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COMPUTER-BASED PROCEDURES FOR CONSTRUCTING GEOLOGICAL MAPS:
An example from the Rocky Mountain Foothills in British Columbia.

by

Peter Charles Jahans

A thesis submitted to the Faculty of Graduate Studies
and Research in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
FALL, 1993

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled COMPUTER-BASED PROCEDURES FOR CONSTRUCTING GEOLOGICAL MAPS: An example from the Rocky Mountain Foothills in British Columbia submitted by Peter Charles Jahans in partial fulfillment of the requirements for the degree of Master of Science in Geology.

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ABSTRACT

Computer-based procedures were used to produce a 1:50,000 scale geologic map of a 1,460 km^2 area in the Rocky Mountain Foothills of northeastern British Columbia. Topographic and geologic data obtained in digital form from various sources were transformed and placed in databases. A computer program was written to digitize traces of faults, axial traces of folds and stratigraphic contacts on 21 large-scale maps. Computer files containing data from 14,922 outcrops were obtained. Digitized data and outcrops referenced to the older NAD27 datum were be converted to the newer NAD83 before being used. Computer programs were written to perform this conversion and to convert between geographic and Universal Transverse Mercator coordinates. Two other programs were written to obtain outcrop elevations from TRIM digital elevation models. Spreadsheet procedures were used to select outcrops for display. Two commercial software packages were used throughout the project for 1) structural analysis, and 2) interactive drafting and display of the final maps.

In the map area, the foothills are characterized by northwesterly trending folds and southwest dipping thrust faults, and are divided into inner and outer belts. Two distinct stuctural styles are observed: 1) in the outer belt, exposed strata, belonging to the Gates and younger formations, are gently folded, and 2) in the inner belt, exposed strata, belonging to the Moosebar and older formations, are more tightly folded. The outer and inner belts are separated by a detachment in the upper Moosebar Formation. A 5 km^2 klippe of the younger, less highly deformed strata occurs in the inner belt.

ACKNOWLEDGEMENTS

This project was undertaken with the support of the British Columbia Ministry of Energy, Mines and Petroleum Resources and is a continuation of the B.C. Geological Survey Branch's 1:50,000 scale geological mapping program in the Peace River coalfield. I received a summer contract to undertake field mapping in 1991, and a B.C. Geosciences Research Grant. The author wishes to thank Ward Kilby and John Cunningham of the B.C. Geological Survey Branch for their invaluable advice and discussion throughout the project.

During the course of this study I was the beneficiary of several Teaching Assistantships and a Graduate Appointment (Research) from the University of Alberta.

Outcrop data were generously supplied by Bruce Wrightson of Gaia Resources, Calgary, Alberta. Dr. Yves Beaudoin advised me in some of the more complex mathematical techniques and stimulated my interests in all aspects of computing. Dr. Philippe Erdmer kindly provided laboratory and computing facilities during the latter stages of this study. Thanks also go to Kevin Yakiwchuk for his able-bodied field assistance, and to Byron Vellieux and other fellow grad students for lightening the load of academic work through friendship and diversion.

Dr. Henry Charlesworth is especially thanked for his guidance, criticisms and tireless support. His door was always open and assistance was offered at every turn. Finally, my deepest gratitude goes to Cindy for her love, encouragement and monumental patience while I spent many evenings and weekends behind the computer or away from home.

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CHAPTER 1

INTRODUCTION

The main objective of this thesis was to use computer-based procedures to produce a 1:50,000 scale geologic map of a 1,460 square kilometre area in the Rocky Mountain Foothills of northeastern British Columbia. This area covers NTS areas 93O/9, 93O/10 and 93P/12 (Figure 1).

Geographical information was obtained in the form of digital TRIM (Terrain Resource Information Management) files, which contain topographic, cadastral, drainage and cultural data. Geological data came from 3 sources: 1) outcrop data collected by the author, 2) outcrop data in ASCII files provided by Gaia Resources of Calgary, Alberta, and 3) traces of stratigraphic contacts, faults, etc. displayed on 21 maps in the Coal Files of the British Columbia Geological Survey.

Two software packages, QuikMap and Tripod were used extensively throughout the project. QuikMap is a Geographic Information System/Computer Aided Drafting program for displaying and interactively drawing maps in various projections. Tripod is a program for analyzing outcrop and drillhole data and for displaying these data in different kinds of graphical output format.

The computer-based procedures used during the project were as follows:

1) use of QuikMap to determine eastings and northings of outcrops located in the field;

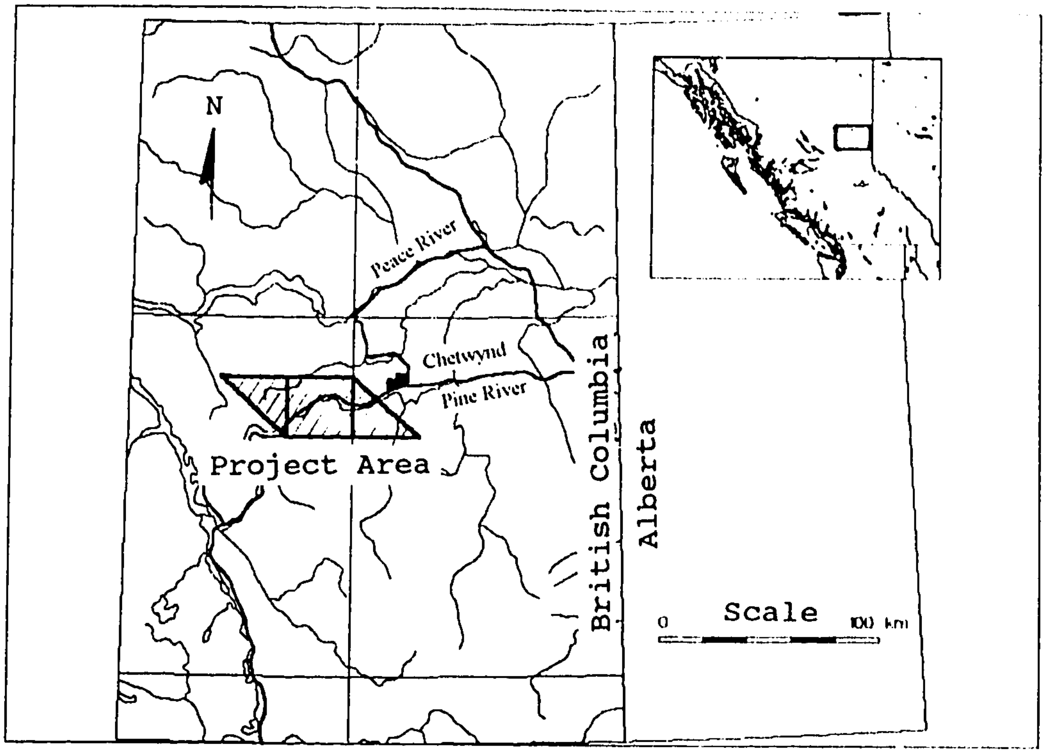

Figure 1. Map showing the location of the study area.

2) use of a digital elevation model to determine the elevations of outcrops located in the field and outcrops in the Gaia ASCII files;

3) digitization of the traces of stratigraphic contacts, etc. displayed on Coal File maps;

4) transformation of outcrop and trace locations from the NAD27 datum and various projections to the NAD83 datum and the Universal Transverse Mercator projection;

5) structural analysis of orientations;

6) selection of outcrops to be displayed on the geological map;

7) generation of QuikMap files which, when plotted, produce the final maps.

Chapter 2 of this thesis describes the data used for the study. Chapter 3 contains a description of the main computer-based procedures used during the project. Many of the details of these procedures have been placed in appendices. Chapter 4 is a description of the geology of the study area. The final geological maps involved some interpretation on the part of the author, so this chapter contains a brief structural analysis of the study area. Chapter 5 summarizes the work carried out during the project and draws conclusions concerning the usefulness of computer-based procedures in generating geological maps.

CHAPTER 2

DATA COLLECTION & STORAGE

Introduction

The map area is located in the Rocky Mountain Foothills of northeastern British Columbia near the town of Chetwynd. Lying between latitudes 55° 30' and 55° 45', it is bordered on the west by the Rocky Mountains and in the east by an arbitrary line marking the limit of significant deformation. The area is generally covered by thick vegetation except for the highest ridges in the west, and is divided in two by the east-flowing Pine River. Access to most of the area is good, made up of a network of logging and drilling roads, cut-lines, seismic lines, and transmission line roads. Elevations in the map area range from about 600 to over 1900 metres.

Stott (1982) published a 1:500,000 scale regional geological map of northeastern British Columbia. Earlier maps by Hughes (1967) and McKechnie (1955) were also published at scales of 1:500,000. There are no previously published 1:50,000 scale maps of the area. Detailed mapping on larger scales was carried out by several coal and petroleum exploration companies within their respective leases from the late 1960's until the mid 1980's. The maps and reports documenting these independent geological studies are now located in the Coal Files of the British Columbia Geological Survey. Stratigraphic nomenclature used here is based on that of the Geological Survey of Canada.

The steps taken in data collection and storage are illustrated in a flow chart (Figure 2). The arrows in the flow chart indicate the data paths and the processes are shown as labelled boxes. At the end of the collection stage, three databases were obtained which were used in map construction. Outcrop data were contained in a QuikMap database, the structure of which is similar to a table made up of rows and columns. Rows are called records, each record representing one outcrop, and each record is divided into fields which make up the columns in the table. All the information about an outcrop, including its number, lateral coordinates, bedding orientation, map symbol, symbol color, and formation or horizon code are contained in these fields. Traces from the Coal File maps were stored in a database of similar structure but designed to also hold strings of consecutive coordinates in each record representing a line. The outcrop data in the Tripod database are similar to those in the Quikmap database.

Lateral coordinates of outcrops and traces obtained from Gaia and Coal File sources were referenced to an older surveying system and had to be converted to the system currently in use before being incorporated into the databases. Elevations for all outcrops had to be calculated and stored for use in producing temporary working profiles of complex areas and in structural analysis. The methods used to transform lateral coordinates, and find elevations are described in Chapter 3.

Field Data

Mapping during the 1991 field season concentrated on areas with little or no coverage on existing detailed maps. Coverage is generally good near the Pine River and in most of the western parts of the 93P/12 and 93O/9 map sheets. Means of

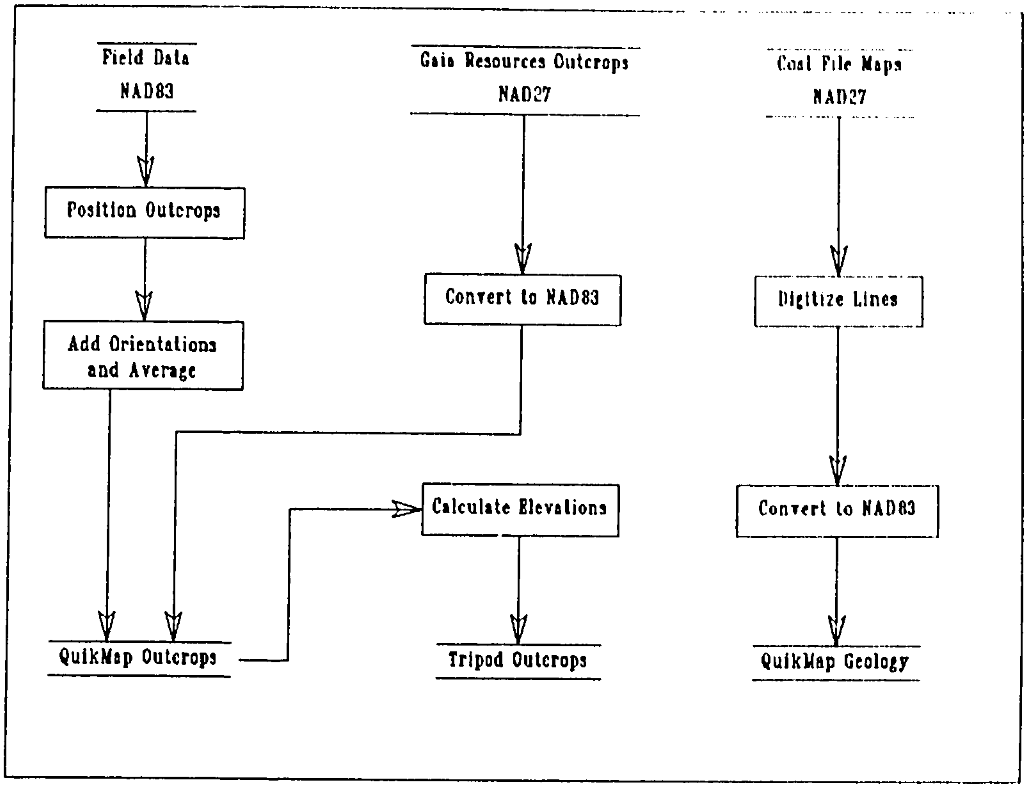

Figure 2. Flow chart indicating the paths followed during the data collection and storage stage. The three sources of data are at the top of the chart. Arrows show the directions that data flow leading to three intermediate databases at the bottom of the chart.

transport was by four-wheel-drive vehicle, mountain bicycle, helicopter, and hiking on foot. Aerial photographs were used for navigation, for plotting outcrops in the field, and in geological interpretation.

Outcrop data were recorded in field notebooks and locations were plotted on aerial photographs in the traditional way. At the end of each day, outcrop data were entered into a temporary QuikMap database using the mouse and digitizing tablet as interactive pointing devices. This procedure automatically assigned lateral coordinates to each outcrop. Small areas were magnified to enable accurate positioning to within a few metres. An identification code associated with the formation exposed at the outcrop was assigned to each outcrop at this stage. The temporary database was designed to hold traces of contacts and faults for preliminary geological interpretations of each day's field work. These were added to the database by progressively extending geological contacts or fault traces interactively on the screen into areas in where new outcrops had been entered. At the end of the mapping season, the temporary database contained about 250 outcrops and several traces of stratigraphic contacts and faults which were referred to during final map preparation.

