, at least in part, validate the usefulness and justify further development of these methods.

The tools that have been developed help to visualize subsurface extension and extrapolation of observations made at measurement points either at the surface, from boreholes, or from underground excavations. Presumably one would choose to visualize the most likely geometry. In many cases, it might be useful to visualize also alternative geometries (or "scenarios"). Indeed, other geologists may consider one of these alternative geometries more likely than the one selected by the first interpreter. Also in many instances one of these alternative geometries may be considered more likely later on, when further knowledge is developed, either on geological processes or the site itself.

To the non-experienced reader (or "viewer"), the most likely geometry determined by one interpreter may be considered as the "truth". Much like a standard geological map may be considered as the "real thing" by a non-geologist, although a map is simply a model. The more real a model looks, the more likey is the confusion of model and reality.

Since 3-D shapes in general look more real than their 2-D equivalent, the confusion of model and reality will likely be more frequent in the future with further development in computer visualization.

In the future, more attention will have to be placed on the expression and modelling of the degree of uncertainty – or its inverse, the degree of confidence – attached to the visualized objects. One approach for doing this is simply the visualization of more than one possible "scenario" (or "working hypothsis") based on the same data set. Another approach is the assignment of some uncertainty (or fuzziness) parameter to the visualized objects; the value which would increase with uncertainty. For example surfaces could be given increasing transparency with object depth. Alternatively the interpreter could assign numeric confidence values from 0 to 1 that could be subjectively placed on critical points of the model and the values propagated throughout the model by various interpolation schemes. The level of uncertainty could be treated as another model property value and updated as new supporting or contradictory data arrived.

5.1.3 Synthesis of papers

The papers of this thesis deal with spatial domain representations, and focus on the construction of individual geological surfaces. There are problems specific to the construction of geologically meaningful solids, but that is beyond the scope of this study. The creation of volumes are largely a computational and topological problem better handled by experts (e.g. Lattudo, 1998). The heuristic in this study as regards to volume construction, was that surfaces, as the bounding objects to volumes, needed to be more elaborately controlled. A volume object is understood as a pointer to a set of enclosing surfaces (manifolds), or alternatively a continuous property range across 3-D space. Once the surface definitions for a given complex geological object are made, then the volume definition will generally follow, through the assignment of surface intersection and edge joining functions.

A summary of the papers (Chapter 1) highlighted the results and some problems encountered during the course of this study. Detailed description of the parametric problem indicated that these functions have been avoided in the 3-D geoscience software industry because they can potentially compromise model stability. In the Kiglapait example, presented in the second paper, the points along the simple Bézier skeletons are re-interpolated to represent the basal contacts of magmatic emplacement surfaces. The fact that parametric tools were used as a starting point to densify a structure does not necessarily affect the stability of the final object. A parameterized object can be resampled and converted to a more stable spatial object (Farin 1997). The parametric control frame to the object can also be saved and updated. The result is a frame which effectively spawns the parametized curve or surface, and the atoms of this parameterization are either disgarded or saved. The Kiglapait example underlines the need for parametic design tools in earth science visualization and modeling software. These tools will likely be introduced once software designers became convinced of their utility.

The program *trace.awk* (de Kemp 1999) was developed to estimate local planar solutions to map traces, provided these map traces have significant elevation variation. It is based on the three-point plane solution method, and has the possibility of working out statistical values for given segments of a map trace. The main application for this tool is in generating 3-D planar solutions useable as the basis for total surface construction. Local plane solutions can be symbolized with disks or tablets, and extended with down-dip trajectory lines. The cross-over and divergent regions of projection lines can indicate where surfaces converge or diverge as well as provide guide lines, or a framework, for other construction methods. The *trace.awk* program requires a high degree of accuracy for the DEM and the map trace. Digitizing inaccuracies will produce artifacts of anomalous dips. Computation of other regional data sets from alpine and moderate relief terrain indicate that line traces from regional mapping at 25 000 to 100 000 scales have variable accuracy. Accuracy is high on traverse lines, but low in the interpreted areas. Structures appear to flatten out as a result of other inaccuracies from the DEM, likely originating from inaccurate 250 000 scale topographic contours. Horizontal coordinate values are generally an order or two orders of magnitude greater than the vertical dimension values and any spatial errors would tend to exaggerate the horizontal dimension. The benefit of the technique, which computes local planes without field observations, will only become realized when mapped contacts are highly accurate and leveled with high-resolution DEM's.

