THE UNIVERSITY OF ALBERTA

Digital Terrain Modelling Applied to the Alberta 1:20,000 Mapping Project

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

Department of Geography

EDMONTON, ALBERTA

Fall 1988

ISBN 0-315-45622-1

THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR Valerie A. Johnson

TITLE OF THESIS Digital Terrain Modelling Applied to the Alberta 1:20,000 Mapping Project

DEGREE FOR WHICH THESIS WAS PRESENTED Master of Science

YEAR THIS DEGREE GRANTED 1988

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ABSTRACT

For well over a hundred years geographers have sought more precise and complete expression of landform characteristics in empirical, usually quantitative terms. A specific objective of quantitative landform analysis has been the development of a comprehensive description by which various topographic types can be compared and classified numerically. The use of digital terrain models (DTMs) is proving to be a valuable methodology for implementing this type of quantitative terrain analysis. DTMs are derived from digital elevation models (DEMs) in the form of regularly gridded elevation data sets.

This study utilises DEMs produced by the Alberta 1:20,000 Mapping Project of the Land Information Services Division of Alberta Forestry Lands and Wildlife. Three study areas were chosen, the Aden area (NTS 72E03/NW); the Fort McMurray area (NTS 74D11/NE) and; the Kakwa region (NTS 83L04/NE). Using differential geometry procedures the first and second derivatives of the DEM were produced. These DTMs provided measures of slope magnitude, slope azimuth, directional curvature and incident solar radiation for the study areas. These models proved to be valuable as a means of mapping terrain attributes; as a means of checking errors contained in the DEMs and; as a data base for terrain analysis applications.

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1. INTRODUCTION

1.1 Background

There has been a general change in the philosophy and methodologies within the discipline of geomorphology from a subjective and deductive science based upon observation, to an objective and inductive science based upon measurement (Jones 1980; Gardiner 1982). Although the most important focus of geomorphology is still the basic examination of earth surface processes, the applied geomorphological techniques directed towards the study and analysis of landforms (terrain analysis) is becoming an integral part of the field (Hails 1977).

Geomorphology has been defined as the study of landforms, and in particular, of the origin, processes of development and material composition of landforms (Cooke and Doornkamp 1974). In the past geomorphology has been mainly an academic discipline but the field is rapidly becoming more applied and utilized by a number of disciplines. Recent compilations of applied geomorphic studies can be found in Cooke and Doornkamp (1974), Hails (1977), Thornes (1979), Jones (1980), and Costa and Fleisher (1980). Whittow (1984 p.34) defined applied geomorphology as the "application of geomorphological methods of survey and analysis towards the solution of problems occurring within man's physical environment". According to Jones (1980), this also includes "resource surveys, terrain analysis, evaluation of ground conditions, hazard surveys and process monitoring" (p.50).

Numerous methods of terrain analysis have been introduced over the years, these include genetic, landscape and parametric approaches.

These approaches rely upon the analysis of available literature, maps, aerial photographs, field verification and recently upon the development of remote sensing techniques, including digital terrain models (DTMs). A specific objective of quantitative landform analysis has been the development of a comprehensive description by which various topographic types can be compared and classified numerically (Pike and Rozema 1975). The use of DTMs is proving to be a valuable methodology for this type of quantitative terrain analysis (Craig 1982). DTMs provide a flexible, quantitative means of defining the shape of the terrain. DTMs are derived from digital elevation models (DEMs) which are regularly gridded elevation data sets, and have been used to measure slope, aspect, curvature and other geomorphic parameters.

The present study utilizes three DEMs produced by the Alberta 1:20,000 Digital Topographic Data Base (DTDB) Mapping Project of the Land Information Services Division of Alberta Forestry, Lands and Wildlife. The study areas are located in three geographically and topographically diverse areas of Alberta which is advantageous for comparative purposes. Another advantage of this project is the ready access to digital data sets, for one the major costs of computer methods comes from the initial data entry and gridding (Dole and Jordan 1978).

The objectives of this research are to create digital terrain models from the Alberta 1:20,000 DTDB mapping project DEMs using differential geometry and digital raster image processing techniques and to discuss and evaluate these models in terms of: 1) methods of presentation (mapping) DEMs, and DTMs; 2) their use as a means of error checking DEMs; 3) their application to digital terrain analysis and finally 4) to discuss and compare terrain attributes derived from the models with published land classification maps. The overall objective is to show that these digital image and map products can be used to supplement or replace traditional image and map products in terrain analysis.

1.2 Study Areas

The three study areas were chosen primarily on the basis of availability of data. The areas happened to be in very different and geographically disparate regions of Alberta, thus providing a means of producing digital terrain mo s of very diverse topographic regions (Figure 1.1). The Aden and Fort McMurray areas are both within the Interior Plains physiographic region but the former is an area of rolling ground moraine and incised coulees within the prairie Shortgrass ecoregion, whereas the Fort McMurray region exhibits the characteristic glaciofluvial and glaciolucustrine landscape within the Boreal Mixedwood ecoregion (North 1976). The high relief terrain of the Kakwa area is located in the Rocky Mountain Foothills. Study area locations are given as the latitudinal and longitudinal boundaries of the 1:20,000 base map; the actual mapped areas consist of 512x512 subsets of 25m grid cells, resulting in study areas that are 12.75 kilometres square.

The Aden study area (NTS 72E03/NW) is in southern Alberta, latitude 49°7'30"N to 49°15'00"N and longitude 111°15'00"W to 111°30'00"W, and is part of the Milk River Drainage Basin. The Milk River flows east through the southern part of the area and is incised into the Milk River sandstone along the axis of the preglacial Whiskey Valley (Westgate

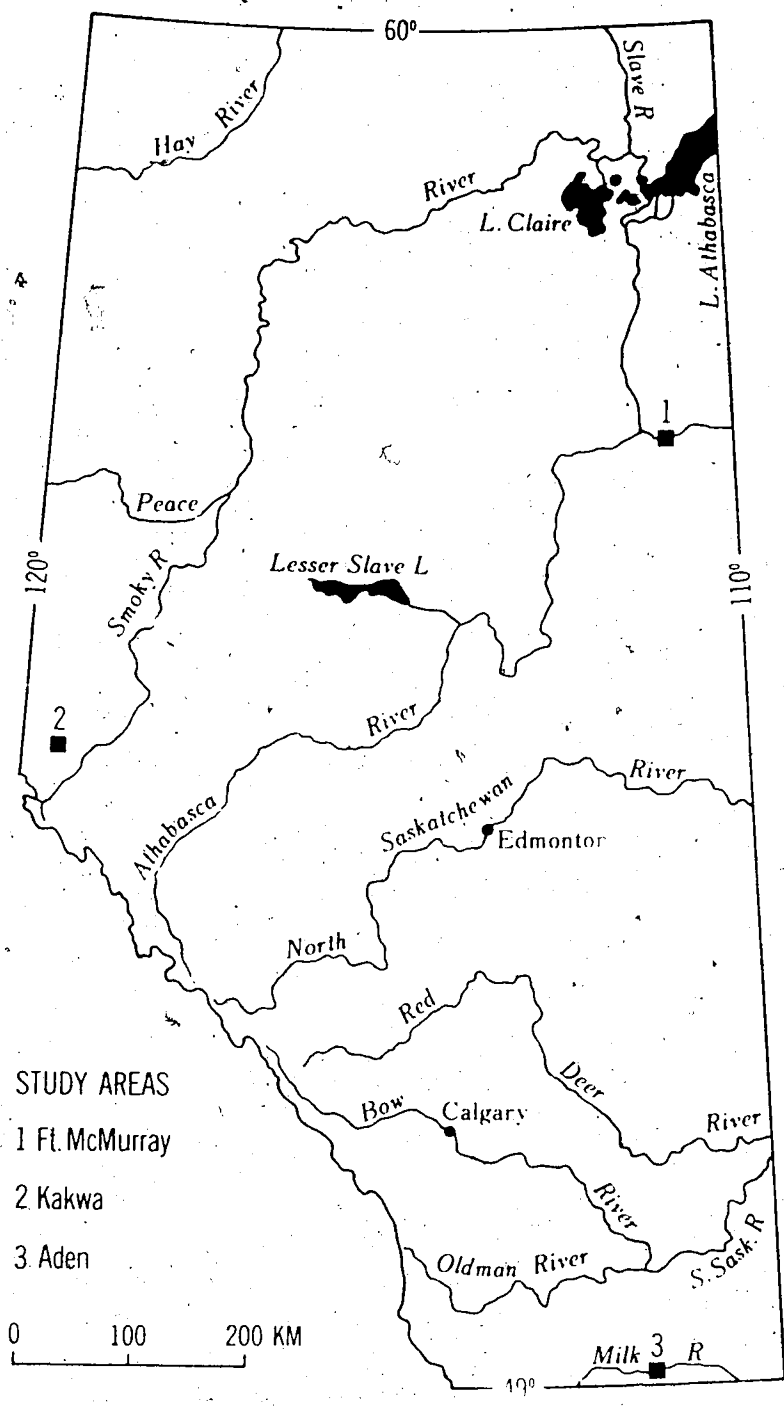

Figure 1.1 Study area locations

1968). Elevations range from 879m to 1033m a.s.l., producing a relative relief of 158m.

Situated on the broad, northerly plunging anticline known as the Sweet Grass Arch, the topography is a result of preglacial, glacial and post-glacial erosion and deposition. The surface is gently rolling, interrupted by deeply eroded coulees (meltwater channels) which provide internal drainage for the area and are considered to be relics of post-glacial drainage (Meyboom 1960). The Milk River channel was ice marginal and formed during retreat of Wisconson ice. Terraces present along the Milk River are covered by till, indicating a glacial advance which interrupted phases of meltwater flow. The area is covered by different morainal forms as well as flutings composed of till or bedrock which are oriented in the direction of ice movement. The flutings have a low relief and are difficult to discern from the ground but show up clearly on aerial photographs (Westgate 1968). These fluting features are not generally evident on the DTMs due to the resolution of the data. Only one large fluting feature is visible in the northeast quadrant.

The till mantle is derived from Upper Cretaceous strata of soft sandstone and Pawkowki marine shales and has a fine loamy texture (Wyatt et al. 1941). The climate is semi-arid and cold, influenced by chinook winds (Bc neu. 1974). These winds are believed to play an indirect role, in combin ion with the aspect of the river valleys, in the distribution of landslides (Beaty 1975).

The Fort McMurray area (NTS 74D11/NE) is in northeastern Alberta between latitudes 56°37'30"N and 56°45'00"N, longitude 111°00'00"W to 111°15'00"W (Figure 1.2). The study area includes part of the broad U-shaped valley of the westerly flowing Clearwater River, a major tributary of the Athabasca River. The tributary valleys flowing into the Clearwater River show a V-shaped cross-sectional form. Elevations range from 240m to 474m a.s.l. producing a relative relief of 234m.

The upper surface shows little variation in relief. The surface north of the Clearwater valley displays the level topography of glaciolacustrine deposits and has been modified by aeolian processes evidenced on aerial photographs by a number on dune fields (these dune fields could not be detected on the DTMs due to their low relief). South of the valley, glaciofluvial action has left a large terrace-like feature incised by paleochannels (INTERA 1978). The large U-shaped valley of the Clearwater River is thought to have been a major meltwater channel during the retreat of the Wisconsin ice sheet. The valley walls are fairly straight and parallel, and the valley floor is approximately 1.5km wide. The present-day topography is assumed to be very similar to the preglacial topography (Carrigy 1959). The glacial deposits overlie the Cretaceous Grand Rapids, Clearwater and McMurray Formations which outcrop along the valley walls . The sharp changes in the sedimentary sequences between these formations are apparent on the DTMs. For a more detailed description of the geology of the area see Carrigy (1959).

The vegetation of the prairie surface consists mainly of muskeg bogs supporting black spruce, whereas in the river valley and well-drained areas heavy growths of trembling aspen, white spruce and jackpine are found (Intercontinental Eng. 1973).

The Kakwa study area (NTS 83L04/NE) is in west-central Alberta close to the Alberta-British Columbia border, between latitudes 54°7'30"N and

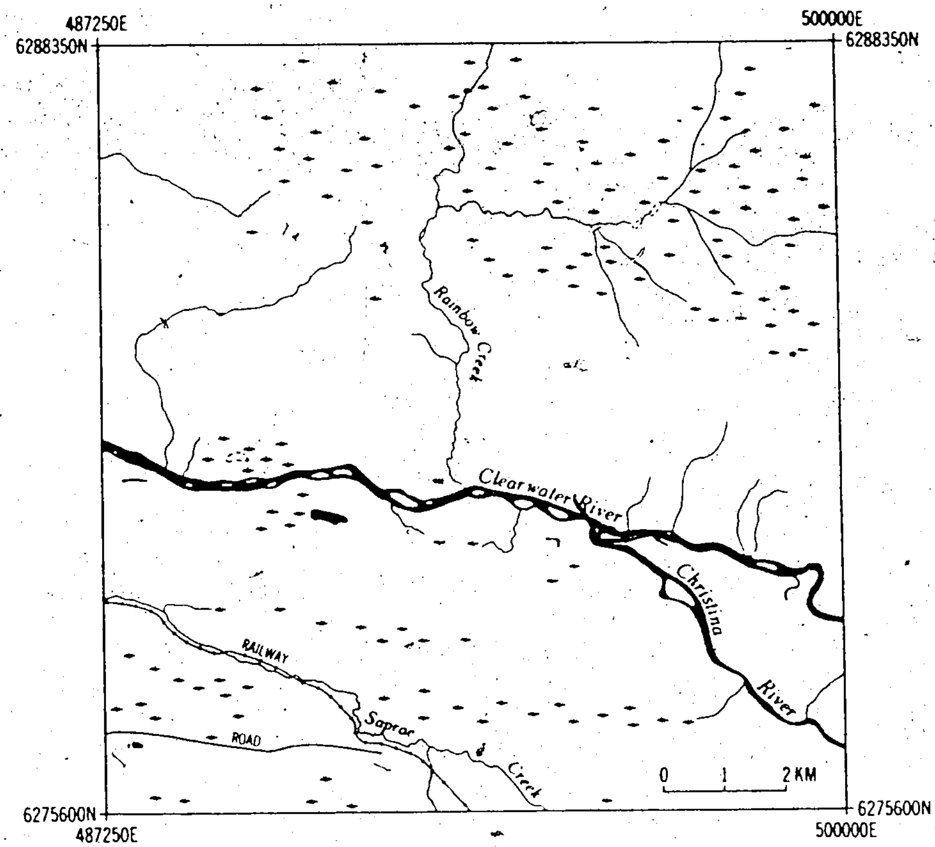

Figure 1.2 Fort McMurray Study Area Location Map

54°15'00"N; longitude 119°30'00"W to 119°45'00"W (Figure 1.3). Within the Rocky Mountain Foothills physiographic region and the Smoky River Drainage Basin, the area includes portions of the Boreal Uplands, the Subalpine and the Alpine ecoregions which are characterized by distinctive climatic conditions (Strong and Leggat 1981). The high relief terrain plays a major role in the great diversity of ecological and physical characteristics of the area. Elevations range from 1106m a.s.l. where the Kakwa River leaves the study area to 2334m a.s.l. in the southwest, giving a relative relief of 1228m.

The geology of the region is structurally complex. The numerous parallel and subparallel, southwest-dipping thrust faults and folds have a northwest structural trend (Irish 1968). The surface has been modified by the Cordilleran Glacier Complex which originated to the west and southwest of the area (Archibald et al. 1984). The aretes and cirque basins in the southwest corner, the glacial meltwater channel now occupied by the Kakwa River and a mantle of unconsolidated morainal material are the major glacial and postglacial erosional and depositional forms. The surface has been subsequently eroded by postglacial processes including weathering, mass movement and fluvial action. For a thorough review of the literature pertaining to the structural and surficial geology see Archibald et al. (1984).

The vegetation patterns and climatic conditions in the Kakwa region are controlled mainly by elevation, slope and aspect. The forest pattern changes from aspen at low elevations; lodgepole pine at mid-elevations; Engelmann spruce and alpine fir at high elevations and finally to alpine meadows at the highest points (Archibald et al. 1984).