Once data from all 250 outcrops had been entered into the temporary QuikMap database, they were exported to a plain text file. This file was edited to record the orientation measurements associated with each outcrop. Elevations at each outcrop location were determined (see Chapter 3) and placed in the text file which was subsequently imported into a Tripod database for analysis. The average orientation for each outcrop was calculated by Tripod and colors were chosen to represent the various formations. The data were then exported to a permanent QuikMap database to be used in the map compilation stage. Using different colors for each formation assisted correlation of geological units when displayed on the computer screen. The C++ program dBFile was written to create a permanent QuikMap database from Tripod's format, and to extract outcrop data from QuikMap for input into Tripod. For each outcrop, the appropriate dip symbol and its display angle was automatically determined by the program from the mean orientation of bedding at the outcrop.

Gaia Data

Eastings, northings and bedding orientations for 14,922 outcrops were obtained from Gaia Resources in the form of ASCII files. Most of these data had been digitized from maps contained in the Coal Files. Coordinates were referenced to the older NAD27 datum and had to be converted to the newer NAD83 datum (see Chapter 3). Some outcrops were located outside the study area. The program dBFile was used to append those outcrops lying within and immediately surrounding the study area to the permanent QuikMap database. Elevations for all outcrop locations were determined and were included with the outcrop data which were subsequently appended to the Tripod database.

Coal Files Data

Detailed geological maps of 21 areas were obtained from the Coal Files and data from these maps were incorporated into this study. These maps were of various scales and included only those areas leased by the various companies (see Appendix F for a list). Geological contacts, fault traces and axial traces of folds were digitized from the Coal File maps and stored in text files as large collections or strings of consecutive point coordinates. These strings were then imported into a second permanent QuikMap database designed to hold linear map data. As with outcrop symbols, lines could be assigned color, style and thickness attributes appropriate to the feature being represented.

Topographic Data

A topographic map provides an appropriate base upon which to draw a geological interpretation. The government of British Columbia provides its most up-to-date geographic information in the form of digital TRIM files (Terrain Resource Information Management), which contain topographic, cadastral, drainage and cultural data. Using QuikMap, TRIM data were converted into a base map with topographic contours, roads, rivers, etc., and displayed on the computer screen, printer or plotter as a backdrop on which graphical geologic data could subsequently be drawn. Base maps at various scales were also plotted for use in the field and provided the most current information available on roads, bridges and cutlines.

CHAPTER 3

PROCEDURES

As stated previously, computer-based procedures were used at all stages of the project. Three of these procedures, namely, 1) digitization, 2) datum and projection transformations, and 3) determination of outcrop elevations, involved considerable programming. Programs were written in Pascal, C or C++, based on the suitability of a language's constructs for implementing the various algorithms.

Digitization

A Pascal digitizing program was developed to capture and store data for use with QuikMap and Tripod. This program employs an affine transform to translate, rotate and change the scale of coordinate data and to correct for distortions in the maps which accumulated through repeated use and errors in reproduction.

Geometrical transformations of map coordinate data are operations which alter some spatial relationships while others remain unchanged. For example, distances and angles may be altered but straight lines remain straight (Loudon et al, 1980). Transformation of spatial data from one frame of reference to another is required in order to produce maps or cross-sections which can be presented, stored or manipulated on a video screen or plotted at any scale on an output device. A map is distorted to a degree if it is not perfectly rectilinear. This type of distortion is due to paper stretching or inaccurate reproduction and should not be confused with the distortions inherent in map projections.

A geometric illustration of the affine transform used in the digitizing program is shown in Figure 3. Matrix algebra is used in the equivalent computer implementation (see Appendix A). First, the X and Y coordinates of any four calibration points are digitized and their respective map values are entered to calculate a transformation matrix. Thereafter, digitized X and Y data are converted to map coordinates when post-multiplied by the transformation matrix (Loudon et al, 1980).

Datum and Projection Transformations

Two main problems encountered when digitizing data from geological maps are: 1) how to convert the coordinates on older maps to those compatible with newer maps and 2) how to acquire elevations for outcrop locations. The procedure for obtaining elevations is described below. The first problem occurs when data from old and new maps are to be combined. Prior to 1990, most maps in North America used a coordinate system based on a datum which is no longer considered accurate, no longer used in government surveys or maps, and is incompatible with coordinates referred to a new datum which has been adopted throughout North and Central America. Further explanation requires a brief introduction.

Ellipsoids and Datums

For very large scale maps, the earth's surface may be considered flat. Geologic mapping at scales less than 1:5000, however, require a more precise model of the earth to achieve accurate lateral positioning. The earth approximates an oblate ellipsoid which can be represented in a computer model as an ellipse rotated about

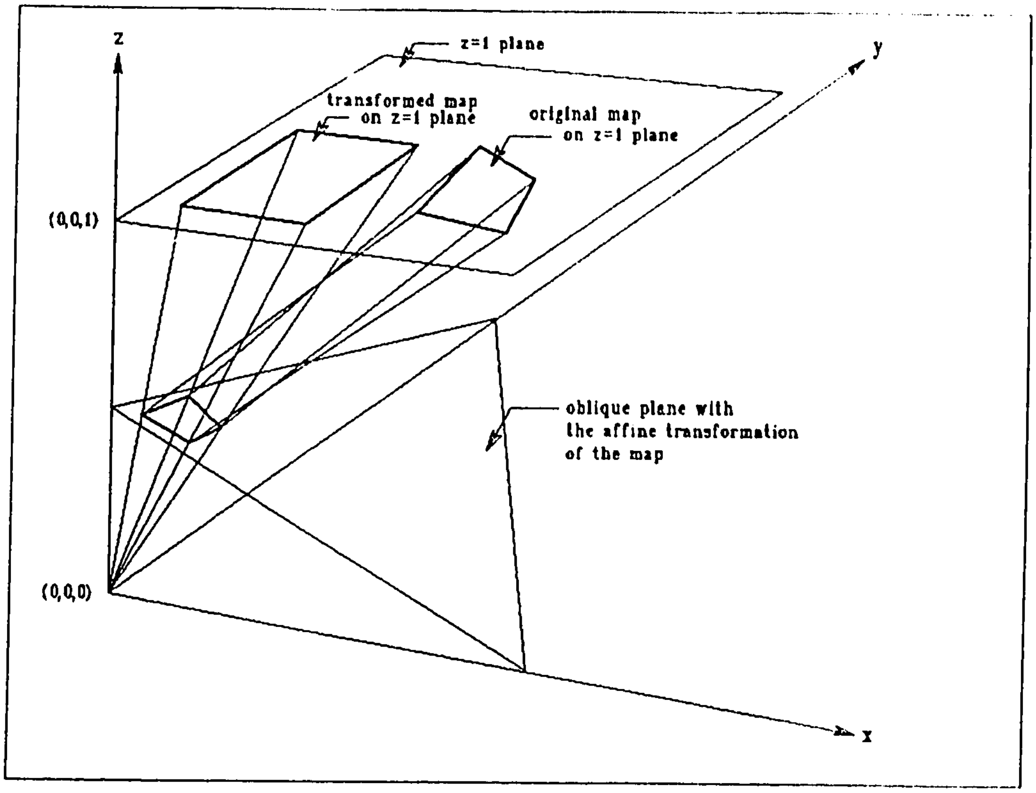

Figure 3. The affine transform used in map digitization is graphically illustrated. Coordinates are post-multiplied by the transformation matrix (see text) which is represented by refraction through the oblique plane. The transformed values of X, Y and Z can be regarded as homogeneous coordinates corresponding to vectors passing through the origin. Although the transformation occurs in three dimensions, both the original and transformed maps exist only in two dimensions on the z = 1 plane. Adapted from Loudon et al, 1980.

its shorter axis. The exact shape of this principal or reference ellipsoid depends on the dimensions given to its semimajor (a) and semiminor (b) axes. By convention, ellipsoids are uniquely described using the semimajor axis (a) and the flattening (f) where

$$f = \frac{a - b}{a}$$

Many principal ellipsoids are used today around the world not only because of differences in the accuracy of geodetic measurements but also due to irregularities in the curvature of the earth's surface. Ellipsoids are commonly designed to fit the earth's shape over only a particular continent or country. The axes of an ellipsoid, although parallel to, may not coincide with the axes of the geoid, and the centroids of an ellipsoid and of the earth are often offset (Figure 4). The ellipsoid adopted for use in North America was calculated by the British geodesist Alexander Ross Clarke in 1866, has an equatorial radius (semimajor axis) of 6,378,206.4 metres, and an approximate flattening of 1/294.9787 (Snyder, 1982).

Once an ellipsoid has been chosen, a point of reference is selected from which a datum, a smooth mathematical surface representing mean sea-level, is constructed. The datum provides the surface to which all survey control points are referred; the geographic (latitude and longitude) coordinates of any point on the earth's surface are computed relative to the datum. During the five years between 1927 and 1932 all available survey control data in North America were compiled into a system known as the North American Datum of 1927 (NAD27). It is based on the Clarke 1866 ellipsoid and has as its point of reference the station at Meades Ranch, Kansas (Snyder, 1982). For over fifty years, most maps constructed in North America were

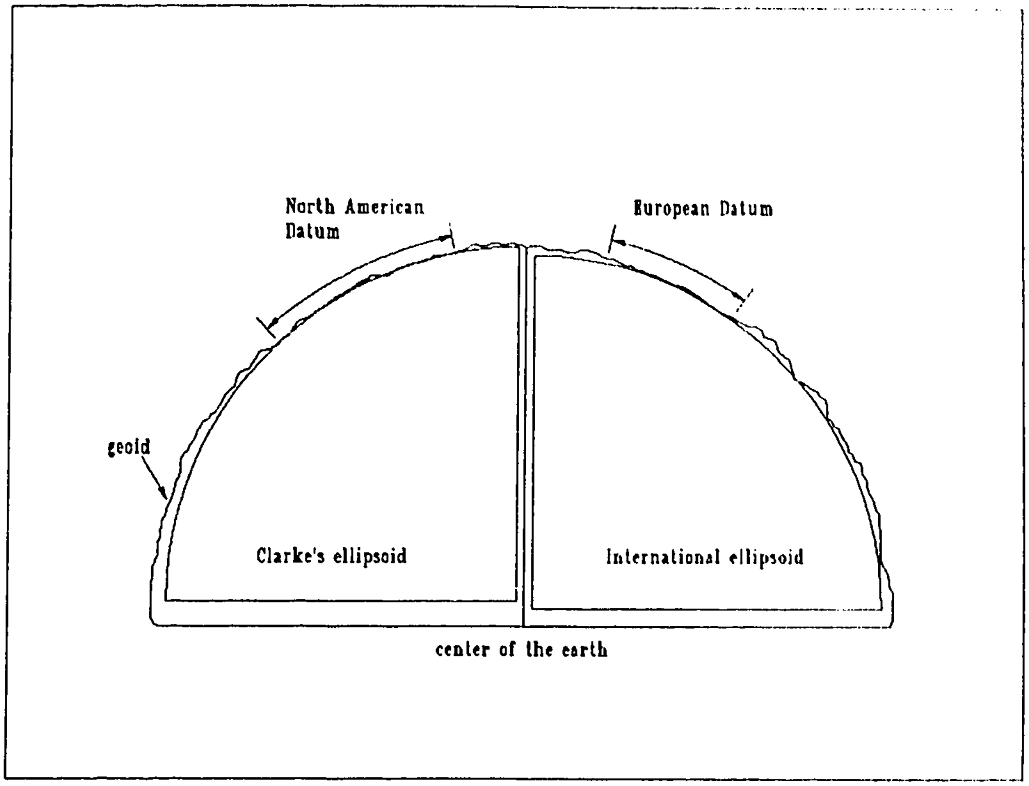

Figure 4. An exaggerated cross-section of the upper hemi-sphere of the earth's geoid and two principal ellipsoids. The axes of these ellipsoids do not coincide with those of the geoid and their centres are offset. Many principal ellipsoids are designed to fit the earth's shape over only a particular continent while geocentric ellipsoids are meant to cover the entire globe. Adapted from Morgan, 1991.

based on NAD27.

Because of 1) earlier surveying inaccuracies, 2) distortions which developed as the NAD27-based survey control network was built up over time, and 3) horizontal tectonic movements in some areas of North America of up to 5 cm per year, the Committee on the North American Datum concluded in 1971 that an adjustment was needed. Canada, the United States, Mexico, Greenland, and the countries of Central America agreed to recompute and readjust the coordinates for all survey control networks and to redefine the datum upon which they are based. With the accuracy of satellite measurements, a new geocentric ellipsoid, known as the Geodetic Reference System 1980 (GRS80), was adopted (Morgan, 1991). Its semimajor (equatorial) axis is 6,378,137 metres long and flattening is 1/298.2572. Instead of a single control point, a best mean fit to satellite and terrestrial observations was used to position and orient the various survey control networks. The resulting North American Datum of 1983 (NAD83) provided a distortion-free, earth-centred coordinate system spanning the continent which coincides with that of global satellite positioning systems.

In 1990, Energy, Mines and Resources Canada announced the adoption of NAD83. The effect of this was to change geographic coordinates of all surveyed points by varying amounts. Coordinates in British Columbia, for example, were changed by +0.1 to -1.1 arc-seconds (+3 to -34 metres) in latitude and by +3.5 to +6.7 arc-seconds (+70 to +120 metres) in longitude. The vast majority of position data for mining and petroleum geology in North America, such as lease boundaries, property lines, well and outcrop locations, are based on NAD27. Government survey data and legal documentation now use the NAD83 system. Because location data referred to one datum are not spatially related to those of another, one set of coordinates must be transformed before combining with the other. Where map projections such as UTM are used, the coordinate shifts are even greater, as described below.