The subsurface extrapolation of map traces can also be controlled by structural field data. The program *field.awk* (de Kemp 1998) searches in the vicinity of a map trace and attaches measurements which match certain user specified criteria. The program acts as a primitive form of intelligent software agent. The important geologic requirement is that near parallel geometry must exist between the field measurements and the surface being modeled. For example, a single primary bedding orientation in the midst of a layered turbidite sequence can approach the orientation of the enclosing upper and lower bounding surface of the unit. However, this may not always be the case. For instance, an eolian deposit of regional extent may have local foreset bedding orientations that can display up to 20 degree dip and 180 degree strike variation along overlapping bounding surfaces. Geometric point observations of volcanic flow boundaries may be unrelated to the regional-scale geometry of the paleotopographic surfaces that bounds these flows. Thus scale dependencies, and the geological context of the specific surfaces being visualized, are important considerations.

Many of the programs developed in this thesis deal with continuous or streamed data. However, most geological objects at the map scale of 1:5,000 to 1:250,000 are not continuous. They can be dissected and offset by subsequent shear zones and/or brittle faults, and by truncating igneous or erosional surfaces. For these situations, it is important to confine the modelling of surfaces and geological volumes to within these discordant boundaries. Collection of field data, seismic interpretations, or drill intersections for enclosing surfaces should be undertaken first to limit the reasonable extent of the detailed and continuous portion of the model.

5.1.4 Software design recommendations

The following general software design recommendations can readily be drawn from this study;

- *3-D construction of geological surfaces from 2-D map traces needs input control from 2-D GIS based data with an emphasis on structural data;* e.g., Better conversion filters or direct reading of raw GIS formats needs to be developed.

- *Structurally meaningful point, line and surface 3-D symbols will be required;* e.g.,3-D symbols that realistically represent point observations of planar, linear and generational elements (S0, S1, S2, L1, L2, L3 etc.).

- *Intelligent software agents are required to selectively assign field derived geometric properties to properly constrain graphics elements;* e.g., Spatial search agents need input criteria, such as relationship of local line geometry and structural orientation of adjacent field data points. Structural attribute query capability such as those common in 2-D GIS is required to filter data before 3-D modelling.

- *Advanced projection functions are required for constructing non-cylindrical, variably plunging surfaces*; e.g., Variable Geometric Projection (VGP) and plunge model controlled propagations.

- *A suite of interactive Bézier-based curve and surface editing tools needs to be incorporated into the existing data-driven interpolation software suite*; e.g., Dynamic grip controlled design of surfaces.

- *Advanced visualization of surfaces from a structural and stratigraphic topology point of view is required;* e.g., Depositional top and bottom of surfaces should be attributes of a single surface.

5.2 Conclusions

The fundamental conclusions derived from this study that impact field geology and related interpretive applications are:

- *Mapping initiatives need to properly collect and manage structural data.*

3-D models are directly depended on the accurate positioning, and the documentation of the linkage between observed local geometry and broader scale surfaces. Accurate 3-D models are impossible without this vital information.

- *Field based structural studies need advanced 3-D methods.*

These include interpolation (Bézier based and DSI), extension (projection and propagation) and advanced visualizing capacity for structural elements in order to interpret subsurface structures.

- *3-D modelling for hard rock geology applications is still under-developed*.