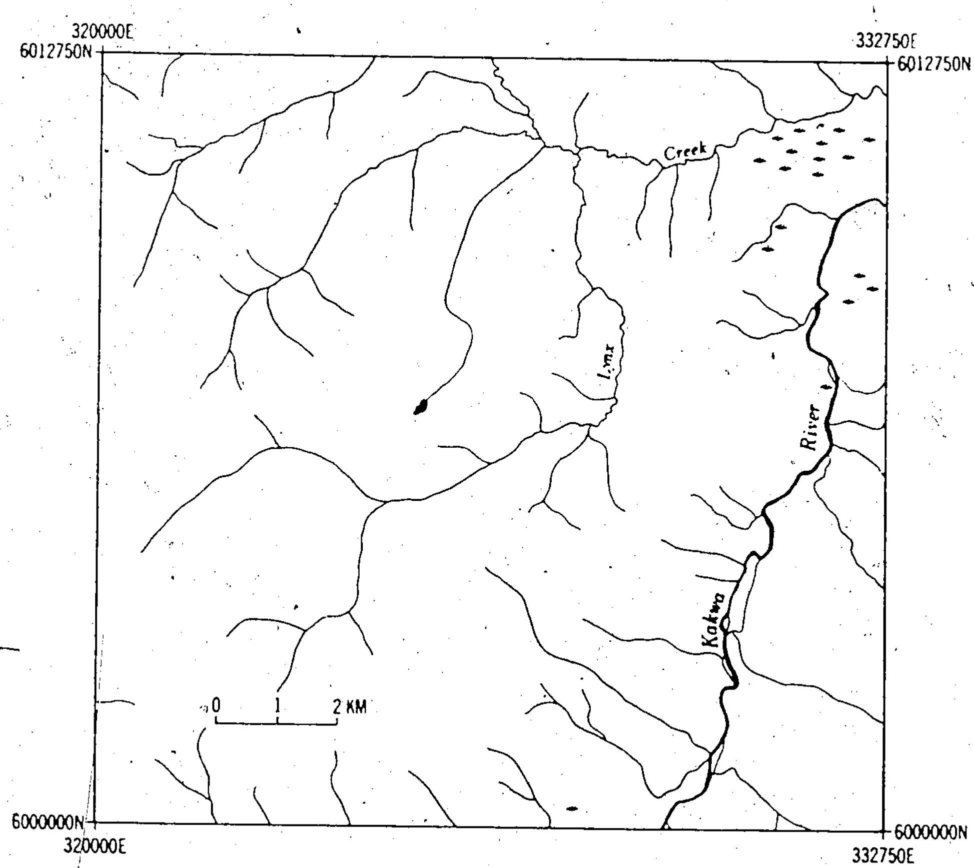

Figure 1.3 Kakwa Study Area Location Map

2. DIGITAL DATA AND DERIVED PRODUCTS

2.1 Introduction

Digital terrain models (DTMs) have been developed and used for a number of years but only recently have they been used for mapping (Ackerman 1978). Generally, DTMs are derived from either terrestrial surveys, photogrammetric surveys or existing contour maps (Yoeli 1983). There is an inconsistency in terminology prevalent in the literature. For the purposes of this study a DEM will be considered to be a regularly gridded elevation set; a DTM is derived from a DEM and consists of a set of terrain parameters corresponding in size and resolution to the original DEM.

The Alberta 1:20,000 Digital Topographic Data Base (DTDB) project was undertaken by Alberta Forestry Lands and Wildlife in 1984 to provide a digital database for use by government agencies and private sector companies. Several private sector mapping companies developed systems for data capture, processing, editing and creating various forms of output. The government expects to complete coverage of the province (650,000 sq. km) by 1991 as part of the digital 1:20,000 project (Toomey 1986). New survey data, aerial photography (1:60,000) and compilation manuscripts are used by the private mapping firms to produce the digital base maps. An important product of this project is the creation of DEMs comprised of X, Y, and Z coordinates captured during the stereocompilation phase.

The DEM data are composed of grid points, breaklines and characteristic spot heights. A variety of photogrammetric instruments were used during data acquisition, including WILD A10, Zeiss-Jena Stereometrograph E and WILD analytical plotters. The data spacing for mass points typically averages between 1.6mm to 2.0mm at a photo scale (Toomey 1986) of 1:60,000, this translates to every 96 to 120 metres on the ground. The procedure for capturing DEM data is left to the contractor; the spacing of grid points, spot heights and breaklines is determined by the nature of the terrain, the interpolation programs used and contractor experience (Land Information Services Division 1985). The DEMs are stored in a variable grid format. The Land Information Services Division uses the Stuttgart Contour Program (SCOP) to create the variable grid files (Toomey 1988). "The varying grid size avoids the densification of an intentionally reduced amount of data and it allows the direct transfer of the progressive sampling grid with additional lines into a corresponding DEM" (Wild and Köstli 1984). This program is also stated to be useful for the automatic generation of a variable grid according to the terrain conditions. The data are processed with overedge coverage to ensure agreement with adjoining map sheets. The private contractors and the Alberta government prepare contour plots from the processed DEM as a means of error checking;

> the check is a simple way of ensuring that gross errors do not pass into the DEM data base due to incorrect file labelling by the contractor or even due to errors in the DEM data which have been corrected by interactive graphics only in the contractor's contour file (Toomey 1986).

2.2 Study Area 1:20,000 Data Sets

Three of the Alberta 1:20,000 DEMs were provided by the Land Information Services Division of Alberta Forestry Lands and Wildlife. The Aden data set will only be used as an example of possible error within a DEM. The data sets were regridded into a 25mx25m regular grid based on the Universal Transverse Mercator (UTM) projection. Elevations were given to the nearest millimetre. Each DEM file covers one 1:20,000 map sheet area (7'30" of latitude by 15'00" of longitude) with a minimum of 200m of overlap between sheets. Each file contains regular grid points, spot heights, sharp breaklines (an abrupt change in slope), round breaklines (break in the terrain where the rate of change is small) and excluded areas (a set of elevation points which define an area to be excluded in contour generation). For the purposes of this study only regular grid points were accessed.

The regular grid format has many advantages over other methods of structuring data, such as the triangulated irregular networks (TINs). Advantages include: ease of manipulation; ability to relate specific data points to neighbouring grid values; ability to store only attribute data in the computer due to the sequential position of the data within an array; and the ease with which overlay operations and statistical testing may be undertaken. The main disadvantages associated with a regular grid format are the inability of the grid to adapt to the changing roughness of the terrain and the large amount of required storage space. For a more thorough discussion of regular grid structures versus other methods see: Evans 1972, 1980; Mark 1975a, 1979; Gold 1979; Peucker et al. 1979; Grayman and Males 1982; Wehde 1982; Burrough 1986; Millington 1986; and Douglas 1987.

2.3 Derivative Products

The production of DTMs from DEMs may be performed in a variety of ways. The method followed in this study uses the differential geometry procedures as described in Eyton (in review). The calculation of spatial derivatives is based on the finite difference approximation of the first and second derivatives of a 3x3 neighbourhood of elevations. The surface is divided into finite elements (grid cells), and the terrain attributes are assumed to be representative within that grid cell area. This method lends itself well to image processing techniques, discussed later, which use 3x3 operators for smoothing, edge enhancement and error detection. Care should be exercised when viewing the images; investigators may be deluded into thinking that more information may be extracted than is possible. High quality graphic displays tend to mask the resolution limits imposed by the data capture and storage procedures. Resolution of individual features can be no better than the resolution of the grid. Accuracy of the derived information (for example, slope and curvature) can be no better than the accuracy assigned to the elevation points (both the horizontal and vertical) through the photogrammetric mensuration process. For a review of other methods to describe the terrain using DEMs such as exact fitting multiquadric equations and least squares polynomials, see Eyton (in review).

Slope magnitude is determined mathematically as the maximum slope of a plane tangent to the surface at a point and represents the rate of change of elevation. Measurements of slope are taken in the X and Y directions for each 3x3 neighbourhood. These vectors are signed according to the slope direction relative to the origin. Positive slopes decrease in elevation as the origin is approached; negative slopes increase in elevation as the origin is approached. The vector cross product of the slopes in the X and Y direction determines the slope magnitude and is expressed as a tangent.

Slope azimuth comprises the directional component of the slopes measured in the X and Y positions. The local angle between the slope magnitude vector and the slope X vector is first determined for each 3x3 neighbourhood and then converted to an azimuth based on the sign of the slope vectors in X and Y. Slope azimuth is represented by a circular 360 degree distribution, grid cells with zero slope do not have an azimuth and are assigned to 361 degrees (flat class).

Curvature magnitude represents the rate of change of slope, or the second derivative of the elevation distribution. This model provides a mechanism for edge detection but as it only indicates the rate, and not the direction (or form) at which the slope is changing it was not reproduced for this study. Similarly, plan curvature, which represents the rate of change of aspect is a valuable edge detector, similar to the edge line or 'skeletal' line maps of previous workers, but it is not considered as valuable a tool for the study of the terrain form as the Laplacian and directional curvature methods. By multiplying each 3x3 neighbourhood of elevations by a Laplacian operator, the curvature (hov convex, concave or straight) of the data set may be calculated. This procedure has also been applied to satellite image processing and acts as a high frequency, non-directional filter (Holderman et al, 1978; Sabins, 1987). Laplacian curvature images illustrate the proper direction of curvature, but the magnitude of curvature is enhanced. In other words, the data are properly signed but not properly scaled.

Directional curvature calculations estimate the curvature of a slope along the direction of maximum slope for the downslope parameter, and orthogonal to the steepest slope for across slope curvature, rather than measuring curvature along the fixed Cartesian axes of each neighbourhood (as in curvature magnitude calculations). The calculations involve linear interpolation to determine the end points of a line represented by the downslope or across slope azimuth passing through the centre of each 3x3 neighbourhood.

The Lambertian reflectance model differs from the previous models in that it does not involve 3x3 neighbourhood operations, but rather, it uses the slope magnitude and slope azimuth data sets to determine the intensity of solar radiation on the terrain surface. The equation used to calculate the relative radiance of a slope facet for differing sun elevations and azimuths is found in Donker and Meijerink (1977). The relative radiances are used to produce hillshaded maps of the terrain.

3. MAPPING METHODOLOGY

3.1 Introduction

To facilitate the visual analysis of the DEMs and derivative products a number of display techniques were used. Digital, electronic representations of the terrain surface enhance landform analysis (Monmonier and Schnell 1988). The use of perspective views, grey scale and classed maps, shaded relief (reflectance) and anaglyph maps provides a number of options for displaying relief besides the conventional methods of contouring. The choice of technique depends on the attributes of the terrain to be portrayed; the type of terrain information to be extracted from the map; the user; and the technology and cost of production (Sherman 1964). A large number of images were produced in this study, but for a variety of reasons, not all maps were reproduced for this thesis. Raster contouring methods have been described fully in Eyton (1984) and will not be discussed here.

3.2 Perspective Views

Manual preparation of perspective views requires highly skilled workers and a large expenditure of time and money (Stefanovic and Sijmons 1984). Using the available DEMs, vector perspective views were easily generated on the computer. This method of displaying elevation provides a three-dimensional approximation of the shape of the terrain and is often used for planning purposes and as teaching aids for map readers unfamiliar with the interpretation of contour maps (Clark 1970). This type of graphic has also been used as a means of evaluating physical and environmental factors that affect surface coal mining and reclamation (Costain 1983), and for flight simulation for pilot training (Chapman 1982). Jones (1984) used three-dimensional plots of dune heights to illustrate dune shape and relative heights during a coastal geomorphology study. The advantage of perspective views is the ability to induce vertical exaggeration to improve visualization of certain terrain aspects (van Zuidam, 1986), and the ability to arbitrarily define the viewing angle and height. Figures 3.1, 3.2 and 3.3 are perspective views of the Aden, Fort McMurray and Kakwa study areas respectively. The DEMs were resampled to a 256x256 grid, due to the limitations of storage space for plot description files. Plots were produced using a CalComp plotter.

3.3 Grey Scale Maps

The production of grey scale maps involved the use of image enhancement techniques in order to improve the image contrast. Contrast enhancement (contrast stretch) expands the original input values to utilize the entire brightness range of the display contrast ratio (Jensen 1986; Richards 1986; Lillesand and Kieffer 1987; Sabins 1987). Prior to grey scaling the DEM was 'smoothed' to de-emphasize high spatial frequency detail, or 'noise'. Smoothing was accomplished by convolution using a 3x3 binomially weighted low-pass filter (Tobler 1970) applied to the original DEM.

Histograms of the data sets were produced. As with the majority of terrain data (except azimuth), the values are usually concentrated within a narrow range. The Decision Images image processing system is capable

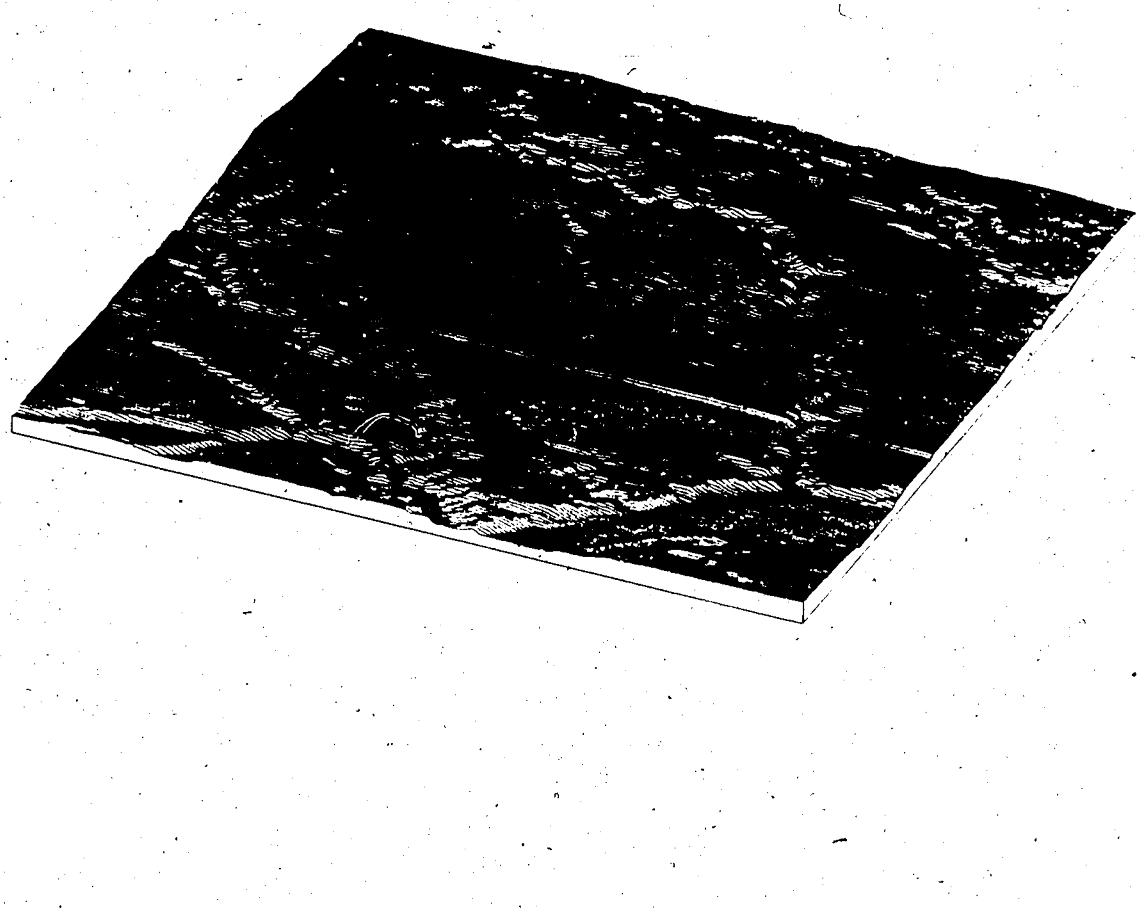

Figure 3.1 Perspective view of Aden, viewed from the SSE (157 degrees), altitude of 30 degrees, 5X vertical exaggeration

