Geographic Information System Modelling of the Subsurface Geology of Gull Lake, Manitoba

A thesis submitted to the Faculty of Graduate Studies
in partial fulfilment of the requirements for the degree of
Master of Arts

University of Manitoba
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GEOGRAPHIC INFORMATION SYSTEM MODELLING OF THE SUBSURFACE GEOLOGY OF GULL LAKE, MANITOBA

BY

MARK MICHAEL WALTER SHYMANSKI

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree of MASTER OF ARTS

ABSTRACT:

The purpose of this project is to create a geographic information system (GIS) that will allow researchers to record, analyze, manipulate and model geologic data. The modelling process being undertaken here has a twofold purpose. The first is to recreate the interpretive capability provided by traditional methods. These traditional methods include the fence diagram, the isopach map and the conventional contour map. The second purpose is to incorporate additional analytical capacity with the traditional cartographic tools that will assist the visualization process as well as providing tools to quantify the observed phenomena. To accomplish these two goals, one must first examine how humans perceive their world and how these perceptions affect the efficacy of any modelling attempt. How humans use a system of logical inquiry to build up a practical and testable model of reality will affect the veracity and effectiveness of any modelling endeavour.

The development of a GIS such as this requires the ability to collect, store and manage the data and information used, the ability to conduct robust analysis on these data, the preparation of cartographically sound representations of the analysis, and the capability to integrate the results of any analysis back into the database as the basis for additional study. Interpretation of the representations created will enable the researcher to integrate visually many factors that were previously difficult to assemble in one cogent form.

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INTRODUCTION

Problem definition

Manitoba Hydro conducts many site investigations prior to developing a hydroelectric generating station. As these stations are quite large and normally built on remote stretches of high volume rivers, selecting appropriate site takes a considerable amount of planning. As life experience tells us an informed decision is better than a guess. Good, accurate data in sufficient quantities make for good decisions. Manitoba Hydro's investigations provide large quantities of high quality data. The ability to interpret these data rely on the experience and training of the investigator, these interpretations can be aided by an effective model of the phenomena being investigated.

This thesis will present a model which provides a mechanism for the logical organization of the collected field data, the interpreted information, and a method to rigorously manipulate these data to create a better understanding of the study area, and then portray the results in a way that is aesthetically pleasing and cartographically sound. The central element of this organizational mechanism is the use of geographic information systems methods and technologies.

How is this a geographical question; why is it not geological?

The data being manipulated and the conclusions being drawn must be validated by geologists, but the geographic information systems methodologies applied have been developed for solving 'geographic' questions. The distinction between what is 'geologic' and what is geographic is largely a matter of focus. The geography oriented researcher has the latitude to consider a variety of topics, the geology oriented researcher has a considerably more focussed approach. The methods developed to address the wider array of topics of the geographer can certainly be applied to the more focussed approaches of any particular topic. In the following discussion, the geologic topic will be the avenue in which these 'geographic' methods will be applied. The model is intended to illustrate or represent the interaction of elements of the physical world and their significance to humans and the effect of these elements on human activities in the study area.

What makes the modelling of subsurface structures a GIS?

A geographic information system (GIS) is, as the name suggests, a method of organizing, in a computer environment, spatial and aspatial data from many sources into a systematic, ordered collection of geographic data. This system consists of three main components; data collection and manipulation, information synthesis and storage, and finally graphic representation of the data or information. These three characteristics can immediately be recognized as the main components in cartography and traditional geographic inquiry. From this writer's perspective the ability of a geographic information system to reduce the time required to assimilate data, to generate effective maps and its ability to allow cartographers and other workers to create, change and update geographic data by making use of the methods and procedures developed for effective cartographic communication demonstrates that GIS is a logical evolutionary descendent of cartography.

The organization of data that have a spatial component is one of the founding principles behind geographic information systems. Whether the phenomena in question is above the surface (e.g. in air pollution distribution models); on the surface (where most geographic information system methods have been developed); or beneath the surface (e.g. modelling of aquifers or mineral deposits), all of these cases have spatially connected data that can be best analysed if they are effectively collected, stored, and manipulated. Specifically, the modelling of subsurface geology is one task or application of a well designed geographic information system.

How valid is the premise that scientific visualization derived from the modelling efforts of a GIS is useful and not just a technological tour de force?

If the visualizations, and the methods which created the visualizations, help the researcher to better understand the study area then the visualizations have met their intended use. If the development of the geographic information system identifies strengths and weaknesses in the current methods of data collection, analysis, and interpretation allowing the researcher to apply or improve theses methods, this is also useful. To be able to discern the patterns and trends inherent in the data and to have the data in a readily manipulated form such that these manipulations can be displayed with clarity and legibility, greatly aids the researcher. While the technological aspect is a large component of the modelling process, the actual cognition, and thus the true value of the model, is performed by the user of the model. An effective GIS contributes to this cognition not by being overly clever but by being so easy to use and rigorous of design that the user need not worry about the mechanics of how the modelling is being done. With such technological transparency (the efficacy of the modelling environment making the methods and technology all but invisible to the user) the model becomes a cognitive tour de force and not just a technological one.

How is this a logical progression from current visualization and inquiry methods?

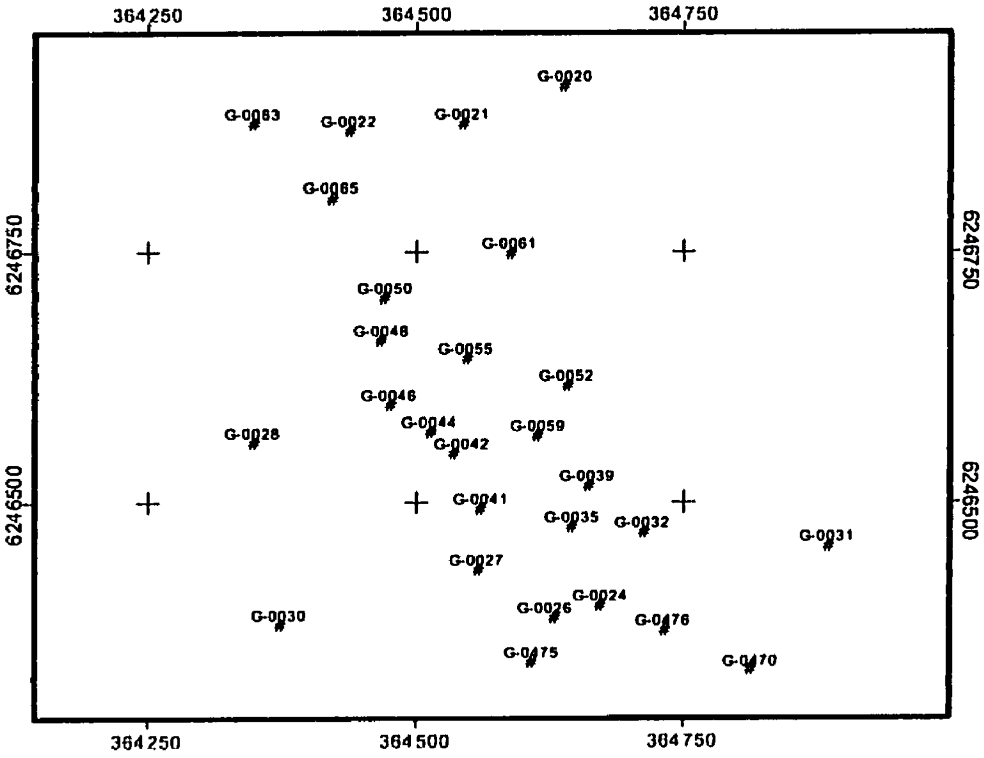
The presentation of the data in digital format is essentially the same as seeing the data on hardcopy. There are some ergonomic differences involved in changing the media of presentation (from paper to digital) but at the most basic level of interaction with these data the user is still able to draw the same conclusions from the digital presentation as the user would draw from the paper presentation. It is essential that previous methods of querying the data do not disappear. The methods developed must be ‘in addition to' not 'instead of' previous capabilities. The organization of spatial and aspatial data in the digital environment reflects the traditional organization of these data. Humans interpret data as they are trained to. To be useful and effective, new visualization methods must incorporate the old methods thus increasing interpretation capabilities and capacities. An example of modifying an existing capability would be for the researcher to have the ability to select a subset of the mapped data and redraw just the selected data. This is an illustration of how the traditional 'area of interest' (which could be an accumulation of data from several mapsheets cut and pasted together to represent the study area) can now be interactively selected from the seamless digital data displayed on screen showing only the relevant data.

While this project is an attempt to demonstrate the application of GIS methodologies to geologic data it must be recognized that there are many facets to this project. This GIS must provide; a system able to organize and assimilate data collected in the field; to develop a model of the subsurface geologic unit; and effectively present this model for intuitive interpretation and rigorous analytical queries. Interpretation of this representation will enable the researcher to integrate visually many factors that were previously difficult to assemble in one cogent form. A parallel can be drawn here to the increase in understanding of a data set that occurs when one looks at a listing of the numbers versus a graphic representation of those data (See Figure 1). If one is looking for trends in the numbers, it is much easier to interpret the proximity of a neighbouring point then it is to individually calculate the differences between adjacent data points and then progress through their neighbours to reveal the inherent but not obvious patterns.

There are benefits derived from applying scientific visualization techniques to geographic investigations as identified by McCormick et al. (1987). A number of these will be identified and demonstrated here. Perhaps the most difficult to demonstrate is the ability of an effective model or graphic to occasion some subconscious connection of assorted and seemingly unrelated or tenuously- related elements of a phenomenon to coalesce in the consciousness of the observer a more thorough understanding of the observed phenomena. Scientific visualization techniques then have the advantage of being able to rigorously and quantitatively test these new found conclusions.

Figure 1 Tabular Versus Graphic Presentation of Data

Point Id	Northing	Easting
G-0020	6246940	364643
G-0021	6246900	364540
G-0022	6246892	364425
G-0024	6246378	364680
G-0026	6246364	364633
G-0027	6246417	364555
G-0028	6246554	364328
G-0030	6246357	364356
G-0031	6246441	364912
G-0032	6246458	364724
G-0035	6246463	364651
G-0039	6246508	364668
G-0041	6246482	364558
G-0042	6246543	364530
G-0044	6246566	364506
G-0046	6246595	364466
G-0048	6246665	364457
G-0050	6246711	364461
G-0052	6246616	364646
G-0055	6246645	364544
G-0059	6246562	364616
G-0061	6246760	364588
G-0063	6246900	364328
G-0065	6246819	364408
G-0470	6246307	364833
G-0475	6246315	364610



The table on the left contains the same information as the graphic on the right. The graphic gives an immediate impression of the relative position of each of the boreholes.

LITERATURE REVIEW:

Richard Chorley identifies, in the book "Models in Geography", a need for "radical methodological and conceptual rethinking in geomorphology" (Chorley 1972). I believe that the use of scientific visualization methods and geographic information systems provide some methods to accommodate the "mass data generation techniques" (Chorley 1972) of modern geographic inquiry. Geographic information system (GIS) technology and methods have evolved out of the need by geoscientists to deal with a large variety of disparate data sources (Goodchild 1992; Burrough 1987; 1992). As in any evolutionary situation, the new generation is not without characteristics of the previous. This is indeed apparent in GIS, where data types and sources, techniques, and methodological concerns that were apparent in the manual geographic methods are still evident in the digital efforts (Bowdon 1992; Chorowicz 1989; Chorowicz 1991). While data collection and manipulation techniques are well understood and the negative aspects can and are being minimized, such aspects as data validity, variety of scales, and imprecision in identifying the phenomena consistently and correctly are still problematic. These latter issues are of particular concern to the mineral exploration and extraction industries. Much of the literature reflects this concern. However, the intent of these works is focussed on maximizing return on effort (Montgomery 1993; Turner 1991; Walsh 1992; Zeitlin 1992). This focus may preclude the development of a more sophisticated approach to GIS but it also forces the field ahead, despite itself. Conversely, the academic literature often expends considerable effort in introspection while foregoing practical applications. This self absorption can be beneficial by ensuring academic rigour, but can also be detrimental if it continues too long, thereby misdirecting resources and discouraging innovation. Therefore, GIS must ensure that it is not being brash or overly hasty in adopting unproven techniques and methodologies, while being aware that too much introspection will cause it to stumble and become ineffectual (Douglas 1988; Foster 1991; Goodchild 1992).

A Brief History of GIS

One can point to two key developments in the history of GIS, the first being an innovative project carried out by the government of Canada (Coppock and Rhind 1991). This project was designed with the intent of identifying, quantifying and mapping numerous aspects of land use classifications in Canada and was one of the earliest geographic information systems. The *Canadian Land Use Survey Inventory* project was carried out using traditional cartographic methods in the late 1960s and early 1970s, but with the profound innovation of the data being digitally recorded for future use. The prodigious amount of data underscored the inadequacies of traditional methods of data storage, analysis and representation.

The second key development in the evolution of GIS was the development and widespread availability of affordable, powerful computers in the early 1980's. This proliferation of a once esoteric and restricted technology made possible the application of sophisticated techniques by the average field researcher, that were once available only to highly trained individuals (Raper 1991). With this new capability, researchers were able to analyze their data more thoroughly and expeditiously. This new-found capacity encouraged increasingly more sophisticated demands of the data and accompanying software-hardware combinations. As workers became more familiar with the capabilities and foibles of GIS, they demanded increasingly more from the available geographic information systems. Further growth was stimulated as people became acclimatized to the flexibility and power of computers and software capable of meeting those demands. In this environment users could identify more tasks for the computer to accomplish (Alexander 1991; Chou 1991; Coulsen 1991). New software, hardware and techniques were required to meet this demand, fuelling a development-application-development cycle (Goodchild 1992b). As these new technologies developed, scientists were increasingly able to tailor the acquisition and interpretation of data to the specific task at hand. In this vital and dynamic growth environment GIS continues to evolve.

The Development of Scientific Visualization

Leonard Guelke (Guelke, 1985) in his discussion of the suitability of the application of the scientific method to the study of human geography identifies some of the merits of scientific method. Guelke observes that the hard evidence needed for objective knowledge can be gained by those who look for it. In this section the development of scientific visualization will be discussed in the context of cartographic communication as well as in the context of geologic inquiry and description.

Scientific visualization, or (as will be developed later) cartographic visualization, is defined as a method which provides a systematic, reproducible way to acquire or synthesize an understanding of the world around us while providing a platform to both display the results of the modelling as well as a providing a vehicle to do additional hypothesis/testing/modelling iterations. Scientific visualization, or "Visualization in Scientific Computing (ViSC)" as the phrase was coined in a 1987 report to the American National Science Foundation's Advisory Panel on Graphics, Image Processing, and Workstations (Rosenblum 1994) referred to the use of computers to aid humans in seeing 'the unseen' and allowing the use of the human interpretive and analytical skills in concert with the computer. The term was originally used in disciplines other than geography. Geographers interpreted this new concept in a much more specific fashion, referring to cartographic visualization. Antle and Klinkenberg (Antle 1999), in their review of the cartographic and visualization literature identify several definitions of scientific visualization. Perhaps the notion that the definitions are contingent on the discipline using the term is indicative of the novelty of the concept. As the focus of this section is on the development of visualization in the aid of cartographic communication, the definitions identified by Antle and Klinkenberg will be the ones examined. These two authors acknowledge the value of maps because of the map's ability to best represent spatial data and spatial relations. They identify a key variance from the map's traditional role as data repository to that of a data modelling tool:

> "*...cartographic communication emphasizes map design, cartographic visualization emphasizes map use...*"(Antle, 1999 p. 150).

Cartographic visualization is defined as the subset of scientific visualization most concerned with the graphic representation and modelling of spatial data (MacEachern in Antle, 1999). As in Roseblum's 'seeing the unseen', cartographic visualization is built on the communication strengths of cartography to help interpret the vast quantities of spatial data now available to the researcher. As the quantity of data available to the researcher increases it is increasingly important to be able to 'know the data better', but to do so in a manner which is reproducible. With additional data, the need to be able to recognize what is being presented, to see what the relationships between elements are, and to be able to discern what patterns exist becomes increasingly difficult. The volume of data overwhelm a human's ability to distinguish, separate and to resolve differences or similarities.

A key concept to emphasize is that 'visualization' is very much a process of the human mind; measuring, interpreting, synthesizing and theorizing about the data provided by the models presented by the software and hardware creating the representations. As Antle and Klinkenberg observe " *visualization is foremost an act of cognition, a human ability to develop mental representations* " (Antle, 1999).

The importance and utility of visualization

In his, then 'state of the discipline', presidential address to the Canadian Association of Geographers, Denis St-Onge identified the characteristics of a sound map, defined the role of a map, and discussed the properties of a proper geomorphologic map (St-Onge 1981). While the article is dated, the concepts are as valid now as they were then.

> *"Because maps are a product of classification, they must result from a definition of units, form a logical synthesis, and form inductive or deductive reasoning."* (St-Onge 1981, p 313)

A scientifically useful visualization must adhere to these same criteria. The units of measure are as crucial as they ever were, an additional criteria to the units is that of the dimension in which the measurements occur, planar or two dimensions (2-D), volumes or 3 dimensions (3-D) or in the dimension of time, the fourth dimension (4-D).

To be useful a scientific visualization must include what dimensions the units are measured in as well as the units themselves. The ability to quantify the observations is what separates a scientific visualization from conventional map analysis. These measurements form the foundations for our conceptual understanding and thus quantification of any of the mapped phenomena. We need to be able to measure precisely before we can begin any rigorous modelling process. From this quantification we can begin to formulate hypothesis, prepare testing scenarios, and then work incrementally to increase our understanding of the phenomena. We could modify St Onge's words to state "Because Scientific Visualizations are a product..." to bring his definition into the present.

> *"Rather, I wish to emphasize that in defining classes and identifying features which belong to the various classes; it also involves the capability to synthesis without distorting or losing any information that is essential for the scientific aim. In this context, a given form is of no particular interest; it is from the relationships among a multitude of forms that understanding stems."* (St-Onge 1981)

St-Onge is writing about conventional maps in the previous and following quotes, but these quotes could quite easily apply to the products of the application of scientific visualization and GIS techniques to spatial data. Some of the conceptual and practical problems referred to in the following quote can be addressed by the use of the new techniques and technologies available to the researcher with the coming of scientific visualization and GIS methods and technology. A properly designed geographic information system or the adoption of scientific visualization methods should remove some of the data handling constraints and the visualization restraints of the conventional methods as exemplified by the paper map.