Datum Transformations

Mathematically transforming coordinates from one datum to the other imposes an impractical computational burden on small computers (Farley and Junkins, 1991). For this reason, and to provide a simplified and consistent method of transformation, the Geodetic Survey of Canada provides a table of shift values which represents the difference in eastings and northings between NAD27 and NAD83 at regularly spaced intervals. This table, known as the shift grid, is constructed by calculating the difference in geographic coordinates between the two datums at every node of a grid superimposed onto a map of the country. Grid spacing is 5 minutes in both north-south and east-west directions, corresponding to about 9.5 km and 5.5 km, respectively, within the study area. Any point can be transformed by applying an amount of shift which is interpolated from the four surrounding nodes (Figure 5). The C program NADCONV converts geographic coordinates between NAD27 and NAD83 in either direction (see Appendix B). The program first scans the grid file for the four closest nodes surrounding the input coordinate, then employs a bilinear interpolation on the values at these nodes to estimate the amount of shift. This value is either added to or subtracted from the input coordinates depending on the direction of conversion.

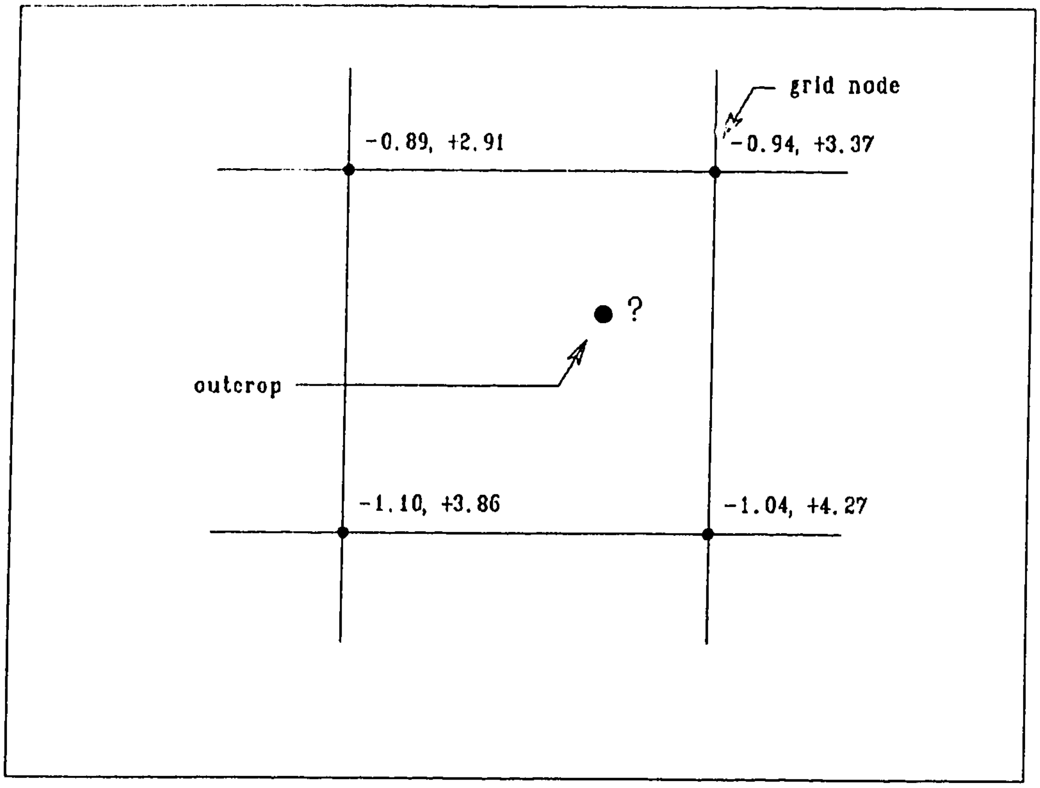

Figure 5. A portion of the shift grid is shown with latitude and longitude offsets between NAD27 and NAD83 in arc-seconds at each node. To determine the correct shift to apply to a random outcrop, a bilinear interpolation between the four surrounding nodes is performed.

Map Projections

Producing a map of all or part of a curved surface on a flat sheet cannot be accomplished without distortion of one form or another. Map projections were developed to reduce the effects of distortion by choosing the characteristic to be shown accurately at the expense of others, or by compromising between several characteristics (Snyder, 1982). The projection most used for geologic maps is some form of Transverse Mercator which is equivalent to wrapping a cylinder around the ellipsoid of the earth so that it touches a longitudinal meridian throughout its length (Figure 6). A commonly used variation on the Transverse Mercator is the Universal Transverse Mercator (UTM).

The UTM projection transforms spherical geographic (latitude and longitude) coordinates into rectangular (cartesian) coordinates to form a grid which can be drawn on a flat sheet (Figure 7). The UTM grid features 60 zones, each of which has an angular width of 6° longitude, extending between the polar regions. Each zone is divided along its length into sections 8° in height and labelled with a letter of the alphabet. Each zone has a central longitudinal meridian which lies halfway between its two bounding meridians. The scale factor along the central meridian is constant at 0.9996 but is subject to increasing error with increasing distance to the east or west of it (Snyder, 1982). The origin of each zone is defined as the intersection of its central meridian with the equator. The X origin is set at 500,000 metres, and the Y origin is set at zero in the northern hemisphere, or 10,000,000 metres in the southern hemisphere. The X and Y coordinates and zone number are sufficient to locate a point anywhere in the world.

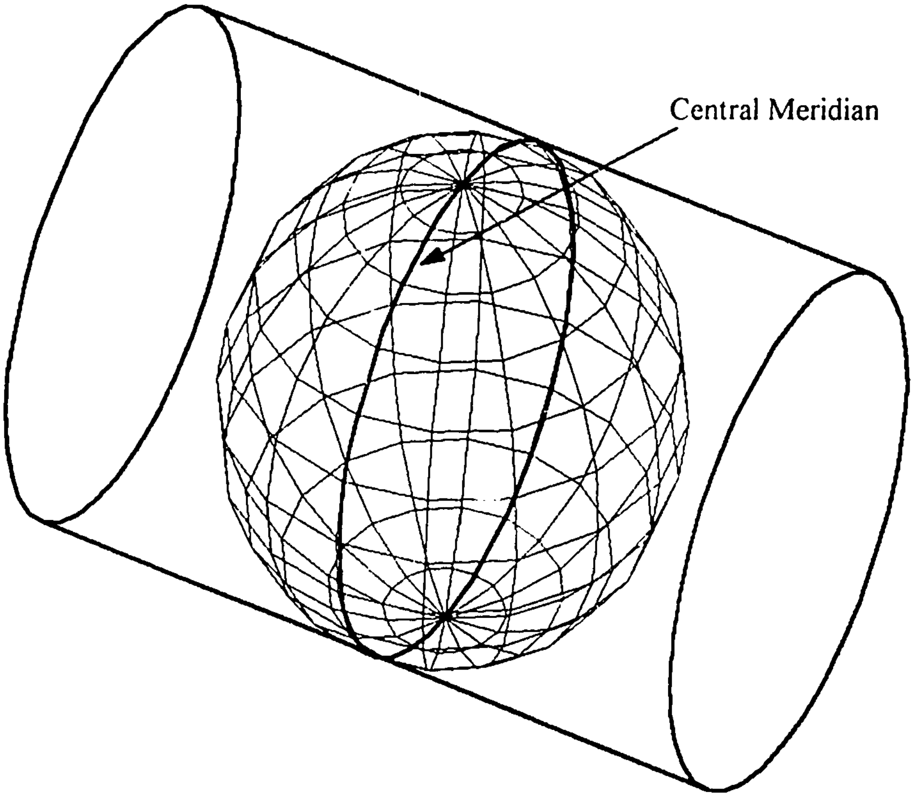

Figure 6. A wire-frame illustration of a cylinder surrounding the earth touching it only along a central meridian. Rays passing through the sphere from its centre to the inner surface of the cylinder produces a Transverse Mercator projection. Adapted from Snyder, 1982.

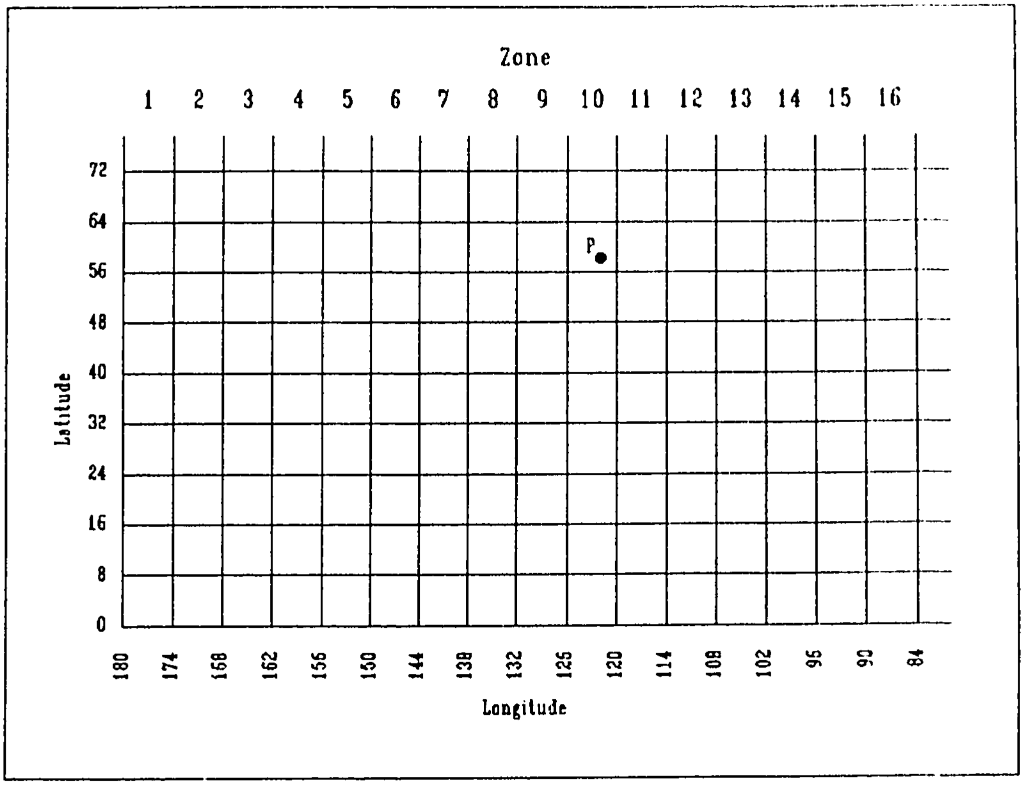

Figure 7. A portion of the Universal Transverse Mercator grid. Zones extend between the polar regions and have an angular width of 6°. P marks the approximate position of the study area located in Zone 10, which extends between 126° and 120° longitude, west of Greenwich, and whose central meridian is 123° longitude. Adapted from Snyder, 1982.

The same ellipsoid parameters used to define the datum are also used in projection equations. The combined effect of the change in geographic coordinates and the change in radius and flattening of the principal ellipsoid when converting between NAD27 and NAD83 results in the UTM coordinates being shifted to an even greater degree than geographic coordinates. In western Canada, eastings are shifted from -75m to -120m and northings from +175m to +215m when converting from NAD27 to NAD83.

Converting Older Data

The Coal File maps used in this study are NAD27 UTM projections. The traces of the geological contacts, faults, etc., were digitized to use in the final map compilation and the digitized outcrops were added to the QuikMap and Tripod databases. The extensive outcrop data obtained from Gaia Resources were also referenced to the older NAD27 UTM system. All the above data had to be converted to NAD83 before combining them with outcrop data from the field mapping which was referenced to the newer system. Because the older data were in UTM form, the error in lateral positioning, referred to NAD83, was of significant magnitude.

Before translating from NAD27 to NAD83 it was first necessary to convert the older data from UTM eastings and northings to ellipsoidal latitudes and longitudes to use with the shift grid file provided by the Geodetic Survey of Canada. For this purpose the C program GEO2UTM was written. The projection formulas for converting in either direction are given in Appendix C. Once the shifts were applied, the geographic coordinates were then converted back to UTM eastings and northings. Digitized geology, which are linear sequences of points representing geological contacts, faults, etc., were processed by QuikMap and entered into the line database. Outcrops were stored in the respective QuikMap and Tripod databases together with outcrop data collected during the field season.

Digital Elevation Models

The problem faced while digitizing geological maps was how to determine the elevation of each outcrop location. Detailed topographic data obtained from recent aerial surveys by the government of British Columbia are available from TRIM digital computer files. This format is based on the National Topographic System which is made up of 1:250,000 scale map sheets with designations like 93P, 87E, etc., each of which is further subdivided into 100 1:20,000 scale rectangles and given identification numbers such as 93P.051, 85F.100, etc.

TRIM data are available as a set of files for a particular 1:20,000 scale area, each file containing a different kind of geographic information. The topographic data used in this project come from "raw" digital elevation model (DEM) files which have not been contoured or interpreted in any way but represent actual spot elevations. Data contained in these files are stored in compressed binary format for space efficiency. Coordinates are in UTM eastings and northings referenced to the NAD83 datum.

Determining the Elevation of an Outcrop

To estimate the elevation at any outcrop location in the map area, it was necessary 1) to determine the closest three DEM spot elevations surrounding it, 2) to calculate the point-normal form of the equation of the plane passing through those three points, and 3) to solve for Z given the X and Y coordinates of the point on the plane. A TRIM DEM file is very large and can contain coordinates for over a hundred thousand points. The density of points is not constant and the points are randomly positioned throughout the map area. The term random in this context is not meant to infer a statistically random distribution but rather to indicate an unpredictable pattern. Finding the closest three points surrounding a given outcrop location could be time consuming because its distance to every point in the file had to be calculated.

To solve the problem, a two stage solution was developed. First, the C++ program TX sorts DEM coordinates into a doubly sorted 'box' order (McCullagh, 1982) enabling very fast retrievals of a cluster of surrounding points. Box ordering is achieved by initially sorting on northings, dividing the map area into east-west strips, then sorting each strip individually on eastings (Figure 8). If the map area is subsequently divided into north-south strips, the result is a rectangular grid or box array which serves an an index into the sorted DEM file.