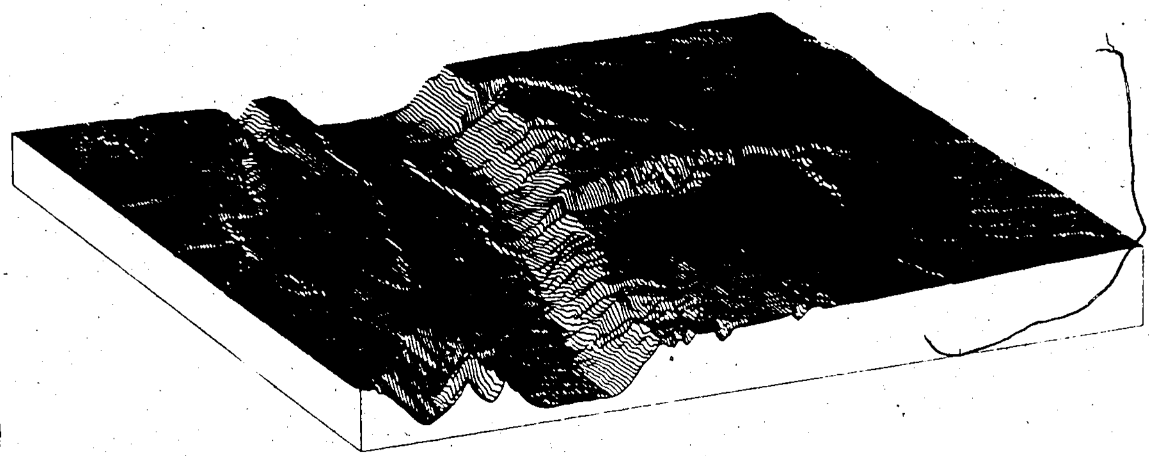

Figure 3 2 Perspective view of Fort McMurray, viewed from the ESE (115 degrees), altitude of 20 degrees, 5X vertical exaggeration

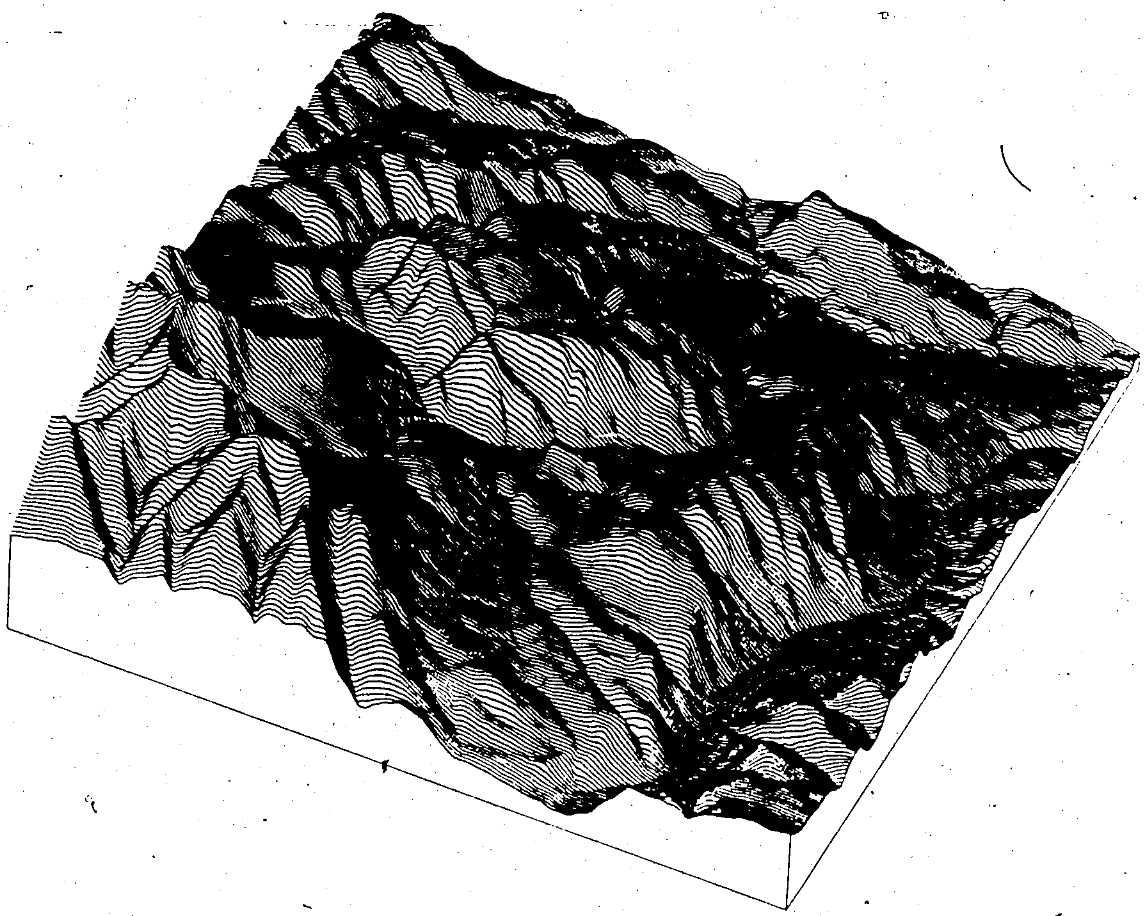

Figure 3.3 Perspective view of Kakwa, viewed from the SSE (157 degrees), altitude of 45 degrees, 5X vertical exaggeration

of displaying 256 grey levels ranging from 0 (black) to 255 (white). By assigning a minimum and maximum value to the range of data values and transforming the data into the 0 to 255 range of grey level values, a linear contrast stretched image with saturation may be produced (Eyton, in review).

The 'clipping' criteria used for the purposes of this thesis were the upper and lower 5% of the tails of the histogram: all values that were less than 5% of the total range of values were assigned to either 0 (black) or 255 (white), and all other values were stretched between, to produce maximum contrast. This was not possible with slope azimuth data since it constitutes a circular distribution.

The grey scale transformations were done using a FORTRAN program (Eyton 1985) on an AMDAHL 580/5870 mainframe computer. Data sets were subsequently transferred to the Decision Images system for viewing on the CRT screen. Hardcopy output was achieved using the Dunn Instruments Multicolor camera.

The grey scale maps of each of the models are based on the premise that the higher the data value, the higher the grey level value. Therefore, high elevations would appear light and low elevations would be dark; likewise, steep slopes would be light and flat areas would be dark. This is not necessarily the method used by all cartographers. The conventional, manual slope maps have usually been produced using the principle "the steeper, the darker" (McGary and McManus 1968; Demek 1982; Horn 1982; Imhof 1982). It has become the practice with modern image processing techniques to follow the principle "the steeper, the lighter". Some users have perception difficulties with this arrangement.

3.4 Classed Maps

Classed maps provide a means of extracting quantitative data and enhancing the readability of the map. A grey scale map can provide the viewer with an excellent overall impression of the spatial distribution of terrain attributes, but specific site values cannot be extracted. A disadvantage of classed maps is the introduction of generalization or quantization error in the map (Tobler 1973).

Classed maps of slope magnitude, slope azimuth and directional curvature were produced in this study. The classed maps of directional curvature (downslope and across slope) proved to be difficult to read; grey scales being preferable for analysis (the classed maps have not been reproduced). Classed maps of slope azimuth were produced, but only the Kakwa map area is discussed in a later section. The classed maps of slope magnitude, perhaps the most important terrain parameter related to various fields of study, forms the basis of this section.

The main factor to be considered when producing a slope map is the classification scheme to be used. "It is entirely possible that the result of the classification will be highly accurate but not useful" (Franklin 1987b p.220). The selection of class intervals must be based on the purpose of the map. Classed slope maps have been used for engineering, military, agricultural, forestry, urban and recreational planning purposes. For geomorphological purposes, categories based on slope frequency are the most satisfactory although slope frequency groups vary from region to region, making comparative analysis difficult (Demek 1972). "More often than not, clear natural break classes do not occur, and subjective judgements based on frequency graphs vary greatly from cartographer to cartographer" (Jenks and Coulson 1963 p.119). Slope classes are often based on threshold or limiting angles for various forms of land use. Ferguson (1981) used only three slope classes for forestry site planning. Gatahi and DaCosta (1986), Gachene and Weeda (1986), McCormack and Sims (1986), Stocking (1986) used various slope classes for soil erosion and agricultural applications depending on other contributing factors such as slope length, soil, climate and lithology. Pitty (1969 p.32) states that "with less than ten classes too much detail is lost. With more than twenty classes calculation becomes increasingly tedious". A more objective means of calculating class intervals is to calibrate the class limits to the frequency distribution mapped. "With six classes, reasonable differentiation is ensured by setting class limits at the mean, the ±0.6 standard deviations and the mean ±1.2 standard deviations" (Evans 1980 p.270). Table 3.1 lists a sample of slope categories which have been cited in the literature.

The Fort McMurray and Kakwa slope magnitude data sets were classed according to the ten-class system adopted from the Canadian System of Soil Survey (CSSC 1978) by the Land Classification Group of Alberta Energy Mines and Resources (now Forestry, Lands and Wildlife). This system was used to allow comparison with published physical land classification (PLC) maps of the same regions. The gridded data sets were classed using a FORTRAN program on an AMDAHL 580/5870 mainframe computer.

Table 3.1. Slope classes (in percent) used by various authors

Slope class	1	2	3	4	5	6	7	8	9	10
Young 1974*	0-3.5	3.5-9	9-18	18-32	32-58	58-100	>100			
Denness & Grainger 1976	0-18	18-27	27-37	37-47	>47					
Garland 1976*	0-9	10-27	28-70	>70						
Grender 1976	<10	10-25	25-50	>50						
Can. Soil Survey Comm. 1978	0-.5	0.5-2	2.5-5	6-9	10-15	16-30	31-45	46-70	71-100	<100
Ferguson 1981	0-20	20-40	40-60							
Sturdevant 1981	0-1	1-2	2-3	3-5	6-12	>12				
Niemann *et al.* 1984	<30	30-50	50-100							
Gachene & Weeda 1986	0-2	2-5	5-8	8-16	16-30	30-45	>45			
Lanyon & Hall 1983	0-3	4-8	9-15	16-25	26-35	36-45				
van Zuidam 1986	0-2	3-7	8-13	14-20	21-55	56-140	>140			
REAP, GIS 1987	0-2.5	2.6-9	10-15	16-45	46-100					
Univ. Soil Loss Equation	1-2	2-7	7-12	12-18	>24					
U.S. Soil Survey	0-2	2-6	6-13	13-25	25-55	>55				

* classes have been converted from degrees to percent slope

4. DIGITAL TERRAIN MODELS AS A METHOD OF ERROR CHECKING

The accuracy and quality of digital elevation models (DEMs) and the derivative products depend upon a number of parameters. Accuracy may be influenced by the "terrain type, density of measured points, type of measurement (selective, profiles, contours, grids, progressive), interpolation method, DEM grid width (if applicable), instrument and operator precision, number location and accuracy control, quality of photographs, and flying height" (Torlegard et al. 1986 p.14). Ackerman (1978) lists data acquisition (density, distribution and quality of measured points) as the first parameter influencing data accuracy; followed by data processing (interpolation and filtering). "It has [also] been shown that the resulting accuracy depends to a great extent on the appropriate data acquisition, in fact more than on anything else" (p.1547). There will always be a level of inherent error within any digital elevation model as it is only a generalization of the original surface. The accuracy of the digital data will be a function of the size of the sampling interval in relation to the variability of the surface (Blais et al. 1986; Torlegard et al. 1986). An increased sampling interval will decrease the standard errors of the DEM but will often result in an uneconomical product (Ostman 1987). "The fewer the samples, the greater the error" (Robinson 1975 p.94). Subsequent interpolation from irregular elevation data points to a regular grid structure can introduce further error in the data representation (Walsh et al. 1987 p.1424). The choice of an appropriate grid size is another factor to be considered (Zevenbergen and Thorn 1987). "The selection of a grid size appropriate to the region of interest must be made on the basis of experience with the scale of the relief that is to be resolved" (Steyn 1976 p.130).

The three data sets used in this study were captured photogrammetrically from 1:60,000 aerial photography. Progressive sampling during data acquisition and subsequent interpolation of elevation values into a 25m regular grid format using the SCOP software could be a primary source of many errors. There may also be a problem during the initial data acquisition stage reflecting operator experience and judgement. "The stereoplotter operator who has plotted contours for several years does not immediately know where to observe DEM data in order to produce a surface from which contours can be interpreted which correctly describe the terrain" (Toomey 1988). The three DEMs were each assigned an accuracy code of '6' according to the Alberta Digital Elevation Model System (ADEMS). The codes represent tolerances within 90% confidence limits. An accuracy code of '6' indicates that 90% of the observations should be within 5m of the contour value on a 1:20,000 map with a 10m contour interval.

The primary method of error checking used by the Land Information Services Branch is the production of contour plots (10m contour interval) from the interpolated SCOP DEM. The SCOP contours are overlaid with the contours produced by the WILD CIP Program, but only approximately 10% of the map sheets are checked (Toomey 1988). Contour plots are a common means of data verification (Heil 1979). Ackerman (1978) superimposed derived contours with contour plots of the same area produced by other methods. Absolute accuracy of contours may also be checked by the conventional way of comparison with true height check points (Aronoff

1982). Stowe and Estes (1981) and Sturdevant (1981) compared DEM elevation and slope values with "ground truth" which consisted of samples taken from topographic maps. Lanyon and Hall (1983a) supported the validity of their maps with qualitative comparison with topographic maps. Refer to Jensen (1986) for a review of accuracy assessment methods.

The method of error check employed in this study involved the visual, qualitative comparison of the DTMs with conventionally produced topographic maps, aerial photographs and published Alberta PLC reports. The various derived models have proven to be a useful means for detecting errors such as discontinuities between patches; pits and peaks and incongruous variations in the digitized land surface. DeGree (1985) produced colour-banded-elevation displays, shaded relief, and anaglyph displays for visual inspection and verification of DEM data. Mulder (1983) used colour coded elevation and hillshaded models for error detection. While all of the DTMs may be useful for error checking, the Laplacian curvature images have proven to be the most useful. The advantage of this transformation lies in the exaggeration of the curvature magnitude. It is particularly useful for identifying anomalies in the data and therefore constitutes a valuable means of error checking. Evans (1980) also found that data errors such as discontinuities between patches show up clearly on curvature maps, thus providing a useful means of quality control.

The methodology used to define error within each of the three DEMs was to first visually scan all models and note any apparent anomalies and gross errors. Aerial photographs and previously published topographic maps and any other ancillary data sources were consulted and compared to the models. Areas deemed to have error were identified on the Laplacian DTM and coordinates were extracted using the Decision Images 'Image Statistics' function. Using these X and Y coordinates, a FORTRAN program was used to extract subsets from the DEM in order to determine the exact elevations (rounded to the nearest integer metre) of the grid points in question.

The Aden area is a region of gently rolling glacial depositional terrain interrupted by deeply incised glacial meltwater channels. Referring to Plate 1 it is immediately evident that there are errors contained in the data. A linear 'cliff' extends east-west across the derived models, cross-cutting all natural features. The 'cliff' feature was found to measure approximately 10 metres in height. This error was not obvious on the 10 metre contour map used for quality control by the Land Information Services Division. There are also two, less obvious, linear features extending north-south, north of the 'cliff'. These may represent mismatched stereomodels. Also visible is a series of ripples in the southeastern quadrant (Figure 4.1). These ripples occur every four grid cells (every 100m), and may indicate an unstable surface possibly introduced by the interpolation algorithm.