> *"An ideal geomorphological map should not only describe and explain landforms based on the morphogenesis of individual landforms but also, more importantly the explanations should be based on the relations between various landforms affected to varying degrees by numerous processes. This ideal, although easily conceived, is rarely if ever achieved because of either conceptual or practical problems"* (St-Onge 1981).

It is hoped that the model developed for this thesis will apply GIS methods to resolving some of the conceptual and practical problems that are a barrier to achieving St Onges' ideal.

Cartography, GIS and Geography

For much of the 50 year history of GIS, research has been directed toward solving particular problems or toward automation of traditional techniques (Coppock and Rhind 1991, Peuquet 1991). Peuquet and Bacastow (1991), Robinson, Gray et al. (1989), and Coppock and Rhind (1991) have all congratulated GIS researchers on their indisputably successful efforts to turn modern technologies to age old geographic and cartographic tasks. The proven routines of data capture, storage, and representation have all been the focus through the early stages. However, the next logical step is to take this painstakingly collected data and develop innovative analysis procedures and representational techniques which will build on the foundation of accumulated geographic research (Davis and Sampson 1992; Dikau 1989; Paradis and Dennis 1989). When used in innovative ways the analytical power of GIS can help the researcher interpret the real world and visualize geophysical phenomena in a more dramatic manner than heretofore possible (Gracia and Hecht 1992; Pascoe 1990; Peddle 1991; Polidori and Chorowicz et al. 1991; Preobrazhenskiy 1984; Raper 1991). Just as word analogies help a speaker place complex images in the mind of the audience, the visualization capabilities of GIS can synthesize analysis of imposing quantities of data in the mind of the researcher (Raper 1989). However, as the practised orator knows a clumsily constructed analogy can blur the intended mental image. Analysis of data and understanding derived from this analysis can only be achieved through the thoughtful and controlled manipulation of appropriate data. Thus, successful studies must be based on the careful utilization of the capabilities of a GIS, tempered by accepted standards (Head 1984; Heuvelink and Burrough 1989; Imhoff 1977). A fundamental obstacle to clear analysis and understanding is the lack of an agreed upon language to communicate what is being analysed and displayed.

Forces of evolution continue to push the spatial analysis aspect of GIS (Lo 1991). Polygon overlays and digital cartography are giving way to three dimensional modelling and computer aided visualization and analysis. The technologies and methods of modelling and visualization instill a new capability and confidence in the geoscientist. Whilst new methods of analysis can be developed, old procedures can also be streamlined and carried out more efficiently, enabling the researcher to benefit from both. Clearly, this overhaul of spatial analytical technique is necessary given the massive data sets being studied. As Bowdon (1992) observes, the need for rapid investigation has become a crucial factor for the vast majority of current research.

Of concern in all discussions of modelling and visualization is the validity of the conclusions made from these new developments in the GIS field (Chrisman, 1991). Data collected at different scales or from different sampling techniques, the occurrence of unconformities, and the known deficiencies in the sensing technologies are all examples of the variety and complexity of the data quality enigma (Gatrell 1987; Howarth 1992). A seemingly straightforward sample may have a multitude of classification methods applied to it. Boundaries may be placed uniquely by separate geologists, or indeed by the same geologist if the purpose of subsequent classifications differs from the first classification. In traditional cartography there are procedural, methodological and technical errors that can be made in representing the data, while these error sources are not to be ignored, concern for these is somewhat limited because they are felt to be known and controllable (Gilmartin 1992; Gold 1984; Haining 1992). Much concern is reserved for conditions where the errors or deviation from the actual situation cannot easily be measured, or indeed if the errors are in fact actually errors and not just artefacts of the observation method (Carver, 1991). While researchers will attempt to compensate for classification differences (which are not errors, but reasonable classification situations) a GIS is very pedantic and cannot yet appropriately respond to multiple conditions for the same phenomena. Therefore, it is required of the modeller that all reasonable efforts are made to ensure data fidelity (Fotheringham 1993).

The need for qualified people to select boundaries illustrates the need for training in the use of GIS technologies (MacQuire et al. 1991a). The ease with which impressive looking, though fundamentally flawed, maps and multiple dimensional representations can be created by the comparatively unskilled using a GIS is a pitfall that must be avoided by those seeking to use such images. Decision makers may be basing their decisions on faulty maps, maps which are generated without due respect for vital cartographic considerations. This difficulty is amplified when the human susceptibility to "seeing is believing" is considered. Uncritical acceptance is a disturbingly dangerous attitude to have when looking at these possibly erroneous constructs (Goldberg 1992).

While it may seem unnecessary to define 'cartography', as it is perhaps a geographer's most basic tool, it is exactly this ubiquitousness that compels a clear definition to be stated. Of course a discussion of cartography is not complete without mentioning maps.

Maps are used by people to record what they've observed in an area; others may use these maps to learn of areas where they've never been, or to increase their understanding of an area already travelled. Maps are a storage medium for the observations and interpretations of people whom have investigated an area. Additional uses for maps are to inform, or add to, an observer's knowledge about an area. New data sources for maps, other than the traditional investigation by someone on the ground traipsing around recording what phenomena exist, is of course the whole range of remote sensing technologies, from passive optical devices such as airborne photographic equipment to the active application of emitted electromagnetic energies. While cartographers are not necessarily the people who have collected these data, and may have only a familiarity with the themes being mapped, they are the people who create maps. Cartographers use any available reliable positional and descriptive data source to enhance the fidelity of the maps they create. New data sources such as the remote sensing technologies just mentioned or the positional data collected from a global positioning system are readily used to enhance the data already available to a cartographer. But what is it that a cartographer does?

A very restrictive definition of cartography is the accumulation of spatially related data for a particular region and representation of these data at some reduced scale. This definition implies the generalization, simplification, symbolization, and projection of the data that are commonly done on maps to increase the legibility of the represented data. The 'region' referred to identifies a spatial extent or a thematic commonality. A map of Canada, the spatial extent, or a map showing where Canadians are, the thematic commonality of Canadian citizenship, would certainly present two very different maps. K. A. Salichtchev presents several, more thorough, definitions. Cartography as defined by the International Cartographic Association as

> "*the totality of investigations and operations - scientific, artistic, and technical - which have as their aim the making of maps and other representations from the materials of surveys and various sources, as well as the uses of maps.*" (Salichtchev 1977, p 79).

The British Cartographic Society echos this definition but broadens it to include

> *"all forms of maps, profiles, three-dimensional models and globes... with the use of any sources; and includes the investigation of the historical development of maps, the methods of cartographic presentation, and the methods of map use."* (Salichtchev 1970, p 79).

What is a model?

The use of models in geomorphological research is a time honoured practice. The ever present topographic map is perhaps the most common example of a model, the realization that it is indeed a model is not quite so common. A fundamental definition of the term model is 'a simplification of reality'. The term modelling is probably as misunderstood and misapplied as is the term GIS (Goodchild 1992c; 1992b; McNamara 1992). For the purposes of this review modelling encompasses representing a real world condition at a reduced scale using maps or computer displays, or other display forums to formulate analysis of phenomena and in turn use these analyses to prepare predictive constructs.

Generation of these models relies on accepted geographical and statistical methods (Pakalanis 1991). It is important that tested procedures not be lost in the rush towards those which are technologically sophisticated but unproven (Milne, Scott et al. 1993; Montgomery 1993; Morris 1991; Murray 1993).

The most basic functions of a model are to communicate and contribute to an understanding of the modelled phenomena. The purpose of this communication is to present data about the phenomena portrayed in a manner which allows the user of the model to increase their understanding of the modelled phenomena. What is being transmitted, how it is conveyed, and how it is perceived once the end user receives it, are important steps in the development and application of the model. Modelling deals with a wide variety of concerns, such as human perception, intuitive interpretation and cognitive processing as well as the more tangible matters of data representation, display methods and cartographic communication (Bayliss and Driver 1993; Bedford 1993; Board 1984; Openshaw 1987, 1988, 1991). Many of the consulted works deal with the mechanics, or 'how to', of modelling (Goldstone 1993; Medycky, Scott 1992; Fisher 1991; Holmes

1991a, 1991b). Fundamental statistical work is delivered in such valuable volumes as Davis (1973), Lin and Harbaugh (1984), McCammon (1975), and Till (1974). Much work has also been done on human perceptions. Recent merging of these two research fields has led to work on human perceptions and cognitive processes involved in interpreting two dimensional models.

As communication is one of the main goals of modelling, statistical analysis seeks to provide a clear understanding of the relationships revealed by the interpretation of the data. The application of the better known tools such as triangular irregular networks (TIN), kriging and trend surface analysis, as well as lesser known routines such as the application of Bayes' theorem, are evolving to accommodate this need (Elfick 1979; Davis 1992; Hodgson 1989; Jones and Nelson 1992; McCullagh and Ross 1980; McEachran 1980; Olea 1992; Oliver 1990; Rasmussen and Olesen et al. 1988; Ruzyla 1992; Schreiber 1992; Strand 1993). The statistical approach quantifies the phenomena, but human intuitive appreciation requires the input of many qualitative elements. The success of a modelling effort requires that both the quantitative and qualitative are responsibly combined to achieve concise clear communication.

Data and Information

While it is clear that data are the results of the recording of observations of the phenomena presented to the observer it is not as clear that actual phenomena are being represented when these data are incorporated into an information system. Just as a cartographer must characterize and then select from the entire spatial and contextual knowledge base available in preparation of a map, so too must the data be characterized and selected for inclusion into a GIS. More particularly the data may alternatively be relevant or irrelevant depending on what the goal is of the particular GIS model being prepared. Setting aside these ambiguities for a moment, there are five general types of data incorporated into a geographic information system; point, line, area, volume and aspatial.

Point data are data collected at a discrete location, commonly described with as little as one descriptor (an x) or by a Cartesian co-ordinates pair (x and y) or sometimes a triplet (x, y and z). Theoretically these points have no dimension, but practically the dimensionlessness of these points are dependent on the scale with which the data are being presented. An example of this dependence on scale may be drawn from the geological borehole data. The drill crew set up their equipment on a site, this site necessarily is located in three dimensional space and has an associated coordinate triplet describing this location. As the crew begin to drill, the scale of the operation limits the essential description of the point to one dimension, that of how many metres (or fractions) of drill rod have been set. (Another example of this one dimensional description common in geographic investigations is the use of chain lengths along a transect.) Note that while the point of interest still has a three dimensional component, as far as the drilling operation is concerned, there is only one relevant dimension, length. This 'one dimensional' point suddenly becomes two dimensional when the geologist scale is applied, looking at a cross-section of the collected core suddenly expands the data point into a plane of data, with different phenomena or mineralogy boundaries occurring across the plane of the core cross-section. This two dimensional point again gains a dimension when the geologist's scale shifts to incorporating neighbouring data points in an attempt to interpolate several of these point data sources to generate a surface.

Line data are data represented as a continuous segment between two points. Generally it is accepted that a line is a border between two different data sets, as in an edge between political entities or soil types. In an apparently opposite definition, a line of collected data can also record the variations in phenomena. This apparently contradictory definition, is seen in the case of electro-magnetic conductivity (EM) sensor readings, where a line represents the variation in the conductivity of the soil along an arbitrarily spatially defined line. A characteristic of these data types is that they fall into two general cases, one where the data are defining the line and the other where the line defines what data are collected.

Area data are data enclosed by a set of lines which define a topologically enclosed set. Again these areas can either be defined by the data, or used to select what data are collected. These datasets are generally considered to be only two dimensional, and planar, (requiring a minimum of three line segments to bound an area creating a 'polygon') while in reality the phenomena they are recording are often not planar and can indeed be on quite a complex surface. An example of this type of broad application of the 'area' definition are the soils maps common in geomorphic research. The broader categories of soil classifications do not mention or reflect the topographic orientation of the material classified, disregarding variations in slope or strike.

This compressing of three dimensional phenomena relates directly to our traditional method of representing our three-dimensional world 'steam-rolled' flat, as with Guelke's fictional cat (Guelke, 1985). For much of the history of geologic and geographic inquiry, researchers have been bound to reproducing three dimensional phenomena on a two dimensional plane. The need for generalization or symbolization of the third dimension was created by the limited ability to portray the third dimension. With the advent of the inexpensive and comparatively powerful computer graphics hardware of the late 1980's and through the 1990s, representing the third dimension became incrementally less difficult to do. Researchers could portray surfaces with effective shadowing, realistic surfaces could have imagery of the area draped over them to add to the ease of cognition and sense of familiarity with the model. This impression of reality aided the researcher by reducing the strangeness of the visualization environment, and as with any effective cartographic creation, the reader's ability to interpret the message of the data is aided if the reader does not have to spend a lot of time 'figuring out' or orienting themselves with the cartographic representation.

The final spatial data type is the volume data. This data type represents three dimensions of a phenomena, often these dimensions will be width, length, and height, often denoted by x, y, and z respectively. Just as there are a minimum of three segments defining the above polygons, polyhedra are defined by their edges and faces. A polyhedron requires a minimum of 4 faces, 6 edges, and 4 points. In many models the height, or z value, represents an aspatial value associated with the phenomena at the defining x and y.

Aspatial data are data that do not directly have, as the name suggests, a spatial component. These types of data tend to be descriptive, supplying information about an observed phenomena without placing that phenomena in any location. The mineralogy of the stratigraphy is an attribute of the material beneath our feet and by itself cannot tell us its location. One may be able to infer a topological relationship to accompanying rock based on the lithologic and mineralogic formation characteristics, but these sort of relationships are relative and not absolute spatial indicators. An experienced geologist may be able to describe what the likely neighbouring minerals and rock would be around a gold-bearing quartz vein, but would only be able to estimate the spatial characteristics of these neighbours.

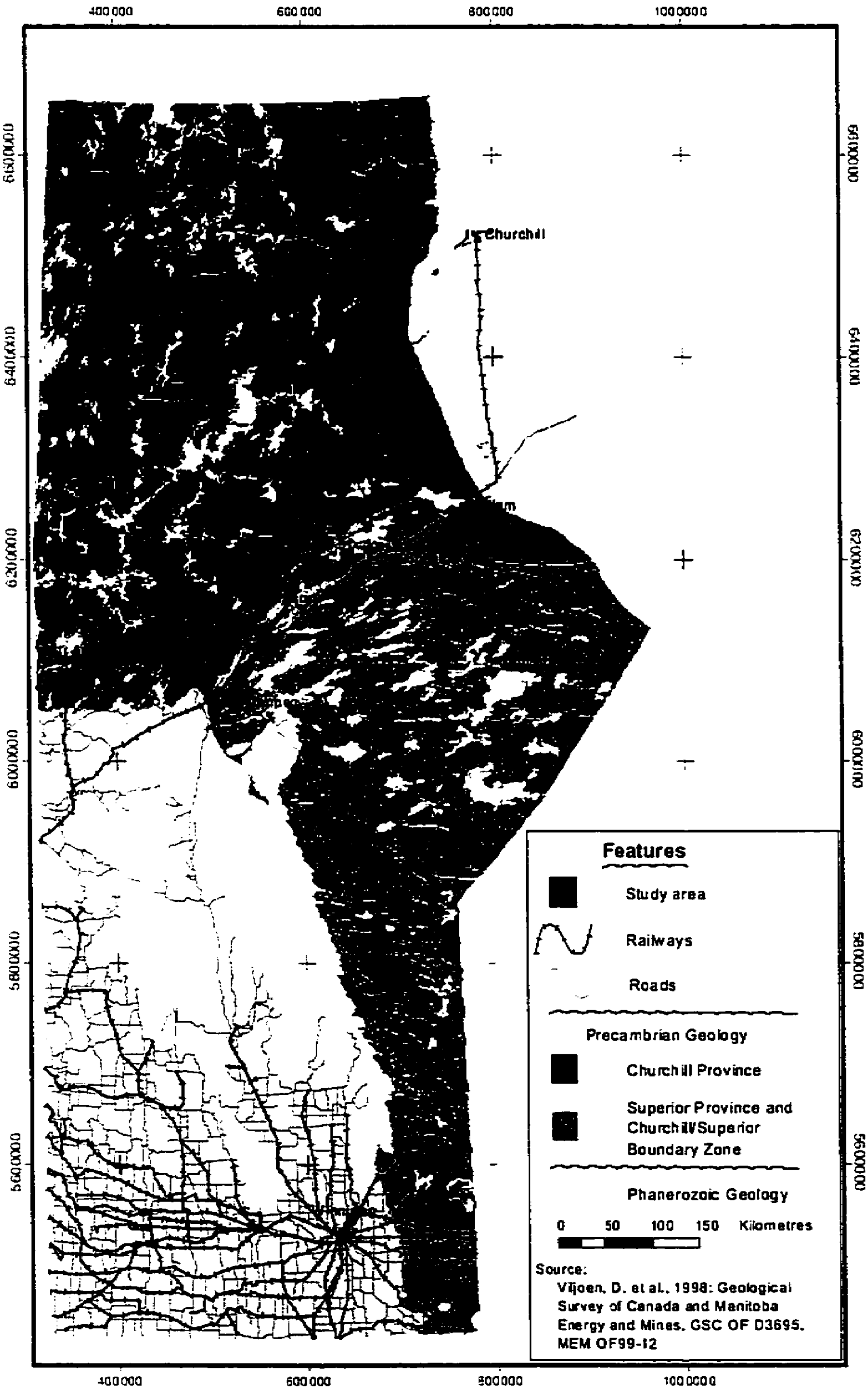
I would now like to draw attention to the increasing complexity of the data types discussed above and how, even though the data are more complex, traditional cartographic methods and general interpretation of these data types seek to simplify or generalize the data in the more complex features. We choose to limit the representation of topography in our soils maps (we generalize these features to a planar homogeneous unit); we denote even the largest of mountains as a series of isolines on a two dimensional plane, and generalize the topography of those complex topographic and topologic surfaces. As stated earlier in this work, the world is very complex and we select our models and their resolution and scales of representation to best communicate the information relevant to the problem being discussed. Herein lies the crux of the problem for the geographic information systems modeller, as the data needs to be collected at the highest possible resolution, the largest possible scale, and the greatest fidelity to represent reality while still being able to integrate different datasets, and accommodate practical realities of storage, processing power and modelling algorithm capabilities.