More regional 3-D visualization studies are required in order to begin to optimize 2-D to 3-D conversions, and to communicate the benefits of 3-D geoscience visualization and modeling to the regional bedrock mapping and software development communities. Detailed software design specifications will need to be articulated by field-based structural geologists in order to ensure software is useful to the community.

- *Subsurface structure models can increase the potential for geologic insight.*

A 3-D form surface of a critical geologic boundary can add to the set of thematic representations of the knowledge base of a given region. This increases the possibility of geologic insight but also communicates geologic knowledge in a more intuitive fashion, especially to the non-expert.

5. 3 Future Research : Structural Visualization and Modeling

Several directions for future research have arose through this study. There are three main areas; 1.interoperability, 2. structural inversion modelling and 3. advanced visualization.

5.3.1 Interoperability

The most immediate need is research into interoperability between 2-D GIS and 3-D systems. Interoperability will be achieved when there is no distinction between 2-D and 3-D GIS. Typical 2-D GIS data (point, line, polygon maps, remote sensing images, annotations) are poorly represented in 3-D systems. 2-D data is difficult to convert, as the various structural data models from source systems do not conform to 3-D data structures. Also, standards for structural map data are not yet universally adopted. Observations are often collected with right-hand-rule strike azimuth, but need to be processing in 3-D as down-dip or normal to dip-plane directions. Metadata tags, descriptive information about data, are not implemented to make this format distinction in large governmental archives. Site observations of structures are often spatially linked to more general station locations that are far from the actual site of the structural measurement. This means that varying accuracy levels with separate spatial data bases are required for some structural information should it be needed for future analysis. Metadata descriptions of structural feature codes is generally non-existent and involves guess work for the integrator.

Methods for preparing 2-D GIS information for 3-D are needed and could be introduced at the 2-D GIS (e.g., Arcview) or 3-D level (e.g., gOcad® or EarthVision®). This research would also touch on development of 3-D GIS which for the earth sciences is still in its infancy. For more work to be done in 3-D structural modelling, full access to related attribute types is needed. For example, 3-D drill core oracle data bases with rich text-based descriptive information in related tables need to be explored from within the 3-D graphics environment. 3-D GIS like tools that perform these tasks need to also have the ability to respect symantic geological models and support interpretive tasks.

5.3.2 Structural inversion

An area of research which is active in the geophysics community is inversion research (Li and Oldenburg 1996). The notion of fitting a model to a given target data set, and initiating the model with a seed solution, can all be applied to structural surface development. Without suggesting that the future will be characterized by push-button structural modelling, there is room for scenario development as a complimentary aid in structural mapping. Originally planar geological surfaces that have undergone several stages of inhomogeneous deformation, are difficult if not impossible to model in any realistic manner from field data alone. Traditional trend surface analysis requires a very dense data set to develop reasonable descriptive surfaces for complex structures (Davis, 1986). These structures can have multi-directional wave forms, with a large range of interference geometries that vary in spacing and style (Ramsay, 1962). Also, the level of complexity increases if these rocks are anisotropic, with highly variable mechanical rock properties (Thiessen and Means, 1980). Complex folds do not behave in a local linear fashion and are rarely fully cylindrical. This makes it difficult to visualize structures at depth by uniaxial projection techniques (Charlesworth et al. 1975, Kilby and Charlesworth, 1980; de Kemp, 1998). Exposed at the earth's surface, these folds represent only a small, naturally selected view of a larger complex structure. Without information to characterize the geometries of the larger structure in several directions, reconstruction of these folds from map data alone can become quite speculative (Marshak and Mitra, 1988).

Despite these concerns, it is still advantageous to implement methods for migrating simple continuous surfaces towards a given structural data set. For example, if a known fold-related foliation is present, along with the geometric and facing orientation of several coeval hinge lines, a 3-D interpretative foliation trajectory map can be constructed in which surfaces can be developed according to traditional vergence rules (Weijermars, 1982). Surface migration methods could include inputs such as degree of local curvature, minimum and maximum spatial ranges, ranges of hinge orientation, mean orientation and specifications for parametric control frames should prove useful.