The Fort McMurray area is characterized by fairly level topography which has been deeply incised by the Clearwater River valley. Several smaller tributary channels drain into the Clearwater River, the largest being Rainbow Creek, the pronounced valley flowing south in the centre of the study area. Referring to the Laplacian curvature map of the area (Plate 2), all light coloured areas are convex, all darker areas are concave, straight slopes being an intermediate shade of grey. A

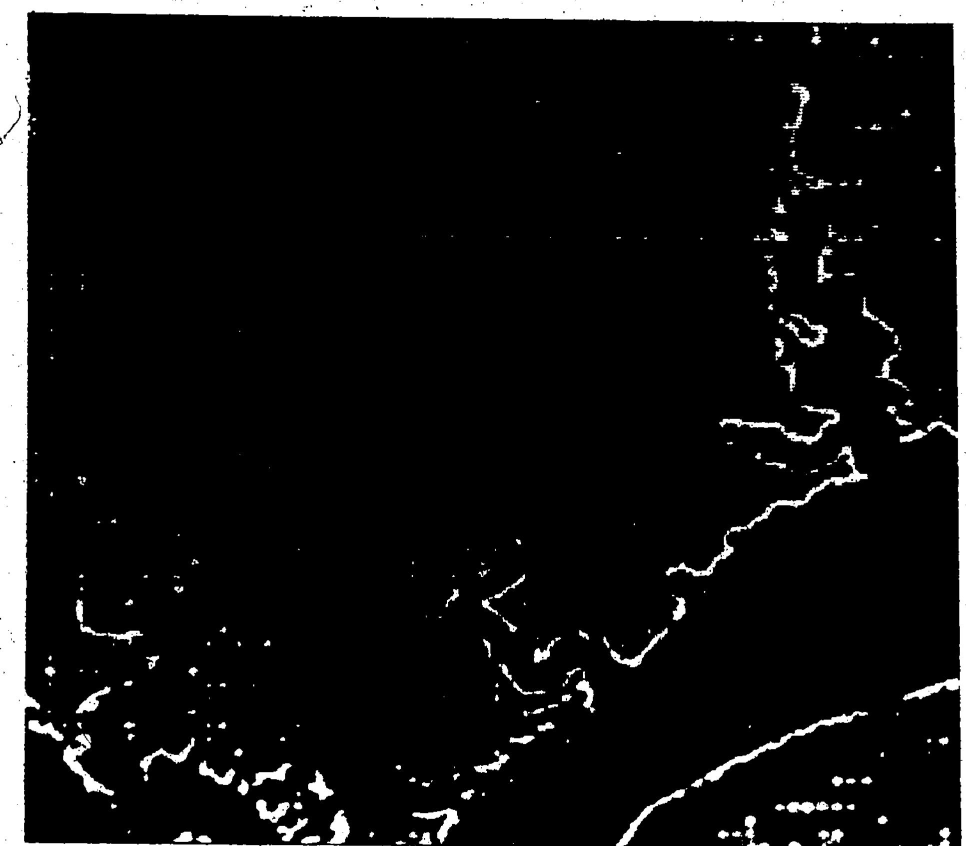

Figure 4.1 Enlargement of the southwest quadrant of the Aden Laplacian curvature map

ridge, or convex feature appears light, compared to the dark, concave drainage lines. The northeast quadrant of the area is notable for its network of convex 'ridges' 'flowing' into Rainbow Creek (Figure 4.2). Similar 'ridges' are also seen in the southeast corner, on the south side of the Clearwater River valley. Upon extracting the elevation values from the DEM it was determined that these 'ridges' are approximately four metres high. Analysis of 1:15,000 aerial photographs and published topographic maps of the same area reveals these features to be tree-lined drainage channels. This type of error is a common problem originating during the data acquisition stage. The combination of the small scale photography, semi-automatic stereoplotters and possible operator error resulted in vegetation being digitized as a topographic ridge. These 'ridges' are also visible on the other models of the region, they are particularly clear on the Lambertian reflectance model (Plate 14). O'Callaghan and Mark (1984) noted a similar problem after visual inspection of hillshaded images of forested areas, elevations were generally those of the tree-top surface and roads and pipelines were visible as grooves.

The Kakwa study area is a region of high relief, in contrast to the two previously discussed areas. Referring to the Laplacian curvature map (Plate 3), the 'pits and peaks' evident throughout the area are a cause of concern. The discrete light coloured 'peaks' and dark, concave 'pits' do not conform to the surface configuration of the terrain as seen on the aerial photographs of the region. The regular pattern exhibited by many of these presumable errors make them suspicious as natural features.

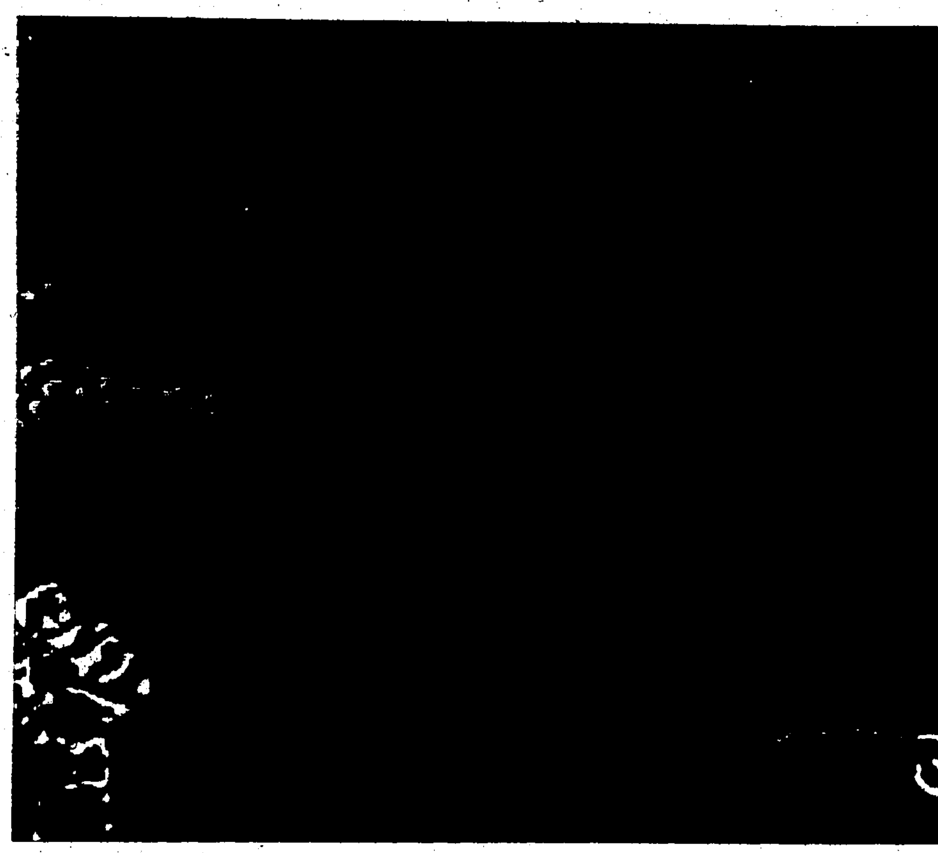

Figure 4.2 Enlargement of the northeast quadrant of the Fort McMurray Laplacian curvature map

"Since pits detectable at a resolution of 30 metres are essentially absent in fluvially eroded topography (except for limestone areas), these pits presumably represent 'errors' in the models" (Mark 1984 p.171). O'Callaghan and Mark (1984) developed a method to cope with artificial pits introduced into the DEM by data collection systems. Figure 4.3 is an enlargement of the 'pits and peaks orchard' found on the Kakwa River floodplain on the east side of the map. Upon extracting the elevation values of this 'orchard' from the DEM and locating the exact locations interactively on the Decision Images image processing system, it was determined that the 'peaks' are eight grid cells apart (200m) in the north-south direction, and four grid cells (100m) in the east-west direction, forming a regular grid pattern. The actual range of elevation values within this 'orchard' is fairly negligible, usually only a few metres (within accuracy specifications). The problem is therefore mainly cosmetic, but the regular pattern is indicative of a problem in the interpolation of the elevation values. Another obvious error is the straight groove pattern trending north-south in the south-central portion of the study area. This linear, concave feature was subset from the DEM; the dark 'pits' were found to be every eight grid cells (200m) apart.

The grey scale maps have provided a convenient means of detecting errors. Upon locating potential errors by visually checking the grey scale maps, the actual grid values may be extracted for more detailed analysis. The elevation values of the DEM are stored as floating point numbers; to simplify the extraction of values from the subsets, the elevation values were rounded and truncated to the nearest integer. This results in a less accurate error reading, but does give a fair

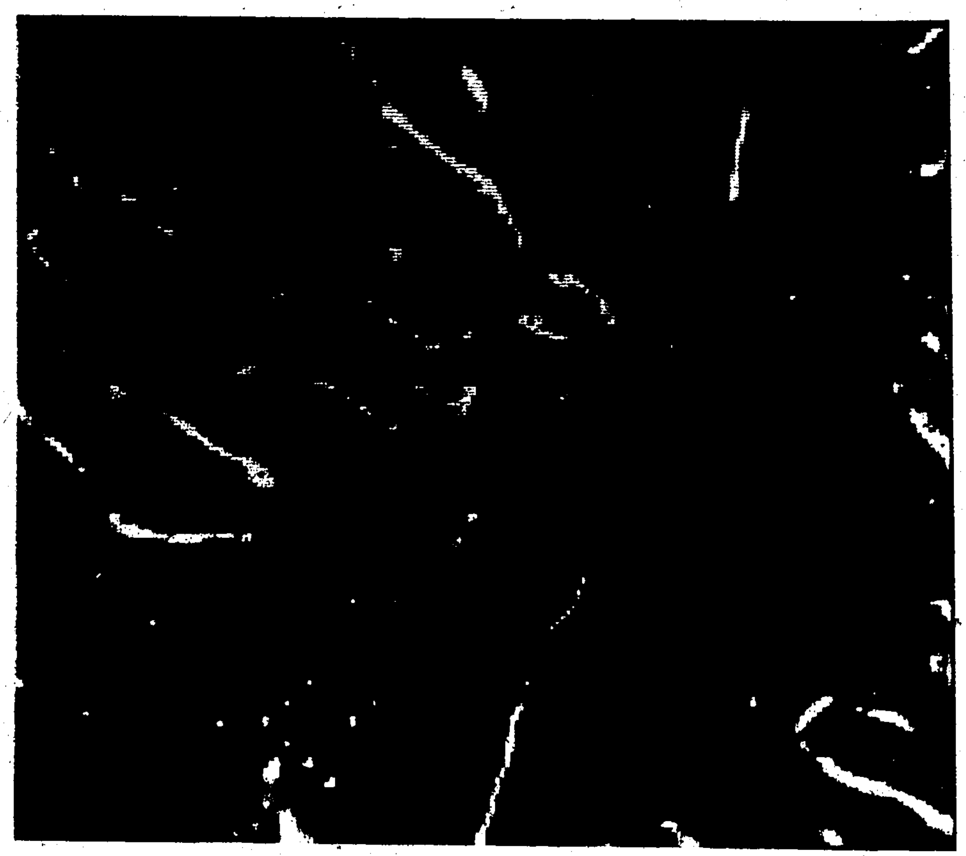

Figure 4.3 Enlargement of the east-central area of the Kakwa Laplacian curvature map

representation of the inaccuracies contained in the data. Should a more precise reading (but not necessarily more accurate) be required, the program could be rewritten.

5. DIGITAL TERRAIN ANALYSIS

5.1 Introduction

Terrain analysis may be defined as the "simplification of the complex phenomenon which is the natural geographic environment" (Mitchell 1973 p.5). Approaches to terrain analysis normally involve the delineation of boundaries based on patterns of landform and vegetation to enclose areas that are reasonably homogeneous (Speight 1977). A variety of terrain analysis techniques have been developed for geomorphology, engineering, agriculture, soil survey and military applications. The two most widely used approaches are the Australian Commonwealth Scientific and Industrial Research Organization's (CSIRO) Pattern-Unit-Component-Evaluation (PUCE) program, and the American Landform approach - both of which fall into the 'landscape' approach to terrain analysis. For a review of these and other methods see Stewart (1968), Mitchell (1973), Speight (1977), Way (1978), Townshend (1981), Barrett and Curtis (1981), Verstappen (1983) and van Zuidam (1986).

Generally, terrain analysis may be subdivided into three main approaches: the genetic method which concentrates on geological, soil genesis and geomorphological processes with little attention paid to landforms (van Zuidam 1986; Franklin 1987a); the physiographic or landscape method, which classifies the terrain into natural units and attempts to measure landform properties quantitatively, and; the parametric method which depends upon precise measurements of land attributes (Mitchell 1973; Parry and Beswick 1973; Ollier 1977). Mitchell (1973 p.28) states that landscape systems or approaches have "three outstanding advantages over [the] parametric [approach]: they help to explain the fundamental causes of landscape differentiation; they assist reconnaissance; and they facilitate the appreciation of regions as a whole". The landscape approach, which bases classification upon patterns in vegetation, soils, landform and lithology derived from aerial photography and field observation has been criticized due to its lack of objectivity and inability to repeat survey results (Franklin 1987a).

The parametric approach is defined as the discrimination and classification of terrain attributes on the basis of selected parameters (Parry and Beswick 1973). Mabbutt (1968) noted distinct advantages of the parametric approach compared with other methods of terrain analysis, notably that this approach 1) achieves a more precise definition of land surface form; 2) being quantitative it avoids the subjectivity of landscape approach; 3) allows for consistency within and comparison between regions and; 4) is suited to computer analysis. The parametric approach is often favoured by users who have need for quantification and "in many situations it appears to produce results remarkably similar to those produced by the landscape method" (Ollier 1977 p.289). The parametric approach does not assume an interrelationship between landform, soils and vegetation as does the landscape approach (King 1987), but allows for correlation between form and other measured variables (Hart 1986).

The parametric approach involves the science of geomorphometry, which is defined as the measurement and mathematical analysis of the configuration of the earth's surface and of the shape and dimensions of landforms (Clarke 1966; Evans 1972, 1980; Singh 1982). The major problem is the choice of morphometric attributes to be considered; the list of attributes suggested by various authors is extensive and there is little agreement on which parameters are useful (Ollier 1977). In addition, the redundancy inherent in the batteries of morphometric variables employed is considerable. Speight (1977) used sixty attributes in his parametric terrain classification system. Vadnais (1965), Mark (1975b) and Gardiner (1982) review and evaluate a number of geomorphometric parameters used by various workers. The most important attributes used to describe the properties and spatial variation of the terrain are considered to be measurements of elevation (relief), slope, aspect, curvature and some measure of roughness - which can be interpreted to be the spatial distribution of elevation variability (Mark 1975b; Frederiksen et al. 1985; Franklin 1987b).

Geomorphometric attributes have been related to environmental characteristics in an attempt to develop classifications of landforms (Mark 1975b; Gardiner 1982; Franklin 1987). Modelling of the terrain using DEMs conforms to the general system of geomorphometry and lends itself well to the parametric approach of terrain analysis (Evans 1980). The following discussions examine four specific DTMs which are considered to be of relevance to geomorphological studies as well as to applied geomorphology and other disciplines. Digital models of slope magnitude, slope azimuth, directional curvature and Lambertian reflectance will be presented.

5.2 Slope

"Most of the land surface of the earth is formed by valley slopes" (Young 1972 p.1). In geomorphological research the investigation of slopes is frequently quite significant (Engelen and Huybrechts 1981), for many geomorphologists view the terrain as a set of slope units, and slope controls the gravitational force available for geomorphic work (Frederiksen et al. 1985). Slope angle influences the rates at which processes act and limits the range of possible processes (Finlayson and Statham 1980). Analysis of slope form has traditionally been performed using qualitative field observation techniques, statistical profile measurement analysis and by quantitative areal measurements and slope mapping techniques (Gregory and Brown 1966; O'Neill and Mark 1985). In the field of applied geomorphology it is the form of the ground surface that is principally involved, rather than its genetic origin.

> The need for a foundation of descriptive work, of considerable mass, is recognized in all of the environmental sciences. Slope studies have until recently suffered from a preponderance of theoretical discussion, without an adequate basis of detailed field observation. The scientific description of slope form per se is a legitimate and necessary part of research (Young 1972 p.18).