THE STUDY AREA:

The study area, a region around the Gull Rapids area of the Nelson River, is approximately 190 kilometres east northeast of Thompson, Manitoba. The Gull Rapids are just downstream of Gull Lake (see Study Area Map, Figure 2). This study area crosses (from southwest to northeast) geology representing the Split Lake Block, Churchill Superior Boundary Zone, Kissyenew and Leaf Rapids major domains (Figure 3 Borehole Locations). A more complete discussion of the geology of the study area can be found in Corkery's 1985 Geological Report GR82-1 (Corkery, 1985).

Early investigations by McInnes, in 1913, and Quinn and Currie, in 1961, as well as the more recent works by Elphick, Frohliger, Haugh and Hubregtse describe a geologically complex area (Corkery, 1985). The cataclastic nature of the material and the unconformity of the geological units make for very difficult phenomena to model. The unconformal nature of such units requires considerable analysis of the borehole samples to identify what lithostratigraphic units are present. For the modelling process to begin

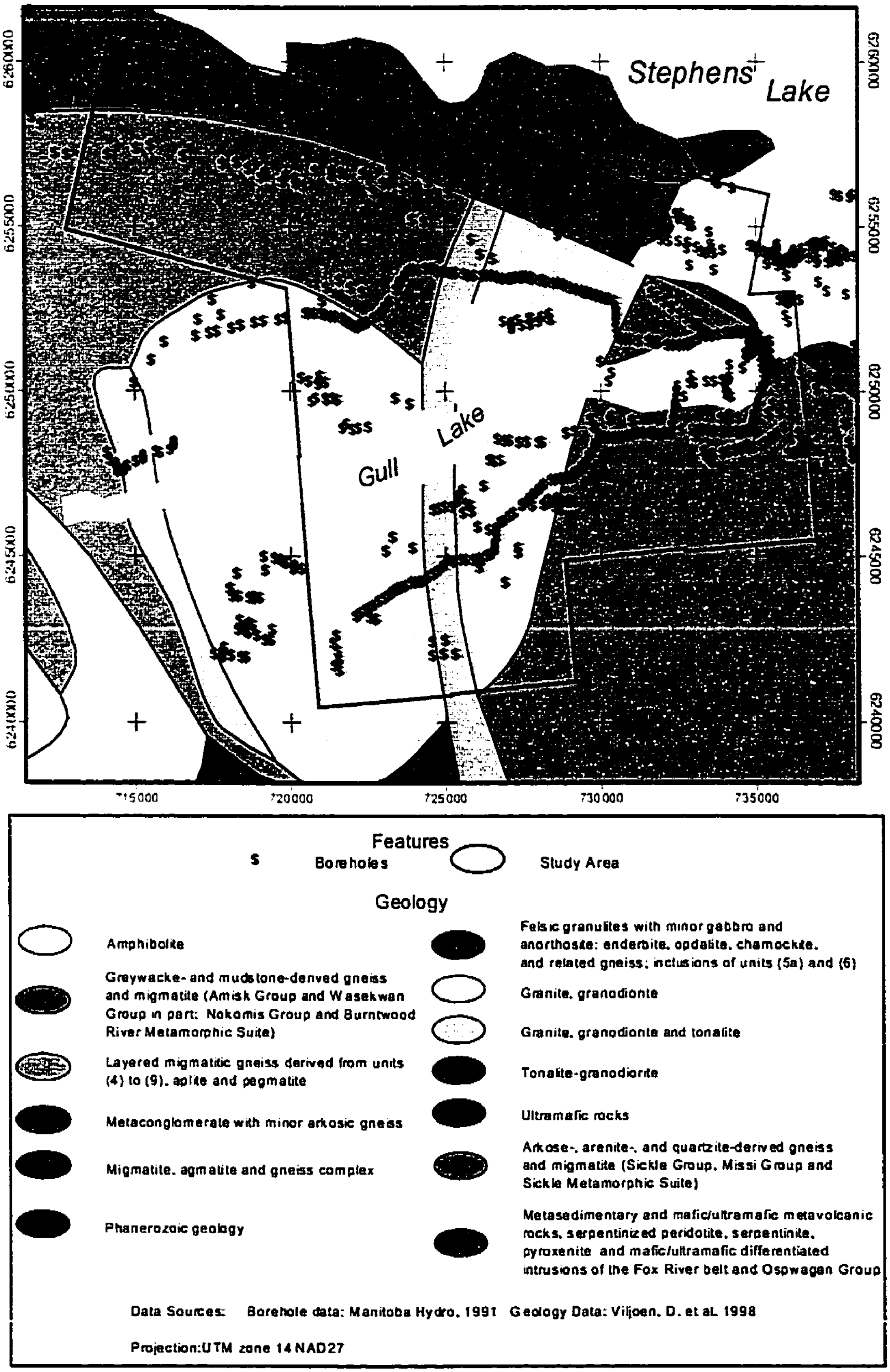
Figure 2 Study Area



Source:
Viljoen, D. et al., 1998: Geological Survey of Canada and Manitoba Energy and Mines. GSC OF D3695, MEM OF99-12

Projection: Universal Transverse Mercator, Zone 14, NAD27

Figure 3 Borehole Locations and Subsurface Geology



Data Sources: Borehole data: Manitoba Hydro, 1991 Geology Data: Viljoen, D. et al. 1998

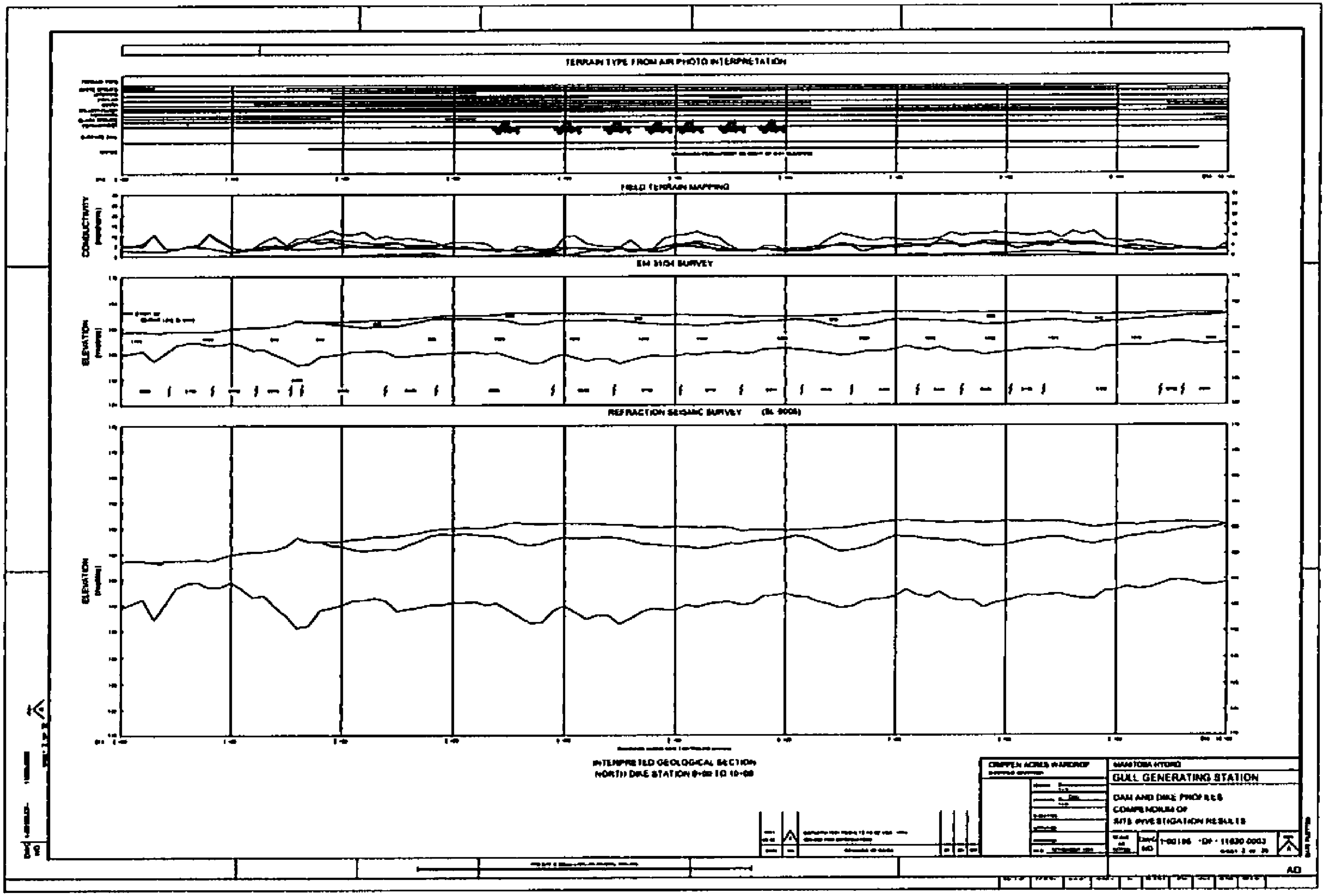
Projection: UTM zone 14 NAD27

some simplifying aggregation of lithostratigraphic units are made. These resulting geologic units will be modelled.

A description of the data available.

Data was supplied by the Geotechnical Engineering Department of Manitoba Hydro. These data consisted of digital 2 metre interval topographic contour maps; digital drill hole logs, refraction seismic and electromagnetic conductivity surveys. Digital drawings contain the data for; terrain type, field terrain, EM31/34, refraction seismic survey and interpreted geologic sections (See Figure 4) and present them in one AutoCAD drawing. The contours were derived from stereoscopic air photograph interpretation. The digital drill hole logs provide lithology, lithological unit thickness, relative position of boundaries between geologic units, and indications of attitude and orientation of these contacts. Seismic and electromagnetic conductivity surveys provide continuous interpreted profiles of geologic unit surfaces, location and approximate depth along a transect.

Figure 4 Linear Data Supplied by Manitoba Hydro



The spatial data collected by Manitoba Hydro are represented in the Universal Transverse Mercator (UTM) projection, zone 15, using the NAD27 datum. The data collection was done by conventional engineering and geology techniques for Manitoba Hydro in site preparation work in the Gull Lake area. The raw data were delivered in ASCII format. The graphics files in Autodesk's drawing exchange format (DXF), and the data files in a comma delimited text file (CSV). While the data collection techniques are fundamental to the fidelity of the data being used, an in depth discussion of these methods are beyond the scope of this work. It should be noted that while the modelling process should use industry standard data collection techniques, the planning of the data collection should incorporate the intention of these data being used in a GIS. This thesis will focus on the organization and compilation of the collected field data to generate the required models.

The difficulties in incorporating the data recorded in the AutoCAD drawings originate from the idea that these digital files hold representations of the data, but not the data themselves. The plots containing the EM traces portray the data without acknowledging that the data may not have been collected in a straight line, or that elevation distorted with a vertical exaggeration, which varies from plot to plot. The organization of the elements in the more traditional portrayal of these data require that the viewer interpolate the variations in elevation, conductivity and seismic response (See Figure 4). If these data were being collected with the intention of being modelled in the GIS it would be appropriate to incorporate the data readings directly into the modelling process and not to try to reinterpret them from the plot files. The portrayal of the data would occur after the modelling had been done, not prior to, as is the case with these data.

The characteristics of the information provided by the EM and seismic sensors plots limited their suitability for their inclusion in the modelling. It had been intended to compare the linear data provided by these sensors to the surfaces derived from the point borehole data to reveal any relationships that may exist between these two representation methods. The way these data were stored presented difficulties that prevented their inclusion in the modelling process.

Data preparation method for subaerial surface data as supplied by Manitoba Hydro.

Requirements for digital spatial data to be incorporated into the GIS model

1 All isolines must have vertices on one plane (this plane must be parallel with all other isoline planes).

2 All contour isolines are on discrete layers identified by their elevation (eg contour 720m will be on layer 720).

3 All other layers will have meaningful names, or if an arbitrary numbering scheme is to be used that scheme must accompany the data.

4 All contours must be closed, if not as a direct result of the digitizing process then by a consistent arbitrary manner which will ensure that the resulting polygon encompasses the `higher' contours between the contour in question and the nearest `high' corner.

5 If in closing a contour on the high side an isoline of the same elevation is encountered it must be determined whether the new segment is a continuation of the first contour or part of another feature.

The site plan drawing files are opened in ArcView 3.2 and then converted to ArcView's data file format, a shapefile. Files not conforming to the above criteria are topologically cleaned and verified. These site plans include cultural, hydrologic and topographic features. The topography is gained from photogrammetric measurement of aerial photographs. The interpreted contour data has a 2 metre interval. The hydrologic and topographic data are preserved in the created shapefiles. The cultural features are dropped from the datasets to reduce the memory and storage space required during the modelling process. It should be noted that the data collected above are two dimensional data representing three-dimensional phenomena. This presents the methodological concerns, how to create models of the volumes, and then how to test the fidelity of the resultant digital representations of these volumes.

The modelling environment

The modelling software decided upon was a suite of tools available from Environmental Systems Research Incorporated (ESRI) based in Redlands, California. Earlier modelling efforts with AUTODESK AutoCAD 12 and later with GMS: Groundwater Modelling Software were found not well suited to the modelling being attempted for this thesis, leading to the evaluation and adoption of ArcView as the modelling platform.

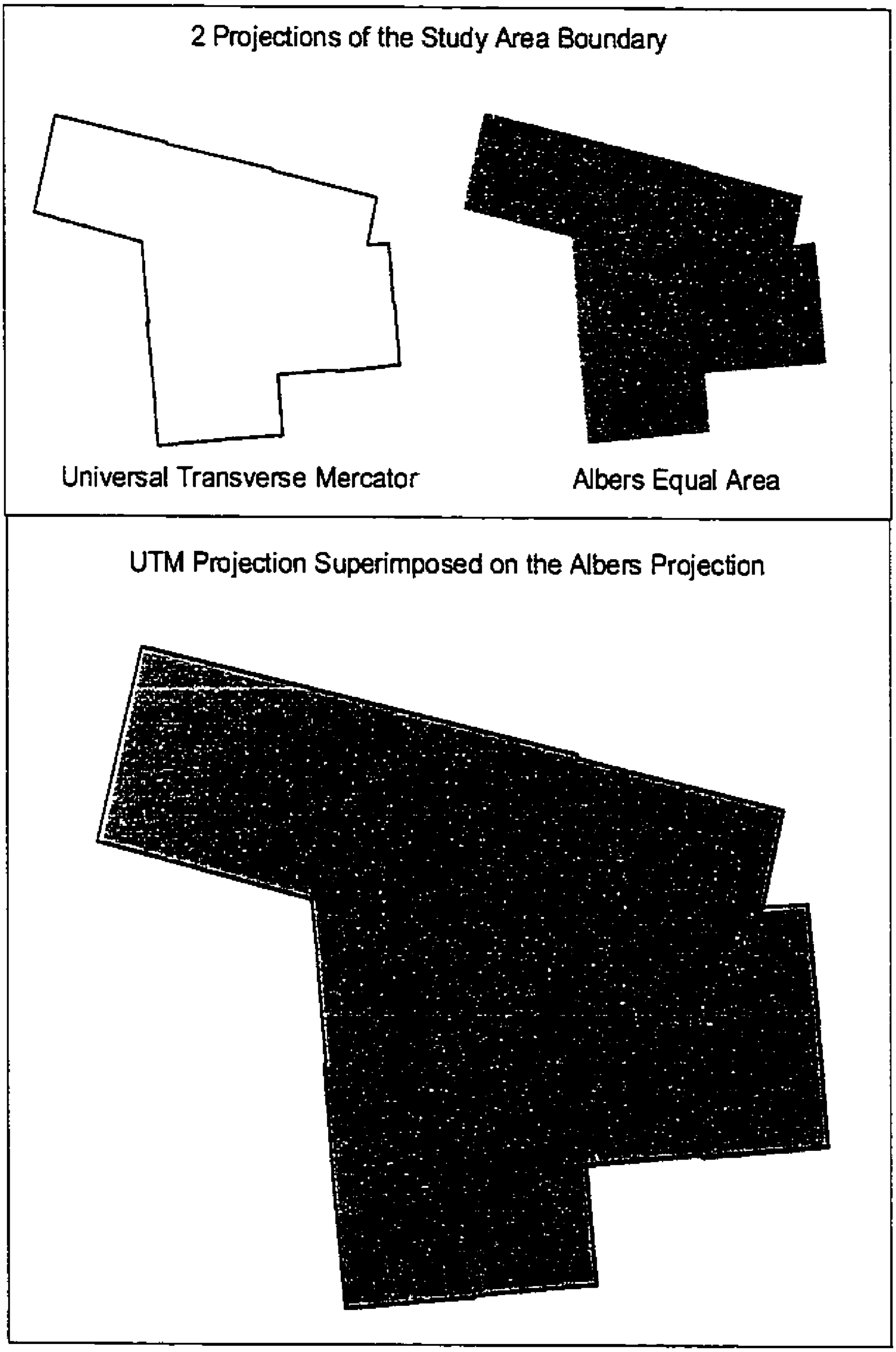
ESRI's ArcView 3.2 data viewing package with the Spatial Analyst, 3D Analyst extensions uses a common aspatial data base and a purpose designed spatial data format. The database that is the foundation of ArcView's aspatial data handling capability is based on dBase 4.0. The 'shapefile' is the proprietary spatial data format for vector data. Grids and TINs emulate the data structure used by ESRI's older Arc/Info GIS.

The versions of both AutoCAD and GMS were not intended to be geographic information systems. While they had some of the capabilities common with a GIS there were many essential capabilities that were lacking from these packages. The most significant difference between these packages and a GIS is the integration of the different operations, tools and database handling mechanisms. In a GIS the user will be able to apply the graphical, the database management, analytical and presentation capabilities to the data with comparative ease, in a common interface, while maintaining connectivity with the products of any one of the software's capabilities. GMS had limited graphical capacity and importing data or exporting the results of a model was cumbersome. An example of the awkwardness with which GMS handled data was seen in the dropping of borehole identifiers when a surface was to be exported. The creation of surfaces in AutoCAD 12 was an extraordinarily time-consuming, complex and intricate procedure. Neither of these packages integrated the analytical capabilities with the presentation capabilities. To go beyond rudimentary initial analysis, it became an exercise in developing the software procedures instead of performing the needed data analysis.