Second, the C++ program TR retrieves the cluster of DEM points within the box at an outcrop location and within any immediate neighboring boxes up to a specified distance. The program then performs a Delauney triangulation on this cluster and determines which triangle contains the outcrop. The vertices of this triangle lie in a plane representing topography. Once the point-normal form of the equation of this plane is calculated, the elevation at the outcrop location can be linearly interpolated. Algorithms for sorting, triangulation and interpolation are

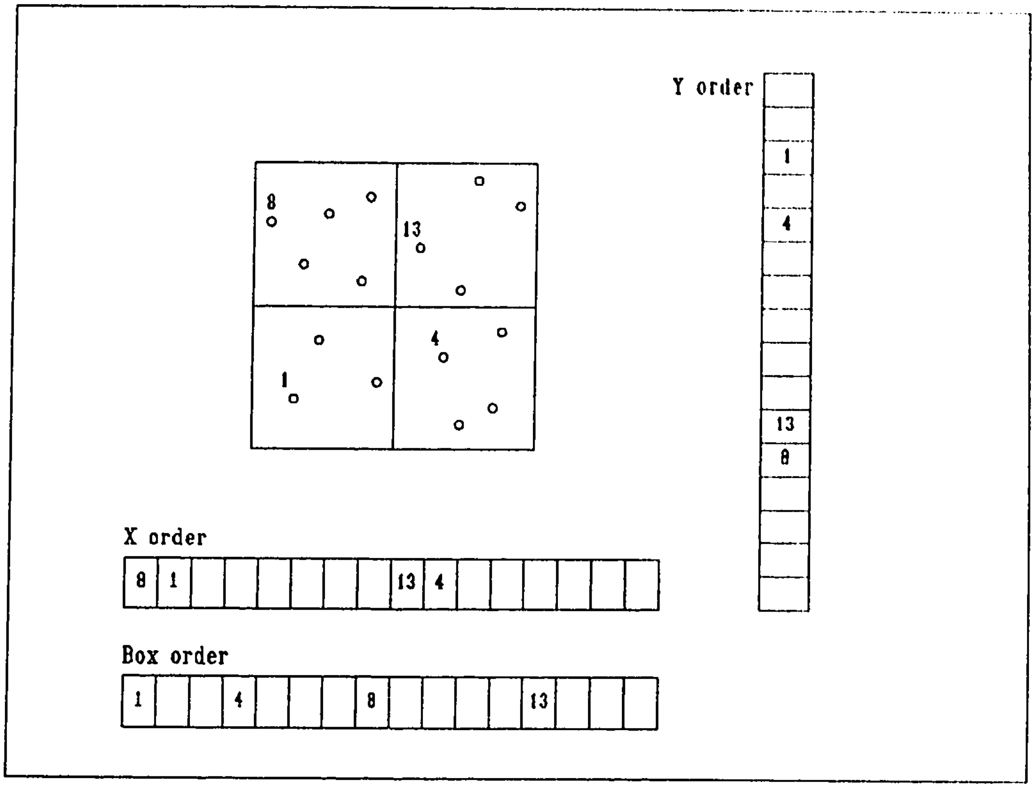

Figure 8. The box-ordered sorting method. Sorting initially along northings (Y order) and dividing the area into east-west strips, then sorting each strip along eastings (X order) and further subdividing produces a box-ordered sort. The index to the first (easternmost) point in each box is stored. This example has only four boxes for simplicity. When searching for a point in an area containing tens of thousands sorted into several hundred boxes, the index to the box containing that point is first determined and only that box is searched. Adapted from McCullagh, 1982.

described in Appendix D.

Map Compilation

At this stage, three separate databases contained all the compiled geological information about the map area. One QuikMap database contained geological contacts, faults and axial traces of folds digitized from older maps. Another QuikMap database contained outcrop data from current fieldwork and those digitized from older maps. A Tripod database contained the same outcrop data but included elevations interpolated from the TRIM digital elevation model. The steps taken to compile these data and produce the final map are illustrated in a flow chart (Figure 9). The three databases are represented at the top of the chart, data paths are shown by the arrows, and processes are identified by the labelled boxes. Three separate paths merge at the bottom as the final map is produced.

Outcrops

The first path in the flow chart shows the methods used to select representative outcrops for plotting on the final 1:50,000 scale map. Several statistical analyses were performed on the Tripod database to determine structural domains, and to calculate the mean orientation of fold axes and the degree of cylindricity in the map area. The scatter angle for each coordinate was also obtained. It was found that strata could be divided into two domains, upper and lower, each with its own structural character. Further interpretation of the results of these analyses are given in Chapter 4. The QuikMap outcrop database was imported into a spreadsheet

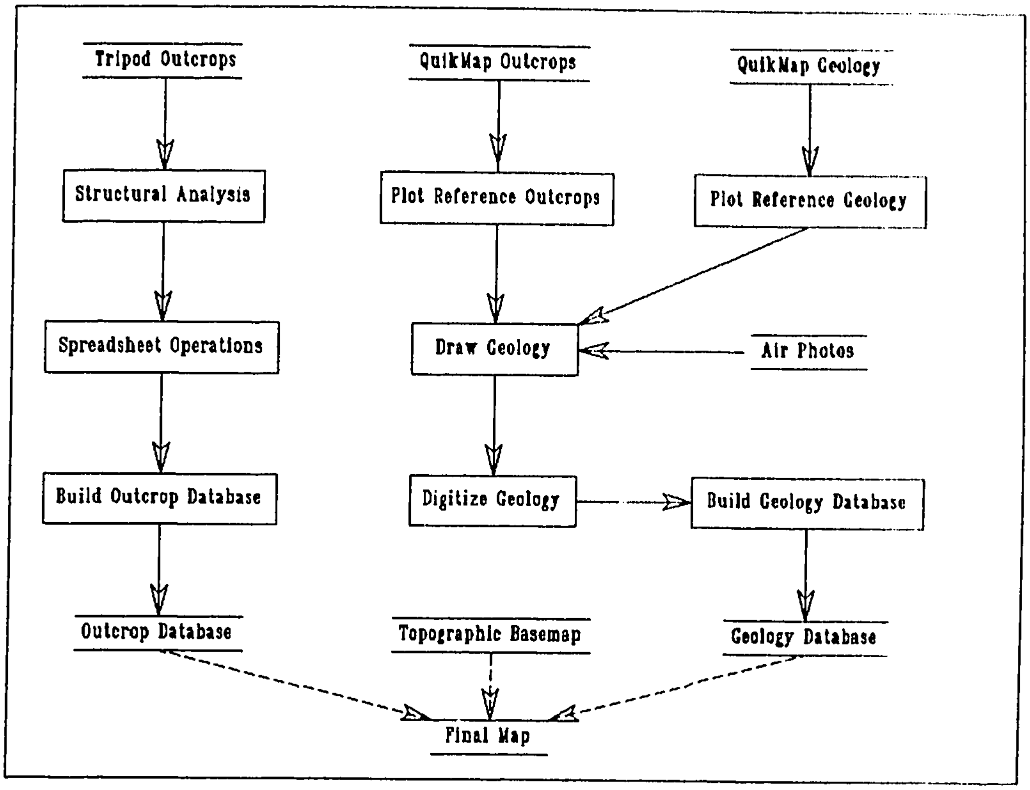

Figure 9. Flow chart indicating the paths taken to compile the geology map. The intermediate databases are at the top. Arrows show the directions that data flow leading toward the final databases and map.

program which allowed the selection or deletion of outcrops based on specified criteria. A scatter angle greater than or equal to 10 degrees was used as one criterion for deleting outcrops and thinning out the database. Another criterion was based on the east-west and north-south distances between outcrops. Those which were closer than 750m in easting and 250m in northing to another outcrop were deleted. For a detailed description of spreadsheet procedures, refer to Appendix E. After all editing was completed, the spreadsheet, now containing 1276 outcrops, was sorted by northings and exported as a new QuikMap database for use in plotting the final map.

Surface Traces

The second and third data paths on the flow chart illustrate the steps taken to produce geological contacts, fault traces and axial traces of folds by combining new field data with older digitized maps and air-photo interpretation. Preliminary maps showing all available outcrops and digitized traces of contacts, faults, etc. were plotted to scale. Using new field information and air-photos, the maps were checked, traces corrected if necessary and extended into areas previously unmapped. Only newly mapped areas or those which needed correction were actually redrafted; much of the older digitized geology was kept unchanged for use in the final map. When all drawing was complete, the new traces were digitized and combined with the older data into a new QuikMap database for final plotting.

Map Production

Topographic contours, roads, rivers, etc., from TRIM data were available in

QuikMap format. These were combined with the newly created outcrop and geology databases to produce the final map. Contours, outcrops and surface traces were each plotted to scale on separate mylar sheets which were screened and photographed separately, then overlaid for printing the paper copies. The database files were retained in digital form for archival purposes. The final map, made up of three 1:50,000 scale sheets covering the NTS zones 93P/12, 93O/9 and 93O/10, is enclosed in the map pocket.

CHAPTER 4

GEOLOGY OF THE STUDY AREA

Introduction

Situated along the eastern margin of the Cordillera, the map area lies within the Rocky Mountain Foothills of northeastern British Columbia. Most strata exposed at the surface belong to the clastic wedge sequence whose structure, at this latitude, is characterized by northwesterly trending folds and southwest dipping thrust faults (McMechan and Thompson, 1989). The author follows McMechan and Thompson in distinguishing inner and outer belts within the Foothills.

The Inner Foothills, underlying the western half of the map area, expose Jurassic to Lower Cretaceous strata and are characterized by broad synclines and narrow box and chevron style anticlines, and bedding dips steeply. The Outer Foothills, underlying the eastern half of the map area, expose Lower to Upper Cretaceous strata and are characterized by gentle, low-amplitude folds and dips which are generally less than 10°. The boundary between the Inner and Outer Foothills coincides with the main, easternmost outcrop of the Moosebar Formation which runs diagonally from southeast to northwest through the centre of the study area.

Marine clastics make up the Jurassic Fernie Formation and Lower Cretaceous Minnes Group. Marine to non-marine clastics alternate with marine shales to comprise the Lower to Upper Cretaceous Bullhead, Fort St. John and Smoky

Groups. Formation names and thicknesses with brief lithological descriptions are given in the Table of Formations (Figure 10).

Moosebar Detachment

A major detachment is situated in the shales of the approximately 30 to 300 metre thick Moosebar Formation. Above the detachment, strata belonging to the Gates and younger formations exhibit shallow dips, whereas those below and within the detachment, are much more tightly folded. The Moosebar Formation crops out for the most part along the boundary between the Inner and Outer Foothills. Thus the strata in the Inner Foothills occur below the detachment, those in the Outer Foothills above. The difference in structural style across the detachment is evident on the geological map (Figure 11). Traces of stratigraphic contacts in the Outer Foothills tend to parallel topographic contours whereas those in the Inner Foothills tend to cut across topographic contours at high angles. Axial traces of folds are closely spaced in the Inner Foothills, widely spaced in the Outer Foothills. Orientations of fold axes in the Inner Foothills often appear to vary slightly along strike, plunges may reverse direction and en echelon folds possibly occur. On a regional scale, trend is nearly constant and folding is considered cylindrical.

Using the Tripod database, pi diagrams showing distribution of bedding orientations for 1) Moosebar and older strata and 2) Gates and younger strata were prepared (Figure 12, a & b). Orientation measurements from 351 outcrops above the detachment form an elongate cluster, with most dips being less than 10°. Orientations from 1852 outcrops within and below the detachment form a girdle with dips ranging from gentle to vertical.

Series	Group	Formation/Thickness	Description
Upper Cretaceous	Smoky	Dunvegan 107-300 m	Fine- to coarse-grained carbonaceous sandstone and shale; minor coal.
	Fort St. John	Cruiser 107-244 m	Dark grey marine shale with sideritic concretions and interbedded siltstones and sandstones.
Lower Cretaceous		Goodrich 15-411 m	Fine- to medium-grained crossbedded sandstone; interbedded shale, mudst.
		Hasler 152-459 m	Dark grey marine shale with sideritic concretions; siltier in lower half.
		Boulder Creek 73-171 m	Fine-grained, well sorted sandstone; massive conglomerate; non-marine sandstone and mudstone.
		Hulcross 0-131 m	Dark grey marine shale with sideritic concretions and interbedded siltstones.
		Gates 67-274 m	Fine-grained, marine and non-marine sandstones; conglomerate, sh. & mudst.
		Moosebar 30-304 m	Dark grey marine shale with sideritic concretions; sandst. and congl. at base.
	Bullhead	Gething 22-549 m	Fine-grained, carbonaceous sandst.; coal, carbonaceous shale; some conglomerate.
		Cadomin 14-213 m	Massive chert & quartzite pebble conglomerate, and med. to coarse gr. sandst.
	Minnes	Bickford 0-427? m	Interbedded fine-grained sandst.; silty sh.; coal.
		Monach 0-304 m	Fine- to coarse-grained, argill. to q'tzose sandst.
		Beattie Peaks 0-396 m	Interbedded silty shales and fine-grained sandst.
		Monteith 0-610 m	Fine- to coarse-grained, quartzose sandstone.
Jurassic		Fernie 0-579 m	Calcareous and phosphatic shales; thinly interbedded sandst, siltst, & shale.

Figure 10. Table of formations for study area in northeastern British Columbia. Adapted from Stott, 1982.