Slope magnitude data, usually in the form of slope maps have been used in the fields of agriculture, forestry, engineering, land and resource management, as well as for academic studies and military purposes. Slope angle affects the volume and velocity of runoff and is therefore one of the most important factors influencing erosion, along with the shape, roughness and azimuth of the surface (Sanders 1986). The steeper the slope, the greater the runoff velocity. Finlayson and Statham (1980), Poesen (1984, 1986), Gachene and Weeda (1986), and Sanders (1986) among others, have performed extensive field studies relating slope angle to soil erosion, rill development and soil surface sealing processes. Niemann et al. (1984), Ward (1984a) and Aniya (1985) related slope angle to mass movement occurrences. Ward (1984a) found that most avalanches release on slopes >30 degrees, and that slope angle, along with other factors, affects the frequency and type of avalanching. Small sluff avalanches occur on slopes >45 degrees, whereas the majority of slab avalanches are prone to fail on slopes of 30-40 degrees (Ward 1984b). Kennedy (1976) used slope maps to identify asymmetrical valleys. Slope angle is also an important factor in the field of agriculture. The inclination of a slope affects the crop yield, the amount of water necessary in irrigated areas, the areas which can or cannot be used by agricultural machinery and the field size and layout (Demek and Embelton 1978; Barsch and Liedtke 1980; Crofts 1981). The maximum cultivated slope angle varies from place to place, ranging from 7 degrees in Central Africa to 25 degrees in Spain, for example (Finlayson and Statham 1980). Lillesand and Kieffer (1987) related slope angle to surface drainage and to residential subdivision development.

The theoretical and practical applications of quantitative slope maps are numerous. The development of slope mapping techniques has seen many changes over the years. In 1914 a Morphological Atlas was presented by S. Passarge, consisting of a set of maps which included a map of slopes (Klimaszewski 1982). Various methods were subsequently developed in a number of countries, notably Poland and France. After 1950, Russia, Czechoslovakia, Hungary, Belgium, Canada and The Netherlands developed geomorphic mapping systems, but not all of them include slope data (Mitchell 1973). Early slope mapping in North America appears to have concentrated on depicting the 'average slope of the land'. Wentworth (1930), introduced a method for measuring mean slopes which has since been termed the 'Wentworth method'. The average slope over distances of a mile or a kilometre were derived from contours of existing maps. Raisz and Henry (1937), produced a slope map of southern New England using "an entirely unorthodox method" (p.469) by dividing the study area into irregular units based on the similarity of the density of the contour lines. Miller and Summerson (1960) introduced a method of "slope-zone" mapping which involved defining discrete zones of successive degrees of slope based on natural divisions (no more than eight zones). The variability of natural slope boundaries was recognized but due to the cartographic limitations of depicting zones, specific boundaries were selected. This method resulted in a very general impression of the distribution of steep and gentle slopes, but quantitative measurement of the area was not possible. Nonetheless, Young (1972) states that this type of isoclinal map (maps showing the slope of angle at a point), "has the merit of simplicity, showing the distribution of a single but important parameter of landforms" (Young 1972 p.183).

The small scale of the maps resulting from the previously mentioned methods results in a loss of the subtle differentiation of slope which contributes to the relief of the landscape. Strahler (1956) concluded that only maps on scales of 1:24,000, 1:25,000 or larger, made by photogrammetric methods, were accurate enough to be used for direct measurement of slope. Smaller scale maps omit numerous surface irregularities and slope becomes too generalized. In order to define slope quantitatively rather than qualitatively, Strahler mapped surface slope at a large scale. Instead of calculating a generalized line or unit of area to represent slope, measurements were made on "unit lengths of line or unit areas of ground surface which are small fractional parts of the linear or areal dimensions of individual landforms" (Strahler 1956 p.574).

Savigear (1965), published a method of morphological mapping which involved the use of large scale maps, field surveys and aerial photographs. This method is simple but relies on subjective field observations. Gregory and Brown (1966) state that this slope data is "best treated statistically although the basic material is obtained by sampling which is subjectively controlled" (p.239). The statistics obtained from such data are questionable. Gregory and Brown (1966) divided the surface into facets of similar slope and measured slope at one or two subjectively chosen points within each facet. This was criticized by Evans (1972 p.37), "The selection of 'typical' points at which to measure slope probably produces bias, and so the facet method cannot be considered an adequate substitute for a proper sampling design".

Denness and Grainger (1976) described three methods of producing manual slope maps: the "circle and grid" method, the "moving circle" method, and their own technique, the "moving interval" method. All three slope mapping techniques involve tedious and time consuming measurements from topographic maps, and "a set of systematic assumptions that gives the best approximation to the true situation..." (p.216).

Every geomorphologist interprets the landscape in terms of the training and experience he has had (Doornkamp and King 1971). The development of automated methods of producing slope maps has one obvious advantage: the subjectivity inherent in a manually interpolated map is removed. Gardiner and Rhind (1974), described a "largely objective photomechanical method for creating slope maps from existing materials" (p.14). It is based on the principle that mapped contours coalesce when the slope angle is such that the contour interval is equal to or less than the width of the line used to draw the contour. Using a "whirling illuminator", contour lines are photographically thickened, providing masks for specified slope zones. Disadvantages of this technique include the necessity for well-drawn maps, slight radial displacement caused by the whirling process, and the designation of erroneous slope zones where contours merge with themselves or with another contour of the same value. Dole and Jordan (1978) described a slope mapping process that used reduced contour maps "to produce instantaneous, detailed, colored slope maps on a television screen" (p.2429). Although this method is fast, simple to implement and relatively inexpensive, only relative slope values are provided.

The production of slope maps using computer generated elevation data has gained widespread acceptance. Clerici (1980) described a method of generating slope maps from contour maps by automatic data acquisition and processing which increases the objectivity and accuracy of the results and allows for quantitative analysis. The contour lines were digitized and the elevations were read by a FORTRAN program to produce a regular grid. Trend surface analysis computations were performed at each grid point and the equation coefficients were used to calculate slope. According to Evans (1980 p.277), producing slope maps from digitized contours may be "clumsy and somewhat inaccurate".

Heil and Brych (1978) described a slope mapping method which used a triangulated irregular network (TIN). This method is analogous to the surveying approach for establishing topographic control by triangulation. The data comprises a network of triangles and is designed manually such that the triangular planes fit the terrain surface as represented on a contour map. Elevation data are assigned to all vertices. Terrain analysis of the original data and choice of appropriate slope breaks require experienced interpreters. Although more efficient in requiring fewer data points than either the digitized contours or the gridded elevation model method, each point requires more time for selection. The varying area of the triangular facets results in triangles of different weights, therefore slopes are measured over varying lengths and are not directly comparable.

Using the regular DEMs provided by the Alberta government, slope magnitude was calculated for each grid cell from finite difference estimates of slope within each 3x3 neighbourhood. The slope values were subsequently grey scaled and contrast stretched to enhance image detail. Dark values show low slopes, light grid cells represent steep slopes. The low slope values (dark) cover much of the Fort McMurray grey scale slope map (Plate 4), indicative of the low relief, smooth topography. The low slope values of the upper surface reflect the glaciolacustrine surface and level sedimentary strata; the floodplain of the Clearwater River is also very flat, a result of the flat-lying sedimentaries (Carrigy, 1959) and past glaciofluvial and present fluvial processes. The only steep slopes found in the area are the valley walls of the Clearwater River valley and its tributary channels.

Figure 5.1 is a slope frequency histogram of the Fort McMurray area. Histograms of frequency distributions offer a helpful way to describe attributes of the terrain and a means of comparison with other areas. "Given fundamental properties which relate to points, the obvious way to describe areas is by their frequency distributions in which frequency (i.e. area) is viewed as a function of magnitude" (Evans 1980 p.280). O'Neill and Mark (1987) review slope frequency analysis techniques and discuss the difficulties of normalizing slope distributions. The major factors determining the shape of the slope frequency distributions are the geomorphic character of an area and the location of the boundaries (O'Neill and Mark 1987). Statistical summaries of an area may be meaningless if there are no definitive natural boundaries such as a drainage basin, but frequency distributions may prove helpful to characterize a region. Referring to the Fort McMurray histogram (Figure 5.1), the slope distribution agrees with those of topographically similar areas described in Evans (1980) and O'Neill and Mark (1987), "the lowland areas have strongly positive skews, especially when analysed with a fine-mesh grid" (Evans 1980 p.280). The Fort McMurray classed slope map (Plate 5) shows a fairly bimodal distribution, with a mean slope of 5%, it is dominated by the first two low slope classes. The steep valley walls are clearly demarcated by the 16-31% (yellow) class. The glaciofluvial channels on the large terrace, south of the Clearwater valley, are indicated by the very flat east-west "swales" between the light blue (3-6%) "bars". Hackbarth and Nastasa (1979) noted that the slope of the land surface appeared to determine whether or not muskeg was present in this area. Manual overlay of a reduced topographic map revealed excellent correlation of the marsh areas with the lowest slope class (0-0.5%).

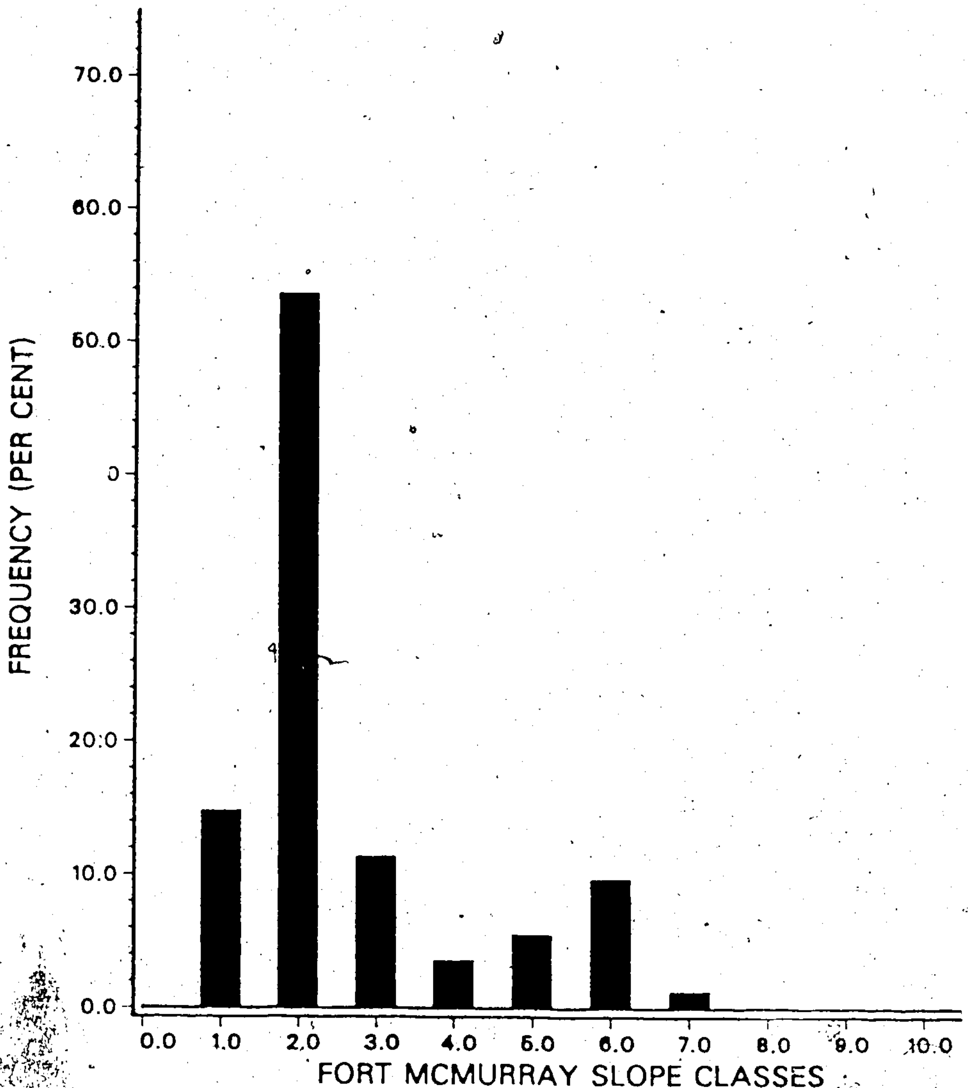

Figure 5.1 Slope ıency histogram of the Fort McMurray classed slope data

The Kakwa region shows a higher incidence of steep slopes, low slopes being confined mainly to the floodplains of the Kakwa River and other drainage paths of the area (Plate 6). Very steep slopes are found along the southwestern cirques and aretes, along the periphery of the central plateau and along the western edge of the Kakwa River valley. This pattern is also evident on the classed slope map (Plate 7). The low slopes (blue) are seen in the Kakwa River valley, the surfaces of the large glaciofluvial terraces, and on scattered areas on the plateaus. The Kakwa region slope frequency histogram (Figure 5.2) also compared favourably with similar areas studied by Evans (1980). This glaciated area has a high standard deviation (0.1515) and a "broad mode with relatively weak tails" (Evans 1980 p.280). The mean slope value of this region is 24%, which is supported by examination of the classed map. The 16-30% slope class (yellow) dominates this rough, high relief terrain. Very steep slopes conform to the arcuate cirque basins and steep bedrock, fluvially eroded valleys.

Comparison of the slope maps of both regions with the PLC maps (Archibald 1984, Karpuk 1988) shows general agreement but as the PLC maps were classed into polygon units representative not only of slope values but also of similar soils, vegetation and drainage properties - direct comparison was not possible. The range of slope values within each polygon is generally higher than the slope magnitude data derived from the DEMs. Niemann (1988) digitally overlaid slope values taken from a PLC map and a DEM derived slope map of an area southeast of Hinton, Alberta. He found similar slope distributions for the lower slope classes but as slope increased there was an increase in apparent misclassification. The polygons of the PLC map representing steep slopes contained a wide range of slope values. "For example, in the polygons with slope class 6, only 33% of the area fell within the range specified" (p.95). Niemann (1988) attributes much of this misclassification of slope values to cartographic generalization; the fact that slope values may not have been the primary reason for delineating polygon boundaries and the inability to accurately interpret slope magnitude in areas of dense forest cover of varying ages, densities and species. Similar observations were made in this study, misclassification of the PLC maps may also be attributed to the manner in which slopes were manually obtained using field and aerial photographic interpretation, observation and measurement (Land Classification Group 1977). The strong vertical exaggeration caused by stereoscopic viewing is an advantage in flat areas when attempting to identify landforms, but it limits the ability to accurately identify slope values (Verstappen 1977; Lo 1986). MacGregor (1957) described similar problems when trying to accurately assess slope angle in the field, "slopes are deceptive features often appearing to be steeper than is actually the case" (p.16). The production of digitally derived slope maps could prove to be advantageous to the delimitation of terrain units.

5.3 Slope Azimuth

Slope azimuth, or aspect, can be defined as the direction of the steepest downslope. The directional portion of the first derivative of a DEM, the slope azimuth model represents a circular distribution which may be either classed or grey scaled to produce useful maps for a number of applications. The direction a slope faces affects temperature, humidity and air movements, which in turn influence microclimate conditions which is of theoretical and practical significance (Wilson 1970; Demek and Embleton 1978). Slope aspect affects crop growth through its affect on radiation, soil moisture and winds (Young 1972; Monmonier 1982; Purnell 1986). In combination with slope magnitude and elevation, aspect plays a key role in the distribution of vegetative communities, often exhibited by denser and different species on northerly aspects in comparison to south-facing slopes (in the northern hemisphere) (Barsch and Liedtke 1980; Johannsen and Sanders, 1982).

In addition to the influence on microclimate and vegetation characteristics, slope azimuth has proved to be a key parameter influencing land form (Macar and Pissart 1964; Gregory and Brown 1966). The distribution of cirque basins has been related to slope azimuth (Dollfus 1964; Graf 1976; Rudberg 1984; Vilborg 1984). Throughout the literature pertaining to periglacial asymmetrical valleys, the orientation of the slopes is also cited as a major factor, the asymmetry is usually ascribed to the differences in solar insolation. South-facing slopes experience more freeze-thaw periods, resulting in increased weathering, solifluction, creep, slumping and downhill transport by water, thereby reducing the slope angle (Long and Stoker 1986). North-facing and northeast-facing slopes, in contrast, remain much longer in shadow, are often sheltered from drying winds, and retain a much steeper slope. The south-facing slopes are commonly heavily dissected by rills and gullies due to the sparsity of vegetation and other factors as mentioned above. The gullying often results in a concave slope profile on the south-facing or west-facing slopes. A complex slope, or a slope lacking a sharp concavity is associated with the north-facing or east-facing slopes (Pitty 1969; Carson and Kirkby 1972). The combination of aspect-controlled solar insolation and lee-side snow drift accumulation has been associated with more frequent avalanche activity on northeasterly facing slopes (Ward 1984a, 1984b) and with the seasonality of avalanche occurrences. Bradley (1970) found that the sheltered north-facing slopes tend to fail around January and May in the northern Rockies, whereas the south-facing slopes show a strong tendency to avalanche around the month of April. Zevenbergen and Thorne (1987) used aspect values to provide information necessary to determine the upslope area that contributes to the flow of a catchment area.