Discussion about the spatial data

Some observations about these spatial data should be made, not the least of which is that while this study is very much concerned about representing volumes, and that while volumes are very much dependent on accurate area measurements, a projection is used here which primarily preserves direction and distance while sacrificing fidelity of shape and area. A more appropriate projection, such as the Albers equal area, will certainly portray the areas more correctly. After consultation with Mavis Young, Cartographer and GIS Analyst with Agriculture Canada's Prairie Farm Rehabilitation Administration, it was decided that the degradation in area calculations (and thus volume calculations) by using a Universal Transverse Mercator projection was a lesser degradation than what may have been caused by recalculating and projecting the UTM based data (See Figure 5 Projection Comparison). An additional argument, and frankly the deciding argument, is data conformity with much of Manitoba Hydro's other data sets. It was considered that any increase in data fidelity by selecting an equal area projection would be offset by continually requiring the final user to be aware of the projection change, and converting back and forth of the data to suit whomever happened to require the data. In addition to this fundamental data format consideration there were some smaller quality control issues concerning these spatial data sets. The naming convention for the assorted layers was not documented, and much of the line data was replicated on

Figure 5 Projection Comparison



more than one layer, creating unnecessarily large and topologically complicated data sets.

Two data sets that are important to ensure the validity of the visual results, are the topographic data and the hydrologic data. These datasets allow the user to visually inspect the representations, checking for proper orientation of the slopes and valleys which were generated by the modelling process.

Borehole data

Lithological data collected from boreholes rely on the interpretation of the lithostratigraphic record presented in a cylindrical sample of rock collected using industry standard drilling and core recovery techniques. The particulars of how cores are recovered is more thoroughly covered in many other works such as Keller and Frischknecht (1980) or Krynine and Judd (1957). Short of physically uncovering the stratigraphy, the borehole sample is perhaps the data collection method of highest fidelity. The properly taken core preserves lithological, positional, topologic and orientation data. It is essential that the field researcher be able to determine mineralogy. In most cases it is crucial to be aware of the depth of where that particular mineralogy occurred and in some cases it is important to know the orientation of the structure. Locating faults or veins are examples of where the orientation information becomes important. In this exploration of modelling, the data available are insufficient to discern which of the multiple occurrence of a particular lithostratigraphic unit in one borehole match lithostratigraphic units in neighbouring boreholes samples. The lithostratigraphic units will be aggregated into 4 geologic units. This coarse aggregation of the multiple non-conformal geological units reduces the complexity of identifying contacts for the initial modelling efforts.

Description of the aspatial or attribute data for the borehole portion of the data sets.

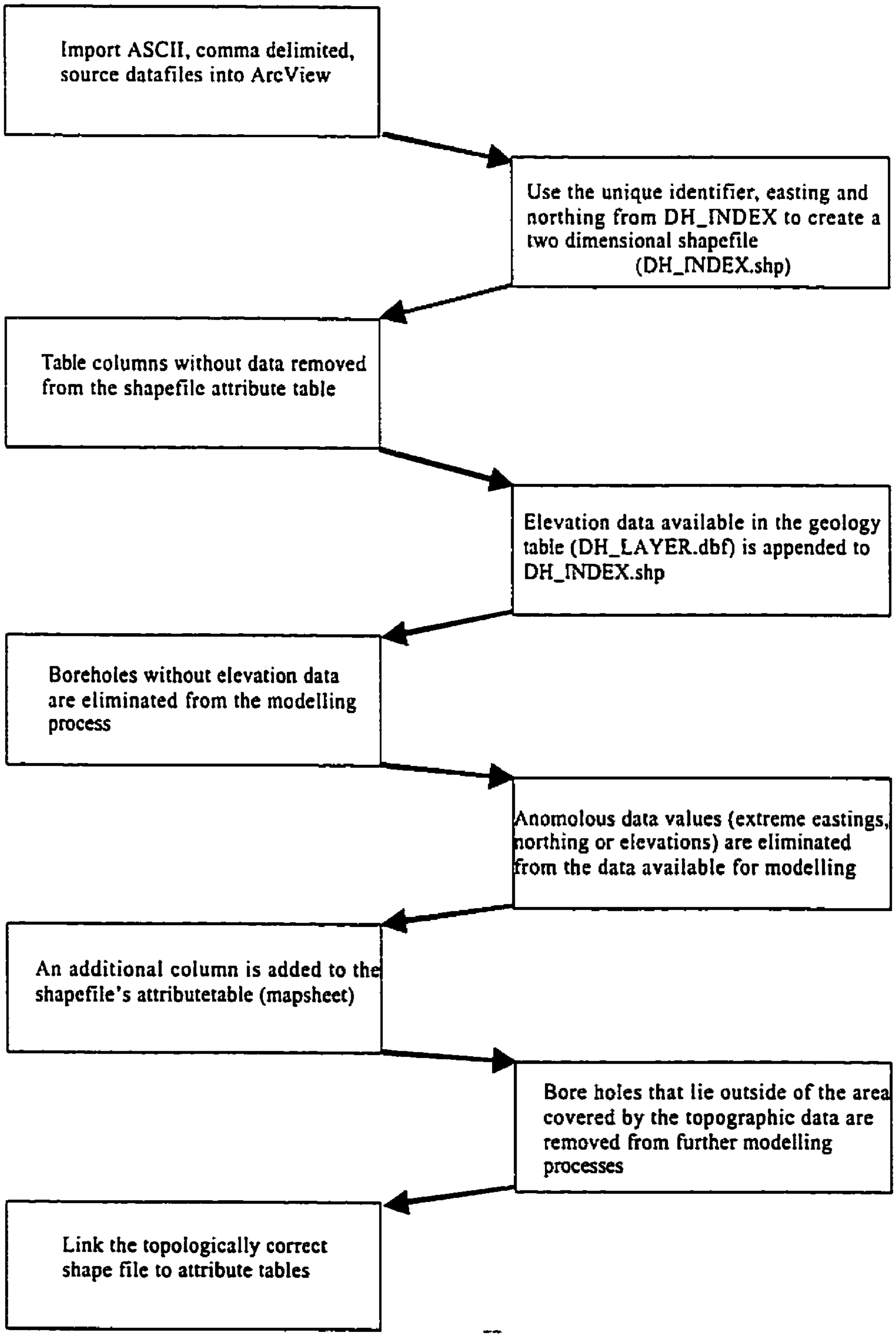
The lithological and methodological data were collected into several data files. These were concatenated into the four tables: dh_index.dbf, dh_layer.dbf, dh_water.dbf, and dh_frost.dbf. The format of the tables are presented in Appendices 1a, 1b, 1c, 1d.

As the aggregated borehole data were accumulated in 4 tables, it was necessary to link corresponding records from each of the tables. The flow chart appearing in Figure 6 presents the data conversion and validation process. This process is presented in Appendix 2. While there are several attribute tables containing data for the study area, only the two used for modelling purposes will be discussed here. The data from the other tables are available for additional GIS queries and are ready to be linked to the modelled data. As with the vector data files the data quality for the attributes is less than ideal. The conversion of these data from the original database (gINT) format to dBase was cumbersome and time consuming.

DH_INDEX.dbf

The drill hole data file, containing the drill hole names and horizontal positions, "DH_INDEX" (originating from the .csv file and imported into ArcView) contains 14 fields. Of principal concern are the easting, northing and unique identifier fields.

Figure 6 Validation andConversionProcess fortheBorehole Data



A shape file was created from the point, northing and easting values with the elevation being appended after the spatial data set was created (See Figure 1). This shapefile becomes the common link for all the attribute data tables, all linking based on the common identifier referring to the name of the borehole (e.g. G-0008). This table was used to locate the boreholes on the site plans provided by Manitoba Hydro.

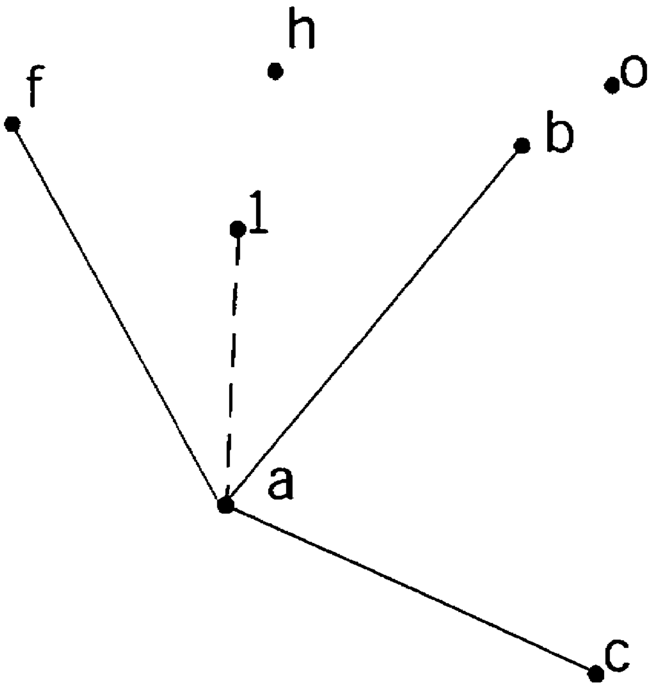
DH_LAYER.dbf

The datafile "DH_LAYER" (originating from the .csv file and imported into ArcView) contains 8 fields. Of principal interest in this table are the unique identifier for the boreholes (called "Hole Number" in this table not "Point" as in the previous file), the absolute elevations of the 'tops' of the rock units, the base or 'bottom' of the rock units and the rock units or petrology descriptor. All 8 fields are linked in anticipation of ad hoc queries that may require the data contained within any of these fields. No fields contained null data.

A simplistic approach to creating a digital volume is by using a linear interpolation, a 'connect-the-dots' approach, connecting the highest limit, or appearance of one geologic unit in a borehole to the highest occurrence of the same geologic unit in the next nearest surrounding drill holes. Nearest neighbour algorithms of the software select which boreholes will be connected to form the surface.

This plan view (See Figure 7) shows point A being the central vertex for several angles (BAC, FAB etc). The angles are determined by their proximity to A and also by the proximity to each other. If a point were placed between the arms of FAB (#1 on the diagram) the nearest neighbours of that angle would have to change to FA1 and now 1AB as well. The logical neighbours aspect comes into the definition of these angles (and the resultant triangular facet of the next step). Points ABCH and O are all in close proximity, with B and C readily discernable as nearest neighbours (there are no points closer). Point H is closer to Point O and so is a near neighbour but for the purposes of this thesis is not a logical neighbour because the points B and C present an intuitively simpler representation of the surface being defined by the angles derived from the points locating the

Figure 7 Nearest Neighbour Illustration



highest occurrence of a geologic unit as recorded in the drill logs (core samples). Closing of these angles by drawing a segment across from B to C creates a triangular facet representing the straight line top surface of a particular geologic unit.

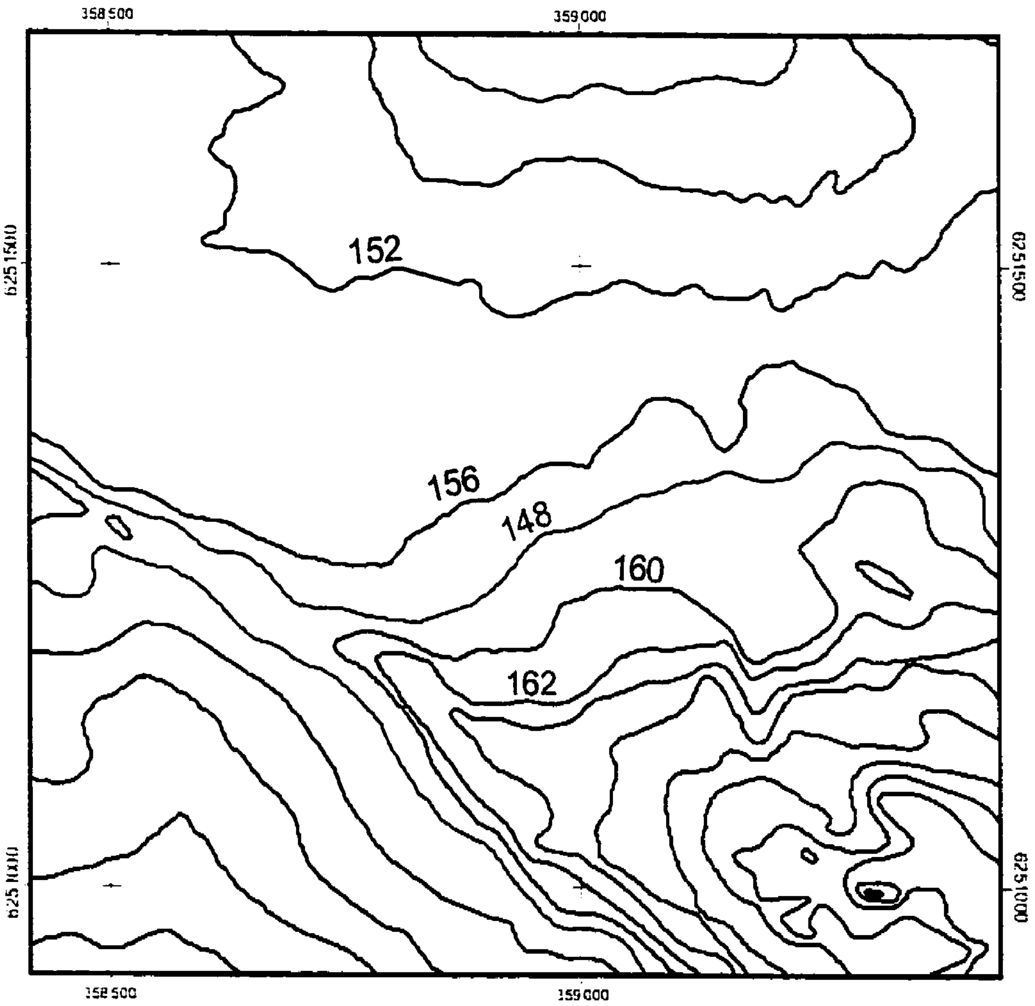
A surface facet is defined by the three nearest neighbour contacts. A contact in this context is the highest occurrence of a common geologic unit in a core sample. The 3 edges of the facets must be the shortest distances possible from the surrounding nearest possible vertices without encompassing any contacts.

Some errors or anomalies in the topographic data

The data derived from the photogrammetric interpretation of the contours displayed some errors. There are four types of errors: discontinuous contours, improbable assignment of elevations to contours, disagreement of the contour elevations with the neighbouring point elevations, and missing data. These errors were resolved by inspecting each segment and point and rectifying the elevation values assigned to the contours. In cases where the contour line had multiple values assigned to the isoline the uphill and downhill contours were looked at and then compared against the values recorded for the suspect contour. In many cases only a few segments (generally at either end of the line) were incorrect. These were manually modified to match the rest of the isoline. In cases where the elevation was at odds with the surrounding isolines the surrounding isolines were used to provide a more logical elevation. In some cases the contours agreed with their immediate neighbours but were at variance with the point elevations. The new elevations were based on which elevation had more supporting evidence. If there were three or more point elevations with a different elevation than the surrounding contour, and if these contours were out of sequence from other contours on the map sheet, the contours were modified to reflect the point elevations. If there were fewer than three point elevations and the contours logically graded from the surrounding elevations, the suspect contour elevations were not changed. Most of the contours had no elevation data, but were assigned to layers identified by elevation values (e.g. *Layer 149* would have the line work for the 149 metre contours)

Illogical elevations were assigned to adjacent contours (Figure 8). If one assumes that the contours above and below the red contour are legitimate it can be inferred that there should be a 158 metre contour continuing between the two contours which would further define the steep slope of this feature. Errors of interpretation such as displayed in neighbouring contours having illogical elevation values assigned to them and require that the data are thoroughly validated before surfaces are generated from them.

Figure 8 Illogical Elevations Assigned to Contours



The logical perceptions of the surface is confused by the apparently illogical deviation in the sequence of the contours. The three dimensional modelling software will see the contour labelled as 148 as a valley between the 156 and 160 metre contours.

Topographic data (Manitoba Hydro, 1991)

Selecting a sample of the data for modelling

Based on the inspection of the entire data set (Figure 3), the subset was selected based on the following criteria:

1 As much of the data were collected along survey lines, there is a pronounced linear orientation of the boreholes. In order for the surfacing algorithms to be able to create more than one dimensional interpretations of these 'lines' the data points had to be distributed somewhat off the centre line of sampling.

2 The distribution of the boreholes are not separated by a major change in elevation that had not been sampled. An example of this type of separation would be a narrow steep sided river valley with sample points only collected at the higher elevation above the rim of the valley and with no sample points collected from the bottom or sides of the valley. This subset of the data was based on overlaying the borehole positions over the orthophoto-generated topographic maps of the study area.

3 The borehole locations were located in an area represented by available topographic data.

4 If the above criteria are met a final selection by a density mask is made. The selected set is then used in developing the surface models.