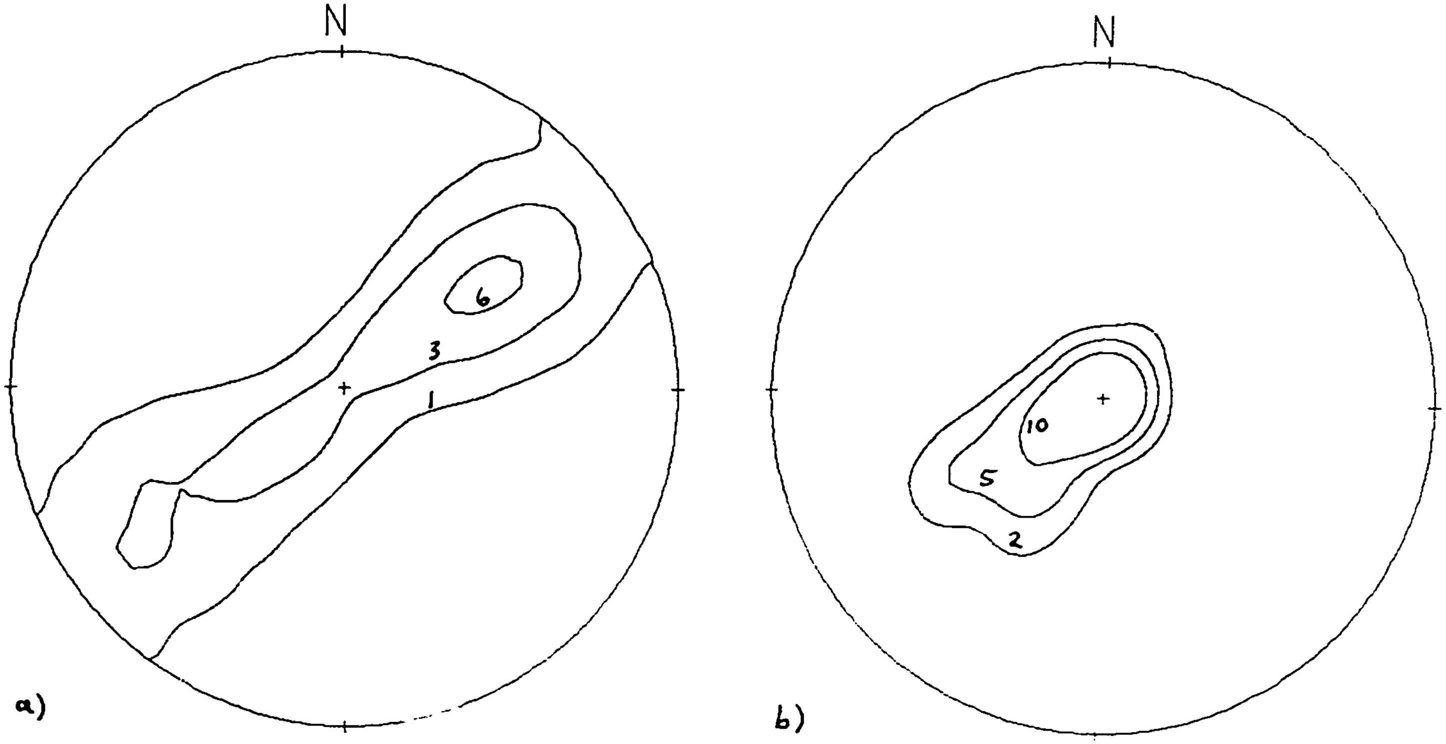

Figure 12. Contoured equal-area pi diagrams showing a) the distribution of 1852 bedding orientations for Moosebar and older strata, and b) the distribution of 351 bedding orientations for Gates and younger strata. The probability method was used with a concentration parameter of 100 (see Charlesworth et al. 1989).

Faulting

Although numerous small faults are visible in outcrop in the Outer Foothills, there is little evidence for the existence of large displacement thrust faults. The Inner Foothills, in contrast, contain many small- and large-scale faults. Linearity of fault traces in areas with considerable topographic relief indicates relatively steep dips. Drillhole data, however, indicate shallower dips at depth as well as the probable existence of blind thrusts (Mudry et al, 1984, McMechan, 1985).

Low-taper Triangle Zone

In an interpretation based upon surface mapping and drillhole data, McMechan (1985) suggested the existence of a structurally thickened wedge between a basal detachment in Upper Devonian shales and an upper detachment in Triassic shales. The geometry and sense of relative motion between this wedge and the overlying package, comprised of Upper Triassic to Cretaceous strata, is that of a classical triangle zone or passive-roof duplex, but on a larger scale and exhibiting a very low-angle eastward taper. Vergence is toward the hinterland as the strata overlying the roof thrust rode passively on top of strata moving in the opposite direction along foreland verging thrusts.

Falls Mountain Klippe

At Falls Mountain, imbricate horses in the Bullhead Group and the Moosebar Formation are overlain unconformably by nearly horizontal upper Moosebar and younger sediments (Figure 13). No sense of shear indicators were found in outcrop.

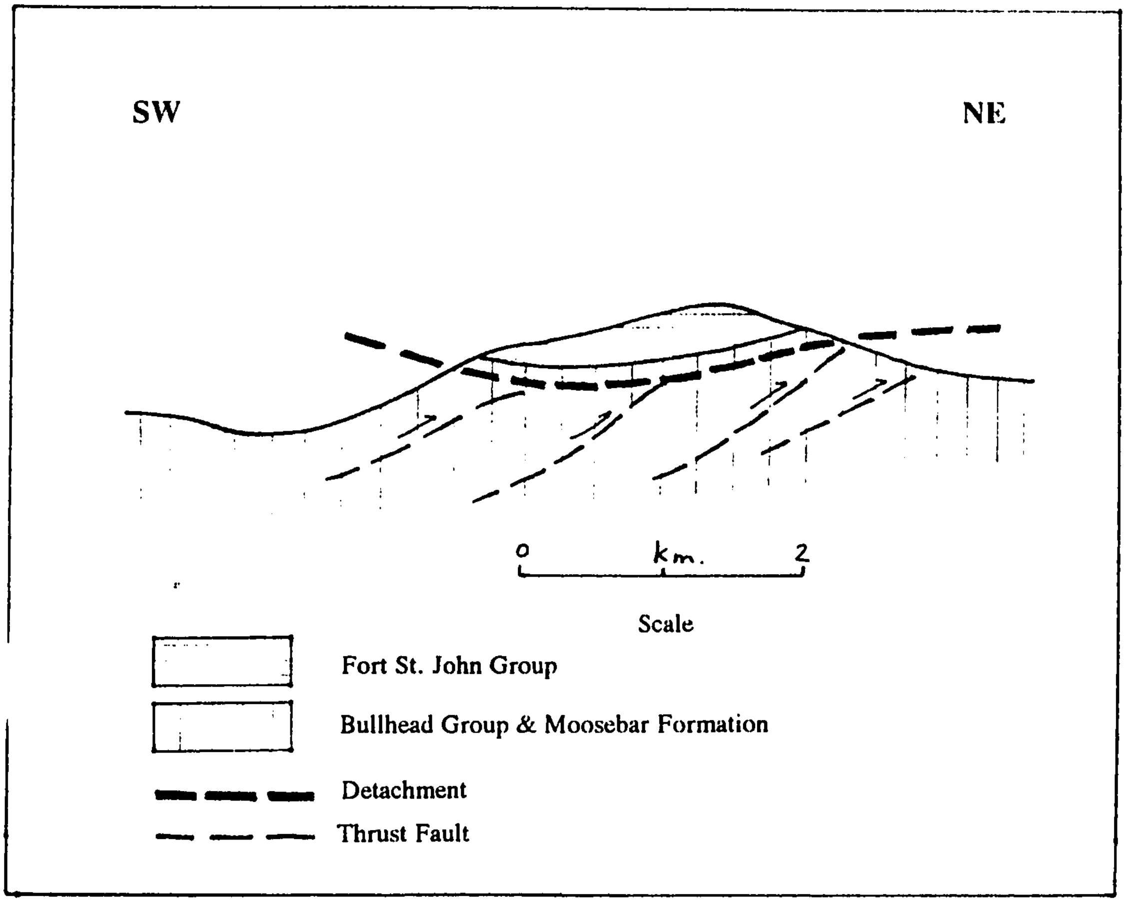

Figure 13. Schematic cross-section of the Falls Mountain klippe. A detachment exists in the upper Moosebar Formation. Amount and sense of displacement is not known. Structure may be explained as a passive-roof duplex or as a true duplex (see text). Adapted from Mudry et al, 1984.

Two possible explanations for the structure around Falls Mountain are 1) that it is a passive-roof duplex (Mudry et al, 1984), or 2) a true duplex. As stated above for a passive-roof duplex, the hinterland vergence of the roof thrust opposes that of the underlying thrusts, whereas the roof thrust in a true duplex verges toward the foreland in the same direction as the underlying thrusts. Because exposures are poor and access is limited, the direction and amount of displacement within the Moosebar is unknown. Passive-roof duplexes are usually associated with external margins of fold and thrust belts. The more internal location of the Falls Mountain Klippe within the Inner Foothills makes the true duplex model more likely.

Regional structural sections and evidence from drillholes have indicated the likely existence of major detachment zones in the Triassic and the Upper Devonian (McMechan and Thompson, 1989; McMechan, 1985). Mapping done for this project has reinforced the suggestion (Mudry et al, 1984) that an additional zone of detachment exists in the Moosebar Formation. Recognition of this detachment and accounting for the additional shortening its existence implies will require re-balancing current structural interpretations.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Until now, outcrop data collected previously by other workers and data displayed on existing maps were difficult to incorporate in a mapping project. The main reason for this was the time involved in transforming manually the older positional data to the new map. The theme underlying this project has been to combine data collected by other workers with information collected by the author. Computer procedures developed during this study enable the storage, conversion and complilation of a large quantity of data to produce such a map in a relatively short period of time.

Computer-based procedures were used in all stages of the project. In the field, outcrop data collected in the traditional way were interactively placed on a computer-displayed topographic map using QuikMap, thereby enabling precise lateral positioning. Later, outcrop data obtained from Gaia Resources were converted to NAD83 and elevations for each outcrop were calculated using computer programs written for the project. An interactive program to digitize traces of faults, axial surfaces of folds and stratigraphic contacts from existing maps was also developed. The digitized data were converted to NAD83, modified using air-photo and field data, and included in the final map. Output from Tripod's structural analysis of outcrop orientations provided one criterion, and distance to the nearest outcrop provided another, by which outcrops were reduced in number and selected for display using a spreadsheet.

Some benefits of using computer-based procedures in this study are as follows. Numerical methods implemented by computer programs provide fast and accurate ways of obtaining outcrop elevations from digital elevation models, for converting between spherical (geographic) and rectangular (UTM) coordinates, and for calculating various structural parameters using outcrop orientation data. Collecting geological data from existing maps is more precise using a digitizing program than by transposing information by hand. A recent problem in mapping involves the change from an older datum to a newer one, between which there is no direct one to one relationship. In this case, the only practical method of transformation involves the use of a digital shift grid file. Distinguishing between NAD27 and NAD83 coordinates avoids inaccurate positioning of outcrops, fault traces, etc.

The large number of outcrops used in this project was best handled using computer-based procedures. Statistical analyses were performed on the outcrop database and orientation data were plotted on pi diagrams. These procedures assisted in the recognition and classification of structural styles in the study area and helped identify a major zone of detachment in the upper part of the Moosebar Formation.

The Moosebar detachment separates two structurally distinct packages: 1) an upper section comprised of gently folded Gates and younger strata, and 2) a lower section, exhibiting much greater deformation, comprised of Moosebar and older strata. Essentially, the upper contact of the Moosebar Formation marks the boundary between the Inner Foothills, exposing strata below the detachment, and the Outer Foothills, exposing strata above the detachment. A klippe comprised of the younger, less highly deformed strata occurs at Falls Mountain in the Inner Foothills.

At the conclusion of this study the following were produced:

1) a 1:50,000 scale geologic map of the area;
2) a database containing 1276 outcrops with orientation data and referenced to NAD83 coordinates;
3) an interactive digitizing program
4) a geographic-UTM coordinate conversion program
5) a NAD27-NAD83 datum conversion program
6) two programs used together to determine the elevation of any point within a TRIM digital elevation model

The final map is in digital form and can be plotted on various output devices. The outcrop database also resides in a computer file and may be used and modified in future work. In this way, using a computer-aided drafting program (CAD) or geographic information system (GIS), updates to the map can be made incrementally as new information is received from time to time.

Although maps have been and still are constructed without the use of computers, the ability to collect and incorporate a large amount of existing data from various sources into a mapping project is much less feasable. With regard to time and manpower constraints, it is not unreasonable to assume that without the use of computer-based procedures and a large base of existing data, constructing the geological map obtained through this project would not have been possible.

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APPENDIX A

USE OF AFFINE TRANSFORMS IN DIGITIZING

The interactive digitizing program QDigit was written in Pascal and employs an affine transform to provide translation, rotation, and change of scale from map to digitizer coordinates. A geometric illustration of the affine transform is shown in Figure 3. Matrix algebra and homogeneous coordinates are used in the equivalent computer implementation. First, the X and Y coordinates of any four calibration points are digitized to calculate a transformation matrix. Thereafter, digitized X and Y data are converted to map coordinates when post-multiplied by the transformation matrix (Loudon et al, 1980).

Although the transformation occurs in three dimensions, both the original and the transformed data exist in two dimensions. For an original point (X, Y), an arbitrary Z-value is set equal to 1, which places it on a horizontal (Z=1) plane. Each 3-component "vector" (X, Y, 1) is post-multiplied by the 3 X 3 transformation matrix T to become (X', Y', Z') intersecting a plane oblique to the Z axis. Because the original value of Z was taken as 1, the value of Z', obtained by multiplying the original vector by the third column in the matrix, is a linear function of X and Y. The transformed values (X', Y', Z') can be regarded as homogeneous coordinates, corresponding to vectors through the origin, and in which the ratio of X' to Y' is constant as Z' varies. To obtain a final image on the horizontal (Z=1) plane, the transformed coordinates are divided through by Z' to obtain (X", Y", 1) where (X", Y") is the desired point. Because the data are projected from the origin through an oblique plane, differential scaling in the X and Y directions is achieved and distorted maps are transformed into geometrically correct ones (Loudon et al, 1980).