Slope azimuth maps of the Kakwa and Fort McMurray data sets were produced using both grey scale and colour classing techniques. The grey scale maps were produced using conventional northwest lighting (not shown). Areas with a northwest aspect, or an azimuth of 315 degrees, appear light; areas facing southeast are dark, and intermediate values were scaled appropriately. Aspect maps are clearest when the terrain exhibits sharp ridges and valleys (Evans 1980). Even those areas which have a very low slope angle will have an azimuth, which may produce a confusing image in an area of low relief. This was true of the Fort McMurray area and for this reason a classed azimuth map has not been reproduced. A grey scale image of azimuth values cannot be contrast stretched due to the circular distribution of values.

Classed azimuth maps may be produced by dividing the circular 360 degree distribution into any number of desired classes. The Kakwa data set was classed into eight 45 degree classes, with an additional flat class representing slopes of 0-0.5% slope (Plate 8). In agreement with the literature previously cited, the Kakwa area also exhibits signs of asymmetrical glacial activity. The largest and most active glaciers were concentrated on the north-facing and northeast-facing slopes. This is evidenced by the cirques and aretes, notably in the southwest corner of the study area. In addition to the applications noted above, the Kakwa slope azimuth map provided striking evidence of geologic structure. The northwest trending lineaments, evidenced mainly by the linear, parallel pattern of the southwest-facing class (red) are immediately apparent upon visual inspection of the map. A lineament has been defined by Sabins (1987 p. 102) as:

> a mappable simple or composite linear feature of a surface whose parts align in a straight or slightly curving relationship and that differs distinctly from the patterns of adjacent features...a lineament may be geomorphic (caused by relief) or tonal (caused by contrast differences).

Lineaments are often mapped on satellite imagery based on tonal differences. The use of DTMs provides the opportunity to map the 'geomorphic' lineaments of the terrain. Although the lineaments are usually indicative of fault zones and structural discontinuities, it cannot be assumed that every lineament detected on a DTM represents fault structures, field checking is necessary to verify the existence and nature of the features identified on the images. Manual overlaying of the bedrock geology maps (Irish 1964; Archibald et al. 1984) showed excellent correlation between the fault trends and the lineaments highlighted by the azimuth classes.

The classed slope azimuth map of the Fort McMurray data set (not shown) does not exhibit sharp patterns as seen on the Kakwa map. This is due to the low relief of the terrain. The features that were the most marked were the valley walls of the Clearwater River and the paleochannels incised into the terrace-like feature on the south side of the river valley.

5.4 Directional Curvature

The curvature of a slope, or the rate of change of slope is one of the most important attributes of landform geometry and one that is often neglected. This may be due to the fact that it is a relatively difficult parameter to measure in the field or from topographic maps and aerial photographs. This difficulty of measurement may be one of the main reasons that the majority of research has concentrated on two-dimensional slope profile analysis. The principle basis of the analysis of profile form has been the division of two-dimensional slope profiles into convex, concave and rectilinear units (Young 1972). Slope profiles are classified into sequences consisting of an uppermost convexity, a maximum segment and a lower concavity, the number and combination of sequences varying, indicative of different phases of development, presence of a bed of more resistant rock, or by rejuvenation causing an acceleration in the rate of erosion at the foot of the slope (Young 1971). Theoretical geomorphological studies have concentrated on the development of slope profile form and the processes tending to produce equilibrium slopes. The upper convexity is commonly attributed to soil creep (humid climates) and rainsplash (arid and semi-arid climates); the straight slopes are described as being controlled by weathering and threshold conditions (Finlayson and Statham 1980), and concavities result from wash-type processes or under conditions of accumulation. It should be noted that slope form depends not only on the processes operating on them but also on initial and boundary conditions, and a given landform can be derived from several different processes (Armstrong 1987).

The influence of three-dimensional land surface curvature has received little attention in previous studies (Anderson and Burt 1978). The ability to calculate curvature using digital data sets may prove to be an important contribution to future methods of terrain analysis. Curvature in the downslope direction affects the acceleration and deceleration of flow, and therefore, aggradation and degradation of sediment; across slope curvature, orthogonal to downslope curvature, affects the divergence and convergence of flow (Ahnert 1976; Finlayson and Statham 1980; Zevenbergen and Thorne 1987). Where the terrain is concave in the across slope direction, greater flows of water and sediment will pass successive points downslope than on a straight slope (Carson and Kirkby 1972), compared to the more arid, freely drained soils of convex slopes (Young 1971; Demek and Embleton 1978).

The influence of curvature on the processes of flow has a great affect on soil development, erosion and mass movement. Concave slopes experience lower soil losses than uniform (straight) slopes, erosion occurs in the upper sections and deposition on the lower (Stocking 1972). On concave slopes, the runoff velocity decreases as the slope angle decreases, resulting in a reduction in the capacity of water to transport soil and an increase in infiltration (Young and Mutchler 1969). Convex slopes erode less on the upper sections than the lower sections and usually deposit large quantities of sediment on the toeslope (Sanders 1986). This is due to the increase of runoff velocity as slope increases, allowing less infiltration and thus increasing the amount of soil loss and runoff (Young and Mutchler 1969). The common methods for predicting soil loss usually assume a uniform slope. "The shape of a hillside may not only affect the rate of erosion at different locations along its slope, but different erosion rates along a slope may appreciably change its shape as erosion progresses" (Meyer and Kramer 1969 p.522). Studies carried out by Meyer and Kramer (1969), Young and Mutchler (1969), Flach (1986) and Gachene and Weeda (1986) show a significant effect of slope shape on soil erosion and runoff, yet the majority of models continue to concentrate on the slope length and magnitude parameters of uniform slopes, which rarely occur in the real world.

Slope form has been related to weathering rates due to the affect on microclimate (Kennedy, 1976; van Zuidam, 1986) and to mass movement. Carrara et al. (1977) and Aniya (1985) found the slopes that were straight in both the across and downslope directions and slopes that were concave in both directions were much more susceptible to mass movement than any other slope form. The resistance of a soil or regolith to gravitational stress is inversely related to its moisture status (Lanyon and Hall 1983b). The hollows formed by concave slopes are more prone to failure due to the greater moisture content which outweighs the increased basal support of the concavity (Carson and Kirkby 1972).

Okimura and Kawatani (1987) used digital curvature data to predict surface mountain slope failures; "failures on all convergent, divergent and planar slopes can be predicted" (p.123). Ward (1984b) found that the slope form affected both the snow-holding capacity and the stress distribution in snow.

The ability to produce digital curvature maps from DEMs could provide valuable input into many mass movement, erosion or drainage models as well as providing a useful description of the terrain form. The traditional methods of mapping surface curvature usually involve a number of generalized symbols on a geomorphological map. Curvature maps are usually analogous to "edge" line maps which trace major breaks of slope. Imhof (1982) discusses "skeletal lines" consisting of concave negative lines and positive convex lines.

> To this group belongs the lines showing breaks of slope,the edges of well formed terraces and plateaus, slopes, ridges, moraine crests, dune crests, polje-edges, crater rims, deeply incised stream beds, the upper edges of steep glaciers etc. (Imhof, 1982, p.105).

The use of grey scale images to map directional curvature provides the map reader with a clear view of the form of the terrain. Light areas represent convexities (positive change of slope), dark areas represent concave areas (negative change of slope) and straight areas appear medium grey. The roughness or dissection of the terrain may be detected on maps of slope or curvature magnitude, but a map of directional curvature must be consulted to differentiate ridges from valleys. The directional curvature maps of the Fort McMurray and Kakwa regions were compared with published topographic maps, PLC maps and aerial photographs by manual overlay and visual inspection. It is clear that the ridges and valleys as seen on the grey scale maps conform with reality, (except the errors mentioned previously), and "in some sense the placement of the ridges and valleys determines the essential character of the image" (Haralick 1983 p.38). The grey scale maps are much easier to comprehend than a map which merely depicts "skeletal lines", for in reality the edge lines, or breaks in slope are rarely sharp or continuous, which is easily shown on a grey scale image but difficult to portray using vector formats or manual cartographic techniques.

5.4.1 Downslope Curvature

Downslope curvature is the rate of change of slope down the steepest slope. Upon examination of the grey scale maps of downslope curvature, it is evident that this parameter clearly defines drainage divides and major terrain forms. The Fort McMurray grey scale map (Plate 9) shows convexities (light areas) bordering the drainage channels, indicating the break in slope between the fairly level upper land surface and the steep valley walls. The base of the valley walls is demarcated by the dark concavity where the walls meet the floodplain of the Clearwater River. The river channel is outlined by the convex levees along the banks. Of special note are the two areas along the northern scarp of the main valley. From the western edge of the map almost to Rainbow Creek, a very straight, light-coloured convexity is apparent running parallel to the upper surface, approximately midway down the valley wall. This feature was at first presumed to be an error in the data due to its extreme regularity. Analysis of aerial photographs and geological maps (Carrigy 1959) indicate that this is a change in the sedimentary sequence, probably between the Clearwater and McMurray Formations. Along the northern valley wall, east of Rainbow Creek, is an uneven surface is markedly different than the other fairly straight sections of the valley and the surface form is suggestive of slumping. This is also an area being actively undercut by the Clearwater River. The arcuate convexity to the west of the outlet of the Christina River appears to be a fluvial terrace modified by mass movement processes when viewed in profile form (Figure 3.2).

Downslope curvature is also a valuable mechanism for error checking. The light coloured convex ridges 'flowing' into Rainbow Creek are evident as are the three 'ridges' flowing into the Christina River in the southeast corner (the westernmost ridge is actually a road, the other two features are drainage channels). The blockiness of the northwest quadrant may be a grid interpolation problem due to the low relief. The linear feature entering the area from the southwest is a highway, bypassing a reservoir and industrial area.

The downslope curvature grey scale map of the Kakwa region defines the major drainage divides, but also provides a useful mechanism for analyzing geological structure (Plate 10). The area consists of faulted and folded Lower to Upper Cretaceous strata which are outlined by the convexities and concavities of the image. The convex crests of the mountainous ridges in the southwest corner, the shape of the central plateau and the eroded folds in the east-central area are clearly visible. Smaller ridge-like features along the north bank of Lynx Creek may be lateral moraines, or they may be bedrock features as they parallel the structural trend of the region. The floodplain of the Kakwa River is outlined by the sharp, concave (dark) break in slope along the valley walls. Large terrace-like features visible on the eastern and western sides of the Kakwa River valley are products of glaciofluvial processes (Archibald 1984). The Kakwa River appears to have breached the linear fold structure that can be seen on either side of the valley.

Downslope curvature seems to be one of the most useful derivative products obtained from the DEMs for identifying the shape of the terrain. Comparison of this parameter with the PLC map shows general agreement between the terrain unit polygon boundaries and the major concavities and convexities in the region as seen on the grey scale maps. The data may also be shown in classed form. Classed maps were produced using Young's (1972) curvature classification categories. For the purposes of visual terrain analysis the classed maps proved to be less comprehensible than the grey scale maps and have not been reproduced, however, they would be invaluable aids to quantitative erosion, soils or mass movement studies where numerical modelling techniques are required. Another application of curvature mapping could be the testing of process-response models such as Dalrymple et al.'s (1968) hypothetical nine unit slope model, using real world examples.

5.4.2. Across Slope Curvature

Across slope curvature is the rate of change of slope orthogonal to the steepest slope. Referring to the grey scaled maps of across slope curvature (Plates 11 and 12), it is clear that this terrain parameter is valuable for defining drainage attributes. Drainage characteristics are important indicators of soil texture, lithology and climatic conditions. Previous studies of drainage basin form and drainage networks required intensive fieldwork and laborious copying of channel networks from aerial photographs or topographic maps before quantitative analysis was possible

(Burrough 1986). Gardiner (1981, 1982) and Mark (1983) give extensive reviews of the manual methods used to identify stream networks and provide tables of previous studies related to the topic. Due to cartographic generalization of contours and variations in scale, the popular methods of using contour crenulations and "blue lines" on topographic maps to identify stream channels are often inadequate. Many channels are omitted unless they are permanent streams. Aerial photographs may also be used but vegetation may hinder identification of channels. Field work is often difficult due to the inability to identify many features from the ground as well as the inaccessibility and size of the area to be covered (Gardiner 1981). An additional problem is the differences in judgement and identification criteria used by different researchers, making quantitative, comparative analysis difficult.

An advantage of using DEMs derived photogrammetrically rather than from digitized topographic maps (which have already been generalized) is the ability to objectively identify a more detailed channel network. Mark (1984), Marks et al. (1984), Burrough (1986) and Douglas (1987) review methods of deriving drainage networks from digital data using both raster and triangulated network formats. Flowpath modelling is also possible, see Mark (1984) and O'Callaghan and Mark (1984) for a discussion of runoff simulation techniques. Morphometric analysis of drainage basins relies heavily on measurements of channel networks. The production of various models from DEMs affords the extraction of quantitative, objective information to be applied to a variety of geomorphological studies.

The across slope curvature maps of the Fort McMurray and Kakwa areas provide clear, synoptic views of the drainage patterns. "A map of concave-upward portions of a digital elevation model could be considered to be an approximation of the drainage network" (Mark 1984 p.170). Comparison of the Fort McMurray grey scale map (Plate 11) with the 1:50,000 topographic map shows that the channels that are identified on the grey scale map by concave (dark) grid cells, are only partially represented on the topographic map. The channels incised into the upper surface, which have eroded back from the walls of the main valley are drawn, but the majority of the first order tributary streams (after Strahler 1952) are not shown. Analysis of the new hardcopy 1:20,000 Alberta Base Map series (a product of the Alberta 1:20,000 DTDB Mapping Project) shows an improved representation of the channel network. Map scale greatly influences resolution but the channel network on the grey scale map is still clear after the map has been photographically reduced to a scale smaller than 1:50,000.

The Fort McMurray drainage system is dominated by the wide, straight Clearwater River valley. The Clearwater River is an underfit stream, flowing in a glacial meltwater channel. The smooth meanders are indicative of fine-grained, flat-lying sediments. The tributary channels exhibit a fairly fine textured dendritic pattern joining the main valley at an acute angle. The fine drainage texture is characteristic to soils of low permeability (Way 1978). This interpretation is also supported by the muskeg areas that are common to the region.

The Kakwa grey scale map also exhibits a larger number of 'streams' than the topographic maps. This area has a fairly high drainage density which is not immediately apparent by looking at the 1:50,000 topographic maps; this is a function of scale and cartographic generalization. The Kakwa river is the principal drainage channel in the study area. The river valley is more clearly defined by the downslope curvature grey scale map (Plate 10) than it is by the across slope curvature map due to the low slope and wide floodplain (this is also true of the Fort McMurray area). The concavities (dark) of the across slope curvature grey scale image provide a striking map of the drainage patterns of the smaller creeks and tributaries. The bedrock control of the underlying structure is evidenced by the annular pattern of creeks flowing off and around the large central plateau, and the northwest - southeast tend of the majority of the tributary streams which form a trellis pattern. Both the trellis and annular drainage patterns are a response to bedrock control. The trellis pattern "indicates tilted, interbedded, sedimentary rocks on which the main, parallel channels follow the strike of the beds" (Way 1978 p.50).

The network defined by across slope concavities does not always correspond to drainage paths. Avalanche chutes, and breaks of slope associated with the eroded fold structure may be misclassified as stream channels. Other problems associated with the identification of drainage networks using DEMs may include missed drainage courses due to grid resolution; lakes may not have the same elevation values on their surfaces, and other level terrain surfaces may exhibit features which result in physically impossible drainage patterns; and the problem of pits, discussed earlier, disrupts flow paths (Marks et al 1984). After comparison of the drainage patterns on the Fort McMurray and Kakwa maps with aerial photographs and topographic maps, the advantages of producing and using the digitally derived maps appear to outweigh any possible disadvantages.