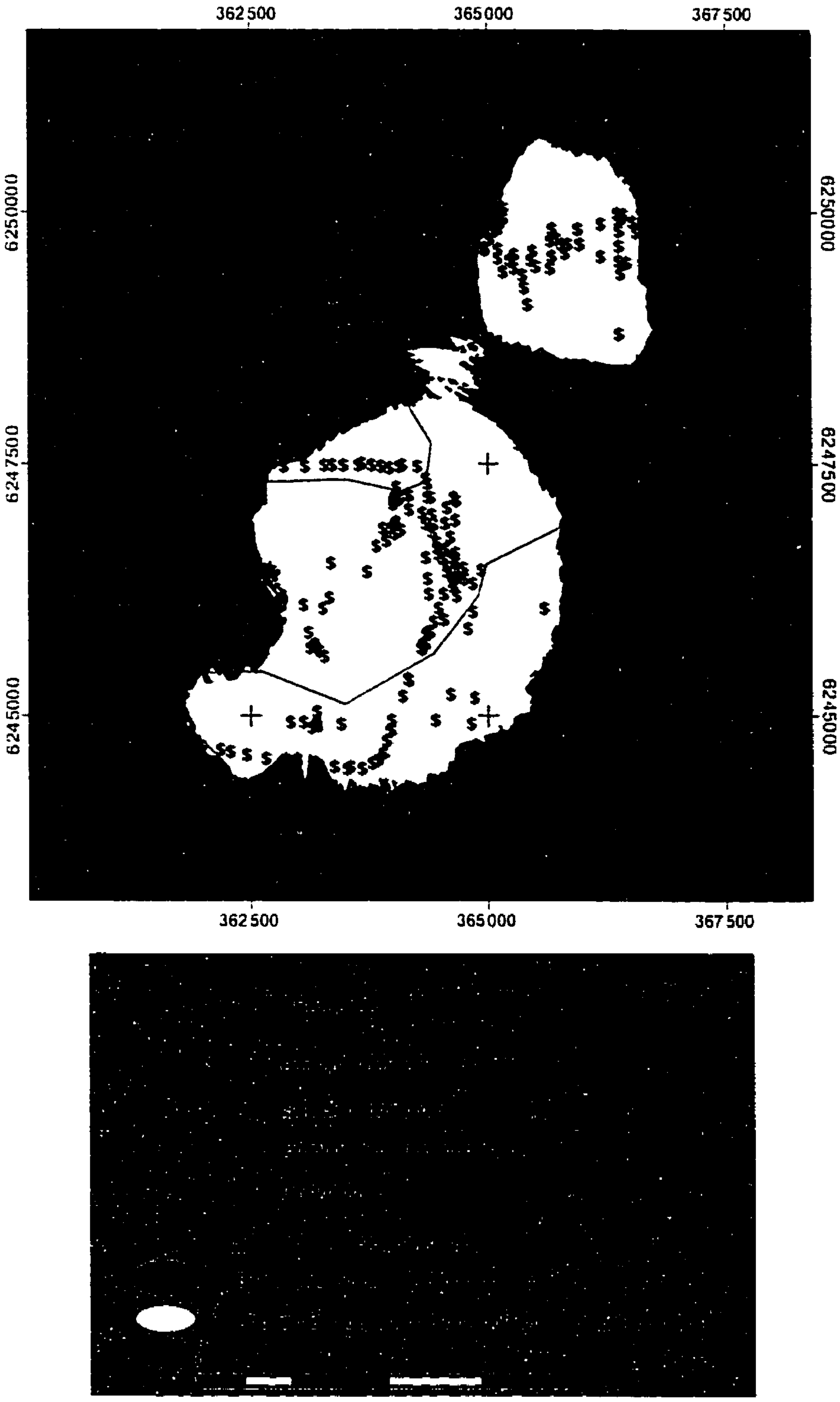
These criteria reduced substantially the number of boreholes available for testing the surfacing methods, which suggests that for modelling to be an effective tool there must be a reflection of these criteria in establishing sampling patterns in future investigations.

For the surfacing algorithms to work there must be some horizontal dispersion to the sampling pattern. This distribution should not encompass too large of an area, particularly if the intervening distances between boreholes are too great, so that the model interprets large planar areas with little data to support such an assumption. Additionally there must be sufficient depth, or more precisely, a sufficient number of layers for the model to be interesting to complete, as there is little utility in preparing a monolithic model which offers no 'new' information to the investigator.

The selection process began by concatenating the five vector topographic themes into one shape file, after cleaning up inconsistencies in elevations. A density mask was used to select a subset based on the density of concentration of the boreholes. The 1205 boreholes are clustered into three large groups spatially separated by topographic features (See Figure 3). These clusters are artifacts of the sampling methodology used by Manitoba Hydro. The sampling was done along transects with only occasional samples being conducted off the transect. This makes for very poor three-dimensional modelling data as there is no breadth to the data. This essentially one-dimensional data creates some difficulties in establishing the three dimensional surface required to create the various models required.

The distance between all boreholes is calculated (See Figure 9). A 3 by 3 filter, used to calculate the minimum distance between points, is applied. The 'precision' in the positional data implied by the numbers of decimal places provided by the software is excessive and not supported by the initial accuracy of the data and thus will be rounded to a less specious value more reflective of the observed data (e.g. to the nearest metre).

Figure 9 Borehole Selection Density Mask



Source: Hydorgraphy, Viljoen, 1998; Borehole data, Manitoba Hydro, 1991

Upon inspection of the results of the above step, the maximum distance between boreholes is approximately 21 kilometres. After inspection of the distance plot and based on some experimentation with different search radii, a search distance to calculate the densities of boreholes was arrived at. A 1 metre cell size and 10 metre search radius created a data set too large for the available software/hardware combination to process. A 4223 by 5585 grid with 10 metre pixels was created from the borehole data. The simple density was calculated using a search radius of 1500 metres with the data being portrayed in numbers of boreholes per square kilometres. Figure 9 illustrates the borehole density mask. A density of 8 boreholes per square kilometre appeared to be the lowest density suitable for successfully interpreting a surface. Those areas having a density less than 8 boreholes per square kilometre were eliminated from the modelling process.

The 175 boreholes selected clustered in two main bodies. The smaller of the two, laying just to the north east of the main body has 45 boreholes. This smaller cluster was removed from the modelling process because of its separation from the main body. This grid was then converted to a shapefile to allow a topological selection of the boreholes.

Using the density mask shapefile, boreholes are selected from the entire dataset This selection results in 88 boreholes with a total of 729 contacts or tops.

One additional constraint on selecting groupings of boreholes, and this restraint is specifically because of the surface testing requirement of this study, was that the grouping must be coincident with the available topographic data. Much of the interesting terrain and borehole data fall just to the east of the available topographic data and so were unsuitable for testing, although the modelling techniques of acceptable accuracy and rigour could certainly be applied to these portions of the larger datasets.

Creation of a surface from the borehole data set.

Once the borehole data were selected, the solid modelling procedure could begin. As stated earlier, the focus of this study is not to create new surfacing algorithms, nor invent new methods of mathematically modelling solids, but to investigate the contributions of the methodologies to geologic inquiry. Boundary surfaces will be created using the borehole unique identifiers (BID), the positional data and the lithological data contained in table *dh_layer.dbf* (Appendix 1b). It should be observed here that many fields from both of these tables are not actively used in the modelling process, but are carried in the datasets to facilitate future data analysis. As additional attribute data become available they can be incorporated into the model, relating on the unique borehole identification numbers, to satisfy ad hoc queries as the need arises.

METHODS:

The use of computer modelling

For a modelling system to be effective and flexible enough for practical application the data entry method must be straightforward and uncomplicated. Developments in the software's graphical user interface increased the ease, reduced the time, and limited the errors in entering data. An effective modelling system requires that data be available for the modelling process. Over the course of the development of this thesis the data handling methods developed markedly, from labour intensive formatting of data into the ASCII data file format required by the earlier software, into the much more graphical and comparatively intuitive interface now available. This interface consists of a dialogue box requesting the user to enter the borehole identifier, the positional data (easting, northing and elevation) of the surface boundary (traditionally the 'top' or highest elevation of the geologic unit), and a descriptor of the lithology (a numeric identifier). Several topics that become apparent at the data entry stage are: insufficient lithology descriptors; the requirement of a lookup table for descriptors; the confusion of data existing on multiple data layers; and the flexibility of the software to accommodate slope/dip data for each borehole. The modelling process must account for and accurately inform the user of how these concerns were dealt with.

Once these positional and lithological descriptors are entered for a sufficient number of boreholes, the identification of surface markers must occur. These surface markers (commonly referred to as 'tops') are the lithological boundaries between two lithostratigraphic units, generally referring to the highest elevation of that particular unit (e.g. β_1 in Fig. 11). Presumably if there were evidence of folded rock units, one would be speaking of a geological 'top' and not necessarily a logically constant 'upper' surface. As can be seen in Fig. 11β_1' β_4, and β_5 all represent the intersection of the borehole with what would have been the surface of the beta rock units when it was laid down, but now with the overturned fold situation the intersection points β_1, β_3, and β_5 are the 'tops' of the geologic unit. The researcher would require more evidence than is readily available upon visual inspection of the hand or borehole sample to typify this feature.

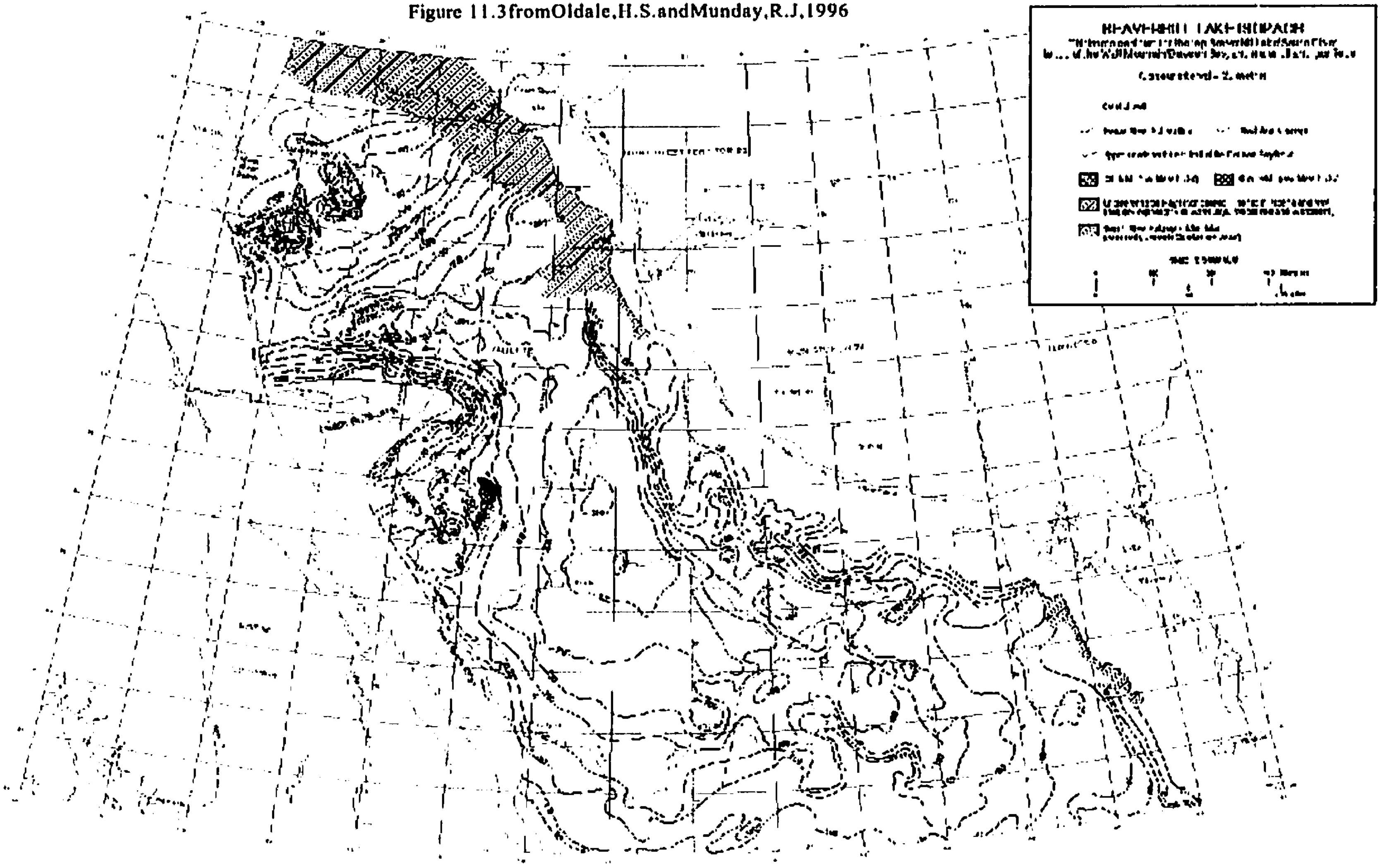
Once the likely 'tops' for a particular geologic unit have been identified, the software is able to generate a triangulated irregular network

(TIN), although the operator can select several parameters which will affect the construction of these networks. It is readily apparent upon generation of the first TIN, which for discussion purposes has been generated with the software's 'default' settings for TIN generation, that the distribution of the boreholes is crucial to even a rudimentary successful attempt at generating a surface with reasonable fidelity. A test of the 'reasonableness of the surface generated is an initial visual comparison with the Manitoba Hydro created topographic data collected from photogrammetric interpretation of the aerial photo images. The subaerial surface was the first layer to be modelled as it would seem logical that if the mathematical models could not adequately model surfaces that have been measured then the model is useless to represent surfaces previously unmeasured.

As part of the preliminary siting investigations for Manitoba Hydro's establishment of large facilities, such as generating stations, much geomorphologic and geologic data are recorded. Traditional interpretive and communication methods require that this field data be sorted, grouped and mapped in a numbers of ways. An illustration of this traditional data organization is the commonly seen 'fence diagram' (See Figure 4). A fence diagram, as the name suggests, is a linear representation of a cross section of the data set. Picture a picket fence with the posts being the drill core samples, the planks representing the geologic unit. A somewhat less familiar diagram is the 'isopach map'(See Figure 10). This is a representation of areas of equal thickness, a concept very difficult for the uninitiated to grasp, and less intuitive than the fence diagram. This map portrays the absolute thickness of a geologic unit (not the dimension above or below a bench mark elevation), with the isolines indicating lines of equal thickness, with no reference to which direction the bulk of the thickness lay. Picture a plan drawing of your head. Laying on your back there would be a concentration centring on your nose. If you were to turn over and create a second isopach map, the isopach map drawn for the back of your head would be the left right mirror of the first but the concentric lines denoting your nose would still be centred on the map, the thicknesses have not changed even though their orientation did. Note the use of two dimensions to convey the volume intrinsic in the real world phenomena.

Figure 10 An Example of Traditional Isopach Mapping

Figure 11.3 from Oldale, H.S. and Munday, R.J. 1996

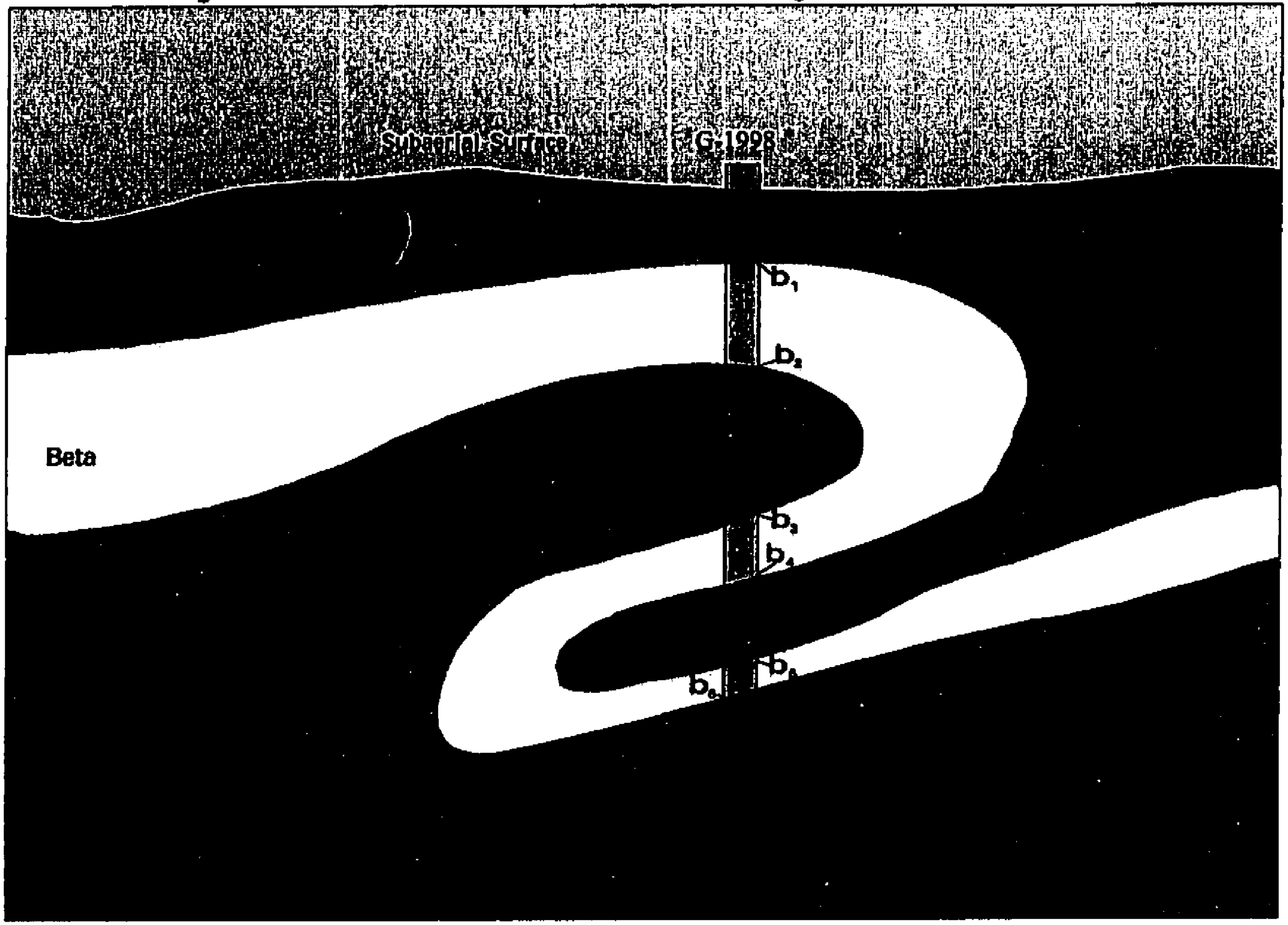


Creation of lithostratigraphic top surfaces.

Some of the petrology in a given borehole may repeat through the geologic record (See Figure 11). This presents a problem of logic for preparing a surface, as defined by discrete xyz triplets, with only one of each of the triplet elements being represented. Multiple occurrences of the same rock type implies multiple z values. As there is not sufficient additional information in the tabular data to attribute or associate particular Z values with a specific surface, an arbitrary method was chosen as a first approximation. This approximation is of course modifiable as additional information becomes available.

To facilitate this first approximation of the rock unit top all the contacts in the boreholes were assigned an order number. Each contact or top of a particular rock unit was assigned a number in an ascending order in turn starting from the subaerial surface and working down the borehole column. For testing this procedure, the process was conducted manually; for a larger data, set it would be appropriate to automate this procedure.

Figure 11 Schematic of a Borehole Intersecting an Overturned Fold



Once the layer contacts were assigned an order number this order was used to associate all the similar contacts (of similar order number) into a selection set which could then be surfaced, with a simple linear interpolation of the coordinate triplets into a triangulated irregular network (TIN). All top contacts of one rock unit of a particular contact order number were collected to create a surface.