To obtain the transformation matrix, the (X, Y) values of four calibration points on the (Z=1) plane are required in both map and digitizer coordinates, no three of which lie on a straight line. Three of these points are post-multiplied by the 3 X 3 transformation matrix T to obtain the matrix of points which lie on the oblique plane of Figure 3. Dividing through by Z' on the right hand side gives the transformed coordinates intersecting the horizontal plane (Z=1).

$$\begin{bmatrix} Xa & Ya & 1 \\ Xb & Yb & 1 \\ Xc & Yc & 1 \end{bmatrix} \cdot T = \begin{bmatrix} X'a & Y'a & Z'a \\ X'b & Y'b & Z'b \\ X'c & Y'c & Z'c \end{bmatrix} \tag{1}$$

Thus rewriting Equation (1) gives

$$\begin{bmatrix} Xa & Ya & 1 \\ Xb & Yb & 1 \\ Xc & Yc & 1 \end{bmatrix} \cdot T = \begin{bmatrix} Z'a & 0 & 0 \\ 0 & Z'b & 0 \\ 0 & 0 & Z'c \end{bmatrix} \cdot \begin{bmatrix} X''a & Y''a & 1 \\ X''b & Y''b & 1 \\ X''c & Y''c & 1 \end{bmatrix} \tag{2}$$

Digitizer Coordinates

Map Coordinates

and,

$$T = \begin{bmatrix} Xa & Ya & 1 \\ Xb & Yb & 1 \\ Xc & Yc & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} Z'a & 0 & 0 \\ 0 & Z'b & 0 \\ 0 & 0 & Z'c \end{bmatrix} \cdot \begin{bmatrix} X''a & Y''a & 1 \\ X''b & Y''b & 1 \\ X''c & Y''c & 1 \end{bmatrix} \tag{3}$$

For the fourth point, we can also write as in (2)

$$(Xd \quad Yd \quad 1) \cdot T = Z'd \cdot (X''d \quad Y''d \quad 1) \tag{4}$$

By selecting an arbitrary value of 1 for Z'd and substituting for T in (4) we obtain an equation which can be solved for Z'a, Z'b, and Z'c. Substituting these values in (3), we solve for T.

APPENDIX B

CONVERSION BETWEEN NAD27 AND NAD83

The difference between the North American Datum of 1927 (NAD27) and the North American Datum of 1983 (NAD83) is mostly due to the different reference ellipsoids upon which each is based. Unlike the Clarke 1866 ellipsoid used in the NAD27 whose centroid not coincident with the centre of the earth, the GRS80 ellipsoid used in the NAD83 is geocentric. In addition, the lengths of the semimajor and semiminor axes differ between the two ellipsoids. To transform ellipsoidal coordinates from NAD27 to NAD83 based on only these differences, the following equations can be used (Morgan, 1991):

$$x = (v + h) \cos\phi \cos\pounds \tag{1}$$
$$y = (v + h) \cos\phi \sin\pounds \tag{2}$$
$$z = [(vb^2/a^2)+h] \sin\phi \tag{3}$$

where

ϕ = latitude in radians
$\pounds$ = longitude in radians
h = elevation above sea level in metres
a = semimajor axis of the ellipsoid
b = semiminor axis of the ellipsoid
$v = a/\{1 - [(a^2-b^2)/a^2] \sin^2\phi\}^{1/2}$

The cartesian coordinates x, y and z are referenced to an origin at the centre of the Clarke 1866 ellipsoid (NAD27). Cartesian coordinates referenced to the centre of the earth (NAD83) are obtained as follows:

$$X = \delta_X + x \tag{4}$$
$$Y = \delta_Y + y \tag{5}$$
$$Z = \delta_Z + z \tag{6}$$

where δ_x, δ_y and δ_z are the offsets from the centre of the earth to the centre of the Clarke 1866 ellipsoid. To obtain NAD83 ellipsoidal coordinates, substitute X, Y and Z for x, y and z in (1) through (3), change a and b to match GRS80 values, and solve for ϕ and £.

The simplified method above is called a datum shift and serves to illustrate the fundamental difference between NAD27 and NAD83. However, geodesists at the Geodetic Survey of Canada have adopted further measures which correct for the inherent distortion in NAD27 and which, consequently, are mathematically more complex (Junkins, 1991). Because of the large number of calculations required for even a relatively small data set, such transformations are best accomplished through the use of computer programs. Also of concern is maintaining the consistency among various agencies and organizations which regularly work with, and convert, survey data. This would require everyone to use exactly the same constants and distortion parameters in complex equations to keep coordinates consistent in general distribution and use.

In order to provide a simple, accurate and consistent means of conversion between the two datums, the Geodetic Survey has made available a conversion technique known as the National Transformation based on a pre-computed grid of datum shifts with distortion corrections applied. This grid is is the form of a binary computer file with a regular spacing of 5 arc minutes of both latitude and longitude. Stored at every grid node is the amount of positive or negative shift in both latitude and longitude between its NAD27 and NAD83 coordinates. Distortion, although exhibiting seemingly random trends from region to region, is locally systematic and therefore, accurate transformations may be linearly estimated between neighboring grid nodes (Junkins, 1991).

The C computer program NADCONV was written to calculate the amount of shift to apply to any point within the area of a specified grid. For each input coordinate, the four surrounding grid nodes are extracted from the grid shift file and a bilinear interpolation is performed (Figure 5). This results in a fast and accurate estimation of the correct shifts to apply to each latitude-longitude coordinate pair for transformation from one datum to another. Transformed coordinates obtained in this way are completely consistent with the datum shift and distortion models used by the Geodetic Survey of Canada.

APPENDIX C

CONVERSION BETWEEN GEOGRAPHIC AND UNIVERSAL TRANSVERSE MERCATOR COORDINATES.

Lateral positions on the earth's surface are usually specified by geographic latitude and longitude or by cartesian coordinates such as UTM easting and northing. The latter choice requires that the corresponding projection, in this case the Universal Transverse Mercator, be used exclusively because cartesian coordinates are meaningless outside the projection they refer to. Geographic coordinates may be transferred from projection to projection as long as the reference datum is consistent.

To simplify distance and angular measurements, it is often more convenient to use rectangular coordinates for mapping and in computer programs. To convert from geographic to rectangular coordinates in the UTM projection the following formulas were used (Snyder, 1982):

$$
\begin{aligned}
x &= k_0 N [A + (1-T+C) A^3/6 \\
&\quad + (5-18T+T^2+72C-58e'^2) A^5/120] \\
y &= k_0 \{M - M_0 + N \tan\phi [A^2/2 + (5-T+9C+4C^2) A^4/24 \\
&\quad + (61-58T+T^2+600C-330e'^2) A^6/720]\}
\end{aligned}
$$

where

x = UTM easting in metres
y = UTM northing in metres
ϕ = latitude in radians
$\pounds$ = longitude in radians
$\pounds_0$ = central meridian in radians
k_0 = 0.9996 (scale factor along central meridian)
a = semimajor axis of the reference ellipsoid
b = semiminor axis of the reference ellipsoid
$e = (1-b^2/a^2)^{1/2}$ (eccentricity of the ellipsoid)
$e'^2 = e^2/(1 - e^2)$
$N = a/(1 - e^2 \sin^2\phi)^{1/2}$
$T = \tan^2\phi$

$$
\begin{aligned}
C &= e'^2 \cos^2\phi \\
A &= \cos\phi \ (\pounds - \pounds_0) \\
M &= a\ [(1 - e^2/4 - 3e^4/64 - 5e^6/256)\ \phi \\
&\quad - (3e^2/8 + 3e^4/32 + 45e^6/1024)\ \sin 2\phi \\
&\quad + (15e^4/256 + 45e^6/1024)\ \sin 4\phi - (35e^6/3072)\ \sin 6\phi]
\end{aligned}
$$

M is the distance along the central meridian from the equator to latitude ϕ, and M_0 is zero for UTM projections. At the poles, x is zero and $y = k_0 M$.

To convert from UTM eastings and northings to geographic coordinates the following formulas were used (Snyder, 1982):

$$
\begin{aligned}
\phi &= \phi_1 - (N_1 \tan\phi_1 / R_1)\ [D^2/2 \\
&\quad - (5 + 3T_1 + 10C_1 - 4C_1^2 - 9e'^2)\ D^4/24 \\
&\quad + (61 + 90T_1 + 298C_1 + 45T_1^2 - 252e'^2 - 3C_1^2)\ D^6/720] \\
\pounds &= \pounds_0 + [D - (1 + 2T_1 + C_1)\ D^3/6 \\
&\quad + (5 - 2C_1 + 28T_1 - 3C_1^2 + 8e'^2 + 24T_1^2)\ D^5/120]\ /\ \cos\phi_1
\end{aligned}
$$

where

$$
\begin{aligned}
N_1 &= a/(1 - e^2 \sin^2\phi_1)^{1/2} \\
R_1 &= a\ (1 - e^2)\ /\ (1 - e^2 \sin^2\phi_1)^{3/2} \\
C_1 &= e'^2 \cos^2\phi_1 \\
T_1 &= \tan^2\phi_1 \\
D &= x\ /\ (N_1 k_0) \\
M &= M_0 + y/k_0 \ (M_0 \text{ is zero for UTM}) \\
\mu &= M\ /\ [a(1 - e^2/4 - 3e^4/64 - 5e^6/256)] \\
e_1 &= [1 - (1 - e^2)^{1/2}]\ /\ [1 + (1 - e^2)^{1/2}] \\
\phi_1 &= \mu + (3e_1/2 - 27e_1^3/32)\ \sin 2\mu \\
&\quad + (21e_1^2/16 - 55e_1^4/32)\ \sin 4\mu + (151e_1^3/96)\ \sin 6\mu
\end{aligned}
$$

ϕ_1 is the latitude at the central meridian which has the same y coordinate as that of the point (ϕ, £). At the poles, $\phi = \pm 90°$, taking the sign of y, and £ is indeterminate.

Because TRIM DEM data were in UTM coordinates and the North American Datum shift grid was in geographic coordinates, it was necessary to convert from one system to the other. The C program GEO2UTM performs this task.

APPENDIX D

INTERPOLATION OF OUTCROP ELEVATIONS FROM DIGITAL ELEVATION MODELS

A digital elevation model (DEM) obtained in TRIM format consists of irregularly spaced spot elevations taken from 1:20,000 scale air photos and stored in compressed binary files. Each file represents a map sheet whose area covers 12' longitude and 6' latitude. Data in these files are stored as Universal Transverse Mercator coordinates referenced to NAD83. DEM files can contain over 100,000 3D coordinates or over 300,000 numbers. If actual UTM eastings and northings were stored, the large values needed to represent them would each require four bytes or 32 bits of computer storage. Instead, only the X and Y offsets from the map centre, together with elevations, are stored. Offsets are much smaller values and, as with elevations, can be represented using only two bytes or 16 bits of storage. However, 600,000 bytes would still be required to store a DEM containing 100,000 points.

Sorting digital data

The C++ computer program TX was written to extract the compressed binary data from TRIM DEM files and arrange them in a two-dimensional sort also called a 'box' structure (McCullagh, 1982). Points were first sorted in the Y direction then divided into many east-west strips. Points in each strip were subsequently sorted in the X direction (Figure 8). The number of strips created was computed from an arbitrarily chosen constant which produced between 1000 and 2000 points per strip on average. Pre-processing a DEM file in this manner creates a new file containing a succession of points such that the strips are in Y-order while the data within each strip are in X-order. Further subdivision into north-south strips creates a grid which can be used as an index to the first point within each box.

The memory requirements for processing the DEM files exceeded the capacity of the microcomputers used, so a two-stage sorting method was developed. Chunks of several thousand points at a time are extracted from the DEM file into an array, sorted in the Y direction using the quicksort method, and stored in a temporary file. As subsequent chunks are extracted, sorted and stored on disk, they are chained together by pointers in a dynamically allocated linked-list structure which grows as needed. In this way, the entire file of DEM points can be processed several thousand at a time without the limitations imposed by available memory. Only pointers to the sorted chunks of data on disk are retained in memory and not the data themselves. When all coordinates have been extracted from the DEM file, the linked-list of Y-sorted points are then combined into a new file on disk using the mergesort method. Starting with the lowest X value and continuing to the highest within the boundaries of each east-west strip, the new file is built up one strip at a time until all the data from the temporary links are used up. Although this file is physically sorted into strips, the box structure is realized by calculating the interval into which each strip can be divided.

Scanning neighboring points

The C++ computer program TR was written to (1) scan the sorted DEM file for a cluster of neighboring points surrounding a particular outcrop, (2) perform a

Delauney triangulation on that cluster, (3) determine which triangle contains the outcrop, and (4) calculate its elevation using the plane passing through the vertices of the triangle. The sorted DEM file allows for very fast seeking in the following manner. On receiving the X and Y coordinates of a specified outcrop, the program calculates which strips contain its closest neighbors (arbitrarily chosen as within the distance of half the width of a strip), jumps to the appropriate location in the file for the start of the strip and reads in any sequential DEM points which lie within the allowed distance, Figure 14. Scanning stops within a strip when the distance in the X direction becomes greater than allowed. The points read in are stored in an array for further processing.

Box indexing could also be used to narrow the search down from whole strips, but the time saved was not significant for the size of TRIM DEM files. When accessing two-dimensional data files exceeding a million points, the program should then calculate which boxes contain the closest neighbors and only search those, thereby significantly improving performance.