5.5 Lambertian Reflectance Model

Relief portrayal has traditionally been performed using manual shading techniques which require the skills of a highly trained cartographer or artist. These manual methods are time consuming, expensive, and inherently subjective due to the different judgement and skill of each cartographer (Horn 1982; Stefanovic and Sijmons 1984; Burrough 1986). The purpose of hillshading has generally been to supply an element of realism to the map; the cartographer often concentrated on the overall impression rather than on objective relief portrayal. Imhof (1982 p.335) goes so far as to suggest that the shading should be "worked over and edited" rather than introducing "untidy complexity" into the map. Sherman (1964), describes shaded relief as a "qualitative form of symbolism...information is in relative, more pictorial and less abstract terms" than the quantitative contouring methods. With the availability of digital elevation models and the development of the digitally derived reflectance map, an objective system of portraying shaded relief is now possible.

The three-dimensional reflectance models of the terrain have proven useful for representing an overall, accurate impression of the terrain and can improve maps intended for persons unfamiliar with symbols such as contours (Monmonier 1982). Holecheck (1981 p.544), used computer-generated relief images as a mechanism for the general validation of digital elevation models, "questionable elevation values are easily located since they produce recognizable anomalies in the resulting images". Mulder (1983) and DeGree (1985) also found hillshaded models to be particularly useful for detecting errors.

Production of digital reflectance maps is based on the theory that the apparent brightness of a surface element depends upon its orientation in relation to incoming solar radiation as well as the properties of the land surface. Horn (1982) gives an extensive and thorough review of some of the different models used for hillshading. Solar radiation incident on a land surface actually depends on five independent variables: terrestrial latitude, time of day, declination of the sun, surface inclination and surface orientation (Wilson 1970). The model requires input concerning the direction and angle of incoming solar radiation and assumes that the land surface is a Lambertian reflector: "an ideal surface that reflects all light incident on it and appears equally bright from all viewing directions" (Horn 1982 p.95). The parameters involved in the production of the model have also been applied to the classification of satellite imagery in an effort to reduce the topographic effect which varies as a function of solar elevation, azimuth and slope magnitude (Holben and Justice 1980; Smith et al. 1980; Hall-Koenyves 1987). The Lambertian reflectance model cannot completely simulate the radiances of all surfaces since a true Lambertian reflector is rare, with most surfaces having different reflectance properties. The Lambertian assumption varies considerably with cover type (Donker and Meijerink 1977). Smith et al. (1980 p.1183), state that the "Lambertian assumption may be more valid when analysis is restricted to slopes of less than 25 degrees and effective illumination angles of less than 45 degrees".

It has been cartographic practice to assume the light source is in the northwest at a 45 degree elevation above the horizon (Horn 1982). A distinct advantage of computer generated reflectance models is the ability to change the angle and orientation of the light source in order to produce a clearer image of the terrain form. If the landforms have the same orientation as the presumed light direction, the three-dimensional impression will be weak (Brassel 1974; Elvage 1980; Elvage and Lidmar-Bergstroem 1987). Maximum contrast occurs when a linear feature is orthogonal to the direction of the light source (Donker and Meijerink 1977). The light source may also be placed in a position which is astronomically impossible in order to enhance relief representation. People are usually able to interpret synthetic images when the light source position varies (Horn 1982). This is a distinct advantage over aerial photographs which are usually taken when the sun angle is high. Lo (1986 p.120) describes the use of low angle photography to detect subtle relief differences and to emphasize linear features, "the detection of photolineaments in terms of type, orientation and length is an important step to the understanding of the geological structure of an area".

Lambertian reflectance models were produced from the Fort McMurray and Kakwa DEMs (Plates 13 and 14). The sun angle was set at 45 degrees above the horizon, at an azimuth of 315 degrees, inducing the conventional three-dimensional effect of northwest lighting. The value of these models stems not only from their use as a quantitative source of insolation values useful to microclimate studies, but also by providing an effective method of displaying landform. The study area is displayed in a realistic manner, allowing an overall view of the terrain. To aid in the interpretation of the landforms, the raster contour maps were digitally overlain on the reflectance models (not shown).

Examination of the Lambertian reflectance model of the Fort McMurray study area (Plate 13), showed that the extremely wide and deeply incised valley of the Clearwater River dominates the map. The valley floor is approximately 1.5km wide and 140m deep on the north and 110m deep on the south side. The magnitude of this terrain feature is easily comprehended when the interpreter has a global view of the area, in contrast to the traditional means of studying a series of aerial photographic stereo-pairs. The banks of the Clearwater River itself are also visible and the river may be defined as an underfit stream flowing through the much larger glacial meltwater channel. The large terrace-like feature on the south side is evidenced by its lower elevation and the channel forms on its surface. The smaller, lower, terrace-like feature at the outlet of Christina Creek is also clearly shown by the three-dimensional model. The esker-like ridges 'flowing' into Rainbow Creek in the northeastern quadrant of the study area are actually present-day drainage features. They represent errors (previously discussed) contained within the data set.

The Kakwa Lambertian reflectance model provides a synoptic view of the mountainous, high relief terrain (Plate 14). Features that are discernable include: the cirques and aretes in the southwest corner; the valley of the Kakwa River flowing northeast along the eastern edge of the study area, including the large fluvial or glaciofluvial terraces; and the northwest trending foothills structure. The hillshading effect of the reflectance map highlights lineaments caused by the sharp ridges and deeply incised drainage valleys.

The Kakwa model provides a good example of the effect of the direction of the light source on the display of terrain features. Due to the northwest-southeast structural trend of the major terrain forms, many features may not be clearly emphasized due to the parallel orientation of the light source. Another reflectance model was produced using a light source azimuth of 225 degrees, simulating solar radiation from the southwest. The resultant image highlights linear features that were unclear in the first image. The resultant image emphasized many of the northwest-southeast trending structures.

Visual comparison of the Fort McMurray and Kakwa reflectance models allows for a rapid appreciation of the extremely different terrain types of these two Albertan examples. The smooth surface of the Fort McMurray area is indicative of the glaciolacustrine and glaciofluvial deposits overlying flat-lying sedimentary formations. The rough terrain apparent on the Kakwa model is characteristic to complex structural geology and the sharply defined glacially eroded cirques and aretes.

6. CONCLUSIONS

Mitchell (1973) defined terrain evaluation as a process which involves: analysis - simplification of complex natural phenomenon; classification - the organization of data and; appraisal - the interpretation and assessment of data. The previous discussions contained in this study have shown that models derived from digital elevation data satisfy the first two requirements of Mitchell's definition. The derivative products provide quantitative descriptions of terrain attributes which are necessary to any system of terrain evaluation. The final stage of the process, appraisal, involves the integration of the quantitative data with the qualitative terrain interpretation completed by a human analyst. The advantages of incorporating DTMs into any system of terrain analysis are numerous. The ability to map large areas using digital methods affords a synoptic view of the terrain surface coupled with the ability to enhance subtle variations, depending on the resolution of the original elevation data. Objective methods of displaying terrain attributes and classifying data have been a hindrance to traditional qualitative landscape methods of terrain analysis due to the intensive labour and high level of skill involved; the inability to maintain consistency due to the involvement of different workers and; the use of different classification schemes.

This study has not produced a terrain analysis system per se but rather, has provided an example of the type of quantitative terrain descriptions which may be generated objectively and consistently and then integrated into any detailed terrain analysis or evaluation system. One of the main advantages of digital data sets of terrain descriptors is the ability to reclassify the attributes for specific applications. The terrain parameters of elevation, slope magnitude, slope azimuth and directional curvature have been discussed in relation to their usefulness and application to a number of natural and 'man-made' processes. The Lambertian reflectance model, which incorporates slope magnitude and slope azimuth has also proven valuable as a graphic for analysing the terrain. Parameters may be integrated into sophisticated modelling schemes for process studies or predictive models for use in a variety of disciplines.

Digital terrain data is becoming more readily available due to the advances in remote sensing and image processing technology. The Alberta 1:20,000 DTDB mapping project is an example of the response to the growing need for objective, digital information concerning the land surface. The development of digital mapping and modelling systems are needed to handle this growing volume of data and also to provide a means of error checking. Objective, digitally produced products must be recognized as approximations of the real world and problems associated with the accuracy and precision of data should be addressed. The large volume of data generated by new remote sensing systems, which include digital elevation data exceeds the capability of trained interpreters. A computer-assisted modelling scheme will provide a convenient data base on which to form an objective land classification system, but the subjective human ability to relate different attributes to each other based on common sense and related background information cannot be replaced. Future terrain classification and analysis systems need to integrate the qualititative human interpretations with quantitative modelling techniques.

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APPENDIX I: PLATES

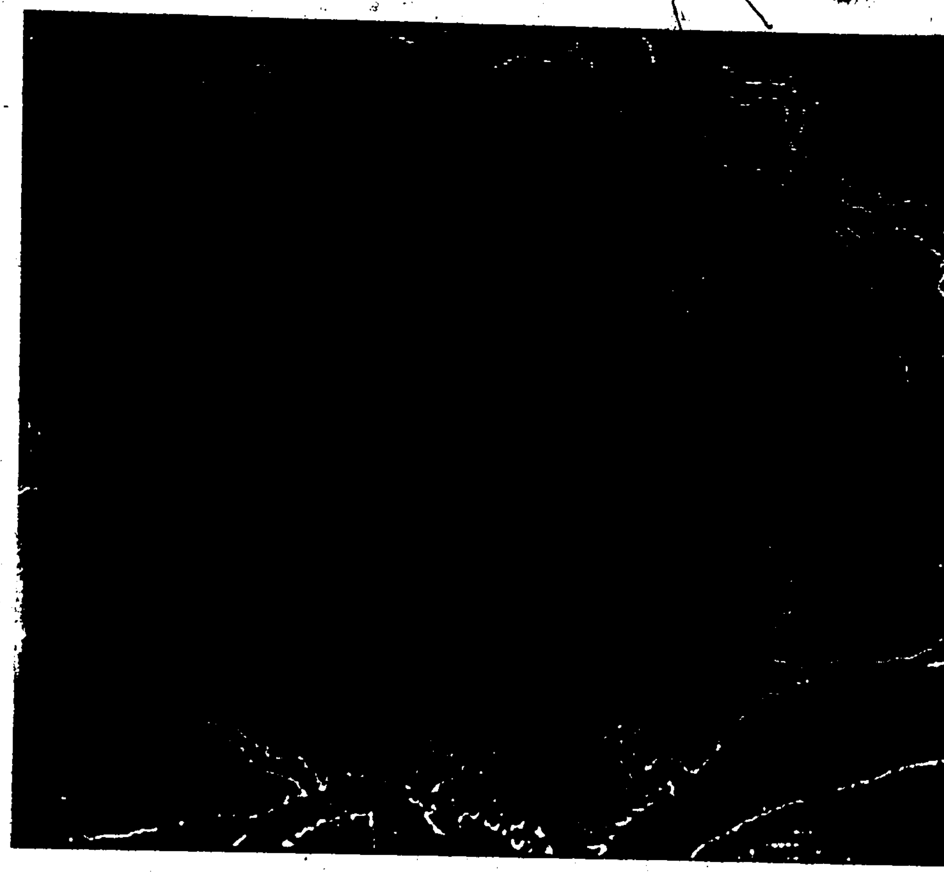

Plate 1. Aden grey scale Laplacian curvature map

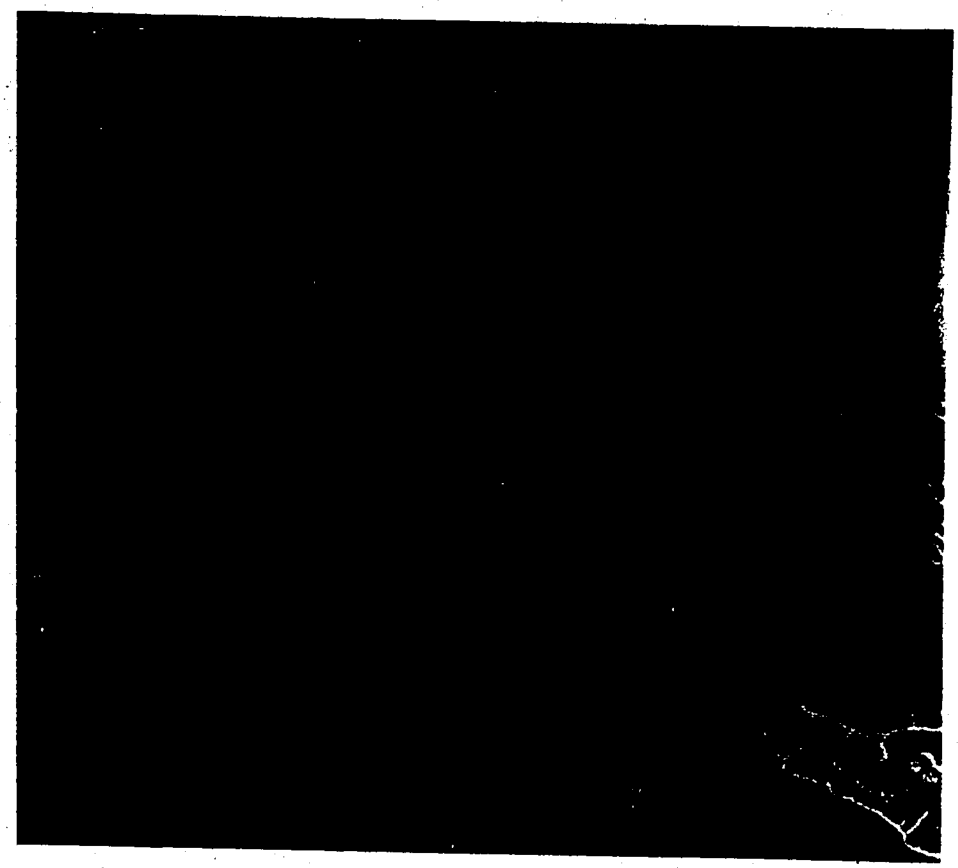

Plate 2. Fort McMurray grey scale Laplacian curvature map

Plate 3. Kakwa grey scale Laplacian curvature map

Plate 4. Fort McMurray grey scale slope magnitude map

THE QUALITY OF THIS MICROFICHE IS HEAVILY DEPENDENT UPON THE QUALITY OF THE THESIS SUBMITTED FOR MICROFILMING.

UNFORTUNATELY THE COLOURED ILLUSTRATIONS OF THIS THESIS CAN ONLY YIELD DIFFERENT TONES OF GREY.

LA QUALITE DE CETTE MICROFICHE DEPEND GRANDEMENT DE LA QUALITE DE LA THESE SOUMISE AU MICROFILMAGE.

MALHEUREUSEMENT, LES DIFFERENTES ILLUSTRATIONS EN COULEURS DE CETTE THESE NE PEUVENT DONNER QUE DES TEINTES DE GRIS.