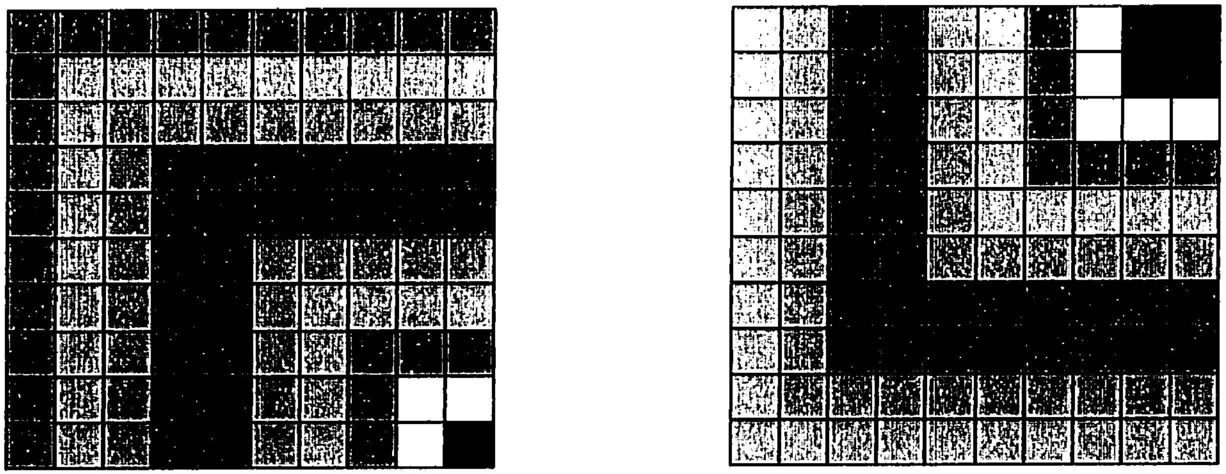
Methods applied to the scientific visualization of geological data.

The traditional methods are the benchmarks by which any new methods must be tested, but there are some inherent difficulties with manually interpreting and charting data. As identified earlier, the necessity of cutting and pasting paper maps together to 'create' a map of a particular study area is eliminated with seamless databases and computer cartography. The rapidity and ease with which a cartographer can update and produce maps is greatly aided by new technologies. Creating contours on large datasets is prohibitively time consuming and there are new graphic portrayals of data that are not practical for manual cartography. The oblique views generated by the three dimensional modelling of this GIS are quite complicated figures to create. It would take a cartographer of considerable skill to generate such a drawing with traditional tools. The suite of software tools available for this thesis project allow this artistically challenged writer to generate not one oblique view but several. Not only can multiple graphics be generated but each view can have incremental changes in shading, viewing position or lighting. These incremental changes will allow the researcher to better be able to make the cognitive leaps necessary to better understand the phenomena at hand.

Illustration of the TIN modification process using a synthetic surface.

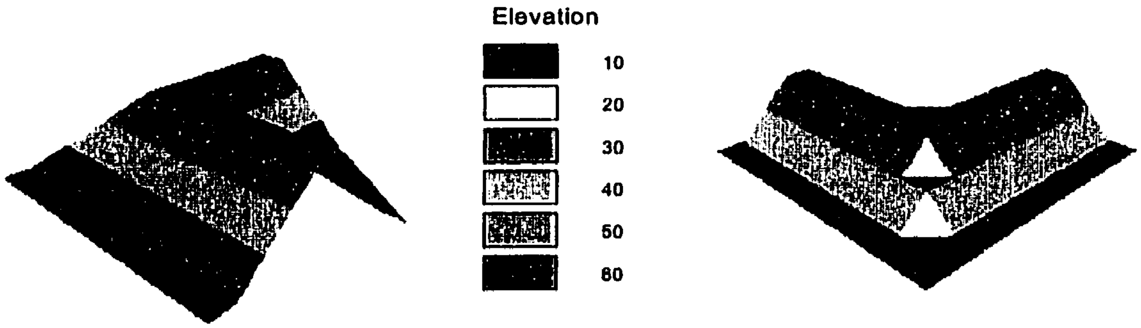
To illustrate the creation of a triangulated irregular network (TIN) surface a data set was constructed (See Figure 12). The test data are two 100 metre grids composed of 10 metre cells or pixels. Each pixel was assigned a value as seen in Figure 12a and 12b. Surfaces generated from these are portrayed with the same colouring scheme (See Figure 12c and 12d).

Figure 12 Generic Data Matrices and the Associated Surfaces



12 a. The generic 'superior' data set.

12b. The generic 'inferior' data set



12c. A surface generated from the superior data set.

12d. A surface generated from the inferior data set.

The test data sets consist of 10 metre grid cells.

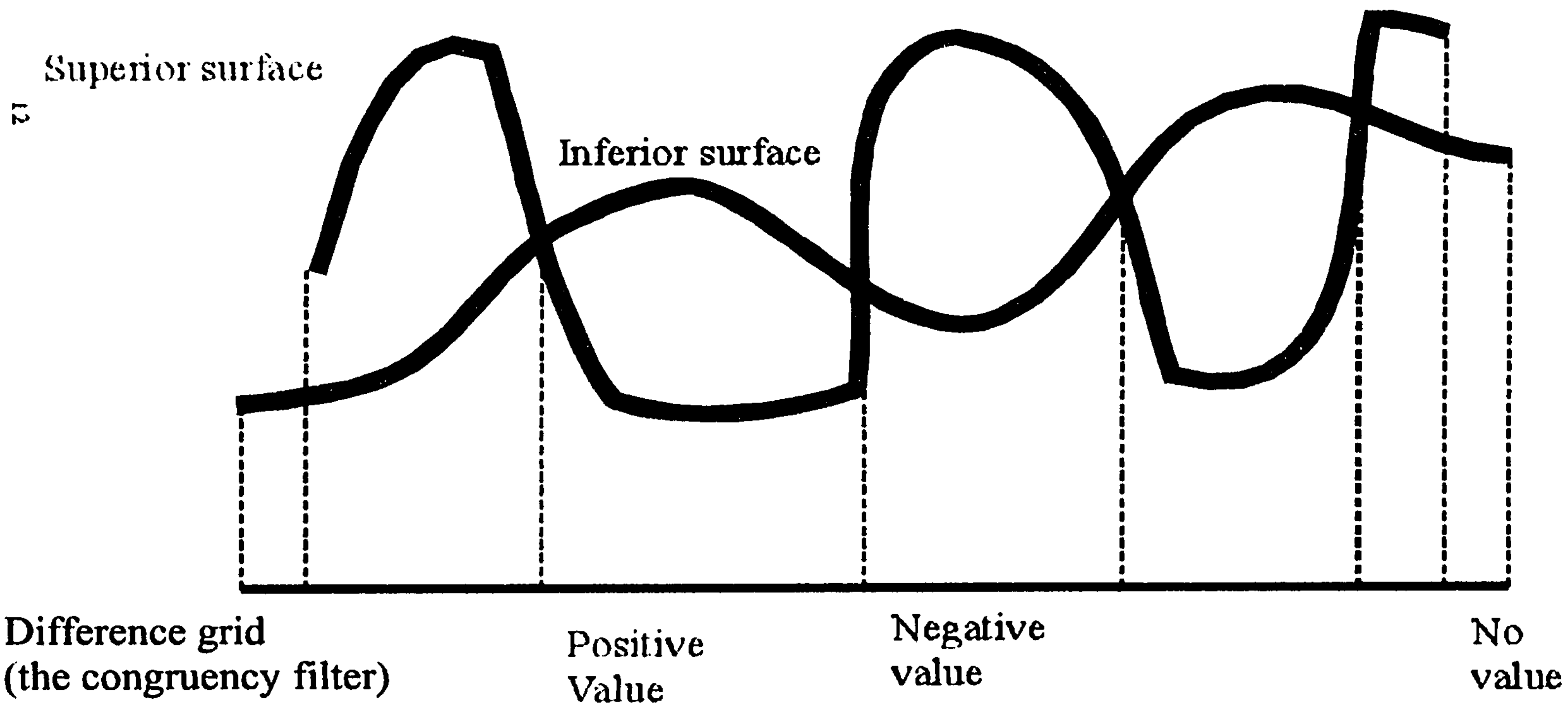
The surfaces generated from the test data are portrayed here with an apparent illumination source with a 255 degree azimuth and a 30 degree elevation.

A simple subtraction of the higher surface from the lower surface (by definition the upper surface cannot be beneath the lower surface) results in a grid with positive (green) and negative (red) values. In this illustration, the negative values represent the areas that are properly above the lower surface (the elevations of the upper surface are greater than the lower surface's elevations resulting in a negative value when subtracted). The positive areas of the difference grid (See Figure 13) are where the lower surface pierces the interpolated upper surface (the lower upper surface elevations subtracted from the higher lower surface elevations result in a positive number). The positive areas must be accounted for in the modelling process.

This modelling begins by creating a surface from the original elevation data points. The inferior/superior nature of those points, with respect to the previous layers, whether they are above or below the previously generated (and by definition the lower and the controlling) surface is determined. Starting with the lowest geologic unit a grid is created from an interpolated TIN surface made of the elevation points. A similar grid from an interpolated TIN surface of the data points for the next superior surface is made. Each of these grids is a matrix representation of their respective surface, which in

Figure 13 Congruency Filter Creation

Inferior surface - Superior surface = positive and negative grid



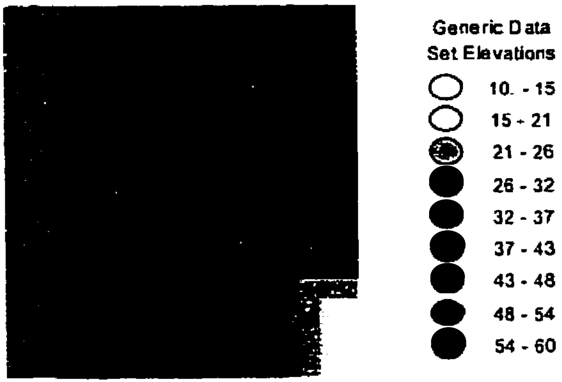
turn can be used to establish the corrected morphology for subsequent layers. It should be noted that the resultant grid of the 'correct' high surface will only be a subset of the original gridded area. This will create odd looking surfaces with data that are beyond the measured range of elevation values. To minimize the peculiarity of the appearance and more importantly to control the surface correctly the immediately inferior surface or surfaces adjacent to the top portion will be appended to the grid to minimize artifacts created by the TIN creation process. This is accomplished by creating a composite grid of the lower top and the polygons identifying the anomalies in the superior surface. In the software being used this requires the calculation of a grid from the TIN surface generated from the observed data. This grid is then reclassed, to 1 metre intervals, allowing the software to create a vector coverage from the gridded data. These reclassed data are then vectorized to allow the topological relationship between the positive/negative regions derived to determine the extent of the superior surface.

Generichi (Figure 14a) and genericlo (Figure 15a) are two grid files generated from an AutoCAD drawing of a 10 by 10 matrix of 10 metre cells. These grids would be similar to those generated from an interpolation of the borehole data available in the Gull Lake study area. Genericlo.avl and generichi.avl are ESRI legend files used to simplify the legend creation process, they store an established interval and colour selection. In each of these cases the values of the grid cells runs from 10 to 60, but the two different hues have been chosen to illustrate their respective positions and not their grid cell (elevation) value.

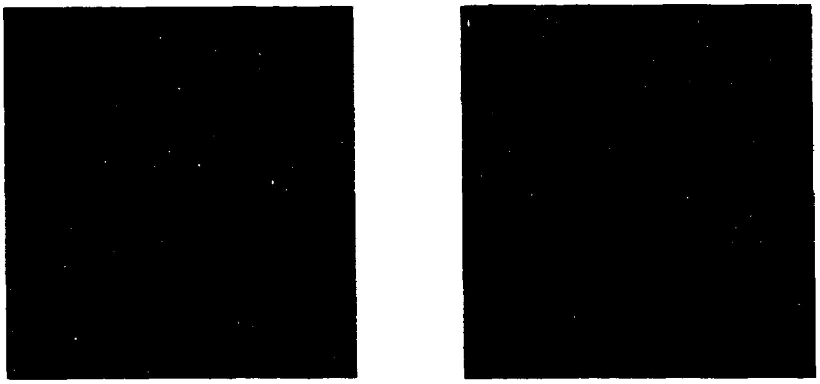
The grid values from generic high (the superior layer or surface) are subtracted from the inferior, or lower layer (genericlo). This results in a grid that has positive (red) and negative (green) values, which can be reclassed into a coverage with just positive or negative values (Figure 14b and 14c).

To test the topological relationship between elements of the two grids it is necessary to convert the non-topological grid to a topologically capable vector dataset. As discussed earlier the grid data are discontinuous and, as is inherent in the grid data structure, lacking in topology. The creation of a

Figure 14 Matrix manipulation for the Generic High Data Set



14a) Generic high data set prior to application of the congruency filters.

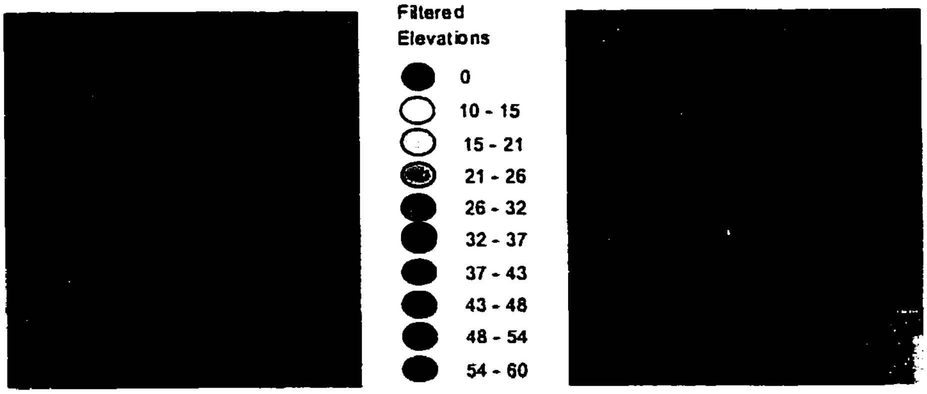


14b) Positive congruency filter

● Negative (0) ● Positive (1)

14c) Negative congruency filter

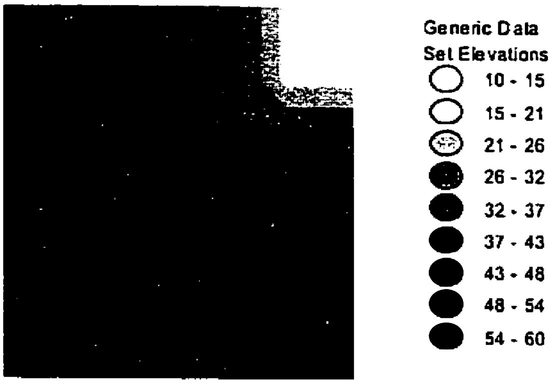
● Positive (0) ● Negative (1)



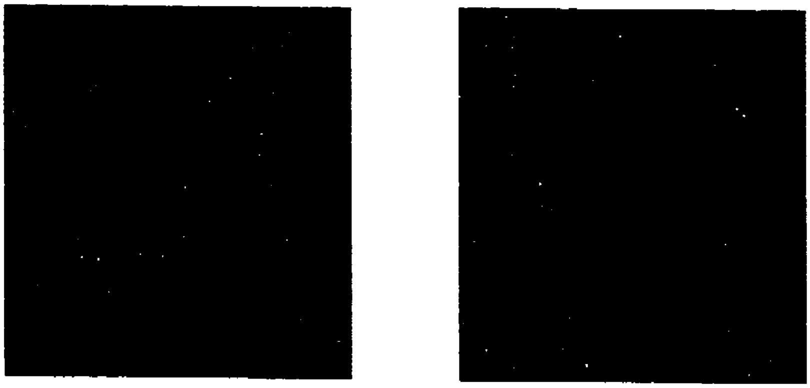
14d) Product of the Positive congruency filter applied to the generic high data set.

14e) Product of the Negative congruency filter applied to the generic high data set.

Figure 15 Matrix manipulation for the Generic Low Data Set



15a) Generic low data set prior to application of the congruency filters.

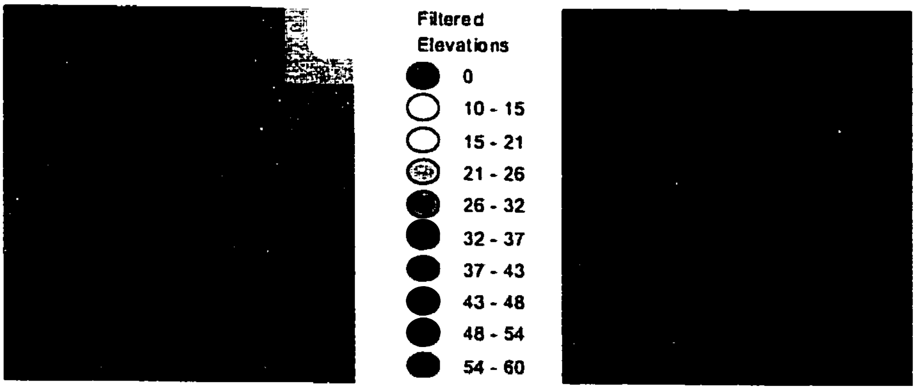


15b) Positive congruency filter

● Negative (0) ● Positive (1)

15c) Negative congruency filter

● Positive (0) ● Negative (1)



15d) Product of the Positive congruency filter applied to the generic low data set.

15e) Product of the Negative congruency filter applied to the generic low data set.

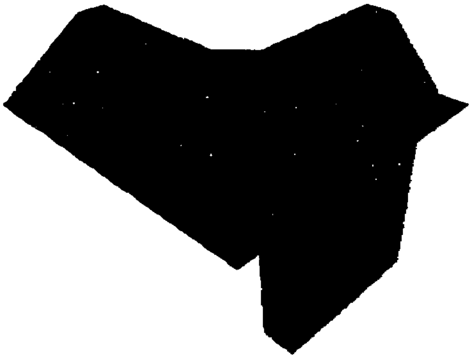
shape file coalesces the individual grid cells of similar values adjacent to each other. This process creates polygons that hold the same values as did each of the individual grid cells. Once this topological reordering has taken place it is a straightforward task to check whether a particular area is within the positive or negative region of the superior layer. If it is in the positive area these data must be eliminated from the TIN creation process for the superior surface or retained for the inferior surface. Using the topology of the two vector covers it is possible to reveal the areas where the superior surface cannot logically lie beneath the inferior surface.