Triangulating neighboring points

Once the neighboring points have been collected, a Delauney triangulation is performed. This is a method of connecting irregularly spaced, two-dimensional coordinates to form triangles which are the most equilateral possible. In other words, a Delauney triangle is one whose circumcircle contains no other points, Figure 15. When the elevation at each triangle apex is included, a good three dimensional representation of the topographic surface results. Unlike other methods such as inverse distance weighted interpolation, false features are not produced

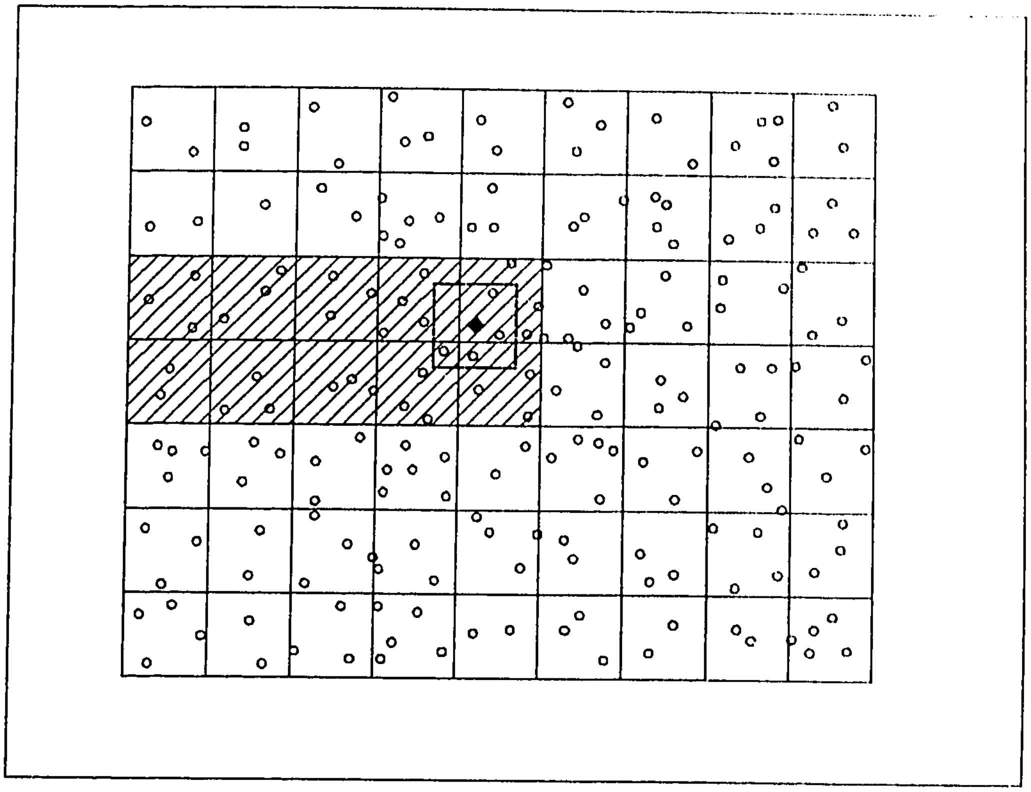

Figure 14. Seeking points within a strip. The map area shown contains many points and is arranged in box-order. The diamond shape represents the point being sought. Only the strips (striped areas) overlain by the minimum search area (dashed box) are scanned by the program.

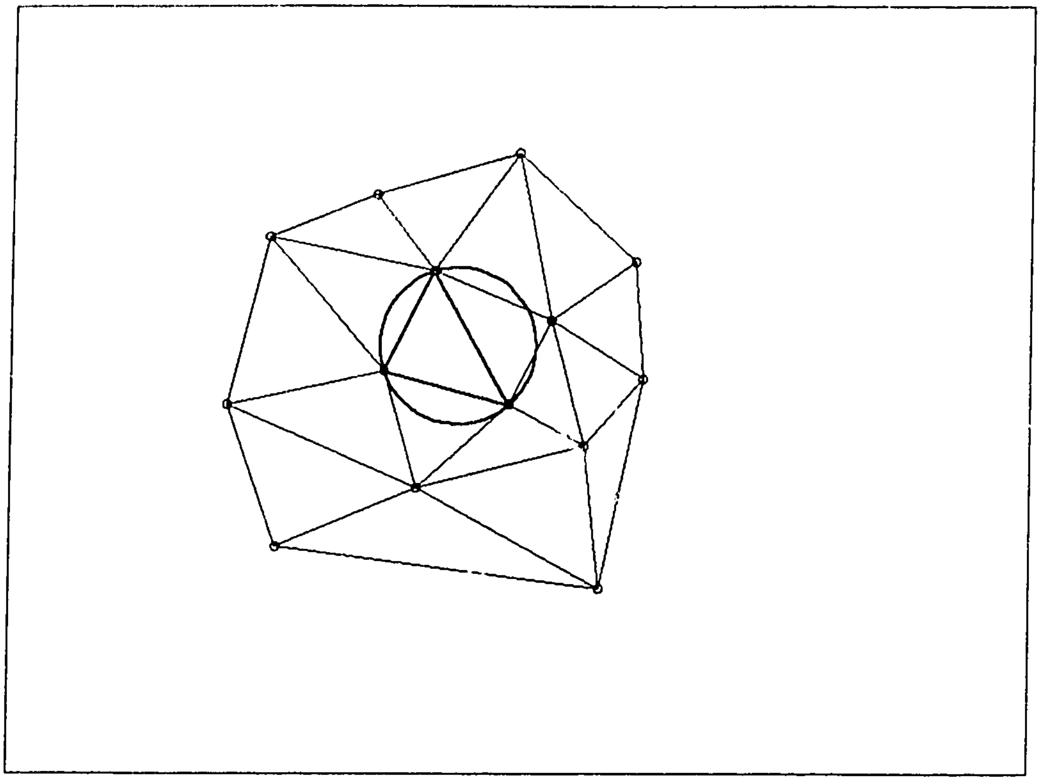

Figure 15. A Delauney triangulation connecting a set of irregularly spaced points is one in which each triangle's circumcircle contains no other point. An example is shown. The desirable characteristic is that each triangle is the most equilateral possible and most suitable for interpolating elevations between points.

where no data exists.

The triangulating algorithm was adapted from the FORTRAN program ACORD by D.F. Watson (Watson, 1982). It begins by normalizing the X and Y values of each DEM point so that they range between zero and one. Then a list of triangles is built by subdividing an initial arbitrary triangle which was constructed to surround all the normalized data. As each normalized DEM point is introduced it is checked to see whether it lies within the circumcircle of any triangle in the list. This is done by comparing the distance of the point to the circumcentre of the triangle with the radius of the circumcircle. Those triangles whose circumcircles contain the point are deleted and replaced with triangles involving the new point. When all data points have been processed, the triangulation is complete and all triangles have empty circumcircles, that is all triangles are Delauney triangles (Watson, 1982).

Determining which triangle contains the outcrop

For each outcrop location in the DEM map area, a triangle should exist which contains it. This surrounding triangle is found by going through the list of triangles, starting in the middle and going out in both directions until a triangle is found whose boundaries laterally enclose the outcrop location. Speed is the reason for using this inside-out search method because the appropriate triangle will most likely be somewhere in the middle of the list.

The simplest and fastest method to determine whether a point lies within the perimeter of a triangle was implemented in the following manner. The outline of each triangle was made up of three vectors, the head of one pointing to the tail of the next. A fourth vector, originating at each apex in turn, ended at the point's location (Figure 16). One at a time, the cross-product of this vector and a perimeter vector originating from the same apex was calculated. If the cross-product was greater than zero, the fourth vector was clockwise to the perimeter vector, and if the cross-product was less than zero, the fourth vector was counter-clockwise to the perimeter vector. The goal was to find the triangle in the list for which the fourth vector is towards the interior of the triangle for all three perimeter vectors, in which case, the outcrop must be inside that triangle. If a perimeter vector sees the fourth vector in a different direction from any other perimeter vector, then the point must lie outside the triangle.

Interpolating the Z value

Once the triangle is found whose perimeter encloses the outcrop, the Z value (elevation) of the outcrop location can be calculated. The triangle's apices lie in a plane representing the topographic surface. Using the cross-product of the vectors making up two sides of the triangle and the outcrop's location coordinates, the point-normal form of the equation of the plane can be obtained. Knowing the X and Y coordinate of the outcrop, the program solves for Z to obtain the elevation on the plane at that point. From Figure 17,

$$\alpha = AB \times AC$$

$$= \begin{bmatrix} (Xb-Xa) & (Yb-Ya) & (Zb-Za) \\ (Xc-Xa) & (Yc-Ya) & (Zc-Za) \end{bmatrix}$$

The direction cosines for α are

$$l = (Yb-Ya)(Zc-Za) - (Yc-Ya)(Zb-Za)$$
$$m = (Xc-Xa)(Zb-Za) - (Xb-Xa)(Zc-Za)$$
$$n = (Xb-Xa)(Yc-Ya) - (Xc-Xa)(Yb-Ya)$$

The point-normal form of the equation of the plane is given as

$$l(Xp-Xa) + m(Yp-Ya) + n(Zp-Za) = 0$$

and, solving for Zp,

$$Zp = Za - \left[\frac{l(Xp-Xa) + m(Yp-Ya)}{n}\right]$$

$$= Za - \left[\frac{[(Yb-Ya)(Zc-Za) - (Yc-Ya)(Zb-Za)](Xp-Xa) + [(Xc-Xa)(Zb-Za) - (Xb-Xa)(Zc-Za)](Yp-Ya)}{(Xb-Xa)(Yc-Ya) - (Xc-Xa)(Yb-Ya)}\right]$$

Note that any triangle with at least one apex associated with the original arbitrary triangle is ignored.

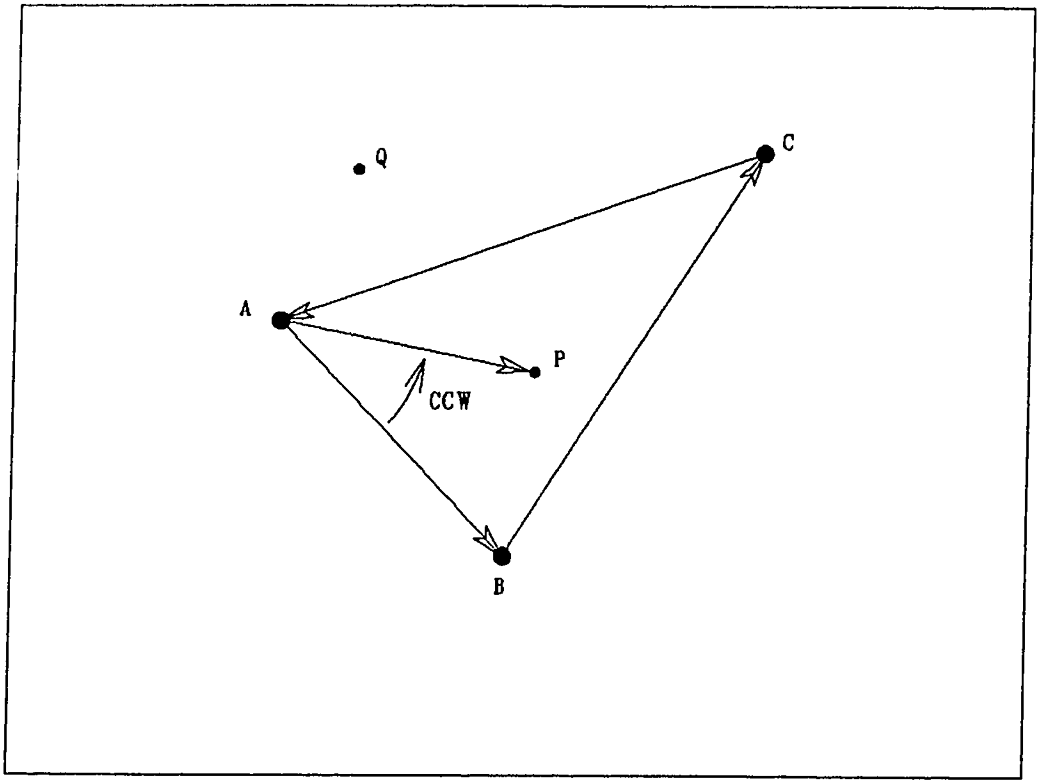

Figure 16. The method used to determine whether a point lies within the boundaries of a triangle is illustrated. Each side of the triangle is represented by a vector whose head points to the tail of the next. A fourth vector, originating at one apex and ending at point P is counter-clockwise to the side originating at the same apex. Placing the tail of the fourth vector at the next apex, its position relative to the side originating at that apex is also counter-clockwise. It can be seen that if the fourth vector is counter-clockwise to each side in turn as its tail moves from apex to apex, then point P must be inside the triangle. It can be also seen that if the fourth vector is constructed with point Q at its head, it will be clockwise to one side and counter-clockwise to another.

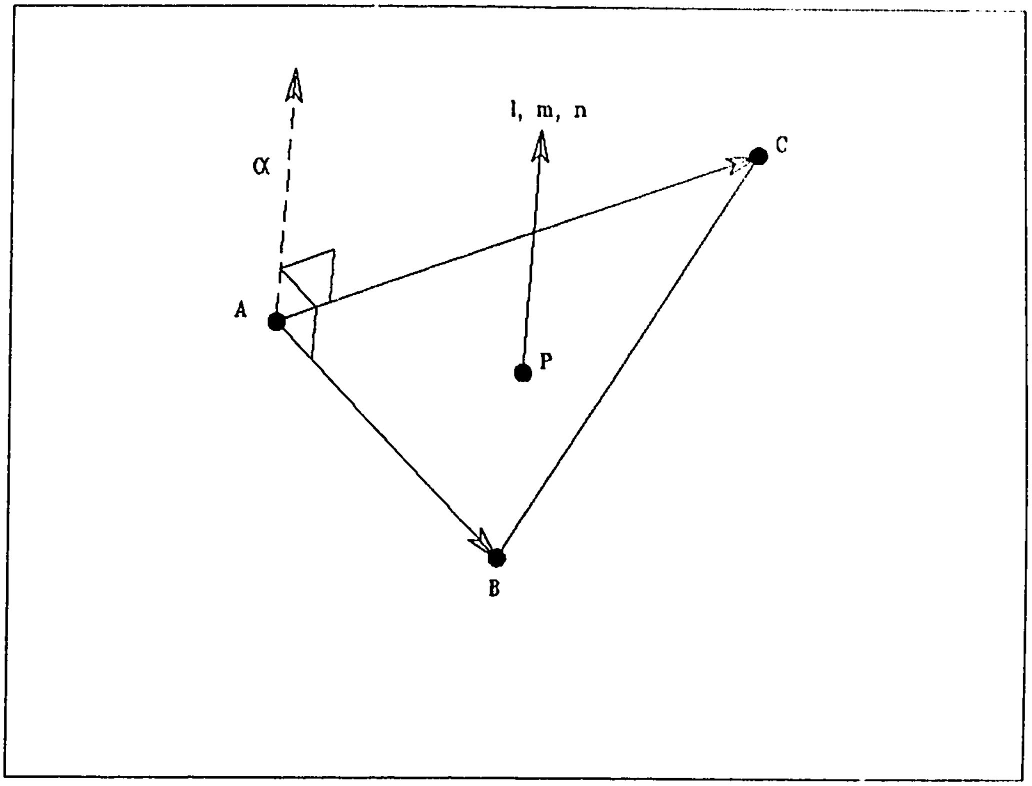

Figure 17. Point normal form of an equation of a plane (see text).