Structural visualization tools, such as the forward modeling tool Noddy® (Jessell and Valenta, 1996; Pinto and Casas, 1996) can now be used in conjunction with the tools presented herein. Field constrained structural models could be imported into forward or inverse geophysical modeling environments (Li and Oldenburg, 1996), and a series of synthetic magnetic and gravity field responses generated. These responses can then be compared to available geophysical observations. High residual differences between modelled and real data can then act as a general guide for areas that need to be re-modelled or where additional field data could be collected with the aim of further constraining the 3-D model (Jessell and Valenta, 1996). The development of optimization strategies for co-modelling of multi-thematic geological data in 3-D will be an active area for future research. When the structural tool kit is sufficiently evolved as to provide rapidly editable realistic subsurface scenarios, optimization and inversion of the structural model using structural field observations as the target data set would be quite valuable.

5.3.3 Advanced visualization

The 3-D environment for fold construction and visualization needs to be highly interactive, with a tool-set for easy foliation draping and Bézier-like feature line manipulation, in which feature lines are topologically linked and constrained to the fold surface being visualized. Consequently, if one element such as a hinge line is moved the whole axial surface moves with it. Propagation of surface traces towards some other surface such as a décollement, another construction line, or a point source would all be useful core tools that still need to be developed. Often an interpreter does not have continuous structural control. For example, a regionally distributed fault may be imaged as a series of discontinuity patterns on a seismic line and mapped at surface, with no intervening data. In such a case, it would be useful to apply propagation tools that effectively 'migrate' the known geology between two features in a smooth, geologically sensible manner. For more complex modeling, the propagation path should pass through a user-defined vector field. This is one way that observed geometric patterns can be amplified, suppressed, or undergo orientation transformations by a 3-D merging or morphing process, in which sparse distant data and proximal data sets are geometrically respected.

5.4 Philosophy of regional 3-D mapping

The goal of regional bedrock mapping in the past has been firstly to document through interpretive surface mapping, the spatial distribution and character of rock types in a given region, and secondly to understand the region's complex geological evolution. Supported by advanced geotechnologies (GIS, Remote sensing, GPS, CAD, Digital data capture), the focus has perhaps shifted slightly to a thematic approach that engages in the mapping exercise primary to understand the geologic evolution, and secondarily to produce a range of thematic oriented map products which articulate clearly the underlying relations. In the more traditional approach, the map could be treated as having higher value than the scientific knowledge that may be derived through reading it. In the thematic approach, the map is only a representation of an underlying natural phenomena for which the understanding is always being refined. The map can be changed as the scientific understanding increases.

These are perhaps subtle distinctions in mapping philosophy, but this distinction is relevant for 3-D modeling. The development of 3-D models seems to fit better into this thematic approach to regional mapping particularly because the models can be constrained to key observations. They can be updated when new data arrives and can represent multi-disciplinary views of the same terrain volume. For example, a fault network or a specific lithologic marker unit can be displayed, similar to turning a theme on and off in a 2-D GIS except in 3-D. The goal of regional mapping, aided by new visualization technologies, is not to just make one subjective plan view representation, but to represent current geological understanding with several spatially compatible thematic views of a region (e.g., lithologic, tectonic, temporal-geochronologic, geochemical, topographic-DEM, thermal-barrometic, observational-traverse, geophysical, pictoral-image). All of these themes collectively articulate the underlying science knowledge of an area. A natural extension of this approach is the development of several supporting 3-D geometrically testable models, which have some predictive value at depth. These 3-D models could be used in, constraining ore body geometries (McGaughey and Vallée, 1997), planning engineering projects (Mayoraz,1993), and now for subsurface visualization of regional geologically significant structures (de Kemp, 1998, 1999, 2000).

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