The following illustrations show this in the generic data set case. Figures 14d, 14e, 15d,and 15e are the representations of the surfaces created from filtering the grid data. Figure 16a shows the superior surface, 16b the inferior surface. Figure 16c shows the net superior surface.

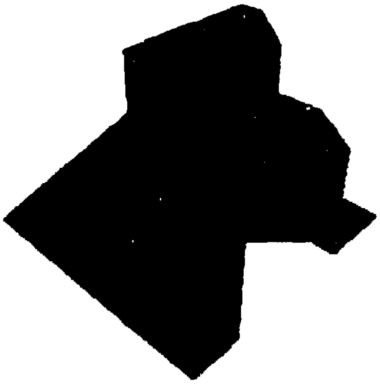
One final step must be completed before subsequent geological units can be added to the model. A new inferior surface (Figure 16d) must be generated, one that is a composite of both the old inferior layer as well as the old superior layer. The portion of the inferior layer that lies beneath the

Figure 16 Comparison of Generic Data Set Surfaces

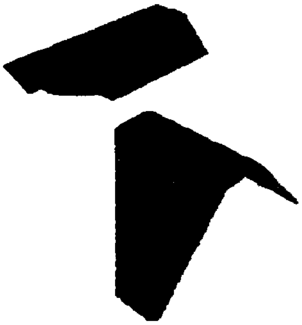
The illumination is from an apparent sun azimuth of 225 degrees with a 30 degree sun altitude.



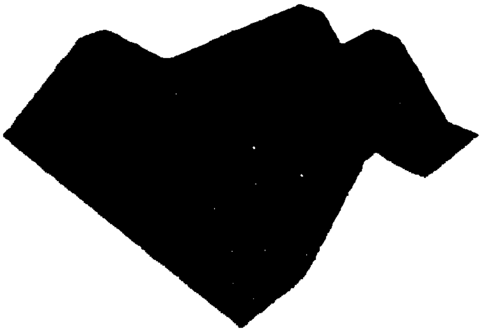
16a) Inferior Negative Surface
A TIN representing the product of applying the negative congruency filter to the generic lowdata set, the inferior surface.



16b) Superior Positive Surface
A TIN representing the product of applying the positive congruency filter to the generic high data set, the superior surface.



16c) Net Superior Positive Surface
The portion of the superior surface that is entirely superior to the generic low data set.



16d) New Inferior Surface
Combination of Net superior and net inferior grids.

superior portions need not be carried along into the new surface as it does not add data, and can, in some cases substantially overtask the computers ability to manipulate the necessary data.

As the process is applicable to both the inferior and superior surfaces it will be described for the inferior surface and implied for the superior (the only difference being the change in polarity of the congruency filter from positive to negative). To create the required surface, the values required from each TIN must be preserved while discarding the areas submerged beneath the uppermost regions. As the software is unable to do this in the vector format TINS are generated from the grid of the superior surface data. The inferior surface already has the required grid from the previous generation cycle, and this grid is used again. To concatenate the two data sets requires that the areas to be preserved are left with their original cell values, whilst the areas beneath the superior surfaces are calculated to have a zero (0) elevation value (Figure 16a). These vector (and topology capable) data sets are now converted to a grid data set, the two data sets then being added one to the other as seen in Figure 16d.

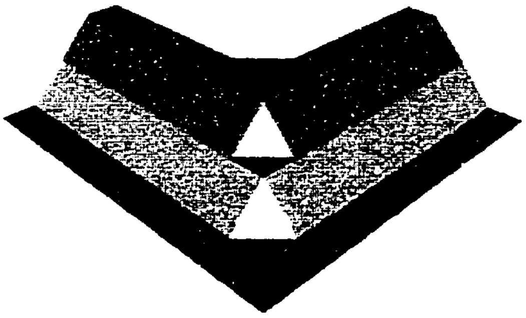
The final step in the model generation process is the creation of an isopach map showing the thickness of the geologic unit being modelled. This final data representation requires the subtraction of the inferior surface grid from the just generated combination of superior and inferior grids. The difference of these two matrices will result in a final matrix with the differences in elevation between the superior surface and the inferior surface (Figure 17).

Figure 17 Isopach Creation

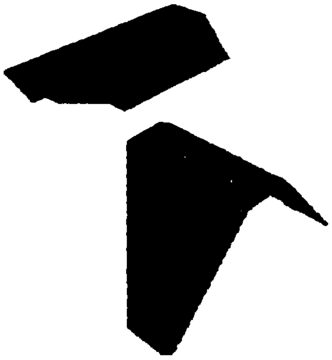
Elevation (metres)

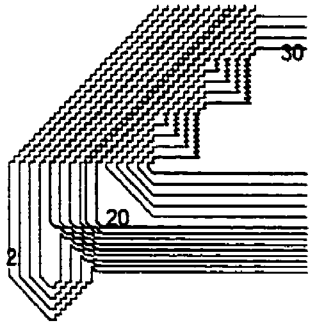
●	10 - 20
○	20 - 30
▨	30 - 40
○	40 - 50
▨	50 - 60
○	60 - 70

17a) The inferior surface

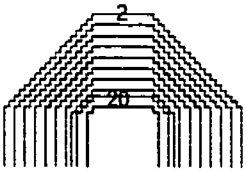


17b) The net superior surface





17c) The resulting isopach data



The 2 metre interval contours appear unnaturally angular as a reflection of the gridded data set.

RESULTS:

The application of the model to the data collected by Manitoba Hydro

For the purposes of modelling, each rock unit (consisting of lithological and positional data) is categorized into four basic groups or lithostratigraphic units. These geologic units are igneous, metamorphic, sedimentary and unconsolidated rock (Table 1). Each of these units will be modelled, beginning with the lowest (most inferior) and then accumulating the consecutively higher (superior) units, with the previous unit controlling or constraining to some degree the morphology of the superior layers.

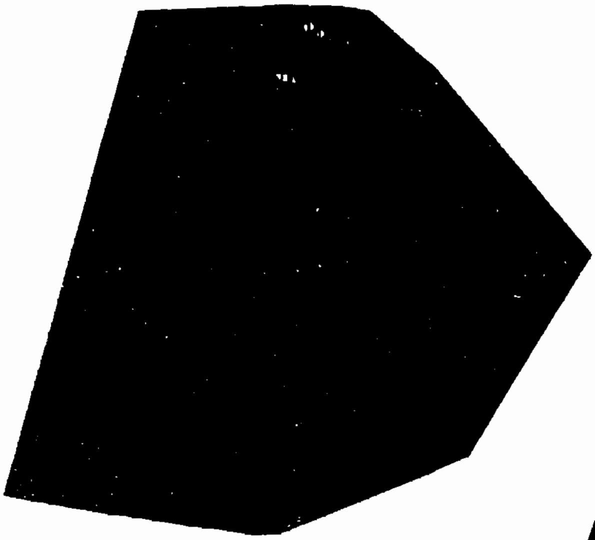
The data required to begin the modelling process are grids generated from TIN surfaces calculated from the contacts of the assorted lithological groups. For application of the model the igneous, sedimentary and unlithified surfaces will be used.

To create a surface the highest contact of a particular geologic unit is selected. In the selected sample there are 414 unlithified contacts, 279 sedimentary, 3 metamorphic, and 335 igneous. As there are multiple contacts of a geological unit only the highest contact will be chosen from each borehole. Each subsequent geological unit will have a surface generated.

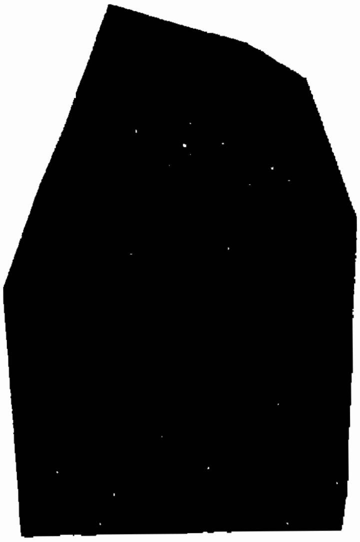
The highest top for each geologic unit was selected from each borehole and a TIN was generated. These TINs, their filenames in brackets, are Unlithified (Figure 18a) (*top_unlithif*), Sedimentary (Figure 18b) (*top_sediment*) and Igneous (Figure 18c) (*top_igneous*). The geological unit metamorphic had insufficient contacts and was eliminated from modelling.

Each of these TINs were in turn converted to grids (Table 2). These grids were then compared against the subaerial surface, any portion of the grid exceeding, or protruding above the subaerial surface would have the TIN modified appropriately.

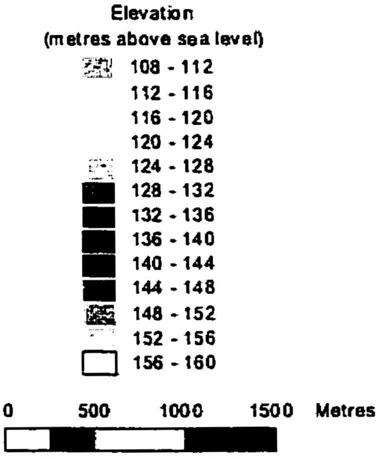
Figure 18 TINs for the Three Modelled Geological Units

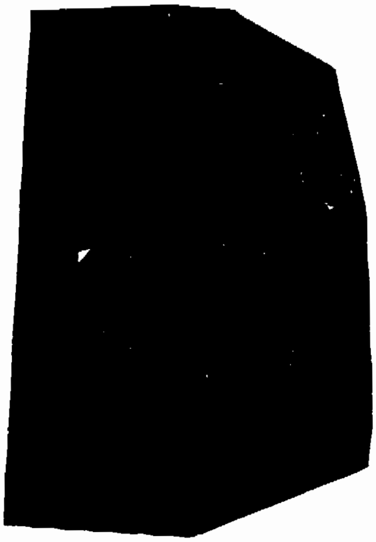


18a) Unlitihfied Geological Unit



18b) Sedimentary Geological Unit





18c) Igneous Geological Unit

Table 1 Preparation of Lithostratigraphic layers

Observed Rock Units	Geologic description	Rock Unit Modelling Designation
AMPH	Amphibolite	Metamorphic
B/R	Bedrock	Igneous
BLDR	Boulder	Unlithified
BOULDER	Boulder	Unlithified
CBLS	Cobbles	Unlithified
CH	High plasticity clay	Unlithified
CI	Intermediate pl. clay	Unlithified
CL-ML	Borderline class	Unlithified
DIABASE	Diabase	Igneous
Gabbro	Gabbro	Igneous
GM	Silty gravel	Unlithified
GNEISS	Gneiss	Metamorphic
GP	Clean sorted gravel	Unlithified
GP-GM	Borderline class	Unlithified
GRANITE	Granite	Igneous
GRANODIO	Granodiorite	Igneous
GREYWKE	Greywacke	Sedimentary

Table 2

Source TIN	grid cell size (metre)	rows and columns	Grid created
GUll5lt300	10	368X 403	Gul5subair
top_unlithif	10	185X185	Untithifd_top
top_sediment	10	163X166	Sed_top
top_igneous	10	169X157	igneous_top

The modelling process

Step 1 Creating the initial grids

Each stratigraphic unit has the uppermost contact selected, these contacts are interpolated into a gridded data set. The 5 metre grid cells are interpolated using an inverse distance weighted 12 nearest neighbours interpolation routine provided by the software.

The data that begins the modelling process are the grid data sets derived from the lithological contacts as described (G_sedi1, G_igne and G_unlith).

Step 2 Subtracting the inferior grid from the superior grid

The superior grid cells (populated with the elevation values) have subtracted from them the elevation values of the horizontally congruent inferior grid cell. This results in a grid which has values for the cells that each grid has in common, and null values for the areas of the two cells which are not congruent. The resultant grid for the difference between the sedimentary layer and the igneous layer is the grid data set *Sedminusigne.*

For other than the initial two surfaces the subtraction becomes somewhat more intricate. The two surfaces referred to as inferior and superior are not consistently above or below the other surface; the label inferior or superior referring to the assumed depositional precedence not their respective elevation. The TINs used to create the grid surfaces interpolate between the existing borehole data with no consideration of the other surfaces being generated. This would of course not happen in the real world, deposition necessarily occurring over pre-existing geologic units. To approximate this sequential depositional environment, the portions of the superior surface that descend below the defined surface of the most inferior surface (in this example, that of the igneous lithological group) are excluded from the modelling of the superior surface and are removed from the data set in the next step (See Figure 13). Subsequent lithological surfaces would follow, with a combination of the inferior and superior surfaces of the previous two lithological groups combining to become the 'inferior' surface which would control the next superior surface. This sequence of inferior controlling superior concatenation into a new inferior surface controlling the next superior surface continues until the subaerial surface is encountered. This surface is another dominant control in the surface generation process, for it is a measured absolute. The assorted accumulated surfaces must conform to the measured data, and thus this subaerial surface controls the morphology of the inferior surfaces.

Step 3 Creating the congruency filters: Reclassing the positive and negative values into two categories

All of the positive values are reclassed to 1, the negative values reclassed to 0 creating a positive congruency filter (*pos_cong*). This grid is then converted to a shapefile, (*Pos_cong.shp*), for later use. Reclassifying the data in the converse fashion (negatives reclassed to 1 positive values to 0) creates a negative congruency filter.

Step 4 Applying the two congruency filters to the two surface grids: differentiating the superior surface from the inferior surface

Creating a surface immediately beneath the superior surface developed in Step 3 requires that the portion of the inferior surface vertically congruent beneath the superior surface be identified. This surface is identified in the same fashion that the superior surface was filtered out from the entire data set. To create the vertically congruent inferior surface the negative congruency filter is applied to the inferior surface. To create the isopach map of the layer delimited by the inferior and superior surfaces requires that the vertically congruent inferior surface be identified. To identify the subsequent layers above the superior layer the segment of the superior surface above the inferior surface as well as the portions of the inferior surface that were above the superior surface must be combined to form the new 'inferior' surface for the next lithological category. In defining the vertically congruent inferior surface segment the same congruency filter is applied (the positive congruency filter). To identify the portions of the inferior surface which are not vertically congruent with preserved portions of the superior surface the negative congruency filter is applied to the inferior surface.

The positive congruency filter (created in step 3) is multiplied against the superior discrete grid data set (See Figure 18a). This results in a grid where the cells of the superior layer that would be beneath the inferior layer, are calculated to 0. The remaining cell values retain their original elevation values (*sedi_net*).

The negative congruency filter (from step 3) is multiplied against the inferior discrete grid data set (See Figure 19b), resulting in a grid of 0 values and cell values retain their original elevation values. The grid cells that are inferior to the superior surface (the cells with negative values, the value that places them below the superior surface, having been reclassed the previous step) (ingnexneg).

Step 5 Removing data noise from the grid data sets

The application of the congruency filters creates grid cells which have elevation of 0 (i.e. all the superior grid values are beneath the inferior surface) which will cause considerable clutter in later analysis. While the positive elevations retain their original values, the zero value pixels are reclassed to 'NULL'. Reclassing to NULL removes the pixels from the data set and thus will not be included in any further modelling iterations. It also reduces the size of the data file.

Figure 19
Sedimentary Isopach

Only the boreholes that contributed to the bounding surface generation for the Sedimentary geological unit are shown here.

Projection: UTM zone 15 NAD27
Data: Manitoba Hydro, 1991

0 500 1000 1500 Metres

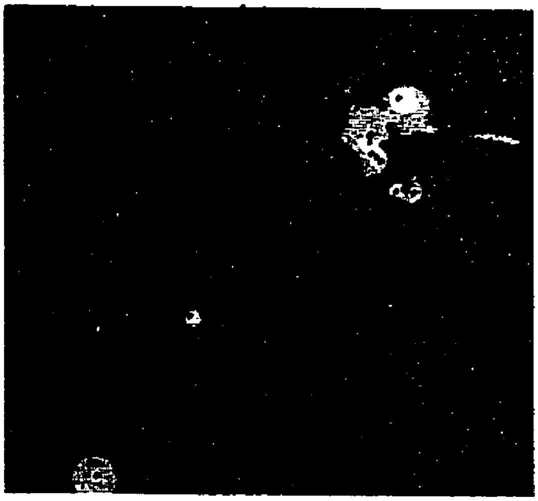


Figure 19a Igneous Geological Unit Grid

Geological Unit Data Points

- Geologic unit contact

Elevation (msl)
▨ 108 - 112
□ 112 - 116
□ 116 - 120
□ 120 - 124
▨ 124 - 128
■ 128 - 132
■ 132 - 136
■ 136 - 140
■ 139 - 140
■ 144 - 148
▨ 148 - 152
▨ 152 - 156
□ 156 - 159

Figure 19b Sedimentary Geological Unit Grid

Positive Congruency Filter
■ Negative Values (0)
■ Positive Values (1)

Figure 19c Positive Congruency Filter
(Sedimentary Layer)

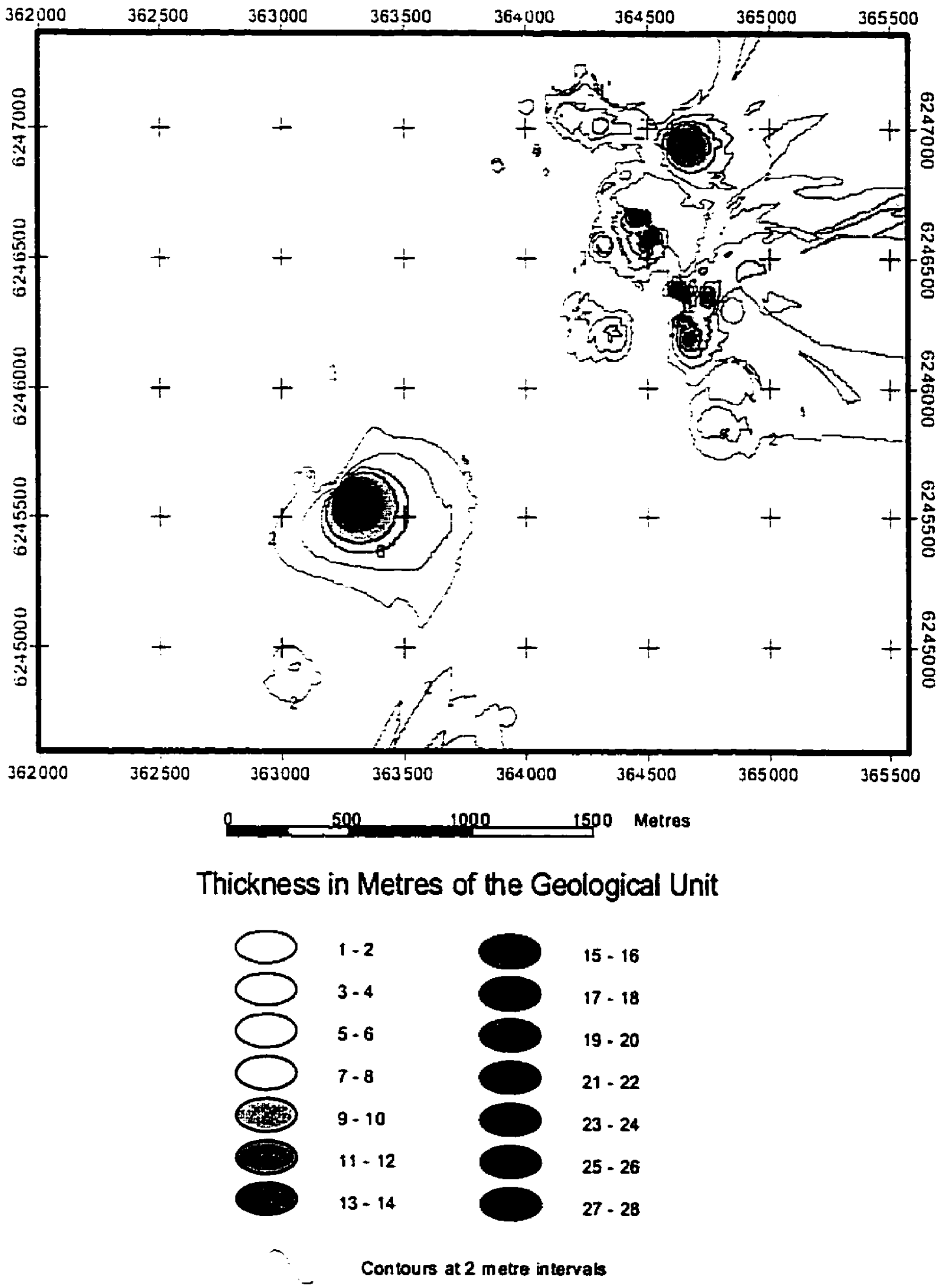
Step 6 Deriving the layer thicknesses

The remaining congruency filtered surfaces are subtracted, inferior from superior, to derive the differences in elevation of the respective layers. These differences are the thickness of the layer bounded on the upper surface by what has been referred to as the superior surface. Therefore the thickness of the geological unit bounded by the superior layer has been derived.