APPENDIX E

SPREADSHEET PROCEDURES

The statistical analyses performed on the Tripod database produced output in the form of plain text files, one for each domain, which listed the scatter angle and coordinates for each outcrop. These files were used to eliminate outcrops from the QuikMap database, based on the degree of scatter within its domain, in the following manner. A spreadsheet program, into which the statistics output files and the QuikMap outcrop database were directly imported, contained functions enabling the deletion of records according to specified criteria. In this case, the criterion was designed to locate any records possessing a scatter greater than or equal to 10 degrees, thus eliminating those outcrops that showed small scale aberrations from the regional structural character. The scatter angle used in this criteria was an arbitrary choice. A smaller or larger value would have resulted in a greater or lesser number of outcrops eliminated.

The next step in reducing the number of outcrops was to eliminate those which were too close together to be easily visible on a 1:50,000 scale map. This was accomplished using the spreadsheet program as above but by specifying a search criteria based on distance between outcrops both in the east-west and north-south directions. To make the process efficient, the record delete function was executed only after first sorting the database by northings and then again after sorting by eastings. In both cases, as each successive record became the current record, the function checked the distances in both directions between the outcrop of that record and those of the next three or four records past it. When the database was sorted on northings, for example, the next record past the current one was that of the closest outcrop in the north-south direction. Similarly for the case when the database was sorted on eastings, the next record in succession was that of the closest outcrop in the east-west direction (Figure 18). By checking three or four records past the current one, any outcrops that were within the minimum distances were quickly found. The current record was deleted when any outcrop was found. Deletion continued in this manner until there were no more outcrops in the database situated within the minimum distance from another outcrop. Using this method prevented having to check the entire database for nearest neighbors for every outcrop, a much more time consuming process.

The final step in reducing the number of outcrops was to sort the database by elevation and check for obvious wrong values. By viewing the first and last records in such a sorted database it was immediately evident whether any outcrops possessed elevations that were too high or too low.

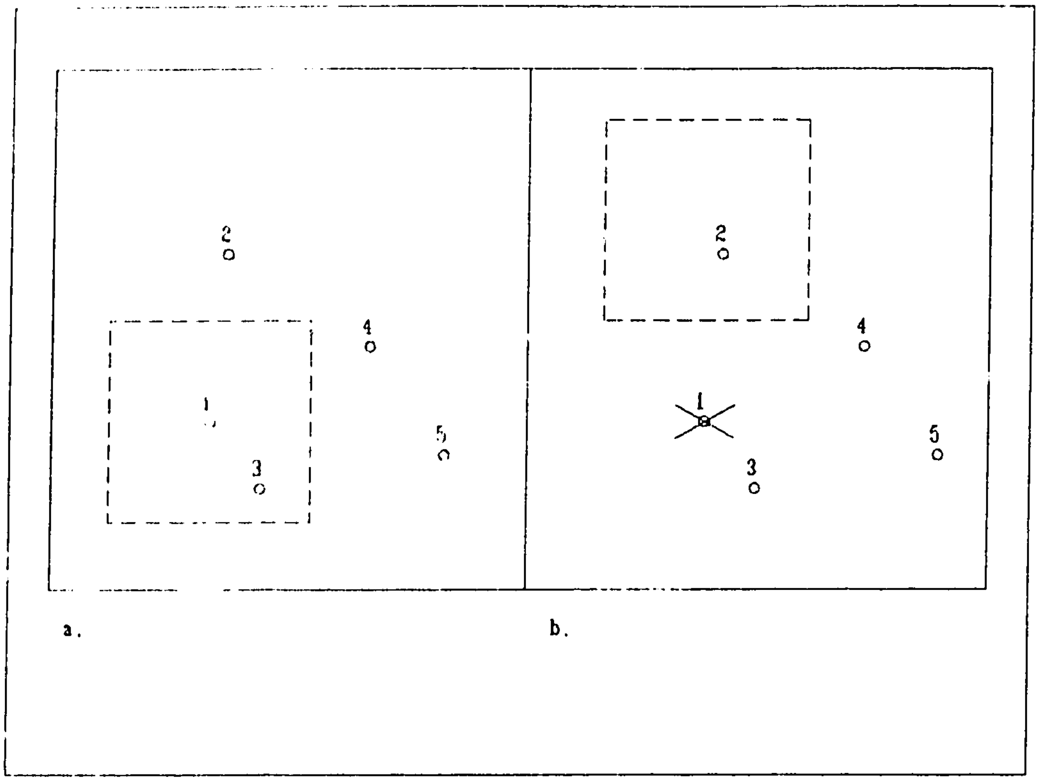

Figure 18. A spreadsheet procedure for deleting points within a minimum X and Y distance of subsequent points is graphically illustrated. The minimum distance is represented by a dashed box and points are sorted by eastings (X). 18a) Point 2 is outside the box centred over point 1, but point 3 is within the minimum distance so point 1 is deleted. 18b) No other points lie within box centred over point 2 so point is kept.

APPENDIX F

LIST OF COAL FILE MAPS

Date	N.T.S.	Report	Project	Company	Scale
1980	93O/9	#680	Trefi	Gulf Canada Res.	1:50,000
1980	93P/12	#680	Trefi	Gulf Canada Res.	1:50,000
1981	93O/9C	#531	Goodrich	Gulf Canada Res.	1:10,000
1981	93O/9D	#531	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/10H	#532	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/9	#533	Goodrich	Gulf Canada Res.	1:20,000
1982	93O/9C	#533	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/9D	#533	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/9E	#533	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/9L	#533	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/10	#533	Goodrich	Gulf Canada Res.	1:20,000
1982	93O/10I	#533	Goodrich	Gulf Canada Res.	1:10,000
1982	93O/10J	#533	Goodrich	Gulf Canada Res.	1:10,000
1983	93O/9E	#534	Goodrich	Gulf Canada Res.	1:10,000
1983	93O/9F	#534	Goodrich	Gulf Canada Res.	1:10,000
1983	93O/9K	#534	Goodrich	Gulf Canada Res.	1:10,000
1983	93O/9L	#534	Goodrich	Gulf Canada Res.	1:10,000
1986	93O/9	#713	Willow Cr.	Crows Nest Res.	1:10,000
1984	93O/8	#525A	Falling Cr.	Esso Res. Canada	1:5,000
1984	93O/8	#525B	Falling Cr.	Esso Res. Canada	1:5,000
1984	93O/8	#525C	Falling Cr.	Esso Res. Canada	1:5,000

APPENDIX G

COMPUTER PROGRAMS

QDigit

QDigit is an interactive, menu-driven digitizing program for IBM AT-compatible machines designed to operate with most digitizers in ASCII or binary mode and at transfer rates up to 9600 bits per second (9600 Baud). It includes an on-line, context-sensitive help facility in lieu of an instruction manual. It can display text files (such as digitized data) on the screen, and can send output to a printer or disk file. Output is in the form of a text file of lateral coordinates and other relevant data depending on the digitizing option selected.

The usual procedure is to first calibrate the program to the map coordinates using the Setup/Calibrate Map menu selection, then to choose the type of data to be digitized. The program can digitize lines (traces), points, contours, well locations, and outcrops. Outcrops can be digitized in two ways, 1) digitizing their locations and orientations from a map, and 2) positioning outcrop locations on a map while recording their lateral coordinates. When digitizing outcrops, it is necessary to first indicate the direction North using the Setup/Calibrate North menu selection.

dBFile

dBFile is a command-line driven program for IBM AT-compatible machines designed for creating, modifying and printing QuikMap (or dBase III+) database files. Data are printed in Tripod format to standard output (screen) and may be redirected to a file or printer. The command-line syntax can be viewed on screen by typing the program name by itself which gives:

```
Usage: DBFILE -caudp [inputfile] databasefile
     where: -c = create a database file
                  -a = append to a database file
                  -u = update a database file
                  -d = delete records from a database file
                  -p = print data to standard output
     inputfile = TRIPOD LISTING.OPT file
databasefile = dBase IV or Quikmap database file
```

Only one of the '-' options may be used at one time. Input must be a Tripod listing file. If no input file is given with the -c option, an empty database file is created. Except for the -c and -p options, both input and database file names must be provided. Only database files created by this program can be modified.

DD2DMS

Geographic (ellipsoidal) coordinates may be specified in decimal degrees (eg. 65.2549°) or in degree-minute-second (eg. 34° 12' 56") format. Various software and data files sometimes require data to be in one or the other formats, so a program for IBM AT-compatible machines was developed to perform the conversions. Input is in the form of a text file, as above, with each line of the file containing one or two numbers in decimal or dms format. A syntax screen is obtained by typeing the program name followed by a question mark (DD2DMS ?):

```
Usage: <standard output> | DD2DMS [-rh] > filename
Options: -r convert dms to decimal degrees
              -h show this help screen
```

This program is of a type often called a filter. It is only used within a data stream whereby input is piped or redirected from a file or another program, and output goes to the screen or is redirected to a file or device. Example run commands are shown below:

```
DD2DMS < inputfile > PRN or,
TYPE inputfile | SORT | DD2DMS -r > outputfile
```

In the first example, the file "inputfile" is directed into the standard input of DD2DMS whose output is sent to the printer. The second example shows how to set up a command pipeline: 1) the DOS command TYPE sends the contents of "inputfile" to the DOS command SORT, 2) the output of SORT is piped to the input of DD2DMS with the option to do the reverse conversion, and 3) the output of DD2DMS is directed to a file called "outputfile".

GEO2UTM

To convert geographic (ellipsoidal) coordinates to Universal Transverse Mercator coordinates and back, this program for IBM AT-compatible machines uses numerical integration methods which achieve accuracies to 100ths of an arc-second.

Input and output may be in decimal degrees or degree-minute-second format. Typing the program name followed by a question mark (GEO2UTM ?) provides a syntax and information screen:

```
Usage: GEO2UTM [-rgsdnh] [inputfile] [outputfile]
Options: -r convert UTM to geographic coordinates
         -g use GRS80 (NAD83) spheroid
         -s switch input column order to lon-lat
         -d degrees, minutes, seconds format
         -n use negative longitudes west of Greenwich
         -h show this help screen
Defaults: ■ convert geographic to UTM coordinates
          ■ use Clarke 1866 (NAD27) spheroid
          ■ input column order is lat-lon
          ■ decimal degrees format
          ■ use positive longitude west of Greenwich
```

The default action, when no option is specified, is shown above. More than one option may be used at a time. Input is in the form of a text file in which each line of the file contains a latitude and longitude, or UTM easting, northing and zone, to be converted to the other form. Output will be in a similar format. Note that either the NAD27 (default) or NAD83 spheriod can be used in the calculation. The program uses standard input and output, and supports piping as described above. This allows use within a data stream as shown below:

```
TYPE utmfile | SORT | GEO2UTM -r > LPT1
```

In this example, a data stream is set up by sending UTM coordinates residing in the file "utmfile" to the DOS command SORT, the sorted output from which goes to GEO2UTM to be converted into geographic coordinates and finally sent to the printer attached to port LPT1.

NadConv

To convert from NAD27 to NAD83 coordinates and back, this program, written for IBM AT-compatible machines, uses a file obtained from the Geodetic Survey of Canada which consists of a grid of correctional shifts for large regions of the country. The program uses the same bilinear interpolation used by government agencies as a standard means of determining correct latitude and longitude for any point within the shift grid area. The grid shift file must first be obtained from the Survey or Energy, Mines and Resources Canada, Ottawa, Ontario. Input is in the form of a text file with each line containing the values of latitude and longitude for each point. The default action is to convert NAD27 to NAD83. To get a syntax screen type the program name:

```
Usage: NADCONV [-roh] [inputfile] gridfile
Options: -r convert NAD83 to NAD27
            -o reverse order of input coordinates (LON LAT)
            -h show this help screen
Notes: Input coordinates must be in decimal degrees.
          Uses standard input / output and supports piping.
```

Output goes to standard output as described above, so to print it or save it to a file refer to the examples below:

```
NADCONV -o coordfile grid.dac > prn or,
NADCONV coordfile grid.dac > outputfile
```

TX, TR

These two programs, written for IBM AT-compatible machines work together to calculate elevations for input coordinates from TRIM digital elevation models. TX is first run as below:

```
TX trimfile [outputfile]
```

where the trimfile is the TRIM DEM file obtained from Maps B.C. or B.C. Crown Publications, Victoria, B.C. Output is sent to the file name specified or to trimfile.SRT and consists of box-ordered binary DEM data to be used with TR.

The program TR takes the box-ordered output file produced by TX and input coordinates provided by the user. To get a syntax screen type the program name:

```
Usage:  TR [-fh?] srt_file < inputfile [> outputfile]
Options:  -f floating point input (default integer)
              -h or ? this help screen
Note:  Requires box-ordered DEM file (.SRT) generated
from by TX from T.R.I.M. DEM files.
```

Input is in the form of a text file (or interactive with the console as standard input) where each line of the file contains an easting and northing in Universal Transverse Mercator coordinates refered to NAD83. Note the input and output redirection operators ('<' and '>'). This program can be used as a filter as described above. The parameter 'srt_file' is the box-ordered DEM file produced by TR. Using Delauney triangulation, the elevation at each input point is calculated and sent to standard output. See above for descriptions on redirecting output to a file or printer.