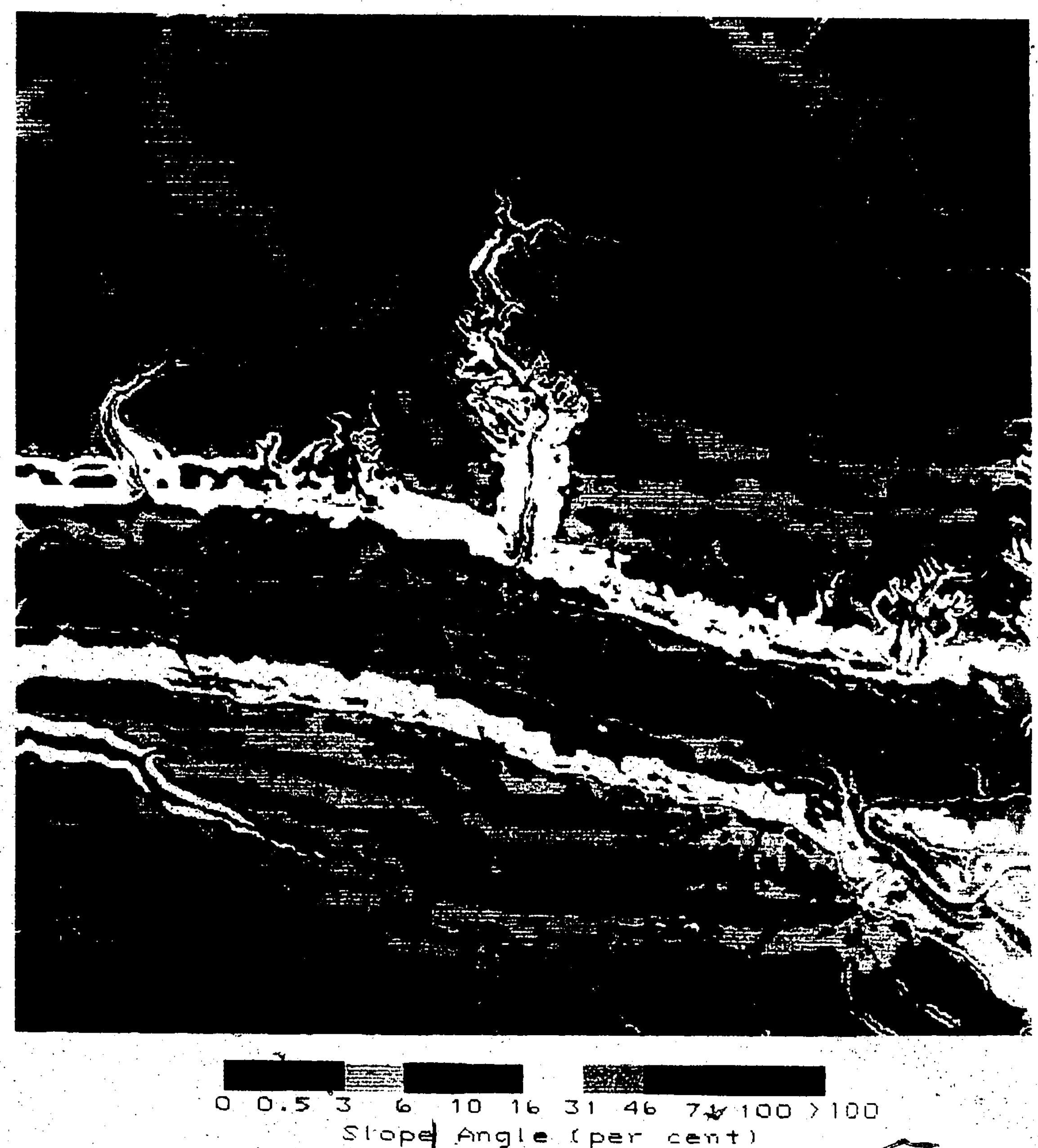

Plate 5. Fort McMurray classed slope magnitude map

Plate 6. Kakwa grey scale slope magnitude map

Plate 7. Kakwa classed slope magnitude map

Plate 8. Kakwa classed slope azimuth map

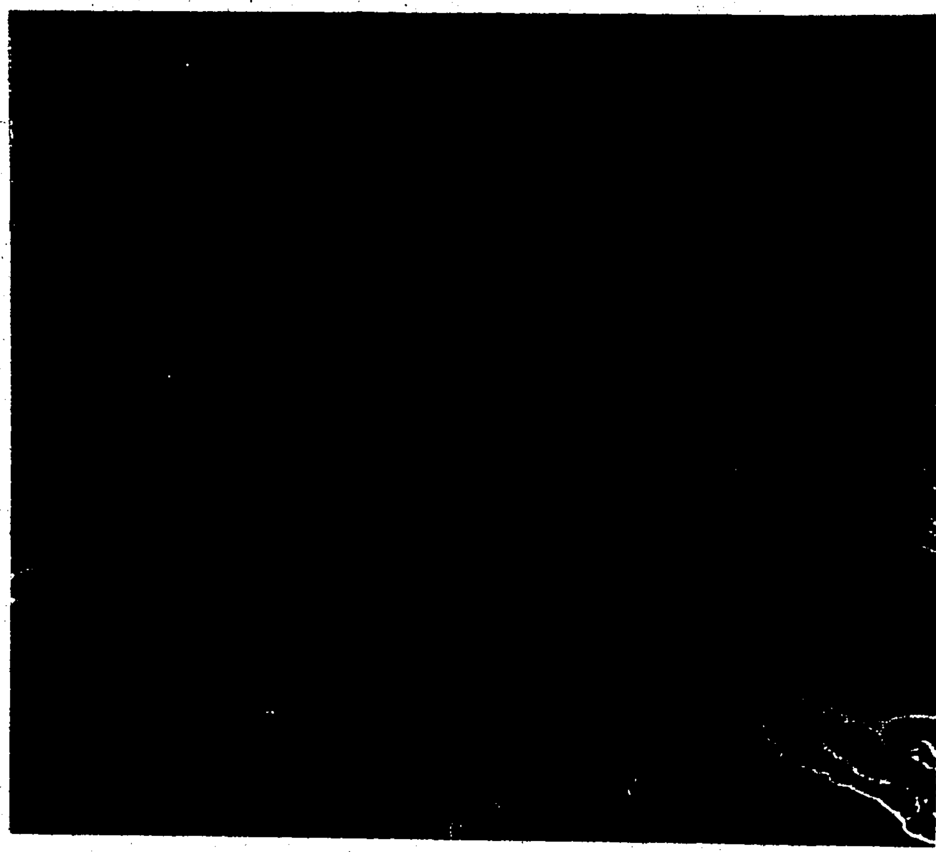

Plate 9. Fort McMurray grey scale downslope curvature map

Plate 10. Kakwa grey scale downslope curvature map

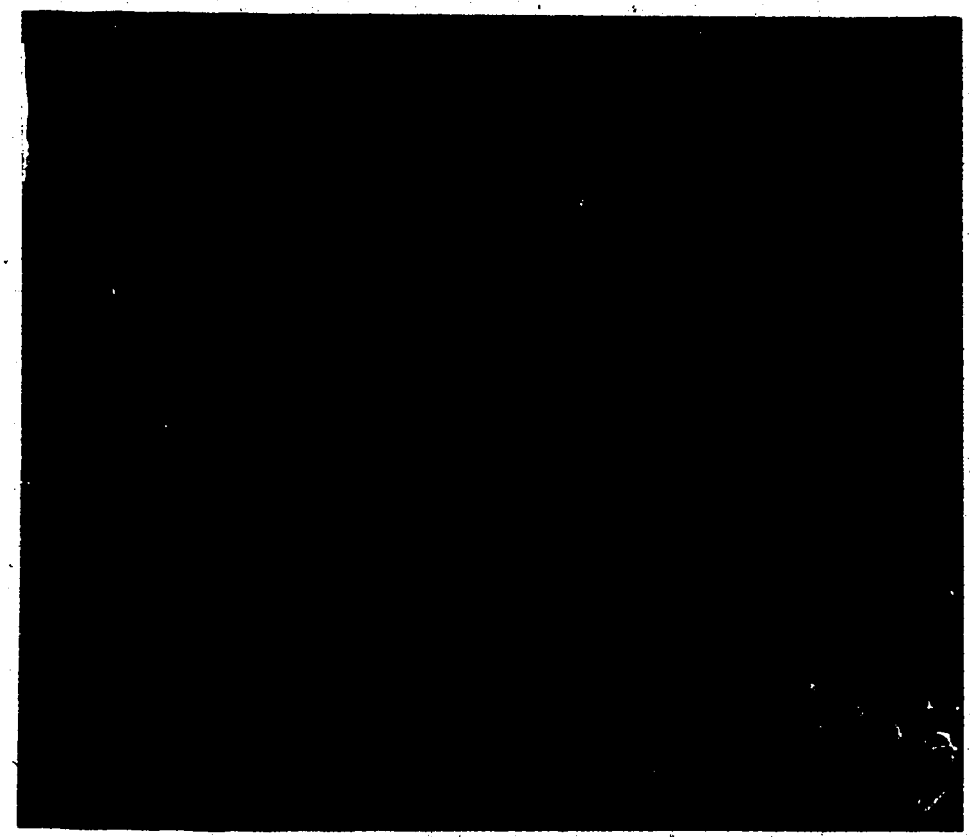

Plate 11. Fort McMurray grey scale across slope curvature map

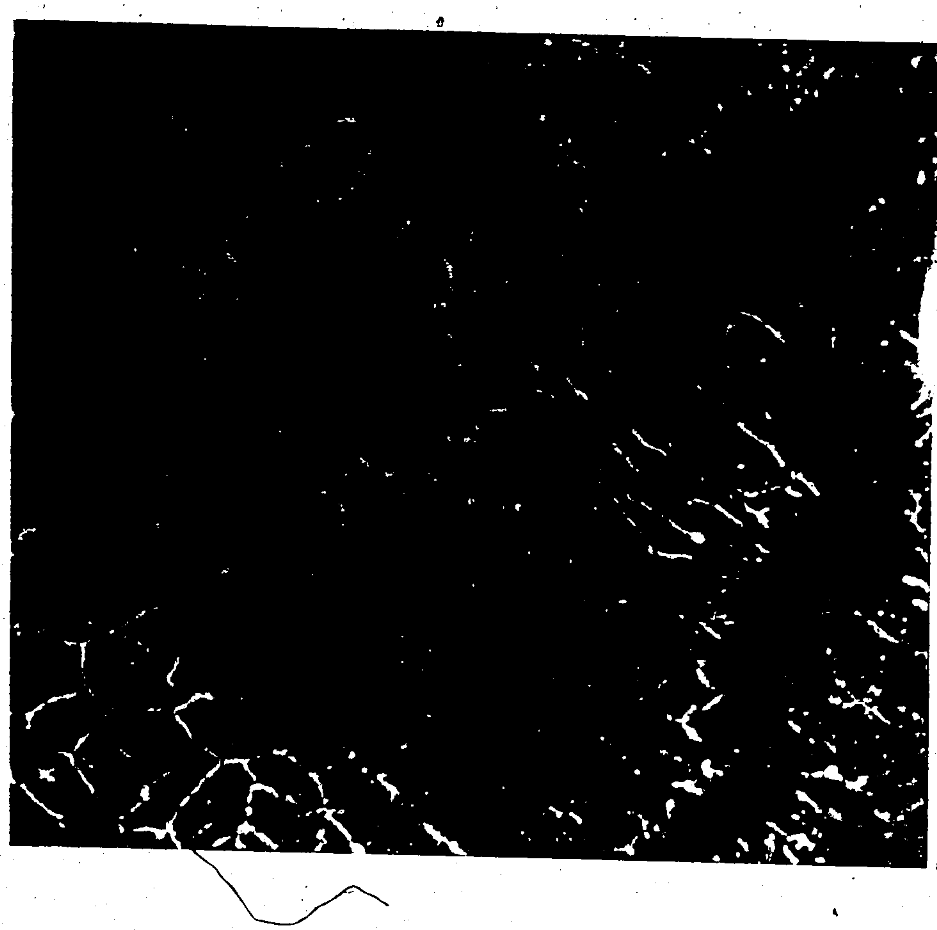

Plate 12. Kakwa grey scale across slope curvature map

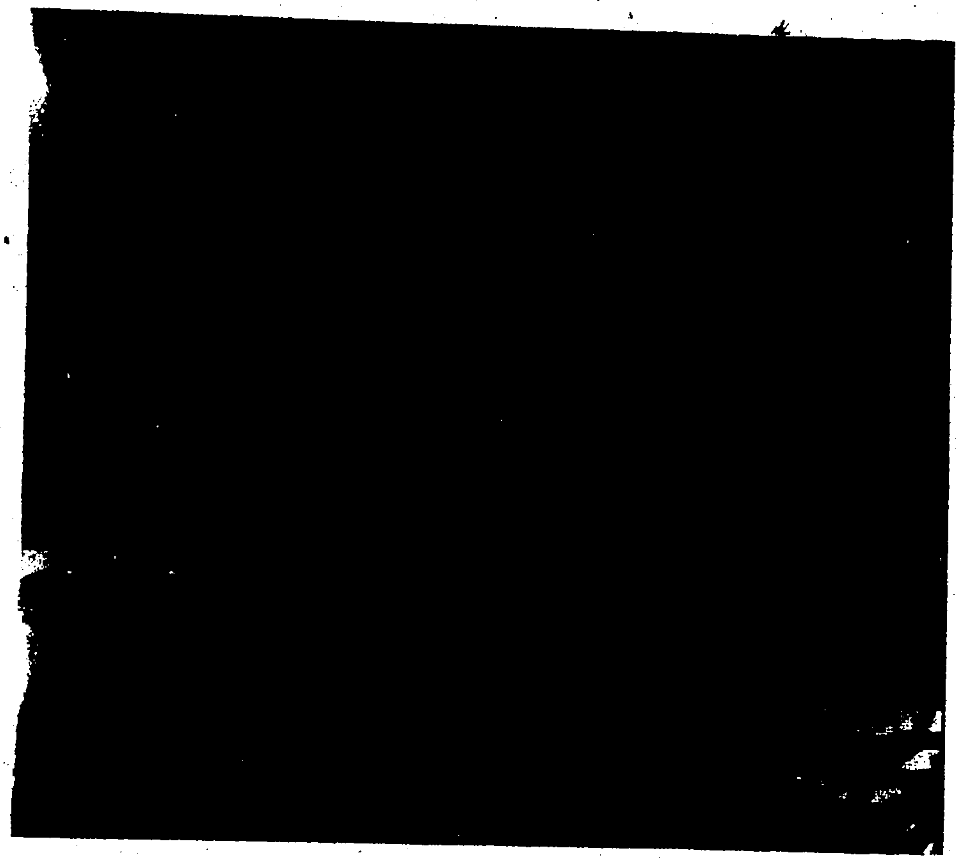

Plate 13. Fort McMurray Lambertian reflectance map

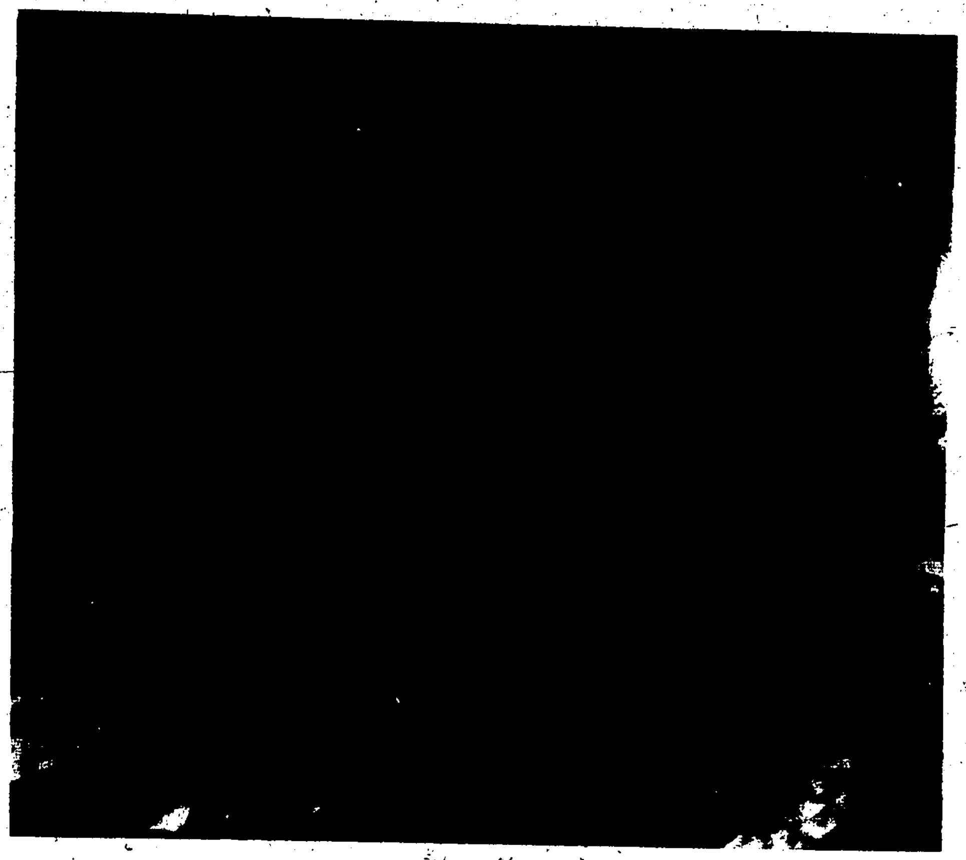

Plate 14. Kakwa Lambertian reflectance model