Step7 Generating the isopach lines for the derived thicknesses

Isopach lines are interpolated from the derived grid from Step 6, generating an isopach map (See Figure 20).

Figure 20 Isopach Map for the Sedimentary Geological Unit



Data: Manitoba Hydro, 1991
Projection: UTM Zone 15, NAD27

DISCUSSION AND CONCLUSIONS:

When this work began in the early 1990s, the hardware and software capabilities were a fraction of what is now available. This writer had explored many hardware and software options, consulting with people from the utilities industry and from software developers. In total, four different software platforms and three different computers were acquired and modelling attempted on them. There was even a period of collaboration with one ephemeral software developer to create software suitable to accomplish the modelling goals of this thesis. It was as St-Onge identified *"This ideal, although easily conceived, is rarely if ever achieved because of either conceptual or practical problems"* (St-Onge, 1981). The modelling desired was conceptually very easy to imagine. It proposed to develop bounding surfaces for a particular geologic unit, and determine the difference between them in the creation of an isopach map. Easily said, easy to picture, not even that difficult to sketch on a piece of paper, but to create a computer based system that can interpolate the connectivity and topology required to develop the answer to this query was not quite so simple. One of the greatest practical problems was selecting what data were germane to the modelling question.

Imposing order on the data was the first step to resolving these practicalities. Six concerns became apparent during the planning stage for the models:

1 *The incorporation of existing digital spatial data and the entry of lithostratigraphic, and other aspatial, data into the GIS.*

Bringing the data into the GIS became considerably easier as the software evolved. Interpreting ASCII files into proprietary data structures gave way to robust importation procedures and intuitive data table editing interfaces.

2 *Cartographically legible presentation of the geological units for interactive graphic selection from the data set.*

The graphical and ad hoc querying environments developed along with the increased capabilities and capacities of the computer platforms on which they operated. Queries that once took 45 minutes to run and to redraw the display on the initial computers can now be conducted in around 20 or 30 seconds with the current computers. ESRI having adopted a standard database management software package provided an intuitive interface that many users will already be familiar with. This familiarity reduces the time spent learning the software; time which may more productively be spent doing research.

3 *The process for the interpretation of the surface of a geologic unit presumed to exist between data points.*

Having the lithostratigraphic units generalized into four geological units presented the modelling process with some difficulties. In many cases, the boreholes had multiple instances of the same lithologic descriptor interspersed with others. A process to deal with this interleaving of apparently identical phenomena had to be established.

4 *How to resolve topological conflicts such as intersection or piercing of one layer by another.*

The surface generation process for each geological unit modelled the surface defined by the contacts for only that geological unit. These surfaces would often have portions that would be beneath logically inferior surfaces. In the absence of more detailed petrologic descriptions of the lithostratigraphic units, it was decided that the inferior surface would control what the upper, or superior, surface would look like (See Figure 13).

5 *The calculation of a volume between adjacent surfaces and the cartographic presentation of the volumes.*

Once the bounding surfaces had satisfactorily been deciphered, volumetric calculations can be made on the particular geological unit. The representation that is of particular interest is the isopach map.

6 *The need to prepare cartographic representations of the resultant data or information resulting from analysis of the models.*

While the bounding surfaces allows for the calculation of volumes, the creation of the absolute thickness model is what this modelling was specifically undertaken to accomplish. To generate the isopach maps requires the determination of the difference in elevation of the two vertically congruent cell values from each bounding surface. The resultant isoline map is somewhat harsh in appearance because the contours follow the edges of the grid cells, creating an angular 'unnatural' appearance. Experimentation with generalizing routines and grid cell size may result in more aesthetically pleasing contours while minimizing loss of data fidelity.

With these six concerns in mind, developing a system to generate isopach maps was undertaken. It is to be hoped that with this system researchers will be able to more fully concentrate on research and not on the methods or technologies needed to provide answers. For example, instead of focussing on how to ask a query to minimize data processing time, the researcher can focus more on preparing data, or focus on interpreting the information derived from the models.

One of the main difficulties of this project was the condition of the spatial and aspatial data. The topographic data were not topologically clean, having missing, duplicated or improbable elevation values. An example of the topological confusion of the spatial data would be contour lines that have multiple z values associated with them. Some of the contour lines would have segments that would have z values that are not only inconsistent with the surface they are representing but also with neighbouring segments of the same line. The large volume of aspatial data was of frustratingly dubious utility, due to inconsistent data quality controls. Missing values and lack of referential internal integrity made it necessary to carefully validate individual records as well as the entire series for the borehole specified by the records. An illustration of one of the problems with the aspatial data is that field descriptions of the petrology were rudimentary with insufficient detail provided to more effectively correlate the geologic unit data across the boreholes.

While methods of interpreting the lithology are beyond the scope of this work, it should be noted that these geologic designations must be sufficiently descriptive to allow the modelling process to represent what is being described. Vague descriptions will not allow the cartographer to portray data with any degree of fidelity. For example, it would be difficult to distinguish which cylinder of rock matches a corresponding cylinder of material from an adjacent hole if the fieldworker uses inconsistent descriptors or provides insufficient detail. This shortcoming of the project data collection process is seen repeatedly throughout the project data sets, with the fieldworker using insufficient descriptions, preventing the modeler from being certain if the geology being grouped, is in fact, from one geologic unit. It should be clarified that the field descriptions do not have the level of analysis that would provide more thorough petrologic distinctions to be made. The uncertainty of the field descriptions often prevented reliable lateral correlations of geological units.

Field data were not collected with the idea of conducting three-dimensional modelling. So it is not surprising that some adaptations have to be made and that some considerations allowed in the final product. While there are shortcomings with surface models developed, the methods can be applied to better data as they become available or to similar data collected for other tasks.

In the initial stages of developing the model procedures it had been hoped that the linear data as provided by the EM or seismic surveys could have been incorporated into the data modelling. Two factors kept these data out of the models. One factor was the arbitrary vertical exaggeration assigned to the representations of the traces and the second was the inability to register the trace data to a physical location. The use of GPS receivers mounted on sensors would certainly eliminate this type of problem from future data collection efforts. Once these positional and representational concerns have been addressed, EM or seismic sensor data can be incorporated into better defined surface models. A correlation between the EM and seismic surveys with the modelled surfaces would strengthen the reliability of any analysis that could be done with these surface models. Having multiple data sets with complimentary information would increase the reliability of the surfaces being generated. The information derived from modelling the point source borehole data would be greatly enhanced by data correlation from linear data, such as provided by the refraction seismic or EM surveys.

As discussed earlier, the concept replicating the traditional representation methods is one of the goals of this project. Computer aided cartography is a methodology that is well established. Recreating the interpretive capability of the hardcopy map is of course a minimum requirement of any new system. By itself, recreating the traditional cartographic component is not a particularly interesting task; of interest, the addition of analytical capabilities. During writing of the thesis there were many occasions where the methodologies being developed could have been applied to other tasks. Some examples of such tasks follow.

The need for estimating timber volumes before and after harvest is a continuing concern of the forestry industry and related government agencies. The before and after volumes of standing timber for measures of harvested lumber could be determined by the methods discussed here. This volume could be estimated using LIDAR (Light Detection and Ranging) data collected before and after the harvesting.

During the spring of 1997, bathymetry was of large concern of colleagues working on minimizing the impact of the Red River spring flooding. The isopach creation methodology developed here could readily have been applied to quickly creating bathymetry from the impromptu sonar and depth finding tools used in that crisis. The ease with which point data, such as that gathered in boreholes or during the 1997 flood, or surface data, (LIDAR imagery or the geological rock unit TINs), can be converted into isoline information enables the geologist, forester or evacuation personnel to better perform their tasks.

Another avenue the author is presently exploring is in bathymetric mapping of freshwater lakes in southern Manitoba. Knowledge of the bounding planes of a geologic unit is not unlike developing a bathymetric map. The isolines that conveyed absolute thickness in the thesis modelling can, given one planar surface (such as a lake surface) to work from, be interpreted as lines of depth.

The ease with which these models can be generated will assist the visualization process by providing a more easily interpreted view of the three-dimensional object than the traditional two-dimensional representations. The analytical modelling capability relies on computer software sufficiently sophisticated to interpret the location of the boundary surfaces of each geologic unit. Being able to determine where the surface is allows the calculation of volumes between two vertically congruent surfaces. As additional borehole data, or indeed any type of point or surface data, become available, it will be possible to use them to refine the surfaces generated. The method is robust enough that it should be applicable to tasks other than geologic modelling.

One of the practical limitations the geographic, or more specifically the geologic, modeller has had is the plethora of data available. The large quantity of data requires that the modeller develop strategies to interpret and manipulate large datasets. The incrementally increasing capability of the software and computer platforms is easing technological limitation of dealing with these sizeable data sets. Increasing the ability of the researcher to be able to cognitively interpret the vast quantity of data has not kept pace with the increases in data processing capability. Innovative applications of the capabilities available in the software, such as the interpretation model this thesis presents, give the researcher another tool to aid in that cognitive process. As has been observed earlier "...visualization is ...an act of cognition..." (Antle, 1999). This model aids in that cognitive act. Tools such as these will contribute to the training of new interpretive skills, increasing the researchers abilities and capacities to understand the phenomena at hand.

APPENDICES:

APPENDIX 1A Data Format for DH_INDEX.DB

Field identifier	Data Type	Field Dimension	Example of data stored
Point Identification	ASCII	8	G-0008
Northing	ASCII	8	6246851
Easting	ASCII	7	363883
Elev	ASCII	4	141
Bearing	ASCII	7	N27.9E
Plunge	ASCII	6	-45
Hole Depth	ASCII	5	58.01
Top of Bedrock	ASCII	7	13.11
Loc Station	ASCII	7	*this field empty**
Loc Offset	ASCII	6	*this field empty*
Start Date	ASCII	7	91-6-6
End Date	ASCII	7	91-6-7
Location Note	ASCII	20	GR-4/GR-5 Powerhous~
Method	ASCII	19	Diamond

*denotes that the actual data field contains no data

APPENDIX 1B Data Format for DH_LAYER.DB

FIELD IDENTIFIER	DATA TYPE	FIELD DIMENSION	EXAMPLE OF DATA STORED
Hole Number	ASCII	8	G-0008
Depth Layer Top	ASCII	5	0
Depth Layer Base	ASCII	5	0.25
Elev Layer Top	ASCII	5	141.5
Elev Layer Base	ASCII	5	141.2
Layer Thick	ASCII	5	0.25
Blank1	ASCII	1	*this field empty**
Layer Matl	ASCII	8	PT
Layer Group Name	ASCII	5	*this field empty*

*denotes that the actual data field contains no data

APPENDIX 1C Data Format for DH_WATER.DB

FIELD IDENTIFIER	DATA TYPE	FIELD DIMENSION	EXAMPLE OF DATA STORED
Point Identification	ASCII	8	G-0295
Northing	ASCII	7	6248338
Easting	ASCII	6	365293
Null	ASCII	0	*this field empty**
Bearing	ASCII	6	-----
Plunge	ASCII	4	-90
Elev G/S	ASCII	3	*150*
Elev Datum	ASCII	3	150
Null	ASCII	0	*this field empty**
Datum Description	ASCII	20	Top of Pipe
Datum Stickup	ASCII	3	0

*denotes that the actual data field contains no data

APPENDIX 1D Data Format for DH_FROST.DB

FIELD IDENTIFIER	DATA TYPE	FIELD DIMENSION	EXAMPLE OF DATA STORED
Hole Number	ASCII	8	G-0281
TOP DEPTH	ASCII	7	1.2
LENGTH	ASCII	5	2.9
Null	ASCII	0	*this field empty**
P/F TYPE	ASCII	12	*Vs
GROUND TEMP	ASCII	4	null
PERCENTAGE ICE (%)	ASCII	3	40

*denotes that the actual data field contains no data

APPENDIX 2 Data conversion and validation

1 The data from the DH_INDEX.CSV are ported from the source format of a comma delimited ASCII file (*.csv) to an ArcView native (.DBF) format

2 The data from DH_LAYER.CSV and DH_TESTS.CSV contain formatting errors that prevent an import directly into ArcView as the above data file so they are imported into Microsoft Excel 5.0 and from there exported to the required *.DBF form and then imported into ArcView.

3 DH_WATER.CSV, DH_TESTS.CSV, DH_FROST.CSV were treated in a similar fashion.

4 Headers were included at the top of each 'page' in the text files, these non-data values were selected from the data set and deleted (the column headings were incorporated as proper headings during the import procedure)

5 Three fields from DH_INDEX.dbf were selected to create a shape file of the boreholes positions and their identifiers

6 An avenue script was used to create the borehole shapefile (id_x_y.shp) converting an ASCII file exported form the DH_INDEX database (using fields; Point, Northing and Easting).

7 Once the shape file was created the id_x_y.dbf and DH_INDEX.dbf were temporarily joined so that the elevations could be appended to the borehole position data. Nine hundred seventy six of the twelve hundred ten boreholes had elevations, the balance were maintained as borehole sites but necessarily were omitted from any further surface creation

8 Hole G-2111 had a northing about 400 km north of the study area and was omitted from consideration of this study area.

9 Hole G-0019 had an northing about 3600 km south of the study area and was omitted. This may be an example of a typographic transposition error of the first two digits.

10 These 36 boreholes while in the database had no eastings or northings associated with them, and where excluded from the modelling process.

G-0438 G-7300 G-7301 G-7302 G-7303
G-7304 G-7305 G-7306 G-7307 G-7308
G-7309 G-7310 G-7311 G-7312 G-7313
G-7314 G-7315 G-7316 G-7317 G-7318
G-7319 G-7320 G-7321 G-7322 G-7323
G-7324 G-7325 G-7326 G-7327 G-7328
G-7329 G-7330 G-7332 G-7333 G-7334
G-0257S2

11 A field (Mapsheet) was added to the index positional data file (DH_INDEX.dbf), this was to allow associating the boreholes with their respective mapsheets

12 Boreholes that did not fall with in the area represented by the topographic data were coded “not in area”, in the mapsheet field, and excluded from the study area and any surface creation process

13 Boreholes not within the study area remain in the data set but are filtered out of the modelling process

14 Gull05 mapsheet has several data deficiencies, all the point data have an elevation of 0, the contours lines have no elevations associated with them and a graticule imposed on the drawing detracts from the visual clarity of the data available.

15 To associate elevations with this mapsheet’s contours several steps were taken that differ from the previously described process.

16 Contours and point data from the adjacent mapsheets are the primary elevation indicators, where there are sufficient point sources these determine the elevations of the contours, when these are unavailable the contours of the adjacent sheets are used to indicate the elevation for contiguous contours. Only mapsheet Gull04 had useable point and contour data; the adjacent sheets Gull06, ...08,...09 had no useable elevation data. Some of the text fields for these sheets had elevation recorded these were used as a last resort if no other elevation data could be found or interpolated.

17 To use the borehole head elevation as 'point heights' for contour interpolation, a field was added to the id_x_y.dbf (contour) to group the elevations into the 2 metre contour intervals used on the rest of the map sheets

APPENDIX 3 COMPACT DISK DATA AND PROGRAM FILE LOCATIONS

These data are presented in formats most suitable for ArcView 3.1. ArcExplorer has been provided on the accompanying CD to view data appropriate for this data viewer. The software and licence agreements are provided in the documentation in the ArcExplorer folder. Additional information on the installation and licensing of ESRI products are at http://www.esri.com.

Directorory of C:\Thesis\ArcExplorer

AE31JavaSetup.zip using-ae31.pdf

The source data and derived data files are stored on the compact disk associated with this thesis. If the directory structure is replicated all of the project files will open up the associated data files. No licensing of ESRI products is provided or implied here.

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